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An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards

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ABSTRACT

To bring to fruition the capability of nature-based solutions (NBS) in mitigating hydro-meteorological risks (HMRs) and facilitate their widespread uptake require a consolidated knowledge-base related to their monitoring methods, efficiency, functioning and the ecosystem services they provide. We attempt to fill this knowledge gap by reviewing and compiling the existing scientific literature on methods, including ground-based measurements (e.g. gauging stations, wireless sensor network) and remote sensing observations (e.g. from topographic LiDAR, multispectral and radar sensors) that have been used and/or can be relevant to monitor the performance of NBS against five HMRs: floods, droughts, heatwaves, landslides, and storm surges and coastal erosion. These can allow the mapping of the risks and impacts of the specific hydro-meteorological events. We found that the selection and application of monitoring methods mostly rely on the particular NBS being monitored, resource availability (e.g. time, budget, space) and type of HMRs. No standalone method currently exists that can allow monitoring the performance of NBS in its broadest view. However, equipments, tools and technologies developed for other purposes, such as for ground-based measurements and atmospheric observations, can be applied to accurately monitor the performance of NBS to mitigate HMRs. We also focused on the capabilities of passive and active remote sensing, pointing out their associated opportunities and difficulties for NBS monitoring application. We conclude that the advancement in airborne and satellite-based remote sensing technology has signified a leap in the systematic monitoring of NBS performance, as well as provided a robust way for the spatial and

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temporal comparison of NBS intervention versus its absence. This improved performance measurement can support the evaluation of existing uncertainty and scepticism in selecting NBS over the artificially built concrete structures or grey approaches by addressing the questions of performance precariousness. Remote sensing technical developments, however, take time to shift toward a state of operational readiness for monitoring the progress of NBS in place (e.g. green NBS growth rate, their changes and effectiveness through time). More research is required to develop a holistic approach, which could routinely and continually monitor the performance of NBS over a large scale of intervention. This performance evaluation could increase the ecological and socio-economic benefits of NBS, and also create high levels of their acceptance and confidence by overcoming potential scepticism of NBS implementations.

1. Introduction

Hydrometeorological hazards (HMHs) are the outcomes of the processes or phenomena of hydrological, oceanographic or atmospheric origin that may cause socio-economic and environmental losses (UNISDR, 2009). These include floods, droughts, heatwaves, landslides, storm surges and coastal erosion, excess nutrient loadings, etc. The probability of occurrence of such undesirable events of grave danger at a particular time and place is called hydrometeorological risk (HMR). In response to HMHs, HMRs are modulated by the ecosystem, given its vulnerability and adaptability. The intensity, duration, and frequency of hydro-meteorological (HM) events, as well as the scale of affected areas, have been projected to increase and aggravate HMR, owing to global warming and concomitant climate change (IPCC, 2018). Adaptation and mitigation measures for HMRs are mostly structural (built/grey/engineered) and non-structural (forecasting, early warning and evacuation). Structural or grey approaches are the hard, engineered built up measures to manage HMRs to human lives, their assets and environments. For example, floodgates, storm sewers, dikes, pipes, and other drainage systems are grey measures for stormwater management. These man-made structures are often constructed by using traditional building materials i.e., concrete, steel, or other long-lasting materials. They are designed to avoid any type of ecosystem to flourish on it and are not flexible, sustainable, and resilient with the on-going urbanisation and climate change. The structural measures, such as construction of large sea walls, levees, embankments, breakwaters and concrete dams to prevent coastal and riverine flooding, are expensive and lack long-term sustainability in a spatial frame (Jones et al., 2012; Kitha and Lyth, 2011). Their failure can have catastrophic impacts on societies and ecosystems (Debele et al., 2019). These shortcomings of traditional, technology-based measures paved the way for disaster mitigation experts and policy-makers to introduce nature-based solutions (NBS), a novel approach, inspired by or copied from nature and a more efficient, cost-effective and sustainable measure to mitigate increasing HMRs.

The International Union for Conservation of Nature has defined NBS as measures to preserve, reinstate and control the natural or altered ecological systems in an adaptive manner. It encourages sustainability values in the process, thereby not only solving the environmental or social obstacles but also inducing human mental and physical wellbeing by providing positive environmental externalities of increased biodiversity (Cohen-Shacham et al., 2016). NBS can be green (vegetation-based), blue (waterbody-based) or hybrid (different combination of green and blue NBS with grey structural measures) (Debele et al., 2019; Martín et al., 2020; see Supplementary Information (SI) Section S1, Table S1). The relative performance and efficacy of NBS with respect to that of grey solutions is an essential factor to be considered while opting them for mitigating HMRs. Such NBS, if designed and constructed properly, would need lesser maintenance and be more cost-effective and efficient over a longer period (Naumann et al., 2014). Nature's energy augment the robustness and competence of the systems (e.g. recovery after forest fire, natural bending of rivers, wetlands) and deliver viable providence to the sector (Kabisch et al., 2016; Villegas-Palacio et al., 2020; Schaubroeck, 2017). The assessment of NBS will encourage citizens' involvement and create trust among stakeholder groups during the implementation phase of NBS and beyond (Kabisch et al., 2017; Kumar et al., 2020).

Monitoring is a process of measuring, recording and comparing the achievements against a set of predefined targets, and thereby informing the project outcomes to the managers and policymakers to assist them in decision-making. It is usually carried out throughout the lifespan of NBS projects (ex-ante and ex-post project execution stages; Fig. 1), either by internal (individuals or project participants) or external organisations/institutes (e.g. European Commission), or in a collaborative way for assessing performance and effectiveness of NBS, revealing their wider benefits and impacts. It is a transversal and continuous process, which needs to be carried out across all stages of NBS operationalisation (Raymond et al., 2017a, 2017b). This 'across all stages' approach helps devising long-term plans and goals (Kabisch et al., 2016) for an effective NBS implementation utilising the acquired knowledge about NBS functioning (Connop et al., 2016). Monitoring should be carried out before as well as after the implementation of NBS. In the pre-NBS implementation phase, record datasets from municipalities, past monitoring studies, statistical databases/platforms, peer-reviewed and grey (i.e., materials and research produced by organisations outside of the traditional commercial or academic publishing and distribution channels) literature, interviews, workshops and questionnaires are used to set the baseline/reference period of monitoring. In the post-NBS implementation phase, on- and off-site monitoring of physical (e.g. land use, green NBS growth rates) and socio-economic (cost/benefit data and social changes, e.g. migration rates) indicators are carried out.

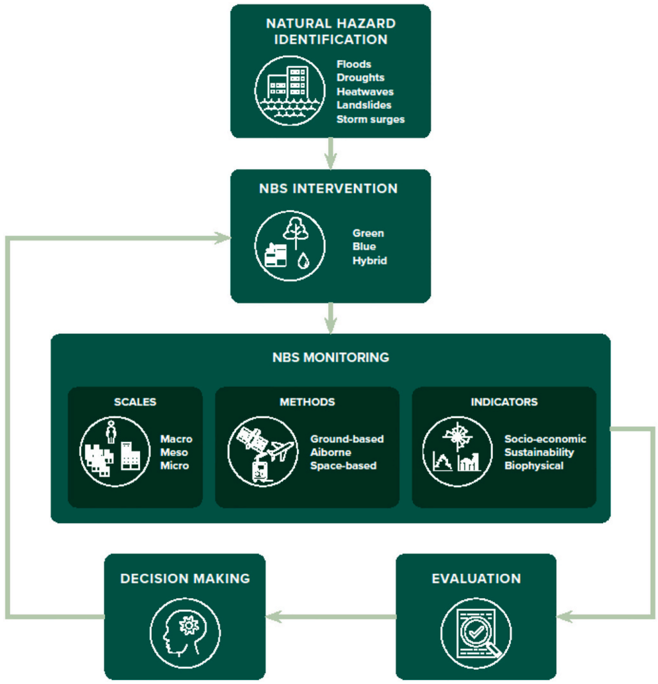

Fig. 1. A schematic diagram showing the NBS monitoring cycle along with the potential methods, technologies and the scale of monitoring.

Evaluation is performed by comparing the information available from different monitoring sources and fieldwork with present targets, such as annual targets compared to annual achievements or long-term targets to cumulative annual achievements to assess NBS effectiveness and impact. The NBS project monitoring and evaluations set out three major intentions: (1) offer information and response for further advancements and timely execution of the project, (2) account for the expenses made, and (3) fill the gaps for effective and successful implementation of future projects. Precise and measurable 'Key Performance Indicators (KPIs)' and 'key impact indicators (KIIs)' are required to monitor the potential effects of NBS implementation on specific HMRs and their possible mitigation by influencing the three crucial risk components: the intensity, commencement and spreading probabilities (Section 3).

Extensive works (Table 1) have often focused exclusively the use of NBS in addressing issues, such as, global warming, food safety and water supplies or HMRs (Kabisch et al., 2016; Wendling et al., 2018; Debele et al., 2019; Sahani et al., 2019; Keesstra et al., 2018; Moos et al., 2018), its progress, performance and impact (Klein, 2020; Yu et al., 2020), and co-planning, co-design, co-management and implementations (Kumar et al., 2020; Nesshöver et al., 2017; Raymond et al., 2017a, 2017b; Paul et al., 2018; Paulet et al., 2018). Raymond et al. (2017a, 2017b) emphasised on developing indicators to measure the efficacy and achievement of different NBS. Others studied classifications and principles of NBS (Cohen-Shacham et al., 2016; Nesshöver et al., 2017; Depietri and McPhearson, 2017; Debele et al., 2019) and indicator-dependent risk and vulnerability assessment framework in NBS settings (Raymond et al., 2017a, 2017b; Shah et al., 2020). Very few studies have explicitly reviewed existing methodologies to measure the impacts, performances and co-benefits of NBS (Raymond et al., 2017a, 2017b; Nika et al., 2020). While Dumitru et al. (2020) derived a set of principles for developing an efficient impact evaluation framework for NBS, yet an authoritative list of internationally acknowledged methodologies, manuals or guidelines, monitoring tools, instruments, sensors and indicators is lacking throughout the scientific databases for tracking the changes caused by NBS and analysing its advantages and disadvantages. Such routinely and globally applicable information is needed in 'climate change adaptation (CCA)' and 'disaster risk reduction (DRR)' for keeping various stakeholders (emergency response agencies, disaster mitigation experts, researchers, policymakers, and insurance companies) up-to-date with recent developments and future pathways towards upscaling and replication of NBS. This universal approach can guide the selection of the most appropriate monitoring methods, benefits and potential trade-offs while escaping unenviable and economically destructing characteristics of other methods in practice.

Thus, this review intends to tackle the following questions: What are the standard indicators and optimal/robust methods to measure and monitor the performance of NBS? What are their main advantages and disadvantages? In particular, we (1) provide a systematic review of the broadly utilised approaches for the performance and impact monitoring of NBS; (2) identify the advantages and limitations of the most used approaches to catalyse their enhanced uptake in future; and (3) offer recommendations to future studies to enhance the knowledge base in this significant research field.

This article is structured into eight sections starting with a discussion and review on the importance of monitoring the NBS for HMR mitigation (Section 1), followed by the methodology adopted (Section 2). We discussed the indicators used for monitoring and assessing the NBS performance, along with their selection criteria, types and scale, in Section 3. Section 4 describes how these indicators are utilised in various NBS monitoring methodologies for the five selected risks. Section 5 analyses the monitoring techniques for different hazards, their advantages and limitations. Section 6 provides conclusions underlining the opportunities and prospective advancements for further research considering current challenges in developing an NBS monitoring framework, to allow practitioners and scientists to decide the best monitoring method based on NBS geography, phenotype, climate and

Table 1
Summary of past review papers on design, implementation, effectiveness and performance of NBS.

Article focus and key findings	Reference
• Through a SLR, the impact assessment of NBS in Europe was reviewed and four conceptual challenges and three practical barriers were identified that hinder the build-up of robust proof regarding the efficiency of various kinds of NBS for various social classes; their efficiency, resilience and sustainability. • Upon the identified gaps, a series of standards were derived to lead the advancement of strong impact evaluation methodology for NBS.	Dumitru et al. (2020)
• Through a SLR, the available techniques, approaches and indicators that have been applied to measure NBS performances for water balance management under both anthropogenic and natural elements were summarised. • They found that the multiple benefits of NBS for hydrological cycle monitoring were not properly monitored and evaluated. Therefore, a holistic approach evaluating complete water cycles is still required integrating existing tools and integrating current and/or recently advanced indicators.	Nika et al. (2020)
• Reviewed current showcases of conventional built wetlands and incorporated with NBS such as green walls and roof for wastewater purification and reutilisation, with a particular target on their purification efficiency as a function of hydraulic working variables. • Results from the reviewed studies on groundwater treatment applications showed good purification efficiency, showing the applicability of these methods in treating local groundwater.	Boano et al. (2020)
● Reviewed the performance and impact of different trees and forest species that could resist drought. ● To achieve the robust and effective results of drought tolerant forest species, continuous monitoring of tree health was suggested to be further improved with the adoption of the standards of the European forest monitoring network.	Klein (2020)
● The latest progress and impact of green-blue areas (waterbodies, greenspaces, and parks) on the cooling effects of urban areas were evaluated. ● The green-blue areas' cooling effects are the key factors that contribute to mitigate urban thermal discomfort and need more attention. The design, scale and size of city green area, including the element and structure, could also be assumed in their efficiency; and, for the city greenery, the maximum portion of green-blue areas requirement need to be solved.	Yu et al. (2020)
● Aimed to develop an indices focused exposure and risk evaluation method in the concept of NBS by considering established NBS principles. ● The developed method targeted to permit a good assumption of the many benefits given by NBS and which influence the entire components of risk.	Shah et al. (2020)
● The deployment of NBS by using the notation of 'Open-Air Laboratories (OAL)' was shown to play a vital role in wider acceptance of the NBS. ● The OAL can serve as the basis for NBS wider uptake and use in decision-making processes via measuring by field experiments, assessing using indicators and developing strong tangible evidence on their multifunctionality in various climate, ecological, and socio-economic circumstances.	Kumar et al. (2020)
● The application of NBS for HMH intervention, their categorization, efficiency, profitability and databases were reviewed. ● Based upon the site, climate situations and design of NBS (i.e., roof slope and depth, greenery, urban spaces, and roof architecture), the lowest noted decrease of HMH by NBS was 5%, while the optimum decrease reached up to 100%. The comparison between NBS and grey approaches showed that up to 85% of the HMH reduction by applying NBS was cost-efficient.	Debele et al. (2019)
● Types of NBS were presented and their importance of promotion was discussed for HMH management, in particular for three HMH- floods, droughts and	Sahani et al. (2019)

(continued on next page)

Table 1 (*continued*)

Article focus and key findings	Reference
heatwaves, after detailing their existing risk assessment methodologies.	
● EKLIPSE, and Smart City Performance Measurement Framework (CITYkeys) projects were extensively examined as NBS with regard to Sustainable Development Goal (SDG11). ● The NBS assessment scheme should be selected strategically, which should align with the sub-objectives of SDG11 so that their operational efficiency can be increased.	Wendling et al. (2018)
● Evaluated NBS co-profit through different problem fields considering useful indicators and approaches using schemes consisting of a seven stage NBS implementation process. ● Challenges to be solved by NBS are multidimensional and sophisticated, hence the selection and appraisal of NBS and associated issues need the engagement of a broader range of stakeholders, cross-disciplinary groups, and decision and policy-makers.	Raymond et al. (2017a, 2017b)
● The significance of NBS amongst research, end user and real world targets in the European context was discussed. ● To recognise the complete performance of NBS, their advancement and co-advancement must include the lessons learnt, needs and attitudes of all relevant practitioners. Thus 'solutions' can support to achieve entire elements of sustainability.	Nesshöver et al. (2017)
● Aimed to find out different circumstances in which NBS are appropriate for CCA in city regions and to recognise indicators for evaluating the efficiency of NBS. It also explored current gaps and feasible chances for enhancing the scale and potential of NBS excursion through a multidisciplinary workshop with professionals from science, local authorities, policy, and citizens. ● A broader area of feasible indicators was recognised through the course of the stakeholder meetings. The recognised indicators had a particular target on relative evaluation of NBS both at urban level and among cities.	Kabisch et al. (2016)

customised goals, either in terms of social, economic or ecological benefits.

2. Methods and scope

We used systematic literature review (SLR) approach for identifying, screening and filtering suitable, peer-reviewed and grey literature from different scientific databases: Web of Science, Scopus, ScienceDirect and Google Scholar etc. These databases are overarching and enclose a wide domain of various disciplines. Fig. S1 shows the adopted approach, the number of papers considered in this review and ground for elimination of other papers. A strand of keywords (Table S2) was put in for different hazard's NBS, and the exploration in these scientific databases amounted 10,125 journal reviews, research papers and credible reports deemed for full-text review (after removing duplicates). Out of 10,125 articles, 9,110 publications were eliminated from full-text review based on their titles, abstracts and conclusions. We carried out a further screening and eliminated 753 papers from 1,015 papers based on types of hazards, scope, lack of focus on NBS indicators, methods and technologies used to monitor NBS performance and language of study to include only the most suitable scientific papers. The approach led to a total of 262 articles for meta-analyses and discussion in this review. The temporal distribution of studies included has been shown in Fig. 2a. The distribution of the selected literature by topic area revealed that 44.7% of the articles and reports addressed monitoring methods, tools, instruments and sensors for HMRs and HMHs, 1.9% addressed NBS monitoring, 10.7% covered NBS performance and impact indicators, 33.2% covered five HMRs (floods, 9.9%; droughts, 3.8%; heatwaves, 4.2%; landslides, 2.3%; and storm surges and coastal erosion, 13.0%) focused in this paper while 9.5% covered other concepts, such as climate change, monitoring scales, other HMHs etc. (Fig. 2b and 2c). In terms of geographical distribution, all included papers cover 55 different countries across the world where the maximum contribution was from the USA (69 papers) (Fig. 2d). Continent-wise distribution showed that 57.2% of papers came from the Europe and North America (28.8% and 28.4% respectively) while 42.8% of the papers were documented from rest of the world: Asia, 19.3%; Global (i.e., multi-country NBS case studies), 14.7%; Africa, 6.2%; South America, 1.3%; and Australia, 1.3% (Fig. 2e).

We limited the review to articles written in English and issued between 1965 and 2021. Some applicable articles might have been excluded from our review because of: (1) the search strand applied and (2) the language of articles. The scope of paper includes reviewing various monitoring methods and techniques for the monitoring of NBS benefits not only in terms of reducing the five key HMRs (floods, droughts, heatwaves, landslides, and storm surges and coastal erosion) immediate consequences but also for other co-benefits, such as socio-economic ones. A review of specific details concerning the operation of various equipment used for ground-based, airborne and space-based observations and/or their maintenance are beyond the scope of this work.

3. NBS performance and impact monitoring indicators

An indicator can be a qualitative or quantitative variable or statistic that allows measuring variations in a particular phenomenon, situation, value, quality or attribute regarding a specific purpose (Martins et al., 2018). Haase et al. (2014) defined an indicator as a tool which contains verifiable data useful to convey some information, e.g. markers of the progress towards achieving project objectives. The attributes of any NBS project performance (efficiency, cost-effectiveness and other characteristics) against outlined targets can be measured/monitored, analysed and communicated through standard NBS indicators (Sparks et al., 2011). Indicators are measured with respect to baseline and target testimonial values. Baseline values describe the circumstances at the kick-off of the project while targets describe the required state after the considered period. In general, the following aspects must be determined in order to build an indicator: (1) the intended and achievable objectives of the project (underlying problems); (2) the typology of NBS and their attributes; (3) the characteristic of NBS to be measured; (4) the scale (spatial and temporal) of monitoring, which affects the accessibility and significance of data for specific indicator; (5) the potential anticipated repercussions, including positive (synergies) and negative (disservices or trade-offs), direct and indirect; (6) the assets and expertise accessible for measuring the outcomes; (7) the correct interpretation of their values. Their maximum and minimum values and their qualitative significance should be stated (FAO, 2017). Thus, indicators are a salient means of appraising the latent performance and the true efficacy of particular NBS operations. We further elaborate on the concept of performance and impact monitoring of NBS in Section 3.2 and Section 3.3.

3.1. Selection of indicators

Binnendijk (2001) noted that as indicators are chosen based on project aims (impact indicators), its works (work or process indices), and results (outcome indices), the selection of indicators for NBS performance and impact monitoring depends on the needs of the end-users (i.e., stakeholders, such as farmers, researchers, funding agencies or policymakers). For instance, several studies in the past selected and categorized NBS achievement and effect indicators based on their goals, applications and measurability, into three main groups: (1) *biophysical indicators* (Nambiar et al., 2001), (2) *socio-economic indicators* (Darin-Mattsson et al., 2017) and (3) *sustainability indicators* (Keeble et al., 2003). These three main categories are further subdivided into different sets of indicators. We present a comprehensive list of HMH associated indicators in terms of HMH characteristics and socio-ecological effects

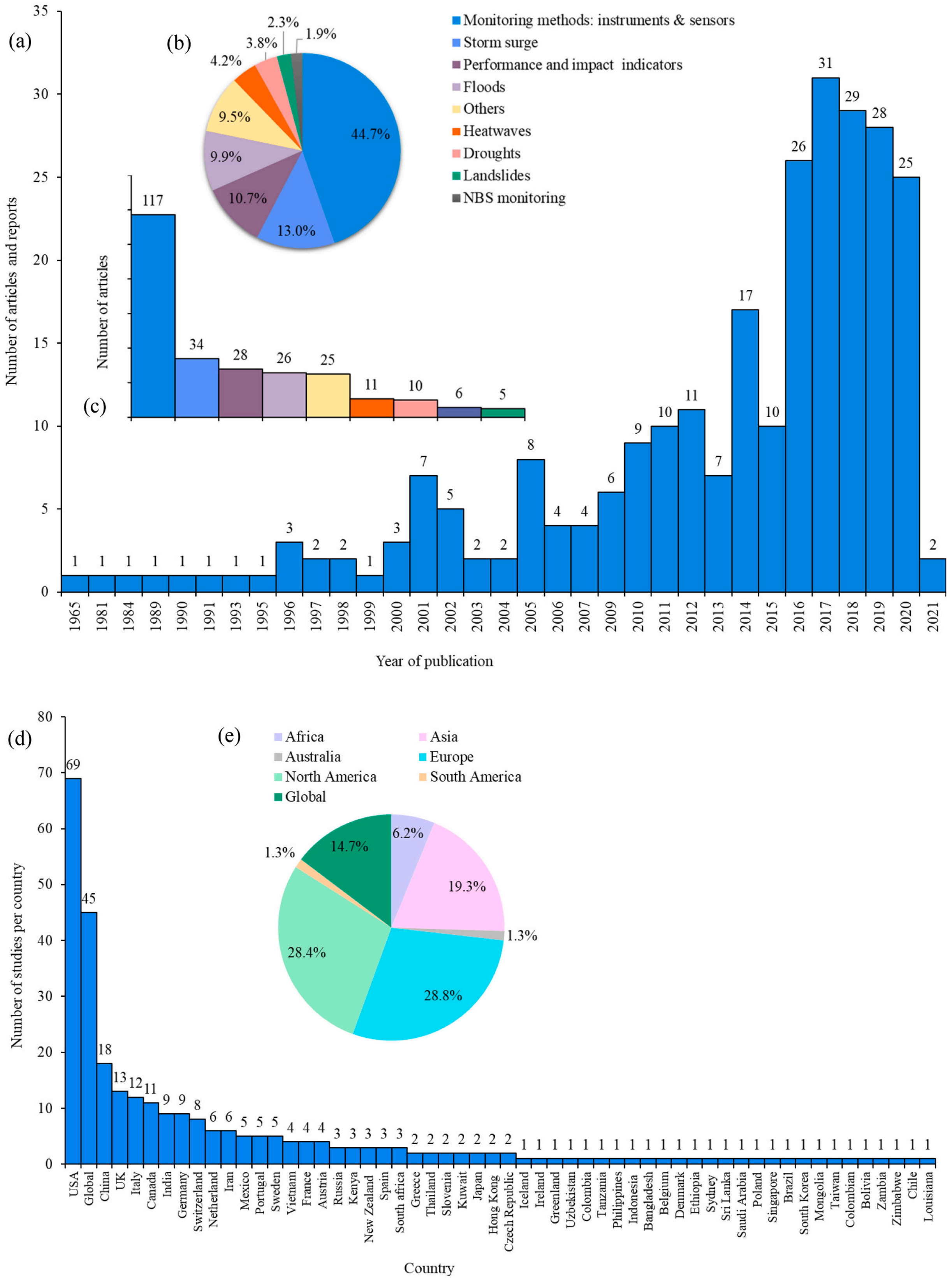

Fig. 2. (a) Full-text articles (262) included in the review by year of publication; (b) percentage and (c) numbers of relative contributions regarding the topic areas covered in this review, (d) number of papers per country, and (e) percentage distribution per continent.

for analysing the NBS performance and impacts at any scale of implementation in Fig. 3. Tables S3 provides the corresponding detailed information presented in Fig. 3, and a summary of common indicators extracted from Table S3 are presented in Table S4. HMR indicators normally describe extreme event attributes, such as their severity, extent, periodicity or appositeness for its mitigation by different measures, e.g. NBS (Kumar et al., 2020). These indicators have the capacity to systematically and scientifically assess the benefits and co-benefits of various NBS interventions on biophysical and socio-economic spheres as well as on health, well-being and sustainability criteria. Distinguishing key indicators of NBS performance start with an initial engagement of stakeholders and continue to progress throughout the NBS co-creation process (Pagano et al., 2019). The indicators developed in such a participatory way are called subjective indicators, which is a good method for non-recursive processes in the project and training exercise, e.g. while designing, planning or ex-post assessment of the project's desired and undesired effects (Vahlhaus and Kuby, 2001; López-Ridaura et al., 2002). At the same time, there is a tendency to formulate more consistent and objective indicators through the inclusion of impact modelling, which allows differentiating outcomes from different appraisals, e.g. comparing results of different or same NBS projects within the same region or at different times, respectively while operationalisation. For the sake of measurability, quantifiable objective indicators are better (Dumanski and Pieri, 2000). In general, selecting suitable indicators for NBS performance monitoring is a crucial and complex task, considering that they have to be measurable, simple, achievable, less time-consuming and are relevant to the objectives of the project.

3.2. NBS indicators

KPIs are measurable parameters that keep track of the project towards achieving its objectives. KPIs are derived from environmental (e.g. hydro-meteorological) and socioeconomic variables. KPIs describe progress made towards higher-level goals (e.g. contribution of NBS to improved food safety, human well-being and life standard). Impacts are normally the long-lasting consequences of a project. Long duration projects need their effects to be measured to corroborate the improving conditions of the expected beneficiaries. In this case, partners and stakeholders could monitor effects via the pre-evaluated set of impact indicators. For instance, using impact indicators in a soil and water conservation project, there may be a need to monitor the effect of erosion preventive plans on temporal crop production in the project region. In this scenario, impact evaluation would be considered as impact monitoring.

Various potential indicators of NBS performance and impact have been issued in the scientific publications (e.g. Calliari et al., 2019; Faivre et al., 2017; Nel et al., 2018; Wendling et al., 2018). Kabisch et al. (2016) identified four kinds of NBS performance indicators: (1) indicators for consolidated ecological performance, (2) indicators of mankind fitness, (3) indicators for public participation, and (4) transferability indicators, which can be applied to multiple NBS. The use of these indicators depends upon the type of NBS adopted (Section 4). Some examples of performance indicators for NBS could be runoff factor in terms of rainfall quantities (mm/%) (Armson et al., 2013; Getter et al., 2007; Iacob et al., 2014; Scharf et al., 2012), flood waves and time to peak (Iacob et al., 2014), groundwater availability, water and soil moisture retention capacity (Feyen and Gorelick, 2004), crop yield, the absorption potential of greenery, bioaccumulating structures and trees (Armson et al., 2013), pollutants degradation, heavy metals and nutrients, enhanced evapotranspiration (Litvak and Pataki, 2016), temperature and energy cutting for cooling (Demuzere et al., 2014), improvement in human health and biodiversity, carbon storage capacity (Raymond et al., 2017a, 2017b). Indicator values for NBS performance can help decision-makers to include them in administration and budget allocation for developing a particular NBS as a climate change mitigation measure.

3.3. Monitoring scale for NBS

HMRs impact natural environment, human life and infrastructure at different scales. The monitoring of an NBS project needs to take into account both spatial (area affected by NBS implementation) and temporal (the time duration at which NBS responds to HMHs and becomes fully effective) scales. It is recognised that NBS impacts vary across these scales and it is important to determine critical thresholds for monitoring NBS performance at any scale of implementation which starts from the local level (i.e. roadside, roofs, walls and gardens). The scale at which a pre-defined NBS performance indicator can be monitored depends upon the project objectives. Past studies have monitored NBS at micro, meso, macro, and mega spatial scales (Haghighatafshar et al., 2018), and short, medium and long-term temporal scales by which individual NBS actions become fully effective (Raymond et al., 2017a, 2017b).

The *spatial scale* over which the NBS performance can be monitored varies with the kind of NBS selected, the extent of its implementation and the effect considered. For example, the efficiency of green NBS or a rainwater harvesting facility can be monitored at the micro-scale of a single house; advantages of reduction in run-off and so the flood can be monitored at the micro (roadway, locality, neighbourhood) or meso (village, town, city) scales. The effects monitored at micro-scale can help quantify the effects at meso or macro scales. For example, the impact of NBS on urban heat island (UHI) can be quantified at micro-scale (house) and explained in terms of money saved due to lesser heating and cooling energy demand. In contrast, the associated depletion in carbon can be reflected at the meso (village/city) and macro (country/continent) scales.

Physical dynamics, such as heat and pollutant fluxes, water flows etc., help in quantifying NBS impacts at different scales. For instance, the enhanced shading and evapotranspiration impacts of heatwaves-NBS are not only because of their types, dimensions and the location but also due to heat fluxes established by the street or urban morphology (Gunawardena et al., 2017). In many impact monitoring scenarios, the change brought about is too small to be measured at the micro-scale but is crucial for the change at mesoscale. For instance, the mass of air pollutants removed by green NBS may not be measurable at the micro-scale (tree surrounding) but can show significant results at the meso-scale. The social benefits of NBS, such as access to green parks or natural surroundings with ecological interactions, can be monitored often at the local community scale. But these impacts also interplay at larger scales (macro and mega) and so there exists a future scope for such studies (Raymond et al., 2017a, 2017b).

Temporal scale over which a specific NBS becomes fully effective is not widely available in the scientific literature as it varies across HMRs, selected NBS and their location. Monitoring can be done each hour, day, week, month or yearly depending upon the problem being faced, its priority, NBS design and agreed goals. For example, the quantity of and duration for CO_2 capture and reduction will depend on the nature of the ecosystem adopted as NBS (Raymond et al., 2017a, 2017b). Raymond et al. (2017a, 2017b) categorised NBS temporal scale into three broad categories, i.e. short (within 5 years), medium (5-10 years) and long-span (over 10 years). They noted that some indicators' values could change over the short-term, such as per person accessible area of green spaces, water or soil salinity, etc. Other indicators will only show change after a long period, e.g. change in air quality or public exercising habits, and so will do the associated mental health benefits for the community. However, exercise as a behaviour change will be noted as an immediate effect due to the availability of green areas. Hence, NBS will definitely have its temporal impacts, but some projects will only be able to show their full potential after a specific period until they become fully functional. The monitoring process has to take into account this time period without neglecting other elements which influence the time scale of its efficiency.

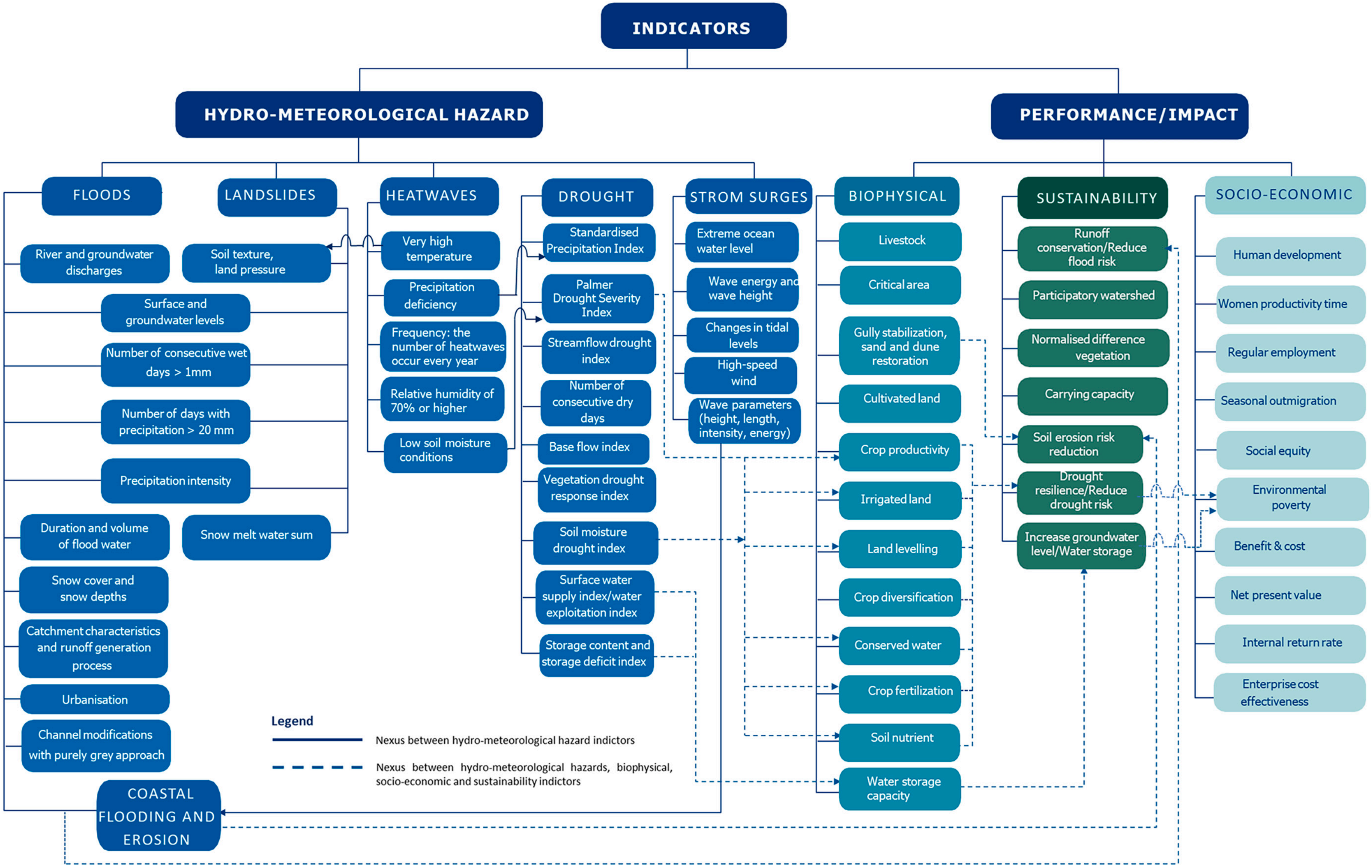

Fig. 3. A set of HMH associated indicators based on hazard characteristics and socio-ecological impacts (biophysical, sustainability and socio-economic) for monitoring and analysing the HMR reduction and thereby analysing the performance of NBS projects at any scale of implementation. Linkages show the nexus among different indicators as few indicators can be associated with more than one HMH and they can also be used to derive other socio-ecological impact indicators.

4. Experimental approaches for monitoring NBS performance

4.1. Overview of monitoring approaches

Experimental monitoring of NBS is the methodical collection of NBS performance and impact data during and after project implementation. The aim is to compile robust information on the NBS profits, such as its superior cost-efficiency and sustainability compared to other types of interventions. This kind of evidence helps build stronger and widespread support in favor of NBS implementation. The experimental monitoring data is acquired during the project life cycle (Fig. 1). Based on the objectives of NBS project, there are various types of monitoring; for instance, impact monitoring, fiscal monitoring, supposition monitoring, expert monitoring and procedure monitoring (DWAF, 2005). Both airborne and space-based Earth observation offers a range of capabilities for systematic and routinely monitoring of NBS performance, from local to worldwide scales, providing information on decreases in HMRs. Over the 20 years' developments in the domain of 'remote sensing' and 'Geographic Information Systems (GIS)' have also significantly eased the monitoring, delineating and assessing HMRs, and their management strategies (e.g. green infrastructure-based DRR). Apparently, GIS plays a significant part in the mapping, analysis and response to HMHs because of their innate spatial dimension and close link to territorial characteristics. Thus, with the 'remote sensing' technologies and GIS recently accessible, monitoring the spatiotemporal patterns of NBS such as green (trees, forest, grass, etc.) and blue (wetlands, water bodies, etc.) can be easily quantified on high intervention and impact scales. However, low spatial resolution and shorter observed time series hinder this method. It is difficult to seize the larger spatiotemporal resolution images at the same time. The use of remote sensing image data, multi-spectral or synthetic aperture radar (SAR), to delineate flooded areas and their evolution in time, is an efficient and effective way to assess the impacts of HM events and to support the mitigation of HMRs. For example, the Normalized Difference Water Index (NDWI), calculated with green and near infra-red spectral measurements, enables the detection of surface water. This can be used to map the river flood. Space-based and airborne datasets and GIS tools can be applied to swiftly evaluate damage due to the impact of actual HM events. It can allow the emergency leaders, scientists, and government institutions to estimate the damage and the performance of implemented NBS. SAR interferometry is the tool of choice to assess terrain or building movements after HMRs, such as landslides. Regarding remote sensing data sources for NBS monitoring, the options are increasing rapidly. Earth observation satellites from public space agencies include the European *Sentinel constellation, Landsat (Land Remote-Sensing Satellite (System)), TerraSAR-X, RADARSAT-2, Advanced Land Observation Satellite (ALOS)* (Anusha and Bharathi, 2020) which could be applied to monitor the performance of NBS, when implemented within large spatial units, such as a whole catchment.

As an effective alternative, a holistic monitoring approach that integrates ground observations with remote sensing could provide accurate monitoring of NBS efficiency and assessment of their value towards mitigating vulnerabilities. This approach assesses a project's success by measuring certain associated indicators or parameters in terms of its achievements compared with the original goals, benefits obtained and cost-effectiveness. Such techniques help in adjusting the project design and plan over time corresponding to changed external conditions, such as funding modalities, failures in technical implementation, stakeholder interests and others. To evaluate the impacts and benefits of the project, a baseline, i.e. the initial state of the monitored indicator must be defined. Monitoring of the project engagement process can be initiated over the short term for assessing its effectiveness and adjusting the associated parameters for further improvements. However, monitoring of the outcomes can be initiated at the end of the engagement process requiring longer timelines based on a wider set of drivers and conditions, which can increase the funding requirements. There are many tools and methods to retrieve data, and they may differ with the type of data. These methods can also be used to monitor the performance of NBS. Quantitative methods (e.g. surveys, questionnaires, field measurements, published articles) and qualitative methods (e.g. stakeholder meetings, interviews, case studies, spider diagrams) are the two broad categories used by scientific communities to gather data (Santamouris et al., 2018). Quantitative observation of NBS efficiency and performance could be done based on ground-based, space-based and airborne observations; while the qualitative approach is carried out through a participatory approach (Pagano et al., 2019).

There are many factors in the choice of a specific measurement or monitoring approach; the main choice amongst these is the goal or target of the quantification/monitoring method and type of NBS implemented against specific HMRs (Sections 4.2 to 4.5). There are some basic factors to be considered while planning a framework to measure NBS performance including the main objectives of the NBS, performance rating criteria, elements affecting NBS performance, source of available data, existing assets and practical scale of monitoring. However, there are elements that also need to be evaluated when choosing monitoring/measuring tools, instruments and sensors (Raymond et al., 2017a, 2017b); for example, (a) end-user acceptance of data acquisition techniques; (b) precision of the instrument/tools; (c) prices of the tools/instruments/sensors, including setting up, functioning and repair; (d) running conditions and flexibility to site circumstances; (e) tool/instrument/sensors validation requirements; (f) periodicity of monitoring; (g) operationalisation needs; (h) estimated lifetime of the tools/instruments/sensors and repair needs and (i) sensitivity to hooliganism (for monitoring devices to be set up ground-based). Of those elements, the most important is the price and the precision of the monitoring. Overall, the price of acquisition data rises with rising accuracy of these data (Raymond et al., 2017a, 2017b). Therefore, it is crucial to take into consideration the accuracy needed. For example, considering the cost and the accuracy of equipment, a list of experiments planned to monitor NBS performance over project lifetime (2018-2022) in the OPERANDUM project has been shown in Table 2. In general, ground-based, space-based and airborne observatories developed for other purposes, such as assessing the impact of different HM events could be used for monitoring the performance of NBS in different regions of the globe. From Section 4.2 to Section 4.6, we have summarised tools, instruments and sensors used in these observatories that can also be applied to measure the efficiency of NBS implemented to mitigate five HMRs.

4.2. Floods

Floods can be classified according to their cause into three broad categories: pluvial or rainfall-induced flooding, fluvial or river flooding and tidal flooding. The efficiency of a flood control system depends considerably on the type of floods in a given area. Increasing infiltration into the soil, temporarily storing excess water in wetlands, creating runoff attenuation structures, can reduce the flooding generated from all categories; however, their efficiency varies considerably, making the decision to select a particular NBS a challenge which requires consideration on a case-to-case basis. Quantification of flooding is performed by measuring mainly the following flood-related variables: water level, flooded area, flood hydrograph, water velocity and the time lag between peak rainfall intensity and peak discharge. However, several other meteorological variables that directly/indirectly affect flood generation mechanisms are generally monitored to understand the flooding process. The primary meteorological phenomenon generating flooding is rainfall. Also, parameters, such as temperature, wind speed, relative humidity, and soil moisture, that have an indirect effect in the flooding process, are monitored to understand flood generation mechanisms. The majority of these flood-related hydrological and meteorological variables are measured using on-site sensors. However, water level can also be indirectly measured based on remote sensing images of flood extent

Table 2
Summary of OPERANDUM project key HMHs, intended NBS, planned experiments and variables required to monitor the performance of NBS (Operandum, 2020).

Country	HMHs	Candidate NBS	Experiments	Monitoring
Austria	Landslides	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 temporarily placed measures. Controlled snow accumulation – controlled snowmelt discharge	LiDAR monitoring, automated tracking, tachymeter, artificial and spray irrigation for controlled conditions	Monitoring of soil water status by TDR (time-domain reflectometry)-probes, observation of land cover with focus on surface hydrology and vegetation phenology by multispectral UAV and satellite remote sensing, quantification of surface morphology for landslide characterization and displacement observations by geodetic networks, LiDAR UAV, TLS, and satellite-based InSAR
Finland	Nutrient and sediment loads	Construction of sedimentation ponds, wetlands and peak runoff control structures in the catchment areas and choice/restriction of forest management applications	Trials on the effectiveness of sedimentations ponds and pits, buffer zones, wetlands, peak runoff control structures	Water quality: a fractional abundance of water; SOM (sediment organic matter), sediments
Germany	Floods	Reinforcement of decentralized retention areas in the marshland, re-activating flooding areas, renaturation of leeves.	Micro-scale experiments to evaluate intended NBS	Test fields to measure sedimentation rates
Greece	Flood and droughts	Increasing soil infiltration, potentially decreasing quick flows, by free-draining soil. Greening flooded areas. Decreasing hydraulic connectivity through intervening surface runoff, by greening buffer strips of trees and grass.	Continuous monitoring	Hydromet monitoring network
Italy	Flood and drought	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	Test the strength resistance of deep rooting plants under different load conditions, and different rainfall regimes.	Water level and velocity; solid transport; water infiltration; roots strength; surface erosion; soil moisture; land surface temperature and albedo; Water salinity; Land subsidence; Sea-level rise; Dendrometry.
Ireland	Floods	Sustainable Urban Drainage Systems (SUDS)	Trial on SUDS: water velocity, river levels, rainfall	SAR, Water Level Observations
UK	Storm surges and coastal erosion	Eco-engineering solutions to reduce erosion. Enhance the stability of earthworks and natural slopes.	Vegetation reinforcement, vegetation cover, terrestrial LiDAR monitoring of slope and cliff soil mass displacement and numerical modelling using site-specific HM and biophysical indicators	Autonomous soil monitoring probes (see Experiments), vegetation cover and plant community composition, terrestrial LiDAR monitoring of slope and cliff (see Experiments) and implementation of custom numerical models

combined with digital elevation models of the terrain. Monitoring changes in flood magnitude is essential for flood reduction and adaptation purposes in flood-vulnerable areas where flooding affects critical infrastructure and human life.

Hybrid NBSs have been recognised as the best possible mix of the protection given by engineered approach along with other many co-benefits of NBS (Jongman, 2018; Debele et al., 2019). Monitoring the efficiency and performance of nature-based flood protection might be carried out by various approaches. For instance, evaluation of flood risk might be carried out by in situ observations before and after the building of a nature-based flood protection system. Flood indicators from ground measurement (e.g. gauging stations) and airborne observations can be an effective approach to monitor the efficiency of NBS in reducing flood extent and the associated damages (Zeng et al., 2020). One of the significant challenges with monitoring natural flood management measures is obtaining in situ observations of flow conditions at adequate spatiotemporal resolutions (Ip et al., 2006). ‘Satellite remote sensing’ provides unique data for timely evaluation of flood risk and impacts over large areas and offers worldwide coverage at recurrent and sometimes occasionally daily intervals.

Tables 3 and S3 summarise past investigations on types of NBS for flood alleviation, instruments, sensors and data collected to monitor their performance and efficiency indicators. Flood indicators play a crucial role to understand, assess and predict flood events and their impacts (Fig. 3 and Table S3). Flood risk assessment and management strategies rely on the accuracy of these indicators (Table 3). Depending on the type of floods and their management strategies (i.e. types of NBS), monitoring the performance and efficiency of nature-based flood protection could be done based on: (1) ground measurements (flow and

Table 3
Indicators along with measured or derived information utilising ground-based, airborne and/or spaceborne instruments/methods to monitor NBS performance against flood risk.

NBS (place)	Monitoring techniques	Data collected	NBS performance indicator	Author (Year)
Wetlands (Bojiang Haizi River, Erdos Larus Relictus)	Rain gauge, thermometer, stream gauges, hygrometer, anemometer, pyrheliometer	Daily rainfall, temperature, wind speed, relative humidity, solar energy	Flood peak and drought reduction	Li et al. (2019)
Wetlands (Global)	Thermometer, rain gauge	Temperature, daily precipitation, evapotranspiration, runoff	Water quality improvement, soil moisture regulation	Thorslund et al. (2017)
Salt marshes (cordgrass and grass weed) and coastal wetlands (Western Scheldt estuary, the Netherlands)	Fathometer, SONAR (sound navigation and ranging), ADCP, tide gauge, satellite altimetry, wave gauges (ocean sensor systems)	Field measurement on two salt marshes to collect bathymetry, ocean current, ocean water level, bottom fraction, and wind speed.	Coastal flood and erosion reduction.	Vuik et al. (2016)
Estuarine wetlands (mudflats and channels) (USA)	Barometer, anemometer	Wind velocity and atmospheric pressure	Coastal resilient thought damping of ocean waves	Highfield et al. (2018)
Wetland and vegetation roughness (Southeast Louisiana)	Barometer, anemometer, ADCP, tide gauge	Wind velocity, atmospheric pressure, topo bathymetric, manning coefficient	Coastal resilient by attenuating storm surges	Barbier et al. (2013)
Wetlands, saline marsh vegetation (oyster grass) (South Louisiana)	Water level sensors, ADCP, tide gauge, MODIS	Water level profiles, storm surge attenuation rate, surge elevation, wind speed, bathymetric	Coastal resilient and number and amount being physically active	Wamsley et al. (2010)
Wetlands (Prairie Pothole, central North Dakota)	Helicopters, weather balloon	Multi-temporal NAIP (National Agriculture Imagery Program) imagery, national wetlands inventory dataset, NDVI	Improved water supplies	Wu et al. (2019)
Wetlands/ponds (Shiawassee River watershed, Saginaw Bay)	Rain gauge, thermometer, stream gauges, evaporimeter, hygrometer, anemometer, pyrheliometer	Land use, topography, soils, wetland field data, precipitation, temperature, solar radiation, wind speed, relative humidity, potential evapotranspiration	Less frequency of flooding and drought events	Martinez-Martinez et al. (2014)
Contracted wetland (Greensboro Watershed, Mid-Atlantic Region of USA)	Rain gauge, thermometer, stream gauges, evaporimeter, hygrometer, anemometer, pyrheliometer, LiDAR, wetland delineation	Digital elevation model (DEM), land use map, wetland drainage zones, daily precipitation, other meteorological variables, and streamflow, inundation maps (Landsat), wetland	Flood and drought events were reduced	Yeo et al. (2019)
Wetland conservation, pond, lake (upper Lunan basin Scotland)	Rain gauge, stream gauges, global positioning system, propeller flow meter, valeport flowmeter	Maximum elevation, maximum, minimum river water levels, discharge, lake water levels, precipitation	Flood reduction	Vinten et al. (2019)
Hybrid (Wetlands combined with dike) (Western Scheldt estuary, the Netherlands)	Anemometer, water level sensors	Bathymetric, topography, hourly averaged wind speeds, water level	Coastal resilience, reducing coastal flooding and erosion	Stark et al. (2016)
Wetland soils (Momoge National Nature Reserve, China)	Tensiometer	Soil samples and characteristics	Flood reduction and improved water quality	Ming et al. (2007)
Wetlands, salt marshes and mangroves (global scale)	General bathymetric chart, shuttle radar, topography mission	Topography, bathymetry, mangroves forests, salt marshes, country boundaries, storm surge heights, population distribution, cyclone tracks	Coastal resilience, reducing coastal flooding and erosion	Van Coppenolle and Temmerman (2019)
Wetland reconnection or enhancement of floodplain ecosystem (Lower Tisza River, Hungary)	Cableways and stilling well located in stream gauge	Daily discharge, maximum annual discharges, levees height	Reduced flood risk and improved water quality	Guida et al. (2015)
Hybrid flood (the Netherlands)	Cableways and stilling well located in stream gauge, anemometer, water level sensors	Wind speed, water level, significant wave height, mean wave period	Flood risk reduction and water quality improvement	Vuik et al. (2019)
Hybrid (blue green) (Łódź, Poland)	Diver model DI501, baro model DI500	Precipitation, discharge	Flood risk reduction and improved water quality	Jurczak et al. (2018)
Green-blue-grey approach (Sint Maarten Island, Saint Martin)		Model simulated precipitation data and evaporation	Reduction of urban flood and sustainable drainage system	Alves et al. (2020)
Wetland soils (Prairie Pothole, North America) (Prairie Pothole Region of North America)	Rain gauge, stream gauges	Water level, rainfall	Improved quality and availability	Ameli and Creed (2017)
Blue-green (Augustenborg, in Malmo, Sweden)	Rain gauge, stream gauges	River cross section, DEM, discharge, water level both open and groundwater, water depth, rainfall/recharge	Flood peaks reduced up to 80%.	Haghighatafshar et al. (2018)
Marshland to attenuate water levels associated with flood inundation from storm surge in Chesapeake Bay, USA.	A low frequency pressure transducer (Hobo onset U20L-01, U20-001-01 Ti and U20-001-04).	Water level monitoring campaign that resulted in a large collection (52 flood events) of rates of reduction from marsh transects situated in two natural preserves in the study areas.	Reduction of water levels	Glass et al. (2018)
Over 400 natural flood management interventions, Stroud River Frome catchment, south west England, UK.		Hourly rainfall measured at two sites, and hourly stage height data from two gauging stations in the catchment	River stage height reduction	Short et al. (2019)
Bhitarkanika mangrove ecosystem, India		Data on demography, land use	Avoided damage costs	Badola and Hussain, 2005)
		Data on the sewer system		Majidi et al. (2019)

(continued on next page)

Table 3 (*continued*)

NBS (place)	Monitoring techniques	Data collected	NBS performance indicator	Author (Year)
Green roofs, previous pavements, bio-retentions, and rain gardens. Sukhumvit area, Bangkok, Thailand			Reduction in run-off volume, peak discharge, and delay in time to peak	
RAF: storage ponds, permeable timber barriers, soil bund, and vegetation (Belford Burn catchment, UK)	Stream stage gauge	Peak flow discharge	Percentage reduction in peak flow	Nicholson et al. (2020)
Runoff Attenuation Features (Belford Burn catchment, UK)	River level sensor	Volume of water stored in several RAF such as overland flow interception features, online ditch features, offline ponds, large woody debris, and opportunistic RAF	Total storage	Quinn et al., 2013

water level gauges, tide gauges); (2) airborne and space-based optical and SAR data, such as the one acquired by Sentinel-1, Sentinel-2/ multispectral instrument (MSI), Sentinel-3/ Ocean and Land Colour Instrument (OLCI) and Sea and Land Surface Temperature Radiometer (SLSTR), Landsat Operational Land Imager and Thermal Infrared Sensor (OLI and TIRS), Moderate Resolution Imaging Spectroradiometer (MODIS), Soil Moisture Active Passive (SMAP), Soil Moisture and Ocean Salinity (SMOS). Ground-based monitoring of nature-based flood protection is conducted by hydrologists at the hydrometric stations using several instruments and sensors, such as acoustic doppler current profiler (ADCP), current meters, pressure operated electronic meter, flow stations, pressure transducers and rain gauges (both manual and automatic) and later combined with knowledge of timing and duration of floods. For instance, many researchers in the past used gauging stations to monitor the effectiveness of natural flood risk reduction (e.g. Thorslund et al., 2017; Jurczak et al., 2018; Vuik et al., 2018; Yeo et al., 2019) while others used remote sensing tools (Wamsley et al., 2010; Yeo et al., 2019) to monitor the performance and efficiency of NBS. Water has a distinctive spectral signature which allows its discrimination from other surface materials on optical images acquired from satellites and airborne platforms. Several indexes based on optical data have been proposed to enhance open water detection (McFeeters, 1996; Rogers and Kearney, 2004; Xu, 2006; Ji et al., 2009; Feyisa et al., 2014;). Among them, the NDWI has been specifically designed to exploit the unique spectral signature of water bodies. NDWI has been identified as the most suitable band combination to map inundated areas (Rokni et al., 2014). Photogrammetric techniques can be applied to the overlap between images acquired from aircraft or unmanned airborne vehicles (UAV) at different view angles. This technique, known as Structure from Motion (SfM) method, enables the detailed and accurate mapping of the surface elevation. UAVs can be flown at low cost and swiftly, facilitating the opportunistic capture of the geometry and conditions of NBS deployed to mitigate flood risk and impact. As a result, UAV-based SfM provides a powerful tool for mapping fluvial geomorphology changes (Langhammer and Vacková, 2018), and therefore for collecting evidence of NBS performance against flooding.

The SAR system on Radarsat-2 (Zhang et al., 2019) is pointable, thus improving access to specific terrestrial targets. This manoeuvring potential demonstrates extreme importance in positioning the flood-inundated zone in various types of topography and land cover, and planning proper nature-based flood monitoring mitigation measures. Microwave remote sensing techniques, on the other hand, are beneficial due to good penetration through heavy clouds and thus providing more efficient flood monitoring during rainy periods. Flood monitoring and mapping efforts also combine the benefits of both 'microwave' and 'optical' remote sensing tools for the best outcome. At the same time, this method also results in the formulation of best flood mitigation strategies, such as NBS.

Rahman and Thakur (2018) highlighted the advantages, potential and capacity of SAR satellite data to measure the flood peaks and to map flood extent and duration. Iacob et al. (2014) investigated monitoring of nature-based flood risk reduction using direct measurements. The indicators used for monitoring the performance and efficiency of nature-based flood reductions strategies were: (a) flood wave attenuation for various flood event return periods (e.g., 10, 20, 50, 100, 200, 500 or 1000 yrs); (b) rise of flood peak through time; and, (c) decline in the yearly likelihood of flood risk for the catchments under study (Table 3). Short et al. (2019) considered large woody debris dams composed of tree trunks and major tree branches in the riparian floodplain as an NBS. This structure would reduce peak flows during flood events by causing in-channel and on-floodplain impoundment and slowing down the runoff that contributes to the river flow. Based on monitored data at stream gauges using current meter and ADCP before and after deployment of this NBS as a natural flood management practice, they noted a decrease in the average river stage at two locations (Merrywalks and Slad Road) in the Stroud Frome Catchment, UK. The monitoring period before NBS deployment ranged from 2010 to 2014 and post-NBS deployment from 2014 to 2017. The average river level post-deployment of NBS was found to drop from 0.252 m to 0.204 m at Merrywalks and from 0.130 m to 0.113 m at Slad Road. Nicholson et al. (2020) investigated the effect of a set of nature-based runoff attenuation features (RAFs), including storage ponds, permeable timber barriers, soil bund, and plantation of vegetation, in flooding downstream of rivers during intense local storm events. Pressure transducers are installed at the upriver of the offline reservoir regions and draw-off channels to monitor the reductions in the water stage to monitor the performance of NBS. The other pressure transducers are also installed within each pond to monitor the performance of NBS in enhancing the water storage depth. The study area considered for the analysis is the Belford catchment in the UK, having an area of 5.7 km^2 that includes 40 RAFs. Based on mass balance analysis and using monitoring data, they noted that the RAFs could reduce the peak flow discharge by 12% in the river. The study concluded that a set of runoff attenuation features is needed to effectively control the flooding in the river. Vuik et al. (2019) monitored the long-term efficiency and performance of salt marshes in mitigating flood reduction in the Dutch Wadden Sea, Netherlands. The performance of salt marshes was monitored by an anemometer and ADCP, and later was compared with model simulations. The author demonstrated that the changes of marsh height because of sediment accumulation could dissipate the excess wave energy, thereby it was proven to be a highly effective solution for mitigating coastal flood risk across the ecosystems. Furthermore, this study also examined the effects of human interventions, i.e., (1) beach nourishment for increasing vegetation cover in foreshore; (2) installing detached earthen breakwater on beach shore; (3) installation of brushwood dams at foreshores for enhancing sediment accretion at the beach shore. In Section 5, we analyse the advantages and limitations of monitoring approaches used to measure the performance and efficiency of NBS implemented against flood risk.

4.3. Droughts

Sustained, abnormally low precipitation, a phenomenon known as meteorological drought, can lead to agriculture and hydrological droughts (Debele et al., 2019), which impact food production and water availability for human activities. Droughts typically occur at the macro scale, affecting entire catchments, while NBS mitigate the agriculture and hydrological droughts at the micro- to the meso-scale. However, there is also a way to reduce drought risks by using drought-resistant crops and varieties with a shorter growth cycle (to avoid peak drought) that can potentially impact large areas. Detection of drought is the first measure into human adjustment and associated remediation of drought risks (Yu et al., 2019). Forecasting the occurrence of meteorological droughts, especially their onset and duration, is crucial for the time-bound realization of plans to mitigate agriculture and hydrological droughts, such as implementing NBS (e.g. water conservation measures, drought-tolerant crops) (Ramezani et al., 2019). The performance of NBS needs to be assessed by estimating drought risks before and after implementing NBS, which is commonly measured based on indicators (Tables S3 and S4), for example, the Palmer Drought Severity Index (PDSI) (Palmer, 1965) or the Standardized Precipitation Index (SPI) (McKee et al., 1993), among others (Heim Jr, 2002; Mishra and Singh, 2010). PDSI estimates soil water demand and supply using a water balance formula and only precipitation and temperature data to reproduce soil moisture fluctuations. Nowadays, it is the utmost broadly applied drought indicator (Ma et al., 2014; Nam et al., 2015). SPI identifies meteorological droughts on the basis of the departure of observed rainfall from the long-term mean rainfall using a particular time frame (McKee et al., 1993; Kumar et al., 2016; Mohammad et al., 2018). Traditionally, the meteorological input data required for the calculation of these parameters were acquired by meteorological stations. Nowadays, global meteorological datasets are regularly produced using satellite observations, sometimes combined with in situ records, for example, CHIRPS (Climate Hazards Group InfraRed Precipitation with Station Data; Funk et al., 2015; Torres-Batlló et al., 2020).

The performance of NBS used against agricultural drought risk can be monitored using observed soil moisture values and plant health indices, and by comparing them to those in areas undergoing similar meteorological drought in the absence of NBS. Normalized Difference Vegetation Index (NDVI) was the first indicator used to monitor the agricultural drought. NDVI uses light reflected by vegetation in different spectral bands to assess its photosynthetic activity (Martínez-Fernández et al., 2016; Sepulcre-Canto et al., 2012; Sivakumar et al., 2011; Narasimhan and Srinivasan, 2005; Ji and Peters, 2003). NDVI is a common satellite-based index used for the periodical monitoring of plant health over large areas. This index flags reduced plant growth (e.g. due to low soil moisture), thus informing vegetation drought (Anyamba and Tucker, 2005). Land Surface Temperature (LST) is an indicator of the terrestrial energy balance and provides a measure of the changes in the surface latent heat fluxes as a consequence of plant stress. It has been found to be correlated to the surface moisture condition (Gutman, 1990). Indicators based on space-borne relationships between LST and NDVI have been broadly applied for drought tracking by thermal and optical remote sensing. Kogan (1995) proposed the Vegetation Health (VH) index that was successively applied globally for drought monitoring purposes. Indexes constructed from the scatter plot of LST – NDVI pixels by pixels have also been used to extract information on surface moisture conditions (Unganai and Kogan, 1998; Wang et al., 2001; Patel et al., 2012; Ou et al., 2011; Rahimzadeh-Bajgiran et al., 2012). Normalized metrics of anomalies in NDVI and LST are better drought indicators and are widely used (Kogan, 1995; Kogan, 2002). Jia et al. (2012) evaluated two indices based on the anomalies in NDVI and LST against widely accepted drought indicators demonstrating that these indicators provide a better measure of anomalies and evolution of drought in three drought events in India and China.

Due to the adopted NBS measures (e.g. terrace farming, mulch covers for moisture retention), plants are healthier than in neighbouring areas without NBS. This spatial variation of plant health is revealed by NDVI maps. Tucker et al. (1991) showed that comparative studies of prolonged-time series of NDVI data give helpful evidence for drought tracking in the Sahel region without NBS intervention. In the last 20 years, many other studies have used NDVI for monitoring drought risk and the performance of nature-based drought interventions. For instance, Peters et al. (2002) used NDVI to show that remote sensing data is a valuable tool in drought tracking in the central US. Karnieli et al. (2010) concluded that NDVI (and satellite monitoring in general) of plants and droughts on the basis of empirical associations are effective for much of the US throughout the middle of the agricultural season. Nanzad et al. (2019) used NDVI to map the drought intensity and its spatial allotment through Mongolia during the growing season from 2000 to 2016.

Hydrological droughts are monitored based on measurements of river flow discharge, lake or reservoir water surface levels, and groundwater table elevation. Satellite data can be used to monitor some of these parameters, although at a coarse scale. For instance, satellite altimeters provide periodical information of surface elevation over big reservoirs and lakes (Crétaux et al., 2011), while gravity changes detected from a satellite can be related to groundwater depletion of replenishment (Thomas et al., 2014; Yi and Wen, 2016). Similarly, to the SPI, the SDI (streamflow drought index) (Nalbantis and Tsakiris, 2009) is based on the time series of the streamflow discharge records and quantifies their departure from normality. The effectiveness of an NBS against hydrological drought should be revealed by a change in the SDI to SPI relationship, before and after implementation. In general, the effectiveness of NBS for drought mitigation is monitored by the increase of water supply reliability, aquifer replenishment (increase in water table elevation), increased soil moisture, crop yield and livestock production, and vegetation greenness and biomass. Table 4 compiles the most used methods, instruments and sensors to monitor the performance of NBS implemented against drought risk along with the NBS performance indicators.

4.4. Heatwaves

Monitoring methods for the assessment of NBS for heatwaves rely mostly on ambient heat measurement among other meteorological parameters (Tables 5 and S3). Ambient heat can be quantified through steady monitoring and recording of mean, maximum or minimum daytime or night time air or surface temperature in the vicinity of the implemented NBS prior to and post their execution (Marando et al., 2019; Jain et al., 2020). Marando et al. (2019) used the application of remote sensing tools to measure air temperature while the other studies monitored air temperature based on field campaigns using sensors (Taleghani et al., 2014; Yan et al., 2020). For example, Shih (2017) assessed the effect of NBS configuration (size, shape and closeness) in Taipei metropolis during summer daytime using remote sensing data by calculating NDVI and LST, and spatial analysis of clouds and mountains, revealing that the factors responsible for lowering LST within NBS area may not affect the surroundings. Takebayashi and Moriyama (2009) captured thermal images to calculate mean surface temperature and heat flux for estimating the effect of replacing asphalt with grass in parking areas. Yan et al. (2020) performed field-experiments and utilised temperature and relative humidity (RH) sensors to measure the air temperature every two hours for one year across an 8 km road encompassed by different land-use patterns. They found nights had more UHI intensity than daytime. Studies of the dependence of urban LST and of the surface UHI on urban geometry suggest how to design urban space to mitigate urban surface temperature (Yang et al., 2019).

The NBS monitored in the past for UHI mitigation, or extreme temperature includes green roofs, green walls (Feitosa and Wilkinson, 2020; Taleghani et al., 2019), green spaces (e.g. trees, parks, garden) (Marando et al., 2019; Tiwari and Kumar, 2020; Tiwari et al., 2021), ponds and water bodies (Marando et al., 2019; Taleghani et al., 2014). Bevilacqua et al. (2017) performed surface temperature analysis of green roofs and traditional roofs in southern Italy through different

Table 4
Indicators along with measured or derived information utilising ground-based, airbonre and/or spaceborne instruments/methods to monitor NBS performance against drought risk.

NBS (place)	Monitoring techniques	Data collected	NBS performance indicator	Author (Year)
Tree planting, pits, earthen dams (Puebla Tlaxacala Valley, Mexico)	Piezometers, meteorological variables, tree counting.	Water table elevation, infiltration. Number of planted trees.	Aquifer recharge, biomass.	WBCSD (2020)
Drought-tolerant, short-cycle crops, water retention and infiltration ditches, organic fertilizers, mulching (Kagera basin, Burundi, Uganda, Tanzania, Rwanda)	WOCAT (World Overview of Conservation Approaches and Technologies) questionnaires on land degradation and conservation completed by specialists in consultation with land users	Crop yield, household income, stream flow, fire incidence.	Increase in crop yield, household income and stream flow. Reduction in land-related disputes and fire incidence.	FAO (2017)
Barley straw mulching in vineyards (Valencia, Spain)	Use of a rainfall simulator over bare soil and mulched vineyard plots. Overland flow, Samples of soil moisture at different layers.	For both, bare soil and mulched vineyards: total runoff, sediment yield, erosion rates, time to ponding, time to runoff, soil moisture.	The use of mulch resulted in delayed ponding and runoff generation, increased infiltration and retention of water in the soil.	Prosdocimi et al. (2016)
Sand dams, terracing, crop diversification, agroforestry (Makueni County, Kenya)	Surveys of household water supply. Tree counting. Satellite-based vegetation indices.	Water supply reliability: number of supplied households and percentage of time. Expansion of terrace area. Inter-annual increase of vegetation greenness.	Increase in water supply reliability, increased soil moisture, extension of growing season.	Ryan and Elsner (2016)
Infiltration ditches, terracing and run-off harvesting. Harvesting of roof runoff into a surface tank or earth dam (Katumani and Makindu dryland sites, Kenya)	Interviews to farmers, water budget modelling.	Time series of precipitation and other meteorological parameters. Farmer's soil and water management practices and yearly production	Crop and livestock production versus modelled water budget deficits.	Recha et al. (2016)
Litter cover for enhanced soil infiltration and moisture retention (Khabr National Park, Iran)	Use of a rainfall simulator. Monitoring of superficial soil moisture in litter-covered and bare soil	Litter mass and superficial soil moisture for different rainfall conditions.	Decreased evaporation from litter-covered soil compared to bare soil.	Sharafatmandrad et al. (2010)
Soil cover with crop residues, growing plants for enhanced infiltration and moisture retention (Henderson Research Station, Zimbabwe, Farmer Training Centre, Zambia)	Use of a rainfall simulator. Monitoring of soil moisture and runoff.	Soil moisture, infiltration, runoff for different rainfall conditions. Crop above-ground biomass and yield.	Increased infiltration and soil moisture. Improved crop development and yield in dry spells.	Thierfelder and Wall (2009)
Green-NBS, e.g vegetation (uMngeni and Baviaanskloof-Tsitsikamma catchments South Africa)	Hydrological modeling using an integrated physical conceptual model. Computation of costs and benefits using an Integrated ecological-economic model	Daily rainfall and temperature, time series, soil data, land use. Stakeholders engagement	Increased base-flows and water resources during dry periods	Li and Norford (2016)
Managing forest structure to mitigate drought impacts (Chippewa National Forest, in northern Minnesota, USA)	Use of self-calibrating drought indicator through R statistical package, tree counting	Time series of Monthly temperature and total precipitation, number of thinning and living trees	Increased soil moisture, increase of water resources availability	Jones et al. (2019)
Effect of two observations on open and groundwater droughts in two lowland catchments (Poelsbeek and Bolscherbeek -eastern Netherlands)	Use of a distributed physically based model to simulate groundwater and streamflow time series	Time series of daily meteorological data and flow data. Hydrological measures	Increased groundwater levels, decreasing groundwater droughts	Querner and Van Lanen (2001)

temperature indices and showed that a vegetated roof helps reduce UHI in summer without compromising its thermal performance in winter. Oliveira et al. (2011) measured weather parameters and found small gardens to be cooler than neighbouring areas while exploring their cooling potential (inside and nearby) in a heavily built-up region in Lisbon. A pavement-watering experiment was performed by Hendel et al. (2016) during 2013 and 2014 summers at two locations in Paris to observe the micro-climatic distinctions on watered and reference days, and showed that footpath-watering was an effective way of decreasing heat stress.

Trees and greenery, in general, are the most referred NBS for heat risk management by many authors (Yan et al., 2020; Marando et al., 2019; Shih, 2017; Oliveira et al., 2011). The efficiency of trees as NBS was shown by Ballinas and Barradas (2016) by measuring transpiration and vapour pressure deficit for total conductance and stomatal conductance daily. Leaf area index computations for canopy conductance was done over a 2-week period in four tree species (four trees each) in México City to show that vapour pressure deficit strongly influences transpiration, which is controlled by stomatal conductance and capable of reducing up to 20% of excess absorbed energy to be dissipated as sensible heat at higher surface temperature. Monitoring methods were sometimes combined with modelling to evaluate NBS, e.g. ENVI-met for thermal estimation of heat alleviation effect of vegetation and water body suggesting both can lessen air temperature and mean radiant temperature in canyons (Taleghani et al., 2014). Table 5 shows different monitoring methods, tools and instruments/sensors being practised for the assessment of NBS for extreme heat or heatwaves, their data and instrument needs along with NBS performance indicators.

4.5. Landslides

Suitable monitoring strategies and techniques for quantifying the effects of NBS depend on how the mitigation measure targets the landslide process. The effectiveness of an NBS designed against hydrometeorologically driven shallow and deep-seated landslides can be assessed by either monitoring the impacts of a landslide process (e.g., landslide displacement, topographic changes) or the direct effects of the NBS itself (e.g., soil reinforcement, hydrological effects). Evidence for the effectiveness of NBS could be provided if the derived time series show a trend towards reduced landslide activity compared to the pre-implementation period (e.g., decreasing displacement, reduced number/volume of shallow landslides), Table S3. Various measurement

Table 5
Indicators along with measured or derived information utilising ground-based, airbonre and/or spaceborne instruments/methods to monitor NBS performance against heatwave risk.

NBS (Place)	Method used	Data collected (with Instrument used)	Performance Indicator	Author (year)
Urban Vegetation (Shenzhen, China)	Field observations by mobile traverse method	Air temperature (T-type thermocouple), relative humidity (HMP60 sensor)	Reduction in UHI intensity, discomfort index	Yan et al. (2020)
Water bodies and vegetation (Nagpur, India)	Remote sensing satellite imageries and field survey to quantify biophysical parameters (NDVI, Normalized Difference Build-up Index, Normalized Difference Bareness Index)	LST (Time series Landsat (Thematic Mapper amd Enhanced Thematic Mapper Plus, TM and ETM+) satellite data products); Air temperature, precipitation, relative humidity, wind speed (Indian Meteorological Department and Lutron AH-4223)	UHI Intensity	Jain et al. (2020)
Green Infrastructure-peri-urban forest, urban forest, street trees (Rome, Italy)	UHI estimation from air temperature, LST estimation for surface UHI analysis	LST (Landsat-8 OLI/TIRS images), air temperature (weather stations)	UHI intensity, Surface UHI	Marando et al. (2019)
Green-roof, green wall (Sydney Australia)	Two uniform residences are compared in a scaled-down approach	Temperature and RH (USB data logger Extech RHT10), Meteorological data-temperature, RH, wind speed (Airport)	Wet-bulb globe temperature index	Feitosa and Wilkinson (2020)
Greenspace (Taipei)	Remote sensing for LST, NDVI and greenspace characteristics calculation and spatial analysis using GIS	Remote sensing data (Landsat 8 satellite images)	LST, buffer LST	Shih (2017)
Green irrigated roof (Southern Italy)	Roof surface temperature analysis	Meteorological data: air temperature, RH, precipitation, atmospheric pressure, wind direction and speed (weather station), solar radiation (pyranometer), thermal infrared sky radiation (The Eppley Laboratory, EPLAB precision infrared radiometer), water content of volumetric (water content measuring probe), surface temperature (infrared thermometers)	Temperature Excursion Reduction, External Temperature Ratio, Surface Temperature Reduction	Bevilacqua et al. (2017)
Trees (Mexico City)	Transpiration rates and stomatal and canopy conductances monitoring	Sap flow (xylem water mass-flow metering systems); Stomatal conductance (diffusion porometer); temperature, RH and photosynthetically active radiation (porometer sensors); irradiance (pyranometer), air temperature and RH (temperature-humidity probe), wind data (anemometer and vane set)	Irradiance and air temperature	Ballinas and Barradas (2016)
Pavement watering (Paris, France)	Black globe temperature, air temperature and wind speed monitoring	Temperature (Sheltered Pt100), Humidity (Sheltered capacitive hygrometer), Globe temperature (Black Globe Thermometer), wind speed (2-axis ultrasonic anemometer)	Universal Thermal Climate Index (UTCI), Air temperature, humidity, wind speed and mean radiant temperature, UTCI equivalent temperature	Hendel et al. (2016)
Grass (Japan)	Surface and underground temperatures measurement	Surface and underground temperature (thermocouples), solar radiation and infrared radiation, Air temperature & RH (thermo-hygrometer), surface temperature distribution (infrared camera), solar reflectance (net radiation meter)	Surface and underground temperatures, sensible heat flux, air temperature	Takebayashi and Moriyama (2009)
Green space (Lisbon)	Itinerant recording of the meteorological variables that affect the planetary energy balance	Temperature, RH, wind speed (Testo probe), solar radiation (Pyranometer) and infrared radiation (pyrgeometer)	Air temperature, mean radiant temperature, physiological equivalent temperature	Oliveira et al. (2011)
Vegetation and water bodies (Portland, oregon, USA)	Field measurement of air and globe temperature, wind speed, spectral reflectivity and albedo, thermal photography	Air and planetery temperatures and wind data (HOBO U12-006 data loggers with outside sensors), Thermal photographs (Forward-looking infrared, FLIR-i5 infrared camera), albedo, and spectral reflectivity of surface materials (spectrophotometer)	UHI, air temperature, mean radiant temperature, globe temperature	Taleghani et al. (2014)

techniques are feasible to assess a landslide's movement over time at specific points, along profile lines or area-wide (Zangerl et al., 2010; Hormes et al., 2020). Monitoring techniques applicable to assess the displacement at specific points include repeated positional measurements with a DGNSS (Gili et al., 2000; Squarzoni et al., 2005) and distance measurements to a reference on stable grounds based on wire extensometers, laser distance meters or a total station (Hofmann and Sausgruber, 2017; Thuro et al., 2010). Measurement techniques suitable for monitoring displacements along profile lines include inclinometers (Simeoni and Mongiovì, 2007) and fibre optics (Schenato et al., 2017). Area-wide displacement or topographic volume change measurements typically rely on remote sensing techniques including terrestrial laser scanning (TLS) (Pfeiffer et al., 2018), laser scanning from airborne platforms (Zieher et al., 2019), interferometric synthetic aperture radar (InSAR) (Darvishi et al., 2018) and photogrammetric techniques including SfM (Lucieer and Jong, 2014) and dense image matching (Balek and Blahut, 2017). Choosing the most appropriate technique to assess a landslide's displacement depends on the specific case study (e.g., characteristics of the landslide in terms of expected movement behaviour or land cover) and on the respective advantages and limitations of the chosen monitoring technique, which are expressed by spatio-temporal resolution and coverage (Zieher et al., 2018).

In further considered case studies, the stabilizing and hydrological impacts of roots of various plant species on shallow soils have been assessed by field investigations and/or laboratory experiments. In many studies, the assessment of the root system and its manifold contribution to slope stability involved destructive measurements which do not allow monitoring past the intervention. In these cases, models have been established which can fill this gap. Furthermore, laboratory tests with plant species grown under controlled conditions for various periods allow quantifying root reinforcement over time (e.g. Bordoni et al., 2016; Vergani and Graf, 2016). Further studies on the monitoring of NBS against landslides focused on soil bioengineering techniques including drainage systems, slope stabilization using natural resources (e.g. live fascines, live palisades, live crib walls; e.g. Petrone and Preti, 2010) and adapted land management including land-use change. The reviewed studies were conducted mainly in the Alpine region of Italy and Switzerland. The instrumentation of these sites ranges from micro-scales (laboratory experiments, single plant root system) to a regional-scale (catchment area, several tens of square kilometres). Most studies have been carried out in Europe and include various kinds of tensile strength tests both in the field and in the laboratory, sensors for directly measuring hydrological conditions, indirect geophysical measurement techniques and high-precision differential global navigation satellite systems (DGNSS). Furthermore, plant root systems have been excavated for characterizing their hierarchical structure including the measurement of root diameters and the relative area occupied by roots (root area ratio). Table 6 summarizes the methods, tools, instruments/sensors to monitor the performance of NBS used against landslides. Scientific literature provides scarce evidence on the actual use of remote sensing to assess the performance of NBS designed and implemented to mitigate the risk of landslides.

In general, roots can affect slope stability in different ways, including (i) basal anchoring in case the roots penetrate the slip surface, (ii) lateral reinforcement under tension and compression mainly along slope-parallel oriented roots, and (iii) increased stiffness of rooted soils (Cohen and Schwarz, 2017). For assessing these effects, field investigations mainly focus on the characterization of mature root systems (spatial distribution of roots, root diameter, root area ratio; e.g. Bordoni et al., 2016; Schwarz et al., 2012; Vergani et al., 2016) and on quantifying the tensile strength of single roots based on root pullout tests (e.g. Vergani et al., 2017; Yamase et al., 2019). Besides tree root systems, root systems of low vegetation and their contribution to slope stability have also been investigated (e.g. Comino et al., 2010; Balangcod et al., 2015). The general goals of these studies are (i) to quantify root reinforcement of single plants, (ii) to compare the stabilizing effects of different plant species, (iii) to investigate the effects of common forest practices on slope stability, (iv) to estimate the area-wide contribution of root reinforcement to slope stability and (v) to assess the decay of root reinforcement following forest clearance by timber harvest or forest fires.

Many of these studies also include or are focusing on laboratory tests employing a direct shear test apparatus for quantifying and comparing soil shear strength with and without roots. These studies typically include young saplings grown in boxes suitable for performing a direct shear test (e.g. Loades et al., 2010; Veylon et al., 2015; Zhu et al., 2020). Also single and bundles of roots collected in the field are tested to derive their tensile strength (Bordoni et al., 2016; Sanchez-Castillo et al., 2017). Yamase et al. (2019) used ground-penetrating radar (GPR) to quantify root reinforcement in stands of Japanese cedar (*Cryptomeria japonica*) in the Mineyama Highlands (Hyōgo Prefecture, Japan). The results of the GPR data have been compared with measurements in excavated soil pits, including root diameter and root tensile strength derived from pull-out tests. The comparison showed that GPR could generally detect roots, but the fraction of correctly detected roots depends on their diameter. Therefore, the root reinforcement derived from GPR can also differ considerably from the in situ measurements. Nevertheless, using GPR for quantifying root reinforcement offers a non-destructive alternative to conventional measurement techniques, especially when a survey should cover a large area.

Meijer et al. (2018a, 2018b) employed a custom-built pull-out device including a garden corkscrew weeder to assess root reinforcement of Sitka spruce (*Picea sitchensis* L) and blackcurrant (*Ribes nigrum* L.) in two study areas close to Dundee (UK). The results of the field tests where the force was recorded while pulling the corkscrew out of the rooted soil were then interpreted in terms of strengthening. The authors concluded that in shallow depths root strengthening helps the slope stability over considerable displacement ranges. The developed corkscrew method proved feasible for assessing root reinforcement more efficiently compared to other field testing techniques (e.g. direct shear test).

Besides the roots of woody plants, roots of grass variety and their support to slope stability have also been investigated (e.g. Comino et al., 2010; Balangcod et al., 2015). Comino et al. (2010) analysed the root strengthening of five different grass varieties in the Pellice Valley (province of Turin, Italy). The authors tested rooted and unrooted clods of soil till a depth of 15 cm in the field using a direct shear apparatus, recorded the respective root area ratio and performed tensile strength tests in the laboratory. Their results indicate that grassroots can contribute to slope stability in shallow depths while root reinforcement, the root area ratio and the roots' tensile strength vary considerably depending on the plant species.

Several studies show that root reinforcement decreases markedly following timber harvest or forest fires (e.g. Ziemer, 1981; Schmidt

Table 6

Indicators along with measured or derived information utilising ground-based, airbonre and/or spaceborne instruments/methods to monitor NBS performance against landslide risk.

NBS (place)	Instrument/sensors used	Measured and used data	NBS performance indicator	Author (Year)
Fern cover reducing erosion on steep slopes (laboratory experiments at The Chinese University of Hong Kong, China)	Rainfall simulator, boxes collecting runoff and sediment loss	Root area ratio, Runoff, sediment loss, plant cover, leaf area index, and root density	Runoff, sediment loss	Chau and Chu (2017)
Hydrological effects of vegetation on slope stability (Catterline Bay, UK)	Custom-built rainfall samplers and stemflow collectors, tensiometer (Irrometer), soil moisture probe (Delta-T)	Gross rainfall, interception, stem flow, soil matric suction, soil water content on vegetated and fallow slopes	Amount of intercepted rainfall, stem flow, root water uptake; suction stress, factor of safety (via modelling)	Gonzalez-Ollauri and Mickovski (2017)
Root reinforcement of slopes (Invergowrie and Dundee, UK)	Custom-built pull-out device including a garden corkscrew weeder (De Wit), field tensiometers (SWT4R, Delta-T), laboratory tensile strength tests (Instron 5966)	Pull-out force, root tensile strength, soil characteristics	Root reinforcement	Meijer et al. (2018a, 2018b)
Root reinforcement of slopes, reinforcement decay after timber harvesting (Obergross, Schwyz, Switzerland)	Root pullout field and laboratory tests, digital caliper, high-precision DGNSS	Root pullout force and displacement; root distribution, number and diameter; stem diameter at breast height; tree location	Root reinforcement and its decay after timber harvesting	Vergani et al. (2016)
Root reinforcement (Mineyama Highlands, Hyōgo Prefecture, Japan)	Ground-penetrating RADAR (SIR SYSTEM 3000 with 900 MHz antenna), root pullout field tests	Root distribution (diameter > 5mm) in excavated soil pits and derived from reflected GPR waveform profiles	Root reinforcement	Yamase et al. (2019)

et al., 2001). In a more recent study, Vergani et al. (2016) investigated the spatio-temporal evolution of root reinforcement following timber harvest in a spruce stand (*Picea abies* L. Karst) located in the Swiss Alps. The authors showed that root reinforcement decreased to 60% after 5 years compared to the initial condition and vanished after 15 years. In another study, Vergani et al. (2017) assessed the decrease of root strengthening following a forest fire in a Scots pine stand (*Pinus silvestris* L) in the Swiss Alps. The results showed that four years after the fire the protective function of the forest was severely reduced. In both studies, the authors applied techniques including measurements of root diameter and distribution as well as root pull-out test in excavated soil profiles. Gonzalez-Ollauri and Mickovski (2017) investigated hydrological effects of willow (*Salix viminalis* L. and *Salix caprea* L.) on the stability of shallow soils at Catterline Bay (eastern Scotland, UK). The authors conducted in situ measurements of gross rainfall, interception, stem flow, soil matric suction, soil water content on vegetated and fallow slopes. The results indicate that compared to the fallow slopes, willow can have distinct hydrological effects. Particularly root water uptake and the related reduction of the soil water content can enhance slope stability. Interception and stem flow had only minor effects. Chau and Chu (2017) investigated the hydrological effects of a vegetation cover composed of fern species and its influence on soil erosion. The authors considered five different fern species which are common on landslide-prone slopes in southern China. The ferns were planted in inclined metal boxes with coverage of 40 and 80%. After reaching maturity, their ability to prevent soil erosion was tested in a rainfall simulator. Compared to tests without vegetation, particularly the dense fern vegetation proved feasible to reduce the runoff volume and the sediment loss.

4.6. Storm surges and coastal erosion

For the most common NBS against storm surges and coastal erosion, the monitoring methods usually comprised monitoring of the wave/current height/level, velocity, and direction; storm parameters (e.g. duration, surge height; wind strength and direction); vegetation/coral/oyster species coverage, type, dimensions; topography; bathymetry (Tables 7 and S3). The evaluation methods include in situ direct measurements, the use of past/current global climate data, case studies, laboratory studies, numerical modelling, and systematic literature reviews. The scale of the reviewed studies ranged from micro (laboratory experiments) to macro (global scale). The places of the study were most commonly associated with the coastal Tropics, although several case studies from the coastal USA were also noted. The instrumentation used included high/low-frequency pressure transducers, differential global positioning system (GPS) and total stations, ADCP, and capacitance wave gauges. The data needed usually included the topographic/bathymetric measurements before, during. and after a storm; wave data during a storm; NBS coverage and details. Usually, the wave attenuation and water level within the NBS were simulated for each NBS and compared to a case when no NBS is constructed. Usually, wave height reduction, water level change, flow attenuation and NBS damage/erosion/loss were used as indicators of the efficiency of the NBS.

Anderson et al. (2013) showed that salt marshes of *Spartina. alterniflora* are effective in reducing wave height and energy of 60% to 80%, based on measurements of seawater levels, vegetation height, vegetation density and wave heights. This reduction is non-linear and occurs quickly and the highest at the edge of the marsh and diminishes with distance from the edge. Field measurements and observations of wave energy dissipation effectiveness, compiled by Anderson et al. (2011), showed that NBS transect lengths ranging between 10 m and 300 m are capable of reducing the wave height, and thus energy, between 0.3% and 4.0% per metre of vegetated NBS. Similarly, an experimental study by Paquier et al. (2017) showed that salt marshes can attenuate the water level within the salt marsh at a rate of approximately 600 mm per km of marsh, which falls within the values measured in seven other studies carried out in Europe and the USA (Paquier et al., 2017). Their study was based on inspections and surveys, as well as continuous in situ measurements and monitoring using pressure transducers, differential GPS and ADCP to capture the storm, sea, vegetation and seabed characteristics. In situ measurements of sea/wave levels and current velocities adequately quantify the depletion rate of wave height inside a mangrove forest used as an NBS against storm surges in various parts of Vietnam (Mazda et al., 2006; Quartel et al., 2007). Similarly, Krauss et al. (2009) measured the depletion rates of peak water level along mangroves, and Fernando et al. (2005) through coral reefs, during an extreme storm surge event. The disadvantage of in situ measurement and monitoring of the storm surges attenuation is the cost of construction, maintenance, and instrumentation of NBS and adjacent coastal areas as well as the costs of potential damage in an extreme event.

The magnitude of coastal erosion resulting from storm surges and/or wave action can be measured by post-storm surveys and assessments feeding into long-term shoreline trends (elevations, temperature, atmospheric pressure), as well as the measurement of wave run-up, erosion and volume loss of dunes/beaches/sediment (Hallermeier and Rhodes, 1989; Suzuki et al., 2011; Barone et al., 2014; Griffith et al., 2014). Laboratory studies in flumes and with geometrically scaled NBS (e.g. Anderson et al., 2013; Servold, 2015) have brought in understanding and knowledge on the fundamental processes of wave attenuation through the NBS, but there is a lack on their uptake and application for NBS design and construction.

Overall, the review of methods, tools, instruments and sensors-related literature presented above has shown the potential of monitoring the efficiency and performances of different types of NBS. The most noticeable finding to arise from these subsections (Section 4.2 to Section 4.6) is that space-based and close-range sensing can capture NBS performance effectively. In-situ measurements are accurate, but their footprint is generally limited, and direct visits are necessary to interpret the measurements in terms of the conditions of the entire NBS intervention.

5. Advantages and limitations of NBS monitoring approaches

5.1. Floods

Monitoring of NBS for floods using conventional gauge sensors provides only single dimension physical variables, whereas visual sensors provide dynamic and real on-site details. These sensors support disaster prevention authorities in decision or policy formulation for flood risks alleviation. Monitoring stations do not provide whole coverage of flood-plains because they are generally ground-based, limited in number and scattered sparsely. However, remote sensing technique furnishes cost-effective and comprehensive coverage of a huge area. This also makes monitoring easier in extreme weather and climate events when ground-based data measurement would be difficult. Furthermore, pictures taken at different time-scales help in assessing the change or development after the occurrence of flood events in the past. GIS-based monitoring of flood management assists in not only envisaging the flood as well as estimating possible associated damage (Hattermann et al., 2018) and the effectiveness of used NBS measures. Precipitation can be retrieved to a satisfactory accuracy using satellite data. Flood mapping is often based on high and medium resolution satellite images, like Advanced Very-High-Resolution Radiometer (AVHRR) or MODIS data for monitoring the NBS implemented against floods of a regional dimension. Although AVHRR pictures are often distorted by cloud cover and lack good spatial-resolution, they have a high temporal resolution. This feature allows us to monitor the advancement of nature-based flood management in almost real-time. Shang et al. (2014) showed that microwave emittance is very sensitive to surface water so that flooded areas can be retrieved accurately from the data acquired by a microwave radiometer at 37 GHz, notwithstanding the very low spatial resolution.

Table 7
Indicators along with measured or derived information utilising ground-based, airbonre and/or spaceborne instruments/methods to monitor NBS performance against storm surges and coastal erosion risk.

NBS (place)	Instrument/sensors used Method used	Type of measured data	NBS performance indicator	Author (Year)
Saltwater marsh including S. alterniflora	Laboratory study	(Sea)water level and vegetation height – water level should be below the plant top in order for NBS to be effective Plant density (number of stems per unit area) Wave height dies	Wave height reductions of 60% to over 80% are reported in a laboratory study of an approximately 10 m span of marsh grass. Wave height decline happens inside the first 3 m of the marsh border	Anderson et al. (2013)
Saltwater marsh (Alabama, USA)	Numerical modelling	Existing wind-wave model	Stability of a salt marsh - marsh vegetation is stable	Roland and Douglass (2005)
Saltwater marsh, (Chesapeake Bay; USA)	Non-destructive vegetation survey in situ; high-frequency pressure transducers deployed along a transect; differential GPS for survey; Two Acoustic Doppler Current Profilers deployed during storm; Five low-frequency pressure transducers deployed close to seabed	Surveys data of marsh, wave height, velocity and water levels.	Relative reduction in flood/wave velocity; Net sediment loss; Water level attenuation rates	Paquier et al. (2017)
Mangrove (forests); (Tong King delta, and Vinh Quang coast, Vietnam.)	Water stages and flow velocities monitored at different locations	Measured waves of swell with periods of 8–10 s from a typhoon ∼40 cm.	Decrease of wave heights up to 20% per 100 m of mangroves. The rate of reduction varied from 0.0014 and 0.0058 per m crossshore. Over 100 m the rate of wave decrease due to mangrove forest reaches upto 45% when the water height is 0.2 m and 26% when the water height is 0.6 m.	Mazda et al. (1997) Mazda et al. (2006) McIvor et al. (2016)
Mangrove (forests); (Red River Delta, Vietnam.)	Water height and flow velocity recorded at three locations.	Water height and flow velocity; periods of wave 3.5–6.5 s.	Decrease in wave height (0.002- 0.011 per metre).	Quartel et al. (2007) McIvor et al. (2016)
Mangrove (forests); The Red River Delta (northern Vietnam) and Can Gio mangrove forest (southern Vietnam).	Pressure sensors and wave gauges placed along a transect	Initial wave heights between 20 to 70 cm (no wave periods given); Six mangrove species present.	Average wave height decrease	Vo-Luong and Massel (2006) Vo-Luong and Massel (2006) McIvor et al. (2016)
Mangrove (forests): (estuaries in the southern Andaman region of Thailand)	High frequency pressure sensors along transects	Wave heights, energy, velocity of water, water levels, wave periods measured at different locations.	Wave damping rate, which varied from 0.002/m in poorly planted forest and it could reach upto 0.012/m in dense vegetation forests	Horstman et al. (2014) McIvor et al. (2016)
Mangrove (forests) (Global)	Existing global wave height maps/data; systematic review; numerical models	Wave height decay (20-50% over 100 m or 2-7.5 times better than bare)	Water level relative to the root structure – when water level within the root structure NBS most efficient against wave action; when above root structure, NBS most efficient against storm surge	Blankespoor et al. (2017) Hashim and Catherine (2013) Mazda et al. (1997) Zhang et al. (2012)
Mangrove (forests) Ten Thousand Islands National Wildlife Refuge, and Shark River (Everglades) in Florida, USA	Empirical measurements of rates of peak water level reduction through mangroves during hurricane (Krauss et al., 2009) Validated numerical model (Zhang et al., 2012)	Peak water levels recorded about 4 locations ∼1 km apart and from each other, and other locations were salt marsh. peak water level height reduction across all recording point pairs, wind speeds, trees species, tree density, width of mangrove forest; Storm surge decay rates (reduction 9-50 cm/km; or up to 30% decay in the initial width of mangroves)	Mangrove density and width	Krauss et al. (2009) Zhang et al. (2012) Ismail et al. (2012)
Mangrove (forests); Cocoa Creek, Australia and Iriomote Island, Japan.	Measured date of water levels and flow along cross sections	Cocoa Creek: Reduction of waves heights and periods (1.5 and 4.5 s). Island: majority wave energy reduction happened within the periods of 1.5 to 3s.	The transfer of wave energy factor differs within 0.45 and 0.8 (where 1 is no decay of wave energy) 150 m toward the forest.	Brinkman et al. (1997) Massel et al. (1999) McIvor et al. (2016)
Maritime forests (Pacific)	Numerical study	Wave height reduction, width of forest strip	Forest with – forest width should be about the same as the wavelength to achieve reduction of 40%	Mei et al. (2014)
Maritime forests (Pacific)	Numerical study	Storm surge and flow velocity reduction (22% and 49%) for a 300m wide forest belt	Forest width	Das et al. (2011)
Reefs (oyster or coral)	Geometrically scaled laboratory experiments	Reduction in the average water height due to wave decaying.	Mean water level	Servold (2015).

(*continued on next page*)

Table 7 (*continued*)

NBS (place)	Instrument/sensors used Method used	Type of measured data	NBS performance indicator	Author (Year)
Reefs (Pacific rim)	SLR; meta-analysis of coral reefs; data collected from wave instruments at cross section offshore (control) and inshore (treatment)	255 findings on coral reefs and wave damping and wind (period ¼ 3–8 s); records addressing multiple tidal cycles (and depths) of water; reef depth;	Wave attenuation; wave energy reduction;	Ferrario et al. (2014)
Reefs (Pacific rim)	Cost-benefit analysis from SLR; meta-analysis of coral reefs	255findings on coral reefs and wave damping	(Construction) cost per metre length of reef; total restoration project cost	Ferrario et al. (2014)
Coral reefs (Sri Lanka)	Empirical measurements during extreme event	Reefs dissipated wave energy and decreased wave height	Wave height	Fernando et al. (2005)
Beach nourishment / dunes (New Jersey, USA)	Post-storm survey and assessment; long-term shoreline trends (elevations measured using total station), measurement of wave run-up, erosion and volume loss of dunes, temperature, atmospheric pressure,	Widening the beach decreased storm loss equivalent to shifting infrastructure landward by uniform amount amount	Beach width Beach soil (sand better than cobbles)	Dean (2001) Barone et al. (2014)
Dunes (vegetated) (East Coast, USA)	Measured erosion cross sections before and after a storm using total station	Crest elevation above wave/surge and volume of the dune affect dune stability	Volume above storm water level; crest elevation	Hallermeier and Rhodes (1989)
Dunes (vegetated)	Physical model experiments in a moveable-bed wave flume;	Wave height, dune height, wave velocity, vegetation density, vegetation coverage.	Vegetation density, coverage and survival rates on the dunes	Figlus et al. (2014) Gralher et al. (2012) Kim et al. (2017) Kobayashi et al. (2013) Silva et al. (2016)
Vegetated berms (similar to dunes); Henderson Point, Mississipi, USA	Long-terms seal level gauge readings;	Historic hurricane records (tracks), high water mark elevation records, ground surface elevations (digital terrain model), flood hazard maps, storm return periods, 1:100 flood elevation, future sea level rise, US Army Corps of Engineers (USACE) Sea Level Change calculator,	Redirecting storm surge flow, decreasing flow velocity. Vegetation is used for reinforcement of the berm so percentage ground cover indicates efficiency of the measure.	Web et al. (2018)
Seagrass meadows (Albany coast, Western Australia)	General/systematic review	Wave height, seagrass density	Wave height decreases with seagrass density up to 30%	Gracia et al. (2018)
Seagrass meadows (south-west Madagascar)	General/systematic review	Wave height	Wave height decrease	Gracia et al. (2018)
Hybrid NBS – oyster reef with marsh vegetation (Florida, USA)	Indoor wave tank with 1:1 scale; Three capacitance wave gauges were used with Ocean Sensor Systems Incorporated V3_1 software;	Free surface displacements were converted to wave heights using the statistical zero-crossing method	Wave attenuation through living shorelines	Manis et al. (2015)
Hybrid NBS – coral reef, mangrove, sea grass (Belize)	Numerical model	"Colson" reef profile, present day sea-level conditions; storm/hurricane conditions; Existing seagrass coverage patterns in Belize; seagrass stem diameter, height, density; mangrove tree/root diameter, height, density; reef accretion rates,	Coastal protection services supplied by two 1-Dimensional (1-D) idealized seascapes	Guannel et al. (2016)
Combined green-grey solutions: saltwater marsh and sheet pile wall/ barrier, (Brookhaven, NY, USA)	Adaptation Decision-Making Assessment Process	Climate data; worst-case scenario; stability assessment; costs of adaptation	Support managerial decision	FHWA (2016)
Mangroves, salt-marshes, coral reefs and seagrass/ kelp beds for wave height reduction. Global analysis.		Meta-analysis of data from sixty-nine field measurements in coastal habitats globally. Analysis of costs and benefits was based on results from 52 projects in the various habitats.	Wave reduction field measurements in coastal habitats, Cost-Benefit Analysis	Narayan et al. (2016)

5.2. *Droughts*

The characterization of *meteorological droughts* across time and areal scales through indices, such as SPI or PDSI, is done using meteorological data, obtained from in situ gauges, satellite-based measurements, or from simulation models that process meteorological data (Norman et al., 2016). They characterize the most common triggering factor for droughts, which is reduced precipitation. The SPI is only sensitive to statistical changes in precipitation, and long-term historical records are needed for its calculation (McKee et al., 1993). The use of this index has been hampered in remote and undeveloped areas due to temporal inconsistencies in precipitation time series, spatial inhomogeneities and limitations in observational support (Diamond et al., 2013; Sorooshian et al., 2011; Wardlow et al., 2017). This limitation has been overcome to a large extent by the combined use of ground and satellite-based measurements, which provide a spatio-temporal interpolation of measurements in a consistent manner globally (Funk et al., 2015). The PDSI uses a soil water balance approach, providing estimates of soil moisture fluctuations (Wanders et al., 2010). It goes then one step forward in characterizing drought impacts, compared to the SPI precipitation anomaly detection. However, water balance estimates require the input of an additional meteorological parameter, which is the air temperature (Palmer, 1965). Again, this additional requirement was a difficulty for its application in poorly gauged areas, which has been largely overcome by the use of satellite-based meteorological data. Alley (1984) pointed out several limitations of the PDSI, where no distinct definitions of the onset and end of a drought or wet spell, which are only built on Palmer's work, was identified as the most predominant constraint (Wanders et al., 2010). As a landmark in meteorology, PDSI has proved to be a fulfilling parameter for characterizing the intensity of long duration droughts at a particular place. However, it has been unsuccessful in resolving short duration droughts and differentiating inconsistencies among various climatological zones (Guttman, 1998; Zhao et al., 2017; Liu et al., 2020). Advanced data processing techniques have been applied (Hoek et al., 2016; Zhou et al., 2020) to disentangle the components of complex signals and to determine quantitatively the response of vegetation to precipitation at different time scales, considering differences related to soil type.

Earth observation measurements, such as the NDVI are sensitive to agricultural drought. Therefore, they can inform the impact of meteorological drought on natural ecosystems and food productivity (Peters et al., 2015; Norman et al., 2016; Lu et al., 2019). NDVI data are available in a broad spectrum of spatial scales and temporal intervals, covering from pixel sizes of a few km to smaller than 1 m, and intervals from bi-weekly to sub-daily. The spatial scale of the NDVI data allows to monitor the performance of NBS practices in agriculture and natural vegetation and to provide a comparison with areas where solutions are not implemented. Furthermore, given the long-term archive of satellite data, the impact of droughts can often be analysed historically for a given location in terms of NDVI, e.g. before and after NBSs have been implemented. Datasets for NDVI mapping with pixel size down to 10 m, are freely available at 6-day intervals (West et al., 2018). Finer spatial and temporal resolution datasets exist (Houborg and McCabe, 2016) but are normally available at a considerable cost. NDVI is only competent in manifesting delayed reactions to alterations in greenery but is insufficient in identifying early droughts because of its inability in recording early photosynthetic differences (Rossini et al., 2015; Sun et al., 2016; Liu et al., 2018). Despite the shortcomings of satellite-based monitoring, like the need for inter-scene and inter-sensor calibration and big data processing, the NDVI still provides near-real-time data at sufficient frequency which is seamless, consistent, and easy to use (Norman et al., 2016; Zhang et al., 2017).

NDVI limitations and shortcomings include its saturation over dense vegetation canopy areas like the northern hemisphere's boreal zone or tropical forests (Section 4.3). As a consequence, the association between NDVI and canopy dynamics breaks down (Anyamba and Tucker, 2012). NDVI's seasonal differences are insufficient to ascertain noteworthy drought events when the growth of vegetation is not much affected by soil moisture (Wang et al., 2005). The combined signal from plants and soil in low vegetated areas can cause misapprehension of the vegetation dynamics and overrating of ecosystem yield and state of droughts (Karnieli et al., 1996) as well as the performance of NBS. On top of these problems, we also have typical shortcomings of satellite systems like monitoring ground conditions in areas with persistent cloud coverage (Fensholt et al., 2006). The saturation of the NDVI has been partially overcome by the introduction of the Enhanced Vegetation Index (EVI, Huete et al., 2002). EVI is sensitive to vegetation canopy changes beyond the NDVI saturation, and it is hence preferred for monitoring rainforests and other regions of the planet of high biomass. An additional approach for monitoring agricultural drought is to use estimates of actual and potential evapotranspiration (ET) at high spatial resolution (Jia et al., 2018). The ratio of actual to potential ET is a sensitive indicator of soil water availability and of vegetation response to that.

Monitoring of *hydrological droughts* normally requires measurements of water depth in lakes and reservoirs, soil moisture, groundwater table elevation and river flow discharge. The adequate representation of these parameters over large areas requires hydrometric networks acquiring continuous and consistent measurements, which in turn demands systematic equipment maintenance and data curation. While such a network is available in many developed countries, it continues to be a major obstacle for water resources tracking in poorer regions of the World. Satellite data can provide accurate measurements of the surface area of water bodies (Keys and Scott, 2018). Laser and radar altimeters can be used to retrieve water surface elevation in large lakes and rivers (Crétaux et al., 2011). Soil moisture can be retrieved for the top 5 cm of the soil at the coarse spatial resolution, with pixel sizes typically larger than 1 km (Zhu et al., 2019), and gravity changes provide information of aquifer depletion trends (Yi and Wen, 2016) over large river basins. However, satellite data fails to capture river flow rates or aquifer levels. It is fair to say that satellite-based monitoring can reasonably inform hydrological droughts at the catchment scale, but is not adequate to capture the more localised effect on NBS on water resources. Monitoring this local effect would require ground sensors, e.g. soil moisture probes to evaluate the increased infiltration or moisture retention of conservation agriculture practices (Montenegro et al., 2019), in the area under the NBS influence and in reference sites without NBS.

5.3. *Heatwaves*

Monitoring of air temperature for NBS performance assessment relies mainly on ground meteorological stations, whose data can be spatially interpolated by the use of models. Earth observation can inform of air temperature, achieving continuous spatial coverage at the expense of reduced accuracy and sampling frequency. It is easier to observe the cooling effect of urban greening in open areas, e.g. recreation grounds, where a gauging station can be placed, than along more extended areas, such as street canyons (Yan et al., 2020). Blue-NBS for heatwaves, such as applying water on pavements, is reversible, i.e. the site can be reverted to the original state when not being watered. This allows the collection of baseline/reference and test data simultaneously (Hendel et al., 2016) To assess the performance of permanent blue-NBS such as ponds, baseline data need to be gathered before the implementation of the NBS. The duration of the monitoring study may also be important. The outskirts of metropolitan areas are rapidly evolving, so the baseline data gathered over a specific period may rapidly lose representativeness. So, the baseline data need to refer to a reasonably stable site over the whole research period. Where satellite-derived LST is used as an indicator of NBS efficiency, it is difficult to measure the NBS cooling effect during nights (Marando et al., 2019). In any case, the radiometric temperature observed by a remote imaging radiometer should be corrected to estimate the complete urban surface temperature that captures the radiative and convective contributions of all facets of the built-up spaces (Yang et al., 2020).

Due to insufficient site description parameters to feed numerical thermal models, estimating the green roof's potential in reducing the cooling energy demand has been difficult. The thermal efficiency of green roofs also varies with the growth or senescence of vegetation all-round the year (Bevilacqua et al., 2017). Monitoring methods can be improved by using high accuracy devices and calibrating them frequently against each other in a controlled environment. Using solar shields can obliterate the insolation reverberations on air temperature and humidity monitoring, and so for data loggers. The monitoring study may be insufficient to assess NBS implementation at a large scale. Here, the modelling approach replaces monitoring. For example, Taleghani et al., 2014 used computer simulations to evaluate the thermal performance of study sites for different NBS combinations at varying scales.

5.4. *Landslides*

In case of continuously moving deep-seated landslides, the efficacy of an NBS designed to reduce the landslide's activity can be assessed by monitoring the displacement over time. However, it is then necessary to establish a plausible correlation between the effects of the implemented NBS and the displacement without having additional (grey) solutions implemented.

Investigating root reinforcement involves destructive tests which cannot be repeated at the same location. Hence, monitoring over time can only be carried out by repeated (destructive) measurements of root systems, grown under controlled and comparable conditions (e.g. Vergani and Graf, 2016; Zhu et al., 2020) or by means of indirect measurements such as ground-penetrating radar (e.g. Yamase et al., 2019). Also, the custom-built pull-out device presented in Meijer et al. (2018a, 2018b) is less destructive than conventional testing methods and could be used for monitoring the evolution of root reinforcement over time. Furthermore, a major difficulty for quantifying a root's tensile strength is to properly fix the root in the pulling device (Giadrossich et al., 2017). This matter is addressed by many of the reviewed studies, and various technical solutions have been found. It appears that most studies focus on mitigating relatively shallow landslides, typically occurring in engineering soils (debris and earth, (Cruden and Varnes, 1996)). Only in rare cases other landslide types are addressed, such as falls, topples or spreads. Also, studies on hydrological effects of NBS on large, deep-seated rotational landslides are lacking. The few examples involve artificial drainage systems (e.g., Hong-yue et al., 2019; Yua et al., 2019) which do not qualify as NBS.

5.5. Storm surges and costal erosions

It is challenging to measure the value of storm surge protection by NBS, because of the highly variable and uncertain trajectories, frequencies, intensities and impacts of storms. Most of the monitoring tools and approaches are based on inspections and surveys, as well as continuous in situ measurements and monitoring using pressure transducers, differential GPS, and Acoustic Doppler Current Profilers to capture the storm, sea, vegetation and seabed characteristics. The advantage of these approaches includes the use of readily available sensors, technologies, and data. The disadvantages of the methodologies reviewed above include the lack of potential success of different NBS application outside the reported geographical spread (i.e. outside the Tropics), the lack of measurements and analysis on a meso-scale (e.g. small bays), the lack of high-resolution climate data (e.g. anything less than 2 km resolution), the lack of long-term monitoring of the health of the NBS against the experienced surges; and the lack of quantification of the ecosystem services value on an NBS-scale.

Overall, passive and active remote sensors, functioning in the visible, microwave, thermal near-infrared and infrared segments of the electromagnetic spectrum are economical in bestowing indispensable details on the HMHs affected regions and the effectiveness of enacted NBS. However, the acquisition of detailed topographic data using LiDAR (Light Detection and Ranging) scanners continues to be expensive, which is a prime drawback for its use. Development of miniaturized, low-cost imaging LiDAR systems and their implementation on UAV is very active research and development area (e.g. González-Jorge et al., 2017). The SfM or UAV-based photogrammetry is a much more affordable option, yet accurate, but it lacks the canopy penetration capacity of LiDAR signals. 3D point clouds thus obtained, hitherto restricted to terrestrial data acquisition, may attain precision and resolution of a few millimetres. Processing outcomes of integrated multi-view-stereo image matching and LiDAR range measurement provide additional advantages while generating high-accuracy, dense 3D point clouds. The special airborne equipment usually required for the acquisition of these data has high purchase and operational costs. Freely available space data provides an alternative left for mapping HMH destruction and NBS performance. Satellite radar can image the Earth in adverse weather conditions, which is of specific interest during the occurrence of some HMHs. However, the analysis of radar data can be intricate and even strenuous to inexperienced analysers. Insufficient spatial resolution and ground truth data for interpretation also constitute essential constraints.

6. Conclusions and future outlook

We reviewed and analysed the status and advancements of NBS monitoring instruments and techniques (ground-based, airborne and space sensors) used to measure the performance, impact and benefits of the implementation of NBS against five HMRs (floods, droughts, heatwaves, landslides, and storm surges and coastal erosion). We discussed their advantages and limitations, provided recommendations and highlighted the future needs. The key conclusions are outlined as follows:

- Indicators are necessary to measure the effectiveness of a specific NBS intervention. They can be subjective or objective in measuring a certain NBS's progress towards project goals. Indicators of efficiency and performance are selected when drafting the monitoring project, and corresponding measuring methods are adopted. The chosen indicators have to be measurable, simple, achievable, not too time-consuming and relevant to the objectives of the project.
- There are three key components of the monitoring process, namely: (1) Identification of project goals; (2) Selection of relevant performance indicators/metrics; and (3) Selection of appropriate measurement methods, tools and sensors. Additionally, the monitoring may be required for long-term and over large areas to compare NBS effects to those of traditional grey solutions. This information can be helpful in estimating the efficiency of NBS while upgrading from micro- to macro- scales.
- Monitoring of NBS implemented against HMRs can be done directly on the study area (i.e. in situ information collection) or through remote sensing (airborne or satellite). In situ measurements typically require substantial maintenance and are exposed to errors and data acquisitions gaps. Airborne information may also lack sufficient observation frequency, as well as be expensive to obtain. Satellite-based monitoring can cover NBS over vast geographical areas, including unreachable regions at a consistent frequency for long periods. Their main drawback is generally the lack of resolution or opportunity of observation, which sometimes can be overcome at a high cost by using data from recent commercial constellations of satellites.
- The indicators used for monitoring the performance and efficiency of nature-based flood mitigation actions are: (a) peak discharge reduction for various flood event return periods (e.g. 10, 20, 50, 100 or 200 years); (b) flood duration; (c) decline in the annual flood likelihood for the chosen region. These indicators can be drawn from data collected by hydrometric stations, airborne and space-based observations. In particular, the combined application of in-situ monitoring and remote sensing (e.g. stream gauges and airborne or satellite based flood maps) provide accurate evidence of the flood severity and therefore of the effects of NBS in flood attenuation.
- The performance of NBS implemented against meteorological, agricultural, and hydrological droughts can be monitored based on the indices, such as PDSI, NDVI, VH or LST, by comparing their values at experimental monitoring site(s) with NBS to that site without NBS, or before and after the implementation of NBS at any test site.
- Temperature and humidity monitoring, measured with on site thermometers and hygrometers, or mapped over large areas using remote sensing measurements , is the most popular method for assessing the thermal comfort provided by NBS for heatwaves, which includes pavement watering, green spaces and green-roofs. Although station-based measurements provide accurate records of temperature at their location, they fail to capture spatial gradients. Satellite-based thermal remote sensing can inform spatial gradients, but its application in urban environments is complex and lacks spatial resolution. Airborne thermal sensors can accurately map temperature over urban areas but at a high cost.
- Monitoring of NBS against landslides focuses on the effect of roots of various plant species, soil bioengineering techniques including drainage systems, slope stabilization using natural resources (e.g. live fascines, live palisades, live crib walls) and adapted land management including land-use change. In case of continuously moving

landslides, evidence for the efficacy of NBS can be provided by monitoring their displacements with a suitable technique and setting (e.g. spatial and temporal resolution). However, a decreasing landslide activity proven by displacement monitoring after the implementation of one or multiple NBS must then be linked to the effects of the mitigation measures while excluding other potential effects of the landslide's causes and triggers (e.g. reduced HM forcing).

- Some approaches and instrumentation have beem implemented for monitoring the effect of NBS against storm surges and coastal erosion. However, the resolution and geographical distribution of these are limited and do not reflect the variety of the impact and benefits the NBS can provide against the effects of storm surges and coastal erosion.
- Earth observation satellites offer numerous possibilities to explain the pre- and post-NBS interventions scenarios to farmers, researchers, emergency managers or policymakers. Though being excessively complex and requiring high-level expertise, they have good synoptic coverage and spatial resolution to monitor the extent of HMRs impacted regions and the performances of NBS. Compared to in-situ collected information, it also commissions a perpetual documenting of HMHs. Furthermore, passive and active sensors, working in the visible, microwave, thermal and infrared segments of the electromagnetic spectrum are economical in bestowing necessary details on the HMHs affected regions and the effectiveness of enacted NBS.
- Throughout scientific databases, there are no internationally recognised standard methodologies to monitor NBS implemented against HMRs. How to consolidate varying techniques, tools, instruments and sensors within an integrated approach to monitor the performance of NBS still prevails as a question. Therefore, ensuring investigations in this subject should tackle ongoing troubles, obligations, impedances and hurdles ushering the evolution of NBS monitoring foundation and enabling scientists and professionalists to put efforts in this direction.

Here, we reviewed and consolidated the available monitoring methods, tools, instruments and technologies that have been utilised and/or could be used to monitor the performance of NBS projects against five HMRs. Future studies should focus on presenting specific details concerning the operation of various equipment used for ground-based, airborne and space-based observatories and/or their maintenance.

Authors' contributions

PK: Conceptualization, supervision, writing of original draft, reviewing and editing; **SD, JS, BM and NR**: writing of original draft: all authors; review and editing of the manuscript, methodology, formal analysis, Section 4.1, 4.3 and 5; **BB, AB, FP, SS, PB and JP**: Writing - review and editing (Section 4.1 and Section 5); **BM, NC, ML and CS**: Writing - review and editing (Section 4.2 and Section 5); **SBM**: Writing - review & editing (Section 4.5 and Section 5); **JP, MR, MM** and **TZ**: Writing - review & editing (Section 4.4 and Section 5); **BP, JJ and HT**: Review & editing the manuscript.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

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