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A review of hydro-meteorological hazard, vulnerability, and risk assessment frameworks and indicators in the context of nature-based solutions

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ABSTRACT

Nature-based solutions (NBS) are increasingly being implemented as suitable approaches for reducing vulnerability and risk of social-ecological systems (SES) to hydro-meteorological hazards. Understanding vulnerability and risk of SES is crucial in order to design and implement NBS projects appropriately. A systematic literature review was carried out to examine the suitability of, or gaps in, existing frameworks for vulnerability and risk assessment of SES to hydro-meteorological hazards. The review confirms that very few frameworks have been developed in the context of NBS. Most of the frameworks have emphasised social systems over ecological systems. Furthermore, they have not explicitly considered the temporal dimension of risk reduction measures. The study proposes an indicator-based vulnerability and risk assessment framework in the context of NBS (VR-NBS) that addresses both the above limitations and considers established NBS principles. The framework aims to allow for a better consideration of the multiple benefits afforded by NBS and which impact all the dimensions of risk. A

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list of 135 indicators is identified through literature review and surveys in NBS project sites. This list is composed of indicators representing the social sub-system (61% of total indicators) and the ecological sub-system (39% of total indicators). The list will act as a reference indicator library in the context of NBS projects and will be regularly updated as lessons are learnt. While the proposed VR-NBS framework is developed considering hydro-meteorological hazards and NBS, it can be adapted for other natural hazards and different types of risk reduction measures.

1. Introduction

Natural hazards such as floods, droughts and heatwaves pose threats to social-ecological systems (SES) around the world. In most cases, floods and droughts are caused by a combination of naturally occurring extreme weather events and anthropogenic activities [1–3]. The increasing pressures of urbanization, food production and economic activities are contributing to the degradation of regulatory functions of natural ecosystems that normally help to maintain hydrological cycles [4,5], causing e.g. increased flooding [1,6]. Furthermore, global climate change is aggravating the severity of hydro-meteorological hazards towards extremes that can irreversibly alter natural ecosystems [7]. Against this backdrop, understanding the vulnerability and risk of SES to natural hazards requires an in-depth systematic analysis, based on which risk mitigation measures can be proposed [8].

Over the last centuries, man-made engineering structures have been deployed to reduce the risk associated with natural hazards. For instance, levees, dams, river channelization and artificial drainage systems have been built to mitigate floods and droughts [9–11]. However, these conventional risk mitigation measures, based on engineered structures that primarily give priority to social and economic needs, have often negatively affected ecosystems in the long term [12,13]. Nature-based Solutions (NBS) for reducing risk have been conceptualised more recently [14–17], showing promising results in terms of risk reduction and biodiversity preservation [18]. However, NBS approaches are yet to be established as broadly accepted suitable risk mitigation measures with demonstrated benefits.

NBS are considered an umbrella concept that encapsulates various ecosystem-based approaches [18], such as Ecosystem-based Adaptation (EbA), Ecosystem-based Disaster Risk Reduction (Eco-DRR), Green Infrastructure and Natural Infrastructure, used to address ecological degradation, risks from natural hazards, and climate change adaptation. The International Union for Conservation of Nature (IUCN) define NBS as “actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges (e.g. climate change, food and water security or natural disasters) effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits” [18]:2). The European Commission (EC) also provides a definition for NBS which places particular emphasis on resource-efficiency and socio-economic benefits along with environmental benefits [19]. To support uptake and implementation of NBS, IUCN proposed a set of general principles that were endorsed by IUCN, which should be considered by experts developing NBS globally [18]. The principles focus on balancing ecosystem conservation as well as socio-economic benefits in a fair and equitable manner and with broad societal participation. While the principles form the general basis of characterizing NBS, there is no specific reflection to mitigating or reducing vulnerability and risk of SES to natural hazards by NBS. However, these are central to concepts such as Eco-DRR and EbA. IUCN will release the standards for NBS in 2020 [20].

In parallel to the development of the IUCN NBS principles, the World Bank proposed comprehensive guidelines for the implementation of NBS to reduce flood risk [21]. This guideline proposed an assessment of flood risks and benefits of a full range of solutions (i.e. not limited to green solutions only) as one of the five overarching principles before making a final decision on risk reduction approaches. Also, in 2017, Friends of EbA (FEBA) published a framework for qualification criteria and quality standards for EbA. The framework consists of a first attempt at providing guidance as to what EbA should be and what it is not. Two of the qualification criteria emphasise that EbA should reduce social and environmental vulnerabilities as well as facilitate climate change adaptation [22]. Finally, in 2019, the Convention for Biological Diversity (CBD) published voluntary guidelines for ecosystem-based approaches to climate change adaptation and disaster risk reduction [23]. All these partially overlapping and at times complementary sets of principles and guidelines are relevant to the acceptance of NBS at global scale because they address knowledge gaps and provide explicit guidance to decision-makers on planning for and implementation of NBS in the context of climate change adaptation and disaster risk reduction.

While most of the above-mentioned principles and guidelines address the disaster risk reduction role of NBS, designing appropriate NBS to reduce disaster risks requires a better understanding of the exposure, vulnerability and risk of SES. In order to understand the complex interaction of natural hazards and SES, it is essential to conduct vulnerability and risk assessments considering both environmental and socio-economic conditions related to natural hazards and climate change risks at a location [24]. In recent years, a wide range of vulnerability and risk assessment approaches/frameworks/tools have been developed [25] to determine SES vulnerability and risk to natural hazards. These include the SUST model [26], MOVE framework [27] and the Delta-SES vulnerability assessment framework [28]. Most of these approaches have emphasised both ecosystems/the environment and social systems in determining risk. Despite this, in most cases, capturing the ecosystem component in these frameworks through e.g. indicators is overshadowed by the social components [28,29]. This is problematic in itself if a comprehensive characterization of an SES is to be achieved, but constitutes a bottleneck when NBS are to be considered for risk reduction measures as both (1) the opportunity for NBS to contribute to hazard reduction (e.g. in terms of frequency and magnitude), exposure, and vulnerability and (2) the level of dependence on ecosystem services cannot be explicitly captured. In this case, it is indeed essential to understand in more detail the exposure, susceptibility and robustness of the ecosystems themselves as well as the interaction between social and ecological systems through the provisioning of ecosystem services. The objective of this review paper is therefore to explore the current state of knowledge in vulnerability and risk assessments (frameworks and indicators) to natural hazards in the context of NBS implementation, and propose a conceptual framework and a preliminary list of indicators for this purpose. This paper presents the findings of part of a research project funded by the European Commission (under the H2020 framework) entitled ‘OPEn-air laboRAtories for Nature baseD solUtions to Manage hydro-meteo risks (OPERANDUM)’ in which NBS will be implemented for reducing risk to hydro-meteorological hazards in various Open-Air Laboratories (OALs) (https://www.operandum-project.eu/).

Section 2 of the paper describes the approach to the systematic literature review carried out in this study. In section 3, the findings of the review related to existing vulnerability and risk assessments frameworks are described and the major gaps in the frameworks in the context of NBS are identified. In section 4, a modified vulnerability and risk assessment framework is proposed in the context of developing NBS for reducing risk to natural hazards. Finally, a set of indicators for vulnerability and risk assessment is proposed in section 5. The paper finishes with a discussion of the findings and a conclusion.

2. Methodology

A systematic literature review of journal articles was carried out in Scopus and later supplemented with grey literature found in Google Scholar to determine the state of the art in terms of vulnerability and risk assessment in the context of NBS. Initially, a list of possible keywords was drafted, focusing on three main categories: a) risk components, b) types of NBS, and c) assessment elements. Risk components were taken from the IPCC AR5 [30] (see definitions of the risk components in Supplementary material S1), while a list of types of NBS was taken from a recent IUCN report [18]:10). Comprehensive vulnerability and risk assessments should be grounded in explicitly defined theory, often in the form of a conceptual framework [31]. Thus, although assessments were considered in the literature review, the keywords "framework," "concept*", "model", and "tool" were also included in the third category. Furthermore, the keyword "indic*" was added to the list as composite indicators are commonly used in such assessments [29,32].

Given the rapid evolution of terminology used to describe concepts of NBS, and the fact that most publications on the topic are relatively recent [18], the search was limited to articles published from 1990 to 2018. As the study mainly focused on hydro-meteorological hazards, irrelevant papers in other fields of research that employ terms such as risk, vulnerability, and indicator were removed by adding a number of exclusionary terms to the search, using the AND NOT Boolean operator. An iterative trial and error process of screening was followed using the exclusionary terms. The search in Scopus using the final keywords (Table 1) yielded 1745 articles. Considering the relevancy to hydro-meteorological hazards and NBS types, a title screening resulted in 432 articles. Abstracts of these articles were independently screened by five of the authors which resulted in 45 most relevant articles for this review. Important information about the vulnerability and risk assessment methods as well as all indicators presented in the articles were extracted into a pre-prepared matrix. Where there was any disagreement in extracted information among reviewers, these reviewers would return to the article and discuss it further until a consensus was reached.

Table 1
Categories of search terms and final search string. The search was conducted for terms appearing in the title, abstract or keywords.

Category	Search Terms
Risk components	hazard OR risk OR exposure OR vulnerab*
NBS types	"nature-based solution" OR "eco-engineering" OR "Ecological restoration" OR "Ecological engineering" OR "Forest landscape restoration" OR "Ecosystem-based adaptation" OR "Ecosystem-based mitigation" OR "Climate adaptation services" OR "Ecosystem-based disaster risk reduction" OR "Natural infrastructure" OR "Green infrastructure" OR "Integrated coastal zone management " OR "Integrated water resources management" OR "protected area management" OR "ecosystem-based management" OR "social-ecological"
Assessment elements	assessment OR framework OR model OR tool OR concept* OR indic*
Exclusion criteria: terms in title/abstract/keywords	non-native OR invasive OR ozone OR seismic* OR earthquake OR contaminant OR antibiotic OR pesticide OR marine OR nuclear OR pm OR bacteria* OR toxic* OR metal*
Exclusion criteria: terms in title	economy OR species* OR urban OR city OR pollution
Exclusion criteria: year	PUBYEAR >1990
Combined Search String	
TITLE-ABS-KEY ((hazard OR risk OR exposure OR vulnerab*) AND ("nature-based solution" OR "eco-engineering" OR "Ecological restoration" OR "Ecological engineering" OR "Forest landscape restoration" OR "Ecosystem-based adaptation" OR "Ecosystem-based mitigation" OR "Climate adaptation services" OR "Ecosystem-based disaster risk reduction" OR "Natural infrastructure" OR "Green infrastructure" OR "Integrated coastal zone management " OR "Integrated water resources management" OR "protected area management" OR "ecosystem-based management" OR "social-ecological") AND (assessment or framework OR model OR tool OR concept* OR indic*) AND NOT (non-native OR invasive OR ozone OR seismic* OR earthquake OR contaminant OR antibiotic OR pesticide OR marine OR nuclear OR pm OR bacteria* OR toxic* OR metal*)) AND NOT TITLE (economy OR species* OR urban OR city OR pollution) AND (PUBYEAR > 1990)	

In addition, a search for relevant grey literature (e.g. reports, policy briefs, dissertations) was used to supplement the results of the systematic review of journal articles. Using Google Scholar, a simplified and targeted search string was employed: (hazard OR risk OR exposure OR vulnerable OR vulnerability) AND ("nature-based solution" OR "Ecosystem-based disaster risk reduction" OR "Eco-DRR"). The search returned 903 results, sorted automatically by Google Scholar in order of relevance to keywords. The titles, descriptions, and (if necessary) content of the first 200 documents were screened, since no relevant additional literature was found beyond the first 180 hits. Thirteen new documents were judged to fit the search criteria used in Scopus. These were reviewed by two of the authors, and information inserted in the review matrix. In the end, 58 papers including the 45 articles from Scopus and 13 from Google Scholar were reviewed for this study. Of the 58 articles reviewed, 69.0% were peer-reviewed journal articles, 22.4% reports, dissertations or theses and 8.6% peer-reviewed book chapters (Fig. 1). As for previous reviews on this topic (e.g. Ref. [28,29], most of the publications reviewed were recent: 77.6% were published after 2015, and none published before 2005 (Fig. 1).

We supplement the systematic literature review with a narrative review of key articles that present either conceptual frameworks and/or practical applications of risk assessment relevant to NBS, but without reference to any specific NBS and thus not captured by the keywords. The review of these papers helps to understand the detailed risk assessment approach and processes applied in different cases.

Further, information on the existing risk assessment framework and indicators used at the OALs of the OPERANDUM project were collected. A total of four Focus Group Discussions (FGD), a questionnaire survey with stakeholders (ten respondents) and three meetings with experts were carried out in various OALs. This was important for the development of the risk assessment framework and identification of indicators based on the requirements of implementing NBS.

Combining the inputs from the literature review and surveys, a conceptual framework for vulnerability and risk assessment in the context of NBS was developed in addition to a preliminary list of indicators.

3. Review of vulnerability and risk assessment frameworks in relation to NBS

In this section, we present a critical review of existing vulnerability and risk assessment frameworks, and gaps in those frameworks in relation to NBS. Of the 58 articles reviewed, 38 focused on describing and/or implementing vulnerability and/or risk assessments to natural hazards. 17 articles focused on ecosystem-based disaster risk reduction (Eco-DRR), Ecosystem based Adaptation (EbA) and climate risk management in general, without actually applying any method or framework for risk assessment. Another three articles [33–35] dealt with vulnerability and risk assessment but focused on ecological vulnerability to human interference in wetlands and river basins such as water pollution, agricultural land degradation. Although these three papers do not address natural hazards directly, they provide useful information related to indicators. Most of the 38 articles addressed multiple hazards - generally hydro-meteorological hazards (23 articles) or a combination of two hazards, such as floods and landslides, or floods and droughts (eight articles). One paper addressed a variety of natural and anthropogenic hazards. Other papers focused on single hazards: two on landslides, two on droughts, one on flood, and one on rock fall. Further, more than half of the reviewed papers carried out or considered spatially explicit risk assessments. A majority of risk assessments considered administrative boundaries such as districts, provinces and regions or

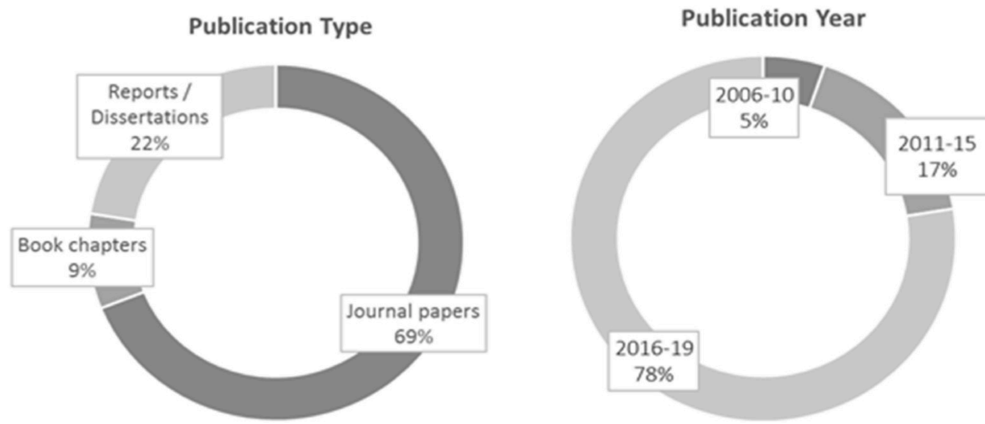

Fig. 1. Type of publications reviewed (left) and year of publication (right).

more localised projects as the spatial scale of assessment. Only a few papers (5.2%) focused on more natural boundaries such as river basins or watersheds (Fig. 2).

A wide variety of approaches, models and frameworks (or combinations thereof) have been applied for vulnerability and risk assessment to natural hazards in recent years. Predominant approaches used in the reviewed articles were indicator/index-based assessments or scoring systems (18 articles), followed by modelling/decision support systems (13 articles). Some modelling papers also combined index-based approaches. Other papers presented only conceptual SES frameworks (four articles), or other more general conceptual frameworks for risk assessment (two articles).

From the broader literature, various indicator-based vulnerability assessments were developed and implemented at global or national to local level. Examples of global or national level risk assessment methods include the indicator-based Global Risk Analysis [36], the World Risk Index [37], Disaster Risk Index [38,39] and Global Delta Risk Index [8]. The global or national level methods are complemented by local level participatory risk assessment approaches, such as the Community-Based Risk Index [40]. Of the reviewed papers, Asare-Kyei et al. [41] and Hagenlocher et al. [8] both applied indicator-based risk assessment approaches informed by the multi-hazard risk assessment framework [42] and the Delta-SES vulnerability assessment framework [28], respectively. Hagenlocher et al. [8] introduced a novel concept of developing a so-called modular "indicator library" of hazard-dependent and independent indicators, which allows the user to have readily available indicators that can be used for specific contexts (e.g. geography/hazard combinations) or that can be used interchangeably when, for example, data do not exist for one indicator. Apart from indicator-based risk assessment approaches, several other tools have also been used in the reviewed papers, such as the InVEST models which include a coastal vulnerability model [43], CRiSTAL [44] or the more recent Coastal Resilience decision-support platform [45]. These tools can be used on their own but generally, in the context of complex multi-hazards-based risk assessment, are combined with other tools and approaches.

A closer look at some of the influential vulnerability and risk assessment frameworks has explored insights of the components of the frameworks and their implementation. For example, Turner et al. [26] proposed a framework for vulnerability assessment of SES in sustainability science, referred to as the SUST model, which includes elements from risk/hazard approaches to vulnerability as well as ecological resilience theory into a multiscale (spatial and temporal) model of SES vulnerability. The SUST model aims to provide a suitable prototype for 'reduced form' vulnerability analysis considering the limitation of data availability of real-world larger complex systems [26]. Damm [46] developed and applied a modified SUST framework for vulnerability assessment of the SES to floods in Germany. The SUST framework has served as an example or basis for many subsequent vulnerability and risk assessment frameworks.

Birkmann et al. [27] developed a vulnerability and risk assessment framework (MOVE framework) considering vulnerability, resilience, coping and adaptation capacities of SES in the context of natural hazards and climate change at different spatial and temporal scales. It emphasises that these factors are related to the social-ecological exposure to a natural hazard or stressor, the susceptibility of the SES exposed to the

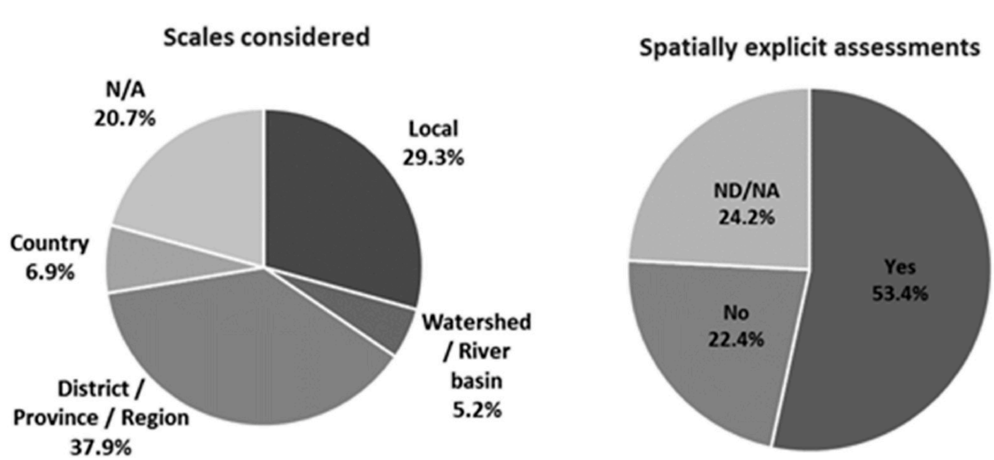

Fig. 2. Scale considered in assessment or when discussing frameworks (left) and percentage of assessments that were spatially explicit (right). ND = Not Determined, NA = Not Applicable.

hazard or stress, and the resilience and adaptive capacity of the system or society. The MOVE framework can be regarded as a conceptual tool to be used for guiding systematic risk assessment processes and developing indicators. However, the framework does not provide any particular methods or a set of indicators for risk assessment [27].

Recognising that SES are usually exposed to multiple hazards, contemporary risk assessment approaches have addressed multi-hazard contexts rather than addressing a single hazard. For example, Kloos et al. [42] developed a multi-hazard risk assessment framework with particular reference to the SES of the Western Sudanian Savanna Zone. This framework was built on integrating the relevant elements of the modified SUST Framework [26,46], the MOVE framework [27], and the Ecosystem Stewardship Framework [47]. The framework outlines the linkages between hydro-climatic hazards/stressors, shocks and risks, environmental and socio-economic factors/stressors, and actual coping and adaptation actions at various spatial and temporal scales. Garschagen [48] proposed a similar framework for assessing vulnerability to natural and man-made hazards and adaptation in the context of changes in climatic, environmental, and socioeconomic conditions, and the transformation processes within SES.

Recognising the necessity of geographical boundary-based vulnerability analysis in the context of multi-hazards, as noted by Kloos et al. [42]; Sebesvari et al. [28] proposed the Delta-SES vulnerability assessment framework, which is a visually simple yet broadly inclusive framework for multi-hazard vulnerability and risk assessment of river deltas. The Delta-SES framework was originally developed to address the gap between the ecological and social sub-components in terms of their representations in vulnerability and risk assessments. The framework was built on major elements of the risk assessment frameworks proposed by Turner et al. [26]; Damm [46]; Kloos et al. [42]; IPCC [49]; and Garschagen [48]. The Delta-SES framework considers the relationships of social and ecological sub-systems at various spatial and temporal scales. Although the effect of hazards on SES occurs at all spatial scales, the sub-delta scale is considered to be the essential place of the vulnerability assessment so that the variations in vulnerabilities among the delta sub-regions (e.g. floodplains, coastal zone) affected by various natural and anthropogenic hazards can be captured. The Delta-SES framework provides a strong basis for indicator-based risk assessment as was carried out by Hagenlocher et al. [8]. One of the latest publications related to climate risk and NBS is a guidebook for climate risk assessment, published by GIZ, EURAC & UNU-EHS [50]; focusing specifically on EbA. The guidebook places stress on understanding and establishing the strong linkages between social and ecological systems that are needed for implementing EbAs. Among other steps, the approach focuses on developing impact chains, choosing indicators to characterise the risk components and the identification of EbA solutions [50].

Some articles from the systematic literature review have proposed risk assessment frameworks specifically related to climate risk and NBS action in coastal areas. For instance, Arkema et al. [51] developed a general framework to demonstrate how an NBS (i.e. marsh restoration) can affect the ecosystem structure and function of coastal areas (i.e. attenuation of hydrodynamic conditions), which then affects the provisioning services of ecosystems (i.e. avoided erosion and/or flooding) and changes societal benefits (e.g. protection of people and assets) [51]:8). Bhattachan et al. [52] proposed an SES framework to analyse sea-level rise impacts on an island of the east coast of the United States, including key components such as social and ecological sub-systems, ecosystem services and policy/management decisions. Further, an Adaptive Gradient Framework is proposed by Hamin et al. [53] for assessing coastal resilience, which incorporates eight metrics (exposure reduction, institutional capacity, cost efficiency, ecological enhancement, adaptation over time, greenhouse gas reduction, participatory process, and social benefits) used to evaluate projects that can provide better coastal resilience.

The papers reviewed cover a wide range of risk assessments or discussions of NBS for disaster risk reduction and climate change adaptation. However, very few of the risk assessment frameworks have been developed comprehensively in the contexts of implementing NBS and linkages with NBS principles. This can be problematic when NBS are to be implemented because the provision of multiple benefits these approaches provide cannot be effectively captured. However, current approaches can be used to adapt frameworks for the NBS context. Most of the recent papers which presented a general framework to inform risk assessment had the tendency to build on older approaches (such as on the SUST framework of Turner et al. [26]. One of the latest “evolution” of such older frameworks is the Delta-SES vulnerability assessment framework [28] used by Hagenlocher et al. [8] and which was also compared to the Social Vulnerability Index (SoVI) framework of Cutter et al. [54] by Anderson et al. Anderson et al. (2019). The Delta-SES framework could serve as a basis for developing a vulnerability and risk assessment framework in the context of NBS, as it considers equal weight to both ecological and social sub-systems of an SES which is essential when working with NBS.

4. Conceptual framework for vulnerability and risk assessments of SES in the context of developing NBS

Considering the geographical and social-ecological contexts of the NBS implementation sites of the OPERANDUM project and IUCN’s NBS principles, a conceptual framework for vulnerability and risk assessment of SES in the contexts of NBS (VR-NBS) is proposed (Fig. 3). The VR-NBS framework is built primarily on the main concepts of the Delta-SES framework developed by Sebesvari et al. [28]. The version presented here is a second iteration, building on the work by Shah et al. [55]. The original focus of the Delta-SES framework was to characterise natural hazard risks in deltaic environments, but it is not restricted to deltas by design. It is also linked to an indicator library presented by Hagenlocher et al. [8] which can be extended to the context of the places where NBS could be implemented. A major departure from the Delta-SES framework is that we explicitly consider hazard characteristics for the risk assessment. Therefore, risk is calculated here as Hazard x Exposure x Vulnerability [49,56,57] (Fig. 3). This will allow for a better characterization of risk, introducing probabilities of events of specific magnitude affecting exposed areas. We have also changed the basic geographical boundary of risk assessment to smaller areas where NBS could be implemented, though the areas are part of larger sub-catchments and catchments and we recognize that NBS may also be implemented at these scales. Furthermore, we did not consider the tipping and transformation processes linked to impacts within the SES scale presented in the original Delta-SES framework. However, we consider the changes in social-ecological systems over time that would capture the maturation time lag of the ecological components [58] of an NBS, as well as the sustainability of the system with the intervention of risk reduction measures such as NBS and others (Fig. 4).

NBS projects, which are designed in line with NBS principles, are usually aimed to reduce risks by modifying hazard characteristics and reducing the exposure and vulnerability of SES (Fig. 3). The geographical boundary of NBS projects is usually confined to smaller landscape boundaries (e.g. lake, river floodplain, coastal bay) and related to socio-economic activities of local communities. Although the ecosystem and local community within the NBS project sites have specific characteristics, they are linked to sub-catchment or catchment level processes through climatic and hydrological cycles as well as government policies. Interaction with larger spatial scales should therefore be taken into account when performing risk assessments. In the proposed VR-NBS framework, we considered all the environmental/ecological aspects of the NBS project sites within the ‘Ecosystem’ domain, and all the social, economic and governance/institutional issues within ‘Social system’ domain. The elements within the entire SES of NBS project sites would be the basic space of risk assessment.

The VR-NBS framework considers that the NBS project sites could

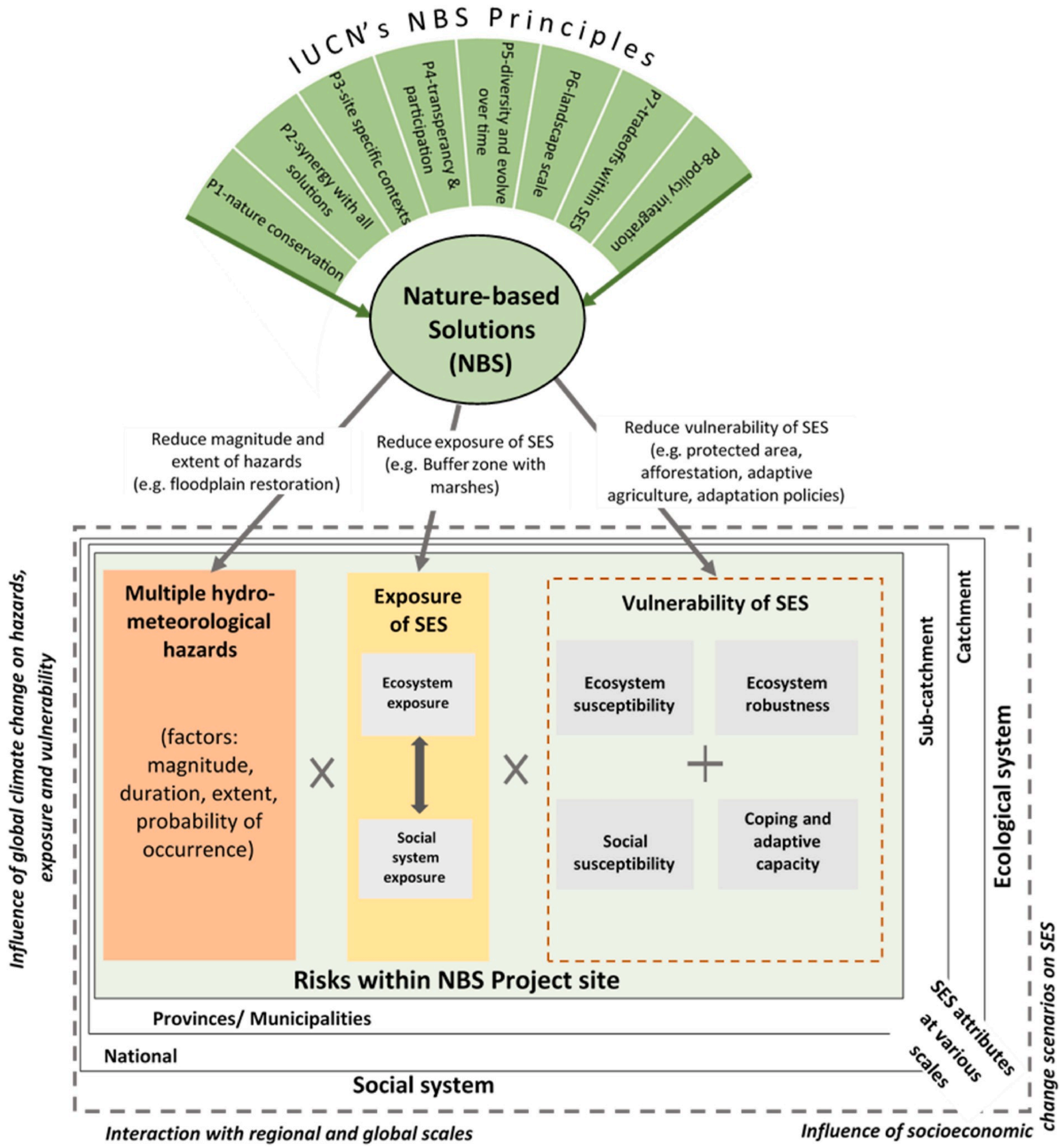

Fig. 3. Conceptual framework for vulnerability and risk assessment of SES in NBS project sites in the contexts of NBS (VR-NBS). Adapted from Sebesvari et al. [28]; Shah et al. [55].

experience single or multiple hydro-meteorological hazards originating either locally or in the surrounding regions. The hazards would be characterised by their magnitude, duration, extent and probability of occurrence. Different climate change scenarios can also be considered to assess changes in the hazard, exposure, and vulnerability components of risk (left-hand side of Fig. 3). Although the framework considers only “natural” hydro-meteorological hazards in this paper, it could be applied in the context of multi-hazards from other natural and anthropogenic sources in future research.

The exposure of the social and ecological elements within NBS project sites and their vulnerability to hazards (in various magnitudes and frequencies and for different climate change scenarios) determine the risks to the SES. The vulnerability of the SES has four domains: social susceptibility, ecosystem susceptibility, ecosystem robustness, and coping and adaptation capacities of the social system (as per [28]. The vulnerability and risk of SES will be influenced by socioeconomic change and this can be captured by developing scenarios (lower-right corner of Fig. 3). Therefore, the impact of the changes can be considered in the vulnerability and risk assessment.

As NSB projects are designed and implemented based on NBS principles with the aim of reducing one or more of the risk domains (hazards, exposure, vulnerability), risk assessment in the NBS project site would essentially be linked with the NBS principles in a direct or indirect manner. Table 2 illustrates further the linkages of NBS principles with the risk components shown in Fig. 3. The conceptual understanding of integrating NBS principles in the risk assessment will be reflected through incorporating suitable indicators for the assessment. The framework will also be linked to the IUCN standards and indicators

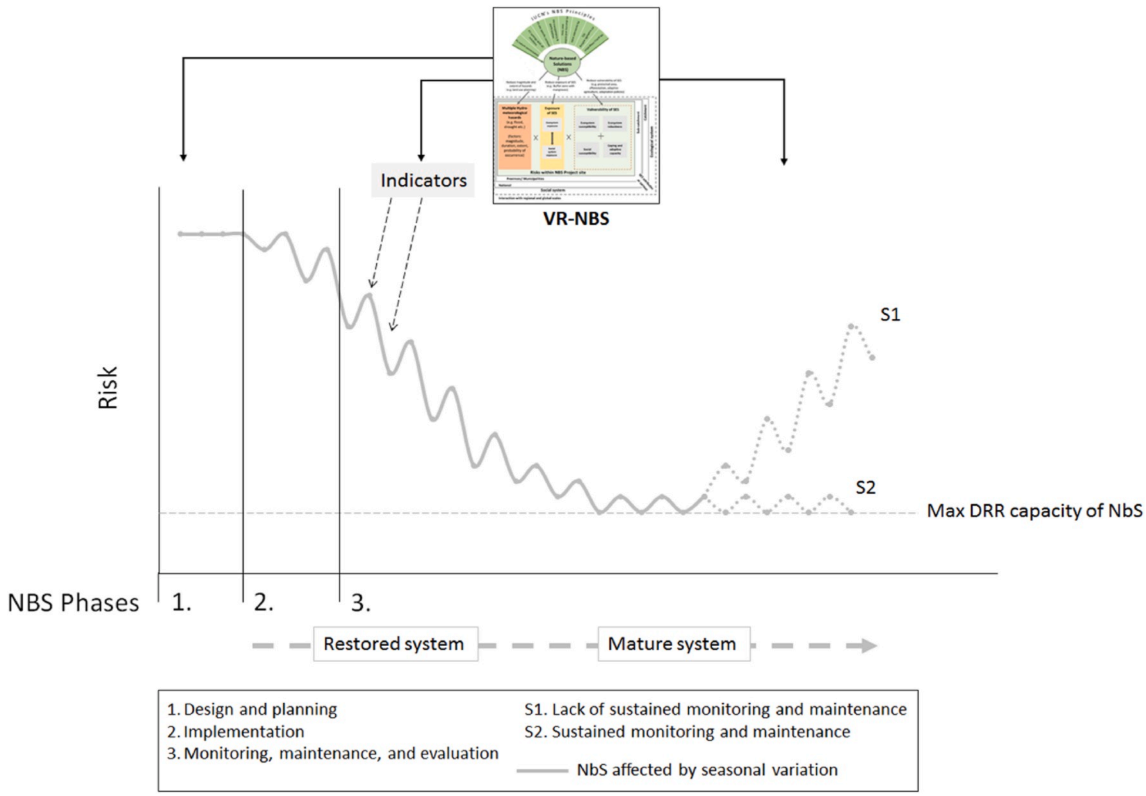

Fig. 4. Risk levels throughout time (denoted by NBS phases) of an idealized NBS that relies on organic elements to reduce risk. Risk reduction can thus fluctuate seasonally. The VR-NBS framework can be applied throughout NBS phases to assess vulnerability and risk and contribute to successful NBS design and long-term monitoring and maintenance to achieve sustained and maximum disaster risk reduction capacity. Indicators from the framework can be applied to capture changes in seasonality.

currently under preparation and to be released in 2020 [20].

The VR-NBS framework is designed with an underlying goal of increasing the success of NBS projects. In this regard, the framework can inform various project phases (Fig. 4). By conducting a risk assessment during the design and planning phase, risks can be identified that should be targeted by the NBS. Indicators from the framework can be prioritized and when repeat assessments are conducted during the maintenance and monitoring phase, an indication of the success of the NBS at reducing risk becomes possible. Because many NBS rely on the growth of organic elements over time which are also dependent on seasonal fluxes, the VR-NBS incorporates indicators that are sensitive to seasonality. For this, risk must be assessed at multiple snapshots throughout time and during different seasons. Wetland restoration, for example, requires time for the restored system to become mature and thus fits this description (Fig. 4). However, other NBS will immediately reduce risk after implementation (e.g. natural water retention basins) and are not sensitive to seasonal fluctuation in effectiveness, so the process of using the VR-NBS should be carefully considered within different NBS and SES contexts. Sustained monitoring (S1 in Fig. 4) is required to ensure that the implemented NBS continues to deliver the required risk reduction benefits in the long run. It is important to note that the desired risk reduction level of the NBS can only be reached and sustained if the NBS principles have been adhered to, in particular Principle 3.

Indicator-based methods [8,41,42]; OECD 2008) can be employed to assess vulnerability and risk of SES in the NBS project sites following this conceptual framework. Potential indicators for different risk components of the framework identified in the study are presented in the following section.

5. Vulnerability and risk assessment indicators

Building on the work of Shah et al. [55]; we have identified 135 indicators in the reviewed literature as well as through a questionnaire survey and FGD in the NBS project sites (OALs) of the OPERANDUM project. These indicators are categorised according to the six main components of the VR-NBS framework. The full list of indicators is provided in supplementary material-S2 (Table S2). Initially, the literature review and surveys in the OALs yielded 270 indicators. After removal of duplicates, indicators were screened with the selection criteria such as relevance to hydro-meteorological hazards, SES of the NBS project sites, and the major components of the VR-NBS framework. The 135 indicators in Table S2 reflect the final result of the screening process and originate from 23 articles (88 indicators) out of the 58 reviewed and from OAL surveys (47 indicators). From the literature, most of the indicators (41%) were taken from three articles [41] (4%) [8]; (28%); and [59] (17%)), that are relevant to risk assessment of SES.

Distribution of the selected indicators among the vulnerability components shows that, of the 135 indicators, 24 indicators are related to SES exposure, 43 to ecosystem vulnerability and 68 to social vulnerability components. A major portion of the indicators (61%) are related to the social system, while the rest (39%) are related to the ecological system. Proportionally to social system indicators, more indicators linked to the ecological system were found in this review when compared to previous reviews (e.g. Refs. [28,29]. This is linked to the fact that the review focused on NBS-relevant risk assessments. Nevertheless, social system indicators still outnumber ecological-related indicators. Surveys in the OALs have helped to address this imbalance by identifying further ecological indicators. The following sections provide further details of the indicators in the different components of the VR-NBS framework.

Table 2
Linkages of IUCN's NBS principles with different components of the VR-NBS framework.

IUCN's NBS principles [18]	Linkage with main components of VR-NBS framework
Principle 1: NBS embrace nature conservation norms (and principles) (**NBS–P1**)	This principle is linked to the 'ecosystem robustness' component of the framework. Nature conservation through NBS can enhance ecosystem robustness so that the ecosystem can maintain its multi-functionality.
Principle 2: NBS can be implemented alone or in an integrated manner with other solutions to societal challenges (e.g. technological and engineering solutions) (**NBS–P2**)	This principle is related to overall 'risk within NBS project sites' component. NBS and/or other risk reduction measures can be implemented to reduce overall risk of SES in the area.
Principle 3: NBS are determined by site-specific natural and cultural contexts that include traditional, local and scientific knowledge (**NBS–P3**)	The framework considers vulnerability and risk assessment of SES in the NBS project sites, which would guide the selection of NBS appropriate to the natural and cultural contexts of the site. Therefore, the basic space of vulnerability and risk assessment, i.e. NBS project sites are in line with the NBS principle 3. Inappropriate consideration of site-specific context will inevitably lead to a reduction of the risk reduction potential of the NBS (see Fig. 4).
Principle 4: NBS produce societal benefits in a fair and equitable way, in a manner that promotes transparency and broad participation (**NBS–P4**)	This principle is associated with 'coping and adaptive capacity' component. Social benefits of NBS would be largely demonstrated through increasing social coping and adaptive capacity for risk reduction by NBS.
Principle 5: NBS maintain biological and cultural diversity and the ability of ecosystems to evolve over time (**NBS–P5**)	This principle is also linked to the 'ecosystem robustness' component. Maintaining biological and cultural diversity are part of ecosystem conservation efforts, which ultimately enhance the ecosystem's ability to adjust and continue its functions and services.
Principle 6: NBS are applied at the scale at a landscape (**NBS–P6**)	Although NBS projects are depicted as being implemented at the local scale, the risk assessment and design of NBS would consider the linkages with regional sub-catchment or catchment level SES.
Principle 7: NBS recognize and address the trade-offs between the production of a few immediate economic benefits for development, and future options for the production of the full range of ecosystems services (**NBS–P7**)	The framework emphasises balancing social and ecological contexts in the risk assessment. By placing equal weight on ecosystem components, the framework implicitly considers long-term and varied ecosystem service benefits.
Principle 8: NBS are an integral part of the overall design of policies, and measures or actions, to address a specific challenge (**NBS–P8**)	The overall policies and risk reduction measures for SES management across spatial scales are taken into account in risk assessment.

5.1. Indicators relevant to exposure and vulnerability of ecological systems

The OPERANDUM NBS project sites cover both terrestrial and aquatic ecosystems located in diverse geographic regions. Exposure of the ecosystems to hydro-meteorological hazards depends on the land cover in the NBS project sites. The indicators addressing ecosystem exposure include the proportion of land use/ecosystem area exposed to different hazards. Hazard specific indicators for measuring ecosystem exposure were chosen to address single or multi-hazard contexts in the NBS project sites. In addition, general ecosystem types (e.g. urban green space, agricultural land) were included as an ecosystem exposure indicator. Examples of some of the indicators related to ecosystem exposure are presented in Table 3.

Table 3
Examples of indicators related to exposure and vulnerability of ecosystems identified from the literature review and surveys in the OALs (see Table S2 for a full list and corresponding references).

Risk components and categories	Indicator name
Ecosystem Exposure	
Exposed area/land use	Ecosystems exposed to drought (%)
	Ecosystems exposed to flood (%)
Ecosystem Susceptibility	
Agriculture	Increased use of chemicals and fertilisers (qualitative/ quantitative)
Biodiversity	Levels of biodiversity (Scoring or Index)
	Population of protected species (No./m^2)
Habitat degradation	Land reclamation rate (km^2/yr)
Habitat destruction	Percentage of shoreline eroded (%)
	Soil erosion (RUSLE output)/Erosion rate (mm/year)
	Deforestation rate (km^2/yr)
Habitat fragmentation	Forest connectivity (probability of connectivity index (PC))
Land	Protection of land from hazard (% of area)
Water - natural state	Groundwater levels (m)
	Rates of surface water drainage (m^3/s)
Ecosystem robustness	
Agriculture	Proportion of drought tolerant crops (% of crop production)
	Percent of area with intensive/extensive agriculture in floodplain (% of agriculture land)
Conservation policies/ funding	Government expenditure on environmental protection (% expenditure)
Ecosystem conservation	Percentage of area covered by Wetlands of International Importance (Ramsar Sites) (%)

Ecosystem susceptibility to natural hazards usually depends on the status and dynamics of the ecosystem and the status of biodiversity within the ecosystem. Ecosystem susceptibility, in terms of status of the habitats, could be determined by their level of degradation, fragmentation or destruction. For instance, indicators such as deforestation rate (e.g. Ref. [8], soil erosion rate (e.g. Ref. [59,60], and river connectivity (e.g. Ref. [8] (Table 3) can measure the status of the habitats in different ecosystems. In relation to hydro-meteorological hazards, some important hydrological factors, such as status of surface water and groundwater table influence the susceptibility of both terrestrial and aquatic ecosystems. Therefore, hydrological indicators such as groundwater level, rates of surface water drainage, river water level, and water holding capacity of soil were selected (Table 3). In addition, some water quality-related indicators such as water clarity (turbidity) and nutrient loading help to define the quality of aquatic habitats.

While habitat-related indicators were largely used in determining ecosystem susceptibility, very few biodiversity related indicators were considered in previous studies. Indicators such as population of protected species and cattle population are identified in this study through the surveys in the OALs. Previous studies (e.g. Ref. [61,62] have used 'biodiversity scores' as an overall measure of biodiversity status. Ecosystem robustness, i.e. the capability of the ecosystem to adapt with changing conditions due to natural hazards, has been addressed by a few studies (e.g. Ref. [8]. For SES-type studies, Hagenlocher et al. [8] have provided a number of indicators related to ecosystem conservation policies, funding, habitat restoration and ecosystem services which define robustness of the ecosystem. Some of these indicators include the Ecosystem Functionality Index and percentage of wetlands restored (Table 3 and Table S2, respectively). Surveys in the OALs have also identified indicators related to the robustness of agro-ecosystems such as proportion of drought tolerant crops and percent of area with intensive/extensive agriculture in floodplain (Table 3).

Many of the ecological indicators such as surface water drainage and river water are related to the impact of climate change. Also, some of the co-benefits of NBS projects such as carbon sequestration, reducing temperature are related to forest cover and wetland conservation which could be linked to regulation of climate change. As such, the indicators will directly or indirectly capture impact of climate change.

5.2. Indicators relevant to exposure and vulnerability of social systems

A wide range of socio-economic indicators have been identified from the recent literature and surveys in the OALs that represent exposure and vulnerability of social systems in NBS project sites. A complete list of indicators is provided in supplementary material-S2 (Table S2) and examples of indicators related to the social system are presented in Table 4. Indicators relevant to social exposures are clustered into major categories such as exposed area, population, infrastructure and services, economy, and livestock population (Table 4). While most of the common social exposure indicators - for instance, the proportion of total population exposed, population exposed to drought and flood - were referred to by both the reviewed papers and surveys, some specific indicators were suggested by either literature (e.g. proportion of critical physical infrastructure [41]) or by the surveys (e.g. proportion of livestock) (Table S2).

Table 4
Examples of indicators related to exposure and vulnerability of social system identified from the literature review and surveys in the OALs (for references, please see Table S2).

Risk components and categories	Indicator Name
Social System Exposure	
Economy	Proportion of businesses exposed to hazards (%)
Exposed area/land use	Proportion of residential area (ha)
Exposed buildings	Proportion of properties/buildings in hazard prone area (%)
Exposed population	Proportion of total population exposed to multiple hazards (%)
	Population exposed to floods (%)
Infrastructure and services	Proportion of critical physical infrastructure (%)
Livestock	Proportion of livestock in OAL (%)
Social Susceptibility	
Agriculture	Agricultural crop production (ton per yr)
Economy	GDP per capita (US$ per capita)
	Poverty (% of population)
Population	Population density (inhab/km^2)
Housing	Proportion of house ownership (% of households)
Information/awareness	Education level (N/S)
Infrastructure and services	Proportion of drainage blocked (% of drainage area coverage)
Land rights/ownership/ management	Access to land or land ownership (% of households)
Social context	Human Development Index (rating low, medium, high) (HDI score)
Coping capacity	
DRR and emergency services	Existence of hazard/vulnerability/risk maps (yes/no)
	Food stocks (months per household)
Information/awareness	Knowledge of hazard causes & prevention (N/S)
Infrastructure and services	Access to social services (N/S)
	Access to transportation network (Density of transportation network) (road (km) per 1000 population)
Livelihood	Alternative livelihood (% of households)
NGOs and community organizations	Community leadership (N/S)
	Mutual assistance (N/S)
Previous experience of hazard	Previous disaster experience (N/S)
Adaptive capacity	
Adaptation planning and finance	Existence of adaptation policies/strategies (yes/no)
	Presence of land use policies (yes/no)
Agriculture	Agriculture land use planning (yes/no)
Conservation policies/ funding	State policy on forest designation (yes/no)
Water - human use	Volume of water storage in a safe reservoir/container (m^3)
	Managed sharing and allocation of water (N/S)

The social susceptibility indicators are clustered into several major categories in relation to different social aspects or economic sectors. Most of the social susceptibility indicators are within the economy and infrastructure and services categories. Economic indicators include Gross Domestic Product (GDP), poverty, and employment rate (Table S2). Although some of the economic indicators (e.g. GDP) may not be quantifiable at the local level (NBS project site that covers a small area), these are well-recognized measures of economic strength of a community. The social susceptibility indicators related to infrastructure and services include, for example, dependency on road communication, proportion of drainage blocked (Table S2), which were mainly identified by the surveys. Some studies have also considered similar susceptibility indicators related to infrastructure and services, but used more generic terms (e.g. density of infrastructure [8]) which were not included in this list as they might not represent clear understanding of susceptibility of specific infrastructure in the NBS project sites. Other major social susceptibility indicators are related to social/societal and demographic characteristics, such as population, housing, and land rights, used by many reviewed papers (e.g., Refs. [41,63]. Proportion of house ownership [59] and access to land or land ownership [8,59,64] are also crucial indicators of social susceptibility as these demonstrate the community's predisposition to experience damage to their homes or land due to natural hazards. A composite social indicator, the Human Development Index (HDI), usually measured at national level to represent overall social contexts, was used by Leal Filho et al. [65] for coastal vulnerability assessment in four countries. The HDI could be used in large OALs where socio-economic conditions of the area are comparable to national level.

Regarding coping and adaptive capacities, the reviewed articles and the surveys provided a large number of indicators within major categories such as DRR and emergency services, infrastructure and services, information and awareness, and adaptation policies and funding. For measuring coping capacity, the majority of the indicators are within the DRR and emergency category which consists of indicators such as existence of hazard/vulnerability/risk maps [8], emergency management committee [41,59], early warning system/monitoring, and government assistance [59] (Table S2). Several studies and surveys also emphasised the availability of infrastructure and services, and access to information as determinants of coping capacity, represented by the indicators like access to transportation network [8], capacity of engineered structures to prevent flooding, and knowledge of hazard causes and prevention [59] (Table S2). A few articles and surveys have recognized the role of community organizations and social cohesion in strengthening coping capacity and have suggested some related indicators such as community leadership, mutual assistance [59], participation in decision making [64] and degree of collaboration (Table S2).

The study also identified some indicators related to adaptive capacity in major categories such as adaptation planning and finance, conservation policies, and information and awareness. Relevant policy and plan development is essential to foster long-term strategic action to reduce disaster risks. As such, Hagenlocher et al. [8] and some OALs suggested indicators for adaptive capacity such as existence of adaptation policies/strategies, land use policies, and agriculture land use planning (Table S2). Further, adequate information and awareness of future hazards and risks are also important for adaptation in the long term. Hence, knowledge on climate and risks [61] is considered as an adaptive capacity indicator.

5.3. Relationship of the indicators to NBS principles

Some of the vulnerability and risk assessment indicators identified in this study are closely linked to the IUCN's principles for NBS [18]. As discussed earlier, NBS principles were mapped to the different components of the VR-NBS framework (Table 2). Likewise, the indicators for different SES exposure and vulnerability domains are related to the NBS principles. For instance, the indicators measuring the level of ecosystem conservation under the ecosystem robustness component of vulnerability assessment are linked to the first principle for NBS, i.e., embracing nature conservation [18]. Some of the indicators determining ecosystem robustness such as percentage of wetland restored are also related to the fifth principle for NBS (maintain biological diversity and the ecosystem). The second NBS principle (implemented alone or combined with other solutions) can be related to some NBS project sites where indicators such as area protected by structural measures (see Table S2) would be used to determine coping capacity and performance of NBS for reducing impacts. The third NBS principle (determined by site-specific natural and cultural contexts and knowledge) is generally relevant to all the indicators as these are sorted out in the contexts of specific locations, i.e. the NBS project sites. And, most of the indicators related to social coping and adaptive capacity (Table S2) are linked to the fourth principle for NBS (producing societal benefits). The sixth NBS principle (application of NBS at landscape scale) may not be directly related to some NBS project sites which have a smaller area than others; nevertheless, considering social, political, economic and environmental factors outside the place of NBS implementation remains critical. In the case of large project sites, the indicators such as river connectivity and forest connectivity under ecosystem susceptibility could be linked to the sixth principle. The seventh principle for NBS (addressing trade-off between economic benefit and future ecosystem services) is not related to particular indicators; instead, the balanced trade-off will be achieved by ensuring equal weighting for social and ecological indicators in risk assessment using the VR-NBS framework. Finally, the adaptation planning and conservation policy related indicators such as presence of land use policies, state policy on forest designation under adaptive capacity (Table 4) are associated with the eighth NSB principle (an integral part of the overall policies and actions).

5.4. Application of the framework

Together with the indicator library, the framework avoids the development of a “one size fits all” set of indicators for all OAL contexts. Core indicators are being selected that are applicable to all OAL sites and these are complemented with OAL-specific sets of indicators that allow for addressing the specific risks in each OAL. The aggregation method is similar to that of Hagenlocher et al. [29] but with the addition of the hazard component. The assessment will provide equal weights to the main components of the risk equation. Initially, each indicator will be given equal weights, but stakeholder consultations in all OAL sites will allow for the determination of whether different weights need to be applied to different indicators. Data for the indicators will be collected from different primary and secondary sources. All the data as well as vulnerability and risk assessment results will be stored in the Geospatial Information Knowledge Platform (GeoIKP) of the OPERANDUM project.

6. Discussion and conclusions

This paper presents a systematic review of vulnerability and risk assessment frameworks and indicators, and proposes an updated vulnerability and risk assessment framework in the context of NBS to hydro-meteorological hazards (VR-NBS framework) as well as a preliminary set of indicators. A review of 58 articles confirmed that there is a growing tendency of developing risk assessment frameworks that consider both social and ecological dimensions of risk, and that only few studies have developed comprehensive SES-type risk assessment frameworks (e.g. Ref. [27,28,52]. Our review also confirms that there is an imbalance in consideration of social and ecological contexts (in the form of indicators) in most of the existing vulnerability and risk assessment frameworks. It is important to address this imbalance as ecosystem-based approaches provide multiple benefits [18] that are relevant to the entire risk equation (i.e. reducing hazard characteristics, exposure and vulnerability of SES). Another important feature of NBS is linked to the temporal dimension of risk reduction (i.e. project phases, seasonality) [58] which is not captured in the existing risk assessment frameworks. The proposed indicator-based VR-NBS framework (Fig. 3) is designed to overcome the above limitations by depicting temporality and including indicators capable of its assessment. The framework has conceptually incorporated the principles for NBS [18] which can be enhanced through the inclusion of relevant indicators, an area requiring further research.

We have built on previous research and continue to develop an ‘indicator library’ [28] with possible indicators related to SES vulnerability and multi-hazard contexts. A total of 135 indicators (Table S2) were selected from reviewed papers and surveys in the OALs. Social indicators outnumbered the ecological indicators to some extent. Further ecologically relevant indicators need to be explored through ad-hoc data collection techniques to fill the gap. Contextualising the indicators to the smaller areas (NBS project sites, e.g. OALs) might have eliminated some essential indicators that could be applicable in large regions (e.g. ‘flooded area within delta’ used by Ref. [66] for delta environments). Further, the indicator list only includes those that are relevant to a limited number of hydro-meteorological hazards (i.e. flood, drought, landslide, storm surge, and salinity intrusion) that are dominant in NBS project sites of the OPERANDUM project, and not other hydro-meteorological hazards such as cyclone, hailstorms, tornados, heavy snowfall that could be relevant in other contexts. Therefore, the proposed indicator library can be expanded in the future. While the ‘indicator library’ provides a readily available reference for the NBS projects, not all the indicators are applicable to each NBS project site because each site experiences different types of hazards and has different SES dynamics. Therefore, the list of indicators will require further revision to maintain consistency with the contexts of the NBS project site. The framework provides flexibility while keeping the core components of risk assessment and can be adapted to different SES contexts, for different hazards and for different types of NBS.

As for all risk assessments, the main challenge for implementing the conceptual framework will be to obtain data for the indicators that determine the multiple hazards, exposure and vulnerability of SES at NBS project sites. Particularly, data collection for indicators relating to the direct and indirect effects on vulnerability components such as ecosystem susceptibility and robustness which are closely linked to determining the cost and benefits of an NBS project will be challenging due to a lack of adequate studies as well as unavailability of historical records. Further, downscaling of regional catchment or sub-catchment level information will be required to generate information for local scale NBS projects, along with conducting primary data collection for some indicators where existing data are not available.

Despite the limitations, the proposed VR-NBS framework and indicator library provide a basis for vulnerability and risk assessment in the context of NBS, which can be further developed through practical application and customized to specific contexts and stakeholders’ needs. The framework is being tested within the OPERANDUM project and the indicator library expanded over time.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2020.101728.

Abbreviations

CBD Convention for Biological Diversity
CRiSTAL Community-based Risk Screening Tool – Adaptation and Livelihoods
EbA Ecosystem-based Adaptation
EC European Commission
Eco-DRR Ecosystem-based Disaster Risk Reduction
FEBA Friends of EbA
FGD Focus Group Discussions
HDI Human Development Index
InVEST Integrated Valuation of Ecosystem Services and Trade-offs
IPCC Intergovernmental Panel on Climate Change
IUCN International Union for Conservation of Nature
MOVE Methods for the improvement of vulnerability assessment in Europe
NBS Nature-based solutions
OALs Open-Air Laboratories
OPERANDUM OPEn-air laboRAtories for Nature baseD solUtions to Manage hydro-meteo risks
SES Social-ecological systems
SoVI Social Vulnerability Index
SUST model A framework for vulnerability assessment of SES in sustainability science
VR-NBS Vulnerability and risk assessment framework in the context of NBS

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] P. Sayers, G.G. Yli, E. Penning-Rowsell, F. Shen, K. Wen, Y. Chen, T. Le Quesne, Flood Risks Management: a Strategic Approach, UNESCO, Paris, 2013.
[2] S.D. Schubert, M.J. Suarez, P.J. Pegion, R.D. Koster, J.T. Bacmeister, Causes of long-term drought in the US great plains, J. Clim. 17 (3) (2004) 485–503.
[3] A.I. van Dijk, H.E. Beck, R.S. Crosbie, R.A. de Jeu, Y.Y. Liu, G.M. Podger, ., N. R. Viney, The Millennium Drought in southeast Australia (2001–2009): natural and human causes and implications for water resources, ecosystems, economy, and society, Water Resour. Res. 49 (2) (2013) 1040–1057.
[4] R.S. De Groot, M.A. Wilson, R.M. Boumans, A typology for the classification, description and valuation of ecosystem functions, goods and services, Ecol. Econ. 41 (3) (2002) 393–408.
[5] MA, Millennium Ecosystem Assessment Ecosystems and Human Well-Being: Synthesis, 2005, Island Press, Washington, DC, 2005.
[6] J. Steiger, M. James, F. Gazelle, Channelization and consequences on floodplain system functioning on the Garonne River, SW France, Regul. Rivers: Res. Manag. Int. J. Devot River Res. Manag. 14 (1) (1998) 13–23.
[7] IPCC, in: C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T. E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A. N. Levy, S. MacCracken, P.R. Mastrandrea, L.L. White (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014, p. 1132.
[8] M. Hagenlocher, F.G. Renaud, S. Haas, Z. Sebesvari, Vulnerability and risk of deltaic social-ecological systems exposed to multiple hazards, Sci. Total Environ. 631 (2018) 71–80.
[9] M. García-Mollá, C. Sanchis-Ibor, M.V. Ortega-Reig, L. Avellá-Reus, Irrigation associations coping with drought: the case of four irrigation districts in Eastern Spain, in: Drought in Arid and Semi-arid Regions, Springer, Dordrecht, 2013, pp. 101–122.
[10] J. Richards, I. White, J. Carter, Local planning practice and flood risk management in England: is there a collective implementation deficit? Environ. Urbain/Urban Environ. 2 (2008) 11–20.
[11] I. White, J. Richards, Planning policy and flood risk: the translation of national guidance into local policy, Plann. Pract. Res. 22 (4) (2007) 513–534.
[12] J.W. Day, D.F. Boesch, E.J. Clairain, G.P. Kemp, S.B. Laska, W.J. Mitsch, C. A. Simenstad, Restoration of the Mississippi delta: lessons from hurricanes katrina and rita, Science 315 (5819) (2007) 1679–1684.
[13] B.K. van Wesenbeeck, J.P. Mulder, M. Marchand, D.J. Reed, M.B. de Vries, H.J. de Vriend, P.M. Herman, Damming deltas: a practice of the past? Towards nature-based flood defenses, Estuar. Coast Shelf Sci. 140 (2014) 1–6.
[14] D.E. Bowler, L. Buyung-Ali, T.M. Knight, A.S. Pullin, Urban greening to cool towns and cities: a systematic review of the empirical evidence, Landsc. Urban Plann. 97 (3) (2010) 147–155.
[15] N. Kabisch, N. Frantzeskaki, S. Pauleit, S. Naumann, M. Davis, M. Artmann, K. Zaunberger, Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action, Ecol. Soc. 21 (2) (2016).
[16] K. MacKinnon, C. Sobrevila, V. Hickey, Biodiversity, Climate Change and Adaptation; Nature-Based Solutions from the World Bank Portfolio, the World Bank, Washington, 2008.
[17] A.R. Rizvi, Nature Based Solutions for Human Resilience: a Mapping Analysis of IUCN's Ecosystem-Based Adaptation Projects, IUCN, Geneva, 2014. https://portals.iucn.org/library/sites/library/files/documents/Rep-2014-008.pdf.
[18] E. Cohen-Shacham, G. Walters, C. Janzen, S. Maginnis (Eds.), Nature-based Solutions to Address Global Societal Challenges, xii, IUCN, Gland, Switzerland, 2016, p. 97.
[19] J. Maes, S. Jacobs, Nature-based solutions for Europe's sustainable development, Conserv. Lett. 10 (1) (2017) 121–124.
[20] IUCN, A Global Standard for Nature-Based Solutions, International Union for Conservation of Nature (IUCN), Geneva, 2019. Retrieved from, https://www.iucn.org/theme/ecosystem-management/about/our-work/a-global-standard-nature-based-solutions.
[21] World Bank, Implementing Nature-Based Flood Protection: Principles and Implementation Guidance, World Bank, Washington, DC, 2017.
[22] FEBA (Friends of Ecosystem-based Adaptation, Making ecosystem-based adaptation effective: a framework for defining qualification criteria and quality standards (FEBA technical paper developed for UNFCCC-sbsta 46), in: M. Bertram, E. Barrow, K. Blackwood, A.R. Rizvi, H. Reid, S. von Scheliha-Dawid (Eds.), GIZ, vol. 14, IIED, London, UK, and IUCN, Gland, Switzerland, Bonn, Germany, 2017.
[23] Secretariat of the Convention on Biological Diversity (CBD), Voluntary Guidelines for the Design and Effective Implementation of Ecosystem-Based Approaches to Climate Change Adaptation and Disaster Risk Reduction and Supplementary Information. Technical Series No. 93. Montreal, 2019, p. 156.
[24] A. Jurgilevich, A. Räsänen, F. Groundstroem, S. Juhola, A systematic review of dynamics in climate risk and vulnerability assessments, Environ. Res. Lett. 12 (1) (2017), 013002.
[25] J. Sahani, P. Kumar, S. Debele, C. Spyrou, M. Loupis, L. Aragão, S. Di Sabatino, Hydro-meteorological risk assessment methods and management by nature-based solutions, Sci. Total Environ. 696 (2019) 133936.
[26] B.L. Turner, R.E. Kasperson, P.A. Matson, J.J. McCarthy, R.W. Corell, L. Christensen, C. Polsky, A framework for vulnerability analysis in sustainability science, Proc. Natl. Acad. Sci. Unit. States Am. 100 (14) (2003) 8074–8079.
[27] J. Birkmann, O.D. Cardona, M.L. Carreño, A.H. Barbat, M. Pelling, S. Schneiderbauer, T. Welle, Framing vulnerability, risk and societal responses: the MOVE framework, Nat. Hazards 67 (2) (2013) 193–211.
[28] Z. Sebesvari, F.G. Renaud, S. Haas, Z. Tessler, M. Hagenlocher, J. Kloos, C. Kuenzer, A review of vulnerability indicators for deltaic social–ecological systems, Sustain. Sci. 11 (4) (2016) 575–590.
[29] M. Hagenlocher, I. Meza, C. Anderson, A. Min, F.G. Renaud, Y. Walz, S. Siebert, Z. Sebesvari, Drought vulnerability and risk assessments: state of the art, persistent gaps, and research agenda, Environ. Res. Lett. 14 (8) (2019), 083002, https://doi.org/10.1088/1748-9326/ab225d.
[30] IPCC, Summary for policymakers, in: C.B. Field, V.R. Barros, D.J. Dokken, K. J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R. C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. Maccracken, P.R. Mastrandrea, L. L. White (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, vol. 2014, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014, pp. 1–32.
[31] J. Birkmann, Measuring vulnerability to promote disaster-resilient societies: conceptual frameworks and definitions, Part One, in: J. Birkmann (Ed.), Measuring Vulnerability to Natural Hazards—Towards Disaster Resilient Societies, United Nations University Press, Tokyo, New York, Paris, 2006, pp. 9–54.
[32] B. Beccari, A comparative analysis of disaster risk, vulnerability and resilience composite indicators, PLoS Current. 8 (2016).
[33] G. Song, Z. Li, Y. Yang, H.M. Semakula, S. Zhang, Assessment of ecological vulnerability and decision-making application for prioritizing roadside ecological restoration: a method combining geographic information system, Delphi survey and Monte Carlo simulation, Ecol. Indicat. 52 (2015) 57–65.
[34] L. Xue, J. Wang, L. Zhang, G. Wei, B. Zhu, Spatiotemporal analysis of ecological vulnerability and management in the Tarim River Basin, China, Sci. Total Environ. 649 (2019) 876–888.
[35] X. Zhang, L. Wang, X. Fu, H. Li, C. Xu, Ecological vulnerability assessment based on PSSR in yellow river delta, J. Clean. Prod. 167 (2017) 1106–1111.
[36] UN (United Nations, Global Assessment Report on Disaster Risk Reduction 2015. Making Development Sustainable: the Future of Disaster Risk Management, United Nations, Geneva, 2015.
[37] J. Birkmann, M. Garschagen, P. Mucke, A. Schauder, T. Seibert, T. Welle, I. Matuschke, World Risk Report 2014. Bündnis Entwicklung Hilft and UNUEHS, 2014.

[38] P. Peduzzi, H. Dao, C. Herold, F. Mouton, Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index, Nat. Hazards Earth Syst. Sci. 9 (4) (2009) 1149.
[39] UNDP/BCPR, A Global Report: Reducing Disaster Risk, A Challenge for Development, United Nations Development Programme. Bureau for Crisis Prevention and Recovery, New York, 2004.
[40] C. Bollin, R. Hidajat, Community-based disaster risk index: pilot implementation in Indonesia, towards disaster resilient societies, in: J. Birkmann (Ed.), Measuring Vulnerability to Natural Hazards, UNU-Press, Tokyo, New York, Paris, 2006.
[41] D. Asare-Kyei, F.G. Renaud, J. Kloos, Y. Walz, J. Rhyner, Development and validation of risk profiles of West African rural communities facing multiple natural hazards, PloS One 12 (3) (2017).
[42] J. Kloos, D. Asare-Kyei, J. Pardoe, F.G. Renaud, Towards the Development of an Adapted Multi-Hazard Risk Assessment Framework for the West Sudanian Savanna Zone, vol. 11, UNU-EHS Publication, 2015, pp. 4–26.
[43] R. Sharp, H. Tallis, T. Ricketts, A. Guerry, S. Wood, R. Chaplin-Kramer, et al., InVEST User's Guide. User Guide. Stanford (CA): the Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, World Wildlife Fund, 2018.
[44] IUCN, ISSD, SEI, Combining Disaster Risk Reduction, Natural Resource Management and Climate Change Adaptation in a New Approach to the Reduction of Vulnerability and Poverty. A Conceptual Framework Paper Prepared by the Task Force on Climate Change, Vulnerable Communities and Adaptation, International Institute for Sustainable Development, Winnepeg, Canada, 2003.
[45] A.W. Whelchel, M.W. Beck, Decision tools and approaches to advance ecosystem-based disaster risk reduction and climate change adaptation in the twenty-first century, in: F. Renaud, K. Sudmeier-Rieux, M. Estrella, U. Nehren (Eds.), Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice. Advances in Natural and Technological Hazards Research, vol. 42, Springer, Cham, 2016.
[46] M. Damm, Mapping social–ecological Vulnerability to flooding: a sub-national approach to Germany, in: Graduate Research Series, vol. 3, UNU-EHS, Bonn, 2010, pp. 1–85 (ISBN-10: 393992346X).
[47] F.S. Chapin III, S.R. Carpenter, G.P. Kofinas, C. Folke, N. Abel, W.C. Clark, F. Berkes, Ecosystem stewardship: sustainability strategies for a rapidly changing planet, Trends Ecol. Evol. 25 (4) (2010) 241–249.
[48] M. Garschagen, Risky Change? Vulnerability and Adaptation between Climate Change and Transformation Dynamics in Can Tho City, Vietnam, vol. 15, Steiner, Stuttgart, 2014.
[49] IPCC, Managing the risks of extreme events and disasters to advance climate change adaptation, in: C.B.V. Field, T.F. Barros, D. Stocker, Q. in, K.L. DJ Dokken, M.D. Ebi, K.J. Mastrandrea, G.K. Mach, S.K. Plattner, M. Allen, Tignor, P. M. Midgley (Eds.), A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, and New York, 2012.
[50] GIZ, EURAC, UNU-EHS, Climate Risk Assessment for Ecosystem-Based Adaptation – A Guidebook for Planners and Practitioners, GIZ, Bonn, 2018.
[51] K.K. Arkema, R. Griffin, S. Maldonado, J. Silver, J. Suckale, A.D. Guerry, Linking social, ecological, and physical science to advance natural and nature-based protection for coastal communities, Ann. NY Acad. Sci. 1399 (1) (2017) 5–26.
[52] A. Bhattachan, M.D. Jurjonas, A.C. Moody, P.R. Morris, G.M. Sanchez, L.S. Smart, E.L. Seekamp, Sea level rise impacts on rural coastal social-ecological systems and the implications for decision making, Environ. Sci. Pol. 90 (2018) 122–134.
[53] E.M. Hamin, Y. Abunnasr, M. Roman Dilthey, P.K. Judge, M.A. Kenney, P. Kirshen, L. Nurse, Pathways to coastal resiliency: the adaptive gradients framework, Sustainability 10 (8) (2018) 2629.
[54] S.L. Cutter, B.J. Boruff, W.L. Shirley, Social vulnerability to environmental hazards, Soc. Sci. Q. 84 (2003) 242–261.
[55] M.A.R. Shah, F.G. Renaud, A. Wild, C.C. Anderson, M. Loupis, D. Panga, A. Polderman, C. Thomson, K. Munro, J. Sahani, F. Pilla, E. Pouta, J. El Zohbi, S. Preuschmann, X. Xue, A. Votsis, M. Stefanopoulou, N. Pangas, B. Basu, S. Ma, W. Zixuan, B. Pulvirenti, E. To the, A. Domeneghetti, Vulnerability and risk assessments of socio-ecological systems (SES): conceptual framework, impact chains and indicators, in: OPEn-Air laboRAtories for Nature baseD solUtions to Manage Hydro-Meteo Risks (OPERANDUM) Project, Italy, 2019.
[56] C. Moos, P. Bebi, M. Schwarz, M. Stoffel, K. Sudmeier-Rieux, L. Dorren, Ecosystem-based disaster risk reduction in mountains, Earth Sci. Rev. 177 (2018) 497–513.
[57] N.D. UNDRO, Vulnerability analysis, in: Report of Experts Group Meeting, Geneva, 1980.
[58] S.R. Biswas, A.U. Mallik, J.K. Choudhury, A. Nishat, A unified framework for the restoration of Southeast Asian mangroves—bridging ecology, society and economics, Wetl. Ecol. Manag. 17 (4) (2009) 365–383.
[59] K. Sudmeier-Rieux, On Landslide Risk, Resilience and Vulnerability of Mountain Communities in Central-Eastern Nepal, PhD Dissertation, University of Lausanne, 2011.
[60] A. Bourne, S. Holness, P. Holden, S. Scorgie, C.I. Donatti, G. Midgley, A socio-ecological approach for identifying and contextualising spatial ecosystem-based adaptation priorities at the sub-national level, PloS One 11 (5) (2016).
[61] E.K. Antwi, J. Boakye-Danquah, A.B. Owusu, S.K. Loh, R. Mensah, Y.A. Boafo, P. T. Apronti, Community vulnerability assessment index for flood prone savannah agro-ecological zone: a case study of Wa West District, Ghana, Weather Clim. Extrem. 10 (2015) 56–69.
[62] S.B. Mickovski, C.S. Thomson, Developing a framework for the sustainability assessment of eco-engineering measures, Ecol. Eng. 109 (2017) 145–160.
[63] A. Satta, M. Puddu, S. Venturini, C. Giupponi, Assessment of coastal risks to climate change related impacts at the regional scale: the case of the Mediterranean region, Int. J. Disast. Risk reduction 24 (2017) 284–296.
[64] G. Fedele, B. Locatelli, H. Djoudi, Mechanisms mediating the contribution of ecosystem services to human well-being and resilience, Ecosyst. Serv. 28 (2017) 43–54.
[65] W. Leal Filho, F. Modesto, G.J. Nagy, M. Saroar, N. YannickToamukum, M. Ha`apio, Fostering coastal resilience to climate change vulnerability in Bangladesh, Brazil, Cameroon and Uruguay: a cross-country comparison, Mitig. Adapt. Strategies Glob. Change 23 (4) (2018) 579–602.
[66] R. Van Coppenolle, C. Schwarz, S. Temmerman, Contribution of mangroves and salt marshes to nature-based mitigation of coastal flood risks in major deltas of the world, Estuar. Coast 41 (6) (2018) 1699–1711.