Title	A review of hydro-meteorological hazard, vulnerability, and risk assessment frameworks and indicators in the context of nature-based solutions
Authors(s)	Shah, Mohammad Aminur Rahman, Renaud, Fabrice G., Anderson, Carl C., Basu, Bidroha, Pilla, Francesco, et al.
Publication date	2020-11
Publication information	Shah, Mohammad Aminur Rahman, Fabrice G. Renaud, Carl C. Anderson, Bidroha Basu, Francesco Pilla, and et al. “A Review of Hydro-Meteorological Hazard, Vulnerability, and Risk Assessment Frameworks and Indicators in the Context of Nature-Based Solutions.” Elsevier, November 2020. https://doi.org/10.1016/j.ijdrr.2020.101728.
Publisher	Elsevier
Item record/more information	http://hdl.handle.net/10197/11952
Publisher's version (DOI)	10.1016/j.ijdrr.2020.101728

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Article *in* International Journal of Disaster Risk Reduction · June 2020

DOI: 10.1016/j.ijdrr.2020.101728

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Accepted for publication on 14 June 2020 in International Journal of Disaster Risk Reduction (IJDRR). Please visit journal website for full citation details

Title:

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

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Accepted for publication on 14 June 2020 in International Journal of Disaster Risk Reduction (IJDRR). Please visit journal website for full citation details

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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 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.

Keywords: *Risk assessment, multiple hazards, social-ecological systems, open air laboratories, ecosystem-based approaches*

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 (Sayers et al., 2013; Schubert et al., 2004; van Dijk et al., 2013). 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 (de Groot et al., 2002; MA, 2005), causing e.g. increased flooding (Sayers et al., 2013; Steiger et al., 1998). Furthermore, global climate change is aggravating the severity of hydro-meteorological hazards towards extremes that can irreversibly alter natural ecosystems (IPCC, 2014a). 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 (Hagenlocher et al., 2018).

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 (García-Mollá et al., 2013; Richards et al., 2008; White & Richards, 2007). 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 (Day et al., 2007; van Wesenbeeck et al., 2014). Nature-based Solutions (NBS) for reducing risk have been conceptualised more recently (Bowler et al., 2010; Kabisch et al., 2016; MacKinnon et al., 2008; Rizvi, 2014), showing promising results in terms of risk reduction and biodiversity preservation (Cohen-Shacham et al., 2016). 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 (Cohen-Shacham et al., 2016), 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” (Cohen-Shacham et al., 2016:2). 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 (Maes & Jacobs, 2017). 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 (Cohen-Shacham et al., 2016). 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 (IUCN, 2019).

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 (World Bank, 2017). 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 (FEBA, 2017). Finally, in 2019, the Convention for Biological Diversity (CBD) published voluntary guidelines for ecosystem-based approaches to climate change adaptation and disaster risk reduction (CBD, 2019). 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 (Jurgilevich et al., 2017). In recent years, a wide range of vulnerability and risk assessment approaches/frameworks/tools have been developed (Sahani et al., 2019) to determine SES vulnerability and risk to natural hazards. These include the SUST model (Turner et al., 2003a), MOVE framework (Birkmann et al., 2013) and the Delta-SES vulnerability assessment framework (Sebesvari et al., 2016). Most of these approaches have emphasized 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 (Sebesvari et al., 2016; Hagenlocher et al., 2019). 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 (IPCC, 2014b) (see definitions of the risk components in Supplementary material S1), while a list of types of NBS was taken from a recent IUCN report (Cohen-Shacham et al., 2016:10). Comprehensive vulnerability and risk assessments should be grounded in explicitly defined theory, often in the form of a conceptual framework (Birkmann, 2006). 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 (Beccari, 2016; Hagenlocher et al., 2019).

Given the rapid evolution of terminology used to describe concepts of NBS, and the fact that most publications on the topic are relatively recent (Cohen-Shacham et al., 2016), 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 1,745 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 (Figure 1). As for previous reviews on this topic (e.g. Sebesvari et al., 2016; Hagenlocher et al., 2019), most of the publications reviewed were recent: 77.6% were published after 2015, and none published before 2005 (Figure 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.

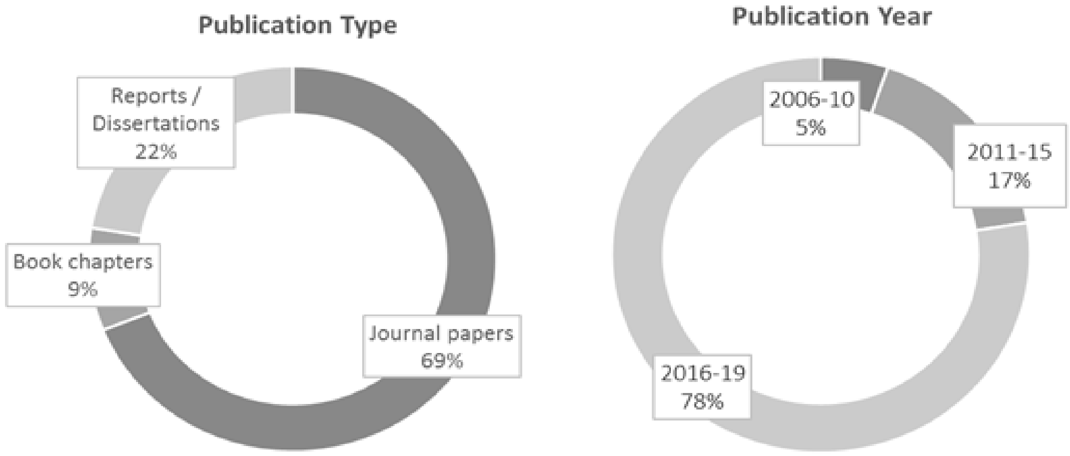

Figure 1. Type of publications reviewed (left) and year of publication (right)

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 (Song et al., 2015; Xue et al., 2019; Zhang et al., 2017) 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 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 (Figure 2).

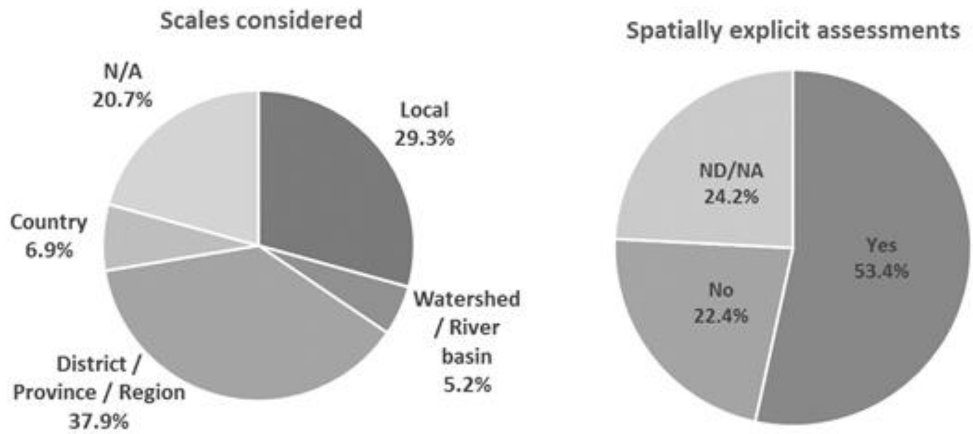

Figure 2. Scale considered in assessment or when discussing frameworks (left) and percentage of assessments that were spatially explicit (right). ND = Not Determined, NA = Not Applicable

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 (UN, 2015), the World Risk Index (Birkmann et al., 2014), Disaster Risk Index (Peduzzi et al., 2009; UNDP/BCPR, 2004) and Global Delta Risk Index (Hagenlocher et al., 2018). The global or national level methods are complemented by local level participatory risk assessment approaches, such as the Community-Based Risk Index (Bollin &Hidajat, 2006). Of the reviewed papers, Asare-Kyei et al. (2017) and Hagenlocher et al. (2018) both applied indicator-based risk assessment approaches informed by the multi-hazard risk assessment framework (Kloos et al., 2015) and the Delta-SES vulnerability assessment framework (Sebesvari et al., 2016), respectively. Hagenlocher et al. (2018) 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 (Sharp et al., 2018), CRiSTAL (IUCN, IISD & SEI, 2012) or the more recent Coastal Resilience decision-support platform (Whelchel and Beck, 2016). 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. (2003) 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 (Turner et al., 2003). Damm (2010) 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. (2013) 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 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 (Birkmann et al., 2013).

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. (2015) 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 (Turner et al., 2003, Damm, 2010), the MOVE framework (Birkmann et al., 2013), and the Ecosystem Stewardship Framework (Chapin et al., 2010). 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 (2014) 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. (2015), Sebesvari et al. (2016) 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. (2003), Damm (2010), Kloos et al. (2015), IPCC (2012), and Garschagen (2014). 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. (2018). One of the latest publications related to climate risk and NBS is a guidebook for climate risk assessment, published by GIZ, EURAC & UNU-EHS (2018), 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 (GIZ, EURAC & UNU-EHS, 2018).

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. (2017) 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) (Arkema et al., 2017:8). Bhattachan et al. (2018) 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. (2018) 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. (2003)). One of the latest “evolution” of such older frameworks is the Delta-SES vulnerability assessment framework (Sebesvari et al., 2016) used by Hagenlocher et al. (2018) and which was also compared to the Social Vulnerability Index (SoVI) framework of Cutter et al. (2003) by 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. (2016). The version presented here is a second iteration, building on the work by Shah et al. (2019). 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. (2018) 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 (IPCC, 2012; Moos et al., 2018b; UNDRO, 1980) (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 (Biswas et al., 2009) 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.

Accepted for publication on 14 June 2020 in International Journal of Disaster Risk Reduction (IJDRR). Please visit journal website for full citation details

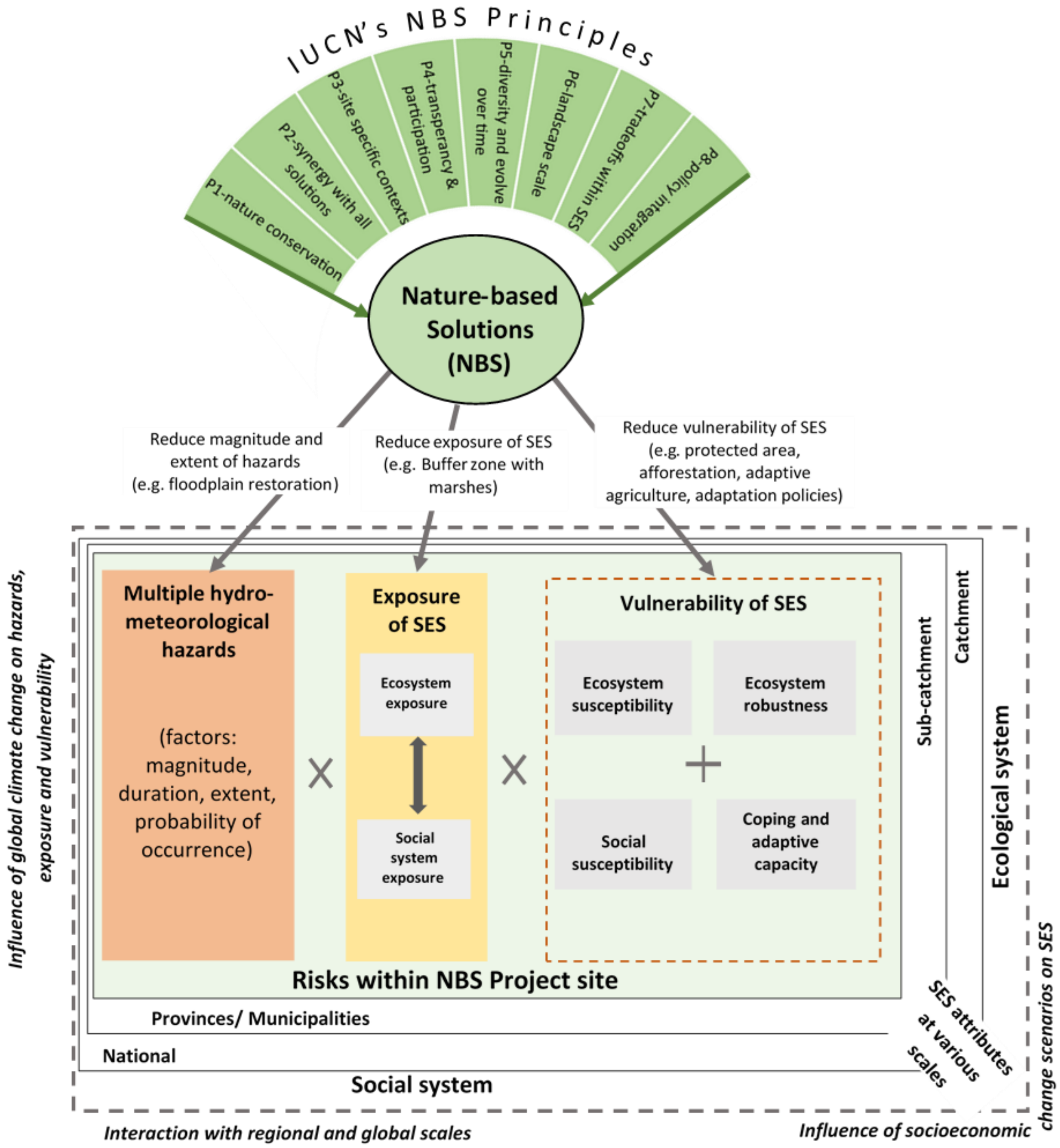

Figure 3. Conceptual framework for vulnerability and risk assessment of SES in NBS project sites in the contexts of NBS (VR-NBS). Adapted from Sebesvari et al. (2016), Shah et al. (2019).

The VR-NBS framework considers that the NBS project sites could 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 Figure 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 Sebesvari et al., 2016). The vulnerability and risk of SES will be influenced by socioeconomic change and this can be captured by developing scenarios (lower-right corner of figure 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 Figure 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 currently under preparation and to be released in 2020 (IUCN, 2019).

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

IUCN's NBS principles (Cohen-Shacham et al. 2016)	**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 Figure 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.

IUCN's NBS principles (Cohen-Shacham et al. 2016)	**Linkage with main components of VR-NBS framework**
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 recognise 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.

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 (Figure 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 Figure 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.

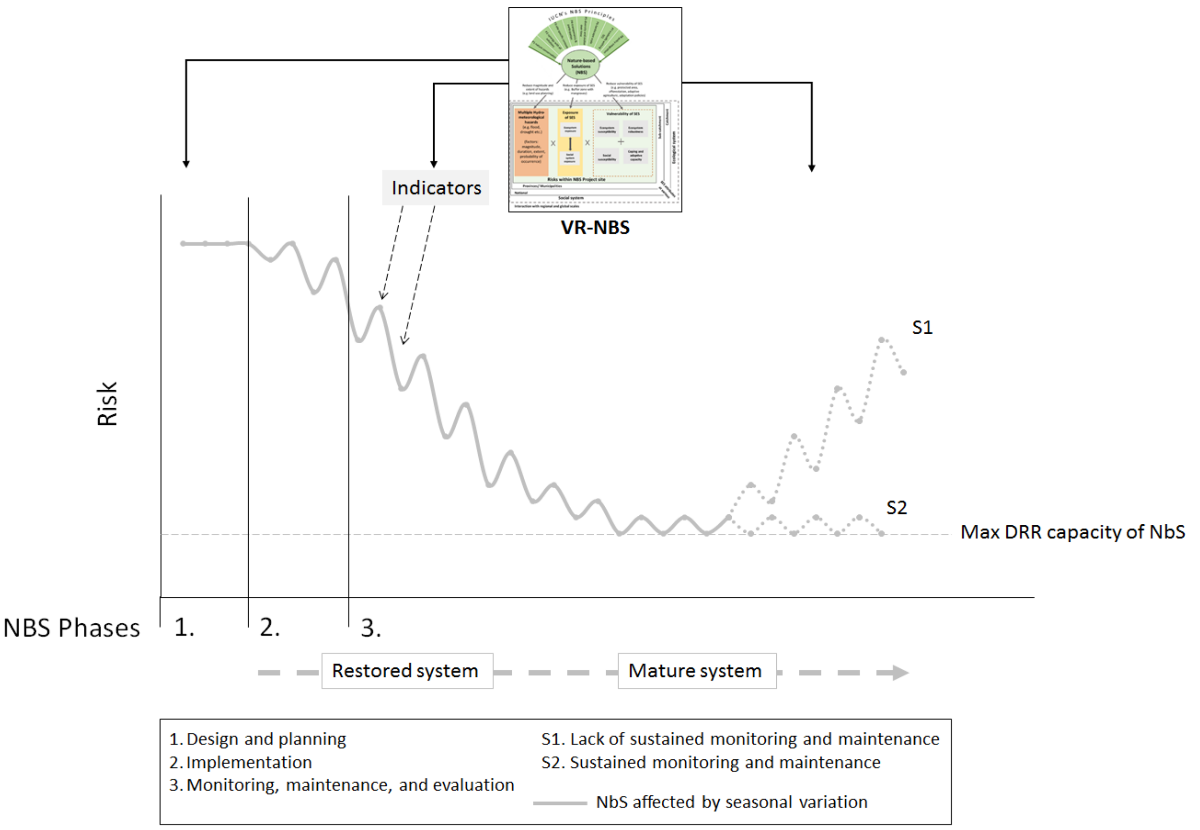

Figure 4. Risk levels throughout time (denoted by NBS phases) of an idealized NBS that relies on organic elements to reduce risk. Risk reduction can thus fluctuate seasonally. The VR-NBS framework can be applied throughout NBS phases to assess vulnerability and risk and contribute to successful NBS design 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.

Indicator-based methods (Asare-Kyei et al. 2017; Hagenlocher et al. 2018; Kloos et al. 2015; 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. (2019), 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 (Asare-Kyei et al. 2017 (4%); Hagenlocher et al. 2018 (28%); and Sudmeier-Rieux 2011 (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. Sebesvari et al., 2016 Hagenlocher et al., 2019). 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.

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.

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. Hagenlocher et al. 2018), soil erosion rate (e.g. Sudmeier-Rieux, 2011 and Bourne et al., 2016), and river connectivity (e.g. Hagenlocher et al., 2018) (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. Antwi et al., 2015; Mickovski & Thomson, 2017) 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. Hagenlocher et al., 2018). For SES-type studies, Hagenlocher et al. (2018) 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

Accepted for publication on 14 June 2020 in International Journal of Disaster Risk Reduction (IJDRR). Please visit journal website for full citation details

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.

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) (%)

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 (Asare-Kyei et al., 2017)) or by the surveys (e.g. proportion of livestock) (Table S2).

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 (Hagenlocher et al., 2018)) 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., Asare-Kyei et al., 2017; Satta et al., 2017). Proportion of house ownership (Sudmeier-Rieux, 2011) and access to land or land ownership (Fedele et al., 2017; Hagenlocher et al., 2018; Sudmeier-Rieux, 2011) 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. (2018) 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 (Hagenlocher et al., 2018), emergency management committee (Asare-Kyei et al., 2017; Sudmeier-Rieux, 2011), early warning system/monitoring, and government assistance (Sudmeier-Rieux, 2011) (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 (Hagenlocher et al., 2018), capacity of engineered structures to prevent flooding, and knowledge of hazard causes and prevention (Sudmeier-Rieux, 2011) (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 (Sudmeier-Rieux, 2011), participation in decision making (Fedele et al., 2017) 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. (2018) 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 (Antwi et al., 2015) is considered as an adaptive capacity indicator.

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)

Risk components and categories	Indicator Name
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 organisations	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)

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 (Cohen-Shacham et al., 2016). 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 (Cohen-Shacham et al., 2016). 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. (2019) 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. Birkmann et al., 2013; Bhattachan et al., 2018; Sebesvari et al., 2016). 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 (Cohen-Shacham et al., 2016) 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) (Biswas et al., 2009) 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 (Cohen-Shacham et al., 2016) 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' (Sebesvari et al., 2016) 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 Van Coppenolle et al. (2019) 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.

Acknowledgement

This work was supported by the European Union's (EU) Horizon 2020 research and innovation programme. It was funded by and carried out within the framework of OPERANDUM (OPEn-air laboRAtories for Nature baseD solUtions to Manage hydro-meteo risks) project (Grant no. 776848).

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

References

Antwi, E. K., Boakye-Danquah, J., Owusu, A. B., Loh, S. K., Mensah, R., Boafo, Y. A., & Apronti, P. T. (2015). Community vulnerability assessment index for flood prone savannah agro-ecological zone: A case study of Wa West District, Ghana. *Weather and Climate Extremes*, *10*, 56-69.

Arkema, K. K., Griffin, R., Maldonado, S., Silver, J., Suckale, J., & Guerry, A. D. (2017). Linking social, ecological, and physical science to advance natural and nature-based protection for coastal communities. *Ann. NY Acad. Sci*, *1399*(1), 5-26.

Asare-Kyei, D., Renaud, F. G., Kloos, J., Walz, Y., & Rhyner, J. (2017). Development and validation of risk profiles of West African rural communities facing multiple natural hazards. *PLoS one*, *12*(3).

Beccari, B. (2016). A comparative analysis of disaster risk, vulnerability and resilience composite indicators. *PLoS currents*, *8*.

Bhattachan, A., Jurjonas, M. D., Moody, A. C., Morris, P. R., Sanchez, G. M., Smart, L. S., ... & Seekamp, E. L. (2018). Sea level rise impacts on rural coastal social-ecological systems and the implications for decision making. *Environmental Science & Policy*, *90*, 122-134.

Birkmann, J., Garschagen, M., Mucke, P., Schauder, A., Seibert, T., Welle, T., ... & Matuschke, I. (2014) World Risk Report 2014. Bu¨ndnis Entwicklung Hilft and UNUEHS.

Birkmann, J. (2006). Measuring vulnerability to promote disaster-resilient societies: Conceptual frameworks and definitions, Part One in Birkmann, J. (Ed.). *Measuring Vulnerability to Natural Hazards—Towards Disaster Resilient Societies* (pp. 9-54.). Tokyo, New York, Paris: United Nations University Press.

Birkmann, J., Cardona, O. D., Carreño, M. L., Barbat, A. H., Pelling, M., Schneiderbauer, S., ... & Welle, T. (2013). Framing vulnerability, risk and societal responses: the MOVE framework. *Natural hazards*, *67*(2), 193-211.

Biswas, S. R., Mallik, A. U., Choudhury, J. K., & Nishat, A. (2009). A unified framework for the restoration of Southeast Asian mangroves—bridging ecology, society and economics. *Wetlands Ecology and Management*, *17*(4), 365-383.

Bollin, C., & Hidajat, R. (2006). Community-based disaster risk index: pilot implementation in Indonesia, towards disaster resilient societies. In: Birkmann, J. (ed.) Measuring vulnerability to natural hazards. UNU-Press, Tokyo, New York, Paris.

Bourne, A., Holness, S., Holden, P., Scorgie, S., Donatti, C. I., & Midgley, G. (2016). A socio-ecological approach for identifying and contextualising spatial ecosystem-based adaptation priorities at the sub-national level. *PloS one*, *11*(5).

Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and urban planning*, *97*(3), 147-155.

Chapin III, F. S., Carpenter, S. R., Kofinas, G. P., Folke, C., Abel, N., Clark, W. C., ... & Berkes, F. (2010). Ecosystem stewardship: sustainability strategies for a rapidly changing planet. *Trends in ecology & evolution*, *25*(4), 241-249.

Cohen-Shacham, E., Walters, G., Janzen, C. & Maginnis, S. (eds.) (2016). Nature-based Solutions to address global societal challenges. Gland, Switzerland: IUCN. xiii + 97pp.

Cutter, S.L., Boruff, B.J., & Shirley, W.L. (2003). Social vulnerability to environmental hazards. *Social science quarterly*, *84*, 242-261.

Damm, M. (2010). Mapping social–ecological Vulnerability to flooding: a sub-national approach to Germany. Graduate Research Series 3, UNU-EHS, Bonn, p 1–85. (ISBN-10: 393992346X).

Day, J. W., Boesch, D. F., Clairain, E. J., Kemp, G. P., Laska, S. B., Mitsch, W. J., ... & Simenstad, C. A. (2007). Restoration of the Mississippi Delta: lessons from hurricanes Katrina and Rita. *Science*, *315*(5819), 1679-1684.

De Groot, R. S., Wilson, M. A., & Boumans, R. M. (2002). A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological economics*, *41*(3), 393-408.

FEBA (Friends of Ecosystem-based Adaptation) (2017). Making Ecosystem-based Adaptation Effective: A Framework for Defining Qualification Criteria and Quality Standards (FEBA technical paper developed for UNFCCC-SBSTA 46). Bertram, M., Barrow, E., Blackwood, K., Rizvi, A.R., Reid, H., and von Scheliha-Dawid, S. (authors). GIZ, Bonn, Germany, IIED, London, UK, and IUCN, Gland, Switzerland, 14.

Fedele, G., Locatelli, B., & Djoudi, H. (2017). Mechanisms mediating the contribution of ecosystem services to human well-being and resilience. *Ecosystem Services*, *28*, 43-54.

García-Mollá, M., Sanchis-Ibor, C., Ortega-Reig, M. V., & Avellá-Reus, L. (2013). Irrigation associations coping with drought: the case of four irrigation districts in Eastern Spain. In *Drought in arid and semi-arid regions* (pp. 101-122). Springer, Dordrecht.

Garschagen, M. (2014). *Risky change? Vulnerability and adaptation between climate change and transformation dynamics in Can Tho City, Vietnam* (Vol. 15). Stuttgart: Steiner.

GIZ, EURAC & UNU-EHS (2018). Climate Risk Assessment for Ecosystem-based Adaptation – A guidebook for planners and practitioners. Bonn: GIZ.

Hagenlocher, M., Renaud, F. G., Haas, S., & Sebesvari, Z. (2018). Vulnerability and risk of deltaic social-ecological systems exposed to multiple hazards. *Science of the total environment*, *631*, 71-80.

Hagenlocher, M., Meza, I., Anderson, C., Min, A., Renaud, F.G., Walz, Y., Siebert, S., & Sebesvari, Z. (2019). Drought vulnerability and risk assessments: state of the art, persistent gaps, and research agenda. *Environmental Research Letters*. *14*(8), 083002. https://doi.org/10.1088/1748-9326/ab225d.

Hamin, E. M., Abunnasr, Y., Roman Dilthey, M., Judge, P. K., Kenney, M. A., Kirshen, P., ... & Nurse, L. (2018). Pathways to coastal resiliency: The adaptive gradients framework. *Sustainability*, *10*(8), 2629.

IPCC (2012). Managing the risks of extreme events and disasters to advance climate change adaptation. In Field, C.B.V., Barros, T.F., Stocker, D.,Q. in, DJ Dokken, K.L., Ebi, M.D., Mastrandrea, K.J., Mach, G.K., Plattner, S.K., Allen, M., 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.

IPCC (2014a). 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 [Field, C.B., 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, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.

IPCC (2014b). 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.). (2014). *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, United Kingdom and New York, NY, USA: Cambridge University Press, pp. 1–32.

IUCN, ISSD, & SEI. (2003). 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*.

IUCN (2019). A Global Standard for Nature-based Solutions. International Union for Conservation of Nature (IUCN), Geneva. Retrieved from https://www.iucn.org/theme/ecosystem-management/about/our-work/a-global-standard-nature-based-solutions

Jurgilevich, A., Räsänen, A., Groundstroem, F., & Juhola, S. (2017). A systematic review of dynamics in climate risk and vulnerability assessments. *Environmental Research Letters*, *12*(1), 013002.

Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., ... & Zaunberger, K. (2016). Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society*, *21*(2).

Kloos, J., Asare-Kyei D., Pardoe J., & Renaud, F.G. (2015). Towards the development of an adapted multi-hazard risk assessment framework for the West Sudanian Savanna Zone. UNU-EHS Publication, *11*, 4–26.

Leal Filho, W., Modesto, F., Nagy, G. J., Saroar, M., YannickToamukum, N., & Ha'apio, M. (2018). Fostering coastal resilience to climate change vulnerability in Bangladesh, Brazil, Cameroon and Uruguay: a cross-country comparison. *Mitigation and adaptation strategies for global change*, *23*(4), 579-602.

MA, 2005 Millennium Ecosystem Assessment Ecosystems and Human Well-Being: Synthesis, 2005. Island Press, Washington, DC.

MacKinnon, K., Sobrevila, C., & Hickey, V. (2008). Biodiversity, Climate Change and Adaptation; Nature-Based Solutions from the World Bank Portfolio. Washington: the World Bank.

Maes, J., & Jacobs, S. (2017). Nature-based solutions for Europe's sustainable development. *Conservation Letters*, *10*(1), 121-124.

Mickovski, S. B., & Van Beek, L. P. H. (2006). A decision support system for the evaluation of eco-engineering strategies for slope protection. *Geotechnical & Geological Engineering*, *24*(3), 483-498.

Mickovski, S. B., & Thomson, C. S. (2017). Developing a framework for the sustainability assessment of eco-engineering measures. *Ecological engineering*, *109*, 145-160.

Moos, C., Bebi, P., Schwarz, M., Stoffel, M., Sudmeier-Rieux, K., & Dorren, L. (2018b). Ecosystem-based disaster risk reduction in mountains. *Earth-science reviews*, *177*, 497-513.

Shah, M.A.R., Renaud, F. G., Wild, A., Anderson, C. C., Loupis, M., Panga, D., Polderman, A., Thomson, C., Munro, K., Sahani, J., Pilla, F., Pouta, E., El Zohbi, J., Preuschmann, S., Xue, X., Votsis, A., Stefanopoulou, M., Pangas, N., Basu, B., Ma, S., Zixuan, W., Pulvirenti, B., To the, E., Domeneghetti, A. (2019). *Vulnerability and risk assessments of socio-ecological systems (SES): conceptual framework, impact chains and indicators*. OPEn-air laboRAtories for Nature baseD solUtions to Manage hydro-meteo risks (OPERANDUM) project, Italy.

Peduzzi, P., Dao, H., Herold, C., & Mouton, F. (2009). Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index. *Natural Hazards and Earth System Sciences*, *9*(4), 1149.

Richards, J., White, I., & Carter, J. (2008). Local planning practice and flood risk management in England: is there a collective implementation deficit? *Environnement Urbain/Urban Environment*, *2*, 11-20.

Rizvi, A. R. (2014). Nature based solutions for human resilience: a mapping analysis of IUCN's ecosystem-based adaptation projects. IUCN, Geneva. https://portals.iucn.org/library/sites/library/files/documents/Rep-2014-008.pdf

Sahani, J., Kumar, P., Debele, S., Spyrou, C., Loupis, M., Aragão, L., ... & Di Sabatino, S. (2019). Hydro-meteorological risk assessment methods and management by nature-based solutions. *Science of the Total Environment*, *696*, 133936.

Satta, A., Puddu, M., Venturini, S., & Giupponi, C. (2017). Assessment of coastal risks to climate change related impacts at the regional scale: The case of the Mediterranean region. *International journal of disaster risk reduction*, *24*, 284-296.

Sayers, P., Yli, G.G., Penning-Rowsell, E., Shen, F., Wen, K., Chen, Y. & Le Quesne, T. (2013). *Flood risks management: a strategic approach*. Paris: UNESCO.

Schubert, S. D., Suarez, M. J., Pegion, P. J., Koster, R. D., & Bacmeister, J. T. (2004). Causes of long-term drought in the US Great Plains. *Journal of Climate*, *17*(3), 485-503.

Sebesvari, Z., Renaud, F. G., Haas, S., Tessler, Z., Hagenlocher, M., Kloos, J., ... & Kuenzer, C. (2016). A review of vulnerability indicators for deltaic social–ecological systems. *Sustainability Science*, *11*(4), 575-590.

Secretariat of the Convention on Biological Diversity (CBD) (2019). 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, 156 pages.

Sharp R, Tallis H, Ricketts T, Guerry A, Wood S, Chaplin-Kramer R, et al. (2018). InVEST User's Guide. User Guide. Stanford (CA): The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, World Wildlife Fund.

Song, G., Li, Z., Yang, Y., Semakula, H. M., & Zhang, S. (2015). 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. *Ecological Indicators*, *52*, 57-65.

Steiger, J., James, M., & Gazelle, F. (1998). Channelization and consequences on floodplain system functioning on the Garonne River, SW France. *Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management*, *14*(1), 13-23.

Sudmeier-Rieux, K. (2011). On Landslide Risk, Resilience and Vulnerability of Mountain Communities in Central-Eastern Nepal. PhD Dissertation, University of Lausanne.

Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., ... & Polsky, C. (2003). A framework for vulnerability analysis in sustainability science. *Proceedings of the national academy of sciences*, *100*(14), 8074-8079.

UN (United Nations) (2015) Global Assessment Report on Disaster Risk Reduction 2015. Making Development Sustainable: The Future of Disaster Risk Management. United Nations, Geneva

UNDP/BCPR (2004). A Global Report: Reducing Disaster Risk, A Challenge for Development. United Nations Development Programme. Bureau for Crisis Prevention and Recovery, New York.

UNDRO, N. D. (1980). Vulnerability Analysis. In *Report of Experts Group Meeting,* Geneva.

Van Coppenolle, R., Schwarz, C., & Temmerman, S. (2018). Contribution of mangroves and salt marshes to nature-based mitigation of coastal flood risks in major deltas of the world. *Estuaries and coasts*, *41*(6), 1699-1711.

van Dijk, A. I., Beck, H. E., Crosbie, R. S., de Jeu, R. A., Liu, Y. Y., Podger, G. M., ... & Viney, N. R. (2013). The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. *Water Resources Research*, *49*(2), 1040-1057.

van Wesenbeeck, B. K., Mulder, J. P., Marchand, M., Reed, D. J., de Vries, M. B., de Vriend, H. J., & Herman, P. M. (2014). Damming deltas: A practice of the past? Towards nature-based flood defenses. *Estuarine, coastal and shelf science*, *140*, 1-6.

Whelchel A.W., & Beck M.W. (2016). Decision Tools and Approaches to Advance Ecosystem-Based Disaster Risk Reduction and Climate Change Adaptation in the Twenty-First Century. In: Renaud F., Sudmeier-Rieux K., Estrella M., Nehren U. (eds) Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice. *Advances in Natural and Technological Hazards Research*, *42*, Springer, Cham.

White, I., & Richards, J. (2007). Planning policy and flood risk: The translation of national guidance into local policy. *Planning, practice & research*, *22*(4), 513-534.

World Bank (2017). Implementing nature-based flood protection: Principles and implementation guidance. Washington, DC: World Bank.

Xue, L., Wang, J., Zhang, L., Wei, G., & Zhu, B. (2019). Spatiotemporal analysis of ecological vulnerability and management in the Tarim River Basin, China. *Science of the Total Environment*, *649*, 876-888.

Zhang, X., Wang, L., Fu, X., Li, H., & Xu, C. (2017). Ecological vulnerability assessment based on PSSR in Yellow River Delta. *Journal of Cleaner Production*, *167*, 1106-1111.

Supplementary material S2

Table S2: List of vulnerability and risk assessment indicators

Sl.	Risk components and categories	Indicator Name	References	Possible data sources
	Ecosystem Exposure			
1	Exposed area/ land use	Ecosystems exposed to drought (%)	Hagenlocher et al (2018)	Hazard (all countries): Own calculation based on climate station data; Land use/land cover (all countries): ESA CCI, https://www.esa-landcover-cci.org
2		Ecosystems exposed to floods (%)	Hagenlocher et al (2018)	Hazard (all countries): Global Assessment Report 2015, http://preview.grid.unep.ch; Land use/land cover (all countries): ESA CCI, https://www.esa-landcover-cci.org
3		Ecosystems exposed to salinity intrusion (%)	Hagenlocher et al (2018)	Hazard (Bangladesh): SRDI, Hazard (Mekong): ICEM ; Land use/land cover (all countries): ESA CCI, https://www.esa-landcover-cci.org
4		Ecosystems exposed to storm surges (%)	Hagenlocher et al (2018)	Hazard (all countries): UNEP Preview, http://preview.grid.unep.ch; Land use/land cover (all countries): ESA CCI, https://www.esa-landcover-cci.org
5		Exposure of insecure farms (share of farms in slopes >5%) (%)	Asare- Kyei et al (2017)	From 30 m spatial resolution Global Digital Elevation Model developed jointly by the Japanese Ministry of Economy, Trade and Industry (METI) and the United States National Aeronautics and Space Administration (NASA)
6		Protected area (%)	Asare- Kyei et al (2017)	LULC maps for the three study areas were generated by classifying high spatial resolution (5m) multitemporal RapidEye images developed by (Forkuor et al., 2014). Flood map from Asare-Kyei et al. (2015)
7		Urban green areas *(green surface per capita)*	OAL	Field survey and historical record from authorities
8		Proportion of area exposed to landslide (%)	OAL	Field survey and historical record from authorities

Sl.	Risk components and categories	Indicator Name	References	Possible data sources
9		Proportion of area exposed to water pollution (algal bloom) (%)	OAL	Field survey and historical record from authorities
	Social System Exposure			
10	Economy	Proportion of businesses exposed to hazards (%)	OAL	Field survey and historical record from authorities
11	Exposed area/ land use	Proportion of Residential area (ha)	Cheng et al. (2017); Brunner & Grêt-Regamey (2017)	MassGIS 2005 land use categories; For Europe (10m): https://ghsl.jrc.ec.europa.eu/esm_R2019.php
12		Proportion of area of heritage sites exposed to hazards (%)	OAL	Field survey and historical record from authorities
13	Exposed buildings	Proportion of properties/ buildings in hazard prone area (%)	OAL	Field survey and historical record from authorities
14	Exposed population	Proportion of total population exposed to multiple hazards (%)	Sobey & Monty (2016); Arkema et al. (2017); OAL	International composite indices like the WorldRiskIndex and the INFORM index
15		Population exposed to drought (%)	Hagenlocher et al (2018)	Hazard (all countries): Own calculation based on climate station data; Population (all countries): WorldPop, http://www.worldpop.org.uk
16		Population exposed to floods (%)	Hagenlocher et al (2018)	Hazard (all countries): Global Assessment Report 2015, http://preview.grid.unep.ch ; Population (all countries): WorldPop, http://www.worldpop.org.uk
17		Population exposed to salinity intrusion (%)	Hagenlocher et al (2018)	Hazard (all countries): Global Assessment Report 2015, http://preview.grid.unep.ch; Population (all countries): WorldPop, http://www.worldpop.org.uk
18		Population exposed to landslide (%)	OAL	Field survey and historical record from authorities
19		Population exposed to algal bloom (%)	OAL	Field survey and historical record from authorities
20		Proportion of tourist or participants in recreational activities exposed to hazards (%)	Satta et al. (2017), OAL	Field survey and historical record from authorities

Sl.	Risk components and categories	Indicator Name	References	Possible data sources
21	Infrastructure and services	Proportion of critical physical infrastructure (%)	Asare-Kyei et al. (2017)	Number of physical infrastructure in an area (irrigation dams, hospitals, schools, food markets and major bridges located in floodplains). Local councils.
22		Proportion of area/ length of water supply network in hazard prone area (% of area or length)	OAL	Field survey and historical record from authorities
23		Proportion of length of road exposed in hazard prone area (%)	OAL	Field survey and historical record from authorities
24	Livestock	Proportion of livestock in OAL (%)	OAL	Field survey and historical record from authorities
	Ecosystem Susceptibility			
25	Agriculture	Increased use of chemicals and fertilisers (qualitative/ quantitative) (N/S)	Rahman et al (2016)	Primary data collection, secondary data analysis
26		Outbreak of pest and diseases (N/S)	Khadka et al. (2018)	Primary data collection
27		Fertility of agricultural soils (cation exchange capacity (CEC))	OAL	Field measurement, historical records from authorities
28	Biodiversity	Biodiversity (Scoring or Index)	Mickovski & Thomson (2017); Antwi et al. (2015); Bourne et al (2016)	Data collected via survey, focus groups, transect walks and key informant interviews; National/ regional databases
29		Population of protected species (No./m^2)	OAL	Data from OAL and historical record from authorities
30	Vegetation	Normalized Difference Vegetation Index (NDVI)	Asare-Kyei et al. (2017); Zhang et al. (2017)	Data obtained from SoilGrids1km which is a global soil data product generated at ISRIC – World Soil Information (https://www.isric.org/).
31	Habitat degradation	Land reclamation rate (km2/yr)	Zhang et al. (2017)	Statistical yearbooks

Sl.	Risk components and categories	Indicator Name	References	Possible data sources
32		Groundwater quality (categorical or proxy unit e.g. arsenic content ((probability of occurrence))	Hagenlocher et al (2018)	UNEP Environmental Data Explorer (IGRAC) at http://geodata.grid.unep.ch ; Probability of arsenic in groundwater for each administrative unit was calculated based on the polygon dataset
33		Soil organic matter (g/kg)	Hagenlocher et al (2018); Asare-Kyei et al. (2017)	Soilgrids at https://soilgrids.org
34		Sedimentation rate (cm/yr)	Rahman et al. (2016); Belle (2016)	Both primary (Key Informants Interview, Household Survey, and Focus Group Discussion) and secondary (climatic, literature review) data
35		Air quality *(Air Quality Index - AQI)*	OAL	Monitoring at OAL
36		Degree of pollution in sediments (heavy metals, etc.) (proxy - concentration of heavy metals in sediments)	OAL	Monitoring at OAL
37		Proportion of area covered by algal boom (%)	OAL	Monitoring water quality
38		Water clarity (Turbidity, Secchi depth)	OAL	Monitoring water quality
39	Habitat destruction	Percentage of shoreline eroded (%)	Hagenlocher et al (2018)	Multiple data sources incl. census data, publicly accessible national and global repositories, expert knowledge
40		Bank stability / erosion (scale 1-5)	Belle (2016)	Questionnaires, interviews, field observations and secondary data
41		Soil erosion (RUSLE output)/ Erosion rate (mm/year)	Song et al. (2015); Rahman et al. (2016); Sudmeier-Rieux (2011) ; Bourne et al. (2016)	Harmonized World Soil Database; Database for Human-earth System; DEM Elevation Data Service System (Computer Network Information Center, CAS, 2009). Vegetational coverage is supplied by the Spot-Vegetation program

Sl.	Risk components and categories	Indicator Name	References	Possible data sources
42		Freshwater scarcity (N/S)	Hagenlocher et al (2018)	UNEP-WCMC at https://www.unep-wcmc.org; Dataset combines a long-term mean annual water balance with data on water stored in large lakes. Average freshwater availability was calculated for each administrative unit
43		Deforestation rate (km2/yr)	OAL	Field survey and authorities
44	Habitat fragmentation	Forest connectivity (probability of connectivity index (PC))	Hagenlocher et al (2018)	Hansen et al. (2013) at https://earthenginepartners.appspot.com
45		River connectivity (N/S)	Hagenlocher et al (2018)	Nilsson et al. 2005, http://science.sciencemag.org; Impact classification based on river channel fragmentation and water flow regulation by dams. River systems are treated as units and are represented by their catchments in the Nilsson et al. (2005) dataset. For each delta one value representing river connectivity was used. Higher resolution data would be preferable – if available.
46		Wetland connectivity (N/S)	Hagenlocher et al (2018)	Multiple data sources incl. census data, publicly accessible national and global repositories, expert knowledge
47	Habitat restoration	Nutrient loading and removal allocations (nitrogen and phosphorus) for each LULC class	Ronchi & Arcidiacono (2018)	Biophysical tables containing the nutrient loading and removal allocations; InVEST User Guide
48	Land	Protection of land from hazard (% of area)	Sudmeier-Rieux (2011)	Community surveys
49	Livestock	Proportion of cattle killed by wolfs (%)	OAL	Hunting association of Lower Saxony/NLWKN
50		Population density of livestock (Number of cattle /ha)	OAL	Survey/existing data for the managed area
51	Soil characteristic	Soil productivity (N/S)	Sudmeier-Rieux (2011)	Community surveys
52	Water - ecological use	Ecological water use percentage (%)	Zhang et al. (2017)	Ecological water use/total water use. Statistical yearbooks and remote sensing data

Sl.	Risk components and categories	Indicator Name	References	Possible data sources
53	Water - natural state	Groundwater levels (m)	OAL	Field survey and historical record from authorities
54		Rates of surface water drainage (m^3/s)	OAL	Field survey and historical record from authorities
55		River water level above and below a certain threshold (m)	OAL	NLWKN
56		Infiltration rate (mm/h)	Asare-Kyei et al. (2017)	1km resolution soil map from the Harmonized World Soil Database (HWSD) version 1.1 produced in 2009 by the International Institute for Applied System Analysis (IIASA)
57		Water holding capacity (mm)	Asare-Kyei et al. (2017)	Data taken from re-gridded Harmonized World Soil Database (HWSD) (FAO, 2009)
	Social Susceptibility			
58	Agriculture	Agricultural crop production (ton per yr)	OAL	Field survey and Local council
59		Crop diversification (N/S)	Sudmeier-Rieux (2011); Antwi et al (2015); Asare- Kyei et al (2017)	Community surveys
60	Conservation policies / funding	Natural and cultural heritage preservation *(e.g. access to cultural objects or natural heritage sites- as a qualitative indicator) (N/S)*	OAL	Field survey and Local council
61	Economy	Equity (scale 1-5) / Equity GINI Index	Leal Filho et al. (2018); Hagenlocher et al (2018)	Expert assessment based on a variety of indexes and other measures; data.worldbank.org/indicator/SI.POV.GINI
62		GDP per capita (US$)	Sobey & Monty (2016); Satta et al. (2017); Leal Filho et al. (2018); Xue et al. (2019)	International composite indices like the WorldRiskIndex and the INFORM index
63		Level of indebtedness (N/S)	Sudmeier-Rieux (2011)	Community surveys

Sl.	Risk components and categories	Indicator Name	References	Possible data sources
64		Poverty (% of population)	Hagenlocher et al (2018); Leal Filho et al. (2018); Asare-Kyei et al. (2017)	Various national level statistics
65		Economic diversification (scale 1-7)	Karnauskaitė et al. (2018)	Field survey and expert judgement
66		Number of income-generating activities per household (average number)	Hagenlocher et al (2018)	Multiple data sources incl. census data, publicly accessible national and global repositories, expert knowledge
67		Insurance coverage (%)	OAL	Data from insurance companies
68		Employment rate (%)	OAL	Statistical authorities
69		Investment in infrastructure (€/inhab)	OAL	Municipalities
70	Population	Population density (inhab/km^2)	Xue et al. (2019); Daniel et al., 2017; Leal Filho et al. (2018); Arkema et al. (2017); Sudmeier-Rieux (2011); Fedele (2017); Song et al. (2015); Zhang et al. (2017); Satta et al. (2017); Whelchel & Beck (2016); Antwi et al. (2015) ; Bourne et al. (2016) ; OAL Germany	Statistical authorities; For world (250m and 1km): https://ghsl.jrc.ec.europa.eu/ghs_pop2019.php
71	Habitat degradation	Wastewater discharge (cubic meter/ person/yr)	Xue et al. (2019)	Amount of wastewater, not reaching emission standard of environment, discharged by water users. Statistical yearbooks
72	Highly vulnerable population	Dependency ratio (%) includes Young (<15 years) and/or Elderly (>65 years)	Hagenlocher et al (2018); Arkema et al. (2017); Satta et al (2017); Asare-Kyei et al. (2017); Arkema et al. (2017) ; Bourne et al. (2016)	% population children and elderly / working age population. National level databases. Household surveys. World Bank Open Data http://data.worldbank.org/indicator/SP.POP.65UP.TO.ZS. National Census data collected in 2011.

Sl.	Risk components and categories	Indicator Name	References	Possible data sources
73		Proportion of disabled people (%)	Arkema et al. (2017)	Statistical authorities, Field surveys
74	Housing	Proportion of house ownership (% of households)	Sudmeier-Rieux (2011)	Community surveys
75	Information / awareness	Awareness of landslide protection (N/S)	Sudmeier-Rieux (2011)	Community surveys
76		Education level (N/S)	Sudmeier-Rieux (2011); Satta et al (2017); Xue et al. (2019); Arkema et al. (2017)	Community surveys
77	Infrastructure and services	Proportion of drainage blocked (% of drainage area coverage)	OAL	Field survey and Local council
78		Deformation of elements at risk (buildings and infrastructure) (cm/annum)	OAL	Field survey and Local council
79		Dependency on road communication (N/S)	OAL	Community surveys and Local council
80		Access to safe drinking-water *(people having access to water/global population) (% of population)*	OAL	Statistical authorities
81		Level of dependency on ferry communication (N/S)	OAL	Community surveys and Local council
82	Land rights / ownership / management	Access rights to forest resources (N/S)	Sudmeier-Rieux (2011)	Community surveys
83		Access to land or land ownership (% of households)	Asare-Kyei et al. (2017); Fedele et al. (2017); Sudmeier-Rieux (2011); Hagenlocher et al (2018)	Household surveys, Field surveys
84	Livelihood	Off-farm income source (N/S)	Antwi et al. (2015)	Surveys, focus groups, transect walks and key informant interviews

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85		% of income from agricultural production (% of total income)	OAL	Surveys, focus groups, and key informant interviews
86		% of days they cannot use the field/ apply the cultivation necessary practices (%)	OAL	Surveys, focus groups, and key informant interviews
87	Population	Urban vs. non-urban dwellers *(population ratio)*	OAL	Statistical authorities
88	Social context	Human Development Index (rating low, medium, high) (HDI score)	Leal Filho et al. (2018)	www.hdr.undp.org
89	Water - human use	Per capita water resources (cubic meter/ person/yr)	Xue et al. (2019)	Amount of water resources/population. Statistical yearbooks.
	Ecosystem robustness			
90	Agriculture	Proportion of drought tolerant crops (% of crop production)	OAL	Multiple data sources incl. census data, publicly accessible national and global repositories, expert knowledge
91		Percent of area with Intensive/ extensive agriculture in floodplain (% of agriculture land)	OAL	Multiple data sources incl. census data, publicly accessible national and global repositories, expert knowledge
92	Conservation policies / funding	Government expenditure on environmental protection (% expenditure)	Hagenlocher et al (2018)	Multiple data sources incl. census data, publicly accessible national and global repositories, expert knowledge
93		Policies for coastal protection (yes/no)	Hagenlocher et al (2018)	Multiple data sources incl. census data, publicly accessible national and global repositories, expert knowledge
94		Policies supporting biodiversity conservation (yes/no)	Hagenlocher et al (2018)	Convention on Biological Diversity (CBD) at https://www.cbd.int/

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95	Ecosystem conservation	Percentage of area covered by Wetlands of International Importance (Ramsar Sites) (%)	Hagenlocher et al (2018)	Multiple data sources incl. census data, publicly accessible national and global repositories, expert knowledge
96		Percentage of forest area protected and designated for the conservation of biodiversity (%)	Hagenlocher et al (2018)	Multiple data sources incl. census data, publicly accessible national and global repositories, expert knowledge
97	Ecosystem services	Ecosystem Functionality Index (EFI scores)	Hagenlocher et al (2018)	Freudenberger et al. (2012) at http://www.sciencedirect.com
98	Habitat restoration	Rate of afforestation area (ha)	Zhang et al. (2017)	Statistical yearbooks
99		Percentage of wetlands restored (%)	Hagenlocher et al (2018)	Multiple data sources incl. census data, publicly accessible national and global repositories, expert knowledge
	Coping capacity			
100	DRR and emergency services	Monitoring of hydro-meteorological conditions – rainfall (intensity and duration of precipitation) (N/S)	OAL	Meteorological office
101		Existence of hazard zone map (yes/no)	OAL	Data from OAL
102		Food stocks (months per household)	Sudmeier-Rieux (2011)	Community surveys
103		Government assistance (% of population covered)	Sudmeier-Rieux (2011)	Community surveys
104		Area protected by structural measures (%)	Hagenlocher et al (2018)	Multiple data sources incl. census data, publicly accessible national and global repositories, expert knowledge
105		Emergency management Committee (Annual meeting frequency)	Asare-Kyei et al. (2017); Sudmeier-Rieux (2011)	Community surveys

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106		Early warning system/monitoring (% of population covered)	Sudmeier-Rieux (2011)	Community surveys
107		Emergency water supply (N/S)	Sudmeier-Rieux (2011)	Community surveys
108		Existence of hazard/vulnerability/risk maps (yes/no)	Hagenlocher et al (2018)	Multiple data sources incl. census data, publicly accessible national and global repositories, expert knowledge
109		Percentage of population with access to shelter (%)	OAL	Statistical authorities, Community survey
110		Existence of emergency plans (yes/no)	OAL	Data from OAL
111	Housing	Safe building (% of total number of buildings)	Sudmeier-Rieux (2011)	Community survey
112	Information / awareness	Knowledge of hazard causes & prevention (N/S)	Sudmeier-Rieux (2011)	Community surveys
113		Access to information (e.g. radios) (N/S)	Sudmeier-Rieux (2011)	Community surveys
114		Percentage of households that have attended any disaster preparedness training (% of households)	Hagenlocher et al (2018)	Community surveys
115	Infrastructure and services	Access to social services (N/S)	Antwi et al. (2015); Bourne et al. (2016)	Data collected via survey, focus groups, transect walks and key informant interviews; Location of buildings from Eskom data
116		Access to transportation network (Density of transportation network) (road (km) per 1000 population)	Hagenlocher et al (2018)	OpenStreetMap at http://www.openstreetmap.org; Density of the transportation network in the study areas per 100,000 people, inc. roads; rivers, canals and streams; and ferry stations

Sl.	Risk components and categories	Indicator Name	References	Possible data sources
117		Availability of emergency services (N/S)	Hagenlocher et al (2018)	OpenStreetMap at http://www.openstreetmap.org
118		Monitoring of damage to existing defence structures (i.e. cracks) (N/S)	OAL	Field survey and Local council
119		Capacity of engineered structures to prevent flooding (% of area protected)	OAL	Field survey and Local council
120	Livelihood	Alternative livelihood (% of households)	Rahman et al. (2016)	Both primary (Key Informants Interview, Household Survey, and Focus Group Discussion) and secondary (climatic, literature review) data were used
121	NGOs and community organisations	Community leadership (N/S)	Sudmeier-Rieux (2011)	Community surveys
122		Mutual assistance (N/S)	Sudmeier-Rieux (2011)	Community surveys
123	Political influence	Participation in decision making / implementation from interdisciplinary sectors (N/S)	Fedele et al. (2017); OAL Greece	Field survey; Questionnaires
124	Previous experience of hazard	Previous disaster experience (N/S)	Sudmeier-Rieux (2011); Hagenlocher et al (2018); Fedele et al. (2017)	Mixed methods and fieldwork
125	Social cohesion	Degree of collaboration (Likert scale 1-5)	OAL	Authorities
126	Water - human use	Irrigation technology and pumps (N/S)	Fedele et al. (2017); Hagenlocher et al (2018); Antwi et al. (2015)	Various sources available
	Adaptive capacity			
127	Adaptation planning and finance	Existence of adaptation policies/strategies (yes/no)	Hagenlocher et al (2018)	Data collected via survey, focus groups, and key informant interviews;

Sl.	Risk components and categories	Indicator Name	References	Possible data sources
				For Europe(country): https://www.eea.europa.eu/airs/2018/environment-and-health/climate-change-adaptation-strategies
128		Presence of land use policies (yes/no)	OAL	Data collected via survey, focus groups, and key informant interviews
129	Agriculture	Agriculture land use planning (yes/no)	OAL	Data collected via survey, focus groups, and key informant interviews
130	Conservation policies / funding	Existence of integrated development plans: conservation, protection; land use planning; controls by authorities (yes/no)	Hagenlocher et al (2018); OAL Greece	Multiple data sources incl. census data, publicly accessible national and global repositories, expert knowledge
131		State policy on forest designation (yes/no)	Fedele et al. (2017)	Mixed methods, fieldwork
132	Information / awareness	Knowledge on climate / risks (N/S)	Antwi et al. (2015)	Data collected via survey, focus groups, transect walks and key informant interviews
133	Social context	Social capital (% of population)	Asare-Kyei et al. (2017); Hagenlocher et al (2018)	Multiple data sources incl. census data, publicly accessible national and global repositories, expert knowledge
134	Water - human use	Volume of water storage in a safe reservoir/container (m^3)	Hagenlocher et al (2018)	Multiple data sources incl. census data, publicly accessible national and global repositories, expert knowledge
135		Managed sharing and allocation of water (N/S)	Fedele et al. (2017)	Mixed methods fieldwork