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An operationalized classification of Nature Based Solutions for water-related hazards: From theory to practice

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Abstract

Nature Based Solutions (NBS) are currently gaining importance in the EU policy agenda as a promising approach to mitigate and adapt to environmental and climate change. The main advantage of NBS over other adaptation strategies is their capability to deliver multiple benefits. They support the resilience of natural processes and help in reducing adaptation costs. In this paper, we address the current gaps in the literature by providing a comprehensive, easy-to-use classification scheme focussing on hydrological extreme events. The classification scheme is presented as a matrix and contains a portfolio of known NBS as well as the important criteria for their selection. Specifically, we have included disservices/ barriers, and the potential impacts of climate change on NBS. The matrix provides decision-makers with a tool that will guide them through the first phase of the complex process when choosing the most appropriative NBS for a specific challenge. In that way, we aim to support the spread of NBS in the scientific literature as well as their practical application.

Highlights

- An easy-to-use classification scheme for Nature Based Solutions
- Consideration of climate change impacts on Nature Based Solutions.
- Demonstration of opportunities for Nature Based Solutions in the private sector.

Key words

Insurance; risk; resilience; adaptation; classification

Declaration of interest: none

1. Introduction

Climate change and environmental degradation are likely to accelerate losses in European GDP by up to 77% by 2030 (IPCC, 2014). This has boosted the development of new approaches which highlight the role of ecosystems in reducing the socio-economic and environmental costs of climate change. The most recent and perhaps also most promising approach is the concept of Nature Based Solutions (NBS). It is based on the principle that enhancing and protecting natural processes provides multiple benefits for society, thereby ensuring a sustainable delivery of ecosystem services (ES) and buffering the adverse impacts of climate change. For example, restoring or protecting riverine ecosystems can reduce the vulnerability of eroding riverbanks against current and projected increases of extreme rainfall, with manifold benefits to the social-ecological system around the watershed (Anbumozhi et al., 2005). Their main advantage over other adaptation strategies is their capability to deliver multiple benefits. The implementation of a particular NBS may create bundles of ecosystem services, together generating various social, economic and environmental co-benefits. For example, restoring or protecting coastal wetlands can increase resilience against storms by acting as a barrier against natural disasters. In addition, they provide multiple co-benefits, such as carbon sequestration, fish provision, job creation, or tourism (Woodward and Wui, 2001; Clarkson et al., 2013).

A number of definitions for NBS have been formulated (e.g. Cohen-Shacham et al., 2016; Maes and Jacobs, 2017; Eggermont et al., 2015). In this article, we use the definition applied by the European Commission which understands NBS as: "... living solutions inspired by, continuously supported by and using nature, which are designed to address various societal challenges in a resource-efficient and adaptable manner and to provide simultaneously economic, social, and environmental benefits.[1]" (Maes and Jacobs, 2017). This definition highlights

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[1] According to this definition, approaches such as biomimicry should be considered as NBS since they are solutions inspired by nature. However, this approach is not contemplated in the text as many of the biomimicry solutions do not deliver multiple co-benefits as they are often designed to target one specific problem. Biomimicry technology do not necessary look for finding a balance between social, environmental and economic targets.

the functional role of biodiversity and ecosystem functions and processes as part of an overall adaptation strategy to adapt and mitigate the impacts of climate change. For example, protecting and managing wetlands to enhance their water storage capacity is considered to be a NBS. On the contrary, technical adaptation measures to droughts such as water cisterns installation will not be considered a NBS as they do not use ecosystem functions to deliver benefits to society. Nature Based Solutions are often used as an umbrella concept, embedding a wide range of conservation and sustainability measures. Terms such as green infrastructures, ecosystem based adaptation, ecosystem based mitigation, hybrid infrastructures, ecosystem restoration or ecosystem protection are all framed under the NBS concept. For this reason, the NBS definitions found in literature are deliberately vague. However, all definitions share an emphasis on the need of finding a balance between social, economic and environmental targets when applying NBS, and highlight the importance of their long-term sustainability. A very illustrative example are the policies promoting forests as carbon sinks that have been gaining attraction over the past years. Existing international agreements and initiatives often pursue afforestation targets that are more focused on quantity rather than quality. These projects often use monocultures with non-native species, which can produce maladaptation to climate change in the long term and negatively impact biodiversity and sustainable development (Seddon et al., 2019). Despite their use of ‘nature’ to address a societal challenge, such initiatives fail to find the balance between social, economic and environmental targets, and would therefore not be considered as NBS.

Implementing NBS is not only a way for adapting to environmental change, but generally supports the shift to a greener economy and a more sustainable society. At the same time, it helps to reduce the costs of adaptation by simply diminishing the risk in the face of uncertain events.

Baumgärtner and Strunz (2014) argue that the implementation of NBS increases systems capability to cope with extreme hydrological events (HEE), thereby representing an insurance value against unwanted regime shifts. We understand insurance value as “reflecting an ecosystem’s capacity to remain in a given regime and retain its capacity to deliver vital ecosystem services in the face of disturbance and change” (Baumgärtner, 2008). The NBS concept, therefore, enhances the capability of social-ecological systems to cope with risks through exploiting the intrinsic resilience of natural processes. This makes the concept of NBS very valuable to both public and private investors that want to reduce their vulnerability to HEE. In addition, it provides an opportunity to capitalize these services in Natural Assurance Schemes (NAS). When talking about NAS, we refer to strategies aiming at internalizing the insurance value of ecosystems with the objective of improving awareness, valuation and inclusion of

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NBS in HEE (Denjean et al., 2017). Natural Assurance Schemes are very important in terms of re-distribution of HEE risks and therefore a co-benefit of NBS implementation relevant for different economic sectors, including the insurance sector.

Despite their great potential, the spread and standardisation of NBS in the scientific literature is limited. As a result, there is little uptake and implementation of the concept by national and international decision-makers. We believe that this is caused by the lack of a comprehensive, concise and easy to use classification for NBS. Similar to the case of the ecosystem services classification by the Millennium Ecosystem Assessment, a simple and commonly accepted NBS classification would support the transfer of the concept into adaptation and risk mitigation plans.

Existing classifications are mostly descriptive and difficult to understand and use by non-experts (WWAP, 2018, European Commission, 2015, European Environmental Agency, 2015, Eggermont et al., 2015). In addition, the majority of classifications do not mention undesired effects or “disservices” that may arise from malfunctioning or inefficient ecosystem management (European Commission, 2013, Cohen-Shacham, 2016, Zhang et al., 2007, Eggermont et al, 2015). For example, the project URBAN greenUP developed an easy-to-use catalogue of NBS focussing on urban areas, but gives little attention to disservices (GreenUP, 2018). The often cited Eklipse framework presents a set of indicators and assessment methods to evaluate the effectiveness of NBS projects, but is unable to assess the effectiveness of NBS for disaster risk reduction (Raymond et al., 2017), or to indicate possible disservices. Furthermore, none of the studies looking at NBS have taken the potential effects of climate change into account, although it is highly likely that climate change will have significant impacts on ecosystems in general (Pecl et al., 2017), and consequently on NBS. Any decision-making on a particular NBS requires scientifically based and customized information about the potential impacts of climate change (so-called climate services). To our knowledge, there is presently no classification which gathers all information relevant for making decisions on implementing NBS.

In response to these gaps, we present a comprehensive and easy-to-use classification scheme as a basis for assessing and evaluating NBS under different socio-economic and climatic scenarios. Scientifically validated with an extensive literature review, our paper contains three substantial contributions to the NBS concept. Firstly, using the case of HEE as a conceptual focus, we propose a classification of NBS for risks associated with such events. Secondly, we list the co-benefits and disservices that may potentially arise when implementing NBS. And thirdly, we discuss the potential impacts of climate change on NBS, which we believe is crucial for their planning and management. Our classification scheme provides decision-makers with a tool to design cost-effective adaptation measures able to deliver benefits under different environmental and socio-economic scenarios.

2. Methodological classification framework of NBS

Our framework is organised as a matrix (see figure 1). Following Eggermont et al. (2015), we distinguish between three types of NBS according to the level of human intervention (level of engineering required for enhancing the delivery of ecosystem services): Type 1, low intervention; Type 2, medium intervention; Type 3, high intervention. While the classification has correctly been criticized for being too narrow, as well as too difficult for implementation (Potschin et al., 2016), we found its intervention-based distinction to be a useful starting point for our work.

An extensive literature review revealed a number of important factors that were not sufficiently considered in current classification schemes. These factors are: type of risk, area, co-benefits, disservices, impact scale, and the potential effects of climate change on NBS. For this reason, within each type of NBS, we have defined subtypes. In the vertical axis are information on the type of risk (HEE) to be considered, the area where the NBS is applied, the possible co-benefits of the NBS, and a column on the possible disservices. We have additionally included impact scale (local, regional, and global), and finally the potential effects of climate change on the NBS (see appendices A).

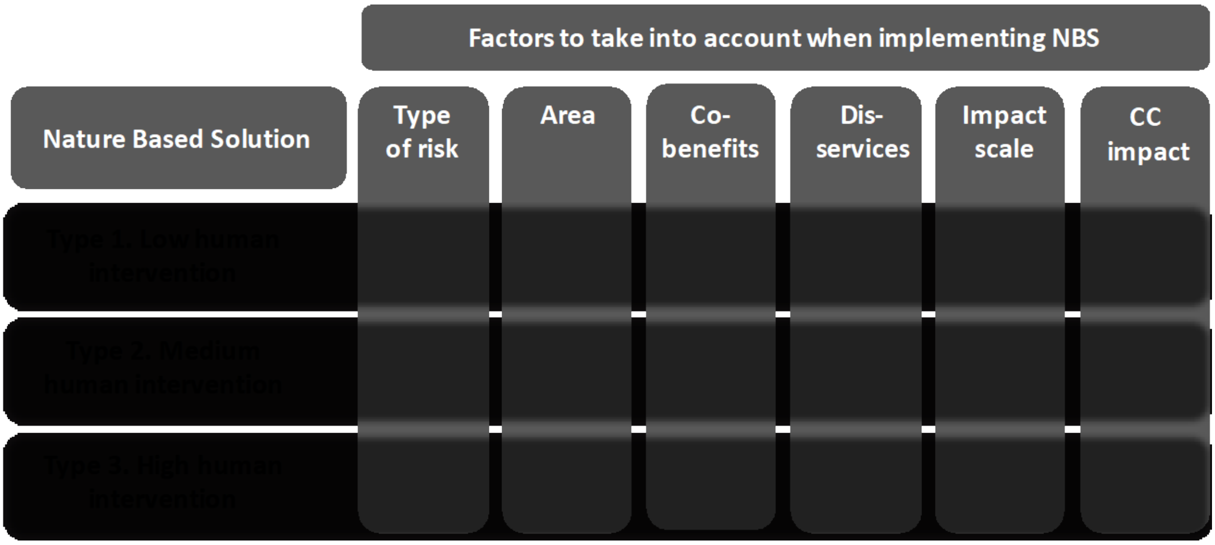

Figure 1. Synthetized Metrix for the methodological framework. The horizontal axis represents the different types of NBS according to the different levels of human intervention. The vertical axis represents key information that should be considered before NBS implementation.

2.1 Horizontal considerations of the NBS framework

2.1.1 NBS Type 1: Low human intervention

Some ecosystems play a fundamental role in regulating the hydrological cycle, and in protecting against the occurrence of flood events and water scarcity (Stürck et al., 2014; Sutton-Grier et al., 2015). The type of NBS that fall into this group include approaches that aim to preserve the integrity and stability of important ecological functions from a group of ecosystems and habitats without an intensive management, or an intervention into the system. The preservation of certain ecosystems can reduce the risks of HEE (World Bank, 2008). For example, applying conservation measures in wetlands which act as barriers against storms may reduce the vulnerability of coastal communities (Costanza et al., 2008). Applying measures to protect soil from wind and water erosion maintains soil stability and structure and is essential to keep an optimal infiltration rate and to preserve soil fertility and productivity (Blanchart et al., 1999). Strategies focused on maintaining the well-functioning of ecosystems are NBS type 1.

2.1.2 NBS Type 2. Medium human intervention

This type of NBS clusters all management approaches that support the enhancement of important ecosystem services in a sustainable and multifunctional way. Within this group, we have included ecosystem restoration approaches, and management interventions in agricultural lands, forests, river morphologies, grasslands, pastures and meadows.

Ecosystem restoration approaches have been defined as “the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed” (SER, 2002). Frequently this degradation is the result of human activities that have disturbed the ecosystem in a direct or indirect way. Some restoration projects aim to restore the structure of a given ecosystem to the historic state prior to its disturbance. Others solely seek to re-establish the ecological processes and functions of a given ecosystem to return to the delivery of targeted ecosystem services.

Management interventions include a variety of measures for managing natural and man-made ecosystems. Agricultural practices such as crop rotation can improve the fertility and structure of soil by increasing the infiltration capacity. Altering deep-rooted and shallow-rooted plants can increase groundwater levels and contributes to a range of other services such as pollution removal or CO2 absorption (NWRM, 2014). Other agricultural practices such as intercropping or green covers to protect soil from erosion can also increase the infiltration rate (Zougmore et al., 2000; NWRM, 2014). Reducing soil surface exposure by maintaining an uninterrupted tree canopy can also provide a number of hydrological effects such as biodiversity preservation or reduction of water runoff. The reduction of exposure can be achieved with the appropriate forest management (Farley et al., 2005).

Another example is the establishment and maintenance of grasslands. Semi-natural grasslands buffer water flows through decreasing water run-off and at the same time attenuating soil erosion. They can also decrease water stress by increasing water retention capacity (Farley et al., 2005).

2.1.3 NBS Type 3: Creation of new ecosystems and hybrid solutions

The last group implies higher modification of ecosystems. The creation of new ecosystems that are designed and managed in a multi-purpose way are also considered type 3. It comprises green (or blue if there are aquatic ecosystems involved) infrastructures which are defined as "a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services" (European Commission, 2013). The combination of nature and grey infrastructure is called a hybrid solution and sometimes involves the creation of new ecosystems. Hybrid structures are especially useful when space is limited, as is often the case in urban areas.

Green infrastructure and hybrid solutions are being increasingly considered in development planning. They are particularly relevant in urban environments, where more than 60% of the European population lives. Measures such as green roofs, permeable surface channels and rills are wide spread in cities to reduce water runoff and the heat island effect (European Commission, 2013). Many of these measures have proven to be more cost-effective when compared with traditional grey approaches such as dikes or levees (Liquete et al., 2016; Schäffler and Swilling, 2013). For example, green alleys or tree planting have been estimated to be 3-6 times more effective in managing storm-water and reducing temperatures than conventional methods. The city of Portland invested $8 million in green infrastructure, saving $250 million for hard infrastructure costs (CCAP, 2011, Liquete et al., 2016; Schäffler and Swilling, 2013).

The creation of new ecosystems has been widely used for water retention or coastal protection measures (Piazza et al., 2005). There is a number of artificial wetlands that have been constructed in seriously degraded areas with water quality or drainage problems. Another example is the creation of artificial reefs to stabilize shorelines and protect coasts from wave erosion and flooding (Scyphers et al., 2011). Such new habitats and ecosystems may need a long time until they are fully established and able to deliver the intended ecosystem service. Until then, the ecosystem can be more vulnerable to disturbances and requires protection measures.

2.2 Vertical considerations of the NBS framework

2.2.1 Type of risk

We identify several types of risks by considering their origin, spatial, and temporal dimensions. Our classification covers the cases of droughts, floods, and water contamination. This is not intended to be an exhaustive list, but serves as a descriptive guidance.

We distinguish between five different types of floods: coastal, urban, fluvial, pluvial and flash floods. Each of them has different effects in terms of impacts, potential damages, and related costs. Additionally, we take into account water contamination, making a distinction between organic and inorganic contamination. Within droughts, we distinguish between the following types: meteorological, agricultural, hydrological, and socio-economic (Liu and Kogan, 1996). In this paper, we understand a meteorological drought as the duration of the dry period in reference to the normal dry period. We talk about an agricultural drought when the soil moisture is insufficient and results in lack of crop growth and production. Hydrological drought is referred to periods of shortfalls on surface and groundwater supply. Additionally, we consider socio-economic drought as droughts associated with the mismanagement of water supply and demand (Wilhite and Glantz, 1985). Depending on the type of drought, the suitability of NBS varies. For example, to reduce agricultural drought measures focused to maintain soil moisture will be appropriated, while measures to reduce the impacts of socio-economic droughts might include the restoration of natural vegetation and control surface flows (Sonneveld et al., 2018).

2.2.2 Area

Our approach distinguishes between three areas: rural, urban and peri-urban. Depending on the discipline, there are a number of definitions used for these categories. The categorization of rural and urban spaces depends exclusively on arbitrary delimitations, usually based on demographic components (i.e. population size), economic sectoral components (i.e. percentage of population working in the primary sector) and a socio-psychological component (i.e. values, attitudes, tastes and behaviours common for urban and rural areas) (Iaquinta and

Drescher, 2000). These components may vary depending on the area where the NBS is going to be implemented. The majority of countries have their own, official definition of urban, rural and peri-urban areas. For the purpose of this paper we have only considered demographic and economic sectoral components to differentiate between rural and urban areas. Urban areas are densely populated areas with generally more than 10.000 people and with low agricultural activities. Rural areas are low densely populated areas with generally less than 10.000 and with agriculture as the main economic sector. Peri-urban areas are areas currently in transition from strictly rural to urban.

Distinguishing between these categories is important, because the differences in demographic, economic and socio-economic factors influence NBS. For example, as explained previously, space restrictions are especially relevant for urban areas, while rural areas may have other limitations to consider, such as infrastructure access. For this reason, measures that have proven to be more effective and more easily to implement in certain areas (rural, urban and peri-urban), should be prioritized.

2.2.3 Co-benefits

One of the key aspects of NBS is their multifunctionality, their ability to provide several ecological, social, cultural and economic benefits (Hansen and DeFries, 2007; Kabisch et al., 2017). In our classification, we distinguish between primary benefits, referring here to the intended HEE risk reduction, and secondary benefits, referring to additional benefits or co-benefits. For example, while the primary benefit of dunes conservation is coastal flood protection, biodiversity maintenance is one of its potential co-benefits.

Following the Millennium Ecosystem Assessment, we classify co-benefits as provisioning, regulating, supporting and cultural ecosystem services (MEA, 2005).

2.2.4 Disservices

Taking limiting factors such as structural complexity, required economic investment, or available space to implement NBS into account, as well as enabling NBS to adapt to changing conditions and disturbances is key for success. If the systemic implications of NBS are not adequately considered, intended services and benefits can turn into disservices. Such unintended negative side effects can potentially lead to the malfunctioning of a NBS and may cause a number of undesired effects including biodiversity loss, fragmentation, change in flow patterns, spread of pests and diseases, or changes in local and regional water availability (Zhang et al., 2007). For example, afforestation projects to control desertification may decrease water availability if non-suitable tree species are chosen. A very illustrative example is the Chinese Three Norths Shelter Forest System Project, a large-scale afforestation project implemented in arid and semiarid areas to stop desertification. The project ignored key differences in topography, climate and hydrology, which led to increased environmental degradation and devastating impacts on soil moisture, hydrology and vegetation coverage (Shixiong, 2008).

Identifying potential disservices is also necessary to effectively evaluate the life cycle cost of NBS, including all cost associated with designing, building and maintaining a functioning NBS. The vast majority of NBS require ongoing management. For example, parts of urban nature are maintained through trimming, irrigation or collecting leaf litter. Lack of funding or inefficient planning causes management failures, potentially resulting in decreasing ecosystem services delivery, the loss of social acceptance due to accidents, unpleasant views, damages in infrastructures, and several other issues, with impacts on costs. For example, if urban trees are not well managed, infrastructures such as pavements can be damaged by tree roots of fallen limbs, requiring costly repairs.

The relationship between the different ecosystem components and socio-economic factors is complex. For this reason, being aware of the potential disservices in the prior stages of NBS implementation may help to identify factors that need to be considered in the design and evaluation the NBS. Consequently, our classification also includes a column in which the most common disservices and socio-economic factors limiting the success of NBS implementation are listed. This list is designed to be used in the prior stages of the decision-making process. It only gives a general idea of the potential disservices that may arise if factors such as budget, maintenance cost or climate change impact are not considered. The table can be used to narrow down the list of potential disservices as a check box exercise.

2.2.5 Impact scale

The co-benefits delivered by NBS can have impacts at different spatial scales. For example, a reforestation project might have a primary impact at the local scale reducing soil erosion in hillsides and at the same time a global impact by capturing CO2. However, to facilitate management decisions we only consider, for each NBS, the scale of the impacts that the primary benefit may have. The definition of the scales depends on the particular context and should be clearly stated when assessing the impact of NBS. In our framework, we use the scale provided in the Eklipse framework which considers the impacts of NBS at the mesoscale (regional, metropolitan, urban) and microscale (neighbourhood/street, building) (Raymond et al., 2017).

2.2.6 Climate change impacts

The impacts of climate change on NBS need special consideration. The latest IPCC report makes specific reference to the impacts of climate change on ecosystem functions due to increasing and/or decreasing climate variability, increase in mean temperature, change in precipitation patterns, increase of extreme events, or sea level raise (IPCC, 2018). At the same time, an increase in the frequency and intensity of HEE may overwhelm the capability of NBS to cope with these risks. Changes in rain patterns may also affect water and energy demand exacerbating social and cultural divisions.

Potential impacts of climate change on NBS have not been adequately addressed in the literature so far (Seddon 2019). However, such considerations are of utmost importance to make sure that the effects of NBS will last, especially in the long term. There are two relevant aspects: Firstly, the impacts of climate change on the performance of NBS and their effectiveness. And secondly, the costs that are related to dealing with and adapting to those impacts.

The effectiveness of NBS to cope with risk can be influenced in many ways. For example, higher-intensity of rain or flood events may saturate the capability of coastal habitats or green infrastructure to deal with these risks. Changes in the mean temperature, rain patterns, species distribution, fire patterns or HEE have important implications for practices such as ecological restoration. Future biophysical conditions arising as a result of climate change as well as other factors such as habitat fragmentation or land use change create novel environmental conditions never experienced in ecosystems before (Harris et al., 2006; Tilman and Lehman, 2001). For example, a number of plants are shifting their distribution ranges to higher elevations and latitudes (Chen et al., 2011). In some cases, this may challenge the capability of ecosystems to adapt and thus to deliver certain ES. Taking climate change into account is also key in afforestation projects, since droughts, fires, pests and diseases may determine long-term effectiveness of the project (Zhu et al., 2011).

Changes in species distribution range can even have implications for human health as human disease vectors such as mosquitoes are also temperature dependent. Consequently, changes in climate could lead to changes in the dynamics of diseases transmission (Afrane et al., 2012; Martens et al., 1999). This should be taken into account when it comes to the design of NBS. Areas with high risk of being affected by this phenomenon should pay more attention to the design and establishment of blue infrastructure since habitats with stagnant water play an important role in mosquitoes' life cycle.

The resources and cost of implementing NBS may increase in drier and warmer environments. For example, the maintenance of urban green infrastructures through irrigation can increase water use, potentially consuming more water than they infiltrate. The effectiveness of NBS can also be threatened by future development of disservices arising from new climatic conditions. For example, blue infrastructures may be more susceptible to algal blooms with increasing sea surface temperatures.

Considering the potential impacts of climate change in the first stages of NBS development is necessary for identifying factors that influence the delivery of ES and disservices associated with NBS as well as the capability of NBS to resist, recover or adapt to future conditions. This can help to design connected, heterogeneous and ecologically diverse NBS able to adapt to new climatic conditions (Seddon et al., 2019).

2.2.7. An example on how to use the methodological framework

In 2011 a climate adaptation plan was adopted by the city Council of Copenhagen in order to address the enormous challenges that the ongoing and future rainfall events are causing in the city. The Copenhagen Climate Adaptation Plan (CCAP) sets the framework for the implementation of climate adaptive measures in the City Administration area. As part of the CCAP, the Cloudburst Management Plan was developed to reduce the economic and societal problems caused by extreme flood events. The challenges arising from extreme rainfall could not be solved by a single initiative, such as upgrading the sewage system. For this reason, combined and coordinated actions had to be implemented. The development of projects promoting blue and green infrastructures is therefore a core aspect of the management plan (City of Copenhagen, 2012). In this section, we use the Copenhagen case to illustrate how our framework could be used in the first-stages of NBS implementation in an urban area with extreme rainfall problems.

The first step of the decision-making process is to identify the type of risk that the system is facing. In this case, the city of Copenhagen faces urban and pluvial flooding. At this stage, it is important to evaluate the probability of flooding vulnerability of the society in flood-prone areas.

Our table (see appendices a) lists a number of measures that can be applied to reduce flooding in urban areas, ranging from restoration or conservation of upstream floodplain areas to the installation of hybrid infrastructures such as vegetated swales, filter strips or tree pits.

Given that NBS are site-specific, the success of any measure is tightly linked with the environmental and socio-economic conditions of the area in which they will be applied. To effectively evaluate the potential co-benefits and disservices which a NBS can produce, it is necessary to consider hydrological, climatic and socio-economic studies. The table provides a description with the most commonly delivered co-benefits and disservices of each NBS. This can serve as a fist analysis of the best approach that should be considered for a deeper assessment.

For example, pollution and heat waves have been identified as increasing problems in the city of Copenhagen. This means that NBS delivering co-benefits related to climate regulation are highly likely to be more cost-effective, because they address several problems at the same time. Stream bed re-naturalization is usually a suitable measure to tackle urban, fluvial and pluvial flooding. However, the high- economic investment and the required ongoing management cost may be a barrier to the successful implementation of this NBS . In addition, this measure is only suitable if there is enough space. Other low-cost measures such as rain gardens, infiltration tranches or vegetated filter strips may be more adequate if space and budget are limiting factors.

Once the range of available alternatives have been identified, it is important to assess their long-term effectiveness, also under climate change projections. Our classification provides a first overview of the potential impacts that climate change may have on NBS. For example, if green roofs have been identified as an effective NBS, changes in rain patterns and species distribution should be taken into account in order to choose appropriate species or considering an increase of water demand.

3. Discussion

Nature Based Solutions are thought to be a promising approach for mitigating and adapting to environmental and climate change. However, their spread in the scientific literature as well as their practical implementation is currently hampered by the lack of a comprehensive, concise and easy to use classification. Although several classification schemes have been developed, we found that they have three important shortcomings. Firstly, they are often descriptive, which makes both their understanding by non-experts as well as an easy applicability challenging (WWAP, 2018, European Commission, 2015). Secondly, they do neither account for undesired effects (the so-called “disservices”), nor do they explicitly take implementation barriers into account. And thirdly, none of the existing classification schemes does take the potential effects of climate change into account. In light of current predications on the impacts of climate change on ecosystems and the services which they deliver, we see this shortcoming as a major limitation with respect to the long-term sustainability of NBS.

We have addressed all three shortcomings by developing a classification scheme which is comprehensive and clearly arranged. It includes potential disservices/ barriers, and specifically addresses the potential effects of climate change. The classification scheme is organized as a matrix, and provides a suitable and easy-to-use tool which we hope will both be taken up by the scientific literature as well as be useful for decision-making.

It is remarkable that despite the importance of NBS in mitigating and adapting to climate change, there are almost no studies assessing their effectiveness in a climate change context. Like other ecosystems, NBS will also be affected by the impacts of a changing climate. Our classification scheme provides the criteria needed for developing climate services as an important precondition for NBS implementation. Climate services are scientifically based and customised information about the potential impacts of climate change on a particular system (Hewitt et al., 2012). Consequently, they need to be taken into account when choosing a NBS, to avoid increasing costs in the future or even a potential failure.

Our classification scheme does have two potential limitations which we will shortly discuss here. The first is some ambiguity in differentiating types of NBS based on the level of intervention required. However, this distinction is not always entirely clear. For example, the conservation of certain ecosystems such as semi-natural grassland or some types of forests (considered as type 1) requires ongoing management. Consequently, these NBS could also be included in type 2 (medium human intervention). Similar examples can be found for type 2 and type 3 strategies. For instance, some restoration approaches can be seen as NBS type 3 as they use grey infrastructures to recover ecosystem functions. A prime example is the use of concrete blocks to allow the establishment of marine life and encourage the growth of new reefs.

A second potential limitation is that our framework does not consider the cost of NBS implementation. We assume that in general the management and maintenance cost increase from type 1 to type 3. If the level of engineering or management is high, the cost of maintaining the well-functioning such type 3 NBS are also likely to be high, given that such manufactured Nature Based Solutions lack the self-regulation of a purely ‘natural’ ecosystem. In any case, decision-making on what NSB shall be implemented will always require a careful consideration of costs, for example in form of a cost-effectiveness analysis.

The primary aim of NBS is the delivery of ecosystem services, which is a basis for obtaining ecosystem benefits (Schwerdtner Máñez et al. 2014). Generally speaking, all types of NBS 1 and 2 can be expected to deliver a high amount of ES. These services are related to the inherent functioning of the ecosystem. While NBS type 3 might deliver fewer ecosystem services, the fact that they are engineered also means that they can be designed to delivery specific services. As a result, they might be more effective in solving particular problems. Such engineered systems may better fit into environments that do not allow for the establishment of “natural systems”, for example, because of space restrictions. Hence, type 3 NBS are often found in urban areas, where they serve a particular aim, such as preventing urban floods.

The proposed classification scheme summarizes available options for NBS to HEE management. It does not only intend to potentially increase the adoption of NBS measures, but also aims to raise awareness about the added value of planning with NAS, namely to support the capability of ecosystems in reducing the negative effects of HEE through enhancing their insurance value.

Proactive involvement at all societal levels is needed to enhance ecosystem resilience, first in order to analyse the risks, and second to find leverage points for NBS implementation. The need of societal involvement goes far beyond implementing NBS, as it is also connected to insurance companies as “redistributors” of risk. Insurance companies have had important roles in the past, for example by supporting the establishment of fire departments in previous times to reduce the impacts of fire and the possible losses (Chester, 2018). It is time now for them to support the implementation of NBS, considering their implicit insurance value, to reduce the risks to HEE. We believe that our approach can facilitate this process.

4. Conclusions

Our classification scheme is a tool intended to support the spread and implementation of Nature Based Solutions as efficient measures to mitigate and adapt to environmental and climate change. Using the example of Hydrological Extreme Events (HEE) as a conceptual focus, we provide a portfolio of NBS which have proven to be effective in Disaster Risk Reduction (DRR) and climate change adaptation. Most importantly, we introduce the relevant criteria for supporting the complex decision-making processes for NBS. This providess decision-makers with an easy-to-use tool for NBS implementation. This is important not only for public bodies and decision-makers, but also for the private sector, including insurance companies. Given that insurance companies have an important role as “risk redistributors”, and considering the inherent insurance value of NBS, we believe it is now time for insurance companies to get involved in NBS.

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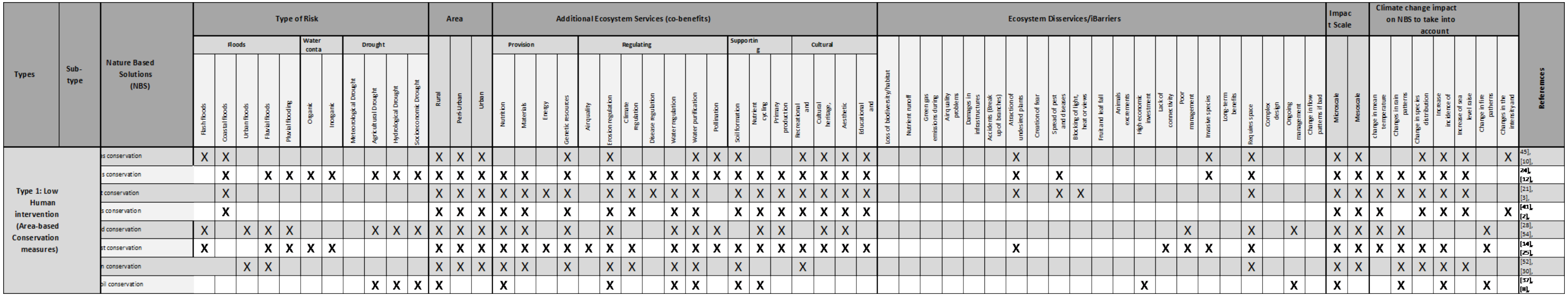
Appendices A



Types	Sub-type	Nature Based Solutions (NBS)	Type of Risk											Area			Additional Ecosystem Services (co-benefits)																		Ecosystem Disservices/iBarriers																					Impact Scale		Climate change impact on NBS to take into account							References
			Floods					Water conta		Drought							Provision				Regulating							Supporting			Cultural																																		
			Flash floods	Coastal floods	Urban floods	Fluvial floods	Pluvial flooding	Organic	Inorganic	Meteorological Drought	Agricultural Drought	Hydrological Drought	Socioeconomic Drought	Rural	Peri-Urban	Urban	Nutrition	Materials	Energy	Genetic resources	Air quality	Erosion regulation	Climate regulation	Disease regulation	Water regulation	Water purification	Pollination	Soil formation	Nutrient cycling	Primary production	Recreational and	Cultural heritage,	Aesthetic	Educational and	Loss of biodiversity/habitat	Nutrient runoff	Green gas emissions during	Air quality problems	Damages in infrastructures	Accidents (Break up of branches)	Atraction of undesired plants	Creation of fear	Spread of pest and diseases	Blocking of light, heat or views	Fruit and leaf fall	Animals excrements	High economic investment	Lack of connectivity	Poor management	Invasive species	Long-term benefits	Requires space	Complex design	Ongoing management	Change in flow patterns if bad	Microscale	Mesoscale	change in mean temperature	Changes in rain patterns	Change in species distribution	Increase incidence of	Increase of sea level raise	Change in fire patterns	Changes in the intensity and	
Type 1: Low Human intervention (Area-based Conservation measures)		s conservation	X	X										X	X	X				X		X				X	X	X			X	X	X	X							X									X		X				X	X			X	X	X		X	45], [10],
		s conservation		X		X	X	X	X		X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X							X		X							X		X				X	X	X	X	X	X	X			24], [12],
		t conservation		X										X	X	X	X	X	X	X		X	X	X	X	X		X	X	X	X	X	X	X							X		X	X								X				X	X	X	X	X	X	X			[21], [3],
		s conservation		X										X	X	X	X	X		X		X	X		X	X		X	X	X	X	X	X	X																						X	X	X		X	X	X		X	[41], [2],
		d conservation	X		X	X	X				X	X	X	X	X	X	X	X		X		X			X	X	X		X	X		X	X																X			X		X		X	X	X	X				X		[28], [54],
		st conservation	X			X	X	X	X					X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X							X							X	X	X		X				X	X	X	X	X	X		X		[14], [25],
		n conservation			X	X								X	X	X	X	X		X		X	X		X	X		X			X																					X				X	X		X	X	X	X			[52], [30],
		il conservation									X	X	X	X			X					X			X	X		X	X																		X								X		X			X		X		X		[37], [8],

Types	Sub-type	Nature Based Solutions	Type of Risk											Area			Additional Ecosystem Services (co-benefits)																		Ecosystem Disservices/iBarriers																					Impact Sca		Climate change impact on NBS to take in							Referen
			Floods					Water contamination		Drought							Provision				Regulating							Supporting			Cultural																																		
			Flash floods	Coastal floods	Urban floods	Fluvial floods	Pluvial flooding	Organic	Inorganic	Meteorological Drought	Agricultural Drought	Hydrological Drought	Socioeconomic Drought	Rural	Peri-Urban	Urban	Nutrition	Materials	Energy	Genetic resources	Air quality	Erosion regulation	Climate regulation	Disease regulation	Water regulation	Water purification	Pollination	Soil formation	Nutrient cycling	Primary production	Recreational and ecotourism	Cultural heritage, Sense of place	Aesthetic	Educational and inspirational	Loss of biodiversity/habitat	Nutrient runoff	Greengas emissions during construction	Air quality problems (Allergies)	Damages in infrastructures	Accidents (Break up of branches)	Atraction of undesired plants or animals	Creation of fear	Spread of pest and diseases	Blocking of light, heat or views	Fruit and leaf fall	Animals excrements	High economic investment	Lack of connectivity	Poor management	Invasive species	Long-term benefits	Requires space	Complex design	Ongoing management needed	Change in flow patterns if bad designed	Microscale	Mesoscale	change in mean temperature	Changes in rain patterns	Change in species distribution	Increase incidence of extreme climatic events	Increase of sea level rise	Change in fire patterns	Changes in the intensity and variability of near surface winds	
Type 2: Medium Human interventio	Interventions in Agricultural land	Meadows and Pastures				X	X							X	X		X	X		X		X	X	X	X	X	X					X			X	X														X			X		X	X	X	X		X				X		[48], [28], [19]
		Buffer Strips and Hedges				X		X	X					X	X					X			X		X	X	X																						X	X			X		X		X									[27], [48], [1]
		Crop Rotation					X	X	X		X			X			X	X					X	X	X	X	X								X	X												X	X			X		X		X		X	X						[7], [34]
		Strip cropping along contours	X			X	X	X	X		X	X		X						X		X	X		X	X																						X						X		X									[48], [20]
		Intercropping						X	X		X	X		X			X			X		X			X			X	X						X	X												X						X		X		X	X						[72], [34]
		No till agriculture						X	X		X			X			X					X	X		X			X	X						X	X													X					X		X		X	X						48], [56], [66]
		Low till agriculture						X	X		X			X			X					X	X		X			X	X						X	X	X											X						X		X		X	X						[48], [56], [66]
		Green cover/cover crop	X				X				X			X						X		X	X	X	X	X		X																										X		X		X	X						[48], [33]
		Early sowing					X				X			X								X	X			X	X																	X										X			X		X	X						[48], [39]
		Traditional terracing	X				X				X			X			X					X			X							X	X		X	X												X	X			X	X	X		X					X		X		[5], [48], [62]
Interventions in Forest (Agroforestry)		Reduced stocking density	X				X							X			X					X			X			X							X														X							X									[48]
		Mulching	X								X			X			X					X			X																													X		X								X	[48], [43], [4]
		Peak flowcontrol structures in managed forests						X	X		X			X			X			X		X	X		X	X			X																					X					X		X					X				[48]
		Targeted planting for catching precipitation	X				X			X	X	X		X	X							X	X	X	X	X		X				X	X																	X		X	X	X		X	X		X	X				X	X	[48]
		Maintenance of forest cover in headwater areas						X	X		X	X	X	X	X			X	X		X	X	X		X	X		X	X		X		X																								X	X	X			X					[30], [48], [54], [71]
		Afforestation	X			X	X	X	X	X				X	X		X	X	X	X	X	X	X		X			X		X																			X	X		X	X	X	X	X	X	X	X	X	X	X			X		[7], [35],[59], [61]
		Forest riparian buffers	X			X		X	X					X	X	X	X	X	X	X		X	X		X	X			X																			X				X					X		X	X				X		[1], [48], [49]
	River morfology intervention	Removal of dams and other longitudinal barriers				X						X		X	X	X	X			X		X					X											X										X									X	X								[48]
		Elimination of riverbank protection	X			X						X		X	X	X	X			X		X			X	X		X			X																	X								X	X	X								[48]
		Streambed re-naturalization			X	X								X	X	X				X		X		X	X																							X				X		X		X	X	X				X				[16], [48], [36]
		Natural bank stabilisation				X		X	X					X	X	X	X			X		X	X		X		X																					X				X		X			X	X				X				[48]
		Re-meandering			X	X		X	X					X	X	X	X			X		X	X		X	X		X		X			X															X				X	X	X		X	X			X		X				[44], [48], [51]
	Interventions in grasslands, pastures and meadows	Prescribed Burning	X								X																								X		X																	X		X									[18], [55]
		Remove shrubs and trees	X								X									X			X			X	X																							X							X									[19]
		Mowing and grazing	X								X									X			X			X	X																												X		X									[9], [50]
		Managing succession	X								X									X			X			X	X										X																X	X		X		X	X		X				[23], [31]
		Planting	X								X									X			X			X	X																					X				X				X	X		X	X	X			X		[54]
	Ecosystem restoration approaches	Rehabilitating natural creeks and streams				X					X			X	X	X				X		X			X	X					X		X															X				X	X	X		X	X	X		X						[72], [48], [63]
		Reconnecting rivers to floodplains (flood bypasses)				X	X			X	X	X	X	X	X		X	X							X																							X				X				X	X									[52], [30], [42]
		Re-naturalization of polder areas				X						X		X	X		X		X			X			X							X	X															X				X		X			X									[48]
		Restoration of natural infiltration to groundwater									X	X		X	X																																	X				X	X	X		X	X	X		X						[22], [40]
		Riverbed material renaturalization				X		X	X			X		X	X	X	X					X				X		X																				X						X		X	X	X				X				[48]
		Reconnection of oxbow lakes				X						X		X								X			X	X					X																	X				X	X	X		X	X	X			X	X				[48]
		Restoration and reconnection of seasonal streams				X	X			X	X	X	X	X	X		X	X					X	X	X																											X	X	X		X	X									[72], [48], [63]
		Lake restoration				X						X		X	X	X	X			X		X			X	X					X	X	X	X							X		X				X				X	X	X	X		X	X			X					[25], [48]
		Coral reef restoration		X													X	X					X	X	X																							X				X		X			X		X	X	X					[41], [2], [3], [57], [26], [29 [60]
		Dunes restoration	X										X	X	X				X							X	X			X	X	X	X															X				X		X			X		X		X				X	[45], [10], [3], [46], [15], [5 [26], [29], [60]
		Mangrove forest restoration		X													X	X					X	X	X																							X				X		X			X		X	X	X					[21], [3], [38], [26], [29], [6
		Floodplain restoration and management			X									X				X	X																													X				X		X			X		X	X	X					[26], [29],[60], [52]
		Wetland restoration		X	X	X	X	X	X	X		X		X	X		X	X		X			X	X	X								X		X													X				X					X		X	X	X					[24], [12], [11], [10], [69], [26], [29], 60]
		River bed restoration	X			X	X																																									X				X		X			X									[26],[29], [60]

Types	Sub-type	Nature Based Soluti	Type of Risk											Area			Additional Ecosystem Services (co-benefits)																	Ecosystem Disservices/iBarriers																					Impact Sc		Climate change impact on NBS to t							Refere
			Floods					Water contamination		Drought							Provision				Regulating						Supporting			Cultural																																		
			Flash fl	Coastal fl	Urban fl	Fluvial fl	Pluvial flo	Orga	Inorga	Meteorolo	Agricult	Hydrolog	Socioecon	Ru	Peri-U	Urb	Nutrit	Mater	Ener	Genetic reso	Climate regu	Erosion regu	Disease regu	Water regu	Water purifi	Pollina	Soil form	Nutrient c	Primary prod	Recreational and er	Cultural heritage, Spi	Aesth	Educational and ins	Loss of biodiversit	Nutrient r	Green gas emissions durin	Air quality problems	Damages in infras	Accidents (Break up o	Atraction of undesired pla	Creation o	Spread of pest and	Blocking of light, hea	Fruit and le	Animals excr	High economic im	Lack of conne	Poor manag	Invasive sp	Long-term b	Requires s	Complex d	Ongoing manageme	Change in flow patterns if l	Micro	Meso	change in mean tem	Changes in rain	Change in species d	Increase incidence of extream	Increase of sea le	Change in fire r	Changes in the intensity and variabili win	
Type 3: High H Interventio	Creation of n Habitats	Bioretention strips			X																																														X				X		X	X	X					[illegible]
		Urban forest parks			X			X	X						X	X	X	X		X		X	X	X						X	X	X	X				X		X	X	X	X	X	X	X	X							X		X		X	X	X					[10], [24], [48]
		Coastal lagoon									X	X	X																																	X				X		X			X		X	X	X					[illegible]
		Rain Gardens			X		X	X	X					X	X	X	X				X	X							X									X																	X		X	X	X					[10], [24], [48]
		Tree Planting			X		X	X	X							X													X								X		X	X			X	X	X										X		X	X	X					[illegible]
		Infiltration Trenches									X	X	X	X	X	X																																			X				X									[10], [24], [48]
		Retention ponds			X		X	X	X					X	X	X													X																						X				X									[illegible]
		Oyster reef		X													X	X			X	X	X	X																						X				X		X			X									[53], [68]
		Coral reef		X													X	X			X		X	X																						X				X		X			X		X	X	X					[illegible]
		Constructed Wetlands		X		X	X	X	X	X		X		X	X	X	X	X	X	X		X							X		X																				X		X	X		X	X	X	X	X					[6], [65], [67]
		Sediment capture ponds				X								X							X																														X		X		X									[illegible]
		Detention basins			X		X							X	X	X													X																						X		X		X									[10], [24], [48]
		Drainage corridors			X		X	X	X							X										X			X		X	X	X																		X				X									[illegible]
		Urban dunes		X	X										X	X				X		X	X						X																	X				X	X	X	X		X		X	X	X					[65]
	Hybrid appro	Green roofs			X		X								X	X					X			X	X	X			X									X	X								X		X			X	X		X		X	X	X					[illegible]
		Permeable surfaces			X		X	X	X						X	X																						X																	X									[10], [24], [48]
		Bioswales			X		X	X	X					X	X	X		X			X		X						X																										X		X	X	X					[illegible]
		Channels and Rills									X	X	X	X	X	X																																							X									[48]
		Filster Strips									X	X	X	X	X	X																																							X									[illegible]
		Soakaways							X					X	X	X													X																										X									[48]
		Infiltration Trenches			X						X	X	X	X	X	X																																			X				X									[illegible]
		Infiltration Basins			X		X	X	X						X	X		X											X																										X									[24], [48], [65]
		Disconnection of Rooftop Runoff					X								X	X																						X																	X									[illegible]
		Blue roofs			X		X								X	X					X			X	X	X							X				X	X			X	X				X		X		X	X	X	X		X		X	X	X					[10], [24], [48]
		Vegetated Swales			X			X	X					X	X						X					X											X											X			X		X		X		X	X	X					[illegible]
		Vegetated Filter Strips			X			X	X						X	X									X	X																						X			X		X		X		X	X	X					10], [24], [65]
		Stormwater Planters			X						X	X	X								X			X		X																											X		X		X	X	X					[illegible]
		Sand Filter			X			X	X																															X		X													X									[65]
		In Situ Water Harvesting (conservation)			X		X			X	X			X	X	X	X	X					X																																X									[illegible]
		Ex Situ Water Harvesting			X		X		X								X	X											X																						X				X									24], [65]
		Establishing flood bypasses				X																																																	X									[illegible]
		Appropriate design of road stream crossings	X			X	X							X				X																																				X	X									[48]
		Coarse woody debris			X	X								X							X		X																																X									[illegible]
		Storm water tree pits			X		X														X			X	X	X				X							X		X	X			X		X								X		X		X	X	X					[10], [24], [48]

Appendices A References

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