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Nature-based solutions for hydro-meteorological hazards: Revised concepts, classification schemes and databases

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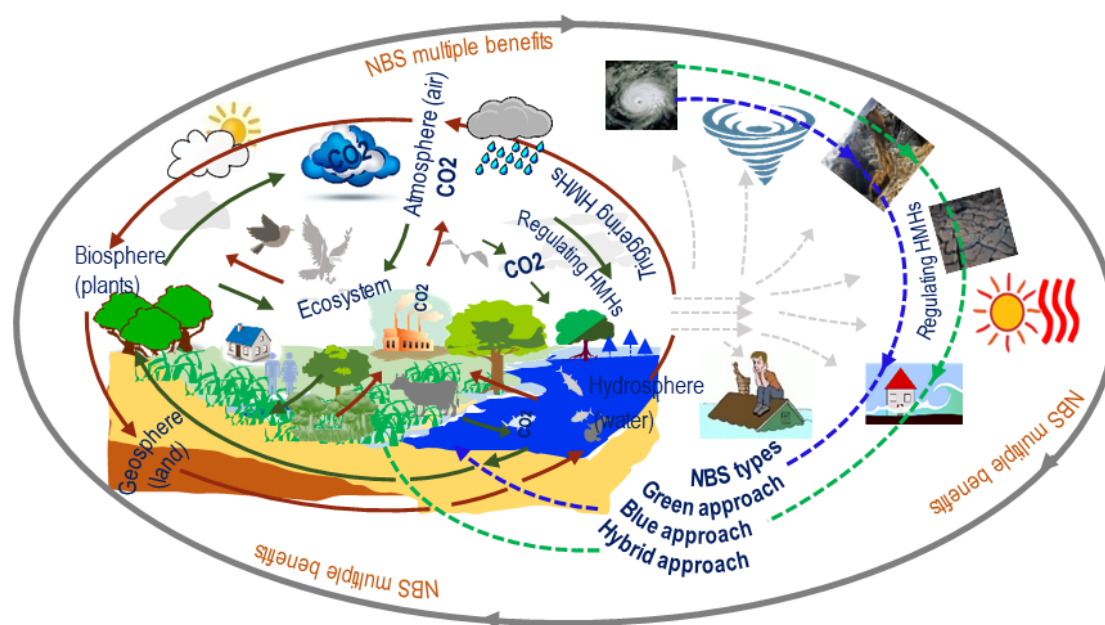
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Graphical abstract



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Abstract

Hydro-meteorological hazards (HMHs) have had a strong impact on human societies and ecosystems. Their impact is projected to be exacerbated by future climate scenarios. HMHs cataloguing is an effective tool to evaluate their associated risks and plan appropriate remediation strategies. However, factors linked to HMHs origin and triggers remain uncertain, which poses a challenge for their cataloguing. Focusing on key HMHs (floods, storm surge, landslides, droughts, and heatwaves), the goal of this review paper is to analyse and present a classification scheme, key features, and elements for designing nature-based solutions (NBS) and mitigating the adverse impacts of HMHs in Europe. For this purpose, we systematically examined the literature on NBS classification and assessed the gaps that hinder the widespread uptake of NBS. Furthermore, we critically evaluated the existing literature to give a better understanding of the HMHs drivers and their interrelationship (causing multi-hazards). Further conceptualisation of classification scheme and categories of NBS shows that relatively few studies have been carried out on utilising the broader concepts of NBS in tackling HMHs and that the classification and effectiveness of each NBS are dependent on the location, architecture, typology, green species, environmental conditions as well as interrelated non-linear systems. NBS are often more cost-effective than hard engineering approaches used within the existing systems, especially when taking into consideration their potential co-benefits. We also evaluated the sources of available data for HMHs and NBS, highlighted gaps in data, and presented strategies to overcome the current shortcomings for the development of the NBS for HMHs. We highlighted specific gaps and barriers that need to be filled since the uptake and upscaling studies of NBS in HMHs reduction is rare. The fundamental concepts and the key technical features of past studies reviewed here could help practitioners to design and implement NBS in a real-world situation.

Keywords: Climate change; Green, blue and hybrid infrastructure; Cost effectiveness; Floods; Droughts; Heatwaves

Research highlights

- Knowledge gaps and lack of evidence are the main obstacles limiting the uptake of NBS.
- Drought is a complex phenomenon and further causes heatwaves and landslides.
- Drought projections under future scenarios are inconsistent in some parts of Europe.
- Flooding appears to be the HMH occurred most frequently across Europe and worldwide.
- Due to triggering factors, the occurrence and magnitude of landslides are uncertain.

1. Introduction

Natural hazards have high impacts on human life, infrastructure and habitats (Paul et al., 2018). The last thirty years have shown a globally increasing trend in the number of events and consequential destruction from natural hazards. For example, there were 18,169 natural hazard events in the world during the period 1980-2018 (Supplementary Information, SI, Table S1), resulting in USD 4.8 trillion of damage. Of which, 91.3% were HMHs distributed among meteorological (39.2%), hydrological (40.5%) and climatological (11.6%) events (Munich Re-NatCatSERVICE, 2019). In the same period (1980-2018), Europe experienced 2,944 natural hazard events (SI Table S1) causing about USD 631 billion of losses; of which 2,796 events were HMHs with damage costs of about USD 537 billion (Munich Re-NatCatSERVICE, 2019). In terms of geographical distribution, the majority of natural hazard events (7,041 out of 18,169) occurred in Asia, followed by North America (3,888) and Europe (2,944), as summarised in SI Table S1.

HMHs are naturally occurring global meteorological/climatological/hydrological phenomena, which can induce environmental damages such as loss of habitats and

infrastructure, and other properties. McBean (2013) stated that HMHs are features of the earth system, which include the hydrological cycle, and the weather and climate system components. They are often associated with, or reliant on, each other, triggering another hazard in a cascading manner, which results in significant damage to societies and properties. Tropical cyclone, extratropical storm, convective storm, local storms, heavy precipitation, storm surges, floods, landslides, heatwaves, coldwaves, droughts and forest fire are examples of HMHs, which account for the dominant fraction of natural hazards and exist in all parts of the world. Figure 1 describes the HMRs that arise from an HMH reliant on the commencement probability of a hydro-meteorological extreme event, its propagation probability to reach an asset or peoples at risk, ‘value and vulnerability’.

A ‘*natural hazard*’ is defined as a natural procedure, or an incident that could induce destruction, injury to humans and damage their assets, economic losses or ecological degradation (Moos et al, 2017). They can normally be characterised by their magnitudes such as volume and area, or ‘intensity’ (e.g., the destructive power) and ‘probability’ of occurrence (Paton and Johnston, 2006; UNISDR, 2009). ‘A *disaster* is a natural hazard event’, which causes serious problems to society, damage assets and environmental losses (UNISDR, 2009). The risk resulting from potential HMH processes refers to the estimated negative consequences such as to the number of loss of life, number of people harmed, loss to property (houses and other infrastructures) and natural environments, the disruption of societal and economic activities (Moos et al., 2017). Within the area of disaster mitigation and climate resilience, the risk is most commonly defined ‘as the product of three factors’ (Eq. 1).

$$\text{HMR} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability} \quad (1)$$

Where ‘hazard’ is defined as the occurrence probability of an HMH event that could potentially cause loss of life and economic damages, the ‘exposure’ is characterised by an aggregation of the likelihood that people and their assets are present ‘at the time of the event’; and the ‘vulnerability’ is defined as the extent of an individual, social, or ecological degradation arising from an HMH (UNISDR, 2009; IPCC, 2018).

Considering the definition of risk (Eq.1), the word hazard depends on the commencement probability (P_{com}) of the HMH event along with its magnitude and “propagation probability” (P_{prop}) arriving an element (e) such as people, and assets at HMR with an intensity (I) (Moos et al., 2017). The exposure is characterised by the value E of certain people or assets at HMR_e and “its probability of presence (P_{pre})” at the time of occurrence of negative consequences. Corominas et al. (2014) reported that the vulnerability $V(I)$ relies on the I of an HMH incident j with preliminary “magnitude M_j ”. Finally, one can express the HMR of peoples or assets to all potential HMH events (Figure 1) by the sum of all estimated negative consequences (Eq.2).

$$\text{HMR}_e = \sum_{j=1}^{\text{HMH}} P_{com,j} \times P_{pro,j,e} \times V(I_j, e) \times P_{pre,e} \times E \quad (2)$$

The genesis of HMHs is a result of interaction and feedback between the four features of the earth system such as the atmosphere (air), hydrosphere (water), biosphere (plants) and geosphere (land), and leading to large anomalies in climatological mean, e.g., extreme precipitation that deviates from the mean value can trigger floods, while extended deficit in precipitation can trigger drought. In such situations, the commencement probability and intensity are crucial criteria for categorizing HMHs. HMH interactions among each other can cause secondary hazard and leading to multiple HMH impacts (Figure 3). For instance, a storm surge can induce flooding, mudslides or landslides.

Recent studies indicate that global warming has increased the intensity of HMRs in terms of magnitude, duration and frequency over the last century at the global scale (Quevauviller and Gemmer 2015; Guerreiro et al. 2018). The detected and projected changes can in turn have direct implications for HMRs. Thus, HMRs, are likely to continue increasing in the future if proper adaptation strategies are not applied to mitigate the latter. Research highlights that most of European cities are predicted to encounter major problems to manage the resulting impacts of extreme weather events under future climate scenarios (Kreibich et al., 2014). For instance, Forzieri et al. (2016) predicted an increase in HMRs – floods, droughts, wildfires, windstorms, heatwaves and cold waves, affecting many European regions.

Guerreiro et al. (2018) studied and projected future changes in heatwaves, droughts, and flood impacts for 571 European cities and found an increasing trend of days with heatwave and the extreme heatwave, i.e., based on the temperature data for all cities using RCP8.5 emissions scenarios, with the cities in southern Europe suffering intensified drought conditions and cities in the northern Europe suffering intensified river flooding. Sippel et al. (2014) also assessed how the variability of HMRs in southeast Europe changes in changing climate conditions. They used a probabilistic event attribution approach, which allows them to assess the potential changes in the occurrence probabilities of hydro-meteorological extreme events. Using this approach, they calculated the hazard probabilities of hydro-meteorological extreme events in South-East Europe, an area that has currently faced extreme summer dryness along with multiple heatwaves and found that HMR has altered in South-East Europe (e.g., summer heatwaves have shown a clear increase in the frequency). In general, to do HMRs calculation and establish risk index by disaster mitigation experts, policymakers (i.e., European Commission, UN), territory planners, civil protection officers, nature conservationists, insurance and financial sectors, are relying on the global or national databases. Furthermore, they also use disaster databases to analyse trends at regional or global scale to guide the design of alleviation measures. These databases have amassed data on the full range of natural hazards. However, for these databases to be useful, they need to be consistent and comparable throughout the entire collection period (Wirtz et al., 2012).

Almost all of the aforementioned studies revealed that European cities are expected to continue experiencing increased magnitude and frequency of HMRs as a result of the negative impact of climate change. Traditionally, responses to HMRs in western cities have relied on hard engineering structural measures (Jones et al., 2012) such as dykes, embankments, dams, levees, storm barriers, and seawalls amongst others. These hard engineering measures, although important for reducing the impact of HMRs, have the growing limitations as follows: (1) Low adaptation capacity; they were designed on the basis of historical records, may be inadequate to fulfil the increasing impacts of global warming (i.e., climate change) (Milly et al., 2008). (2) Single-objective oriented designs with limited co-benefits (Alves et al., 2018). (3) Severe consequences of their failure, which can potentially induce catastrophic impacts (e.g., dam or floodwall collapse). (4) Long term influences ecosystems, for instance, environmental deterioration, i.e., loss of beach and dune areas (Van Slobbe et al., 2013). (5) Elevated prices of structure, maintenance and renovation. Alternative approaches in the form of nature-based solutions (NBS; Section 4) can overcome the above limitations to achieve the transition towards achieving sustainable environmental developments (Kabisch et al., 2016). It has a potential to build resilience and implemented along with the new adaptation measures or used to fit existing systems (Davis and Naumann, 2017). The concept of NBS were introduced toward the end 2000s by the World Bank to point out the use of biodiversity for managing climate change (Pauleit et al., 2017). Many literatures have used an uncommon definition of NBS depending on their context. Here, we refer to the application of nature to manage societal

disruptions (e.g., global warming, urbanisation, water availability or HMRs management), preserve and utilise biodiversity, modify ecosystems in a maintainable way, while simultaneously offers multiple benefits including environmental, social, wellbeing benefits and help enhance resilience (Balian et al., 2014; Cohen-Shacham et al. 2016; European Commission, 2019).

Several review articles have already addressed the role of NBS to tackle global problems, i.e., global warming, water availability or HMRs management (Table 1). A majority of these articles focused on the reduction of one or two HMRs through purely green infrastructures (e.g., Bowler et al, 2010; Fletcher et al, 2015; Norton et al, 2015; Alves et al., 2016; Xing et al., 2017), see Table 1. A few other authors discussed the use of hybrid or mixed approaches of NBS for HMRs reduction (Raymond et al, 2017; Keesstra et al., 2018; Kabisch et al., 2016), Table 1. However, none of them has comprehensively addressed the following topics that are the focus of this review article: (1) compilation of HMH types, driving mechanism and interrelationships; (2) consolidation of detected and future changes in more than three HMHs; (3) classification of NBS; (4) data sources for HMHs and NBS. While NBS are gaining increasing attention for HMRs reduction, the lack of research that focus on the assessment of gaps and barriers is hindering their uptake. For example, comparisons of the performance and cost-effectiveness against hard structures are still not well covered. The concept of NBS has usually been discussed from the point view of application of ecosystems components such as green, blue and mixed approaches to manage HMRs. However, there has been less attention on NBS bringing complex system processes of nature together, which is another focus area of our article.

The overarching goal of this review article is to critically harmonise the published scientific literature on HMHs/HMRs, NBS and databases (i.e., EM-DAT, NatCatSERVICE and others). In doing so, we (i) point out the triggering factors, their cascading effect (how one hazard causes another in a simultaneously manner) and systematically summarise the past, current and future impacts of HMHs; (ii) establish a classification scheme for NBS; (iii) compare effectiveness and cost-effectiveness of NBS against hard engineering; and (iv) critically evaluate the sources of available data for both HMHs and NBS, and highlight challenges, research gaps and future directions to foster the uptake of NBS.

2. Methods, Scope and Outline

We carried out a systematic literature search (SLS) to screen out the most suitable scientific papers related to HMHs, HMRs, NBS, ecosystem-based adaptation, ecosystem services and databases. The scientific databases such as Web of Science, Scopus, Science Direct, PubMed and Google Scholar were searched in different keyword combinations: floods, drought, heatwaves, storm surge, extreme sea levels, coastal hazard, landslides, natural hazards, climate change, multi-hazard risk assessment, quantitative risk assessment/analysis, green, blue and hybrid infrastructures, cost-effectiveness, and well-being. We repeated the search procedure in Google many times using the relevant keyword. In all scientific databases, the search term combinations were modified depending on the success rate and correctness of the outcome. This search resulted in over 1500 papers. After reading their abstracts and conclusions, just over one-tenth (~160) of them were deemed to be relevant to discuss in this review. The discussed articles also consisted of those including contents related to one of the above concepts and additional articles that had underpinned our previous research. As results of literatures in HMHs/HMRs assessment; and quantification are vast and growing extensively we only considered articles written in the English and published from 2000 onwards in peer-reviewed journals or in the form of credible reports.

The scope of this paper is limited to the following HMHs – flood, storm surges, landslides, heatwaves and droughts. These hazards were selected for the following reasons. Firstly, these HMHs occur with regularity and/or intensity, causing significant socio-economic damage (Figure 2c, d, f and g). Finally, all of these HMHs are projected to increase in severity, duration and/or extent under future climate change in Europe. We cover drought because of its complexity and potential to trigger heatwaves and landslides. In the two global databases (EM-DAT and Munich Re-NatCatSERVICE), which are widely exploited by researchers, policymakers, disaster mitigation experts and insurance companies, the five HMHs reviewed in this paper were classified under meteorological, hydrological and climatological disaster families. As a result, we systematically utilise them throughout this paper. We do not consider in more detail the natural hazards classified under geophysical families such as earthquakes, mass movement dry (deep-seated landslides) and volcanic eruption since their frequencies and magnitudes are weakly related to extreme weather or climate events (IPCC, 2018). Overall, the HMHs (SI Table S2, S3) covered here account for about 80.6% loss of life (Figure 2f) and 75.2% economic losses (Figure 2g) in Europe; while about 43.5% and 74.5% are loss of life and economic damages across world (Figure 2c, d).

We start by defining the types and driving mechanisms of HMHs (Section 3), followed by an overview and analysis of several approaches commonly used to classify different NBS (Section 4). This section also describes economic costs and benefits to be considered when comparing NBS to traditional hard engineering solutions. A review of existing sources such as HMHs/NBS databases and platforms is given in Section 5. Section 6 presents the gaps and barriers of NBS and natural hazard data sources. The article concludes with a summary and conclusions, highlighting the research gaps (Section 7).

3. Types, driving mechanisms and trends for HMHs

Hydro-meteorological extremes are triggered by anomalies in the atmosphere and the hydrological cycle. For instance, different flood categories (e.g., snowmelt and rainfall driven floods) are merged in the single annual maxima time-series. Classification of these events into HMH types and estimation of their respective frequency is so important for best interpretation of their behaviour and prediction of risks. However, frequency analysis of HMHs only provides the information on the aggregate consequences of all the HMH generating processes and their interplay in a broader way; and it does not give any detailed information about the physical causes of the HMHs (Merz and Blöschl, 2008). Therefore, using probability distribution functions (PDFs) is important for the occurrence calculations of hydro-meteorological extreme events, only if we use longer time-series and not try to extrapolate their return periods beyond the length of the time-series (Merz and Blöschl, 2003). Hence, fitting hydro-meteorological extreme events and estimating their frequency of occurrence via PDFs has been commonly used (Merz and Blöschl, 2008) on the basis of extreme value theory, EVT (Coles, 2001). In EVT, there are two approaches used to extract extreme events from their entire time-series; namely, seasonal/annual maximum method and threshold approach, known as Peaks-Over-a threshold (POT). Statistical techniques (i.e., univariate and multivariate (copulas) PDFs) are considered to fit the series of randomly distributed hydro-meteorological variables and estimate their frequency of occurrence or extrapolate the magnitude associated with any exceedance probabilities of interest. However, the frequency of presence and magnitude of weather- and climate-related events (e.g., heatwaves, droughts and others) are expected to increase because of the rising impact of climate change, which lead to intensifying their triggering factors, i.e. global water cycle (Vormoor et al., 2016). Therefore, it is crucial to figure out the trends/changes in HMHs in past and future climate scenarios. In particular, global warming can cause an upward or downward trend in the amount and frequency of hydro-meteorological

extreme events as consequences of variations within the natural processes (i.e., atmosphere, hydrosphere, biosphere and geosphere) that generate HMHs.

Table 2 shows an overview of detected and climate model projected changes in HMRs over Europe. It summarises findings and key results from previous relevant studies. In many instances, HMRs are anticipated to increase in severity, duration and/or extent in Europe under current and predicted future climate scenarios (Table 2). For instance, heatwaves are expected to become more severe and to last longer, and heavy precipitation will increase in both frequency and intensity (Russo et al., 2015). Heavy precipitation events, which are the main drivers for floods and landslides, are predicted to become more frequent in northern and north-eastern Europe, with subsequent direct implications on the flooding and landslide risks (Figure 3). However, future projected changes in HMHs are not distributed equally across Europe. For instance, the projected changes in droughts show strong regional differences, with increasing frequency in South Europe and decreasing in the North (Van der Linden and Mitchell, 2009b; Touma et al., 2015).

In general, the HMHs are features of the earth system and associated with forcing mechanisms of atmospheric, geosphere, biosphere and oceanographic components and their interaction with each other. Then, HMHs are triggered by anomalies in meteorological and oceanographic conditions and also frequently linked to, or dependent on, each other (Figure 3). For example (1) Rain deficiency can cause meteorological drought. (2) Meteorological drought further propagates along with evapotranspiration that can cause soil moisture drought. (3) Drought in soil moisture can then deepen into hydrological drought. (4) High soil moisture is subjected to heavy or persistent precipitation and may lead to flooding. (5) Heavy or persistent rainfall induced flooding, which is a major driver for landslides, either through facilitating soil movement or by surface water run-off initiating soil erosion. (6) Heatwaves are further amplified by low levels of soil moisture that restrict cooling from evapotranspiration. Trends in HMHs can be assessed either by analysing a number of extreme events or by analysing economic losses. For instance, Figure 2 provides the number of events, loss of life, and economic damages as a consequences of different natural hazards types occurring across Europe and worldwide; while the summaries in Table 2 reveal trends in HMHs for historical and future climate scenarios. HMHs are normally categorised based on their triggering mechanisms (Figure 3) and statistical behaviour of extreme events, i.e., duration and magnitude of events or consequences, the potential for occurrence, the speed of onset probability and predictability of an extreme event (Glade and Alexander, 2013). Return period and regularity/cyclicality are also the two further elements in the classification of HMHs. The extent of regularity depends on the classification and genesis of the events, i.e., hydro-meteorological events tend to be the most recurrent because of seasonality (Glade and Alexander, 2013). For example, monsoon triggered rains in South Asia causes summer flooding; the El Niño Southern Oscillation (ENSO) in the Pacific region triggers flooding and storms in a 4-year cycle; and large magnitude snowfalls in European mountain frequently linked with temperature fluctuations cause extreme snow avalanches in winter and spring (Glade and Alexander, 2013). Hence, a diverse range of classification methods have been suggested in the numerous studies and the most relevant ones are reviewed in detail (Sections 3.1–3.5).

3.1 Flood types, driving mechanism and trends

Floods are triggered and modulated by meteorological conditions through precipitation, temperature, evaporation, snow processes, and high soil moisture (Hall et al., 2014; Turkington et al., 2016; Hall and Blöschl, 2018), Figure 3. Floods can be categorised based on the water source and on the process causing the water level rise (Turkington et al., 2016). Merz and

Blöschl (2003) suggested categorising floods based on process indexes, for example, the duration of the floods and storm, rainfall distributions, snow covers, catchment characteristics, and time response of the catchment. Hall et al. (2014) also stated as hydrological flood processes, i.e., runoff formation and routing depend on the catchment characteristics, as well as the precipitation distribution in the catchment (Hall et al., 2014). Fischer et al. (2016) used seasonal approaches to study the origin of flood events for German river basin. They subdivided the annual flood peaks into two periods (winter, summer) to investigate different genesis of floods. They fitted many PDFs for rainfall-caused floods (summer flood peaks) and snowmelt floods (winter flood peaks) and found that summer floods are generated by rainfall while winter flood is dominated by snowmelts (Fischer et al., 2016; Hall and Blöschl, 2018). Likewise, numerous approaches for characterising the flood seasonality were studied (e.g., Debele et al, 2017; Vormoor et al., 2016 and many others). Nied et al. (2014) and Turkington et al. (2016) identified three different approaches to categorise floods, based on (i) detailed descriptions of specific events, found in scientific studies or institutional reports; (ii) the atmospheric circulation patterns associated to the flooding; (iii) the generating processes such as precipitation type or snowmelts (e.g., Porcù et al., 2003; Turkington et al., 2016; Merz and Blöschl 2003; Nied et al. 2014; Viglione et al., 2010; Gaál et al. 2012). The flood type description presented in this paper follows the latter approach and focuses on those types most frequently linked to serious threats in Europe (Figure 2h along with SI Table S4).

Riverine (or fluvial) floods: The major drivers of river floods are prolonged or extreme precipitation and snowmelt events occurring within the fluvial catchment (Hall and Blöschl, 2018). Thus, the main drivers are intense precipitation distributions in the basin for a long period, low infiltration rate produced runoff and further enhanced by saturation excess mechanism, and intensification of the floodwater because of concurrence between streams (Viglione et al., 2010; Nied et al. 2014). These phenomena, on their own or in combination, cause the river flow discharge to increase and the water level to rise, where precipitation distribution is not naturally strong. If the water level rises over the banks, the river flow inundated the adjoining areas (Hall et al., 2014). The degree of wetness of the soil in the basin is in several cases seriously vital (Figure 3) since it causes saturation flow during the event (Nied et al., 2014). In catchments where snow cover is dominant, modest rainfall depths can yield a disproportionate runoff discharge in rivers because of generated snowmelt (Vormoor et al., 2016). In such catchments, rapid increases of temperature can also trigger snowmelt and cause flooding (Vormoor et al., 2016; Hall and Blöschl, 2018). In general, floodwater from upstream would flow into a channel and reach at the downstream along different paths (i.e., in combination with tributaries), potentially generating constructive resonance of flood peaks. The process of flood evolution depends on the size of the catchment, so the process for larger catchments may progress relatively slower than for smaller catchment, while the flood peaks may last for days (Turkington et al., 2016).

Urban (or pluvial) floods occur due to heavy rainfall for which the runoff exceeds the capacity of the drainage systems. Typically, there are two types of processes that can lead to urban floods. One is associated with overland flows, which cannot enter the natural or a manufactured drainage system, and the other is associated with a rainfall event that exceeds the drainage system's capacity (e.g., Vojinovic and Abbott, 2012). As described in Vojinovic and Abbott (2012), traditional pluvial flood protection measures can be grouped into the following: (1) runoff control measures (e.g., control over housing developments, infiltration and percolation into the ground, parking places and other public surfaces); and (2) drainage control measures (building of new or extension of current drainage networks and pipes, above-ground and

below-ground storages, construction of new or enlargement of existing dykes, installation of pumping stations, etc.).

Flash floods are caused by high magnitude and short duration rainfall and fast runoff concentration, for which natural and manmade overland flow attenuation systems, such as ground infiltration and drainage schemes, loose effectiveness due to their slower functioning (Amponsah et al., 2016). High and steep topographic relief is often associated to flash floods since it favours both drivers: enhanced precipitation and rapid concentration of streamflow in the channel network (Marchi et al., 2010; Amponsah et al., 2016). Paved surfaces in built-up areas hinder ground infiltration and favour rapid surface flow, exacerbating the risk of flash flooding (Zevenbergen et al., 2010). The rapid cooling of warm air, which has a larger water vapour content capacity, due to contact with atmospheric cold fronts or due to convective updraft currents (Kendon et al., 2014), generally triggers sudden heavy precipitation. Heatwaves intensify the occurrence of convective storms, thus revealing their interconnection with flash floods (Alfieri et al., 2015). Flash floods are also associated with mass movements (landslides) such as large woody debris and debris flow, and the accumulation of water in the soils triggers the phenomenon of substantial mudflows and landslides (Klose et al., 2015), Figure 3. Regardless of the soil moisture status in the catchment, a high intensity and short duration rainfall event may also result in a flash flood due to the infiltration excess mechanism, i.e., rainfall falling at a faster rate than the soil infiltration (Vojinovic and Abbott, 2012). The amount of floodwater and the flood extent in flash floods is somewhat trivial in comparison to river floods and the majority of flash floods usually appear in small, headwater catchments, with fast response (Alfieri et al., 2014). In terms of risks, flash floods are particularly dangerous due to their sudden onset of high-speed flows, faster than for other flood types, which increases their damaging power (Amponsah et al., 2016). Furthermore, heavy rain can suddenly fill dry riverbeds, sporadically occupied (e.g., for recreation), with fast flowing water, dragging along objects in the watercourse (Kendon et al., 2014; Ban et al., 2015; Lehmann et al., 2015).

Coastal floods: high tides, combined with low atmospheric pressures and strong winds, can induce a stormwater surge along the coast, resulting in coastal flooding (Narayan et al., 2016; Reguero et al., 2018). Tsunamis are an additional driver of this flooding type. The storm surge at a river mouth can induce elevated backwater profiles, extending for kilometres upstream and causing further flooding (Ikeuchi et al., 2017). Generally, the main cause of a coastal flood is a severe storm, in many cases a hurricane, where the storm drives the seawater toward the land (Ikeuchi et al., 2017). The aggregation of these anomalies tends to produce high wave rise over the top, which can lead to infiltration and consequent saturation of the inland side with floodwater (Ikeuchi et al., 2017). Even though the impact is higher on the steep slopes, resulting in sliding and collapse, the main feature of a coastal flood is that the water height falls and rises with the tide (Bosello et al., 2011; Watkiss and Hunt, 2012). The secondary triggering factor of coast flood is earthquakes, resulting in high sea waves (e.g., in 2004 and 2011 the tsunamis occurred in the Indian Ocean and Japan) as reported in Munich Re-NatCatSERVICE (2019). In deep offshore water, tsunami waves have a small magnitude and covers a very long distance (i.e., several kilometres long and small centimetres high) (Khazai et al., 2007). When the flood wave reaches depthless water, it steadies down and wave height rises, a situation referred to as “wave shoaling”. Overall, tidal wave triggers risk of destruction by: (1) the increased power of flood wave travelling with large speed causes floodwater; and (2) this large volume of floodwater and debris passing along the coast.

Alongside flood formations, warming is projected to intensify the overall causes and consequences of the aforementioned flood types across Europe in terms of their magnitude and frequency. For instance, Alfieri et al. (2016) and Vormoor et al. (2016) projected that future flood risks in Europe are likely to increase because of ongoing population growth and global changes. The highest increases in flood risks projected over Europe at the end of the 21st century are summarised in Table 2. On the other hand, detection of significant trends in floods is often difficult because the reliable determination and analysis of non-stationary flood frequency require long-term observations (Galloway, 2011).

3.2 Storm surge driving mechanism and trends

A storm surge is unexpected high tide triggered by a storm. It is due to the simultaneous occurrence of a high gravitational tide, low atmospheric pressure and strong winds from the ocean towards the land (Losada et al. 2013), Figure 3. These three factors contribute to an increased sea surface level that can cause flooding in coastal areas. The severity of storm surges has been observed to intensify due to increase in the sea level, which is expected to rise further throughout the 21st century and beyond (Vousdoukas et al. 2016; IPCC, 2018).

Along the European coast storm surge are predicted to escalation exceeding 30% of the relative sea level rise, particularly for the high recurrence interval and using RCP8.5 emission scenario (Vousdoukas et al., 2016). Howard et al. (2014) investigated that the significant increase of 50-year flood height in Western Europe, mainly along the European mainland coast are detected as a result of increases in storm surge (see Table 2). Previous studies also revealed the increasing trend in historical and predicted storms surge levels over Europe and highlighted the need for proper coastal protection to reduce the associated risks (Debernard and Røed, 2008; Woth et al., 2006). For example, Debernard and Røed (2008) analysed likely variations in the prospective climate of storm surge anomalies for regions covering the Northern Sea using downscaled historical climate data for the period 1961-1990, and predictions for 2071- 2100. Their results indicated a significant upward trend in the 99-percentile of storm surge (4-6%) in the Northern Sea. Woth et al. (2006) performed storm surge prediction for historical (1961-1990) and prospective climate scenarios (2071-2100) for the North Sea using regional climate model forced by the 'control climate' and A2 SRES scenarios. Storm surge extremes under changing climatic conditions may intensify alongside the North Sea coast at the end of the 21th century up to 20%. Apart from this, rising sea level will also increase the possibility for saltwater intrusion into coastal aquifers and trigger soil moisture drought (Rasmussen et al., 2013), see Figure 3.

3.3 Landslide types, driving mechanism and trends

Similar to other natural hazards, landslides triggered by the combination of meteorological, geological, morphological, physical and human factors. Figure 3 indicates that hydro-meteorological extreme events, for instance, heatwaves, droughts and torrential precipitation are the main common driver of landslides in Europe (Stoffel et al., 2014; Gariano and Guzzetti., 2016). Shallow landslides are mostly caused by extreme weather or climate events (Stoffel et al., 2014), as shown in Figure 3, while deep-seated landslides are weakly related to those. IPCC (2018) assessed the likelihood of changes in the main climate drivers, which can cause landslides. This review will focus only on shallow landslides as the ones, which are more likely to be caused by hydro-meteorological extreme events (Figure 3). The landslide formation process includes slope mass movements, soil, sand and rock slips driven by the velocity of the movement. One driving mechanism of landslides is shown in Figure 3; surface water run-off caused by heavy precipitation can induce shallow types of the landslide, such as debris flows or mudslides. Heatwaves or soil moisture drought can also cause changes

in mountain environments, such as accelerated snowmelt, rainfall or low soil moisture, leading to landslides, mainly debris flows (e.g., Polemio and Lonigro, 2014; Gariano et al., 2016). Klose et al. (2015) noted that landslides triggered by extreme hydro-meteorological events in several European territories have considered as common HMHs and have induced significant destruction and financial losses. Other hydrological conditions initiating landslides include the fast fluctuations in groundwater table and flows, and natural erosion (Teramoto et al. 2005).

The significant past trends and robust signals for future projections in landslides occurrence and magnitude are not easy to detect, due to the limited availability of historical records on landslide events and the triggering weather patterns, and partly because of the complication of the local physical processes involved – climate anomalies, weather patterns that trigger landslides, and non-linear slope hydrological response (Gariano et al., 2016). Numerous past findings have identified the links among landslides and heavy precipitation: Polemio and Lonigro (2014) and Gariano et al. (2016) found that landslides are mainly caused by torrential precipitation events. Guha et al. (2015) concluded that at the beginning of the 21st century Europe's landslide vulnerable territory is expected to face an increased event of landslide frequency, intensity and fatalities. Schlögl and Matulla (2018) also indicated an overall increase in landslides caused by heavy precipitation in the near (2021-2050) and far future (2071-2100) over the central Europe region (Table 2). Overall, projected changes in heavy precipitation will intensify the occurrence of landslides in some parts of Europe with high confidence (IPCC, 2018). For instance, Stoffel et al. (2014) and others shown in Table 2 projected that the intensity of rainstorms will increase, as will the occurrence of shallow landslides in mountainous areas. Another cause of landslides is the soil surface cracking under heatwaves (Figure 3), followed by precipitation that fills up the cracks, increases interstitial water pressure, and triggers soil movement. Overall, climate projections point at increased likelihood of heatwaves, therefore favouring soil surface cracking and shallow landslides (IPCC, 2018).

3.4 Drought types, driving mechanism and trends

Droughts are naturally occurring hydro-meteorological extreme events and notably takes first priority due to their complexity (Figure 3) and defined in different ways that makes it hard to easily observe and assess its arrival and development (Trenberth et al., 2014; Van Loon, 2015). Van Loon (2015) underlined that the studies of drought mostly dedicated on the investigation of atmospheric and terrestrial components of the water cycle and the association between them, for example, atmospheric variables (precipitation, temperature, evapotranspiration, snow accumulation) and hydrological variables (soil moisture, wetlands, streamflow and groundwater), see Figure 3. Based on the driving mechanisms, droughts are grouped into four types (Mishra and Singh, 2010; Van Loon, 2015), as shown in Figure 3. Meteorological drought is a duration of days to years with a below normal precipitation, or water level and further intensified with above-normal potential evapotranspiration (PET) over a given region; *Soil moisture drought* consists of a water content deficit in the upper, unsaturated soil layer, where the vegetation roots uptake the water from. It is alternatively known by agricultural drought, since it is associated to the low water content in the soils root zone and can induce the crop failure; *Hydrologic drought* can be triggered by one or a combination of factors such as low soil moisture, low stream flows or groundwater level depletion; *Socioeconomic drought* is linked with the three aforementioned drought types, usually measured by social and economic indicators.

It can occur in absence of hydro-meteorological anomalies, being caused by unsustainable exploitation of the catchment water yield, or through a deficiency of the water supply system to satisfy the social and ecological demands (Van Loon, 2015). A persistent meteorological

drought due to rain deficiency can turn into an agricultural drought, destructing plants, crops, etc., which further propagates into a hydrological drought reducing rivers flows, water availability and groundwater table -influenced natural environments (Figure 3). A decrease in groundwater levels and streamflow causes hydrological droughts to detrimentally affect the availability and quality of freshwater, which in turn affects flora and fauna. Hydrological droughts also strongly affect river navigation, and cooling of power plants by decreasing the potential of streams/rivers to purify pollution. Table 2 shows observed changes and future trends in four types of drought in different regions of Europe. For instance, Spinoni et al. (2015) studied the largest drought events in Europe. They subdivided Europe into 13 areas and determined a list of drought occurrences for each. The variables such as time of onset, severity, length of events, mean areas under events, months with extreme low flows, areas under events at the extremely low flow month (X-3 and X-12, where X denotes a calendar year) used to determine the drought events. They calculated a hydro-meteorological variable of the merged indicators for respective area and country to define the 22 largest drought events in 1950–2012, which are shown in Figure 2i (areas under events at the extreme low flow month, in %). They found that an increasing and significant changes in historical periods for droughts occurred over Europe in 2010, 2011 and 2015, with droughts in 2011 being particularly severe and affecting many countries in Europe, especially in the pan-European, central, Eastern and Europe regions. Conversely, Gudmundsson and Seneviratne (2015) and Spinoni et al. (2015) revealed decreasing changes in drought in eastern Europe and northern Europe for the same time period. Some of the studies summarised in Table 2 analysed as drought shown regional variability across Europe. For instance, the finding by Stagge et al. (2015) revealed in some part of Europe (i.e., eastern Mediterranean, southern Italy, and Iberian Peninsula), particularly at the far future, with deference to the baseline period 1971–2000 (Table 2) the biggest increases in intensity and magnitude of droughts were projected. At the same time, Henrich and Gobiet (2012) found as drought frequency (i.e., occurrence) is projected to decrease in northern Europe.

3.5 Heatwaves driving mechanism and trends

Heatwaves are periods of abnormally high temperatures sustained from a one or two days to 7-15 days (Guerreiro et al., 2018; IPCC, 2018), Figure 3. If accompanied by elevated air humidity, heat stress is intensified, directly affecting human health (Guerreiro et al., 2018). Soil moisture droughts can amplify heatwaves by drying soil that reduces evaporative cooling (Mueller and Seneviratne, 2012), Figure 3. IPCC (2018) projected that heatwaves are expected to intensify as a result of the rapid escalation of greenhouse gases and other pollutant concentrations in the atmosphere (i.e., increases the surface temperature by blocking terrestrial radiation).

Table 2 shows the observed and predicted trends for heatwaves over Europe. The last two decades have shown highest temperature extremes across the continent (Barriopedro et al., 2011; Donat et al., 2013b; Seneviratne et al., 2014; Lehner et al., 2016). Eleven intense heatwaves were recorded between 1950 and 2016, six of them occurring after 2000 (Russo et al., 2015; Guerreiro et al., 2018; Spinoni et al., 2015). Furthermore, sustained rise in temperature extremes over the Earth was observed for the last 15 years (1997-2012), although this increase depends on the definition of heatwave (Seneviratne et al., 2014). Similarly, Seneviratne et al. (2014) showed that in all scales including regional and worldwide, days and nights with temperature above normal (heatwaves), were more frequently occurring in the last two decades. IPCC (2018) also predicts that days with extreme temperature (heatwaves) will become more severe and recurrent in the future. Lehner et al. (2016) indicated that using the RCP8.5, in the far future (2065-2100) about 90% of the summertime in some part of Europe

(e.g., northwestern, central and southern European cities) would be hotter than any summertime in the last 94 years (1920-2014). Sensitive areas such as mountain environments, and especially those in northern Europe (Donat et al., 2013a; IPCC, 2018; Jacob et al., 2014), will be the most affected by projected increases in heatwaves and changes in precipitation patterns. Jacob et al (2014) confirmed that these escalations in heatwaves are statistically significant and most robust all over Coordinated Downscaling Experiment - European Domain (EURO-CORDEX) using RCP8.5 emission scenarios.

4. Classification schemes of NBS

The NBS concept aims to offer multiple benefits for society with a notation of “nature” (Nesshöver et al., 2017). However, current studies on NBS and the lack of a methodological approach for their implementation is preventing to take advantage of their full potential for building resilience to HMRs (European Commission, 2015c). In this line, Nesshöver et al. (2017) noted that a central challenge in the concept and characterization of NBS, what is standard and what is considered as NBS. For instance, are artificially modified biota or bioengineering categorised as NBS? There is also a large number of approaches that can utilise the wider components of NBS. For example, conservation and land management (in urban and landscape), restoration of floodplains, green and blue approaches mixed with hard engineering structural (e.g., green rooftops and walls, stormwater gardens, sustainable urban drainage systems and bioswales) to decrease stormwater generated flooding in cities, restoration of lakes, wetland restoration/construction or large-scale climate adaptation and mitigation approaches (i.e., forestation and bioengineering) are planned to increase our adaptive capacity and decrease HMRs. The definition provided by the European Commission (2019) encompasses most of the aforementioned examples, except bioengineering concepts. The availability of many ways to design and utilize the benefits of NBS is not a problem, provided that every case is clear in its reason and a specific clarification of NBS (Nesshöver et al., 2017). As different HMRs need different adaptation measures (Section 4.2.1), the types of NBS adopted to tackle each HMRs needs a logical approach to distinguish the appropriate solutions while avoiding undesirable, and economically damaging, aspects of the selected approach.

Table 3 summarises past studies that have categorised NBS focusing on: (1) supporting policymaking; (2) managing problems related to climate change, food and water availability, or HMRs reduction; (3) location; and (4) functions, e.g., production of goods; habitat and human well-being. However, in some of the studies documented in Table 3, the classification schemes may be unclear and/or not explicitly considering the concepts of NBS. In this section, we thoroughly reviewed the existing classification schemes of NBS and their application to HMRs reductions. At the same time, we also conceptualised the broadest view of NBS.

4.1 Overview of previous classification schemes of NBS

Many researches have classified the typology of NBS based on their functions and services; for instance, in managing societal challenges such as HMRs, wellbeing and application for policy and decision makers (e.g., Kabisch et al., 2016; Pauleit et al., 2017; Nesshöver et al., 2017, Cohen-Shacham et al., 2016). Pauleit et al. (2017) stated that NBS are an umbrella term that incorporates a broader concept, e.g., green and blue approaches as well as many other services provided by ecosystem. In summary, NBS could be used as an envelope for other all components of NBS those are gaining more focus at the level of policymaker and research. Table 3 and SI Table S5 presents a summary of the NBS concepts, classification schemes, types of HMRs and NBS, their linkages with each other and targets of NBS. For instance, recent studies highlighted that all NBS related definitions (concepts) have a wider extent and they are analysed and utilized in a different way in practice (Pauleit et al., 2017;

Cohen-Shacham et al., 2016; Wamsler and Pauleit, 2016). Cohen-Shacham et al. (2016) described NBS as an envelope notion that address an entire domain of ecosystem-related concepts all of which tackling human and environmental problems. They placed NBS into five main categories (Table 3). All of them also have numerous correspondence, e.g., in terms of HMHs they are tackling and the categories of interference they comprise (SI Table S5). The concept of NBS has been critically harmonised on the basis of its benefactions to feasible development in European cities and categorised into six main categories using management and approaches to human needs (Nesshöver et al., 2017), Table 3.

Nesshöver et al. (2017) also evaluated how NBS can be applied in practice with existing solutions and highlighted its applications to support policymakers. These six types of NBS along with their concepts and relationships to the broader concepts of NBS are presented in Table 3. The green approach integrated outlined system of natural and modified regions along other ecosystem characteristics planned and managed to provide a lot of environmental benefits and services (European Commission, 2013). Thus, green infrastructure contains all greenery and blue spaces for marine environments, and other physical characteristics in terrestrial and marine areas (Cohen-Shacham et al., 2016). UNEP (2014) elaborated the terms “green” and “natural” infrastructures are usually used interchangeably; however, they refer to designing and protection work in various environments and at many scales. For example, natural infrastructure is a process of restoring, functioning and composition of ecosystems to provide ecosystems services, while green infrastructural enhance the aspects of ecosystems to provide these services (Cohen-Shacham et al., 2016). Moreover, a green infrastructure operates at urban and landscape scales whereas natural infrastructures are used only at a landscape scale. Xing et al. (2017) identified four meta-types of NBS metropolitan actions based on the site of the metropolitan greenery (Table 3).

We have conceptualised NBS classification schemes in Figure 4 following the literature and our elaboration, for the following reasons: (i) NBS are a complex system processes of nature, wider in its concept and range of application (European Commission, 2015), comprising many components, which may interrelate non-linearly with each other (i.e., self-regulating systems) and result in both triggering and regulating natural hazards. Therefore, they require a classification that can contain all components of ecosystems and their interaction with each other (i.e., geosphere, hydrosphere and atmosphere; Figure 4); and (ii) while the classification of NBS in previous literature is overlapping and lacking systematic categorisation, we attempted to classify NBS into three main components (Table 3, column 4: namely, green, blue and hybrid and four possible combinations of approaches (green-blue, green-grey, blue-grey and green-blue-grey) within the ecosystem domain (Figure 4).

Figure 4 shows the overall framework and aim of NBS in managing HMRs posed by HMHs such as floods, drought, storm surge, landslides and heatwaves through a wide range of green, blue and hybrid approaches. These challenges are features of earth system as a part of nature and associated with forcing mechanisms of the four main components of earth system: atmosphere, oceanographic/hydrosphere (all blue approaches), biosphere (all green approaches) and geosphere components (Figure 4). The main components are interconnected by many non-linear processes at different scales, interlaced by complex mechanisms (Figure 4). Following the definition of NBS (see section 1), which is defined as a complex system processes of nature, supported and governed by many non-linear processes of nature (European Commission, 2019). This complex system is composed of many elements, which may interact with each other and cause a feedback loop (Figure 4). For example, as described in Figure 4 natural hazards are part of nature and triggered by natural phenomena, i.e., natural processes in the atmosphere,

hydrosphere, biosphere, or geosphere. Changes in natural processes that trigger HMRs are the result of a positive feedback mechanism (dotted lines in Figure 4), while changes that lead to a compensating process and mitigate the HMRs triggering factors constitute a negative feedback mechanism (solid lines in Figure 4) (Lahellec and Dufresne, 2013). In general, positive feedback triggers natural hazard formation whereas NBS keeps the natural processes stable (Figure 4). For instance, NBS can serve as a sink for carbon sources (solid lines in Figure 4) and manage hydrological cycle, to accomplish expected results e.g., decreasing HMRs and protect surroundings that enhance societal welfare and sustainable development (European Commission, 2019). Therefore, NBS considered as an envelope that incorporates the feedback between the four components of earth system that triggers societal challenges and regulates these challenges through the process of interactions, and remotely connected complex systems (Figure 4).

4.2. Comparisons of costs, benefits and effectiveness of NBS versus traditional “hard engineering” structures

Relying on the traditional approach to managing HMRs under current and future climate scenarios might not always be cost-effective (Narayan et al., 2016, Depietri and McPhearson, 2017, Reguero et al., 2018). The implementation of NBS is appeared as an effective approach in terms of costs and potentials to manage the impact of HMRs (Temmerman et al., 2013). Nowadays numerous body of literature and practitioners perceived NBS efficiency for adaptation and mitigation of HMRs. For example, IUCN (2016) noted that NBS is an approach that delivers several multi-benefits ranging from local to global environmental protections (i.e., regulating carbon and floodplain) in cost-effective manner. Similarly, Depietri and McPhearson (2017) compared the performances of green, blue and hybrid infrastructures with grey approaches through literature review in the view of tackling problem of heavy rain and surface runoff in the city scale and concluded that, among the types of NBS at a small scale, mixed solutions (i.e., green-blue-grey) are the best methods for HMR management and response to global warming.

Moos et al. (2017) assessed the performance and efficacy of green infrastructure – forests in decreasing damages to the mountainous area due to HMRs, finding that forests are highly efficient and effective to reduce HMRs by reducing their onset probability, propagation probability, and intensity. Keesstra et al. (2018) investigated the application of hybrid/mixed approaches for soil water conservation and restoration in various environmental conditions such as in Ethiopia, Mediterranean basin; Slovenia; Iceland; southern Portugal and Sweden and concluding that NBS are an efficient long-term approach in both managing HMRs and benefit to cost ratio.

4.2.1 Effectiveness of NBS against HMRs

Here, we present recent findings on how NBS can play an important role to adapt HMRs (Figure 5) across Europe. To do this, we systematically explored more than 288 case studies that used the NBS as the main solutions in tackling HMRs over the world. A summary of NBS case studies with location, habitat, HMRs, types of NBS, NBS intervention, NBS approach and targets are listed in SI Table S5. Around 229 case studies implemented green, blue and hybrid approaches to manage HMRs outlined in Section 3 across a different part of Europe (SI Table S5). The summary of results show that flooding is mostly managed by a hybrid approach (23%), followed by the green approaches (20%); heatwave is mostly managed by green infrastructure (20%). Overall 56% of NBS in the EU aim to manage flooding risks and the remaining 44% are designed to manage the other HMRs (Figure 5a).

Table 4 shows the evidence of how effective the NBS have been in managing HMRs (i.e., how much flooding, storm surge, heatwaves, drought and landslides damages have been avoided in %) as compared to traditional grey approach. The hybrid approach (e.g., rain gardens and green roofs) were found to be a more favourable option in reducing floods while blue approach such as small pond/room for river a best option for flood management (Table 4). However, the efficiency of each NBS depends on the place, the types of HMRs and climate conditions (Keesstra et al., 2018). In fact, Figure 5a shows that green approach (20%) is the most adopted NBS, following hybrid approach (23%) for managing floods; however, in the majority of NBS projects there are no clear information compiled on how productive the NBS have been in reducing HMRs. Rowe (2011) and Stovin et al. (2012) concluded that depending on the location, climate conditions (i.e., antecedent dry weather period, rainfall distribution and pre-existing moisture) and architecture of NBS (i.e., roof structure, green and blue areas, roof slope and depth), the minimum reduction of HMRs by NBS is 5%, whereas the maximum reduction reach up to 100%, see Table 4. The effectiveness of NBS in tackling HMRs also depends on its typology. For example, there are many studies underlining the importance of hybrid, green and blue approaches for flood protection (Figure 5a). For instance, Bullock and Acreman (2003) analysed 28 case studies of NBS and found that 82% hybrid approach playing an important role in decreasing or intercepting the quick flows. A hybrid approach shown in Figure 5a was one of the best solutions to play a key role in protecting the coast zone from storm surge generated floods (9.3%), while green approaches (3.2%), particularly forests (all vegetation), have the capacity to decrease the intensity and magnitude of all types of landslides (Moos et al., 2017). Green approaches (i.e., urban green space and parks/trees) can also reduce extreme temperature/heatwaves by as much as 4°C (urban green space) and 3.5°C (parks/trees), as seen from Table 4.

In the case of the landscape where there is enough space, the green approach including all greeneries are the best approach to tackle surface runoff in the urban environment (Kabisch et al., 2016). The green approaches on the ground (i.e. constructed with the denser surface area) are found to be even better than those at heights such as green roofs in terms of effectiveness, and thus the location of NBS hinders its full potentials against HMRs (Kabisch et al., 2016). There is also evidence that supports the grey approach (e.g., concrete seawall) as an effective way in protecting coastal areas from the risks caused by coastal hazards such as storm surges and tidal waves (Khazai et al., 2007).

Narayan et al. (2016) compared the importance of seagrass/kelp beds, mangroves, coral reefs, and salt marshes with submerged breakwaters in reducing flood wave height and coastal erosion using 69 case studies (Figure 5b). The bars in Figure 5b show that green approach (i.e., coastal habitats) reduce coastal flooding between 35 -71%; however, this effectiveness varied with the habitats and the location (Narayan et al., 2016). For instance, across all habitats, salt marshes and coral reefs revealed the highest overall performance in decreasing flood waves by 70% (with a 95% confidence interval: 54-81%) and 72% (95% CI: 62-79%), see Figure 5b. They highlighted that the costs of measures based on salt marshes and mangroves could be two to five times cheaper as compared with engineering structures for flood waves ~ up to 50cm. Others have also indicated that these habitats are reduced coastal flooding and erosions significantly (Ferrario et al., 2014; Pinsky et al., 2013).

4.2.2 Cost-effectiveness of NBS

Constanza et al. (2008) assessed the cost-effectiveness of coastal wetlands across the USA and found that about USD 23.2 billion cost-benefit in coastal flood management are received yearly as compared to purely grey approach. Roebeling et al. (2013) also reported for

Europe the land degradation is as a result of coastal flooding about 4500km² for the historical period (1975 to 2006) and between 3700km² and 5800km² for future years (2006 to 2050). The estimated cost-benefits of green approach in reducing the impact of coastal erosion for the historical period range from 24.77 billion to USD 23.99 billion (2006) and about USD 21.99 billion (2050) for future time periods (Roebeling et al., 2013).

Van Slobbe et al. (2013) demonstrated that the cost-effectiveness of NBS (i.e., small-scale sand nourishment) with grey approach (i.e., big-scale grey infrastructure – dams) in the Netherlands and found that grey approach generally involves low repair expenditures, however, expensive to build and environmental deterioration, i.e., damage of recreation places. Yearly the grey approach provides significant protection to Dutch coastal areas against coastal flooding, which accounts about USD 66.6 million, whereas benefits are limited to the protection of coastal zone and recreation areas. Whereas, one sand nourishment costs USD 77.7 million over twenty years; however, it could be inexpensive after promoted to become a formal implementation, and simultaneously also provides several advantages including protection of coastal areas from flooding, recreation and freshwater abstraction (Van Slobbe et al., 2013).

Reguero et al. (2018) compared the cost-effectiveness of different adaptation measures to compact coastal flood risks. Figure 5c illustrates a comparison of costs (benefit to cost ratio – green bars) vs benefits (total benefit – green bars) of NBS with grey infrastructure and non-structural solutions (i.e., spatial planning) for current and future risks. The results depicted in Figure 5c shows that of the used NBS measures oyster reef and wetlands restorations provide the maximum cost-benefits (benefit-cost ratio) and even jointly offers the maximum total loss reduction (total benefit) compared with grey and policy measures. However, structural measures (i.e., levees and dykes) might provide the highest decrease in loss, but they are usually expensive to build over bigger spaces (see green bars in Figure 5c). At the same time, sandbags (Figure 5c) are less expensive but they provide less effective HMRs management (Reguero et al. 2018). Overall comparison of NBS with grey and policy measures revealed about 85% of the profitable HMRs management can be achieved using NBS, which is worth USD 49 billion. As further knowledge becomes available, the profitability of NBS could increase further by 2050 compared with grey and policy adaptation measures (Reguero et al., 2018).

5. Natural hazard and NBS databases and platforms

For any hazard assessment and reduction, five types of information are crucial; namely, hydro-meteorological inventory data, geo information, triggering factors (Section 3), vulnerable objects to HMRs and NBS inventory data. Geo-information of natural hazard databases and NBS platforms are collected and utilised for many applications by several research organization (e.g., hydrology, meteorology, geology), disaster mitigation experts, researchers, policymakers (i.e., European Commission, UN), spatial planners, civil protection officers, agriculturalists, nature conservationists, insurance and financial sectors, and many others (Wirtz et al., 2012). Moreover, these databases and platforms can be used for global and regional trend analysis of different natural hazards to identify the risks, while the resulting analyses may lead to the design of risk prevention measures. A substantial interest is shown recently by many research institutions, policy and decision-makers in advancing the quality and availability of natural hazards database and NBS platforms to end-users. For example, *INSPIRE Geoportal* (2019), *EM-DAT* (2019), *Munich Re-NatCatSERVICE* (2019), *Swiss Re* (2019), *ThinkNature* (2019), *Oppla* (2019), *Natural Hazards – NBS* (2019) and many others are currently in operation for the purpose of sharing knowledge, experiences, case studies, and datasets. Some other databases and platforms (i.e., *PREVIEW Global Risk Data Platform*) were

designed to serve many end-users to analyse hazard information and give access to natural hazards databases at regional and global scales (Giuliani and Peduzzi, 2011).

Nowadays, there are many databases and platforms of natural hazards and NBS, which allow the user to easily share, use and combine at national, regional and global level. Although numerous gaps could hinder their application for research. Some of these major gaps relates to (1) availability of high spatial and temporal resolution datasets; (2) lack of homogeneity in datasets; and (3) unavailability of data in easy-to-use digital format; and (4) limited accessibility of datasets owing to factors such as data policy and service responsiveness to make all these sources interoperable. In addition to the above-named databases and platforms, a number of others have systematically collected data focusing on specific hazards but failing to deal with all natural hazards ((EEA (2019), *Joint Research Centre Data Catalogue* (2019), *Copernicus* (2019), *EU Biodiversity strategy* (2019) and *Urban Nature Atlas* (2019)). Here, we provide an overview of existing HMs and NBS databases and platforms where five and more hazards and/or two or more categories of NBS were included, as depicted in Figure 6. The classification hierarchy of HMs/events in Section 3, covering 87% of natural hazards continuously and comprehensively collected and stored under the following hazard family: (1) meteorological events; (2) hydrological events; (3) climatological events; (4) geophysical events extra-terrestrial events; and (6) Biological events, as illustrated in Figure 6 (Wirtz et al., 2012).

5.1 Hydro-meteorological hazard databases

The four most important global natural hazard databases are *EM-DAT*, *Munich Re-NatCatSERVICE*, Sigma and the recently developed *INSPIRE Geportal*, Figure 6. *EM-DAT* international disaster database encompasses global dataset on the incident and damage of about 20,000 natural hazards under two generic categories – natural and man-made hazards – since 1900 and still ongoing (Wirtz et al., 2012). The main target of *EM-DAT* is to serve as a backbone for exposure and susceptibility evaluations, damage analysis by insurance company, policy and decision-makers to give reasonable real-time life and property protections and insurance. The natural disaster category in *EM-DAT* further divides into six natural hazard families. The sources for HMs are then located under the first three natural hazard families (see Figure 6 under hazard family). The databases are free to all users, but registration is required. In *EM-DAT* database, each disaster event is stored according to their location, date, and the human and economic impacts (EM-DAT, 2019).

Munich Re-NatCatSERVICE database begun in 1974 and only covers catastrophes caused as results of natural hazards under four categories, see Figure 6 under hazard family (Wirtz et al., 2012). In both *EM-DAT* and *Munich Re-NatCatSERVICE* databases, every data entry contains a methodical explanation of the events. *EM-DAT* data catalog follows four basic criteria: (1) more than ten people observed to be dead; (2) 100 or more people observed to be injured; (3) declaration announcement of a state of emergency; and (4) seek for global aid. Therefore, for a natural hazard to be entered in the data catalog at the minimum one of the above listed principles must be fulfilled. In *Munich Re-NatCatSERVICE*, entry is possible if one person and assets were injured/dead. In *Munich Re-NatCatSERVICE*, based on the important information gathered, i.e., town and regulatory divisions injured by any natural hazards, all locations are geocoded, but the database is not publicly accessible. The two global databases are widely comparable, and the only distinction is associated with hydrological and meteorological hazard families. For instance, the *Munich Re-NatCatSERVICE* data catalog recorded a greater number of storm-related events because of the economic damages. However, it does not fulfil the data recorded criteria of *EM-DAT* database. In both databases, HMs are provided in a tabular

format as comma-separated values (CSV) files. *Sigma* database of SwissRe established in 1970 and on average 350 natural hazards are recorded every year. The data catalog contains both technological and natural hazards. However, the SwissRe database is not publicly accessible. In general, majority of the details and specifications presented for *EM-DAT* and *Munich Re-NatCatSERVICE* apply to the *Sigma* database. Therefore, we do not enter into details of *Sigma* database in this paper.

INSPIRE Geoportal was established in 2007 by EU directive and is still under development (2007-2020), with an aim of improving the accessibility and interoperability of environmental geospatial information (EC, 2007a). This includes spatial or geographical information for broadly aligned aims that help feasible growth. The aim of *INSPIRE Geoportal* is to build a “European spatial data infrastructure (SDI)” that combines geospatial data and information from many sources in a homogeneous way in order to make them freely available for different users (EC, 2007a). Distribution of infrastructure in *INSPIRE Geoportal* is currently based on SDI and functioned by “the Member States”. Data should be collected; quality assured and maintained, Figure 6. In the *INSPIRE Directive*, there are thirty-four spatial data themes identified to support environmental applications (Figure 6). The themes subdivided into three annexes of the directive (Figure 6). The HMHs are categorised under the “theme *Natural Risk Zones* (Annex III theme 12)”. Encoding of the *INSPIRE Geoportal* elements is operated using extensible mark-up language schemes obtained from the Unified Modelling Language (UML) models of ISO 19115 and ISO 19119 following the coding principles specified in ISO/TS 19115 (EC, 2013). In general, each of the reviewed natural hazards databases has its own specificity. The database providers should attempt to use common standards and definitions, so the same disaster is classified consistently across different databases. In particular, this can happen for associated disasters or secondary disasters. For instance, a flood resulting from a windstorm recorded as such on one database and as a hurricane on a different one.

5.2 Existing NBS platforms

To our knowledge, there are more than 11 platforms and websites of NBS under operation across Europe and worldwide. All of them are introduced only recently, with some still under development. The overall aim of these platforms is to adopt NBS to reduce risks resulting from flooding and erosion in the river and coastal areas, improving forest and wetland ecosystem, HMHs outlined in section 3, and reducing impacts of climate extremes in urban areas. Among the 11 platforms and websites of NBS, *Oppla* (2019), *PANORAMA* (2019), *ThinkNature* (2019), *Urban Nature Atlas* (2019) and *Natural Hazards – NBS* (2019) uses a broader concept of NBS. However, except the *Natural Hazards – NBS platform*, they are not comprehensive platforms in terms of databases and the types of HMHs they are aiming to tackle. The *Natural Hazards – NBS platform* was developed by the World Bank to provide guidance on the strategy and development of NBS, and to advance NBS in policymaking and disaster risk reduction. This platform encompasses both HMHs and their NBS. For instance, in the platform one can find blue, green and hybrid approaches to tackle HMHs such as flood, drought, erosion and landslide. The database is publicly accessible in .xls format (NBS, 2019).

6. Gaps and barriers of NBS and natural hazard databases

This paper gives clear summary of the status and identified gaps linked with NBS and HMHs databases. For instance, the gaps (i.e., the lack of systematic mainstreaming of NBS; fragmented climate policy mainstreaming) highlighted by Wamsler et al. (2016), in practice which is still an open problem in the application of NBS. They stated in practice, it is difficult to integrate NBS with climate adaptation and mitigation mainstreaming. Therefore, in reality, many practitioners still do not consider the applicability of NBS as a topic. Integrating science,

policy and practice are the main tools for sustainable environmental development. However, the fragmented approaches can slow down the progress by hindering the effectiveness of NBS. There are several NBS platforms/projects in many European countries and worldwide focusing to address these gaps by developing information platforms, websites, sharing bits of knowledge, experiences, case studies, and data sets. For example, platforms described in Section 5.2 and *OPERANDUM Geo-Information Knowledge Platform (GeoIKP)*, which is under development (2018-2022) are a few examples.

Among the multiple benefits of NBS, the health benefit is well recognized; however, lack of knowledge in linking nature with health benefits as well as the complexity in changing societal and their surroundings elements hampers the implementation of targeted policy involvement. To overcome those limitations in the range of micro and macro scale territories and well-being, Shanahan et al. (2015) proposed to carry out in-depth multidisciplinary research that could promote the wider acceptance of NBS. Enzi et al. (2017) identified the following barriers for the implementation of NBS: (1) technical knowledge gaps; (2) lack of internal collaboration among different sectors; and (3) lack of good information streaming at national level.

The positive effects of NBS for HMRs management are documented in some studies (e.g. Kabisch et al., 2016; Narayan et al., 2016). However, there are still gaps in knowledge, especially corresponding to long-term advantages and co-benefits as well as the effectiveness and performance of NBS to accelerate the adaptability of vulnerable regions against HMHRs. Similarly, Kabisch et al. (2016) also identified knowledge gaps to understand the efficiency of NBS in urban areas and main drawbacks for promoting NBS toward practical application. Kabisch et al. (2016) identified four main knowledge gaps associated with the effectiveness of NBS; (1) lack of monitoring and sharing information about the NBS projects already implemented to tackle social challenges; (2) relationship between NBS and society (drawbacks linking to the recognition of a best method of transferring successful and unsuccessful outcomes of NBS; (3) design of NBS (i.e., the optimal design of different NBS can be unknown); and (4) implementation aspects such as lack of clarity in which types of NBS optimal, for example, to meet sustainable development goals. Thus, they summarised that performance indicators are desirable to handle problems such as conflicts of interest among landlord (i.e. competing for the land for revitalisation) and urban planner (i.e. targeted to city revitalisation), which arises during the revitalisations of cities with green and blue spaces. Kabisch et al. (2016) also highlighted potential barriers that impede the effectiveness of NBS such as lack of solid evidence and research in the area of short and long-terms expected return of a NBS execution, sectoral silos, lack of on-site monitoring, social and political barrier, and the paradigm of growth that needs more research.

Narayan et al. (2016) argued that the application of NBS such as coastline ecosystem for coastline defence against HMHRs yet faces notable obstacle. Firstly, there are still doubts related to the efficiency of NBS in various climatic situations. Secondly, limited research exist on the cost-benefit analysis of studies that have used NBS against HMRs. Lastly, limited studies have integrated grey approach and ecosystem services to give area-based contrast of the efficacy and cost-benefit of NBS against hard structures. Our extensive review of associated studies substantiates the fact that a comprehensive data and metadata category for NBS is currently incomplete. In the four most important global disaster databases and INSPIRE Geportal, comprehensive databases are available; however, their limitations such as the inhomogeneity affecting disaster classification thresholds prevent their wider practical uptake (Section 5.1).

7. Summary, conclusions and future outlook

This paper summaries the overall influence and direct outcome of HMRs in Europe and discusses how NBS can enhance our resilience, decrease the adverse consequences of HMHs and build sustainable environment. We reviewed various HMHs, their types, driving mechanisms, trends and classification schemes of NBS, sources of HMHs, NBS, and gaps that limit the uptake of NBS. Using five HMHs focused on Europe, we identified those drivers intensified by climate change and the types of NBS that protect human life, properties and ecosystems against the HMHs. In general, green and hybrid approaches are playing a significant role in buffering communities from HMHs in different parts of Europe. This paper also conceptualised the main elements of NBS in a broader scope while the benefits of NBS is going beyond the concept of global warming management. In addition, we reviewed and documented the comparisons of NBS versus grey approaches according to the performances and cos-benefits against HMHs.

The following conclusions are drawn:

- An HMH is naturally occurring event, triggered by a physical process in the earth system that has substantial negative influences on societies and ecosystems. Hydro-meteorological extreme events are generated from the interaction and feedback between the four components of earth's system. HMHs could be classified based on origin, triggering factor, seasonality and return periods, and the type of process, onset probability, predictability, and extent of their impact. In general, HMHs are increasing over time, resulting in its potential increase of consequences on societies and ecosystems. The consequences in the last three decades (1980-2018) are evident from the fact that about 2944 natural hazard events occurred in Europe, of which 2796 events were HMHs that caused substantial damages with damage costs of about USD 537 billion (Munich Re-NatCatSERVICE, 2019).
- HMHs cataloguing are an effective tool to evaluate and tackle the associated risks. HMHs are comely grouped under geophysical, meteorological, and hydrological and climatological hazard families. They are characterised in terms of their frequency, severity, duration, and magnitude. Sometimes HMHs could be triggered synchronously, cascading and causing multi-hazards and resulting in huge damage to human and infrastructure. Of the reviewed HMHs, floods are the most frequent events across Europe (37%) and worldwide (43.5%); while drought evolution is the most complicated process and may further cause heatwaves and landslides. Therefore, in the field of water resource management it is important to analyse drought propagation in both the short-term and long-term in current and future climate scenarios for proper drought risk management. In term of damages such as loss of life and economic losses in world, earthquake (56%) and storm (45.5%) were dominant while heatwaves/extreme temperatures (78.5%) and floods (35.1%) were causing substantial damages in Europe (SI Tables S2-S3).
- NBS are useful domain to address societal challenges. Among various classification schemes that are used to benchmark its concepts, the concept used by European research programme Horizon 2020 presents one of the best examples: "NBS actions inspired by, supported by or copied from nature, and uses complex system processes of nature (European Commission, 2019)". The components of this complex system may interact with each other and cause an action-response cycle. This cycle can trigger the formation of natural hazards while NBS tend to keep these natural processes stable. Besides decreasing the adverse impacts of HMHs and many other benefits, NBS can be cost-effective compared with pure grey infrastructures (Narayan et al., 2016, Depietri and McPhearson, 2017, Reguero et al., 2018).
- Of the types of HMHs, flooding appears to be most addressed in the case studies across Europe, while the hybrid approach is the most used type of NBS to manage flooding

followed by a green approach. In the meantime, a green approach is a potential solution for landslides and heatwaves in various parts of Europe. Overall, the proportion of case studies analysed shows that green approach (49%) is contributing a significant role in buffering communities from HMRs at a different location in Europe followed by hybrid (37%) and blue approaches (14%).

- Geo-information of natural hazard databases and NBS is utilized by several users such as scientific organization, insurance companies, governments and policymakers to help make decisions for protecting loss of life and property, to minimize insured losses and to pay insurance claims. These databases (e.g., *EM-DAT*, *Munich Re-NatCatSERVICE*, *Sigma and INSPIRE Geoportal*) provide valuable quantitative information for risk evaluation and application by end-users. Therefore, it is important that the information given by these catalogues and platforms pass through quality check to meet the highest standards.
- Gaps in current knowledge and potential barriers such as lack of on-site monitoring, social and political barriers (Kabisch et al., 2016) hamper the wider uptake of NBS. In order to overcome these gaps and foster the uptake of NBS in responses to HMHs, a greater interdisciplinary and collaborative research amongst different policy areas, stakeholders and many other sectors is required. This will particularly increase the demand and may promote the uptake of NBS implementation in practical situations. Simultaneously, few studies (e.g., Depietri and McPhearson. 2017) pointed out the limitation and drawbacks of using a grey approach or merely green infrastructure for HMHs reduction, suggesting a hybrid approach that combines blue, green and grey approach as a most effective way of tackling HMHs.

Finally, our review highlighted several research gaps. For example, limited research is available on the economic costs and benefits evaluation of NBS against hard engineering structure when implemented for building resilience to HMHs. Likewise, assessment of the uncertainty of future preservation and costs and benefits of NBS require further research. Therefore, good practice and cost-efficiency related research may give a fundamental and explicit knowledge in up taking NBS for HMRs. Furthermore, a set of principles are adopted to assess comprehensive co-benefits of NBS. Any NBS related strategies and execution procedures not only relies on how to observe and assess the efficiency of interferences but also takes into account the linkages among such assessments in a comprehensive procedure of alternatives assortment, NBS plan execution, observing, evaluation, and replication. Other research needs include the development of NBS catalogue that contains harmonized and comprehensive database and metadata models for NBS. A significant gap exists among the science, policy and practice of NBS needs, warranting future investigations to explore and build a bridge that can enhance the market opportunities of NBS over purely grey approaches. Here, we focused our analysis on five HMHs across Europe. Future studies should attempt to extend the analysis of the NBS potential to other continents such as Asia and North America, and also consider the evaluation of additional HMHs such as sandstorm and wildfires.

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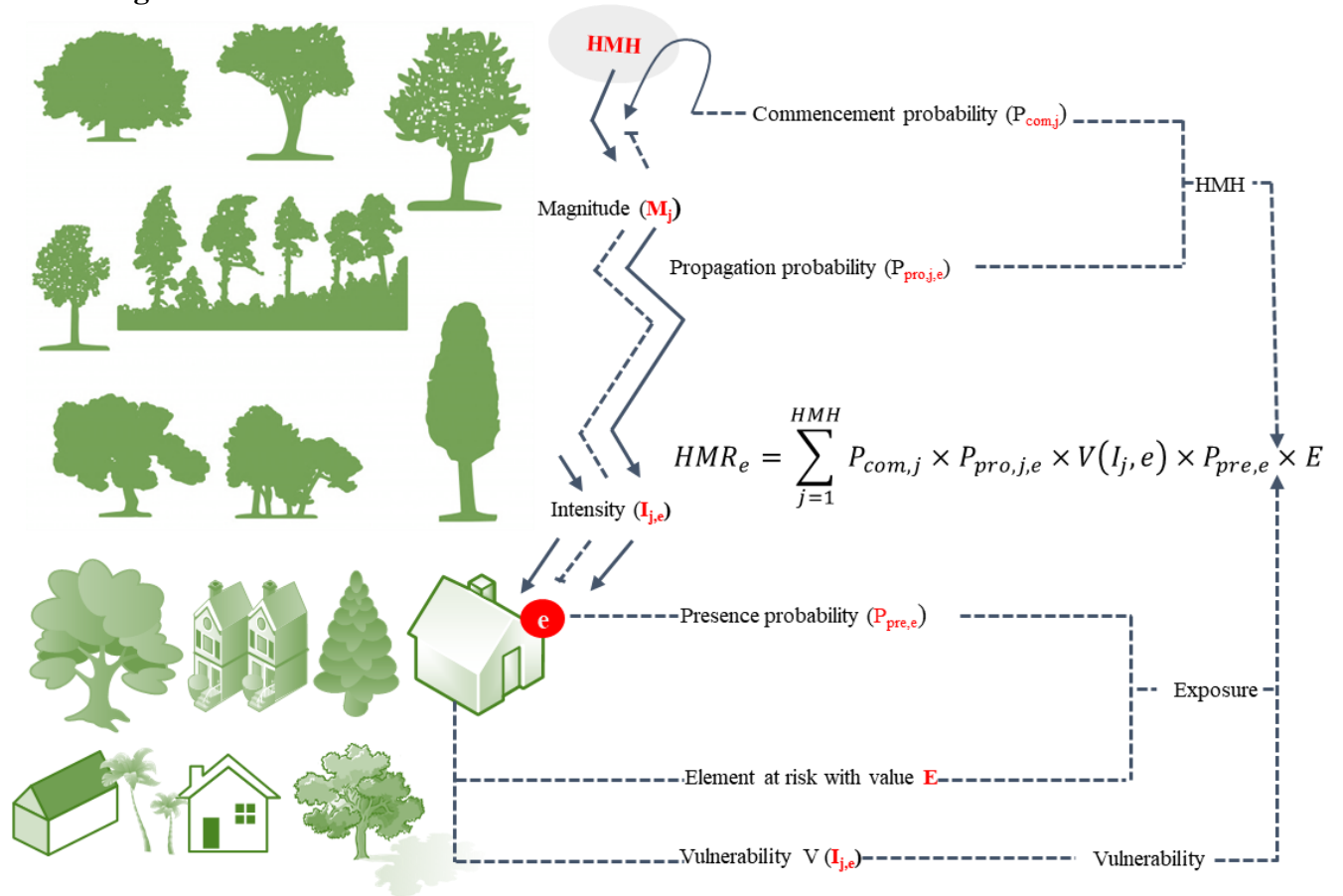


Figure 1. The HMRs which arises from an HMH reliant on the commencement probability of a hydro-meteorological extreme event, its propagation probability to reach an element at risk, value and vulnerability: source (adapted from Moos et al, 2017).

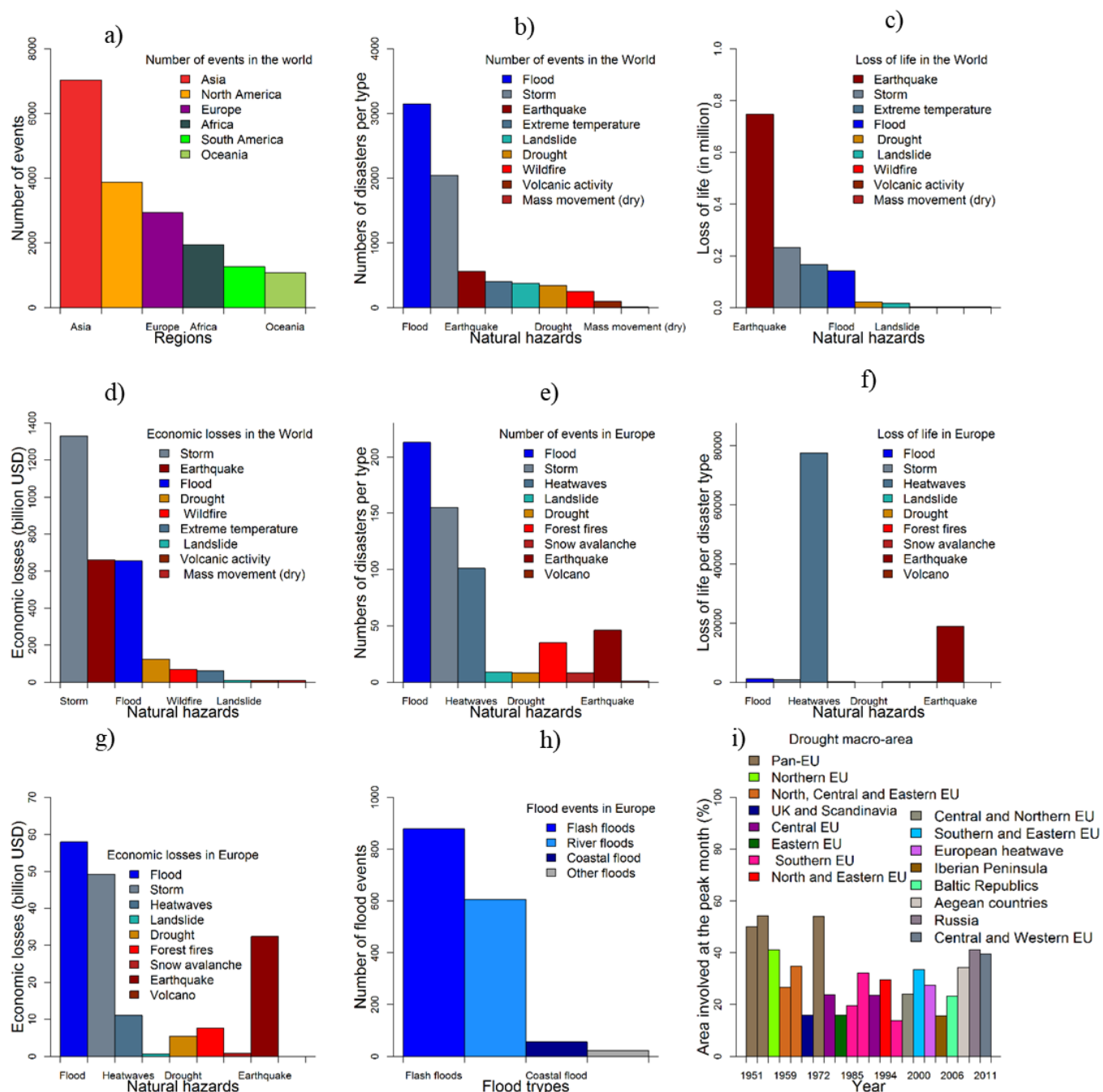


Figure 2. (a) Numbers of events during 1980–2018; (b) number of disasters; (c) loss of life; (d) economic losses in the worldwide over the last 20 years (1998–2017); (e) number of events; (f) loss of life; (g) economic losses in Europe per disaster types during 1998–2009; (h) summaries of distribution of flood events in Europe over the past 150 (1870–2016) years; and 2(i) the 22 largest drought events (% of area involved) in Europe from 1950 to 2012 data obtained mentioned by several studies. The data used in figure a, b-d, e-g, h and i is taken from Munich Re-NatCatSERVICE (2019), EM-DAT (2019), EEA (2019), Paprotny (2018), and Spinoni et al. (2015), respectively.

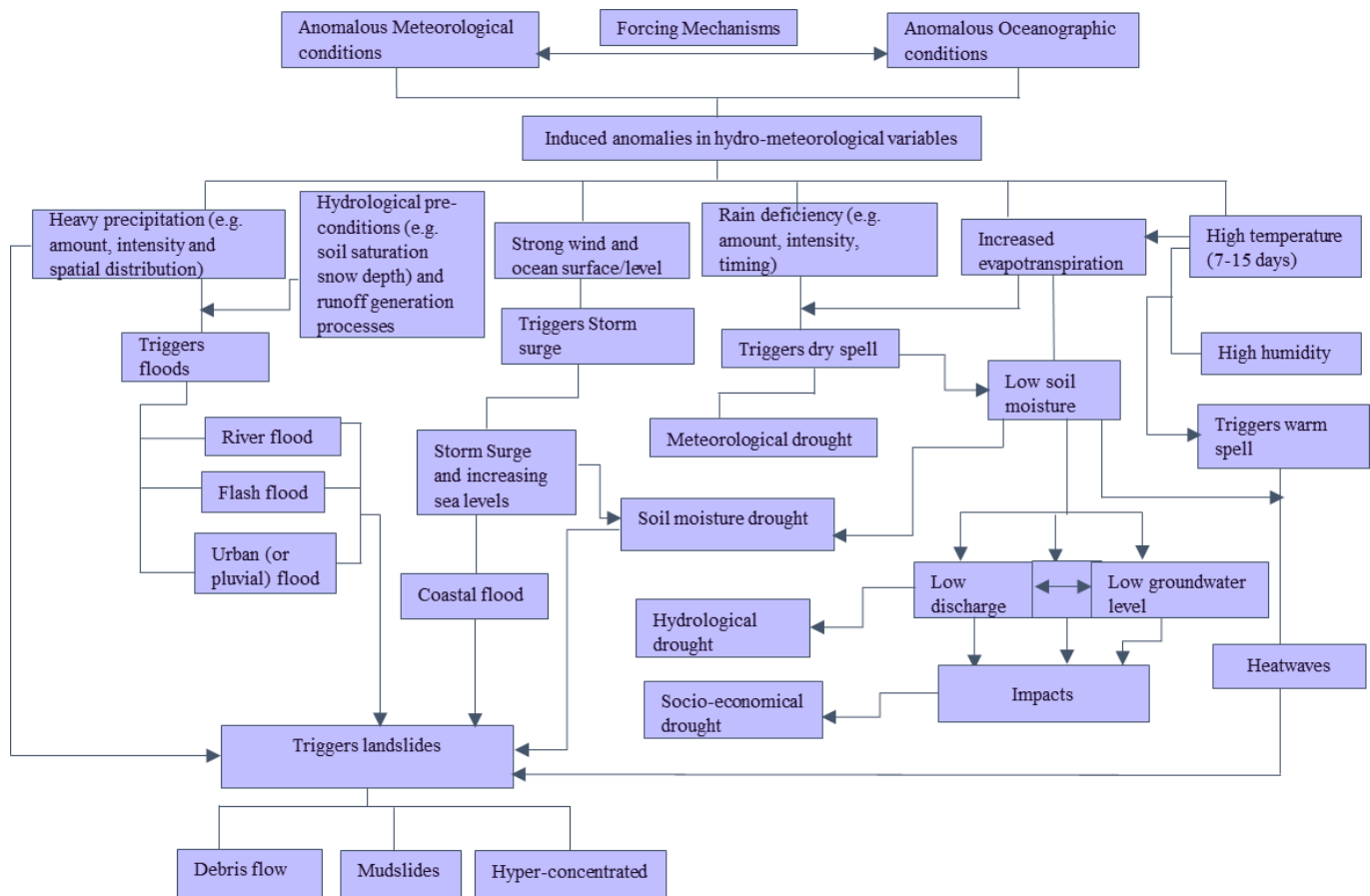


Figure 3. Scheme highlighting driving mechanisms, the relationships between hydro-meteorological hazards and their categories.

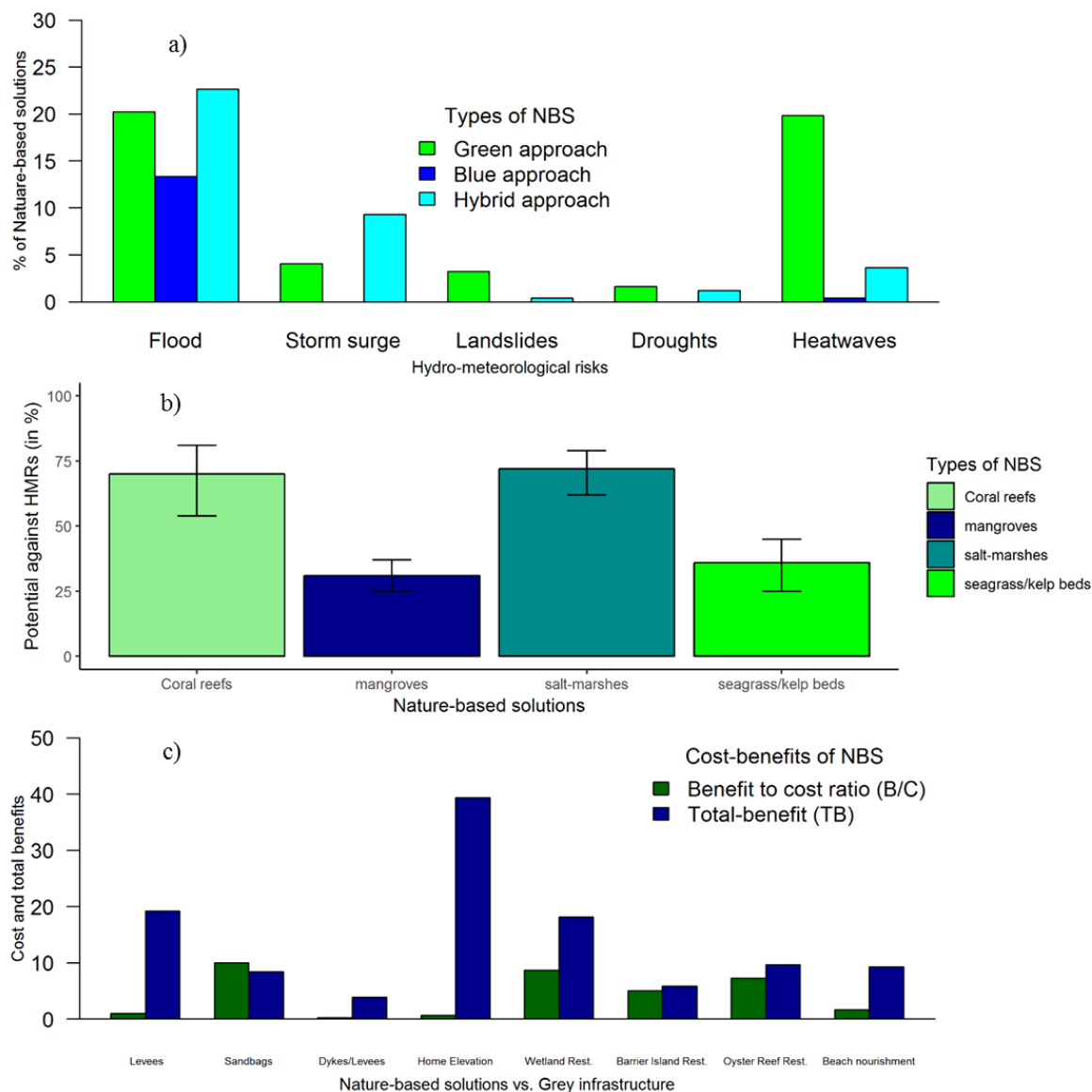
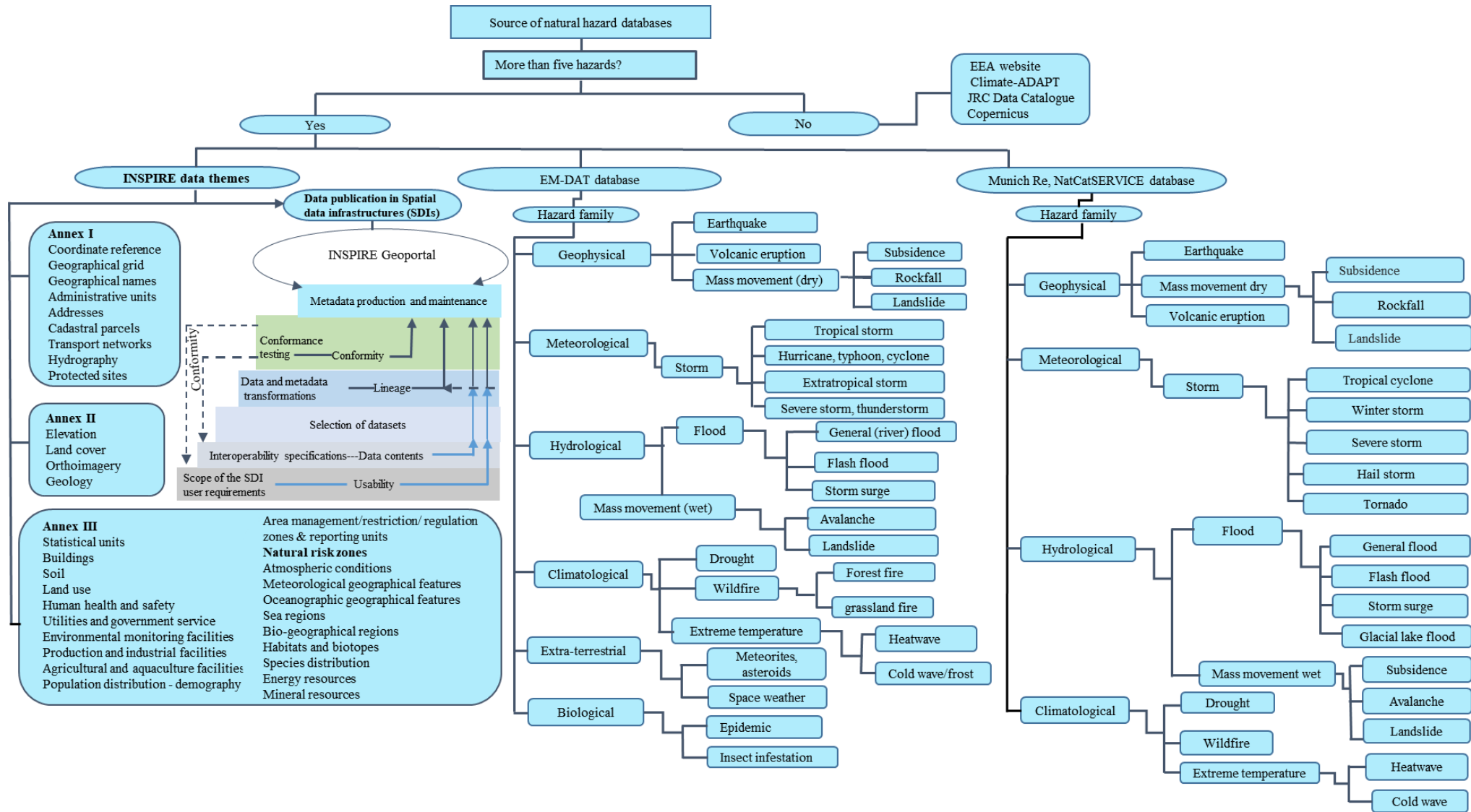


Figure 5. Nature-based solutions (NBS) to tackle hydro-meteorological hazards: (a) Number of case studies (229 in total) with NBS (green, blue and hybrid approaches) against HMRs across EU; (b) the effectiveness of nature-based coast defense in reducing wave height as compared to submerged breakwaters; and (c) comparison of costs vs benefits (benefit to cost ratio) of NBS to purely grey infrastructure solutions. The data used in figure a, b and c from OPERANDUM GeoIKP (2019), Narayan et al. (2016) and Reguero et al. (2018).



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2 **Figure 6.** Sources of databases of natural hazards, classification of subgroups and their main types.

3 List of Tables

4 **Table 1.** Summary of review articles discussing various aspects of NBS for hydro- 5 meteorological hazard reduction. GI and BI are denoted green and blue infrastructure.

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HMH (NBS)	Key finding	Authors (year)
Floods and heatwaves (GI)	Green infrastructure of a city such as greenspace network, a potential to managing climate change.	Gill et al. (2007)
Heatwaves and Floods (GI)	City ecosystems provide crucial services through regulating that buffer cities and the ecosystem from HMRs (heatwaves and floods) impacts.	Depietri et al. (2012)
Heatwaves (GI)	Green infrastructure, i.e., large parks and trees reducing the air temperature of an urban area; however, temperatures have also lower in non-green sites due to evaporative cooling.	Bowler et al. (2010)
Floods (GI)	Green and mixed approaches can increase infiltration and decreases urban flooding and enhancing environmental sustainability.	Foster et al. (2011)
Heatwaves (GI)	Implementation of urban greeneries infrastructure can maximise urban surface temperature cooling; particularly the applications of urban greeneries are identified as the most effective approaches.	Norton et al. (2015)
Built environment (GI)	Based on literature review, four keys characterisations of green approach were analysed.	Xing et al. (2017)
Climate mitigation and adaptation tools (GI, BI, Hybrid)	NBS can serve as the main tool for managing global warming and provide multi-benefits for human health and supports s feasible city development.	Kabisch et al. (2016)
Snow, avalanches, rockfalls, floods, landslides, and debris flows (GI)	Green approach (forest) plays a crucial role in decreasing HMRs by influencing the elements of the risks.	Moos et al. (2017)
Flood, drought and landslides (Hybrid)	NBS are the most effective solution for land management and restoration in various environmental conditions and found NBS are a cost benefit approaches in long-run for reducing HMRs.	Keesstra et al. (2018)
Urban stormwater (GI)	Green roofs have potential for stormwater control, both for new developments and as a retrofit option, i.e., in spring 2006 the mean flood volume and flood peaks decreased by 34% and 57%.	Stovin. (2010)
Climate change mitigation (GI, BI, Hybrid)	NBS are planned to tackle many human problems in cost-effective and flexible way.	Raymond et al. (2017)

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10 **Table 2.** Overview of observed and projected changes in HMR over Europe. ▲: increasing
 11 and ▼: decreasing, str: stronger, EU: Europe N: north, SE: southeast, NW: North West, S:
 12 south, I: Iberian, M: Mediterranean, respectively.

Hydro-meteo risk	Periods			
	Past trends in observations	References	Trend in climate model Projections	References
Floods	1985-2009 ▲	Kundzewicz et al. (2017)	2050-2100 ▲	Alfieri et al. (2015b)
	1980-2015 ▲	Munich RE. (2018)	1971-2100 ▲	Vormoor et al. (2016)
	1976-2005 ▲	Alfieri et al. (2015a)	1971-2100 ▼	Vormoor et al. (2016)
			2006-2035 ▲	
			2036-2065 ▲	Alfieri et al. (2015a)
Storm surges	20 th cent in Baltic Sea ▲	Suursaar et al. (2009)	2066-2095 ▲	
			2010-2100 ▲	IPCC (2018)
			2010-2100 ▲	IPCC (2018)
			1990-2100 ▲	Vousdoukas et al. (2016)
			1971-2100 ▲ (NW EU)	Howard et al. (2014)
Landslides	1960-2011 ▲	Stoffel et al. (2014)	1971-2080 ▼	Dixon and Brook. (2007)
	1990-2016 ▲ weak	Jomelli et al. (2004)	2081-2100 ▲ ▼	Gariano and Guzzetti. (2016)
	1986-2005 ▲	Gariano and Guzzetti. (2016)	2020-2100 ▲	Guha et al. (2015)
			2021-2050 ▲	Schlögl and Matulla (2018)
			2071-2100 ▲	
Drought	1950-2012 ▲ in M. region, C.EU and SE.EU	Spinoni et al. (2015)	2050 ▲ in S. EU	Van der Linden and Mitchell. (2009b)
	1950-2012 ▼ in N. Europe and E. EU	Spinoni et al. (2015); Gudmundsson and Seneviratne. (2015)	2011-2050 ▼ in N. EU	Henrich and Gobiet. (2012)
			2050 ▼ in N. Europe	Spinoni et al. (2015)
			2050 ▼ in N. Europe	Giorgi et al. (2014)
			2050 ▼ in N. Europe	Touma et al. (2015)
			2050 ▼ in N. Europe	Orlowsky and Seneviratne (2013)
			2041-2070 & 2071-2100 ▲ in I. Peninsula, in S. Italy	Stagge et al. (2015)
Heatwaves	2010-2016 ▲ sever	Spinoni et al. (2015)	Near future (2020-2052) ▲	Russo et al. (2015)
	1997-2012 ▲	Seneviratne et al. (2014)	Far future (2068-2100) ▲	
	2003-2010 ▲ sever	Barriopedro et al. (2011)	Far future (2050-2100) ▲ str	Lehner et al. (2016)
	1990-2016 ▲ intense	Russo et al. (2015)		
	1971-2000 ▲	Donat et al. (2013b)		

14 **Table 3.** Classification schemes and types of NBS identified through the literature review.

Old types of NBS	Association to NBS	Classification schemes	New types of NBS	References
Ecosystem services (ES)	To take into account solutions through NBS design and assessment, ES concept can be an excellent way. Nevertheless, ES application is not limited to little ES and their beneficiaries.	Based on management concepts and approaches to human needs.	Green Blue Hybrid	Nesshöver et al. (2017)
Green and blue infrastructures	In some areas similar to NBS and can sometimes, be synonymous through differences between “infrastructures” vs. “solution”.		Green Blue	
Ecological engineering (EE) and Catchment Systems Engineering (CSE)	EE and CSE are subsets of NBS: Both aim at tackling societal challenges but CSE particularly targets on mesoscale protect society from floods.		Hybrid	
Ecosystem based adaptation (EBA) and mitigation (EBM)	In its concept, EBA is not comparable to NBS, but its principles can be used in the framework of NBS to enhance various end-users and to equalise the needs of stakeholders.		Green Blue Hybrid	
Ecosystem Approach (EA)	The objective is focused on dealing about the balance of preservation and services for societal demands. EA is not exactly the same of NBS; however, its concepts could be applied in the planning of NBS.		Green Blue Hybrid	
Natural capital (NC)	Conceptually NC help to show the potential of nature in fulfilling societal needs, and therefore taking into account NBS against various kinds of interferences.		Green	
Ecosystem protection approaches (EPA)	EPA is sub-part of NBS and ideally, area-based conservation approaches including protected area management (e.g. rainforests and mountain areas).	Based on benefits and its applications in risk adaptation and mitigation.	Green	Cohen-Shacham et al. (2016)
Ecosystem restoration approach (ERA)	ERA is focused on protecting ecosystem and biodiversity that has been degraded, damaged. ERA is a version of NBS that aims at addressing societal challenges.		Green Blue Hybrid	
Infrastructure related approaches (IRA)	IRA encompasses natural infrastructure (NI), Green infrastructure (GI) and Blue Green infrastructures (BI).		Green Blue Hybrid	
Issue-specific ecosystem-related approaches (IEA)	IEA approach contains EBA, and EBM, climate adaptation services. Therefore, IEA is part of NBS and has a broader view than others have approaches but it is not equivalent to NBS. The concepts of IEA could be applied in the planning of NBS to enhance the range of community engagement and to equalise various demands.		Green Blue Hybrid	
Ecosystem based management approaches (EMA)	Combined coastline protection and sustainable utilisation of water balance are placed under EMA. This approach considers the entire ecosystem, including humans, and conducted at smaller spatial scales. EMA has similar target to NBS but especially designed to target on aquatic and water resource problems.		Green Blue Hybrid	
Indoor plants; Green roofs; Green facades and Green and blue landscaping including trees, gardens, parks and water futures.	Four of them are part of NBS family and has similar application and benefits. However, their aims are more focused green and blue infrastructure while the concept of NBS broader in its view and serves as an umbrella concept that covers an entire range of ecosystem related approaches.		Based on the location of the urban greenery.	
Better use of natural/protected areas	Focused on better utilizing the available partially modified ecosystems, to provide multiple benefits.	Based on the use of nature in tackling challenges, i.e., climate change, disaster risk management.	Green Blue	Balian et al. (2014)
Sustainability and multifunctionality of managed ecosystems	Focused on the definition of management rules to develop sustainable and multifunctional ecosystems and better deliver selected ecosystem services.		Green Blue	
Design and management of new ecosystems	The concept is to manage environments in very invasive approaches or generating very new environments.		Green Blue Hybrid	
Enhancing the soil health and soil functions via ecosystem services	Soil solutions is a subset of NBS and aim to improve the soil health and soil productivity using indigenous habitat or natural resources.	Based on the application to tackle hydrological risks and environmental issues.	Green	Keesstra et al. (2018)
Landscape solutions (i.e., increasing infiltration – reducing flood risk, increasing soil moisture and reducing droughts and soil erosion).	Landscape solutions mainly focus on soil and water conservation. The concept is similar to NBS, but limited in its applications. For example, using landscape solutions, high infiltration rate and less surface runoff, this decreases risk of flooding, improves crop productivity and managing dry spells and land degradation.		Green	
Green and blue approaches (restoration of ecosystems, various types of EBA).	Principally green approaches constitute by well-functioning biophysical systems. Blue approaches contain full components of water bodies. Both relies merely on ecosystem functions and merges the three types of NBS.	Based on the application, to adapt to climate change impacts.	Green Blue Hybrid	Depietri and McPhearson. (2017)
Disaster risk reduction and climate change adaptation.	Mixed solutions integrate both green, blue and grey approaches together.		Green Blue Hybrid	
Ecosystem-Based Adaptation (EBA)	A subdivision of NBS that explicitly focused on global warming management using nature.	Based on applications to societal challenges and human benefits, i.e., well-being.	Green Blue	Pauleit et al. (2017)
Green space, habitats and biodiversity.	Green Infrastructure (GI) could give planned information for harmonizing NBS in designing multiuse green areas at numerous ranges.		Green	
Ecosystem Services (ES)	To take into account solutions through NBS design and assessment, ES concept can be an excellent way. Nevertheless, ES application is not limited to little ES and their beneficiaries.		Green Blue Hybrid	

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17 **Table 4.** The types and effectiveness of NBS (green, blue and hybrid approaches) in managing
18 hydro-meteorological risks.

HMRs	Green	Hybrid	Blue	Efficiency in reducing HMRs	References
Floods		Green roofs	Small ponds/room	45 – 70%	Kolb (2004)
			Small ponds/room	60 – 85%	Kolb (2004)
			Small ponds/room	57 – 61%	Stovin et al. (2007)
			Small ponds/room	18 – 20%	Eddleston Water (2019)
			Small ponds/room	62 – 98%	Xing et al. (2017)
Storm surges	Coastal wetlands Coral reefs Salt-marshes Mangroves Seagrass			50 – 100%	
				20 – 30%	Munang et al. (2014)
				54 – 81%	Narayan et al. (2016).
				62 – 79%	
				25 – 37%	
Drought	Coastal wetlands	Mulching		25 – 45%	
				25 – 50%	
Heatwaves	Urban green space Urban parks/tress Urban parks/tress			20 – 30%	Munang et al. (2014)
				1.1 – 4oc	Doick et al. (2014)
				2.0 – 3.5°C	Potchter et al. (2006)
Landslides	Forest			0.2 – 2.9 °C	Chen et al. (2009)
				5 – 30%	Moos et al. (2017)

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