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Review article

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

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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 pose a challenge for their cataloguing. Focusing on key HMHs (floods, storm surges, 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 and 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.

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, 2019). In the same period (1980–2018), Europe experienced 2944 natural hazard events (SI Table S1) causing about USD 631 billion of losses; of which 2796 events were HMHs with damage costs of about USD 537 billion (Munich, 2019). In terms of geographical distribution, the majority of natural hazard events (7041 out of 18,169) occurred in Asia, followed by North America (3,888) and Europe (2,944), as

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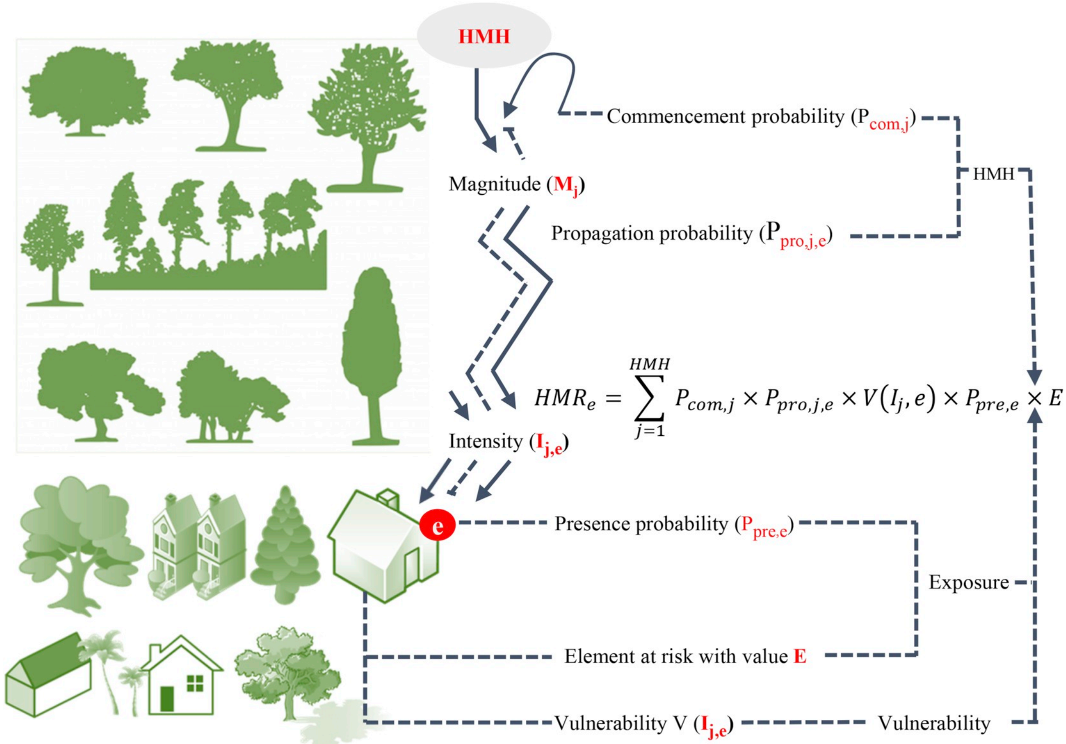

Fig. 1. The HMR which arises from an HMH reliant on the commencement probability of a hydro-meteorological extreme event, its propagation probability to reach an element at risk, value and vulnerability (source adapted from Moos et al., 2017). Trees are an example of NBS, showing their role in affecting all components of risk, while houses are representing a property exposed to HMR.

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 fires are examples of HMHs, which account for the dominant fraction of natural hazards and exist in all parts of the world. Fig. 1 describes the hydro-meteorological risks (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 people 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 et al., 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)).

$$HMR = Hazard \times Exposure \times Vulnerability \tag{1}$$

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 people or assets to all potential HMH events (Fig. 1) by the sum of all estimated negative consequences (Eq. (2)).

$$HMR_e = \sum_{j=1}^{HMH} P_{com,j} \times P_{pro,j,e} \times V(I_j,e) \times P_{pre,e} \times E \tag{2}$$

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 categorising HMHs. Interactions among HMHs can cause secondary hazard and leading to multiple HMH impacts (Fig. 3). For instance, a storm surge can induce flooding, mudslides or landslides.

Recent studies indicate that global warming has increased the intensity of HMHs in terms of magnitude, duration and frequency over

Table 1
Summary of review articles discussing various aspects of NBS for HMH reduction. GI and BI are denoted as green and blue infrastructure.

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 lowered in non-green sites due to evaporative cooling.	Bowler et al. (2010)
Floods (GI)	Green and mixed approaches can increase infiltration and decrease urban flooding and enhance 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-benefit 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 effective 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, e.g. 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)

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 HMHs. 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 the 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 HMHs – floods, droughts, wildfires, windstorms, heatwaves and coldwaves, 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 and Otto., 2014 also assessed how the variability of HMHs 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 HMH 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 planers, 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 HMHs 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 HMHs, 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 ecosystem, 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 can be implemented along with the new adaptation measures or used to fit existing systems (Davis and Naumann, 2017). The concept of NBS were introduced towards the end of 2000s by the World Bank to point out the use of biodiversity for managing climate change (Stephan et al., 2017). Different definitions of NBS have been used in the literature, depending on the 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 offering multiple benefits including environmental, social, wellbeing benefits and helping to enhance resilience (Balian et al., 2014; Cohen-Shacham et al., 2016; European Commission, 2019; Nicolas et al., 2017).

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 of 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 (Fig. 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 issuance 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 Tables S2 and S3) covered here account for about 80.6% loss of life (Figs. 2f) and 75.2% economic losses (Fig. 2g) in Europe; while about 43.5% and 74.5% loss of life and economic damages across world (Fig. 2c and 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 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., floods, 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 (Fig. 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, 2009; Touma et al., 2015).

In general, the HMHs are features of the earth system and associated with forcing mechanisms of atmospheric, geospheric, biospheric 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 (Fig. 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

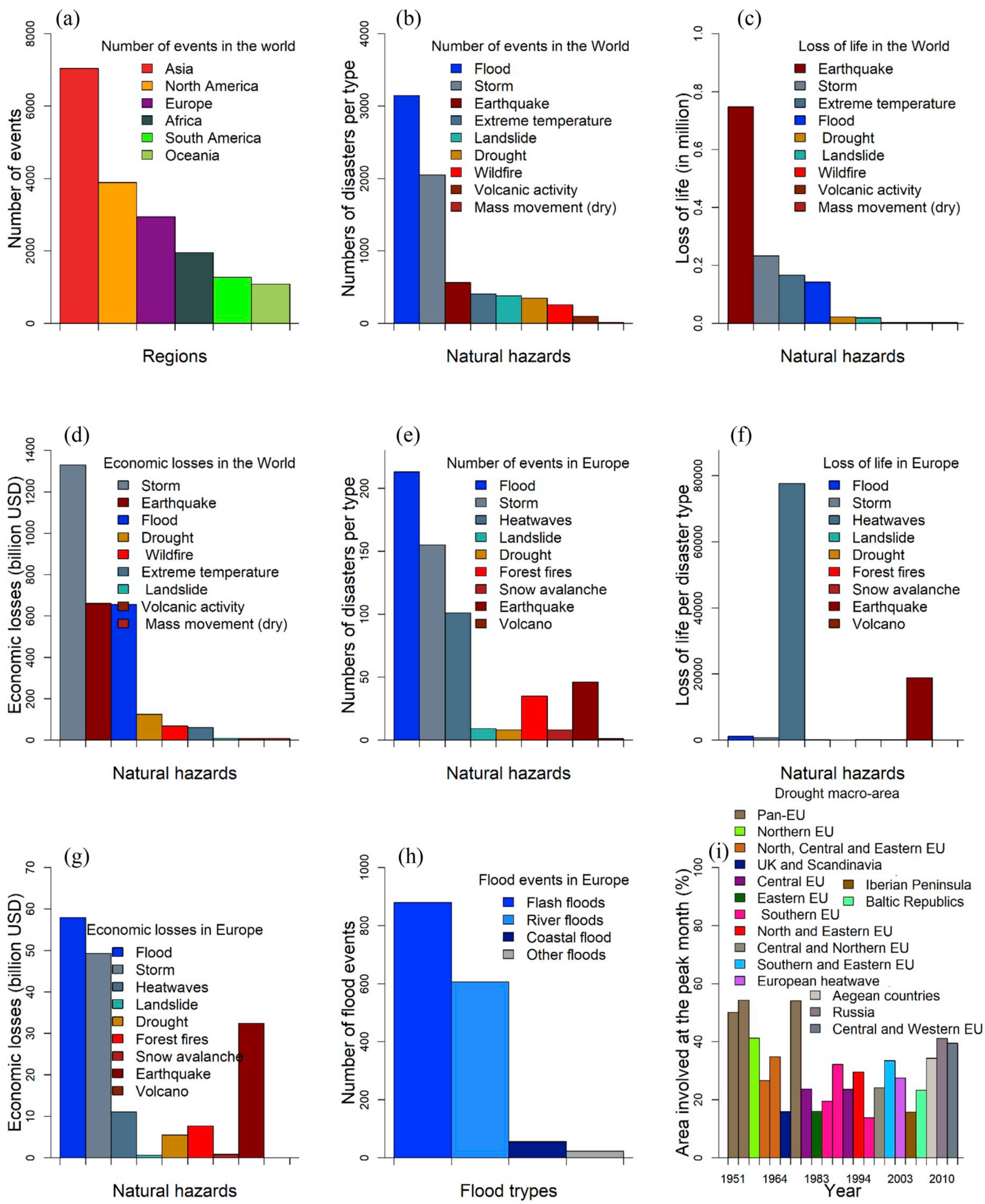

Fig. 2. (a) Numbers of events during 1980–2018; (b) number of disasters; (c) loss of life; (d) economic losses in the worldwide over the last 20 years (1998–2017); (e) number of events; (f) loss of life; (g) economic losses in Europe per disaster types during 1998–2009; (h) summaries of distribution 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. (2019), EM-DAT (2019), EEA (2019), Paprotny et al. (2018), and Spinoni et al. (2015), respectively.

evapotranspiration. Trends in HMHs can be assessed either by analysing a number of extreme events or by analysing economic losses. For instance, Fig. 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 (Fig. 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/cyclicity 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

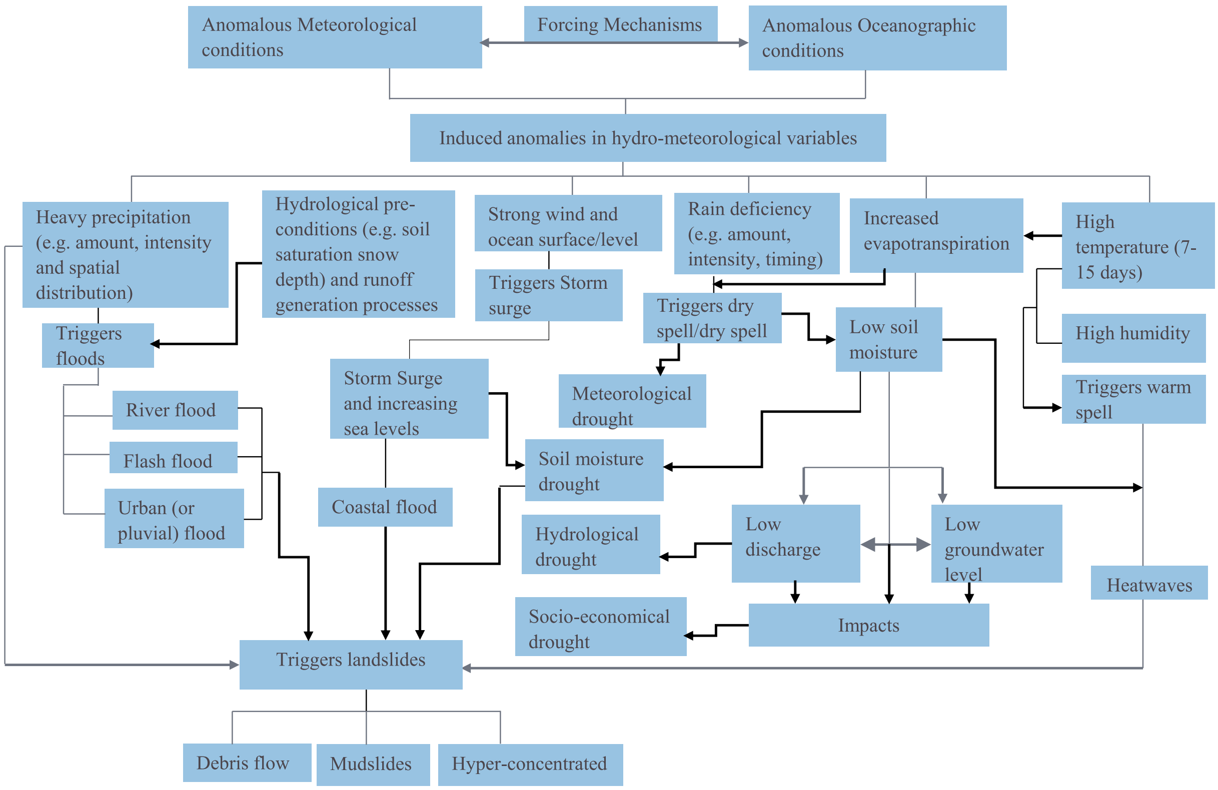

Fig. 3. Scheme highlighting driving mechanisms, the relationships between HMHs and their categories.

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

HMR	Periods			
	Past trends in observations	References	Trend in climate model Projections	References
Floods	1985–2009 ▲ 1980–2015 ▲ 1976–2005 ▲	Kundzewicz et al. (2017) Munich. (2019) Alfieri et al. (2015a)	2050-2100 ▲ 1971-2100 ▲ 1971-2100 ▼ 2006–2035 ▲ 2036–2065 ▲ 2066–2095 ▲	Alfieri et al. (2015b) Vormoor et al. (2016) Vormoor et al. (2016) Alfieri et al. (2015a)
Storm surges	20th cent in Baltic Sea ▲	Suursaar et al. (2009)	2010-2100 ▲ 2010-2100 ▲ 1990-2100 ▲ 1971-2100 ▲ (NW EU)	IPCC (2018) IPCC (2018) Vousdoukas et al. (2016) Howard et al. (2014)
Landslides	1960–2011 ▲ 1990–2016 ▲weak 1986–2005 ▲	Stoffel et al. (2014) Jomelli et al. (2004) Gariano and Guzzetti (2016)	1971–2080 ▼ 2081-2100 ▲ ▼ 2020-2100 ▲ 2021–2050 ▲ 2071–2100 ▲	Dixon and Brook (2007) Gariano and Guzzetti (2016) Guha et al. (2015) Schlögl and Matulla (2018)
Drought	1950–2012 ▲ in M. region, C.EU and SE.EU 1950–2012 ▼ in N. Europe and E. EU	Spinoni et al. (2015) Spinoni et al. (2015); Gudmundsson and Seneviratne (2015)	2050 ▲ in S. EU 2011–2050 ▼ in N. EU 2050 ▼ in N. Europe 2050 ▼ in N. Europe 2050 ▼ in N. Europe 2050 ▼ in N. Europe	Van der Linden and Mitchell. (2009b) Henrich and Gobiet (2012) Spinoni et al. (2015) Giorgi et al. (2014) Touma et al. (2015) Orlowsky and Seneviratne (2013)
	1961–1990 in N. EU	Henrich and Gobiet (2012)	2041–2070 & 2071–2100 ▲ in I. Peninsula, in S. Italy	Stagge et al. (2015)
Heatwaves	2010–2016 ▲ sever 1997–2012 ▲ 2003–2010 ▲sever 1990–2016 ▲ intense 1971–2000 ▲	Spinoni et al. (2015) Seneviratne et al. (2014) Barriopedro et al. (2011) Russo et al. (2015) Donat et al. (2013b)	Near future (2020–2052) ▲ Far future (2068–2100) ▲ Far future (2050–2100) ▲str	Russo et al. (2015) Lehner et al. (2016)

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, 2016; Hall and Blöschl, 2018), Fig. 3. Floods can be categorised based on the water source and on the process causing the water level rise (Turkington, 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 response time of the catchment. Hall et al. (2014) also stated that 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 a 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 (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, 2016; Merz and Bloschl, 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 (Fig. 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, when the precipitation distribution is not naturally strong. If the water level rises over the banks, the river flow inundates the adjoining areas (Hall et al., 2014). The degree of wetness of the soil in the basin is in several cases seriously vital (Fig. 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, 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., 2015a, 2015b). 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), Fig. 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 (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, climate change 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), Fig. 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 heights 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 21st 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 Fig. 3.

3.3. Landslide types, driving mechanism and trends

Similar to other natural hazards, landslides are triggered by the combination of meteorological, geological, morphological, physical and human factors. Fig. 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 Fig. 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 (Fig. 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 Fig. 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 and Guzzetti, 2016). Klose et al. (2015) noted that landslides triggered by extreme hydro-meteorological events in several European territories have been 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 and Guzzetti, 2016). Numerous past findings have identified the links among landslides and heavy precipitation: Polemio and Lonigro (2014) and Gariano and Guzzetti (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 (Fig. 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 priory due to their complexity (Fig. 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 are 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 Fig. 3. Based on the driving mechanisms, droughts are grouped into four types (Mishra and Singh, 2010; Van Loon, 2015), as shown in Fig. 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; *Socio-economic drought* is linked with the three aforementioned drought types, usually measured by social and economic indicators.

It can also 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 (Fig. 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 Fig. 2i (areas under events at the extreme low flow month, in %). They found that an increasing and significant change in historical periods for droughts had 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 that drought showed regional variability across Europe. For instance, the finding by Stagge et al. (2015) revealed that in some part of Europe (i.e., eastern Mediterranean, southern Italy, and Iberian Peninsula), particularly at the far future, with difference 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 that 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 one or two days to 7–15 days (Guerreiro et al., 2018; IPCC, 2018), Fig. 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), Fig. 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., increasing 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 the 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 HMHs (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 utilise 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 HMHs need different adaptation measures (Section 4.2.1), the types of NBS adopted to tackle each HMHs 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 considered the concepts of NBS. In this section, we thoroughly reviewed the existing classification schemes of NBS and their application to HMHs 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; Stephan et al., 2017; Nesshöver et al., 2017, Cohen-Shacham et al., 2016). Stephan 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. Tables 3 and SI Table S5 presents a summary of the NBS concepts, classification schemes, types of HMHs 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

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 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 is 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.	Green Blue Hybrid	Xing et al. (2017)
Better use of natural/protected areas	Focused on better utilising 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 eco-system 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	

(*continued on next page*)

Table 3 (*continued*)

Old types of NBS	Association to NBS	Classification schemes	New types of NBS	References
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 rely merely on ecosystem functions and merge 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	Stephan 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	

extent and they are analysed and utilized in a different way in practice (Stephan 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, 2013a, 2013b). 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 that 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 Fig. 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; Fig. 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 (Fig. 4).

Fig. 4 shows the overall framework and aim of NBS in managing HMRs posed by HMHs such as floods, droughts, storm surge, landslides and heatwaves through a wide range of green, blue and hybrid approaches. These challenges are features of the earth system as a part of nature and associated with forcing mechanisms of the four main components of the earth system: atmosphere, oceanographic/hydrosphere (all blue approaches), biosphere (all green approaches) and geosphere components (Fig. 4). The main components are interconnected by many non-linear processes at different scales, interlaced by complex mechanisms (Fig. 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 (Fig. 4). For example, as described in Fig. 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 HMHs are the result of a positive feedback

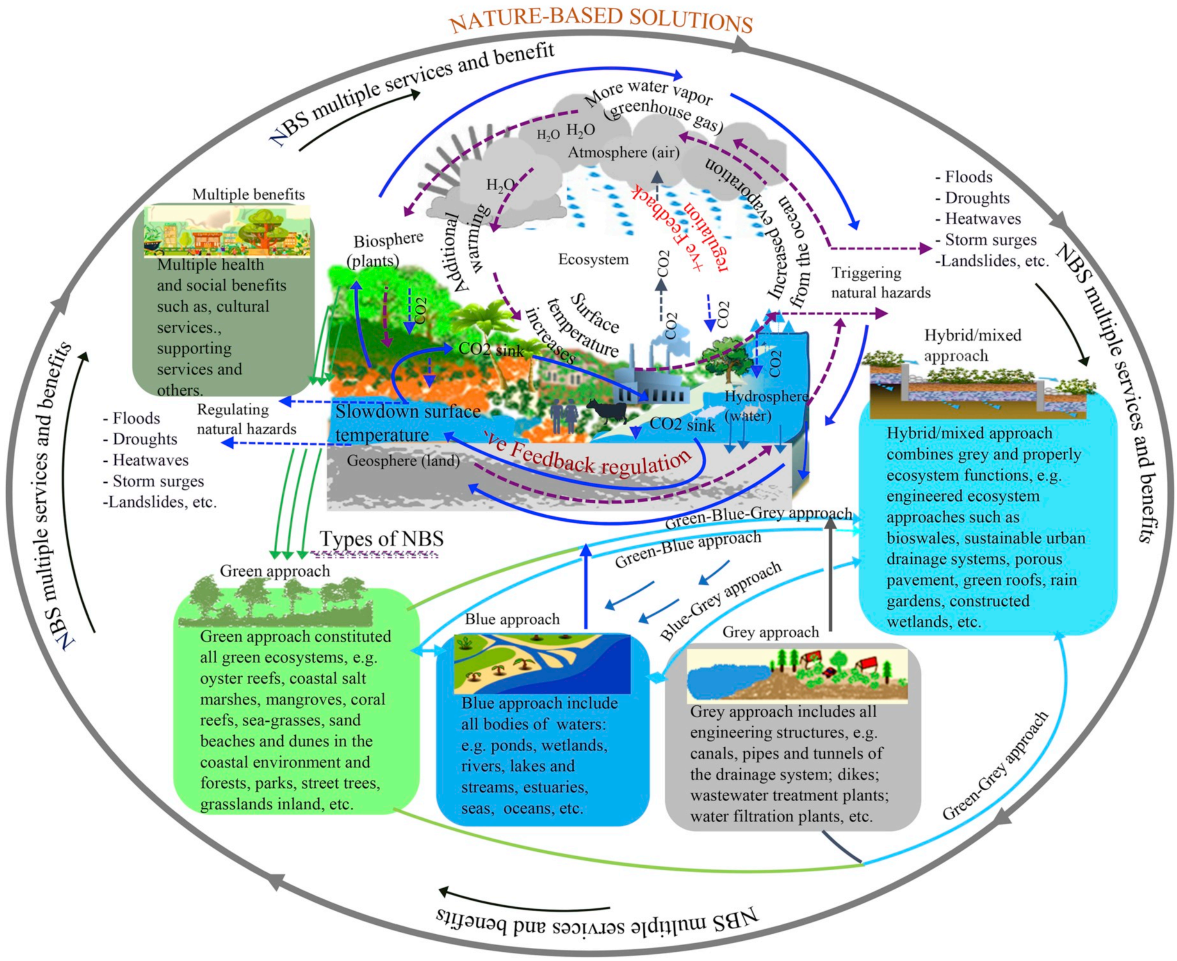

Fig. 4. Conceptualizing NBS as an umbrella term for ecosystem-related approach and use of grey approach with ecosystem functions together in managing natural hazards.

mechanism (dotted lines in Fig. 4), while changes that lead to a compensating process and mitigate the HMHs triggering factors constitute a negative feedback mechanism (solid lines in Fig. 4) (Alain and Jean-Louis, 2013). In general, positive feedback triggers natural hazard formation whereas NBS keeps the natural processes stable (Fig. 4). For instance, NBS can serve as a sink for carbon sources (solid lines in Fig. 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 (Fig. 4).

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

Relying on the traditional approach to manage 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 has appeared as an effective approach in terms of costs and potentials to manage the impact of HMHs (Temmerman et al., 2013; Vineyard et al., 2015). Nowadays, numerous body of literature and practitioners perceived NBS efficiency for adaptation and mitigation of HMRs. For example, IUCN (2018) 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 climate change.

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 concluded that NBS are an efficient long-term approach in both managing HMRs and benefit to cost ratio.

4.2.1. Effectiveness of NBS against HMHs

Here, we present recent findings on how NBS can play an important role to adapt HMRs (Fig. 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, HMHs, 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 approach (20%);

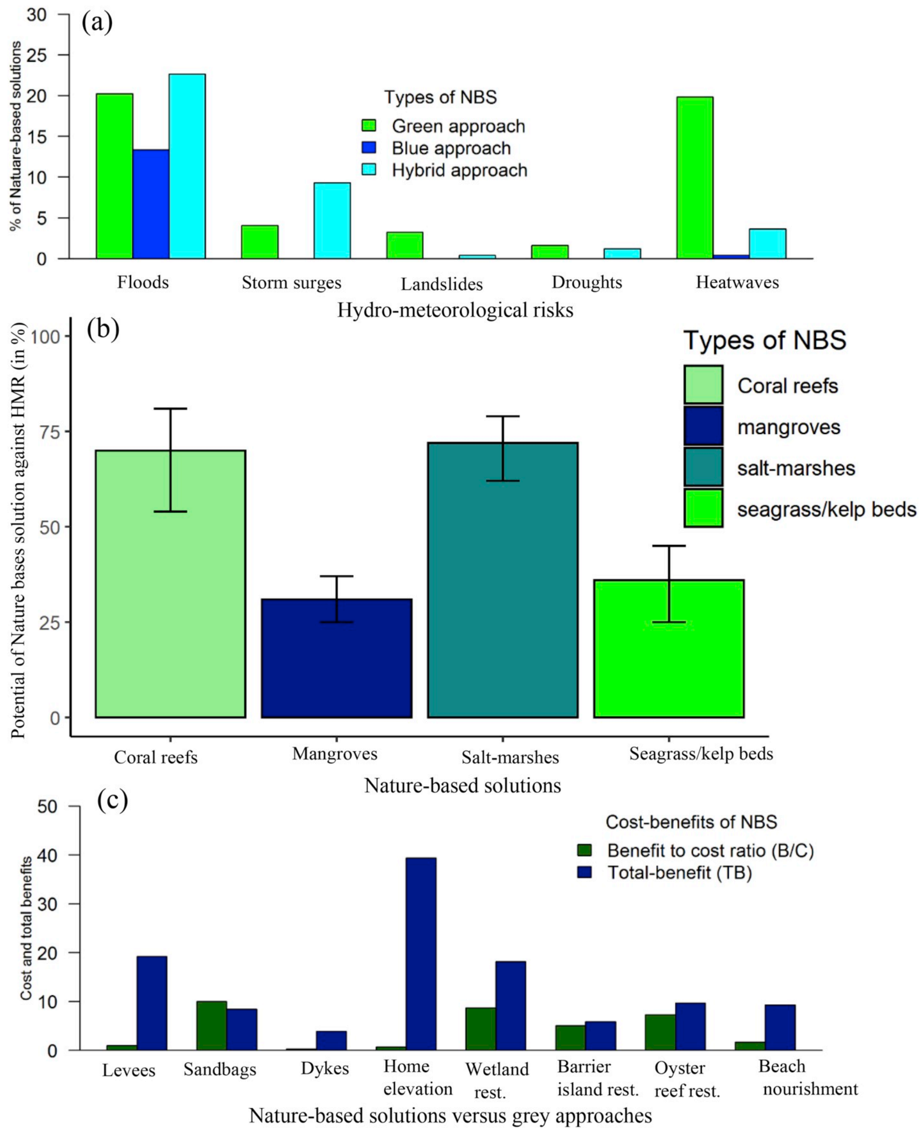

Fig. 5. Nature-based solutions (NBS) to tackle HMHs: (a) Number of case studies (229 in total) with NBS (green, blue and hybrid approaches) against HMHs across EU; b) the effectiveness of nature-based coast defense in reducing wave height as compared to submerged breakwaters; and c) comparison of costs 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). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

heatwaves are 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 (Fig. 5a).

Table 4 shows the evidence of how effective the NBS have been in managing HMRs (i.e., how much flooding, storm surges, 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 HMHs and climate conditions (Keesstra et al., 2018). In fact, Fig. 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 reaches up to 100%, see Table 4. The effectiveness of NBS in tackling HMHs also depends on its typology. For example, there are many studies underlining the importance of hybrid, green and blue approaches for flood protection (Fig. 5a). For instance, Bullock and Acreman (2003) analysed 28 case studies of NBS and found that 82% hybrid approach had played an important role in decreasing or intercepting the quick flows. A hybrid approach shown in Fig. 5a was one of the best solutions to play a key role in protecting the coastal zone from storm surges 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

Table 4
The types and effectiveness of NBS (green, blue and hybrid approaches) in managing HMRs.

HMRs	Green	Hybrid	Blue	Efficiency in reducing HMRs	References
Floods		Green roofs	Small ponds/room	45–70%	Kolb and Diekmann (2004)
			Small ponds/room	60–85%	Kolb and Diekmann (2004)
			Small ponds/room	57–61%	Stovin et al. (2012)
			Small ponds/room	18–20%	Eddleston Water (2019)
		Rain gardens		62–98%	Xing et al. (2017)
		Green roofs		50–100%	
	Coastal wetlands			20–30%	Munang et al. (2013)
Storm surges	Coral reefs			54–81%	Narayan et al. (2016).
	Salt-marshes			62–79%	
	Mangroves			25–37%	
	Seagrass			25–45%	
Drought	Coastal wetlands	Mulching		25–50%	
				20–30%	Munang et al. (2013)
Heatwaves	Urban green space			1.1 – 4oc	Doick et al. (2014)
	Urban parks/tress			2.0–3.5 °C	Potchter et al. (2006)
	Urban parks/tress			0.2–2.9 °C	Chen et al. (2011)
Landslides	Forest			5–30%	Moos et al. (2017)

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 (Fig. 5b). The bars in Fig. 5b show that green approach (i.e., coastal habitats) reduce coastal flooding between 35 and 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 Fig. 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 50 cm. Others have also indicated that these habitats had reduced coastal flooding and erosions significantly (Ferrario et al., 2014; Pinsky et al., 2013).

4.2.2. Cost-effectiveness of NBS

Robert. 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 the Europe the land degradation is as a result of coastal flooding about 4500 km^2 for the historical period (1975–2006) and between 3700 km^2 and 5800 km^2 for future years (2006–2050). 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 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, is 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 for 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 it 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. Fig. 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 Fig. 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 Fig. 5c). At the same time, sandbags (Fig. 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 that about 85% of the profitable HMRs management could be achieved using NBS, which is worth of 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 utilized 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. (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 knowledge, 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 HMHs and NBS databases and platforms where five and more hazards and/or two or more categories of NBS were included, as depicted in Fig. 6. The classification hierarchy of HMHs/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 Fig. 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 Geoportal,* Fig. 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* is further divided into six natural hazard families. The sources for HMHs are then located under the first three natural hazard families (see Fig. 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 Fig. 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 record, a greater number of storm-related events because of the economic damages. However, it does not fulfil the data recording criteria of *EM-DAT* database. In both databases, HMHs are provided in a tabular format as comma-separated values (CSV) files. *Sigma* database of SwissRe was 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 (European Commission, 2007). This includes spatial or geographical information for broadly aligned aims that help feasible growth. The aim of *INSPIRE Geoportal* is to build an "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 (European Commission, 2007). 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, Fig. 6. In the INSPIRE Directive, there are thirty-four spatial data themes identified to support environmental applications (Fig. 6). The themes are subdivided into three annexes of the directive (Fig. 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 (European Commission, 2013a, 2013b). 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 that 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 is 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 are 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 (Natural Hazards-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 and Pauleit (2016), in practice which is still an open problem in the application of NBS. They stated that 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

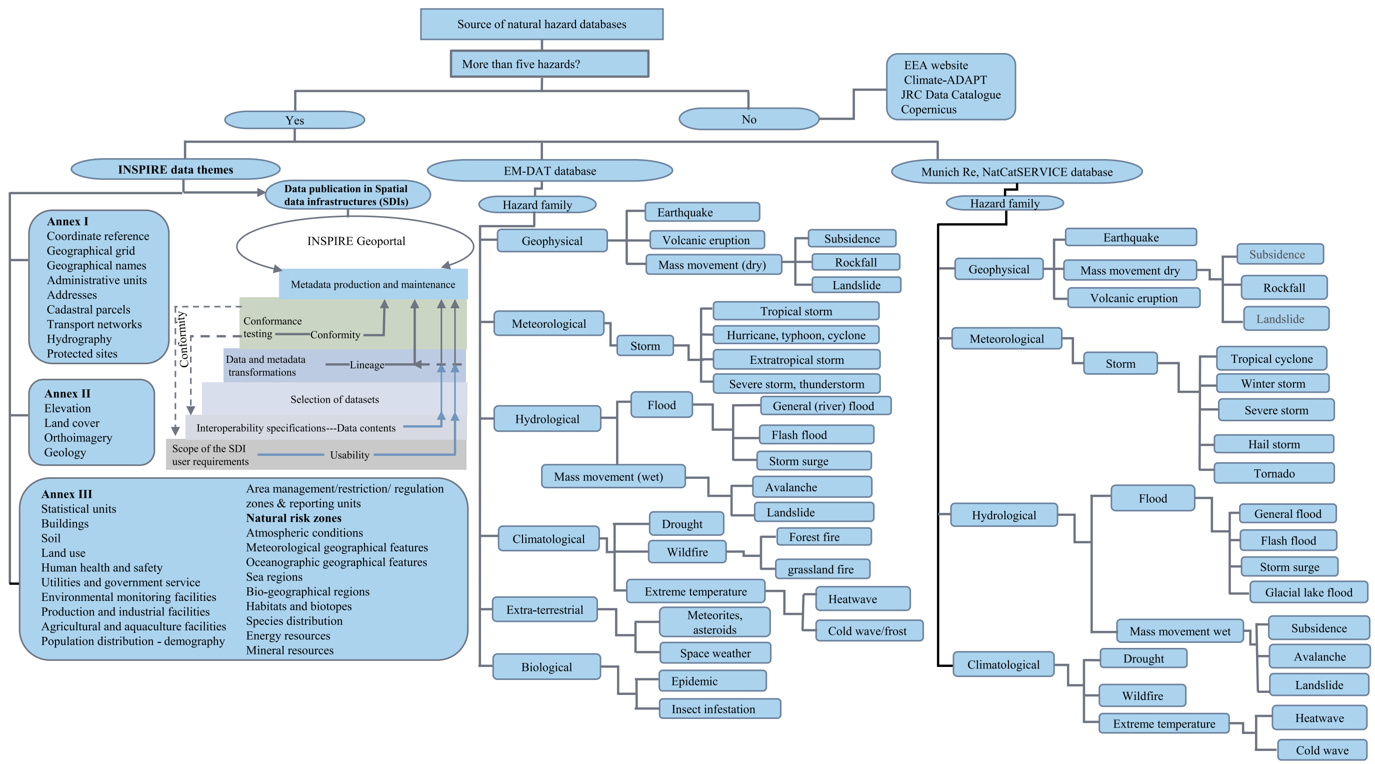

Fig. 6. Sources of databases of natural hazards, classification of subgroups and their main types.

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 HMRs. 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 HMHs 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 Geoportal, 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 summarises 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 climate change adaptation. In addition, we reviewed and documented the comparisons of NBS versus grey approaches according to the performances and cost-benefits against HMHs.

The following conclusions are drawn:

- An HMH is naturally occurring event, triggered by a physical processes 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 the earth's system. HMHs could be classified based on origin, triggering factor, seasonality, 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, 2019).
- HMHs cataloguing are an effective tool to evaluate and tackle the associated risks. HMHs are commonly 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 and 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 are the 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 the 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 the 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 uptaking 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, monitoring, evaluation, and replication. Other research needs include the development of NBS catalogue that contains harmonised 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2019.108799.

References

Alain, Lahellec, Jean-Louis, Dufresne, 2013. A formal analysis of the feedback concept in climate models. Part I: exclusive and inclusive feedback analyses. J. Atmos. Sci. 70, 3940–3958.
Alfieri, L., Pappenberger, F., Wetterhall, F., 2014. The extreme runoff index for flood early warning in Europe. Nat. Hazards Earth Syst. Sci. 14, 1505–1515.
Alfieri, L., Burek, P., Feyen, L., Forzieri, G., 2015a. Global warming increases the frequency of river floods in Europe. Hydrol. Earth Syst. Sci. 19, 2247–2260.
Alfieri, L., Feyen, L., Dottori, F., Bianchi, A., 2015b. Ensemble flood risk assessment in Europe under high end climate scenarios. Glob. Environ. Chang. 35, 199–212.
Alfieri, L., Feyen, L., Di Baldassarre, G., 2016. Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies. Clim. Change 136, 507–521.
Alves, A., Gómez, J.P., Vojinovic, Z., Sanchez, Arlex, Weesakul, S., 2018. Combining Co-benefits and stakeholders perceptions into green infrastructure selection for flood risk reduction. Environments 5, 1–23.
Alves, A., Sanchez, A., Vojinovic, Z., Seyoum, S., Babel, M., Brdjanovic, D., 2016. Evolutionary and holistic assessment of green-grey infrastructure for CSO reduction. Water 8, 1–16.
Amponsah, W., Marchi, L., Zoccatelli, D., Boni, G., Cavalli, M., Comiti, F., Crema, S., Lucía, A., Marra, F., Borga, M., 2016. Hydrometeorological characterisation of a flash flood associated with major geomorphic effects: assessment of peak discharge uncertainties and analysis of the runoff response. J. Hydrometeorol. 17, 3063–3077.
Balian, E., Eggermont Roux, H., Le, X., 2014. Outcomes of the Strategic Foresight Workshop. BiodivERsA Strategic Foresight Workshop. pp. 13–15 Nature-based solutions in a BiodivERsA context report.
Ban, N., Schmidli, J., Schär, C., 2015. Heavy precipitation in a changing climate: does short-term summer precipitation increase faster? Geophys. Res. Lett. 42, 1165–1172.
Barriopedro, D., Fischer, E.M., Luterbacher, J., Trigo, R.M., Garcia-Herrera, R., 2011. The hot summer of 2010: redrawing the temperature record map of Europe. Science 332, 220–224.
Bosello, F., Nicholls, R.J., Richards, J., Roson, R., Tol, R.S.J., 2011. Economic impacts of climate change in Europe: sea-level rise. Clim. Change 112, 63–81.
Bowler, D.E., Buyung-Ali, L., Knight, T.M., Pullin, A.S., 2010. Urban greening to cool towns and cities: a systematic review of the empirical evidence. Landsc. Urban Plan. 97, 147–155.
Bullock, A., Acreman, M., 2003. The role of wetlands in the hydrological cycle. Hydrol. Earth Syst. Sci. 7, 358–389.
Chen, L., Zhang, Z., Li, Z., Tang, J., Caldwell, P., Zhang, W., 2011. Biophysical control of whole tree transpiration under an urban environment in Northern China. J. Hydrol. 402, 388–400.
Cohen-Shacham, E., Walters, G., Janzen, C., Maginnis, S., 2016. Nature-based Solutions to Address Global Societal Challenges Xiii + 97 IUCN, Gland, Switzerland.
Coles, S.G., 2001. An Introduction to Statistical Modeling of Extreme Values. Springer, London978-1-4471-3675-0 (eBook).
Copernicus, 2019. The European Union's Earth Observation Programme Coordinated and Managed by the European Commission in Partnership with the European Space Agency. https://www.copernicus.eu/en, Accessed date: 19 January 2019.
Corominas, J., van Westen, C., Frattini, P., Cascini, L., Malet, J.-P., Fotopoulou, S., Catani, F., van den Eeckhaut, M., Mavrouli, O., Agliardi, F., Pitilakis, K., Winter, M.G., Pastor, M., Ferlisi, S., Tofani, V., Hervás, J., Smith, J.T., 2014. Recommendations for the quantitative analysis of landslide risk. Bull. Eng. Geol. Environ. 73, 209–263.
Davis, M., Naumann, S., 2017. Making the case for sustainable urban drainage systems as a nature-based solution to urban flooding. In: Kabisch, N., Korn, H., Stadler, J., Bonn, A. (Eds.), Nature-Based Solutions to Climate Change Adaptation in Urban Areas. Theory and Practice of Urban Sustainability Transitions. Springer, Cham, pp. 123–136.
Debele, S.E., Bogdanowicz, E., WG, Strupczewski, 2017. The impact of seasonal flood peak dependence on annual maxima design quantiles. Hydrol. Sci. J. 62, 1603–1617.
Debernard, J.B., Røed, L.P., 2008. Future wind, wave and storm surge climate in the Northern Seas: a revisit. J. Compil. 60A, 427–438.
Depietri, Y., McPhearson, T., 2017. Integrating the Grey, Green, and Blue in Cities: Nature-Based Solutions for Climate Change Adaptation and Risk Reduction. Springer International Publishing, pp. 91–109.
Depietri, Y., Renaud, F.G., Kallis, G., 2012. Heat waves and floods in urban areas: a policy-oriented review of ecosystem services. Sustain. Sci. 7, 95–107.
Dixon, N., Brook, E., 2007. Impact of predicted climate change on landslide reactivation, UK. Landslides 2, 137–147.
Doick, K.J., Peace, A., Hutchings, T.R., 2014. The role of one large greenspace in mitigating London's nocturnal urban heat island. Sci. Total Environ. 493, 662–671.
Donat, M.G., Alexander, L.V., Yang, H., Durre, I., Vose, R., Caesar, J., 2013a. Global land-based datasets for monitoring climatic extremes. Bull. Am. Meteorol. Soc. 94, 997–1006.
Donat, M.G., Alexander, L.V., Yang, H., Durre, I., Vose, R., Dunn, R.J.H., Willett, K.M., Aguilar, E., Brunet, M., Caesar, J., Hewitson, B., Jack, C., Klein Tank, A.M.G., Kruger, A.C., Marengo, J., Peterson, T.C., Renom, M., Oria Rojas, C., Rusticucci, M., 2013b. Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: the HadEX2 dataset. J. Geophys. Res. D Atmos. 118, 2098–2118.
Eddleston Water, 2019. Natural Flood Risk Management in the Eddleston Water. https://www.copernicus.eu/en, Accessed date: 30 March 2019.
EEA, 2019. European environment agency. https://www.eea.europa.eu/, Accessed date: 19 January 2019.
EM-DAT, 2019. Economic Losses, Poverty and Disasters 1998-2017. http://www.emdat.be, Accessed date: 9 January 2019.
Enzi, V., Cameron, B., Dezsényi, P., Gedge, D., Mann, G., Pitha, U., 2017. Nature-Based Solutions and Buildings – the Power of Surfaces to Help Cities Adapt to Climate Change and to Deliver Biodiversity. Theory and Practice of Urban Sustainability Transitions. Springer, Cham, pp. 159–183.

EU Biodiversity strategy, 2019. EU Biodiversity strategy. https://biodiversity.europa.eu/, Accessed date: 18 January 2019.
European Commission, 2007. Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 Establishing an Infrastructure for Spatial Information in the European Community (INSPIRE).
European Commission, 2013a. Thematic Issue: Ecosystem-Based Adaptation. Science for environment policy. European Commission, Brussels.
European Commission, 2013. Green Infrastructure (GI) - Enhancing Europe's Natural Capital. Communication from the Commission to the European Parliament. the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, Belgium.
European Commission, 2015. Towards an EU Research and Innovation Policy Agenda for Nature Based Solutions and Re-naturing Cities. pp. 1–74 Final Report of the Horizon 2020 Expert Group on Nature-Based Solutions and Re-Naturing Cities.
European Commission, 2019. Policy topics: nature-based solutions. Available online: https://ec.europa.eu/research/environment/, Accessed date: May 2019.
Ferrario, F., Beck, M.W., Storlazzi, C.D., Micheli, F., Shepard, C.C., Airoldi, L., 2014. The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nat. Commun. 3794, 1–9.
Fischer, S.A., Schumann, M., Schulte, 2016. Characterisation of seasonal flood types according to timescales in mixed probability distributions. J. Hydrol. 539, 38–56.
Forzieri, G., Feyen, L., Russo, S., Vousdoukas, M., Alfieri, L., Outten, S., Migliavacca, M., Bianchi, A., Rojas, R., Cid, A., 2016. Multi-hazard assessment in Europe under climate change. Clim. Change 137, 105–119.
Foster, J., Lowe, A., Winkelman, S., 2011. The Value of Green Infrastructure for Urban Climate Adaptation. Centre for Clean Air Policy, Washington, DC.
Gaál, L., Szolgay, J., Kohnová, S., Parajka, J., Merz, R., Viglione, A., Blöschl, G., 2012. Flood timescales: unde rstanding the interplay of climate and catchment processes through comparative hydrology. Water Resour. 48, 1–21.
Galloway, G.E., 2011. If stationarity is dead, what do we do now? J. Am. Water Resour. Assoc. 47, 563–570.
Gariano, S.L., Guzzetti, F., 2016. Landslides in a changing climate. Earth Sci. Rev. 162, 227–252.
Gill, S., Handley, J., Ennos, A., Pauleit, S., 2007. Adapting cities for climate change: the role of the green infrastructure. Built. Environ. 1, 115–133.
Giorgi, F., Coppola, E., Raffaele, F., 2014. A consistent picture of the hydroclimatic response to global warming from multiple indices: models and observations. J. Geophys. Res. D Atmos. 119, 695–708.
Giuliani, G., Peduzzi, P., 2011. The PREVIEW Global Risk Data Platform: a geoportal to serve and share global data on risk to natural hazards. Nat. Hazards Earth Syst. Sci. 11, 53–66.
Glade, T., Alexander, D.E., 2013. Classification of Natural Disasters. Encyclopedia of Natural Hazards. Encyclopedia of Earth Sciences Series. Springer, Dordrecht, pp. 4020–4399.
Gudmundsson, L., Seneviratne, S.I., 2015. A Comprehensive Drought Climatology for Europe (1950-2013). Research and Science-Policy Interfacing. eBook, pp. 31–37.
Guerreiro, S.B., Dawson, R.J., Kilsby, C., Lewis, E., Ford, A., 2018. Future heat-waves, droughts and floods in 571 European cities. Environ. Res. Lett. 13, 1–10.
Guha, S., Below, R Ph, Hoyois, Ph, 2015. EM-DAT- international disaster database. www.emdat.be.
Hall, J., Arheimer, B., Borga, M., Brázdil, R., Claps, P., Kiss, A., Kjeldsen, T.R., Kriaučiūnienė, J., Kundzewicz, Z.W., Lang, M., et al., 2014. Understanding flood regime changes in Europe: a state-of-the-art assessment. Hydrol. Earth Syst. Sci. 18, 2735–2772.
Blöschl, G., Hall, J., 2018. Spatial patterns and characteristics of flood seasonality in Europe. Hydrol. Earth Syst. Sci. 22, 3883–3901.
Henrich, G., Gobiet, A., 2012. The future of dry and wet spells in Europe: a comprehensive study based on the ENSEMBLES regional climate model. Int. J. Climatol. 32, 1951–1970.
Howard, T., Pardaens, A.K., Bamber, J.L., Ridley, J., Spada, G., Hurkmans, R.T.W.L., Lowe, J.A., Vaughan, D., 2014. Sources of 21st century regional sea-level rise along the coast of northwest Europe. Ocean Sci. 10, 473–483.
Ikeuchi, H., Hirabayashi, Y., Yamazaki, D., Muis, S., Ward, P.J., Winsemius, H.C., Verlaan, M., Kanae, S., 2017. Compound simulation of fluvial floods and storm surges in a global coupled river-coast flood model: model development and its application to 2007 Cyclone Sidr in Bangladesh. J. Adv. Model. Earth Syst. 9, 1847–1862.
INSPIRE Geoportal, 2019. INSPIRE Geoportal is infrastructure for spatial information in Europe. http://inspire-geoportal.ec.europa.eu/, Accessed date: 10 January 2019.
IPCC, 2018. Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. pp. 1–34.
IUCN, 2018. Nature-based Solutions. https://www.iucn.org/, Accessed date: 9 December 2018.
Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., et al., 2014. EURO-cordex: new high-resolution climate change projections for European impact research. Reg. Environ. Chang. 14, 563–578.
Joint Research Centre Data Catalogue, 2019. Joint Research Centre. http://data.jrc.ec.europa.eu/, Accessed date: 22 January 2019.
Jomelli, V., Pech, V.P., Chochillon, C., Brunstein, D., 2004. Geomorphic variations of debris flows and recent climatic change in the French Alps. Clim. Change 64, 77–102.
Jones, H.P., Hole, D.G., Zavaleta, E.S., 2012. Harnessing nature to help people adapt to climate change. Nat. Clim. Chang. 21, 504–509.
Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., Haase, D., Knapp, S., Korn, H., Stadler, J., Zaunberger, K., Bonn, A., 2016. Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. Ecol. Soc. 2, 21–39.
Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A., 2018. The superior effect of nature based solutions in land management for enhancing ecosystem services. Sci. Total Environ. 610–611, 997–1009.
Kendon, E.J., Roberts, N.M., Fowler, H.J., Roberts, M.J., Chan, S.C., Senior, C.A., 2014. Heavier summer downpours with climate change revealed by weather forecast resolution model. Nat. Clim. Chang. 4, 570–576.
Khazai, B., Ingram, J.C., Saah, D., 2007. The Protective Role of Natural and Engineered Defence Systems in Coastal Hazards. Spatial Informatics Group LLC Literature Review Report. https://sig-gis.com/.
Klose, M., Maurischat, P., Damm, B., 2015. Landslide Impacts in Germany: a Historical and Socioeconomic Perspective. Landslides, pp. 183–199.
Kolb, A., Diekmann, M., 2004. Effects of environment, habitat configuration and forest continuity on the distribution of forest plant species. J. Veg. Sci. 15, 199–208.
Kreibich, H., Bubeck, P., Kunz, M., Mahlke, H., Parolai, S., Khazai, B., Daniell, J., Lakes, T., Schröter, K., 2014. A review of multiple natural hazards and risks in Germany. Nat. Hazards 72, 2279–2304.
Kundzewicz, Zbigniew W., Krysanova, V., Dankers, R., Hirabayashi, Y., Kanae, S., Hattermann, F.F., Huang, S., Milly, P.C.D., Stoffel, M.H., Driessen, P.P.J., Matczak, Piotr, Quevauviller, P., Schellnhuber, H.J., 2017. Differences in flood hazard projections in Europe – their causes and consequences for decision making. Hydrol. Sci. J. 62, 1–14.
Lehmann, J., Coumou, D., Frieler, K., 2015. Increased record-breaking precipitation events under global warming. Clim. Change 132, 501–515.
Lehner, F., Deser, C., Sanderson, B.M., 2016. Future risk of record-breaking summer temperatures and its mitigation. Clim. Change 146, 363–375.
Losada, I.J., Reguero, B.G., Méndez, F.J., Castanedo, S., Abascal, A.J., Mínguez, R., 2013. Long-term changes in sea-level components in Latin America and the Caribbean. Glob. Planet. Chang. 104, 34–50.
Marchi, L., Borga, M., Preciso, E., Gaume, E., 2010. Characterisation of selected extreme flash floods in Europe and implications for flood risk management. J. Hydrol. 394, 118–133.
McBean, G., 2013. Hydrometeorological Hazards. Encyclopedia of Earth Sciences Series. Springer, Dordrecht (eBook), pp. 497–507.
Merz, R., Blöschl, G., 2003. Regional flood risk-what are the driving processes, water resources systems - hydrological risk management and development. Int. Assoc. Hydrol. Sci. (IAHS) 281, 49–58.
Merz, R., Bloschl, G., 2008. Flood frequency hydrology: 1. Temporal, spatial, and causal expansion of information. Water Resour. Res. 44, 1–17.
Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., 2008. Stationarity is dead: whiter water management? Science 319, 573–574.
Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. J. Hydrol. 391, 202–216.
Moos, C., Bebi, P., Schwarz, M., Stoffel, M., Sudmeier-Rieux, K., Dorren, L., 2017. Ecosystem-based disaster risk reduction in mountains. Earth Sci. Rev. 177, 497–513.
Mueller, B., Seneviratne, S.I., 2012. Hot days induced by precipitation deficits at the global scale. Proc. Natl. Acad. Sci. 31, 12398–12403.
Munang, R., Thiaw, I., Alverson, K., Liu, J., Han, Z., 2013. The role of ecosystem services in climate change adaptation and disaster risk reduction. Curr. Opin. J. 5, 47–52.
Munich Re-NatCatSERVICE, 2019. Natural Catastrophe Know-How for Risk Management and Research. Natural Catastrophe Online Tool. Available online: http://natcatservice.munichre.com/, Accessed date: 20 July 2019.
Narayan, S., Beck, M.W., Reguero, B.G., Losada, I.J., van Wesenbeeck, B., Pontee, N., et al., 2016. The effectiveness, costs and coastal protection benefits of natural and nature-based defences. PLoS ONE J. Pone 5, 1–17.
Natural Hazards-NBS, 2019. The Natural Hazards – Nature-Based Solutions. https://naturebasedsolutions.org/map, Accessed date: 12 January 2019.
Nesshöver, C., Assmuth, T., Irvine, K.N., Rusch, G.M., Waylen, K.A., Delbaere, B., Krauze, K., 2017. The science, policy and practice of nature-based solutions: an interdisciplinary perspective. Sci. Total Environ. 579, 1215–1227.
Nicolas, Faivre, Fritz, Marco, Freitas, Tiago, Boissezon Birgit de, Sofie, Vandewoestijne, 2017. Nature-Based Solutions in the EU: Innovating with Nature to Address Social, Economic and Environmental Challenges. Environmental Research159, pp. 509–518.
Nied, M., Pardowitz, T., Nissen, K., Ulbrich, U., Hundecha, Y., Merz, B., 2014. On the relationship between hydro-meteorological patterns and flood types. J. Hydrol. 519, 3249–3262.
Norton, B.A., Coutts, A.M., Livesley, S.J., Harris, R.J., Hunter, A.M., Williams, N.S.G., 2015. Planning for cooler cities: a framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. Landsc. Urban Plan. 134, 127–138.
OPERANDUM GeoIKP, 2019. Open-air Laboratories for Nature Based Solutions to Manage Hydro-Meteo Risks, Geo-Information Knowledge Platform. , Accessed date: 18 February 2019.
Oppla, 2019. The Open Platform, Oppla. https://oppla.eu/, Accessed date: 12 January 2019.
Orlowsky, B., Seneviratne, S.I., 2013. Elusive drought: uncertainty in observed trends and short-and long-term CMIP5 projections. Hydrol. Earth Syst. Sci. 17, 1765–1781.
PANORAMA, 2019. PANORAMA Platform. https://panorama.solutions/en, Accessed date: 29 March 2019.
Paprotny, D., Sebastian, A., Morales Nápoles, O., Jonkman, S.N., 2018. Trends in flood losses in Europe over the past 150 years. Nat. Commun. 9, 1–12.
Paton, D., Johnston, D., Thomas, Charles C., 2006. Disaster Resilience: an Integrated Approach, vol. 22. Publisher, Ltd., Springfield, pp. 300–321.
Paul, S.H., Sharif, H.O., Crawford, A.M., 2018. Fatalities caused by hydrometeorological disasters in Texas. Geosciences 186, 1–23.

Pinsky, M.L., Guannel, G., Arkema, K.K., 2013. Quantifying wave attenuation to inform coastal habitat conservation. Ecosphere 4, 1–16.
Polemio, M., Lonigro, T., 2014. Trends in climate, short-duration rainfall, and damaging hydrogeological events (Apulia, southern Italy). Nat. Hazards 75, 515–540.
Porcù, F., Caracciolo, C., Prodi, F., 2003. Cloud systems leading to flood events in Europe: a short term climatology. Meteorol. Appl. 10, 217–227.
Potchter, O., Cohen, P., Bitan, A., 2006. Climatic behavior of various urban parks during hot and humid summer in the Mediterranean city of Tel Aviv, Israel. Int. J. Climatol. 26, 1695–1711.
Quevauviller, P., Gemmer, M., 2015. EU and international policies for hydro-meteorological risks: operational aspects and link to climate action. Adv. Clim. Change Res. 674–679.
Rasmussen, P., Sonnenborg, T.O., Goncear, G., Hinsby, K., 2013. Assessing impacts of climate change, sea level rise, and drainage canals on saltwater intrusion to coastal aquifer. Hydrol. Earth Syst. Sci. 17, 421–443.
Raymond, C.M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Nita, M.R., Calfapietra, C., 2017. A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. Environ. Sci. Policy 77, 15–24.
Reguero, B.G., Beck, M.W., Bresch, D.N., Calil, J., Meliane, I., 2018. Comparing the cost effectiveness of nature-based and coastal adaptation: a case study from the Gulf Coast of the United States. PLoS One J. Pone 1–24 0192132.
Robert, Costanza, Pérez-Maqueo, Octavio, Luisa Martinez, M., Paul, Sutton, Anderson, Sharolyn J., Mulder, Kenneth, 2008. The value of coastal wetlands for hurricane protection, AMBIO. J. Hum. Environ. 37, 241–248.
Roebeling, P.C., Costa, L., Magalhães-Filho, L., Tekken, V., 2013. Ecosystem service value losses from coastal erosion in Europe: historical trends and future projections. J. Coast. Conserv. 17, 389–395.
Rowe, D.B., 2011. Green Roofs as a Means of Pollution Abatement. Environmental Pollution159, pp. 2100–2110.
Russo, S., Sillmann, J., Fischer, E.M., 2015. Top ten European heatwaves since 1950 and their occurrence in the coming decades. Environ. Res. Lett. 10, 1–15.
Schlögl, M., Matulla, C., 2018. Potential future exposure of European land transport infrastructure to rainfall-induced landslides throughout the 21st century. Nat. Hazards Earth Syst. Sci. 18, 1121–1132.
Seneviratne, S.I., Donat, M.G., Mueller, B., Alexander, L.V., 2014. No pause in the increase of hot temperature extremes. Nat. Clim. Chang. 4, 161–163.
Shanahan, D.F., Lin, B.B., Bush, R., Gaston, K.J., Dean, J.H., Barber, E., Fuller, R.A., 2015. Toward improved public health outcomes from urban nature. Am. J. Public Health 105, 470–477.
Sippel, S., Otto, F.E.L., 2014. Beyond climatological extremes assessing how the odds of hydrometeorological extreme events in South-East Europe change in a warming climate. Clim. Change 125, 381–398.
Spinoni, J., Neumann, G., Vogt, J.V., Barbosa, P., 2015. The biggest drought events in Europe from 1950 to 2012. J. Hydrol.: Reg. Stud. 3, 509–524.
Stagge, J.H., Kohn, I., Tallaksen, L.M., Stahl, K., 2015. Modeling drought impact occurrence based on meteorological drought indices in Europe. J. Hydrol. 530, 37–50.
Stephan, Pauleit, Hansen, Rieke, Lorance Rall, Emily, Teresa, Zölch, Andersson, Erik, Luz Ana, Catarina, Luca, Szaraz, Tosics, Ivan, Kati, Vierikko, 2017. Urban landscapes and green infrastructure. Environ. Sci. 23, 1–53. https://doi.org/10.1093/acrefore/9780199389414.013.
Stoffel, M., Tiranti, D., Huggel, C., 2014. Climate change impacts on mass movements Case studies from the European Alps. Sci. Total Environ. 493, 1255–1266.
Stovin, V., 2010. The potential of green roofs to manage urban stormwater. Water Environ. J. 24, 192–199.
Stovin, V., Vesuviano, G., Kasmin, H., 2012. The hydrological performance of a green roof test bed under UK climatic conditions. J. Hydrol. 414 (415), 148–161.
Suursaar, Ü., Kullas, T., Szava-Kovats, R., 2009. Wind and wave storms, storm surges and sea level rise along the Estonian coast of the Baltic Sea. Trans. Ecol. Environ. 127, 149–160.
Swiss, Re, 2019. Swiss Re Databases 9980-2018. https://swissre.com, Accessed date: 9 January 2019.
Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M.J., Ysebaert, T., De Vriend, H.J., 2013. Ecosystem-based coastal defence in the face of global change. Nature 504, 79–83.
Teramoto, Y., Shimokawa, E., Jitosono, T., 2005. Effects of volcanic activity on volcanic ash deposition and erosion rate in the Hikinohira and Saido River Basins in Mt. Sakurajima. Res Bull Kagoshima Univ 33, 21–28.
ThinkNature platform, 2019. ThinkNature Platform. https://www.think-nature.eu/, Accessed date: 10 January 2019.
Touma, D., Ashfaq, M., Nayak, M.A., Kao, S.-C., Diffenbaugh, N.S., 2015. A multi-model and multiindex evaluation of drought characteristics in the 21st century. J. Hydrol. 526, 196–207.
Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R., Sheffield, J., 2014. Global warming and changes in drought. Nat. Clim. Chang. 4, 17–22.
Turkington, T., 2016. A new flood type classification method for use in climate change impact studies. Weather Clim. Extremes 14, 1–16.
UNEP, 2014. Green Infrastructure Guide for Water Management: Ecosystem-Based Management Approaches for Water-Related Infrastructure Projects. UNEP, UNEP-DHI, IUCN and TNC.
UNISDR, 2009. UNISDR Terminology on Disaster Risk Reduction. UNISDR, Geneva, Switzerland 35-35.
Urban Nature Atlas, 2019. Urban Nature Atlas. https://naturvation.eu/atlas, Accessed date: 18 January 2019.
Van der Linden, P., Mitchell, J.F.B., 2009. ENSEMBLES: Climate Change and its Impact: Summary of Research and the Results from the ENSEMBLES Project. Met Office Hadley Centre, Exeter, pp. 160.
Van Loon, A.F., 2015. Hydrological Drought Explained, vol. 2. Wiley Interdisciplinary Reviews: Water, pp. 359–392.
van Slobbe, E., de Vriend, H.J., Aarninkhof, S., Lulofs, K., de Vries, M., Dircke, P., 2013. Building with Nature: in search of resilient storm surge protection strategies. Nat. Hazards 66, 1461–1480.
Viglione, A., Chirico, G.B., Komma, J., Woods, R., Borga, M., Blöschl, G., 2010. Quantifying space-time dynamics of flood event types. J. Hydrol. 394, 213–229.
Vineyard, D., Ingwersen, W.W., Hawkins, T.R., Xue, X., Demeke, B., Shuster, W., 2015. Comparing green and grey infrastructure using life cycle cost and environmental impact: a rain garden case study in Cincinnati. J. Am. Water Resour. Assoc. 51, 1342–1360.
Vojinovic, Z., Abbott, M.B., 2012. Flood Risk and Social Justice: from Quantitative to Qualitative Flood Risk Assessment and Mitigation. IWA Publishing.
Vormoor, K., Lawrence, D., Schlichting, L., Wilson, D., Wong, W.K., 2016. Evidence for changes in the magnitude and frequency of observed rainfall vs. snowmelt driven floods in Norway. J. Hydrol. 538, 33–48.
Vousdoukas, M.I., Voukouvalas, E., Annunziato, A., Giardino, A., Feyen, L., 2016. Projections of extreme storm surge levels along Europe. Clim. Dyn. 47, 3171–3190.
Wamsler, C., Pauleit, S., 2016. Making headway in climate policy mainstreaming and ecosystem-based adaptation: two pioneering countries, different pathways, one goal. Clim. Change 137, 71–87.
Watkiss, P., Hunt, A., 2012. Projection of economic impacts of climate change in sectors of Europe based on bottom up analysis: human health. Clim. Change 112, 101–126.
Wirtz, A., Kron, W., Löw, P., Steuer, M., 2012. The need for data: natural disasters and the challenges of database management. Nat. Hazards 70, 135–157.
Woth, K., Weisse, R., Von Storch, H., 2006. Climate change and North Sea storm surge extremes: an ensemble study of storm surge extremes expected in a changed climate projected by four different regional climate models. Ocean Dyn. 56, 3–15.
Xing, Y., Jones, P., Donnison, I., 2017. Characterisation of nature-based solutions for the built environment. Sustainability 9, 1–20.
Zevenbergen, C., Cashman, A., Evelpidou, N., Pasche, E., Garvin, S., Ashley, R., 2010. Urban Flood Management. CRC Press, London.