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Review

Hydro-meteorological risk assessment methods and management by nature-based solutions

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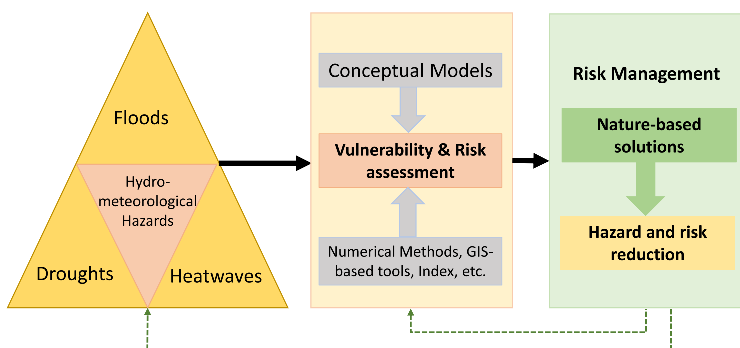
HIGHLIGHTS

- HMRs are an interplay of hazard, exposure, vulnerability and adaptation.
- R and MATLAB are common statistical tools employed to analyse the data.
- Fuzzy logic, FFA and mathematical models are used to evaluate the flood risk.
- Indices, SWI, econometric models are generally used to assess drought risk.
- Vulnerability map and health association are common for heatwave risk assessment.
- Selecting an apt method and NBS for assessment helps in HMR risk management.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydro-meteorological risk (HMR) management involves a range of methods, such as monitoring of uncertain climate, planning and prevention by technical countermeasures, risk assessment, preparedness for risk by early-warnings, spreading knowledge and awareness, response and recovery. To execute HMR management by risk assessment, many models and tools, ranging from conceptual to sophisticated/numerical methods are currently in use. However, there is still a gap in systematically classifying and documenting them in the field of disaster risk management. This paper discusses various methods used for HMR assessment and its management via potential nature-based solutions (NBS), which are actually lessons learnt from nature. We focused on three hydro-meteorological hazards (HMHs), floods, droughts and heatwaves, and their management by relevant NBS. Different methodologies related to the chosen HMHs are considered with respect to exposure, vulnerability and adaptation interaction of the elements at risk. Two widely used methods for flood risk assessment are fuzzy logic (e.g. fuzzy analytic hierarchy process) and probabilistic methodology (e.g. univariate and multivariate probability distributions). Different kinds of indices have been described in the literature to define drought risk, depending

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Vulnerability
Exposure

upon the type of drought and the purpose of evaluation. For heatwave risk estimation, mapping of the vulnerable property and population-based on geographical information system is a widely used methodology in addition to a number of computational, mathematical and statistical methods, such as principal component analysis, extreme value theorem, functional data analysis, the Ornstein–Uhlenbeck process and meta-analysis. NBS (blue, green and hybrid infrastructures) are promoted for HMR management. For example, marshes and wetlands in place of dams for flood and drought risk reduction, and green infrastructure for urban cooling and combating heatwaves, are potential NBS. More research is needed into risk assessment and management through NBS, to enhance its wider significance for sustainable living, building adaptations and resilience.

Contents

1. Introduction

Hazard can be defined as a potential source of damage or harm to people and the environment (Pryor, 2012). Hazards can be natural (e.g. forest fire, landslide) or anthropogenic (e.g. chemicals, radioactive materials, fireworks). Hazard on various scales can be potentially disastrous to vulnerable species and environments (IPCC, 2014b; UNDRR, 2019). Therefore, the two words, '*hazard*' and '*disaster*' are used interchangeably. Exposure denotes the confrontation of a body with hazard, that is susceptible to negative effects, e.g. buildings, infrastructure, population and surrounding environment. Vulnerability represents the sensitivity of different bodies to a particular hazard strength (Lyu et al., 2019). Thus, hazard (or disaster caused by hazard) poses risk to society, assets and ecosystem in a given period, based on the extent of exposure to that hazard, the vulnerability of affected people, property or surroundings (Carrão et al., 2016), and their resilience, or adaptation in response to the hazard. Risk is the possibility of occurrence of an undesirable event (e.g. storm), death (individual risk), and any other kind of probable loss (Mikellidou et al., 2018). Hazards of atmospheric, hydrological or oceanographic origin are called hydro-meteorological hazards (HMHs) (UNDRR, 2019). Floods, droughts, storm surges, landslides, heatwaves, salt intrusion events and excess nutrient loadings are a few examples of HMHs, which pose a significant risk (or multi-risks when occurring simultaneously) to an environment. Merz et al. (2010) define hydro-meteorological risk (HMR) as the probability of damage or harmful consequences in a certain time period due to an HMH and its interplay with vulnerability, exposure and ability of the affected humans and ecosystem to adapt.

Due to global warming and climate change in general, the duration, magnitude, scale and frequency of climate-related risks, in particular HMRs, are projected to increase and become worse (IPCC, 2012a). HMRs linked to climate change include drought, storm-surge, heatwaves, floods, coastal erosion, excess nutrient loading and landslides; these are expected to increase in their frequency and magnitude in the future (Norén et al., 2016; Ahmadalipour and Moradkhani, 2018; Abadie et al., 2019; Gaitán et al., 2019). Loss or damage due to HMRs can be managed or mitigated by planning proper management strategies in advance, along with properly evaluating the risk of the hazard through effective risk assessment methodologies. However, the existing assessment and management solutions may not be sufficient considering the projected scale and nature of HMH. To manage these HMRs in present and future scenarios, long-lasting, cost-effective and environmentally sustainable solutions are required, which is one motivation of this study.

Nature-based solutions (NBS) have proved to be effective for HMR management (Kalantari et al., 2018). NBS, in essence, apply the lessons learned from nature itself in mitigating the damage caused by HMH (Kalantari et al., 2019). NBS is a relatively new concept and offers significant cost-efficient methods while discouraging structural interventions (like concrete buildings). However, the establishment of robust scientific evidence with respect to NBS efficacy, at specific spatial and time scales, remains challenging. The NBS concept is related closely to sustainability, harmonious and green development, resources rational exploitation, coupled human and environment, and ecological protection priority. Therefore, there is currently research on risk management based on NBS.

The concept of risk and its assessment are given different interpretations by various scientific studies and researchers working in the area of hydro-meteorological and other kind of hazards (Aven, 2012). Table 1 provides a summary of past reviews on risk assessment methods used for HMHs. Mikellidou et al. (2018) assessed the research related to the risk towards energy critical infrastructures, such as production and distribution systems, in regard to climate change and extreme weather events as well as protection and building adaptation against them. The author reviewed some risk assessment concepts which defined risk as a product of hazard, exposure and vulnerability, and sometimes prepapredness deficiency or capacity measure. A description on these and other risk assessment types or models in use were missing. A few past reviews, summarized in Table 1, have mentioned some methods and models dealing with flood, drought and heatwave risk assessment. However, these reviews have not comprehensively addressed the following topics that are the focus of this review article: (1) models and tools ranging from conceptual to sophisticated/numerical methods (2D, 3D and copulas) as well as the used techniques (statistical

Table 1
Summary of relevant past reviews on risk assessmentand management for HMHs.

HMR	Summary	Limitation or gap	Reference
Flood	Risk assessment was classified into qualitative and quantitative methods. Few references were given where risk was a function of hazard, exposure, vulnerability and sometimes preparedness deficiency or capacity measure.	Other methods or models for specific hazards were missing.	Mikellidou et al. (2018)
	Numerical modelling technique utilising hydrological and river modelling parameters were reviewed and 1-D and 2-D models were compared. Necessity of 3-D model was pointed out to make elevation difference and vertical roughness in the grids to understand dynamic behaviour of flooding.	Limited to numerical modelling techniques	Anees et al. (2016)
	State-of-the-art economic flood damage assessment is reviewed. Three steps: classification of elements at risk, quantification of exposed asset values and susceptibility in different sectors, were described for assessment of direct economic damage of flood.	Limited to economic flood damage assessment as a tool of risk management.	Merz et al. (2010)
	Methods for the estimation of loss of lives due to different types of floods (e.g. for dam breaks, coastal floods, tsunamis) in different regions have been reviewed. A new method was proposed for flooding of low-lying areas. By combination of the loss of life estimates with available information regarding the probability of occurrence of flood scenarios, the flood risks can be estimated.	Limited to loss of lives method.	Jonkman et al. (2008b)
	Three flood inundation models were reviewed: empirical, conceptual and hydrodynamic models with different dimensions (1D, 2D and 3D). Empirical methods are good for flood monitoring and post-disaster assessment, but hydrodynamic models represent detailed flow dynamics which is required to study the impacts of dam breaks, tsunamis or flash flood.	Restricted to flood inundation only	Teng et al. (2017)
	Four approaches to assess regional flood risk based on representative researches from 2000 to 2017 were mentioned (1) statistical methods (2) multi- criteria analysis, (3) analysis based on Geographical Information System (GIS) and Remote Sensing (RS) techniques, and (4) scenario- based inundation analysis with their limitations of use. They have assessed flood risk and highlighted that the risk anticipation process uses an iterative cycle that includes risk assessment, precaution, prediction, and technical countermeasures.	Missing types of datasets used for methods and lesser description of method/model used	Lyu et al. (2019)
Drought	Fundamental concepts of drought, its classification, indices-based drought monitoring, historical droughts using paleo-climatic studies, and the relation between droughts and large-scale climate indices were presented. More research on developing drought index considering economic losses and methodological cautions were proposed in conclusion. These can be explored further, considering the needs of the user in the region and classifying droughts based on their severity.	Drought indices can only reflect drought conditions based on hydro-meteorological variables, but it is unable to quantify the economic losses.	Mishra and Singh (2010)
	Drought forecasting (regression and time-series analysis; probability, artificial neural network and hybrid models), probability based modelling (return period and frequency analysis; univariate, bivariate and multivariate drought analysis using copula), spatio-temporal analysis, use of Global Climate Models (GCMs) for drought scenarios using large-scale hydrology models, land data assimilation systems for drought modelling, and drought planning (multi-criteria analysis, expert system/decision support system).	Comprehensive review on each type of modelling/method was missing	Mishra and Singh (2011)
	Recent major multivariate drought indices with their development methods, for e.g. blending objective and subjective indicators, water balance model, and multivariate statistical analysis, such as latent variable, linear combination, multivariate distribution, and principal component analysis, are presented with their strength and limitations	Limited to indexing method	Hao and Singh (2015)
Heatwave	Health impacts of heatwaves on global scale were reviewed. Global population density did not match the location of heatwaves and human health studies.	Gap in studies in tropical and high latitude areas.	Campbell et al. (2018)
	Review on assessment of identification of vulnerable groups and heat health interventions such as active outreach programs, exposure reduction measures and monitoring and mapping of at-risk groups to understand the effectiveness and efficiency of those intervention	Risk assessment method was missing	Mayrhuber et al. (2018)
	Variation in mortality effect due to different heatwaves definition were reviewed. Local heatwave definitions were proposed optimal for protecting and preventing people from the adverse impacts of future heatwaves.	Only mortality was focused as risk indicator	Xu et al. (2016)
	Heat-related morbidity and mortality studies from 1958 to 2012 was reviewed for high-risk populations in the U.S. and Europe.	Restricted to only human study	Kravchenko et al. (2013)
Flood and debris flow (HMR management)	Methods and techniques for emergency response were covered. Current risk management strategies mentioned are geo-information and remote sensing, emergency plans and local involvement, cross-institutional cooperation, early warning systems, awareness and preparedness, warning and response activities, forecasting and civil protection activities as decision support systems.	Concept of NBS was missing	Cortes et al. (2013)
Geo-physical and HMH (HMR management)	HMR assessment methodologies and the prevention, protection and preparedness principle for HMR management was reviewed.	Focused mainly on flood and coastal risk management methods. NBS concept was not there.	Cirella et al. (2014)

techniques) and datasets for more than one HMHs; and (2) the potentials of NBS for managing floods, droughts and heatwaves. Of the past review papers (Table 1), only Cirella et al. (2014) published a comprehensive review of current approaches and methodologies for the assessment of risks posed by a wide range of HMHs and their remediation strategies using structural and non-structural approaches. We expand the scope of this previous review by considering the higher dimensional models/tools and the newly emerged approaches, which are inspired and supported by nature such as green, blue and hybrid approach. Currently, a systematic documentation, critical evaluation and the integration of the methods and tools used for risk assessment and management of floods, droughts and heatwaves are lacking in the field of disaster risk management; and this makes the prediction of risks uncertain. Furthermore, there is also a lack of reviews on efficiency of the newly introduced NBS in risk management. NBS are in developing phase for sufficiently managing the rising impacts of climate change.

Management of risks driven by HMHs is a complex process that needs a range of methods/tools and data sets at a high spatial and temporal resolution to assess and make a decision. Additionally, due to the rising impact of climate change, this complex process is more complicated and needs systematic harmonisation of the current status of methods/tools used for risk assessment and management. Our review addresses the following questions: How can the impact of HMR be reduced? What is the existing knowledge on this topic and how it can be dealt more efficiently? The objective of this work, therefore, is to review recent developments in different risk evaluation methodologies for the selected HMHs. We also provide an overview of risk management through potential NBS, which have been applied to mitigate the risks posed by HMHs and documented in the existing literature. Still, many practitioners rely on and recommend built infrastructure projects, such as retention basins as mitigation strategy for flood (Vachaud et al., 2019), supplies of inorganic fertilizers, improved irrigation for drought (Hassan et al., 2019) and use of reflective 'cool' roofs for heatwave risks management (Macintyre and Heaviside, 2019). More research is needed to help foster and accelerate the wider uptake and systematic mainstreaming of NBS (Young et al., 2019), but is outside the scope of this work.

Therefore, this paper contributes to the existing literature by bringing together all the models/tools used in risk assessment, and using NBS as the main risk management strategy. This paper will help in improving awareness and understanding of risks, e.g. by providing adequate numerical/statistical models with those are more accurately representing the risk in all its dimensions. This review is expected to help with the selection and application of current indices for drought and heatwaves to help preparedness and response. Also, the traditional responses to floods, droughts and heatwaves have relied on grey infrastructure approach, which may not be sufficient to cope with future climate change and needs complementary/alternative approaches in the form of NBS.

2. Methods, scope and outline

We used the following keywords to identify articles related to the topic of our review: 'Flood', 'Drought', 'Heatwaves', 'Heat waves', 'Risk, Evaluation', 'Assessment', 'Analysis' and 'Nature-based solutions' in scientific literature databases (i.e. ScienceDirect, Scopus, PubMed, GoogleScholar and SurreySearch). We only reviewed the review and research articles written in the English language. The filter option was used to filter papers from the last ten years and sorted using the order of relevance tab option. The selection of literature for this review was based on the relevance of their contents, in order to fit the scope of this review article. Selected literature was again filtered after reading the abstract to make a final list of papers to be actually included in this review. The scope of this review article is to cover three of the more common risks caused by HMHs; namely, floods, droughts and heatwaves, and their management via NBS, because they are interrelated, being linked with the water-cycle, soil and air moisture, and air temperature.

We carried out a selective and scoping checks for reviewing the literature to identify the most relevant texts. The search into the database looked for a match of the keywords, preferably, in the title of the papers as its first priority, and thus we encountered the following limitations: Firstly, some papers appeared in our search that have our keywords in their title but no relation to the topic of interest. Secondly, since we selected the literature based on relevance and sorting function of the database, it could have been possible that we missed any important literature where the content was related to our study, but the title did not contain any of our keywords, and hence they might have been shown on the very latter of the webpage results. Finally, our search was limited to only publications in the English language; some results could have been worth of including but were neglected due to the language barrier.

The review has been divided into five sections. Section 1 provides a basic understanding of the topic areas covered besides introducing the concept of hazard, disaster, exposure, vulnerability and risk. The section also covers past reviews on the assessment methodologies of flood, drought and heatwaves and justifies the need for this review paper. Section 2 describes our methodological approach and defines the scope of our review paper. Section 3 discusses the HMHs (flood, drought, and heatwaves) and their associated risk evaluation methodologies. It also categorizes the HMR assessment methods into different appropriate groups. Section 4 presents the concept of NBS and the reasoning of them as a better solution over the constructed or engineered, a grey preventive method of HMR management. It also provides a review of past studies and experiences of NBS for HMR management. Finally, Section 5 draws the summary and conclusions from topic areas covered and presents a scope of future research into risk assessment and efficiency assessment of NBS for its wider acceptance.

3. Hydro-meteorological risk assessment methods

HMR assessment can be qualitative or quantitative. Qualitative risk assessments are examination or observation based methods for conformity that qualifies for the condition of a piece of legislation or a relevant norm. Quantitative risk assessments are mathematical, probabilistic or stochastic based on the existing or real-time information fed as model input. Most of these methods depend upon information and predictions on potential climate (Mikellidou et al., 2018). Extreme climatic events that trigger HMHs are generally described by Extreme Value Theory (EVT), which gives a mathematical framework for their analysis and return periods (Coles, 2001). In EVT, two approaches are used to extract extreme events from their entire time-series; namely, seasonal/annual maximum/minimum method and threshold approach, also known as peaks-over-a threshold (POT)/lows-under-a threshold (LUT) (Coles, 2001). The main assumptions in these datasets are: (1) the time series is suitably long, (2) the time-series is assumed to be independent and identically distributed (i.i.d), and (3) the time-series is stationary. Statistical models, including univariate and multivariate (copula) functions, are considered to fit these datasets and estimate their frequency of occurrence or extrapolate the magnitude associated with any exceedance probabilities of interest. Nowadays, a variety of statistical techniques/tools are used in these data mining and analysis process. Of these tools, R (R Core Team, 2019) and MATLAB (MATLAB and Statistics Toolbox Release, 2012) software are the most commonly used tools by researchers and scientists around the world.

There are several types of risk assessment methods reported in the literature to identify hazards and evaluate their risks; some of these deal with HMHs (Fig. 1). Most quantitative HMR assessment methodologies are based on available historical data or projections of future climate models, such as regional climate models (RCMs) and general circulation models (GCMs). GCMs are regionalised by means of dynamic or statistical downscaling techniques (Gaitán et al., 2019) and, although they have improved their ability to predict future climatic changes over the last decade, their estimates are still limited by their incomplete or inaccurate representations of climate-affecting processes (IPCC, 2007). Therefore, high quality data (with high spatial and temporal resolution) and competent methods/models are required for proper risk assessment (i.e. risk identification, risk analysis and risk evaluation) and risk management. Overall, the accuracy of risk management procedures depends on the types of input datasets, methods/models used and the solutions chosen, such as NBS.

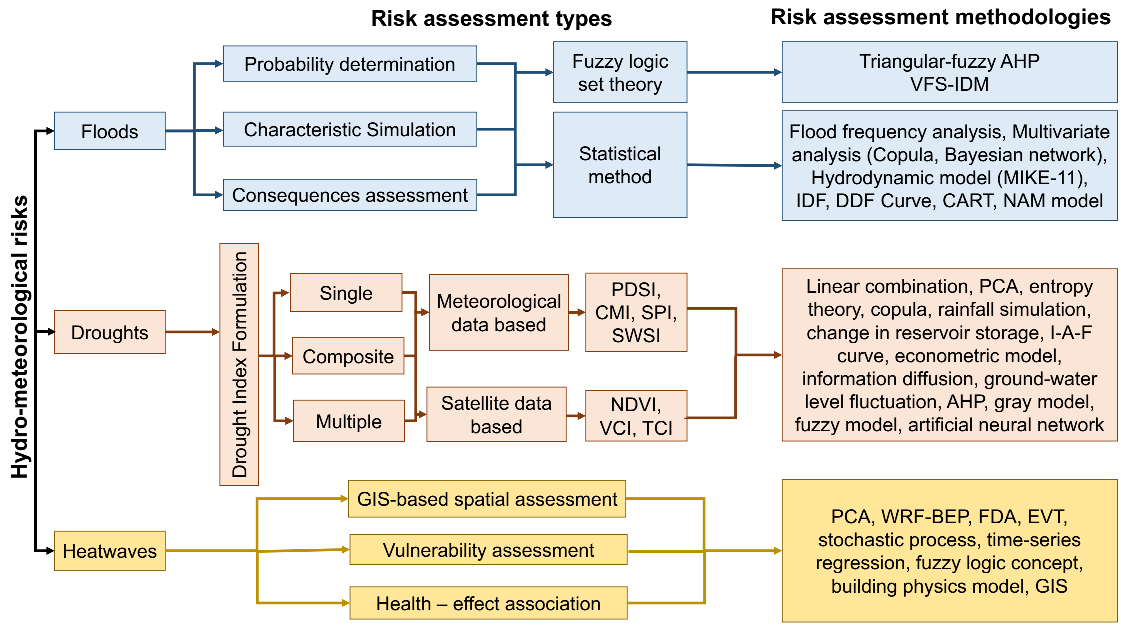

Fig. 1. Types of risk assessment and its methodologies employed in published literature for flood, drought and heatwaves hydro-meteorological risks.

3.1. Flood risk

Flood is a condition in which a landscape is submerged in water due to heavy rainfall, storm surge, high-tides or any other natural cause of water overloading; it causes devastation in lives, resources and economy on a vast scale (IPCC, 2012b). Floods are considered one of the most frequent natural disasters, causing many fatalities and damages every year (Varlas et al., 2019). In Europe between 1980 and 2016, they have caused huge loss of life, injuries, damage to property, infrastructure and ecosystems (EEA, 2010). Floods are expected to become more frequent under future climate conditions (Norén et al., 2016). Flood risk can be described as the probability of an occurrence of flood hazard leading to an associated loss, or negative impact on society (Joyce et al., 2018). Risk of flood is determined not only by the nature of the hazard, exposure to and vulnerability of the population and property, but also by the adaptation, improvement and anticipation of the affected population and ecosystem, collectively called “resilience of the environment”. Flood risks traditionally have been managed by using grey infrastructures, such as drainage systems (Zhou et al., 2019), river dykes, dunes, dams and others (Joyce et al., 2018).

3.1.1. Flood risk evaluation methods

Flood risk assessment can be handled in different ways according to Lyu et al. (2019): (1) *Statistical methods* are a way of relating extreme events to their frequency of occurrence using probability distribution functions based on long term historical/projected records. These methods take hazard and vulnerability assessment into account, need a vast amount of data and involve uncertainty in evaluating the spatial distribution of flood. (2) *Multi-criteria analysis, mostly combined with Fuzzy Analytic Hierarchy Process or GIS,* is based on an indexing system where flood risk is the object layer and hazard, exposure, and vulnerability are index layers. Determination of subjective factors of these layers is the main limitation of this method. (3) *Geographical information system (GIS)* combined with *remote sensing (RS)* techniques can analyse the hazard, exposure, and vulnerability in the output layer based on the data from the input layer (terrain, rainstorm etc.). The high cost of RS, highly resolved data requirement and inaccuracies in quantitative assessments are some drawbacks of this method. (4) *Scenario-based inundation analysis*, based on scenario analysis of risk immediately before its occurrence, is restricted to a small region and uses geomorphology, topography, and urban drainage system data.

One of the main challenges in flood risk assessment is to develop flood inundation scenarios. Currently, inundation modelling for flood are grouped into two types: empirical methods and hydrodynamic models with different dimensions (1D, 2D and 3D). Empirical methods are good for flood monitoring and post-disaster assessment, but hydrodynamic models represent detailed flow dynamics, which are required to study the impact of dam breaks, tsunamis or flash flooding (Teng et al., 2017). Empirical methods of inundation modelling are based on the historical observational data collected through surveys and measurements, which are then analysed to prepare a robust scenario of flood inundation. The findings of these models are generally used for decision making as well as used as an input to other models such as flood extent analysis using remote sensing, or setting the benchmark for hydrodynamic models (Smith, 1997). On the other hand, hydrodynamic models are mathematical computational models that generate scenarios of flood inundation based on simulation of water movement in the potential flood-prone area (Anees et al., 2016). There are 1D, 2D and 3D numerical techniques for hydrodynamic modelling to find out the causes and changes in topography and climate which lead to flooding. 1D models (e.g. HEC-RAS, MIKE 11) simply represent the flood flow in one-dimension along the central line of the river (Brunner, 2016; Anees et al., 2016), whereas 2D models (e.g. FLO 2D Pro) present flood flow in two-dimensions along the longitudinal and horizontal area of river channel (DHI, 2012; Roberts et al., 2015). 2D models are widely applied in preparing flood extent map and flood risk assessment (Anees et al., 2016). 3D models, although considered highly complex and rarely used, were developed adding water depth as the third dimension, which allows the representation of inundation of vertical features during catastrophic flooding such as inundation due to dam brakes, flash flood, tsunamis and breaching of levees (Anees et al., 2016; Monaghan, 1994).

Walker and Burningham (2011) studied patterns of social inequality for flood risk exposure, impact and vulnerability in relation to deprivation, poverty, age and gender in the UK. They found that the factors responsible for social inequality patterns were flood management practices and climate change, and they argue that environmental inequalities should be addressed. Economic flood damage assessment (Merz et al., 2010) and assessment methodologies utilising the loss of lives due to floods (Jonkman et al., 2008b) are also available for comprehensive flood risk assessment. There are some multi-risk assessment methods such as Bayesian networks, agent-based models, system dynamic models, event and fault trees, and hybrid models (Terzi et al., 2019), in which flood risk assessment can be incorporated.

General methods employed to analyse the risk of flood are flood probability determination, flood characteristics simulation and assessment of flood consequences (Jonkman et al., 2008a). Table 2 provides a summary of relevant studies applying different methodologies/models for risk evaluation of flood hazard. These can be broadly categorised into two types (Yang et al., 2013): (1) methods utilising fuzzy logic set theory or a comprehensive index method (Li et al., 2012); and (2) methods involving probability theory (Romanowicz and Kiczko, 2016).

3.1.1.1. Fuzzy logic methodology. Fuzzy logic set theory employs a synthetic value by taking into account all kinds of indicators to measure the level of risk; the value can be a function of mortality or be expressed in monetary terms such as economic loss (Ji et al., 2013). Yang et al. (2013) used a triangular fuzzy analytic hierarchy process (AHP) based model for the importance ranking of risk indices, comprehensive flood prediction and risk response measure analysis. The fuzzy risk of flood disasters was analysed and the flood risk was quantitatively calculated in the area of Lower Yangtze River, China. Li et al. (2012) claimed that a fuzzy model based on variable fuzzy sets (VFS) and information diffusion method (IDM) was better than statistical estimation for flood risk, because the result of the VFS-IDM model was closer to the standard. The assessment of flood risk was done by (1) deciding the flood indicator weights using AHP, (2) converting the multi-dimensional indicators of the samples into the one-dimensional degree value using VFS-AHP, (3) turning the degree value of the sample into a fuzzy set, then getting the required risk estimation value by IDM, and (4) calculating the return period according to the risk estimation value.

3.1.1.2. Flood frequency analysis. Flood frequency analysis (FFA) has been applied to estimate flood quantiles by Romanowicz and Kiczko (2016). They simulated water-levels with a distributed flow routing model, using annual maximum river flows for Vistula catchment in Poland and mapped the probability of inundation of the required return period. Historical discharge samples are inapt in representing the effect of upstream river overflow on downstream extreme flood frequencies because it rarely happens when upstream areas are secured by the river dyke system (Tanaka et al., 2017). Especially, in large river basin which includes several potential flood plain, river overflow in upstream areas needs to be considered when assessing flood risk using FFA techniques to prevent over/underestimation of flood risk downstream. In addition, the underlying conditions of the basin, such as size and shape, vegetation cover, relief and steepness, number of tributaries and antecedent conditions (i.e. snow depth and soil moisture) also yield an over/underestimation of the risk associated with flood events (Merz and Blöschl, 2003). Tanaka et al. (2017) used a rainfall-based flood frequency model (RFFM) to examine the impact of upstream dam operation and overflow from upstream river dykes for Yodo River basin in Japan and estimated extreme flood frequency beyond the design level. In this study, a flood-inundation model of the upstream Kyoto City area was combined with RFFM, which accounted for the probability of spatial and temporal rainfall patterns over the river basin.

Sometimes flood is caused by a combination of factors such as peak flow, its duration and volume. In such a case, a multivariate risk analysis method that takes into account more than one variable can be used. Bayesian networks and Copulas have been utilized for analysing multivariate FFA for the application of hydraulic design (i.e. the estimation of 100 years return period). Joyce et al. (2018) used copula functions to model the association between flood risk and engineering resilience. Risk was formulated using a resilience metric dependent upon the hazard, vulnerability and exposure of the area in question, namely the Cross Bayou Watershed in Florida. A trivariate copula-based methodology

Table 2
Summary of relevant studies applying different methodologies/models for risk evaluation of flood hazard and the type of required data.

Place	Model/Method	Datasets	Reference
Cross Bayou Watershed, Florida (Coastal flood)	Copula analysis, Interconnected Pond and Channel Routing (ICPR) catchment model	Daily rainfall, daily average wind speed, daily barometric pressure and moon phasing for hazard; distance to a major water body, slope, elevation from a digital elevation map (DEM), soil condition and percent imperviousness for vulnerability; terrain data, hydrologic data, hydraulic data, and climate data for exposure and resilience data (green-blue-grey and their respective recovery time)	Joyce et al. (2018)
Warsaw reach of the River Vistula, Poland	Flood frequency analysis using water levels simulated by distributed flow routing model, Generalized Likelihood Uncertainty Estimation (GLUE) for uncertainty	Channel and floodplain geometry data, hydrological data (maximum annual flows, water levels and stages)	Romanowicz and Kiczko (2016)
Delaware River basin at Port Jervis, NY, USA.	Trivariate copula-based approach	Annual maximum peak discharge, volume, and duration of flood event (61 years- 1949 to 2009)	Ganguli and Reddy (2013)
Lower Yangtze River, China	Hybrid evaluation model based on fuzzy analytic hierarchy process (AHP) and triangular fuzzy number (TFN)	DEM (digital elevation model) data, Digital Orthophoto Map (DOM) data, rainfall data, elevation data, land use data, and the social and economic data.	Yang et al. (2013)
Hunan, China	Multiple linear regression and Classification and regression tree (CART) model	Direct economic loss data, total precipitation and rainstorm days data, surface condition data (soil type, river density, relief degree of the land surface (RDLS), leading geomorphic type) and vulnerability data (population, GDP, road and embankment density)	Ji et al. (2013)
China	Analytic hierarchy process (AHP), Information diffusion method (IDM) and Variable fuzzy set (VFS) methodology	Disaster area, collapsed houses, dead population, inundated area	Li et al. (2012)
Yom River, Thailand	Nedbør-Afstrømnings (NAM) Model, a rainfall–runoff hydrologic model and the MIKE-11 hydrodynamic model with GIS, Risk = Hazard factor times vulnerability factor	Temporal rainfall data, run-off data, catchment properties, evaporation, river cross-section, topographic survey data, crop-yield data and unit price of each crop type, infrastructural data	Tingsanchali and Karim (2010)
Mulde river, Germany	Spatial multi-criteria analysis (MCA): a disjunctive and an additive weighting approach with GIS, software tool FloodCalc	Inundation data, value of assets, land-use data, point data of social hot spots and environmental values data	Meyer et al. (2009)
Jiaxing, China	InfoWorks ICM model, Copula	Rainfall data	Zhou et al. (2019)
Hirakata, Japan	Rainfall based flood frequency model	Rainfall data	Tanaka et al. (2017)

was used by Ganguli and Reddy (2013) for effective risk assessment of floods. The joint distribution of three flood variables (annual peak flow, volume and duration) was constructed based on four trivariate copulas, namely, three fully nested forms of Archimedean copula families (Clayton, Gumbel–Hougaard, and Frank copulas); and one elliptical copula family (Student's t copula).

3.1.1.3. Methodology for urban flooding. Failure of urban drainage systems due to hydraulic overloading during heavy rainfall or storm events can lead to urban flooding. Intensity-duration-frequency (IDF) curves, depth-duration-frequency (DDF) curves along with design storm have been used in drainage system design and risk evaluation for urban flooding (Zhou et al., 2019). Zhou et al. (2019) developed a new probabilistic analysis methodology for the assessment of urban flood risks considering catchment-specific drainage system in Jiaxing, China. After extracting characteristic parameters from random hyetographs, a hydrodynamic model which uses InfoWorks ICM, simulated the operating conditions of a drainage system under some input rainfalls. Based on the model simulation results, a correlation analysis was conducted between storm event characteristics and urban flood which provided two most sensitive parameters of storm events - mean rainfall intensity (I) and peak 30-min rainfall intensity (30-Rp) - to the magnitudes of floods and their thresholds. Copula methods were applied to describe the joint probability distribution of the I and 30-Rp, and flood risk was assessed by calculating the frequency of occurrence of all the storm events for which the sensitive parameters exceeded the defined threshold.

3.1.1.4. Mathematical modelling. Meteorological impact factors such as total precipitation and rainfall days in the rainy season have more impact on flood risk than other surfaces (altitude and soil) and vulnerability (population, GDP, roads, embankment) parameters. Ji et al. (2013) used a classification and regression tree (CART) to evaluate flood risk in the Hunan Province of China. CART is a tree-based models and suitable for flood damage modelling because they allow for non-linearities, predictor interactions and the use of categorical and continuous variables (Sieg et al., 2017). The model calculated major impact factors from complex variables and determined their threshold, which was then used to evaluate the flood risk. They used root mean square error (RMSE) as a method of comparison between the two models used and the result showed that RMSE was less for CART than for multiple linear regression. Run-off for a given set of rainfall data was modelled by using the NAM rainfall–runoff model (Tingsanchali and Karim, 2010), and the MIKE-11 hydrodynamic model was used to simulate flood-wave propagation for flooding scenarios of 25, 50, 100 and 200 year return periods, for the Phrae flood plain of the Yom River basin in northern Thailand. Risk was calculated as a product of hazard and vulnerability factors for 50, 100 and 200 year return period floods. A GIS database of economic, social and environmental risk criteria was framed and two approaches of multi-criteria analysis, a disjunctive and an additive weighting approach based on GIS, were utilized for an overall flood risk assessment in the area of the River Mulde in Saxony, Germany (Meyer et al., 2009).

3.2. Drought risk

Natural disasters are increasing at an alarming rate all over the world, and drought is among the most severe natural calamities, causing great harm to humans, agricultural production and society (Yang et al., 2018). It is usually defined as a recurring climate phenomenon characterized by water deficit over a period of time ranging from months to years, in contrast to flooding which happens in a smaller timescale. It is characterized by slow development, long duration, high severity and vast affected areas. Drought can be of four types according to its driving mechanisms (Belal et al., 2014): *meteorological*, *hydrological*, *agricultural* and *socioeconomic*. *Meteorological* drought is a period of months to years with a deficit in precipitation or climatological water balance (i.e. precipitation minus potential evapotranspiration) over a given region. This deficit is defined with respect to the long-term climatology. *Agricultural* drought is a period with reduced soil moisture around the root zone of plants that results from below-average precipitation, less frequent rain events, or above-normal evaporation. *Hydrological* drought occurs when river streamflow and water storages in aquifers, lakes, or reservoirs fall below long-term mean levels (Miah et al., 2017). Hydrological drought develops more slowly because it involves stored water that is depleted but not replenished. *Socioeconomic* drought relates to the availability and the requirements of certain economic goods or services combined with the three previous forms of drought (AMS, 2004). Understanding the inter-relationship of these types of drought propagation could be a crucial part of risk assessment in the field of drought monitoring and management (Carrão et al., 2016; Huang et al., 2017). For example, when there is very low precipitation, it leads to a *meteorological* drought. Then, meteorological drought further propagates into *agricultural* drought, which is characterized by low or deficient soil moisture and can cause crop failure and poor water management. *Hydrological* drought occurs as a result of one or a combination of factors such as low soil moisture, low stream flows or groundwater level. *Socioeconomic* drought is caused by a combination of the aforementioned droughts, for instance, reduced water supply and increased water demand. Therefore drought monitoring is important for early warning and water scarcity risk management.

The demand for water is rising, due to the expanding scale of industry, agriculture, population, urbanisation, global warming and the development of social economy, which is leading to water shortage and a global drought threat (Yang et al., 2018). Drought is expected to become more severe and frequent (Huang et al., 2015). The overuse of water resources such as groundwater during severe droughts also exposes coastal environments to an anomalous penetration of salt water into the fresh water, known as Salt Water Intrusion (SWI). However, SWI can occur naturally also by tidal excursion, overriding of groundwater level due to sea-level rise and decline in river discharge due to changes in channel geometry (Liu et al., 2019 and Tian, 2019). Almost imperceptible at first moment, the detection of this phenomenon is usually late and so the economic costs of repair are extremely high for local communities. In some cases, SWI can reach unmanageable levels, especially in regions highly affected by climate change (Paul and Vogl, 2011; Le et al., 2007; Bhattachan et al., 2018; Pham et al., 2018). Therefore, accurate drought risk assessment is required for preventing, adapting and mitigating drought disaster. Drought risk can be reduced with proper planning and preparation, but uninformed mitigation strategies lead to wastage of energy, materials and money. To prevent this misuse of resources, proper risk assessment and its management through environment-friendly and cost-effective NBS is required (Section 4). As droughts are one of the more costly natural hazards on a year-to-year basis (WMO and GWP, 2016), drought disaster risk assessment is an important scientific method for analysing drought risk, and can provide information to help policymakers formulate disaster prevention and mitigation policies.

3.2.1. Drought risk evaluation methods

Drought risk assessment is a difficult and complicated task because there is no universally accepted definition of drought and it is a natural phenomenon that is not fully understood. Natural factors such as meteorology and hydrology, crop planting structures and resistance capacities all affect the risk of drought. Some of the methods used for drought risk evaluation are principal component analysis, analytic hierarchy process methods, fuzzy evaluation methods, gray model evaluation methods and artificial neural network models (Belal et al., 2014), as summarized in Table 3.

Droughts influence mostly the agriculture and water resources leading to severe socio-economic feedbacks (Rahman and Lateh, 2016). Therefore, a drought risk management model must focus on the

Table 3
Summary of relevant studies applying different methodologies/models for risk evaluation of drought hazard and the type of required data.

Place	Model/method	Datasets	Reference
China	Trivariate Plackett copula	Daily Streamflow data	Chen et al. (2013)
China	Information Diffusion Technology	Affected and covered areas, total sown crop areas, grain production losses from drought (1978–2011)	Xie et al. (2016)
China	Entropy-combination-weighted method, fuzzy comprehensive evaluation method, natural disaster risk index method. Zoning map by GIS spatial analysis technique and gridding GIS technique.	Hydrological, atmospheric, terrain, underway replenishment capability, economic strength, populationand socio-economic data	Sun et al. (2014)
South Korea	Indexing method, Product of hazard and vulnerability index	Precipitation data and vulnerability indicators data (Irrigated Land, Agricultural Occupation, Crop Production, Population Density, Municipal Water, Industrial Water, and Agricultural Water)	Kim et al. (2015)
Global	Product of hazard, exposure and vulnerability	Monthly precipitation, global agricultural land using satellite data, gridded world population and livestock, water stress, fifteen indicators of social, economic and infrastructural factors	Carrão et al. (2016)
China	Information distribution and diffusion	Monthly precipitation, drought induced area, drought affected area, lost harvest area, planting area	Jiang et al. (2018)
China	Multidimensional copulas function	Precipitation, average vapour-pressure, air temperature-minimum, maximum and average, average sunshine hours, average wind speed, runoff, soil type	Yang et al. (2018)
Africa	Multi-collinearity analysis, normalizing, weighting and averaging, cluster analysis, change-point analysis, regression analysis	28 factors data on land use, economy, health, energy & infrastructure, social and water resources	Ahmadalipour and Moradkhani (2018)
India	SPI, Copula-based intensity–area–frequency curve	Gridded precipitation data	Reddy and Ganguli (2013)
Spain	Econometric model	Irrigated area, crop yield, annual crop prices, available water, percentage storage level of reservoirs, historical time series of surface water (SW) and groundwater (GW) deliveries	Gil et al. (2011) Lopez-Nicolas et al. (2017)

individual and collective social, economic and infrastructural needs of a specific region (Vogt et al., 2018). For drought risk assessment, different drought indices have been reviewed. Drought risk management involves the assessment of the drought exposure, vulnerability and impact with the addition of monitoring and forecasting tools (in-situ stations, remote sensing data and numerical models) for preparation and mitigation actions (WMO and GWP, 2016). The end-goal is to provide information well in advance the onset of the drought period to prompt action within a drought risk management plan, in order to minimize impacts. The The European Commission Drought Management Plan Report (EC, 2007) provides two approaches for drought risk management: The reactive approach that is based on crisis management (measures and actions after a drought event has started) and the proactive approach which is based on drought risk management and includes measures taken early on using appropriate tools and stakeholder involvement. In order to support an integrated drought risk assessment, the "Handbook of Drought Indicators and Indices" of WMO (WMO and GWP, 2016) provides three main methods for monitoring drought: Using a single indicator or index, using multiple indicators or indices and using composite or hybrid indicators. It is important that these indices accurately reflect and represent the impacts being experienced during droughts. As the hazard evolves, the impacts can vary region-wise and season-wise. Mishra and Singh, (2010) reviewed commonly used drought indices, for e.g. SPI, CMI, PDSI, SWSI and SRI, and compared their usefulness and limitations (basically all use precipitation either singly or in combination with other meteorological elements). Hao and Singh (2015) presented the construction of major multivariate drought indices such as PDSI, USDM, OBNDI, and VegDRI. The development methods used were a water balance model and multivariate statistical analysis, such as latent variable, linear combination, multivariate distribution, and principal component analysis. In addition a number of studies attempt to correlate the drought risk with the socio-economic hazard and vulnerability of a region and study them in tangent (Pei et al., 2016; Zhang et al., 2010).

3.2.1.1. Indexing method. Drought risk depends upon its duration, frequency, severity, spatial extent and the socioeconomic and infrastructural ability of the region to cope with drought hazard. Drought hazard is characterized by its variables, such as precipitation, soil moisture, air-temperature etc. Drought index formulation is the basis of drought risk assessment and it is employed to identify, monitor or quantify a drought event. Nowadays many drought indices have been developed in the scientific literature, such as single, multiple and composite indices; these have been used to evaluate different types of droughts depending on the number and type of variables involved (Yang et al., 2018). These indices have been categorised into their level of ease and country of use based on the number of variables needed, amount and frequency of required data, complexity of calculation and the free availability of code to run the index (WMO and GWP, 2016). Single or multiple drought indexing can reflect only one type of drought (meteorological, hydrological, agricultural or socio-economic drought). Composite indexing distinguishes different types of droughts occurring simultaneously and attempts to solve the complicated relationship among different variables. *Linear combination*, *principal component analysis*, *entropy weight method* and *copula functions* are a few of the methods available for constructing a composite drought index.

Belal et al. (2014) reviewed drought risk assessment by indices formulation based on remote sensing and GIS techniques. Among the indices extensively used for drought risk evaluation are meteorological drought indices such as the *Palmer Drought Severity Index (PDSI)*, the *Crop Moisture Index (CMI)*, the *Standardized Precipitation Index (SPI)* and the *Surface Water Supply Index (SWSI)*; and satellite-based drought indices such as the *Normalized Difference Vegetation Index (NDVI)*, the *Vegetation Condition Index (VCI)* and the *Temperature Condition Index (TCI)*(WMO and GWP, 2016). SPI is based on a precipitation and probabilistic approach, while PDSI is based on the soil-water balance equation. Miah et al. (2017) used *standardized precipitation evapotranspiration index (SPEI)*, which considers the role of temperature and rainfall in detecting, monitoring and assessing the effects of global warming on drought conditions. Long-term grid data, SPEI-base and medium-term SPEI-weather station data were used with an inverse distance weight (IDW) method to assess the spatiotemporal pattern of drought events and their intensities in Bangladesh at different lags of 6, 12, 24, and 48 months.

Copula functions are helpful in multi-variate index formulation. Multidimensional copula functions were employed by Yang et al.

(2018) to construct a composite *nonlinear multivariate drought index (NMDI)* by integrating meteorological, hydrological, and agricultural drought indices. Then, based on the constructed NMDI and runs theory, three drought characteristics (i.e., drought duration, peak and severity) were identified and the multivariate drought risk was obtained for the Wei River Basin in China. Chen et al. (2013) also used bivariate and trivariate copula functions to construct the joint probability distributions of randomly correlated drought variables (duration, severity and minimum flow), to find out the probabilistic behaviour of hydrological droughts in the East River basin, China. Reddy and Ganguli (2013) modelled drought spatially by computing 6-month SPI (SPI-6) at various grids. Copula-based joint distribution was used to compute conditional return periods and drought intensity–area–frequency (I–A–F) curves.

3.2.1.2. Groundwater or reservoir level fluctuation. Krogulec (2018) evaluated the risk of hydrological drought by analysing groundwater level fluctuation trends on multiannual and seasonal scales and the values of critical levels, during a study period of 1999–2013 in two groundwater dependent ecosystems in the central part of the Vistula Valley, Poland. The periods, in which the groundwater level repeatedly fell below the average of the lowest groundwater depth of each year, were considered as periods of hydrogeological drought. The drought risk of a multipurpose Korean dam due to climate change was analysed by Kim et al. (2014). Statistically downscaled rainfall data were used to simulate the runoff, which in turn was used as input in a water balance model. Risk evaluation was done by analysing the changes in reservoir storage, according to water supply and demand scenarios. Henley et al. (2013) evaluated a climate driver informed short-term drought risk in Australia, based on stochastic rainfall simulations (CIMSS model) conditioned on initial climate derivers and reservoir storage level.

3.2.1.3. Vulnerability assessment and risk mapping. Vulnerability assessment is another way of evaluating the risk of HMHs. Ahmadalipour and Moradkhani (2018) calculated a Drought Vulnerability Index (DVI) for 46 African countries over the period 1960–2015, based on a multi-dimensional analysis of several socio-economic factors divided into six different components, which were examined for dependency using a multi-collinearity test. Various weighting methodologies were applied to calculate DVI. A change-point analysis was employed for the DVI of each country. Regression models were fitted to the historical time-series of DVI for each country and the results were extrapolated for the period of 2020–2100, to provide three future DVI projections (low, medium, and high). Jiang et al. (2018) combined drought damage (DD) and drought strength (DS), calculated from the standardized precipitation index (SPI), to establish the vulnerability relationships between DD and DS for Southwest China, using information distribution and diffusion methods. The drought risk was evaluated by combining the probability function of the DS and the DD vulnerability curve.

Information diffusion technology was also used for agricultural drought risk analysis by Xie et al. (2016) in China. They estimated the drought disaster risk probability and the fuzzy relationship between the annual drought affected rate and grain production losses caused by drought. Provincial drought disaster risk spatial distribution maps were prepared for each major grain producing area. A data-based framework was used by Kim et al. (2015) to calculate drought hazard and vulnerability indices for 229 administrative districts across South Korea. They assessed and mapped the drought risk as a product of hazard and vulnerability indices, utilising hydro-meteorological and socio-economic data. Sun et al. (2014) produced integrated risk zoning for drought and waterlogging in Anhui province in China, by combining the entropy combination weighted method, gridding GIS, a natural disaster risk index method and fuzzy comprehensive evaluation methods. On a global scale, Carrão et al. (2016) proposed a methodology to map the global distribution of drought risk for the period 2000–2014 using a combined product of historical drought hazard, current estimates of drought exposure and vulnerability. Drought hazard was derived from a non-parametric analysis of historical precipitation deficits at a resolution of 0.5 degrees; drought exposure was based on a non-parametric aggregation of gridded indicators of population and livestock densities, crop cover and water stress; drought vulnerability was computed as the arithmetic composite of high-level factors of social, economic and infrastructural indicators, collected at both national and sub-national levels. Their methodology relied on the joint cumulative distribution of the respective hazard, exposure and vulnerability indicators. Therefore, the estimated magnitude of risk did not signify absolute loss, or actual damage to human health or the environment, but is ideal for the grading and comparison of the input geographic regions (Carrão et al., 2016).

3.2.1.4. Salt water intrusion indentification. Another method to evaluate the impact risk of drought, is SWI identification. By definition, SWI is identified by the amount of salt in the water, hence by its salinity concentration. This parameter can be directly monitored at different locations, periods and depth levels. Considering that salinity can be expressed as a function of the ratio between the conductivity of the water sample and the standard potassium chloride solution, three-dimensional distributions of salinity are possible through measurements of the water conductivity, C (or its resistivity $R = 1/C$), over several locations of a water body (Stewart, 2008). These distributions enable detection of the interface between fresh and saline water through isohaline surface assessments. In the absence of permanent stations, dedicated campaigns collecting several samples along the river path at different depth levels helps to identify the magnitude of SWI and hence, the impact risk of drought. Basically, the SWI is driven by the interaction of hydrological systems; namely, the connection between groundwater and open water. As mentioned above, the greater density of sea water tends to displace freshwater, producing a depth dependent counter-flow. The intrusion of sea water in riverbeds persists even if the water table lies above sea level. Thus, the freshwater transported and discharged by the river directly influences the saline incursion. In addition, the amount of precipitation over the watershed, also influences the river flux, which must be accurately monitored to obtain a reliable estimate of the salinity distribution by regression models (Saenger et al., 2006). River discharge can be measured either by a means of permanent station or during dedicated campaigns, while precipitation values can be easily collected by nearby synoptic weather stations. The sea level is another forcing of the SWI which varies due to meteorological conditions, tidal effects and climate change. According to Kim and Johnson (2007), land subsidence also contributes to sea level, within a long-term variation. Its estimation is crucial in assessing the SWI risk, since it influences the global sea-level rise and the phenomenon of shoreline retreat (Nicholls and Cazenave, 2010).

3.2.1.5. Econometric risk modelling. Drought risk can also be assessed by linking water scarcity with the economic productivity. By inputting stochastic changes in the reservoir storage levels into the regression models, econometric risk models connect the hydrological variability with the resulting economic variability. The economic impact of drought was evaluated by Gil et al. (2011) for various provinces in Spain, through observed cropping patterns, yields, water consumption and the prevailing prices in each season. The drought risk in terms of economic impact was simulated (Monte Carlo simulation) based on the stochasticity of the supply source of irrigation water, to obtain ex-ante probability distribution functions of the economic production value, months before the start of the season. This method can aid water managers and decision makers in managing reservoirs. Lopez-Nicolas et al. (2017) also presented drought's economic impacts risk assessment for irrigated agriculture in the Jucar river basin, Spain, through a combination of (1) autoregressive stochastic time series modelling to predict the inflows and changes in future reservoir storages of the system during the start of the irrigation season; (2) simulation of the system operation, using regressions to evaluate water deliveries based on projected inflows and storages; and (3) fitting an econometric model for economic drought impact assessment by evaluating the changes in the production value of agriculture based on irrigation water deliveries and crop prices. Monte Carlo simulations were used to establish probability functions of inflows, which were translated into probabilities of storages, deliveries and finally, the production value of agriculture.

The scope of each type of method of drought risk assessment depends on the type of drought, area of drought and the context of the affected ecosystem. Indexing method has been promoted more than others but their usefulness to policy makers is limited because of its static nature and not involving complexities of vulnerability, exposure and risk (Hagenlocher et al., 2019).

3.3. Heatwave risk

There is no universally accepted definition of heatwaves so far (French et al., 2019) because population acclimatization and adaptation may vary for different climates and different regions (Yang et al., 2019). Definitions in the literature have used percentiles (Stefanon et al., 2012), fixed threshold levels (Hatvani-Kovacs et al., 2016) and temporal duration of extreme temperature values to define heatwaves (Chen et al., 2015). Often these definitions are region specific and relevant to humans only, not applicable to the whole environment and its ecology. Assuming the prevailing atmospheric conditions (humidity, ambient aerosols, etc.) to be constant, heatwaves have been defined in the majority of past studies as periods of extremely hot weather, generally for more than two-three days, which affect human health, socioeconomics and natural systems (Keramitsoglou et al., 2013).

The beginning of the 21st century has presented a variety of heat stress events, such as the 2003 European heatwaves and the 2010 Russian heatwaves (Zhang et al., 2019). More than 70,000 excess deaths have been related to the extreme summer heat of 2003 in Europe (EEA, 2010). Australia, the US southwest, India, Pakistan and the Middle East have also witnessed heatwaves in recent years. With the increase in global temperatures and climate change, a number of studies project an increase in number, frequency and intensity of extreme heat events in future (IPCC, 2012a; Hajat et al., 2014; Perkins, 2015; Coffel et al., 2018; Guerreiro et al., 2018; Abadie et al., 2019; Gaitán et al., 2019). Some recent studies relate human morbidity and mortality (Xu et al., 2016; Heo et al., 2019; Martínez-Solanas and Basagaña, 2019; Yang et al., 2019), hospital admissions (Xu et al., 2019) and other health impacts with heatwaves. The health risk of heatwaves can be modified by individual factors, such as gender and age (Yang et al., 2019). Heatwaves are more of an issue in urban areas due to denser population than the rural background, anthropogenic heat emissions and the increased urban heat island (UHI) effect. Consequently, predicting and analysing the risk of heatwaves is important for public policy development (Blanchet-Scalliet et al., 2018). The probability of occurrence and severity of heatwaves can be calculated using different methods and tools. These are considered in the following section.

3.3.1. Heatwave risk evaluation methods

A review of studies on the health impact of heatwaves on a global scale was performed by Campbell et al. (2018); they found a lack of studies where the global population is at most risk. A relationship between mortality and heat intensity was performed by Kravchenko et al. (2013), and different heatwaves definitions were given by Xu et al. (2016). Mayrhuber et al. (2018) reviewed studies on heatwave vulnerability factors and the efficacy of heat-related public health interventions and pointed out that strong evidence is lacking as for the efficiency and effectiveness of these interventions. Perkins (2015) reviewed measuring methods for heatwaves, their driving mechanisms, both observed and projected changes, and anthropogenic causes for these changes. They proposed a unified heatwave measurement framework to reduce spatiotemporal gaps in the global observation network, but a risk evaluation concept was lacking.

Heatwave risks have been evaluated by many researchers (Table 4) based on historical climate data (Ouzeau et al., 2016) or observational data (Wolf and McGregor, 2013). Some have also used future projections from climate models (e.g. Hajat et al., 2014; Abadie et al., 2019) and analysed future heatwave risk. Some studies have assessed this risk by relating the mortality of a specific location in a specified time-period with heat stress events.

3.3.1.1. GIS-based heatwave risk and vulnerability mapping. In the majority of past studies reviewed in this work, evaluation of heat risk is carried out by using maximum daily temperature datasets from different sources. The datasets for temperature are obtained from weather stations, satellites, model simulations/projections and other regional and global databases of temperature (e.g. ECMWF and others). For example, Tomlinson et al. (2011) used remote satellite sensing of land surface temperatures at high spatial resolution (1 km) for the spatial heat risk assessment of Birmingham, UK, employing GIS and information compiled from credit reference agencies on groups such as the elderly and those with ill health, high population density, and high-rise living. It was found that population sub-groups with ill health and those who reside in the city centre were located in the city's warmest and therefore highest heat risk areas. A limitation of this study was that it examined only a single time temperature data of one night during a heatwave and so did not fully represent the range of temperatures that the population was exposed to, during the heatwave period. Wolf and McGregor (2013) developed a *Heat Vulnerability Index* for London, using an inductive approach based on principal component analysis of socio-demographic factors relating to heat vulnerability (dwelling type, population density, age, illness, socio-economic status, social isolation, and ethnic minority status) combined with land surface temperatures derived from satellite data for the August 2003 European heatwaves. They found clustering of high vulnerability in the east and central areas of the city using ArcGIS. Three different variables for heat risk (UHI, age, and dwellings types) were integrated to estimate the spatial distribution of heat vulnerability across London using GIS (Taylor et al., 2015). With a building physics model, which simulated indoor temperatures for dwellings and monitored weather data, together with information on modelled UHI, housing type and population age, it was found that building type and UHI had a significant impact on the distribution of risk across the city during the summer of 2006; relative risk of mortality derived from Armstrong et al. (2011) was calculated at the ward level of the city as a function of its population and death rate.

A novel risk mapping methodology was presented by Macintyre et al. (2018). The WRF-BEP (Building Energy Parameterization) model simulated hourly high spatial resolution (1 km) modelling of temperatures and quantified heat exposure due to the UHI for populations in the West Midlands, UK during two heatwaves periods (August 2003 and July 2006). This risk mapping using GIS, went beyond previous studies (Tomlinson et al., 2011; Wolf and McGregor, 2013; Taylor et al., 2015) by calculating the factors that influence heat-health effects: the ambient temperature was weighted according to distributions of different housing type, population (including age), and deprivation score. This study also used ambient temperature datasets generated at high temporal and spatial resolutions.

Jedlovec et al. (2017) used a combination of satellite data and demographic information to create a heatwave risk (HWR) map for Atlanta, Georgia for June 29, 2012. Land surface temperature (LST) from satellite data were converted to apparent temperatures through regression to create a heatwave hazard map. The hazard map data and demographic information (population density, age, and economic status) were combined in an adjustable weighting scheme using a generalized formula to produce a HWR map.

Table 4
Summary of relevant studies applying different methodologies/models for risk evaluation of heatwave hazard and the type of required data.

Location	Model/Method	Datasets	Reference
Birmingham, UK	Crichton's risk Triangle i.e. risk as a function of hazard, exposure and vulnerability; Spatial risk assessment using GIS	MODIS Remote satellite data of LST and Experian's commercial social segmentation data on household type	Tomlinson et al. (2011)
Athens, Greece	Fuzzy Logic concept and satellite remote sensing, urban climate modelling, artificial intelligence and advanced computing	Thermal infra-red satellite data, census data (population and non-proper dwelling), 20 year air and dew point temperature, lateral boundary conditions, terrain elevation and others	Keramitsoglou et al. (2013)
London, UK	Inductive approach based on principal component analysis, GIS	Heat exposure (household type, population density) and sensitivity factors (population age, health-status, ethnicity, economic status and social isolation status) from Census data, daily temperature data	Wolf and McGregor (2013)
London, UK	Building Physics Model simulating indoor temperatures, Modelled UHI, ArcGIS	Age and sex stratified population data, mortality data, weather station data, building age and type, indoor temperatures, building archetypes, window characteristics, database of energy efficient installations and high resolution maps for modelled UHI	Taylor et al. (2015)
North-America	EVT (Extreme Value Theory) and FDA (Functional Data Analysis)	Data from the North American Regional Climate Change Assessment Program (NARCCAP): maximum daily surface air temperature	French et al. (2019)
China	Poisson generalized linear model, meta-regression analysis	Daily maximum temperature, mortality, air quality data (API)	Yang et al. (2019)
Queensland, Australia	Quasi-Poisson generalized additive model with a distributed lag non-linear model, random effect meta-analysis	Daily Emergency Department Visit (EDV), maximum and minimum temperature, humidity, daily time series data on air pollution (PM_{10}, O_3, SO_2 and NO_2)	Xu et al. (2019)
Madrid and Bilbao, Spain	Stochastic diffusion model coupling three processes Poisson, Gamma and truncated Gaussian	Time series temperature data from historical observation and outputs from climate models	Abadie et al. (2019)
Spain	Distributed lag non-linear model and quasi-Poisson regression, multivariate meta-analysis	Daily maximum temperature and Mortality	Martínez-Solanas and Basagaña (2019)
South Korea	Quasi-Poisson generalized additive model with a distributed lag non-linear models and meta-analysis for risk estimation.	Mortality and morbidity data, daily 24 h data of temperature, relative humidity, wind speed, 4 km × 4 km binary data of solar insolation	Heo et al. (2019)
European Union Cities	Percentile method for defining heatwaves and impact scenarios (Low, medium and high)	Maximum and minimum temperature output data of from CMIP5 models for RCP8.5	Guerreiro et al. (2018)
Paris, France	A mean-reverting process, Ornstein–Uhlenbeck (OU) process to model temperature dynamics, Monte-Carlo simulation	Daily observed suprema of temperatures	Blanchet-Scalliet et al. (2018)
West Midlands, UK	Building Energy Parameterisation (BEP) with mesoscale meteorological WRF model, Noah Land Surface Model, GIS	Land surface data, Population data, housing type, number of dwellings, locations of hospitals, care homes, child care centres, schools and prisons, indices of Multiple Deprivation (IMD)	Macintyre et al. (2018)
Berlin, Germany	Building model, Risk as a function of three variables: vulnerability, outdoor temperature and global horizontal irradiance	Outdoor air temperature, age-classified number of deaths, population data, global horizontal irradiation	Buchin et al. (2016)

3.3.1.2. Mathematical/statistical modelling approach. A few studies evaluated heatwave risk with the more complex mathematical and statistical concept and computational methods. For example, Keramitsoglou et al. (2013) used a fuzzy logic concept to map intra-urban heatwave hazard severity and spatial risk distribution in Athens, Greece. State-of-the-art technologies such as satellite remote sensing, urban climate modelling, artificial intelligence and advanced computational analysis were used to make monthly hazard and risk maps covering recent years. Satellite-derived land-surface temperature images were assimilated into a simple urban climate model to estimate heatwave hazard in a 1 km grid. An artificial intelligence fuzzy logic model was used to classify heatwaves ranging from mild to extreme, taking into consideration their duration, intensity and time of occurrence. Monthly heatwave risk maps were produced by integrating geospatial information on the population's vulnerability to heatwaves calculated from socio-economic variables.

Another statistical framework, combining FDA (functional data analysis) and EVT (extreme value theorem), was proposed for computing probabilities of heatwaves with specified temporal duration, spatial extent and intensity (French et al., 2019). The probabilities were calculated by determining spatial region, duration and intensity, together with a loss function. This methodology can be applied to the calculation of probabilities of other extreme weather events, including cold waves and droughts. Blanchet-Scalliet et al. (2018) proposed a new stochastic method to estimate risk measures, such as the probability and mean duration of heatwaves. This uses modelling of temperature dynamics with a mean-reverting Ornstein–Uhlenbeck (OU) process. The parameters of the OU process were estimated by the method of least square estimation, based on daily observed suprema of temperatures. The law of hitting time was used to obtain the cumulative distribution function of the supremum. Risk measures related to heatwaves were obtained by analysing temperature dynamics with the estimated parameters using Monte-Carlo simulations. Observed temperature data for summers in Paris from 1950 to 1984 were used for comparison with the simulated data.

3.3.1.3. Health-effects and heatwave risk association. Mortality and health-related data have also been used to evaluate heatwave risk. The mortality attributed to heatwaves has been quantified in term of relative risk; the relationship between increase in mortality and heatwaves was found to be cumulatively and lag distributed (Guo et al., 2017). Yang et al. (2019) used daily maximum temperature and mortality data from 2007 to 2013 to calculate the relative mortality risk with a Poisson generalized linear model for 31 Chinese cities, encampassing 15 definitions of heatwaves. The Akaike Information Criterion (AIC) was used to evaluate the model fits among these 15 heatwave definitions. The same methodology, using a quasi-Poisson generalized additive model with a distributed lag non-linear model, was employed for eight communities in Queensland, Australia using data from 2013 to 2015 to investigate the impacts of heatwaves on emergency department visits (EDVs) (Xu et al., 2019). Random effect meta-analysis was performed to investigate the effects of heatwaves on cause-specific EDVs. Quasi-Poisson regression and the time-dependent distributed lag non-linear model framework was also used in Spain to estimate the relationship between temperature and mortality and the effectiveness of a Heat Health Prevention Plan for two periods: 1993–2003 and 2004–2013 (Martínez-Solanas and Basagaña, 2019). Mortality attributable fractions were calculated to see temporal changes in temperature-related mortality. Heo et al. (2019) also used distributed lag non-linear models and meta-analysis to estimate the mortality risk of heatwaves in South Korea during the summer season of 2011–2014. They found wet-bulb globe temperature (WBGT) and its threshold to be better than other thermal comfort indices, i.e., air temperature and heat index (HI), for the estimation of heatwave risks. They used a generalized additive model with a link function and quasi-Poisson distribution and piecewise regressions for estimating the threshold temperature, i.e. minimum mortality temperature. Applying various thresholds for each index, WBGT was found to be most associated with significant risks for all-cause mortality, hospitalization due to respiratory diseases and hospitalization due to heat disorders, across the other two heatwave definitions considered. Buchin et al. (2016) calculated indoor temperatures from outdoor climate data using a simple building model. Although the risk concept was defined on the basis of vulnerability and hazard formulation, all-cause mortality rates for the age group 65 years and above in Berlin, Germany for 2001–2010 were used for defining risk of heatwaves; it was shown that the countermeasures to UHI (such as cool pavements, urban green, cool roofs, green roofs and green facades) do not necessarily reduce indoor risk of heatwaves.

3.3.1.4. Heatwave risk for future climate. Risk of heatwaves for future scenarios has also been studied using projections of climate model data. Abadie et al. (2019) used a stochastic diffusion model to describe the evolution of annual heatwave probability in view of risk assessment. They employed high-resolution maximum temperature data from two climate model projections between 2006 and 2100 (95 years) based on the Representative Concentration Pathway (RCP4.5 and RCP8.5) scenarios presented in IPCC (2014a). The model coupled three stochastic processes characterising the annual number of heatwaves (Poisson process), their mean duration (Gamma process) as well as the mean excess temperature on heatwaves days (truncated Gaussian process). After using nonlinear least squares for model calibration, Monte Carlo simulations were performed to measure extreme temperature risk with roots in financial engineering, using Value at Risk (VaR) and Expected Shortfall (ES). The mortality risk projections were done with an epidemiological equation.

Guerreiro et al. (2018) used 50 climate model projections from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) for the RCP8.5 emissions scenario to calculate low, medium and high impact scenarios, which correspond to the 10th, 50th and 90th percentiles of heatwave indicators for 571 European cities. Two indicators used for heatwaves were changes in the percentage of heatwave days and changes in the maximum temperature of heatwaves between a future period (2051–2100) and a historical period (1951–2000) from May to September (summer season). Heatwave days and temperatures were found to increase across all cities, especially in southern and central Europe.

4. NBS for hydro-meteorological risks management

HMR management is done through (1) risk characterisation and its assessment by appropriate methodology, (2) planning and preparedness for the risk by technical countermeasures, (3) early warning systems and (4) crisis management, i.e. mitigating the effect of risk when it has occurred (Depietri and McPhearson, 2017). Planning in advance and taking necessary steps in risk prone regions is the most prior HMR management. Traditionally, for reducing the risk or its effect, we have been using engineered, built solutions like dams, dykes, levees etc. for flood, transporting water in drought affected area, using air-conditioner and fans for heat mitigation. These solutions of HMR management are effective but are costly, energy intensive, cause harm to ecosystem and are not coupled with environment. NBS for preparedness to risk as HMR management could be more cost-effective, energy-efficient, beneficial to ecosystem and environmental-friendly approach but its evidence is limited yet. This review, therefore, also brings NBS as one aspect of HMR management and provides an overview of such solutions reported in literature.

NBS are alternative ways and can be applied within new developments or existing systems (e.g. grey infrastructures), inspired by and copying from nature and its fundamentals (EC, 2017), discouraging infrastructure development in a cost-effective and sustainable manner (Frantzeskaki, 2019), to tackle the challenges of societal or environmental problems, such as HMRs in the present context. NBS consequently deliver environmental, social, economic (Faivre et al., 2017) and other multiple ecological benefits (Nesshöver et al., 2017; Raymond et al., 2017), alongside tackling HMHs and building resilience towards HMRs. Keesstra et al. (2018) classified NBS into two major groups: soil solutions and landscape solutions. Soil solutions enhance the soil resilience and soil functions, through which local ecosystem services are maintained or restored. Landscape solutions focus on the concept of connectivity. Making the landscape less connected leads to less rainfall being transformed into runoff and therefore a reduction in flood risk, drought and erosion problems. Lafortezza et al. (2018) compiled case studies from the different regions worldwide where NBS have been applied. Many of these have impacts on flood, drought and heatwave risk.

NBS has functionality similar to engineered or constructed man-made solutions, though the principle could be different in some cases. NBS can be water-based called blue approach or vegetation based called green approach (Depietri and McPhearson, 2017). Examples of green approaches are oyster reefs, coastal salt marshes, mangroves, coral reefs, sea-grasses, sand beaches and dunes in the coastal environment and forests, parks, street trees, and grasslands inland. Blue approaches include all bodies of waters, including ponds, wetlands, rivers, lakes and streams, as well as estuaries, seas and oceans. When these green and blue NBS are used in combination with constructed structures, they are called hybrid approaches, such as bioswales, porous pavement, green roofs, rain gardens, constructed wetlands and sustainable urban drainage systems. We analysed 205 case studies of NBS from Natural Hazards – Nature-based Solutions platform (2019) dealing with HMR reduction management utilising concept of NBS across Europe. It was found that out of total 205 NBS, hybrid approach accounted for 27.3%, followed by green approach (24.4%) and then blue approach (16.1%) for flood risk management; and for heatwaves, the green approach was used for 23.9%, followed by the hybrid approach at 4.4% and then blue approach (0.5%). NBS was used for only 3.4% (green and hybrid) for droughts risk management (Fig. 2).

The key principle of a flood, drought and heatwave risk reduction using NBS is water and local/regional climate management. Kalantari et al. (2018) highlighted the multi-functionality of NBS for flood and drought risk management (Table 5) which were environment-friendly and cost-effective. Table 5 provides a summary of potential NBS used against risks originated from HMHs, such as floods, droughts and heatwaves. Most of the employed solutions mitigate or reduce multiple risks. For example, multifunctional watershed management, water-harvesting, ecosystem restoration, urban regeneration, restoration and construction of lakes and wetlands, blue and green infrastructures, mangroves and salt marshes, river revitalisation, rain gardens and pocket parks are some of the potential NBS for flood and drought risk reduction and management (Liquete et al., 2016; Raymond et al., 2017; Bridgewater, 2018; Quin and Destouni, 2018; Van Coppenolle et al., 2018; Frantzeskaki, 2019; Ronchi and Arcidiacono, 2019). To prevent the misuse of the resources because of unalarmed and unorganised HMR mitigation strategies, proper risk assessment and its management thorough NBS is an optimal approach. Multi-functionality of these NBS needs to be quantified in order to optimize their potential benefits for human well-being. For example, rainwater harvesting can serve a purpose of flood prevention in urban areas and also can be used for drought management in a semi-arid climate. A major focus of these NBS is to increase the water retention and flow capacity of the natural water bodies such as river, wetlands and floodplains along with the restoration and

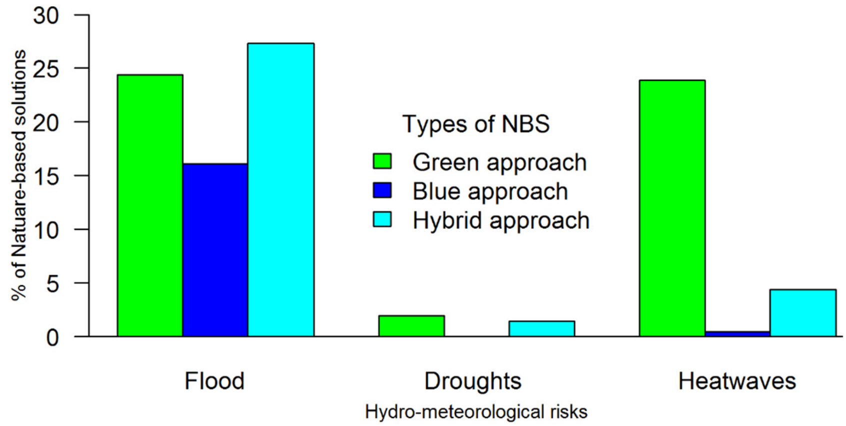

Fig. 2. Nature-based solutions used to manage floods, droughts and heatwaves in various parts of Europe. The data used in this figure have been obtained from Natural Hazards – Nature-based Solutions platform (https://naturebasedsolutions.org/map).

enhancing the ecosystem services and promoting socio-economic development. These NBS also help to enhance the resilience of the social-ecological system towards HMRs (EC, 2017; Faivre et al., 2017; Nesshöver et al., 2017). Therefore, NBS as an HMR management approach delivers multiple benefits including environmental and social wellbeing benefits, and helps enhance resilience in a cost-effective manner.

Berland et al. (2017) reviewed the role of trees as a reduced footprint solution for urban storm-flood management. Trees along with other green infrastructure like bioswales and structural soils can play an important role in reducing flood through canopy interception loss, evapotranspiration and facilitated infiltration. Trees are a subset of NBS with potential for storm-flood mitigation, but more research is needed for showing the effectiveness of different tree species, their morphology and interaction with stormwater in different contexts for long period of time, both geographical contexts (soil, landscape, topology), and meteorological contexts (precipitation seasonality, frequency and intensity in climate change). Berland et al. (2017) also discussed policy and economic challenges along with arboricultural challenges. Choosing species with maximum stormwater control and protection from tree pests and maintaining tree diversity becomes cumbersome with urban expansion.

For heatwave risk reduction and management, potential NBS include increasing the sustainable use of matter and energy, increasing carbon sequestration, urban regeneration (Raymond et al., 2017), urban and peri-urban forests (Davies et al., 2017; Wai et al., 2017), green and blue outdoor natural environments like urban forest, park and water (van den Bosch and Sang, 2017), urban greening (Vieira et al., 2018), planting street trees (Gillner et al., 2015), increasing green walls and roofs (Fioretti et al., 2010). These NBS mainly focus on outdoor energy management using shading and the latent heat of evapotranspiration of plants and soils, recuding the urban heat island effects through

Table 5
List of potential NBS used against risks originated from floods, drought and heatwaves.

Type of hydro-meteorological risks	Types of NBS	Reference
Flood	Wetlands including ponds, rivers, lakes, swamps	Bridgewater (2018) Nesshöver et al. (2017) Pregnolato et al. (2016)
	Mangroves and salt marshes	Van Coppenolle et al. (2018) Vuik et al. (2018)
	Concave green land	Du et al. (2019)
	Vegetated foreshores	Vuik et al. (2018)
	Renature water bodies, reduce canalization of the urban water bodies, re-vegetation in urban areas, protection of riparian flora and fauna, revitalization of flood plains, create artificial water bodies for short term water storage, use of balancing ponds to release water slowly, preventing soil compaction, forest management, wetlands restoration, preventing bank erosion with short and forest vegetation, rerouting floods to wetlands, transforming farmland into grassland or planting buffer stripe	Santoro et al. (2019) Albert et al. (2019)
	Boomjes promenade, river revitalisation, raingardens, pocket park, bioswells, urban parks, nature-based playgrounds, linear urban waterfront park	Frantzeskaki (2019)
	Lakes and wetlands	Quin and Destouni (2018)
Drought	Use of grass strips for trapping sediments, restoration of mangroves, more watering points in national parks and community areas, climate resilient marine protected area management and forest protection.	Kalantari et al. (2018)
	Blue-green infrastructure, agroforestry	Keesstra et al. (2018) Ronchi and Arcidiacono (2019)
Heatwaves	Urban park, urban greening with green infrastructure	Frantzeskaki (2019) Vieira et al. (2018) Kingsborough et al. (2017)
	Planting street tree species with high cooling potential in densely built areas	Gillner et al. (2015)
	Increasing green walls and roofs	Akbari (2002) Alexandri and Jones (2008) Fioretti et al. (2010)

increasing green spaces that cool down temperature, as well as absorb greenhouse gases like carbon dioxide (Davies et al., 2017; Raymond et al., 2017).

While many NBS are developed and implemented around the world for reducing HMRs, there are still challenges that could hinder the sustainability of NBS projects. Stakeholder engagement including the local government and political leaders are vital for project success. Long-term funding remains a major constraint, however it could be eliminated by alternative co-funding arrangement with stakeholders as observed in many NBS projects, for example NBS for greening the city and increasing resilience in Amsterdam, and for urban green connectivity and biodiversity in Berlin (Oppla, 2019). Further, the physical condition of existing landscapes puts limits to implementing new NBS projects, particularly in cities where local authorities are keen to create new green spaces with the aim of reducing urban heat island effect and air pollution, but the bottleneck is lack of space with high-density buildings. The city authorities are also facing the challenge of maintaining numerous fragmented green or open spaces (e.g. City of Bari, Italy) (Oppla, 2019). Moreover, since the NBS are new innovative ideas/technologies, acceptance of these require long term interaction. People more readily accept the solutions once they see and understand the tangible and intangible benefits these may bring. Several reviewed projects have highlighted that "making the case" for the projects, in terms of benefits, was crucial for their acceptance.

5. Summary, conclusions and future outlook

This work has considered published scientific articles and papers surveying a selection of important risk assessment methods (Fig. 1) and their relevant NBS for three HMRs: floods, droughts and heatwaves. It facilitates the synthesis of different methodologies dealing with flood, drought and heatwave risk evaluation, considering exposure, vulnerability and adaptation interaction of elements at HMHs driven risk.

NBS are closely linked to risk assessment and management. An NBS is deployed after an extensive risk assessment has been performed for an area prone to HMHs. The overall design and implementation of the proper solution is based on this assessment. Therefore, NBS can be viewed as part of the risk management techniques those are used to mitigate potential hazard impacts. After deployment of the NBS, risk assessment needs to be re-evaluated to take into account the reduced human and financial costs due to improved disaster prevention.

The key conclusions drawn are:

- Many methods and tools have been utilized in order to identify, analyse and evaluate the risks associated with floods. A number of models and statistical methods are currently in use for this purpose. For instance, fuzzy logic such as AHP process and probabilistic methodologies such as FFA are generally applied for risk evaluation. Copula functions are a widely used statistical method for flood risk assessment, along with techniques such as Bayesian networks, IDF curves and hydrodynamic models.
- Most drought risk assessment is based on formulating different kinds of indices. Several kinds of indices have been used to define drought risk, of which SPI, DVI, PDSI and CMI are just a few. PCA, AHP, IDW, entropy theory, linear combination, I-A-F curve, rainfall simulation, econometric models, changes in reservoir storage, the information diffusion method, copula and fuzzy evaluation are some of the reported methods employed. The choice of method to be utilized for drought risk assessment depends on the type of drought involved and purpose of evaluation, for example a groundwater dependent ecosystem will need the method of groundwater fluctuation while a place where multiple variables cause risk, a multi-variate drought risk assessment will be needed.
- For heatwaves, the risk depends on the type of heatwave definition used, and this is dependent on the location of each study. GIS-based mapping of the vulnerable property and population is a widely used methodology, along with a number of statistical, mathematical and computational methods, including: principal component analysis, EVT, FDA, stochastic processes (OU, Poisson, Gamma, truncated Gaussian), fuzzy logic concept and the association of health effects with temperature using time-series regression analysis.
- HMR can be managed after proper assessment of all possible components of the disaster risk and these are tackled by many measures such as structural (i.e. dykes, embankments, dams, levees), non-structural (i.e. forecasting and early warning, preservation of retention ponds, land use planning, flood zoning, emergency services, shelters, flood proofing, flood fighting and post-disaster rehabilitation measures and evacuations), and NBS, such as green and blue approaches (i.e. wetlands restoration, installation of grass and riparian buffers, urban trees, stream restoration, rivers, lakes, ponds). In this article, potential of NBS has been reviewed as an efficient, cost-effective, long-lasting and sustainable approach towards HMR management. NBS such as blue-green infrastructures are promoted in place of grey infrastructures for risk mitigation, for example marshes and wetlands in place of dams for flood and drought risk reduction, and green infrastructure for urban cooling as a measure against heatwaves.
- From our analysis of 205 NBS case studies (Oppla, 2019), it is concluded that the hybrid approach is the most popular type of NBS, followed by green and blue approaches, to manage flooding. For heatwaves, mostly NBS rely on green compared with hybrid approaches, whereas both the green and hybrid approaches of NBS are applied in similar proportion for droughts. However, blue approach of NBS has been utilized at minimum for drought and heatwave risk management (Fig. 2).
- This paper could be beneficial to a diverse range of readers, such as scientists, researchers and practitioners by providing comprehensive risk assessment methods (e.g. copulas, 2D and 3D hydraulic models), which can accurately represent the risk from all dimensions. Apart from this, the paper also provides the way forward for reducing existing HMR by NBS, contributing to the strengthening of resilience and reduction of disaster losses. This review is intended to help with the selection and application of current indices for drought and heatwaves to help preparedness and response. Due to the increase in data availability (e.g. satellite data for temperature and vegetation) and the need for comprehensive risk characterisation, the development of multivariate risk indices is expected to move forward. The paper provides useful information and guidelines for the development of new multivariate risk indices in the future.

Research into HMR assessment and solutions using NBS will help in building adaptations and increasing the resilience of society in a cost-efficient manner. However, a number of research gaps exist. More research is needed into risk reduction methods through the NBS and their wider uptake to address the ongoing process of climate change, which in turn has direct implication for HMHs. For instance, the NBS are not yet at the stage where they can compete with the long-established approaches and standards used in the water resource engineering domain for managing HMRs. Therefore, long-term maintenance costs, the performance and overall cost-effectiveness of NBS need to be evaluated in practice, with the collaboration of researchers and end-users. Furthermore, research is needed on the clear-cut returns to be expected on an investment in any NBS, in order to convince policymakers/decision-makers and investors to finance the life cycle of NBS projects.

We focused only on three HMHs, the future studies should attempt to consolidate the potential NBS for the other HMHs such as hurricanes and landslides. Since the use of NBS for HMRs management is still in its transition from theory to practice, future investigations to explore and build a bridge as well as comparisons of the performance and cost-effectiveness against grey infrastructures are required.

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