Nature-Based Solutions for hydro-meteorological risk reduction: A state-of-the-art review of the research area

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Abstract. Hydro-meteorological risks due to natural hazards such as severe floods, storm surges, landslides, and droughts are causing impacts on different sectors of society. Such risks are expected to become worse given projected changes in climate, degradation of ecosystems, population growth and urbanisation. In this respect, Nature-Based Solutions (NBS) have emerged as effective means to respond to such challenges. NBS is a term used for innovative solutions that are based on natural processes and ecosystems to solve different types of societal and environmental challenges. The present paper provides a critical review of the literature concerning NBS for hydro-meteorological risk reduction and identifies current knowledge gaps and future research prospects. There has been a considerable growth of scientific publications on this topic with a more significant rise taking place from 2007 onwards. Hence, the review process presented in this paper starts by sourcing 1407 articles from Scopus and 1232 articles from Web of Science. The full analysis was performed on 137 articles. The analysis confirmed that numerous advancements in the area of NBS have been achieved to date. These solutions have already proven to be valuable in providing sustainable, cost-effective, multi-purpose and flexible means for hydro-meteorological risk reduction. However, there are still many areas where further research and demonstration are needed in order to promote their upscaling and replication and to make them become mainstream solutions.

1 Introduction

There is increasing evidence that climate change and associated hydro-meteorological risk are already causing wide-ranging impacts on the global economy, human well-being, and the environment. Floods, storm surges, landslides, avalanches, hail, windstorms, droughts, heat waves and forest fires are a few examples of hydro-meteorological hazards that pose a significant risk. Hydro-meteorological risk is the probability of damage due to hydro-meteorological hazards and its interplay with exposure and vulnerability of the affected humans and environments (Merz et al., 2010). Some of the main reasons for such risks are climate change, land use change, water use change and other pressures linked to population growth (Thorslund et al., 2017). The situation is likely to become worse given the projected changes in climate (see for example, EEA, 2017). Therefore, effective climate change adaptation (CCA) and disaster risk reduction (DRR) strategies are needed to mitigate risks of the extreme events and to increase resilience to disasters, particularly among vulnerable populations. (Maragno et al., 2018; McVittie et al., 2018)

Since biodiversity and ecosystem services can play an important role in responding to climate-related challenges, both mitigation and adaptation strategies should take into consideration a variety of Green Infrastructure (GI) and Ecosystem-based Adaptation (EbA) measures as effective means to respond to present and future disaster risk (see also EEA, 2015). Such approaches are already well accepted within multilateral frameworks such as the United Nations (UN) Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD) and the Sendai Framework for Disaster Risk reduction (SFDRR). As such, they are recognized as effective means for CCA and DRR, and for the implementation of the Sustainable Development Goals (SDGs).

In view of the above, many countries are nowadays developing adaptation and mitigation strategies based on GI and EbA to reduce their vulnerability to hydro-meteorological hazards (Rangarajan et al., 2015, EEA, 2015). Nature-Based Solutions (NBS) have been introduced relatively recently. The reason behind this is that NBS offer the possibility to work closely with nature in adapting to future changes, reducing the impact of climate change and improving human well-being (Cohen-Shacham et al., 2016). NBS have been the focus for research in several EU Horizon2020 funded projects. Horizon2020 offers new opportunities in the focus area of ‘Smart and Sustainable Cities with Nature based solutions’ (Faivre et al., 2017). Some of these important projects are: Nature4Cites, Naturvation, NAIAD, BiodiverEsA, Inspiration, URBAN GreenUP, UNaLaB, URBINAT, CLEVER Cities, proGIreg, EdiCINET, RECONECT, OPERANDUM, ThinkNature, EKLIPSE and PHUSICOS (nature4cities, 2019). Through these projects, the knowledge of NBS has rapidly grown and been documented in a considerable body of grey literature (project reports, etc.). On the other hand, the number of scientific studies focused on NBS to reduce hydro-meteorological risk is continuously increasing all over the world.

The aim of this article is to provide a state-of-the-art review of scientific publications on hydro-meteorological risk reduction with NBS to indicate some directions for future research based on the current knowledge gaps. The analysis focuses on the following hydro-meteorological hazards: floods, droughts, storm surges, and landslides. The review addresses both small and large scale interventions and explores available techniques, methods and tools for NBS assessment, while also providing a snapshot of the major socio-economic factors at play in the implementation process. The key objectives and methods of this study are discussed in Section 3, while Section 2 provides a brief overview of concepts and definitions related to NBS either in general or specifically linked to hydro-meteorological risk reduction. Results and conclusions are discussed in Sections 4 and 5 respectively.

2 Overview of definitions and theoretical backgrounds

There are several terms and concepts which have been used interchangeably in the literature to date. In terms of NBS, the two most prominent definitions are from International Union for Conservation of Nature (IUCN) and the European Commission. The European Commission defines Nature-Based Solutions as “*Solutions that aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions inspired by, supported by or copied from nature; both using and enhancing existing solutions to challenges, as well as exploring more novel solutions. Nature-based solutions use the features and complex system processes of nature, such as its ability to store carbon and regulate water flows, in order to achieve desired outcomes, such as reduced disaster risk and an environment that improves human well-being and socially inclusive green growth”* (European Commission, 2015). The IUCN has proposed a definition of NBS as “*actions to protect, sustainably manage and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits*” (Cohen-Shacham et al., 2016). Eggermont et al. (2015) proposed a typology characterising NBS into three types: i) NBS that address a better use of natural/protected ecosystems (no or minimal intervention), which fits with how IUCN frames NBS; ii) NBS for sustainability and multi-functionality of managed ecosystems and iii) NBSs for the design and the management of new ecosystems, which is more representative of the definition given by the European Commission.

NBS is a collective term for innovative solutions to solve different types of societal and environmental challenges, based on natural processes and ecosystems. Therefore, it is considered as an “umbrella concept” covering a range of different ecosystem-related approaches and linked concepts (Cohen-Shacham et al., 2016; Nesshöver et al., 2017), that provides an integrated way to look at different issues simultaneously.

Due to the diverse policy origins, NBS terminology has evolved in the literature to emphasize different aspects of natural processes or functions. In this regard, nine different terms are commonly used in the scientific literature in the context of hydro-meteorological risk reduction: Low Impact Developments (LIDs), Best Management Practices (BMPs), Water Sensitive Urban Design (WSUD), Sustainable Urban Drainage Systems (SUDs), Green Infrastructure (GI), Blue-Green Infrastructure (BGI), Ecosystem-based Adaptation (EbA) and Ecosystem-based Disaster Risk Reduction (Eco-DRR). The timeline of each term, based on their appearance in literature is shown in Figure 1 and their definitions are given in Table 1.

The commonalities between NBS and its sister concepts (i.e., GI, BGI, EbA, Eco-DRR) are that they take participatory, holistic, integrated approaches, using nature to enhance adaptive capacity, reduce hydro-meteorological risk, increase resilience, improve water quality, increase the opportunities for recreation, improve human well-being and health, enhance vegetation growth and connect habitat and biodiversity. More information on the history, scope, application and underlying principle of terms of SUDs, LIDs, BMPs, WSUD and GI can be found in Fletcher et al. (2015) while the relationship between NBS, GI/BGI, and EbA is described in detail by Nesshöver et al. (2017).

Although all terms are based on a common idea, which is embedded in the umbrella concept of NBS, differences in definition reflect their historical perspectives and knowledge base that were relevant at the time of the research (Fletcher et al., 2015). The distinguishing characteristic between NBS and its sister concepts is how they address social, economic and environmental challenges (Faivre et al., 2018). Some terms such as SUDs, LIDs, and WSUD refer to NBS that specifically address stormwater management. They use landscape feature to transform the linear approach of conventional stormwater management into a more cyclic approach where drainage, water supply, and ecosystems are treated as part of the same system, mimicking more natural water flows (Liu and Jensen, 2018). GI/BGI focus more on technology-based infrastructures by applying natural alternatives (Nesshöver et al., 2017) for solving a specific activity (i.e., urban planning or stormwater). EbA looks at long-term changes within the conservation of biodiversity, ecosystem services and climate change, while Eco-DRR is more focused on immediate and medium-term impacts from the risk of weather, climate and non-climate-related hazards. EbA is often seen as a subset of NBS that is explicitly concerned with climate change adaptation through the use of nature (Kabisch et al., 2016). From the above discussion, it can be concluded that EbA, Eco-DRR and GI/BGI provide more specific solutions to more specific issues. One key distinction is that unlike the sister concepts, the concept of NBS is more open to different interpretations, which can be useful to encourage stakeholders to take part in the discussion.

Moreover, features of NBS provide an alternative to work with existing measures or grey infrastructures. Therefore, it is important to note that very often a combination between natural and traditional engineering solutions (a.k.a. “hybrid” solutions) is likely to produce more effective results than any of these measures alone, especially when their co-benefits are taken into consideration.

An important advance in the science and practice of NBS is given by the EKLIPSE Expert Working Group, which developed the first version of a multi-dimensional impact evaluation framework to support planning and evaluation of NBS projects. The document includes a list of impacts, indicators and methods for assessing the performance of NBS in dealing with some major societal challenges (EKLIPSE, 2017; Raymond et al., 2017). Lafortezza et al., (2018) reviewed different case studies around the world where NBS have been applied from micro-scale to macro-scale. Furthermore, an overview of how different NBS measures can regulate ecosystem services (i.e., soil protection, water quality, flood regulation, and water provision) has been carried out by Keesstra et al., (2018).

3 Materials and methodology

The methodology consisted of two phases as schematized in Figure 2. The first phase consisted of the identification of articles satisfying the search criteria discussed in Section 3.1. Next, all articles were screened and filtered based on the selection criteria discussed in section 3.2.

3.1 Search strategy

The review analysis concerned articles from scientific journals written in English. Two main concepts were used in the search: Nature-Based Solutions and hydro-meteorological risk reduction. As the concept of 'Nature-Based Solutions' appears under different names (which more or less relate to the same field of research), articles related to LIDs, BMPs, WSUD, SUDs, GI, BGI, EbA and Eco-DRR were included in the identification of relevant articles (see Table 2). The review of hydro-meteorological risk included literature on relevant terms (i.e. disasters, risks, hydrology etc.) and different types of hazards (floods, droughts, storm surges and landslides) (Table 2).

During the construction of the queries, the strings were searched only within index terms and metadata "titles, abstract, and keywords" in the Scopus database. The search terms for the two concepts were linked with the Boolean operator "AND" while the Boolean operator "OR" was used to link between possible terms (Table 2). An example of a protocol is shown below:

"TITLE-ABS-KEY ("Nature-based solutions" OR "Nature based solutions" OR "Nature Based Solutions" OR "Nature-Based Solutions" OR "Low impact development" OR "Sustainable Urban Drainage Systems" OR "Water Sensitive Urban Design" OR "Best Management Practices" OR "Green infrastructure" OR "Green blue infrastructure" AND "flood") AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "ch") OR LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "bk")) AND (LIMIT-TO (LANGUAGE , "English"))"

The time window selected for the review process was from 1 January 2007 to 1 December 2018. 1407 articles published in scientific journals were found in the Scopus database and 1232 were found in the Web of Science database. The articles from both databases were combined to 2639 articles. Duplicate articles were removed, resulting in a total of 1204 articles to be considered for further evaluation.

3.2 Selection process

As stated in the introduction, this study aims at reviewing the state-of the-art of the research on NBS that specifically address hydro-meteorological risk reduction. In this regard, the key objectives of the present review work were carefully formulated as follows:

1) To assess the state-of-the-art in research concerning both small and large scale NBS for hydro-meteorological risk reduction;
2) To review the use of techniques, methods and tools for planning, selecting, evaluating and implementing NBS for hydro-meteorological risk reduction;
3) To review the socio-economic influence in the implementation of NBS for hydro-meteorological risk reduction as well as their multiple benefits, co-benefits, effectiveness and costs;
4) To identify trends, knowledge gaps and proposed future research prospects with respect to the above three objectives.

These key objectives were defined for the review with the intention that the results could be both quantitative and qualitative.

The 1204 articles resulting from the search query were thus evaluated with respect to these objectives, and those found of little or no relevance with the topic removed. This selection process involved a set of progressive steps as schematized in Figure 2.

Initially, all articles were analysed on the basis of reading titles and keywords and evaluating their relation to the search terms. Articles were discarded if their title and keywords were considered of little or no relevance to the key objectives. This step served to reduce the number of articles from 1204 to 380.

Secondly, a more in-depth analysis was conducted, based on reading the abstract of each article selected in the previous step. The criteria at this step was that the abstract should discuss hydro-meteorological risk reduction. For example, if the abstract focused more on water quality than risk, that paper was excluded. This step served to reduce the number of articles from 380 to 185.

Finally, articles were read in full to identify those that were relevant to the review objectives. Any studies appearing to meet the key objectives (dealing with subjects such as effectiveness of NBS, techniques, method and tools for planning, and others subjects relevant to the key objectives) were included in the review. As a result, the entire selection process resulted in a total of 137 articles relevant to the objectives of the present review.

4 Findings

4.1 Lesson from research on small and large scale NBS for hydro-meteorological risk reduction

In this review, NBS for hydro-meteorological risk reduction have been divided into small and large scale solutions (Fig 3). "Small scale NBS" are usually referred to as NBS at the urban or local scale (i.e., buildings, streets, roofs, or houses), while NBS in rural areas, river basins and at the regional scale are referred to as "large scale NBS" (Fig.3.)

4.1.1 Research on small scale NBS for hydro-meteorological risk reduction

Small scale NBS are usually applied to a specific location such as a single building or a street. However, for some cases, a single NBS is not sufficient to control a large amount of runoff. Therefore, this review discusses the application and effectiveness of both individual NBS and multiple-NBS combinations. There are 45 articles that have been reviewed on the effectiveness of small scale NBS (Table 3). A majority of these (29 articles) discuss the effectiveness of a single/individual NBS site, while only 16 articles discuss the effectiveness of multiple NBS sites (around 28 percent). A summary of effectiveness, co-benefits and cost of NBS measures at small scale is shown in Table 3.

To date, various types of single NBS sites have been studied with objectives such as reduction of the flood peak (Carpenter and Kaluvakolanu, 2011; Ercolani et al., 2018; Liao et al., 2015; Mei et al., 2018; Yang et al., 2018), delay/attenuation of the flood peak (Ishimatsu et al., 2017), reduction of volume of combined sewer overflows (Burszta-Adamiak and Mrowiec, 2013) and reduction of surface runoff volume (Lee et al., 2013; Shafique and Kim, 2018). The review found just one article, Lottering et al., (2015) that discusses the reduction of drought risk by using NBS to reduce water consumption in suburb areas.

The most common NBS measures in urban areas appear to be intensive green roofs (Burszta-Adamiak and Mrowiec, 2013; Carpenter and Kaluvakolanu, 2011; Ercolani et al., 2018), extensive green roofs (Cipolla et al., 2016; Lee et al., 2013), rain gardens (Ishimatsu et al., 2017), rainwater harvesting (Khastagir and Jayasuriya, 2010), dry detention ponds (Liew et al., 2012), permeable pavements (Shafique et al., 2018), bio-retention (Khan et al., 2013; Olszewski and Allen, 2013), vegetated swales (Woznicki et al., 2018) and trees (Mills et al., 2016). However, the authors of these studies investigated the performance of such measures individually (i.e. at the specific/local/single site) without evaluating them in combination with other NBS sites or in hybrid combinations.

The literature to date acknowledges that the effectiveness of NBS greatly depends on the magnitude and frequency of rainfall events. Green roofs are recognized in reducing peak flows more effectively for smaller magnitude frequent storms than for larger magnitude infrequent storms (see for example, Ercolani et al., 2018). There are also reports that rain gardens are more effective in dealing with small discharges of rainwater (Ishimatsu et al., 2017). Swales and permeable pavements are more effective for flood reduction during heavier and shorter rainfall events. Zölch et al. (2017) suggested that the effectiveness of NBS should be directly linked to their ability to increase (as much as possible) the storage capacities within the area of interest, while using open spaces that have not been used previously and/or while providing benefits to other areas for urban planning.

Several studies evaluated the performance of multiple (or combined) NBS measures (i.e., a train of NBS) (see for example: J. J. Huang et al. 2014; Damodaram et al. 2010; Dong, Guo, and Zeng 2017; Luan et al. 2017). One of the most successful international projects in combining several NBS measures at the urban scale is the “Sponge City Programme (SCP)” in China. The SCP project was commissioned in 2014 with the aim to implement both concepts and practices of LIDs/NBS as well as various comprehensive urban water management strategies (Chan et al., 2018). Nowadays, the concept (‘Sponge City’) is widely used for a city increases resilience to climate change. It also combines several systems, such as source control system, urban drainage system, and emergency discharge system.

Porous pavement appears as one of the most popular measures suitable to be combined with other NBS for urban run-off management. Examples of this are described in Hu et al. (2017) who used inundation modelling to evaluate the effectiveness of rainwater harvesting and pervious pavement as retrofitting technologies for flood inundation mitigation of an urbanized watershed. Damodaram et al. (2010) concluded that the combination of rainwater harvesting and permeable pavements is likely to be more effective than pond storage for small storms, while the pond is likely to be more effective to manage runoff from the more intense storms.

Several studies argue that multiple NBS measures can lead to a more significant change in runoff regime and more effective long term strategies than single NBS measures (Webber et al., 2018). For example, Wu et al. (2018) simulated eight scenarios changing the percentage of combined green roof and permeable pavement in an urban setting. The results show that when green roofs and permeable pavements are applied at all possible locations, a 28% reduction in maximum inundation can be obtained. In comparison, scenarios implementing either green roofs or permeable pavements alone at all possible areas experienced a reduction of 14%. One of the main reasons for the superior performance of combined NBS is that they work in parallel, each treating a different portion of run-off generated from the sub-catchment (Pappalardo et al., 2017). For these combinations, the spatial distribution should be carefully considered because it can improve the runoff regime better when compared to centralised NBS (Loperfido et al., 2014).

Further research on the use of combined NBS and grey infrastructure (i.e., hybrid measures) is desirable as only three contributions were found in the review. Alves et al., (2016) presented a novel method to select, evaluate and place different hybrid measures for retrofitting urban drainage systems. However, only fundamental aspects were touched upon in the methodology and they suggested future work should include the possibility of considering stakeholders' preferences or flexibility within the method. In the work of Vojinovic et al. (2017), a methodological framework that combines ecosystem services (flood protection, education, art/culture, recreation and tourism) with economic analysis for the selection of multifunctional measures and consideration of small and large scale NBS has been discussed for the case of Ayutthaya in Thailand. Onuma and Tsuge, (2018) compared the cost-benefits and performance of NBS and grey infrastructures, concluding that NBS are likely to be more effective when implemented through cooperation with local people, whereas hybrid solutions are more effective than a single NBS in terms of performance.

The first limitation of the above studies is that they only assess the effectiveness of NBS at urban scales. This may not be sufficient for large events, as climate change is likely to increase the frequency and intensity of future events (Qin et al. 2013). A large scale NBS could be a solution for storm events with large magnitude and long duration, which is usually the case for disaster risk reduction applications, and therefore research in this direction is highly desirable (Giacomoni et al. 2012). Although Fu et al., (2018) analysed variations in runoff for different scales and land-uses, the impact of NBS was only examined for the small urban scale. Another limitation is that none of these contributions incorporated cost-benefit analyses (CBA). CBA can be used as a tool to support the decision-making process as they serve the feasibility of implementation costs and the potential benefits of NBS.

4.1.2 Research on large-scale NBS for hydro-meteorological risk reduction

Large-scale water balance, water fluxes, water management and ecosystem services are affected by future changes such as climate change, land use changes, water use changes and population growth. To address such challenges, large scale NBS are needed to make more space for water to retain, decelerate, infiltrate, bypass, and discharge (Cheng et al., 2017; Thorslund et al., 2017). Generally, a large-scale NBS combines different NBS within a larger system to achieve better long-term strategies. There are some examples of NBS measures for DRR summarized in McVittie et al., (2018) and a summary of effectiveness, co-benefits and cost of large scale NBS measures is shown in Table 4.

Only few articles have addressed the combined behaviour of NBS at large scales. One of the possible reasons is that large-scale systems are more complex than small-scale systems. The most common large-scale NBS are flood storage basins (De Risi et al., 2018), preservation and regeneration of forests in flood-prone areas (Bhattacharjee and Behera, 2018), making more room for the river (Klijn et al., 2013), river restoration (Chou, 2016), wetlands (Thorslund et al., 2017), and mountain forestation (Casteller et al., 2018)

A classic example of a large-scale NBS implementation is the ‘Room for the River Programme’ implemented along the Rhine and Meuse rivers in The Netherlands. The Room for the River Programme consisted of 39 local projects based on nine different types of measures (Klijn et al., 2013). These measures are flood plain lowering, dike relocation, groyne lowering, summer bed deepening, water storage, bypass/floodway, high water channels, obstacle removal and dike strengthening. The benefits that the programme achieved are more than just reducing flooding, also increasing opportunities for recreation, habitat and biodiversity in the area (Klijn et al., 2013).

Another case study of a large scale NBS is the Laojie river project in Taoyuan City in Taiwan. The study focused on changing the channelised, culverted, flood-control watercourse into an accessible green infrastructure corridor for the public (Chou, 2016). The landscape changes resulting from this project have increased recreation activities and improved the aesthetic value in the area.

NBS may benefit people in coastal areas by reducing risk from storm surges, wave energy, coastal flooding as well as erosion, as documented by several authors (see, for example, Coppenolle, 2018; Joyce et al., 2017; Ruckelshaus et al., 2016; Sutton-Grier et al., 2018). NBS for coastal areas can be implemented either at large or small scales. They include dunes, beaches, oyster and coral reefs, mangroves, seagrass beds and marshes. These measures can also provide habitat for different species such as fish, birds, and other wildlife (Ruckelshaus et al., 2016). However, only a few articles of the 137 reviewed focused on the potential benefits of NBS in coastal areas.

Casteller et al. (2018) concluded that native mountain forests could be used to reduce hydro-meteorological risk such as flash floods and landslides. To reduce the impact of large-scale hydro-meteorological events, more research is needed on large-scale NBS and their hybrid combinations designed to attenuate flows and improve drainage. They should be implemented to include improvements in solid waste management, community-based river cleaning programs and reforestation (De Risi et al., 2018).

4.2 Techniques, methods and tools for planning, selecting, evaluating and implementing NBS

Figure 4 illustrates a typical process for the selection and evaluation of NBS. The process starts by selecting possible measures that correspond to the local characteristics and project's target. The next step is concerned with evaluating the measures' performance using numerical models, cost-benefit analysis and/or multi-criteria analysis. For more complex systems with a large number of scenarios and parameters, optimisation can be used to maximise the benefits and minimise the costs. The techniques, methods and tools for planning, selecting, evaluating and implementing NBS are reviewed in the following section.

4.2.1 Selection of NBS

It has been a well-accepted fact that not all NBS are suitable for all conditions. Therefore, it is important to consider the feasibility and constraints at the site at an early stage in the selection process. The first consideration in selecting NBS is to define the objective such as the target area (i.e. urban, rural) and performance requirements such as quantity and/or quality (Romnée and De Herde, 2015; Zhang and Chui, 2018). For example, Pappalardo et al., (2017) chose permeable pavements and green roofs because they can detain runoff or enhance infiltrate to the subsoil. Many authors suggest restricting the choice of appropriate NBS based on common site constraints such as land use, soil type, groundwater depth, catchment characteristics, political and financial regulations, amenities, environmental requirements and space available (Eaton, 2018; Joyce et al., 2017; Nordman et al., 2018; Oraei Zare et al., 2012). For example, Eaton (2018) selected bio-retention measures because these are more suitable in low-density residential land use. Moreover, the study of Reynaud et al., (2017) describes how the type of NBS has an impact on individuals' preference for ecosystem services.

Therefore, a screening analysis is necessary to select the NBS measures that are best suited to local constraints and objectives, providing decision-makers with valuable information. The way forward in the selection of NBS is to consider spatial planning principles to locate the position for measures. Spatial planning principles can facilitate and stimulate discussion among local communities, researchers, policy-makers and government authorities.

4.2.2 Frameworks and methods for evaluation of NBS

There are several frameworks and methods that can be used to evaluate the performance indicators of NBS discussed in this review. One of the most popular evaluation approaches is to analyse, simulate and model hydrology, hydraulics and water balance processes. This information is then used to support decision makers, planners and stakeholders in their evaluation of performance and potential of NBS by comparing modelled results against the current situation, baseline scenario or targets (Jia et al., 2015).

In addition to the hydrological and hydraulic analysis, cost-benefit analysis is often used to select and implement a cost-effective NBS (Huang et al., 2018; Nordman et al., 2018; Watson et al., 2016; Webber et al., 2018). The common benefits considered include prevented damage costs, omitted infrastructures, and prevented agricultural losses. One cost-benefit approach is to evaluate NBS by applying the whole life cycle costing approach (LCC) including construction, operation, maintenance and opportunity costs (Nordman et al., 2018) and Return on Investment (ROI) (De Risi et al., 2018).

Another method for the evaluation of NBS is multi-criteria analysis (MCA), which has the potential to integrate and overcome the differences between social and technical approaches (Loc et al., 2017). It can be used to structure complex issues and help find a better understanding of costs and benefits. Such analysis is useful for decision makers when there are multiple and conflicting criteria to be considered (Alves et al., 2018b; Loos and Rogers, 2016). The MCA takes different criteria into account and assigns weights to each criterion. This process can produce a ranking of the different measures that can be implemented on the site (Chow et al., 2014; Jia et al., 2015). For example, Loc et al. (2017) integrated the results from numerical modelling and social surveys into an MCA and ranked the alternatives based on the evaluation criteria of flood mitigation, pollutant removal and aesthetics. Loos and Rogers (2016) applied multi-attribute utility theory (MAUT) to assess utility values for each alternative by assuming that preference and utility are independent from each other. Petit-Boix et al. (2017) recommended that future research should combine the economic value of the predicted material and ecological damage, risk assessment models and environmental impacts of NBS.

Since not all assessments can be done with modelling alone, interviews and fieldwork are often neccessary. For instance, Chou (2016) used eighteen open questions from six topics, namely: accessibility; activities; public facilities; environmental quality; ecological value; and flood prevention. These questions are used to evaluate the qualitative performance of river restoration. However, some of the methods are only appropriate for small scale applications and cannot be applied in large catchments. Yang et al. (2018) proposed Relative Performance Evaluation (RPE) methods, which use a score to calculate the performance for all alternatives. This score is calculated as the weighted sum of the scores of individual indicators.

From the discussion above, it can be observed that there are still challenges in evaluating intangible benefits of NBS and incorporating stakeholders' preferences into the process. For complex systems with a large number of scenarios and parameters, simple trial-and-error methods may not be the feasible approach. In such cases, an automated optimisation method could be effectively applied to handle these tasks and to combine the above mentioned methods. There is also a challenge in combining a range of aspects that can and cannot be expressed in monetary terms into the same framework of analysis.

4.2.3 Optimal configuration of NBS

In order to implement NBS, typical selection factors include the number of NBS measures, size, location, and potential combinations of NBS. Optimisation of NBS strategies has been increasingly used in the context of urban stormwater management. Most of the studies focus on minimising water quantity and improving water quality by selecting the type, design, size and location of NBS (Behroozi et al., 2018; Gao et al., 2015; Giacomoni and Joseph, 2017; Zhang and Chui, 2018). Zhang and Chui (2018) systematically reviewed optimisation models that have different structures, objectives and allocation components. This section reviews some examples of using optimisation to assess NBS.

A comprehensive modelling system typically refers to an optimisation package tool that integrates an “easy-to-use” user interface with physically based deterministic models. Examples include SUSTAIN (the System for Urban Stormwater Treatment and Analysis IntegratioN) (Zhang and Chui, 2018) and Best Management Practice Decision Support (BMPDSS) (Gao et al., 2015). The SUSTAIN model was developed by the United States Environmental Protection Agency (US EPA) and aims to provide decision makers with support in the process of selection and placement of NBS measures, and to optimise the hydrological performance and cost-effectiveness of NBS in the urban watershed (Leslie et al., 2009; Li et al., 2018a). There are several studies that apply SUSTAIN with the aim to minimise the cost of NBS for both runoff quantity (flow volume, peak flow) and runoff quality (pollutant removal) (Gao et al., 2015; Li et al., 2018c). It is, however, important to note that comprehensive modelling systems are not always easily modified to fit with the specific needs of users.

Another optimisation tool approach is integrated model-algorithm tools, which combine numerical (hydrological-hydrodynamic) models with optimisation algorithms. A popular optimisation method used to evaluate NBS performance is a multialgorithm, genetically adaptive multiobjective (AMALGAM) method using the multilevel spatial optimisation (MLSOP) framework (Liu et al., 2016).

In the reviewed articles, Non-dominated Sorting Genetic Algorithm II (NSGA-II) is used in most of the studies to date. Wang et al., (2015) concluded that NSGA-II is one of the most popular multiobjective evolutionary algorithms (MOEAs) despite limited parameter tuning features, and generally outperformed the other MOEAs in relation to the set of solutions generated. There are several examples of the use of NSGA-II. Oraei Zare et al. (2012) minimised run-off quantity while maximizing the improvement of water quality and maximising reliability. Karamouz and Nazif (2013) minimised cost of flood damage as well as minimising NBS cost in order to improve system performance in dealing with the emerging future conditions under climate change. Yazdi and Salehi Neyshabouri (2014) optimised cost-effectiveness, which focused on land use change strategies including orchard, brush and seeding measures in different parts of the watershed. All of the above mentioned studies coupled NSGA-II with the Storm Water Management Model (SWMM) developed by US EPA (Cipolla et al., 2016; Li et al., 2018b; Mei et al., 2018; Tao et al., 2017; Wu et al., 2018; Yang et al., 2018; Zhu and Chen, 2017) to address the optimisation problems.

There are two different optimisation methods of Particle Swarm Optimization (PSO) which have been found in the course of this review. The modified Particle Swarm Optimization (MPSO) is used by Duan et al. (2016) to solve the Multi-Objective Optimal (MOO) of the cost-effectiveness of NBS based detention tank design. Similarly, Behroozi et al., (2018) used the multi-objective particle swarm optimisation (MOPSO) by coupling it with SWMM to optimise the peak flow and mean TSS concentration reduction by changing the combinations of NBS.

Another algorithm that is used for optimising the performance of NBS is Simulated Annealing (SA). SA is a general probability optimisation algorithm that applies thermodynamic theories in statistics. An example of a study with SA is given by Huang et al., (2018) who automatically linked SA with SWMM to maximise cost-benefit for flood mitigation and layout design. The cost-benefit analysis is computed using annual cost, which includes both annual fixed cost and annual maintenance cost. Another study that applied SA is Chen et al., (2017) who combined SA with SWMM to locate NBS in Hsinchu County in northern Taiwan by considering three objective functions. These were minimising depths, durations, and the number of inundation points in the watershed.

It can be observed that most of the optimisation models to date (both comprehensive modelling system and model algorithms) are coupled with SWMM for urban storm management. There is still a lack of research that uses optimisation to maximise the efficiency of NBS on a large scale as well as combining other co-benefits in optimisation (Table 3). Furthermore, there is a lack of research that employs two-dimensional models in the optimisation analysis. This is particularly important when considering estimation of flood damages and other flood propagation-related impacts.

4.2.4 Tools for selection, evaluation and operation of NBS

Recently, several selection and evaluation tools have been developed in order to assist stakeholders in screening, selecting and visualising NBS measures. Examples of web-based applications developed to screen urban NBS measures are Green-blue design tool (atelier GROENBLAUW, 2019), PEARL KB (PEARL, 2019), Climate Adaptation App (Bosch Slabbers et al., 2019) and Naturally resilient communities solutions (Naturally Resilient Communities, 2019). These web-based tools allow the user to filter NBS in relation to their problem type, measure, land use, scale, and location.

In addition to the above, there are also tools that combine both the selection and evaluation processes together to use as planning support systems tool. An example is the SUDs selection and location (SUDSLOC) tool, which is a GIS tool linked to an integrated 1D hydraulic sewer model and a 2D surface model. UrbanBEATS (the Urban Biophysical Environments and Technologies Simulator) aims to support the planning and implementation of WSUD infrastructure in urban environments (Kuller et al., 2018). Other tools that can be used to select and evaluate potential NBS interventions are Long-Term Hydrologic Impact Assessment-Low Impact Development (L-THIA-LID) (Ahiablame et al., 2012; Liu et al., 2015) and the GIS-based tool called Adaptation Support Tool (AST) (Voskamp and Van de Ven, 2015). Although these tools could be useful in assisting decision makers, some of them may not be suitable for every location and scale. For example, source data required into L-THIA-LID cover only the United States and QUADEAU (Romnée and De Herde, 2015) is only suitable for urban stormwater management in a public space scale.

In addition to the above, other models such as MIKE packages developed by DHI (Semadeni-Davies et al., 2008), Soil and Water Assessment Tool (SWAT) (Cheng et al., 2017), IHMORS (Herrera et al., 2017), and Urban Water Optioneering Tool (UWOT) (Rozos et al., 2013) can be effectively used in the analysis effectiveness of NBS.

To date, very few tools have been developed to calculate multiple benefits of NBS in monetary terms as well as to address their qualitative benefits. Some examples are Benefits of SUDs Tool (BeST), which provides a structured approach to evaluating potential benefits of NBS (Digman et al., 2017; Donnell et al., 2018; Fenner, 2017), and the MUSIC tool (Model for Urban Stormwater Improvement Conceptualization), which is a conceptual planning and design tool that also contains a life cycle costing module for different NBS that are implemented in Australia (Khastagir and Jayasuriya, 2010; Schubert et al., 2017).

There are also other tools that can be used for modelling stormwater management options and/or to assess economic aspects of NBS in urban areas. These are documented in the work of Jayasooriya and Ng (2014). However, most of these tools only focus on small-scale NBS such as bio-retentions, pervious pavements, green roofs, swales, retention ponds, biofiltration and rainwater harvesting. There are only a few tools that can address river and coastal flood protection measures and droughts, while none of the tools can be used to reduce the risk from landslides and storm surges. A lack of information systems, information clusters and platforms for information exchange between authorities and practitioners has been recognized by Kabisch et al. (2016).

There is also the need to explore the use of sensors, regulators, telemetry and Supervisory Control and Data Acquisition (SCADA) systems for efficient and effective operation and real-time control of NBS. Such configurations, which are based on the use of real-time control technology for operation of NBS, can be referred to as “SMART NBS”. The value of exploring SMART NBS configurations may be particularly beneficial for hybrid systems, where NBS sites need to be configured to work closely with different kinds of measures.

4.5 Socio-economic influence on implementation of NBS

Investing in NBS for hydro-meteorological risk reduction is essential to ensure the capability for future socio-economic development (Faivre et al., 2018). In this respect, the European Commission has been investing considerably in the research and innovation of NBS or EbA, and some recent efforts have been placed on practical demonstration of NBS for climate change adaptation and risk prevention (Faivre et al., 2017).

The European Commission is dedicated to bring innovative ‘sciences-policy-society’ mechanisms, open consultations, and knowledge-exchange platforms to engage society in improving the condition for implementation of NBS (Faivre et al., 2017). There are some inventories of web-portals, networks and initiatives that address NBS at European, national and sub-national levels (Table 5).

Denjean et al. (2017) noted that the people who propose NBS are in many cases ecologists and biologists who have been trained within a very different scientific paradigm and thus speak a ‘different language’ to the key decision makers, who are often civil and financial engineers, contractors and financing officers. Hence, this may limit the feasibility of implementation of NBS.

Very few articles study actions or processes in relation to stakeholder participation. However, those that do so stress the importance of involving stakeholders in the evaluation and implementation of NBS and the current practical limitations of implementing NBS. One of the important reasons is to ensure that stakeholders and local government are fully aware of the multiple benefits of NBS so that they can integrate them better into planning for sustainable cities (Ishimatsu et al., 2017). For example, Liu and Jensen, (2018) and Chou, (2016) claim that the implementation of NBS with visible benefits on the landscape and the liveability of the city (in terms of amenities, recreation, green growth, and microclimate) can create positive attitudes among stakeholders towards applying NBS. Moreover, as the implementation of NBS is often a costly investment for local communities, and the facilities are expected to be in place for a decade, it is essential for stakeholders to know the effectiveness of NBS (Semadeni-Davies et al., 2008). Involving the community with authorities in both the planning and implementing process can be a very useful strategy (Dalimunthe, 2018). In a case study ofrom the Great Plains in the US, Vogel et al., (2015) addressed how local perceptions of NBS effectiveness and applicability limit its adoption. One of the factors was a lack of awareness of NBS and support from stakeholders and authorities. Another case in Portland, Oregon, USA, (Thorne et al., 2018) concluded that the limited adoption of NBS is caused by the lack of confidence in public preferences and socio-political structures, as well as the uncertainty regarding scientific evidence related to physical processes. To solve this, they suggested that both socio-political and biophysical uncertainties must be identified and managed within the framework for designing and delivering sustainable urban flood risk management.

Schifman et al. (2017) proposed a Framework for Adaptive Socio-Hydrology (FrASH) that can be used in NBS planning and implementation by bringing ideas together from socio-hydrology, the capacity for adaptation, participation and inclusiveness, and organised action. The framework also helps in creating a connected network between municipalities, public works departments, organisations and people in the community. This potentially allows for the management of resilience in the system at multiple scales.

Often, it is not as easy to address socio-economic issues as technical questions. These socio-economic issues include perception and acceptance, policies, interdisciplinary nature, education, and documenting the economic benefit of NBS implementation (Alves et al., 2018a; Vogel et al., 2015). Nevertheless, social science research (i.e. surveys, interviews, and focus groups) helps to review and gain insights about the obstacles and motivations for implementing NBS, as well as to understand a community's resilience and adaptive capacity (Matthews et al., 2015). For instance, bringing the findings to stakeholders and community members to discuss what level of flood hazard is acceptable and what level of climate change adaptation capacity the community plans to achieve (Brown et al., 2012). Moreover, socio-political dynamics in NBS is still lacking. There are few case studies available that critically evaluate the politics of NBS in the role of community mobilization (Triyanti and Chu, 2018).

Not only it is essential to involve stakeholders in the selection, planning, design and implementation of NBS, but it is also important for bridging gaps between researchers, engineers, politicians, managers and stakeholders. This may help to improve our capacity for using both small and large scale NBS. There is a well documentation of policy arrangements, scientific niches and current status of governance studies of NBS that was reviewed by Scarano (2017 and Triyanti and Chu (2018).

4.6 Multiple-benefits of NBS

The literature on NBS and its sister concepts increasingly refers to multiple benefits on social, economic and environmental enhancements. The reason is that NBS are regarded as sustainable solutions that use ecosystem services to provide multiple benefits for human well-being and the environment, which differs from grey infrastructure. One of the processes that could provide these benefits is to give more significant consideration to landscape function, adaptive and multi-functionality design (Lennon et al., 2014; Vojinovic et al., 2017) and promoting desirable soil (Keesstra et al., 2018).

The literature to date shows that multiple challenges can be continually addressed through NBS. These include reducing flood risk (Song et al., 2018), storing and infiltrating rainfall run-off, delaying and reducing surface runoff, reducing erosion and particulate transport (Loperfido et al., 2014) recharging groundwater discharge, reducing pollution from surface water (Donnell et al., 2018), increasing nutrient retention and removal (Loperfido et al., 2014), maintaining soil moisture, and enhancing vegetation growth.

Beyond water management, the case for these natural capital approaches includes their ability to provide additional benefits in improving socio-economic aspects and human well-being through recreational areas and aesthetic value (Song et al., 2018), as well as encouraging tourism through the access to nature (Sutton-Grier et al., 2018). Wheeler et al. (2010) quantified the volume and intensity of children’s physical activity in greenspace and found that time in greenspace is more likely to lead to greater activity intensity amongst children. The use of NBS can bring economic benefits in different ways such as reduced/prevented damage cost from hydro-meteorological events, economic benefit from the reduction of stormwater that typically needs to be treated in a public sewerage system and energy and carbon savings from reduced building energy consumption (heating and cooling) (Soares et al., 2011).

The environmental benefits of NBS measures can have various positive impacts. Some of the most important are the ability to enhance environmental and ecosystem services by connecting habitat and biodiversity (Hoang et al., 2018; Reguero et al., 2018; Thorslund et al., 2017), increasing carbon sequestration, reducing air and noise pollution (Donnell et al., 2018); and improving urban heat island effect mitigation (Raymond et al., 2017).

Zhang and Chui, (2019) reviewed the hydrological and bio-ecological benefits of NBS across spatial scales and suggested that there should be more research at the catchment scale to consider the full benefits of NBS. The hydrological and water quality benefits of NBS have been widely reviewed and discussed, but there are few articles that focus on the assessment of multi-benefits of NBS. Hoang et al., (2018) proposed a new integrated methodology using a GIS approach to assess benefits and disadvantages of NBS, which include habitat connectivity, recreational accessibility, traffic movement, noise propagation, carbon sequestration, pollutant trapping and water quality.

In order to evaluate benefits effectively, Fenner, (2017) recommended that their spatial distribution should be assessed through multi-functional design, making it possible to identify how this is valuable to stakeholders and where the overall aggregated benefits occur. There is still a need for deeper understanding of assessment of multi-benefits of NBS (Liu et al., 2017). A challenge is the lack of information on the values of ecosystem and multi-related ecosystems economic valuation.

4.7 Trends, knowledge gaps and future research prospects

The literature reviewed in this study showed that NBS have not been equally applied to all hydro-meteorological risk reduction contexts. The search strategy adopted in this review (Section 3.1) identified a total of 1204 Journal articles from 2007 to the end of 2018. However, only 85 out of 1204 articles (i.e., 7%) explicitly used the term “Nature-Based Solution” for hydro-meteorological risk reduction (Fig. 5a). This can be explained by the fact that the term NBS has been used only from 2008 (MacKinnon et al., 2011) while other terms have been used earlier in different countries (Figure 1). However, the significant increase of published articles in recent years shows how NBS is a rapidly growing research area (Fig. 5a).

Of the 1204 articles, only 137 publications specifically address NBS for hydro-meteorological risk reduction (Section 3.2). Among those, only 13 articles deal with large scale NBS, mostly focusing on river and coastal flooding (Table 6). The review of the 137 articles indicates that most of the research to date has been carried out in an urban context, whereas the contexts concerning river and coastal floods, droughts and landslides are the least addressed. More specifically, 88% of all articles deal with runoff reduction or flood risk reduction in urban areas (Fig. 5b). It is worthwhile to notice that two out of the ten search terms in Table 2 contain the word “urban”. This was in order to include two popular concepts linked to NBS for hydro-meteorological risk, which are WSUD and SUDs (cf. the overview of terminology given in Section 2). Nevertheless, the literature sourced using these two search terms only accounts for 2.9% of the total 88% urban cases shown in Figure 5b. Therefore, no significant bias was introduced in our findings by the inclusion of the word “urban” through these two search terms.

An overview of quantitative results, some research gaps and future research prospects are given in Table 6 and some of the key challenges are summarised below.

There is a clear gap between the amount of research on small scale NBS in urban areas and large scale NBS at the catchment (river basin), rural, and regional scale. The reason for this is that a large-scale system is more complex than a small system. Therefore, research and frameworks that deal with reducing hydro-meteorological risk by upscaling NBS from urban scale to catchment (river basin) scale would be beneficial. It would be also beneficial to understand both the natural processes of large scale NBS and how they change over time. Furthermore, there are only a few studies that combine NBS at both small- and large-scale, and further research in this direction is highly desirable.

Obviously, there is no single NBS solution that can solve all problems. Every project needs to be designed to address a particular challenge in its local context and in its respective community. Therefore, an understanding of site conditions is necessary for NBS to achieve the target of the project.

Based on the findings of the literature review, there are still challenges in relation to methods and tools for planning and implementing NBS. These include improving and developing methods for assessing co-benefits (especially socio and ecological benefits, i.e. aesthetic values, community liveability, and human health), frameworks and methods for evaluating large-scale NBS and "hybrid measures" (i.e. combinations of grey infrastructure and small and large scale NBS).

There are also challenges in incorporating local stakeholder participation within the framework and models and within the assessment and implementation process. Other challenges regarding governance are to develop guidance on effective models of governance, provide insight information on actors, institutions and legal instruments and other requirements that are relevant for implementing NBS. The reason for this is the lack of workable frameworks that can bring together a variety of stakeholder groups. Moreover, there is still a lack of finance studies and guidelines for cost-effective implementation, maintenance and operation of NBS projects, and mechanisms that can be used to promote new business and finance models for successful implementation of NBS.

There should also be more efforts in the development of assessment tools that incorporate new technologies such as real-time control systems, forecast models, and coupled models to provide more active and integrated operational solutions (i.e., SMART NBS). There is a need for the development of databases that include functions, benefits, and costs of large and small scale NBS to facilitate future research.

5 Conclusions

The present paper provides a critical review of the literature and identifies future research prospects based on the current knowledge gaps in the area of Nature-Based Solutions for hydro-meteorological risk reduction by using a systematic review. The review process started by analysing 1407 articles sourced from Scopus and 1232 articles form Web of Science from 1st January 2007 to 1st December 2018. The final full analysis was performed on 137 articles. The systematic review has shown that considerable achievements have been made to date. However, there are still many challenges and opportunities in extending the knowledge of NBS, and that will play an important role in the coming years. Some examples of research gaps are; combining small scale and large scale NBS, the effectiveness of NBS in reducing risk at the regional and catchments scale, the frameworks, methods, and tools for assessing co-benefits, involvement local stakeholders in the selection, assessment and implementation process, integration of NBS with new technologies and development of NBS databases.

The effectiveness, benefits and acceptances of NBS are dependent on the implementation purposes, local context and cultural setting. For example, small scale NBS (i.e., swales, green roofs, or porous pavements) are more suitable for urban flooding while large scale NBS (river restoration, dunes, or wetlands) are more suitable for river floods, coastal floods, droughts and landslides. Small scale NBS are more effective in reducing peak for smaller magnitude frequent storms (i.e., 2-year return period) than larger magnitude infrequent storms (i.e., 10-year return period). Large scale NBS can provide more benefits compared to small scale NBS because they encompass larger space, thus more function can be included in the design process. For example, Laojie river project in Taoyuan City in Taiwan changed the channel into an accessible green corridor. This project helps in reducing flood risk, improving riverside landscapes, increasing recreation area, increasing the aesthetic value in the area, and improving river water quality. On the other hand, small scale NBS need less area because most of the measures can be implemented in the free space. For example, green roofs can be implemented on the roofs of buildings, and permeable pavements can be implemented in car parks. Investments in NBS will benefit society by providing cost-effective measures and adaptive strategies that protect their communities and achieve a range of co-benefits. Therefore, bridging the gaps between researchers, engineers and stakeholders will help to improve the capacity of NBS in reducing hydro-meteorological risk as well as increasing their benefits. Strengthening these aspects may be beneficial for improving acceptance of NBS at the local level.

Three Horizon 2020 projects including, RECONECT, PHUSICOS and OPERANDUM were initiated in 2018 to bridge the gaps in the innovation of NBS and to test their efficacy in rural, mountain and transition land environments. Development of techniques, methods and tools for planning, selecting, evaluating and implementing NBS are among the common products of RECONECT, PHUSICOS and OPERANDUM.

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Appendix

Appendix A: Abbreviations

AMS	Adaptive metropolis search
AST	Adaptation Support Tool
BeST	Benefits of SUDs Tool
BGI	Blue-Green Infrastructure

BMPDSS	Best Management Practice Decision Support
BMPs	Best Management Practices
CBA	Cost-benefit analyses
CBD	Convention on Biological Diversity
CCA	Climate change adaptation
CEM	Commission on Ecosystem Management
DE	Differential evolution
DRR	Disaster risk reduction
EbA	Ecosystem-based Adaptation
Eco-DRR	Ecosystem-based Disaster Risk Reduction
EC	European Commission
FrASH	Framework for Adaptive Socio-Hydrology
GI	Green Infrastructure
IIED	International Institute for Environment and Development
IUCN	International Union for Conservation of Nature
LCC	Life cycle costing
LID	Low Impact Development
MAUT	Multiattribute utility theory
MCA	Multi-criteria analysis
MLSOP	Multilevel spatial optimization
MOEA	Most popular multiobjective evolutionary algorithms
MOO	Multi-Objective Optimal
MOPSO	Multi-objective particle swarm optimisation
MOUSE	Model of Urban Sewers
MUSIC	Model for Urban Stormwater Improvement Conceptualization
NBS	Nature-Based Solutions
NSGA-II	Non-dominated Sorting Genetic Algorithm II
PSO	Particle swarm optimisation
RECONECT	Regenerating ECOsystems with Nature-based solutions for hydro-meteorological risk rEduCTion
ROI	Return on Investment
RPE	Relative Performance Evaluation
SA	Simulated Annealing
SCADA	Supervisory Control and Data Acquisition

SCP	Sponge City Programme
SDGs	Sustainable Development Goals
SEI	Stockholm Environment Institute
SFDRR	Sendai Framework for Disaster Risk reduction
SUDs	Sustainable Urban Drainage Systems
SUSTAIN	System for Urban Stormwater Treatment and Analysis IntegratioN
SWAT	Soil and Water Assessment
SWMM	Storm Water Management Model
TSS	Total Suspended Solids
UN	United Nations
UNFCCC	UN Framework Convention on Climate Change
US EPA	United States Environmental Protection Agency
UWOT	Urban Water Optioneering Tool
WCPA	World Commission on Protected Areas
WSUD	Water Sensitive Urban Design

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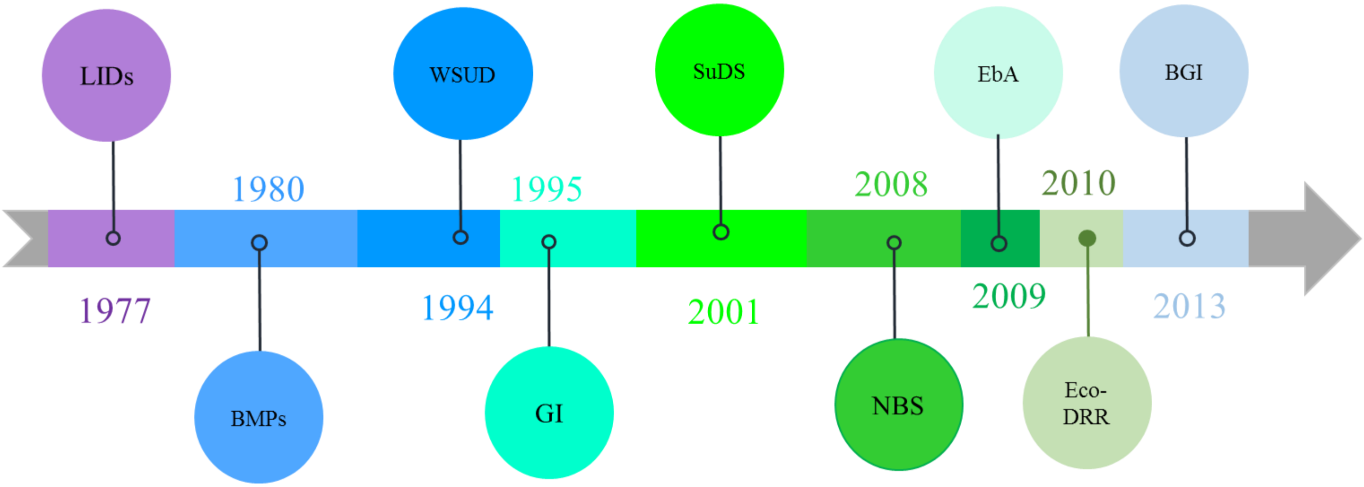


Figure 1: Timeline/year of origin of each terminology (Low Impact Developments (LIDs), Best Management Practices (BMPs), Water Sensitive Urban Design (WSUD), Green Infrastructure (GI), Sustainable Urban Drainage Systems (SUDs), Nature-Based Solitions (NBS), Ecosystem-based Adaptation (EbA), Ecosystem-based Disaster Risk Reduction (Eco-DRR) and Blue-Green Infrastructure (BGI)) based on their appearance in publications

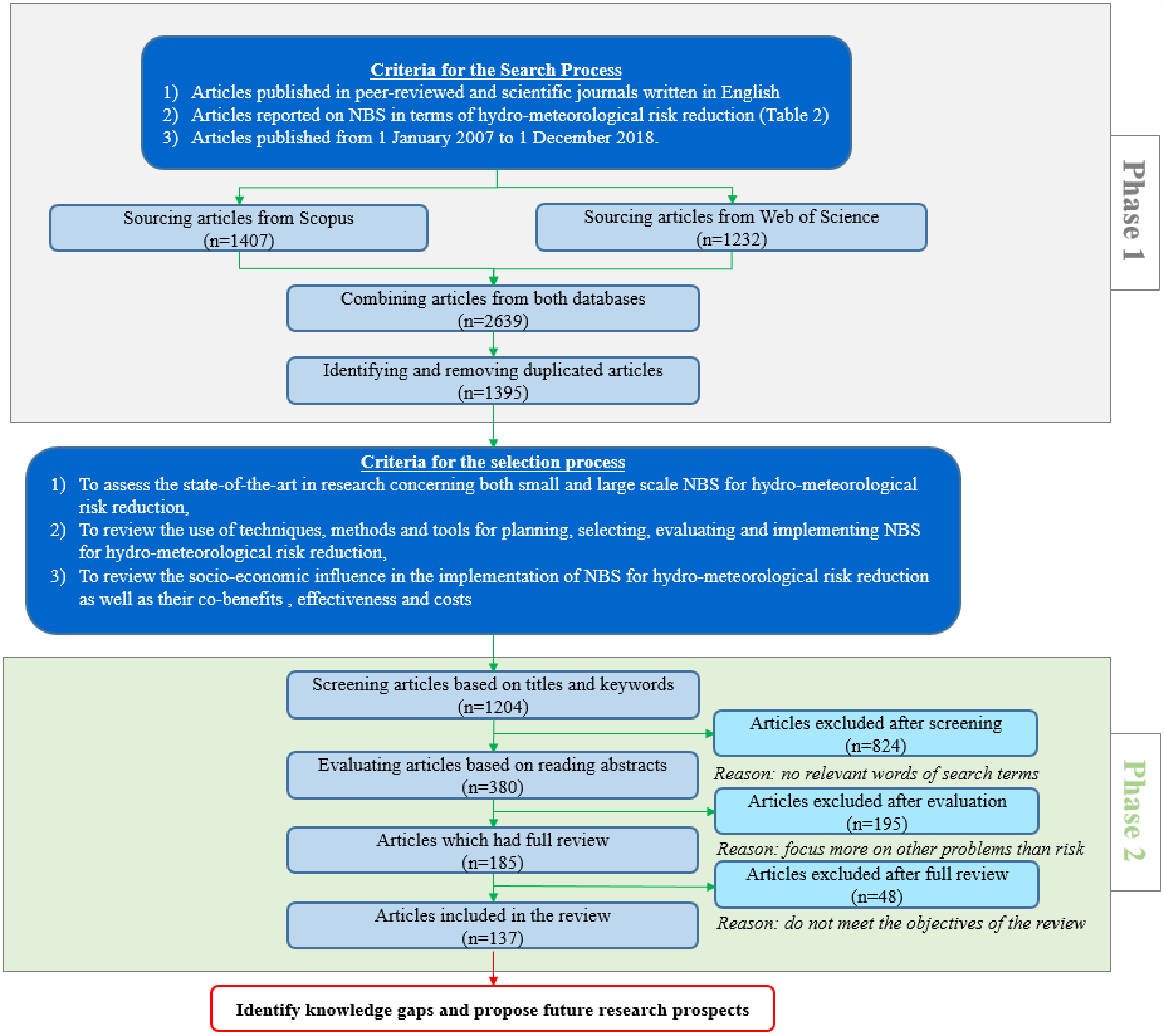


Figure 2: Process of article selection on Nature Based Solutions for hydro-meteorological risk reduction. The final number of fully reviewed articles is 137

Figure 3: Illustration of large and small scale Nature-Based-Solutions (NBS); Large-scale NBS A illustrates NBS in mountainous regions (e.g., afforestation, slope stabilization, etc.), Large-scale NBS B illustrates NBS along river corridors (e.g., widening river, retention basins, etc.) and Large-scale NBS C illustrates NBS in coastal regions (e.g., sand dunes, protection dikes/walls, etc.); Typical examples of Small-scale NBS are green roofs, green walls, rain gardens, permeable pavements, swales, bio-retention, etc.

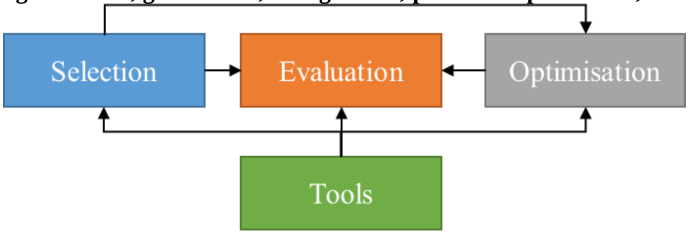
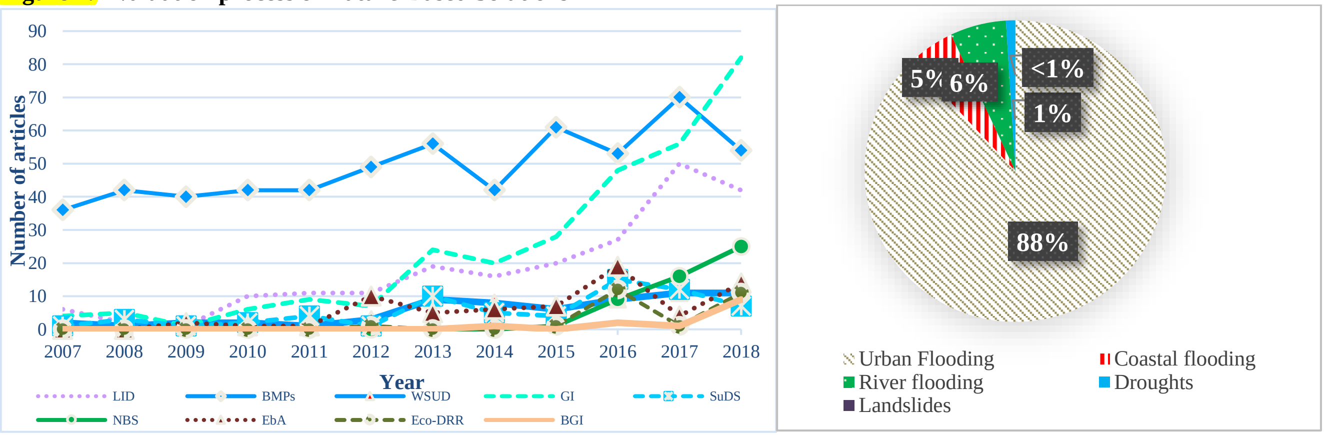


Figure 4: Evaluation process of Nature-Based Solutions



(a) **(b)**

Figure 5: An overview of published articles on: (a) Number/trend of published articles on Nature-Based Solutions (NBS) for hydro-meteorological risk reduction and its sister terms: Low Impact Developments (LIDs), Best Management Practices (BMPs), Water Sensitive Urban Design (WSUD), Green Infrastructure (GI), Sustainable Urban Drainage Systems (SUDs), Nature-Based Solutions (NBS), Ecosystem-based Adaptation (EbA), Ecosystem-based Disaster Risk Reduction (Eco-DRR) and Blue-Green Infrastructure (BGI).Nature-Based Solutions (NBS) for hydro-meteorological risk reduction and (b) percentage of published articles that have been studied for reducing urban flooding, coastal flooding, river flooding, droughts

Table 1: Glossary of terminologies and their geographical usage

Terminology	Definition/Objectives/Purpose	Commonly used in	Reference
Low Impact Development (LIDs)	*"LID is used as a retro- fit designed to reduce the stress on urban stormwater infrastructure and/or create the resiliency to adapt to climate changes, LID relies heavily on infiltration and evapotranspiration and attempts to incorporate natural features into design."*	- United States - New Zealand	(Barlow et al., 1977; Eckart et al., 2017)
Best management practices (BMPs)	*"A device, practice or method for removing, reducing, retarding or preventing targeted stormwater runoff constituents, pollutants and contaminants from reaching receiving waters"*	- United States - Canada	(Biggers et al., 1980; Moura et al., 2016; Strecker et al., 2001)
Water Sensitive Urban Design (WSUD)	*"Manage the water balance, maintain and where possible enhance water quality, encourage water conservation and maintain water-related environmental and recreational opportunities".*	- Australia	(Lottering et al., 2015; Whelans consultants et al., 1994)
Sustainable Urban Drainage Systems (SUDs)	*"Replicate the natural drainage processes of an area – typically through the use of vegetation-based interventions such as swales, water gardens and green roofs, which increase localised infiltration, attenuation and/or detention of stormwater"*	- United Kingdom	(Abbott and Comino-Mateos, 2001; Ossa-Moreno et al., 2017)
Green Infrastructure (GI)	*"The network of natural and semi-natural areas, features and green spaces in rural and urban, and terrestrial, freshwater, coastal and marine areas, which together enhance ecosystem health and resilience, contribute to biodiversity conservation and benefit human populations through the maintenance and enhancement of ecosystem services"*	- United states - United Kingdom	(Gill et al., 2007; Lafortezza et al., 2013; Naumann et al., 2011; Walmsley, 1995)
Ecosystem-based Adaptation (EbA)	*"The use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change."*	- Canada - Europe	(CBD, 2009; McVittie et al., 2018; Scarano, 2017)
Ecosystem-based disaster risk reduction (Eco-DRR)	*"The sustainable management, conservation, and restoration of ecosystems to reduce disaster risk, with the aim of achieving sustainable and resilient development"*	- Europe - United states	(Estrella and Saalismaa, 2013; PEDRR, 2010; Renaud et al., 2016)
Blue-Green Infrastructure (BGI)	*"BGI provides a range of services that include; water supply, climate regulation, pollution control and hazard regulation (blue services/goods), crops, food and timber, wild species diversity, detoxification, cultural services (physical health, aesthetics, spiritual), plus abilities to adapt to and mitigate climate change"*	- United Kingdom	(Bozovic et al., 2017; Lawson et al., 2014; PEDRR, 2010; Rozos et al., 2013)
Nature-Based Solution	*"NBS aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions inspired by, supported by or copied from nature; both using and enhancing existing solutions to challenges, as well as exploring more novel solutions."*	- Europe	(Cohen-Shacham et al., 2016; European Commission (EC), 2015; Faivre et al., 2017; MacKinnon et al., 2008; Stürck et al., 2015)

Table 2: Selected concepts and terms used to search relevant literature on NBS for hydro-meteorological risk reduction

No	Research words		
	First concept (Nature-Based Solutions)	**Connection**	**Second concept (Hydro-meteorological risk)**
1	"Nature-based solutions" OR	AND	"Flood"
2	"Nature-Based Solutions" OR	AND	"Drought"
3	"Low impact development" OR	AND	"Storm surge"
4	"Sustainable Urban Drainage Systems" OR	AND	"Landslide"
5	"Water Sensitive Urban Design" OR	AND	"Hydro-meteorological"
6	"Best Management Practices" OR	AND	"Disaster"
7	"Green infrastructure" OR	AND	"Review"
8	"Green blue infrastructure" OR	AND	"Hydrology"
9	"Ecosystem-based Adaptation " OR	AND	"Coastal"
10	"Ecosystem-based disaster risk reduction OR"	AND	"Risk"
11	"Green and grey infrastructure"		

Table 3 Summary of effectiveness, co-benefits and costs of small scale NBS measures

Measures	References	Case studies	Area/ volume covered by NBS	Effectiveness		Co-benefits	Cost/ m^2*	Remark
				Runoff volume reduction	Peak flow reduction			
Porous pavement	Shafique et al., (2018)	Seoul, Korea	1050 m^2	~30–65%	-	• Removing diffuse pollution • Enhancing recharge to groundwater	~$252	• More effective in heavier and shorter rainfall events.
	Damodaram et al., 2010	Texas, USA	2.99 km^2	-	~10% - 30%			
Green roofs	(Burszta-Adamiak and Mrowiec, 2013)	Wroclaw, Poland	2.88 m^2	-	54%-96%	• Reducing nutrient loadings. • Saving energy • Reducing air pollution • Increasing amenity value	~$564	• More efficient in smaller storm events than larger storm events
	(Ercolani et al., 2018)	Milan, Italy	0.39 km^2	~15%-70%	~10-80%			
	(Carpenter and Kaluvakolanu, 2011)	Michigan, USA	325. 2 m^2	~68.25%	~88.86%			
Rain gardens	(Ishimatsu et al., 2017)	Japan	1.862 m^2	~36-100%	-	• Providing a scenic amenity. • Increasing the median property value • Increasing biodiversity	~$501	• More effective in dealing with small discharges of rainwater
	(Goncalves et al., 2018)	Joinville, Brazil	34,139 m^2	50%	48.5%			
Vegetated swales	(Luan et al., 2017)	Beijing, China	157 m^3	~0.3–3.0%.	2.2%	• Reducing concentrations of pollutants • Increasing biodiversity	~$371	• More effective in heavier and shorter rainfall events. • Not suitable in mountains areas
	(Huang et al., 2014)	Haihe River basin, China	1,500 m^3	9.60%	23.56%			
Rainwater harvesting	(Khastagir and Jayasuriya, 2010)	Melbourne, Australia	1 m^3 -5 m^3	~57.8%-78.7%	-	• Improving water quality (TN was reduced around 72%-80%)	~$865 /m^3	
	(Damodaram et al., 2010)	Texas, USA	1.5 km^2	-	~8%-10%			

Measures	References	Case studies	Area/ volume covered by NBS	Effectiveness		Co-benefits	Cost/ m^2*	Remark
				Runoff volume reduction	Peak flow reduction			
Dry detention pond	(Liew et al., 2012)	Selangor, Malaysia	65,000 m^2	-	33-46%	• Providing recreational benefits.		• Delaying the time to peak by 40-45 min
Detention pond	(Damodaram et al., 2010)	Texas, USA	73,372 m^3	-	~20%	• Providing biodiversity benefits • Providing recreational benefits.	~$60	
	(Goncalves et al., 2018)	Joinville, Brazil	9,700 m^3	55.7%	43.3%			
Bio-retention	(Luan et al., 2017)	Beijing, China	945.93 m^3	~10.2–12.1%.	-	• Reducing TSS pollution • Reducing TP pollution	~$534	Measure has a better reduction effectiveness in various rainfall intensities.
	(Huang et al., 2014)	Haihe River basin, China	1,708.6 m^3	9.10%	41.65%			
	Khan et al., 2013;	Calgary	48 m^3	~90%	-			
Infiltration trench	(Huang et al., 2014)	Haihe River, China	3,576 m^3	30.80%	19.44%	• Reducing water pollutant • Improving surface water quality.	~$74	
	(Goncalves et al., 2018)	Joinville, Brazil	34,139 m^2	55.9%	53.4%			
Green roof and Porous pavement	(Damodaram et al., 2010)	Texas, USA	4.49 km^2	-	~10%-35%	• Saving energy • Increasing amenity value		• More effective in smaller events
Swale and Porous pavement	(Behroozi et al., 2018)	Tehran, Iran	-	5%-32%	~10%-21%	• Decreasing TSS pollution 50-60%		• More effective in smaller events
Rainwater harvesting and Porous pavement	(Damodaram et al., 2010)	Texas, USA	4.49 km^2	-	20%-40%	• Removing diffuse pollution		• More effective in smaller events
Detention pond and Raingarden	(Goncalves et al., 2018)	Joinville, Brazil	18,327 m^2	70.8%	60.0%	• Providing a scenic amenity.		•
Detention pond and Infiltration trench	(Goncalves et al., 2018)	Joinville, Brazil	18,327 m^2	75.1%	67.8%	Improving surface water quality.		•

***Remark** Cost of each measure is based on (CNT, 2009; Nordman et al., 2018; De Risi et al., 2018)

Table 4: Summary of effectiveness, co-benefits and costs of large scale NBS measures

Measures	References	Case studies	Area/ volume covered by NBS	Effectiveness	Co-benefits	Cost/ Unit*
De-culverting (river restoration)	(Chou, 2016)	Laojie River, Taiwan	3 km	• It can reduce flood risk up to 100 year return period	• Increasing landscape value • Increasing recreational value	~$18.6 million
Floodplain lowering	(Klijn et al., 2013).	Deventer Netherlands	5.01 km^2	• It can reduce water level 19 cm	• Increasing nature area • Increasing agriculture value	~€136.7 million
Dike relocation/floodplain lowering	(Klijn et al., 2013).	Nijmegen/ Lent, Netherlands	2.42 km^2	• It can reduce water level 34 cm	• Increasing floodplain area • Increasing recreational value	~€342.60 million
Floodwater storage	(Klijn et al., 2013).	Volkenrak-Zoommeer	200 million m^3	• It can reduce water level 50 cm	• Increasing habitat and biodiversity in the area • Increasing recreational value	~€386.20 million
Green floodway	(Klijn et al., 2013).	Veessen-Wapenveld	14.10 km^2	• It can reduce water level 71 cm	• Increasing floodplain area • Increasing recreational value	
Wetlands (Mangroves and salt Marshes)	(Coppenolle, 2018; Gedan et al., 2011)			• It can mitigate storm surge 80% • It can protect against tsunami impacts	• Providing shoreline protection services	

Table 5: An overview of web-portals, networks and initiatives that address Nature-Based Solutions

Name	References/ Website	Terminology used	Scale level	Funded by	Proposes
OPPLA	(Oppla, 2019)	Nature-Based Solution, Natural capital, Ecosystem services	Europe	FP7 (EC)	A new knowledge marketplace - EU repository of NBS; a place where the latest thinking on ecosystem services, natural capital and nature-based solutions is brought together.
BiodivERsA	(Biodivera, 2019)	Ecosystem services	Europe	Horizon 2020 (EC)	A network of funding organizations promoting research on biodiversity and ecosystem services.
BISE	(BISE, 2019)	Ecosystem services, Green infrastructures	Europe	EC	A single entry point for data and information on biodiversity supporting the implementation of the EU strategy and the Aichi targets in Europe.
ThinkNature	(ThinkNature, 2019)	Nature-Based Solution	Europe	Horizon 2020 (EC)	A multi-stakeholder communication platform that supports dialog and understanding of NBS.
ClimateADAPT	(Climate ADAPT, 2019)	EbA, Nature-Based Solution, GI	Europe	EC, EEA	A platform that supports Europe in adapting to climate change by helping users to access and share data and information relevant for CCIVA.

Name	References/ Website	Terminology used	Scale level	Funded by	Proposes
Natural Water Retention Measures	(NWRM, 2019)	Natural water retention measures	Europe	EC	A platform that gathers information on NWRM at EU level.
Urban Nature Atlas	(NATURVATION, 2019)	Nature-Based Solution	Europe	Horizon 2020 (EC)	A platform that contains around 1000 examples of Nature-Based Solutions from across 100 European cities.
Disaster Risk Management Knowledge Centre	(DRMKC, 2019)	Eco-DRR	Europe	EC	A platform that provides a networked approach to the science-policy interface in DRM.
Natural Hazards – Nature Based Solutions	(World Bank et al., 2019)	Nature-Based Solution	Global	The World Bank	A project map that provides a list of nature-based projects that are sortable by implementing organisation, targeted hazard, and type of nature-based solution, geographic location, cost, benefits, and more.
Nature-based Solutions Initiative	(Nature-based Solutions Initiative, 2019)	Nature-Based Solution	Global	International Institute for Environment and Development (IIED)	The global policy platform that provides information about climate change adaptation planning across the globe openly available and easy to explore.
weADAPT	(SEI, 2019)	Ecosystem-based Adaptation	Global	Stockholm Environment Institute (SEI)	A collaborative platform on climate adaptation issues, which allows practitioners, researchers and policy-makers to access credible, high-quality information and connect.
Nature of Cities	(The Nature of Cities, 2019)	Green Infrastructures	Global		An international platform for transdisciplinary dialogue concerning urban solutions.
ClimateScan	(ClimateScan, 2019)	Blue-Green Infrastructures	Global	EC	Global online tool which acts as a guide for projects and initiatives on urban resilience, climate proofing and climate adaptation around the world.
Partnership for Environment and Disaster Risk Reduction (PEDRR)	(PEDRR, 2019)	Ecosystem-based Adaptation	Global		PEDRR aims to promote and scale-up implementation of Eco-DRR and ensure it is mainstreamed in development planning at global, national and local levels, in line with the SFDRR.
PANORAMA	(PANORAMA, 2019)	Ecosystem-based Adaptation,	Global	IUCN, GIZ, UNDP	It aims to document and promote examples of inspiring solutions across development topics, to enable cross-sectoral learning and upscaling of successes

Table 6: Overview of knowledge gaps and potential future research prospects

Subject	Number of publications	Knowledge Gaps	Future research prospects
1. The effectiveness of small scale NBS	45	- Combination of small and large scale NBS with grey infrastructure.	• Development of a framework and methods to upscale NBS from small to large scale. • Development of a framework, methods and tools to select, evaluate, and design hybrid measures for hydro-meteorological risk reduction
		- NBS for droughts, landslides and storm surges.	• Application of NBS to reduce the risk of droughts, landslides and storm surges.
2. The effectiveness of large scale NBS	13	- Application to hydro-meteorological risk reduction; - Combination of large scale NBS with grey measures	• Development of a framework, methods and tools to select, evaluate, and design large scale NBS individually and in hybrid combinations for hydro-meteorological risk reduction • Development of typologies and guidelines for NBS design, implementation, operation and maintenance.
3. Selection and assessment of NBS with the focus on risk reduction	29	Framework for selection of NBS	• Defining the role of ecosystems in terms of risk reduction, socio-economic and hydro-geomorphological settings • Combining spatial planning and stakeholders participation in the co-selection process
		Framework for cost analysis	• Combining economic value of ecological damage and environmental impact, including the "invisible" ecosystem services (see also Estrella et al., 2013) • Application of the whole life cycle costing and return on investment within the cost-benefit analysis of NBS • Comparing costs and benefits between NBS, GI and hybrid measures • Defining opportunity costs and trade-offs of NBS implementation
		Framework for optimal configuration of NBS	• Use of optimisation techniques to maximise the main benefit and co-benefits of NBS while minimising their costs. • Use of optimisation techniques to maximise the efficiency of NBS and to define their best configurations within hybrid solutions. • Assessing the effectiveness of solutions on short and long terms
		Combination between multi-criteria and qualitative research	• Use of multi-criteria and qualitative research in evaluation of NBS. • How to combine quantitative and qualitative data and research methods. • Application of qualitative research methods and interviews to effectiveness of NBS
4. Multi-benefits of NBS	21	Assessment of multi-benefits of NBS	• Quantification of co-benefits. • Development of a framework, methods and tools to evaluate wide ranging intangible and tangible benefits. • Gaining deeper understanding of NBS benefits for human well-being
		Assessment of ecosystem capacity	• Assessing ecosystem capacity to maintain services over a longer period of time (see Estrella and Saalismaa, 2013) • Long–term monitoring and evaluation of ecosystem performance and function before and after the disaster • Addressing the complexity of coupled social and ecological systems
5. Application of tools	19	Application of new technologies and concepts (e.g., high resolutions numerical models, complex, crowdsourcing tools, real-time control system)	• Integration of real-time monitoring and control technologies for NBS operation. • A trade-off between high resolution numerical models and accuracy of results. • Use of novel modelling techniques such as complex adaptive systems models and serious games.
		Web-based decision support tools/systems	• Development of databases of small and large scale NBS for hydro-meteorological risk reduction. • Development of platforms, info-systems and clusters for exchange knowledge (see also Kabisch et al., 2016). • Development of tools to support decision makers in selecting and evaluating hybrid measures.

Subject	Number of publications	Knowledge Gaps	Future research prospects
			• Development of tools to assess the multiple-benefits for small and large scale NBS and their hybrid combinations.
6. Multifunctional design	2	Framework for multifunctional design	• Development of a framework and methods to support multifunctional design. • Application of novel landscape design techniques. • Combining the knowledge from landscape architecture and water engineering (Kabisch et al., 2016).
7. Stakeholders participation	8	Frameworks for effective stakeholder involvement and co-creation	• Frameworks for involvement of stakeholders in the selection, evaluation, design, implementation, and monitoring of NBS (i.e., the co-called co-creation process).
8. Financing, governance and policy	5	Desirable governance structures to support effective implementation and operation of NBS at different scales and contexts	• Information concerning legal instruments and requirements. • Development of effective governance structures • Compilation of data and information concerning multiple actors and institutions which are relevant for implementation of NBS • Understanding water governance structures, drivers, barriers and mechanism for enabling system transformation (see also Albert et al., 2019) • Development of methods for evaluation of social, political and institutional dimensions of NBS (see also Triyanti and Chu, 2018)
		Desirable finance models (e.g., public-private partnerships, blended financing, etc.)	• Development of finance guidance for implementing maintaining and operating NBS projects • Guidelines concerning development of new business and finance models (see also Kabisch et al., 2016) • Development of financial mechanisms to engage public and private sectors in the implementation of NBS
		Bridging gaps between science-practice-policy	• Bridging gaps between researchers, engineers, authorities and local stakeholders. • Bridging the policy and institutional gaps. • Bringing innovation to engage society in implementing and improving NBS.