Review Article: Potential of Nature-Based Solutions To Mitigate Hydro-Meteorological Risks in Sub-Saharan Africa

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Abstract. Sub-Saharan Africa (SSA) is the region most vulnerable to climate change and related hydro-meteorological risks. These risks are exacerbated in rapidly expanding urban areas due to the loss and degradation of green and blue spaces with their regulating ecosystem services. The potential of nature-based solutions (NBS) to mitigate hydro-meteorological risks such as floods is increasingly recognised in Europe. However, its application in urban areas of SSA still needs to be systematically explored to inform and promote its uptake in this region. We conducted a multidisciplinary systematic review following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol to establish the general patterns in the literature on NBS and hydro-meteorological risk mitigation in SSA. We searched scientific journal databases, websites of 12 key institutions and 11 NBS databases and identified 45 papers for analysis. We found at least one reported NBS in 71% of urban areas of SSA across 83 locations. 62% of the papers were clustered in South Africa, Kenya, Tanzania and Nigeria only, while the most studied cities were Dar es Salaam and Kampala. Moreover, 66 NBS practices were identified, most of which (n=44) were for flood mitigation. With only Mozambique (n=2) among the most at-risk countries reporting NBS, we found that NBS are implemented where risks occur but not where they are most severe. Mangrove restoration (n=10) and wetland restoration (n=7), reforestation (n=10) and urban forests (n=8), and agroforestry (n=3) and conservation agriculture (n=2) were the most common NBS practices identified for floods, extreme heat and drought mitigation, respectively. Traditional practices that fit the definition of NBS, such as grass strips and stone bunds, and practices that are more popular in the Global North, such as green roofs and green façades, were also identified. These NBS also provided ecosystem services, including 15 regulatory, five provisioning and four cultural ecosystem services, while four out of every five NBS created livelihood opportunities. We conclude that the reported uptake of NBS for hydro-meteorological risks in SSA is low. However, there could be more NBS, especially at the local level, that are unreported. NBS can help SSA address major development challenges such as water and food insecurity and unemployment and help the sub-region progress towards climate-resilient development. Therefore, we recommend that NBS be mainstreamed into urban planning and knowledge exchange opportunities between SSA and Europe and other regions be explored to promote uptake.

Keywords. ecosystem services, floods, extreme heat, drought, green infrastructure, ecosystem-based adaptation, hazards

1. Introduction

Climate change, uncontrolled urbanisation and associated biodiversity loss are among the most significant socio-ecological challenges confronting sub-Saharan Africa (SSA) in the 21st Century. These challenges increase vulnerability to hydro-metrological hazards such as floods, storms, heatwaves, droughts and wildfires, which pose a significant hydro-meteorological risk (Malgwi et al., 2020). Hydro-meteorological risk refers to the probability of damage resulting from hydro-meteorological hazards based on the exposure and vulnerability of populations and the environment. Such risks have become more pronounced in SSA in recent decades, and their impacts are already being felt across all sectors (Arias et al., 2021).

The Intergovernmental Panel on Climate Change (IPCC) has made many observations on Africa's climate (Gutiérrez et al., 2021). They report that North and Southern Africa could warm by 4°C or more and record a reduction in precipitation between 10-20% by 2080. Thus, both areas are most susceptible to extreme heat and drought events. East and Central Africa are expected to experience an increase in rainfall by 15% or more by 2080, thereby being most susceptible to floods. The Sahel and the rest of SSA are expected to record a general increase in temperatures and precipitation. From 2000-2019, flooding claimed thousands of lives, injured even more and destroyed properties worth millions. Floods account for 64% of hazard events in SSA (Malgwi et al., 2021). Droughts have also impacted over 269.6 million people and accounted for 46% of climate-induced deaths, while heatwaves have equally affected many over the same period (CRED, 2019). These realities underscore the pressing need for swift climate action among the 48 SSA countries (World Bank, 2022).

Conventional engineering approaches, which depend on grey infrastructure, make little or no room for nature and often serve a singular purpose (e.g., wastewater treatment) (Lupp & Zingraff-Hamed, 2021), like the use of dykes and large drains for addressing flood hazards, have long been favoured by decision-makers (Lucas, 2020). However, many researchers and practitioners agree that such conventional engineering responses to floods and other hydro-meteorological risks produce sub-par outcomes (Depietri & McPhearson, 2017). Conventional engineering solutions are often effective only in the short term (Lafortezza et al., 2018; Zhongming et al., 2014). This is evidenced in the many reported cases of levees being overtopped by waves or completely failing due to internal erosion or instability not long after construction (Özer et al., 2016). Conventional engineering solutions are also comparatively capital-intensive and most at times negatively impact natural ecosystems. Coupled with increasing levels of environmental degradation and recognition of the need for more joined-up approaches that link climate change adaptation, mitigation and development, there have been calls for solutions that work more with nature rather than against it (IPCC, 2022; Pauleit et al., 2017).

Table 1. Earlier NBS-related concepts that sought to work with nature.

Concept	Year coined	Risk targeted/aim	First location of recorded use	Reference
Sustainable urban drainage system	Early 1960s	Stormwater management	United Kingdom	(Poleto & Tassi, 2012)

Ecological engineering	Early 1960s	Solutions that combine ecology with engineering through the design of natural and artificial ecosystems to address various risks and provide benefits to people	Europe	(Mitsch & Jørgensen, 2003)
Soil and water bioengineering	Early 1970s	Combines biology and engineering, especially for addressing erosion and land degradation	Europe	(Bischetti et al., 2014)
Low-impact development	1990	Stormwater management	United States and Canada	(Prince George's County, 1999)
Water-sensitive urban design	1992	Stormwater management	Australia	(Radcliffe, 2018)
Green infrastructure	1994	To reduce risk to hazards, including floods and heat	Europe and North America	(Buddy MacKay & Reed, 1994)
Low impact urban design and development	2003	Stormwater management	New Zealand	(Van Roon & van Roon, 2009)
Ecosystem-based adaptation	2008	Focuses on harnessing ecosystem services as part of overall adaptation efforts	North America, Europe and Africa	(Busayo et al., 2022; UNFCCC, 2008)
Ecosystem-based disaster risk reduction	2012	Premised on curtailing or reversing environmental degradation to minimise exposure to risks	United States	(Nehren et al., 2014)
Sponge city concept	2013	Combines different measures to improve stormwater retention, storage, treatment and infiltration	China	(Hamidi et al., 2021)

Many concepts that seek to work with nature have been proposed over the years and applied in different regions worldwide (Table 1). Despite officially being used for the first time in 2008 by the World Bank (MacKinnon et al., 2008), the concept of nature-based solutions (NBS) has been gaining popularity both in research and practice since 2013, when the first project based on the concept was created (Sowińska-Świerkosz & García, 2021). According to Pauleit et al. (2017), the uniqueness of NBS is that it encapsulates related terms such as ecosystem-based adaptation and green infrastructure and is considered increasingly as an alternative or complement to conventional engineering risk-mitigation approaches (Deng et al., 2022; Kalantari et al., 2018; Lupp, Zingraff-Hamed, et al., 2021). The European Commission has defined NBS as "actions inspired by, supported by, or copied from nature" (European Commission & Directorate-General for Research and Innovation, 2015, p. 5). Such actions can be implemented as site-specific interventions at local scales or transcend national, regional or even international boundaries in rural or urban areas (Lindley et al., 2018). Ultimately, the overarching objective of NBS is to address socio-ecological challenges, including climate change and associated hydro-meteorological risks, food and water insecurity and health concerns, while helping local communities to attain their sustainable development aspirations.

In terms of operationalisation, the application of NBS in Europe has focused significantly on the restoration of degraded or lost ecosystems, the development of green spaces and their socio-economic benefits (Matsler et al., 2021) and implementing solutions to hydro-meteorological risks that mimic natural processes (Solheim et al., 2021), primarily through the European Union Horizon 2020 (EU-H2020) programme (EC, 2016). In SSA, conservation initiatives such as protecting green and blue spaces have been considered to fall under the NBS umbrella (Thorn et al., 2021). This is appreciated in the more recent definition of NBS by the Fifth Session of the United Nations Environment Assembly as "actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human wellbeing, ecosystem services and resilience and biodiversity benefits" (Seddon, 2022). As of 2018, SSA's land area was only 0.16% built-up (Karamage et al., 2018) compared to 4.2% in Europe (EUROSTAT, 2021); thus, it is plausible that more attention will be focused on ecosystem conservation in SSA. Even though there are many definitions of NBS, its principles provide a common understanding and framework for its implementation. NBS, therefore, particularly in urban settings, have to adopt a systems approach (Stringer et al., 2018); mirror natural processes; produce multiple benefits for both people and biodiversity (Somarakis et al., 2019); be inclusively designed, planned, implemented and managed; designed to fit the specific local context in which it is applied; and support mutual learning for sustainability transitions (Kabisch et al., 2022).

In terms of the typologies of NBS, different approaches have been proposed. There are classifications by the level and type of engineering applied, how biodiversity and ecosystems are managed, the stakeholders involved (Eggermont et al., 2015), or the number of ecosystem services delivered (European Commission & Directorate-General for Research and Innovation, 2015). NBS is also classified based on the problem it is deployed to solve, often concerning the Sustainable Development Goals (SDGs) (Somarakis et al., 2019). In this study, however, we adopt the classification by the kind of ecosystem the NBS is based in, whether terrestrial or aquatic. On that account, there are (i) green NBS which are vegetation-based, (ii) blue NBS, which are water-based and (iii) hybrid NBS, which combine green and blue NBS within constructed (grey) structures (Sowińska-Świerkosz & García, 2022). We also refer to NBS practices, conceived as activities related to planning, designing, implementation and management that lead to the actual application of a NBS type. Such practices may include river restoration efforts, rain gardens, green façades and permeable pavements (Zingraff-Hamed et al., 2020).

The justification for focusing on urban areas is that they are engines of growth across the globe, consuming 60-80% of energy and being responsible for 70% of anthropogenic greenhouse gas emissions, thus, accounting for much of environmental degradation and pollution (Trpkov, 2020). Particularly in SSA, the most rapidly urbanising region in the world (Moriconi-Ebrard et al., 2020), green areas continue to be rapidly depleted, and essential ecosystems like wetlands and streams are being degraded as urban populations increase (Abass et al., 2020; Wantzen et al., 2019). Additionally, cities have high population densities, with more than half of the world's population living in urban areas and expected to increase to 60% by 2030 and 68% by 2050 (UN, 2018), putting more people at risk. Even so, many authors have demonstrated the effectiveness of NBS in urban areas. For instance, the effectiveness of NBS in slowing runoff and reducing flood risk has been proven in Europe, North America (Pugliese et al., 2022) and Asia (Li & Zhang, 2022). NBS have also shown their effectiveness in reversing the effect of urban heat islands (Rahman et al., 2019), reducing erosion by up to 90% (Keesstra et al., 2018), as well as improving air quality (Kim & Song, 2019).

In SSA, NBS is plausible for hydro-meteorological risks mitigation for several reasons. First, they are cost-effective and more effective over the long term. In comparison to conventional engineering solutions, NBS can achieve up to 85% of profitable hydro-meteorological risks management (Debele et al., 2019) and, in a broader context, could provide about 30% of the cost-effective mitigation required to keep global warming below 2°C by 2030 (Seddon et al., 2019). This cost-effectiveness is vital for SSA, a region whose climate adaptation efforts have been constrained by financial challenges (Gilder & Rumble, 2020). Second, NBS can deliver multiple ecosystem services, which "are all the benefits that humans can derive from the natural ecosystems for their physical, social, and economic wellbeing" (Mengist et al., 2020, p.1). Ecosystem services range from provisioning services like food and fuel to regulatory services like erosion control and heat mitigation and cultural services such as recreation and aesthetic value (Pauleit et al., 2017). Provisioning services in particular are essential given the high poverty levels in SSA and low employment rates, which means there is a high direct reliance on water, food and energy. Third, leveraging NBS could help SSA to achieve the SDGs, particularly goals 11 (sustainable cities and communities), 13 (climate action) and 15 (life on land). Fourth, NBS are important for SSA because the sub-region is home to significant biodiversity, some located in urban areas. Presently, over 33 major developments are proposed or under development in different locations in SSA, including in major cities, which traverse 400 protected areas (Enns et al., 2019). Thus, embracing NBS may hold the best prospects for addressing hydro-meteorological risks in SSA without compromising the natural system's ability to support life.

Despite these potential benefits from NBS, it is unclear to which extent they have been implemented in SSA, including what NBS types and specific practices have been used and to achieving which aims, especially in the context of increasing incidences and severity of hazards. In the Global North, NBS have seen a massive uptake through, for instance, the EU-H2020, with 32 research projects funded across 59 countries by the EC & Directorate-General for Research and Innovation (2021) since the introduction of the concept. As a result, projects like PHUSICOS, proGIreg, URBINAT, BiodivERsA, CleanUP, CleverCities, OPERANDUM, ThinkNature and CLEARING HOUSE have helped to increase literature on NBS for hydro-meteorological risks mitigation (Ruangpan et al., 2020; Schröter et al., 2021). However, the literature on NBS in SSA is limited. Emerging studies focus mainly on incorporating the concept into urban planning. Such studies are centred chiefly in South Africa (e.g., Molla, 2015; Russo et al., 2017; Venter et al., 2020), leaving the rest of the sub-region, including some of the most at-risk countries, understudied. Furthermore, recent systematic review studies have been published on related concepts like green infrastructure and ecosystem services (Choi et al., 2021; Douglas, 2018; Du Toit et al., 2018; Evans et al., 2022). There is a gap, therefore, in understanding how NBS can be applied for hydro-meteorological risks mitigation in urban areas of SSA. This gap can be a significant setback to the uptake of the concept, which is plausible in many ways for responding to hydro-meteorological risks and obtaining co-benefits. We, therefore, conducted a systematic review to answer the following questions:

1. What is the extent of reported NBS uptake for hydro-meteorological risks mitigation in urban areas of SSA?
2. Are reported NBS being implemented where risks are located?
3. What specific NBS (types and practices) reported in the literature are being used to address floods, extreme heat and drought?
4. Which other benefits are reported to accrue from these NBS beyond hazard risk mitigation through ecosystem services provision and livelihood generation?

2. Methods

2.1. Selection of papers

The research methodology consisted of several steps (Fig. 1). First, we identified peer-reviewed scientific articles satisfying the search criteria. Second, we accessed grey literature by searching websites of key institutions and NBS databases for NBS projects and initiatives to ensure that NBS advanced by development agencies but not scientifically studied were not missed. The peer-reviewed scientific articles were accessed through Scopus, Science Direct and Web of Science and Google Scholar. Grey literature was searched on the websites of 12 key institutions, including United Nations agencies and Local Governments for Sustainability (ICLEI), and 11 NBS databases (Table S1). Eligibility was checked according to the inclusion and exclusion criteria, and a thematic analysis was carried out following this paper selection process.

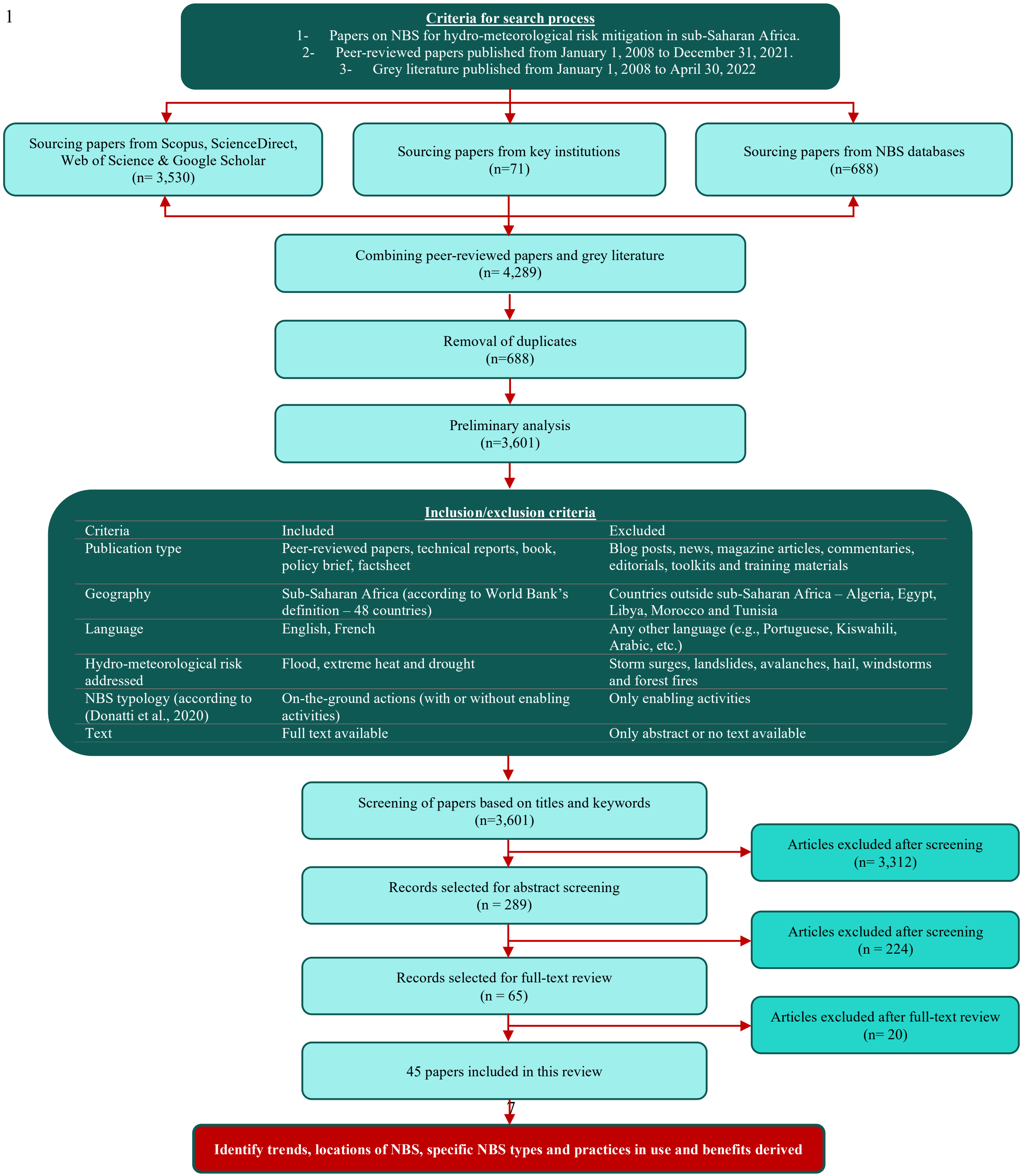
Criteria for search process
1- Papers on NBS for hydro-meteorological risk mitigation in sub-Saharan Africa.
2- Peer-reviewed papers published from January 1, 2008 to December 31, 2021.
3- Grey literature published from January 1, 2008 to April 30, 2022
Sourcing papers from Scopus, ScienceDirect, Web of Science & Google Scholar (n= 3,530)
Sourcing papers from key institutions (n=71)
Sourcing papers from NBS databases (n=688)
Combining peer-reviewed papers and grey literature (n= 4,289)
Removal of duplicates (n=688)
Preliminary analysis (n=3,601)
Inclusion/exclusion criteria
Criteria | Included | Excluded
Publication type | Peer-reviewed papers, technical reports, book, policy brief, factsheet | Blog posts, news, magazine articles, commentaries, editorials, toolkits and training materials
Geography | Sub-Saharan Africa (according to World Bank's definition – 48 countries) | Countries outside sub-Saharan Africa – Algeria, Egypt, Libya, Morocco and Tunisia
Language | English, French | Any other language (e.g., Portuguese, Kiswahili, Arabic, etc.)
Hydro-meteorological risk addressed | Flood, extreme heat and drought | Storm surges, landslides, avalanches, hail, windstorms and forest fires
NBS typology (according to (Donatti et al., 2020) | On-the-ground actions (with or without enabling activities) | Only enabling activities
Text | Full text available | Only abstract or no text available
Screening of papers based on titles and keywords (n=3,601)
Articles excluded after screening (n= 3,312)
Records selected for abstract screening (n = 289)
Articles excluded after screening (n = 224)
Records selected for full-text review (n = 65)
Articles excluded after full-text review (n= 20)
45 papers included in this review
Identify trends, locations of NBS, specific NBS types and practices in use and benefits derived

Figure 1. Flowchart of literature screening and selection process.

Search terms were selected after an initial scoping of other review papers on NBS and related terms (Du Toit et al., 2018; Ruangpan et al., 2020; Thorn et al., 2021) and a review of NBS and green infrastructure definitions, typologies and practices (Koc et al., 2017; Somarakis et al., 2019). Specific terms used during the search process were related to NBS, green infrastructure, ecosystem services, urbanisation, hydro-meteorological risks and SSA (Table 2).

Table 2. Terms used in different combinations for the literature search

Keyword	Related search terms
Nature-based solutions	Nature-based solutions, natural infrastructure, river protection, river conservation, river restoration, river management, flood management, flood mitigation, wetland conservation, wetland restoration, permeable pavement, permeable paving, infiltration basins, infiltration trenches, green roofs, rain garden, blue roof, urban wetland, French drain, low impact infrastructure, bio-retention, dry well, urban waterway, rain barrels and cisterns
Green infrastructure	Green infrastructure, green space, green spaces, low impact development, green infrastructure types, green streets, greenscape, naturalised landscaping, trees, urban forest, urban greening, urban parks
Ecosystem services	Ecosystem services, ecosystem protection, ecosystem conservation, ecosystem restoration, ecosystem management, ecosystem-based adaptation
Urbanisation	Urbanisation, urban growth, urban planning, spatial planning, land-use change
Hydro-meteorological risks	Climate change, climatic extremes, hydro-climatic extremes, hydro-meteorological risks, climate impacts, extreme events, extreme heat, extreme rainfall, heat mitigation, cooling, rainwater runoff, stormwater, surface runoff
Sub-Saharan Africa	sub-Saharan Africa

NB: Table S1 contains the specific terms used for each database search.

According to Donatti et al. (2020), NBS-related concepts like ecosystem-based adaptation can be advanced as on-the-ground actions or enabling activities. On-the-ground actions include ecosystem protection and restoration efforts, agricultural forest and conservation management practices, urban gardens, and green infrastructures. Enabling activities formulate policies, develop strategic plans, and advance awareness-raising campaigns. In many cases, both approaches are married in the NBS roll-out. However, the literature search excluded papers only focused on enabling activities since we aimed to document specific and tangible actions implemented to help address hydro-meteorological risks.

The grey literature search was conducted on the websites of key institutions and the NBS databases from April 23-30, 2022. Peer-reviewed scientific papers were searched using the Publish or Perish software, version 8.2, considering the time window from January 1, 2008- December 31, 2021. These years were selected because 2008 was when the concept of NBS emerged

(Ruangpan et al., 2020). The literature search also allowed papers published in English and French, the top two official languages used by countries in SSA. In all, 3,530 scientific peer-reviewed papers and 759 papers of grey literature were found.

2.2. Screening and eligibility selection

Screening was performed by examining the titles and abstracts and, subsequently, the full text of the papers. The screening and selection process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines, according to Page et al. (2021). Eligible papers had to meet the criteria defined in Fig. 1. Generally, papers included in the review had to provide data on NBS that address specific hydro-meteorological risks; and have an SSA city or peri-urban area—as several SSA countries lack a clear delineation of urban and rural areas—as study area (Du Toit et al., 2018).

Apart from project documents, technical reports, factsheets and policy briefs, non-peer-reviewed literature such as blog posts, news, magazine articles, commentaries and editorials were excluded to ensure that only papers following scientific standards were used for the review. Two people did the screening: one of the authors and a research assistant. Forty-five papers were deemed eligible for the study. Of them, 18 were peer-reviewed papers, while 27 were publications of grey literature. Only one paper, a publication of grey literature, was published in French. The remaining papers were published in English.

2.3. Quality appraisal

The quality and strength of evidence are essential to the systematic review process (Movsisyan et al., 2018). In this study, we used a 14-point framework to assess the quality of included papers (Table S2). We asked a series of questions on three themes—quality of reporting (six questions), risk of bias minimisation (five questions) and appropriateness of conclusions (three questions)—to ensure that quality research was done (Venkataramanan et al., 2018). For each paper, a score of 0, 0.5 or 1 was given for each of the 14 questions, and the scores were then converted to percentages to compare across themes (Figure S1). The studies were rated from the perspective of social-ecological research methods as being of high quality (score of ≥ 10 to 14), medium quality (score ≥ 5 and < 10) or low quality (score <5).

2.4. Data extraction, presentation and analysis

The data from the selected papers were extracted into Notion version 2.0.21, a project management software developed by Notion Labs Incorporated, for assessment. The coded information included:

- study title;
- author(s);
- year of publication;
- city/location;
- country;

- hydro-meteorological risks addressed;
- NBS practices and types used;
- ecosystem services (regulatory, provisioning and cultural) provided and
- livelihood generation (which was added later as an economic benefit of NBS after it was found to be a highly reported variable across the papers).

A narrative summary of the papers is then given with the aid of tables, graphs and figures. ArcGIS Pro (version 2.8) by Esri (2022) was used to create maps to visualise the location of NBS.

2.5. Study limitation

By conducting this study using a systematic review methodology, we could establish general trends in the literature on NBS and hydro-meteorological risks mitigation in urban areas of SSA. However, factors such as the finite selection of keywords and poorly written abstracts could have led to the exclusion of important papers from the review. The impacts of implemented NBS were not assessed to determine whether they were successful or if any lessons could be drawn due to the lack of the requisite data. In addition, the search was limited only to floods, extreme heat and drought, the most frequent hydro-meteorological risks in SSA. However, other risks like landslides and wildfires are recorded in the sub-region. Even though excluded languages like Portuguese and Kiswahili are not as widely spoken as English and French in SSA, the exclusion of papers published in these languages may also limit this study. Furthermore, because the focus was only on reported NBS, some likely implemented or ongoing NBS, which went unreported, were not captured in the analysis.

3. Results

3.1. Extent of reported NBS for hydro-meteorological risks mitigation uptake in SSA

3.1.1. Locations of papers

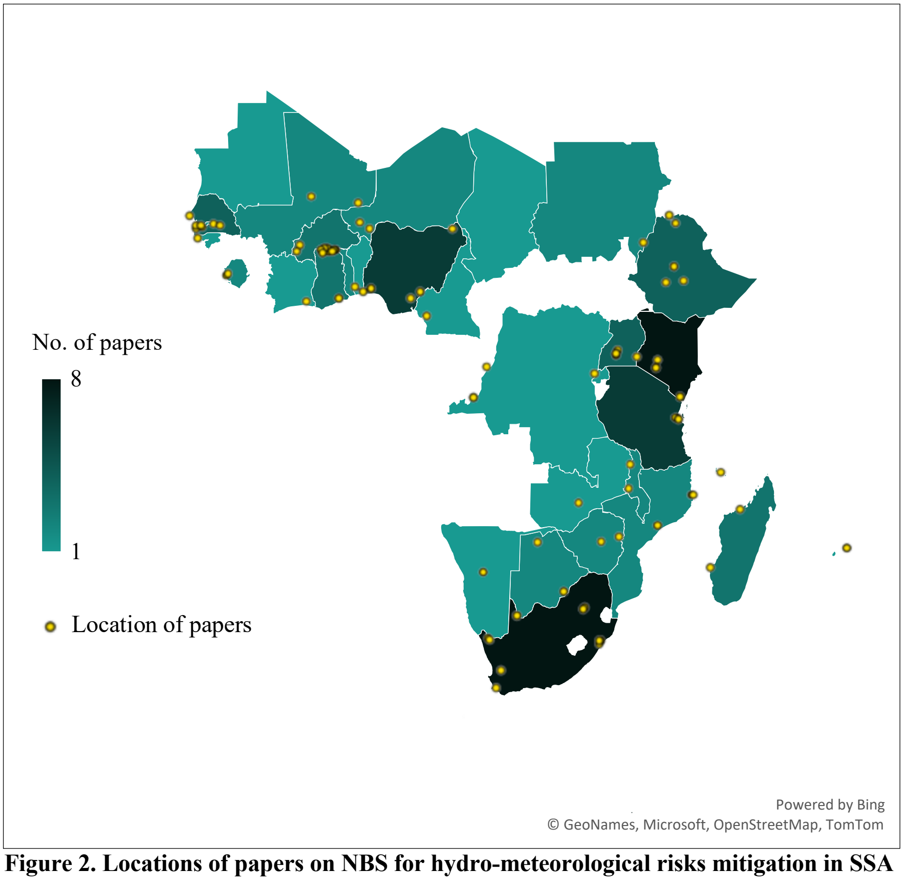

Figure 2. Locations of papers on NBS for hydro-meteorological risks mitigation in SSA

From the analysis of 45 papers, we found NBS used for hydro-meteorological risks mitigation in 34 SSA countries across 83 locations. Thus, there is at least one reported NBS in 70.8% of urban areas of SSA countries. In terms of sub-regional distribution, 34.1% of the papers (n=30) were from West Africa, 20.5% (n=18) from Southern Africa, 34.1% (n=30) from East Africa and 6.8% (n=6) from Central Africa. Four papers (4.5%) covered all of SSA.

Countries with the most papers (62.2%) reporting NBS were South Africa (n=8), Kenya (n=8), Tanzania (n=6) and Nigeria (n=6). The remaining countries had four or fewer papers, with 12 countries (35.3%) having only one paper. Cities with the most reported NBS were Dar es Salaam (n=6) in Tanzania and Kampala (n=3) in Uganda. Nine cities (12.5%), including Accra, Johannesburg and Nairobi, had two papers, while the remaining 63 locations (84.7%) had only one paper reporting on them. Figure 2 gives a graphical representation of the locations of the papers.

3.1.2. Risks addressed

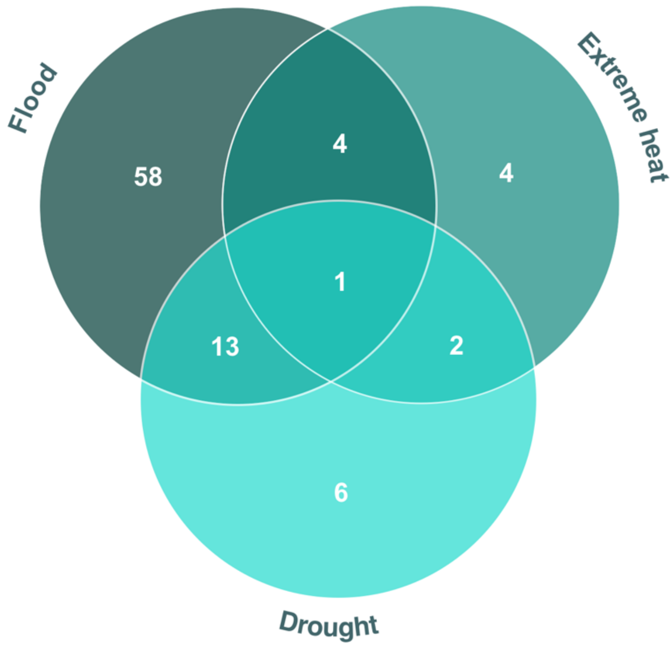

Figure 3. Hydro-meteorological risks addressed with different NBS practices in SSA.

A substantial number of the reported NBS (n=20) were intended to address more than one hydro-meteorological risk in their implemented locations (Fig. 3). For instance, the marine conservation initiative in Johannesburg was found to address all three risks studied (Washbourne, 2022). In Lagos, Nigeria, green conservation efforts were used to mitigate floods and extreme heat (Mauvais, 2018). In cities like Dar es Salaam in Tanzania and Windhoek in Namibia, urban agriculture was used to address floods and droughts (Thorn et al., 2021). Similarly, rainwater harvesting techniques across many countries, including Mali, Chad, Sudan and Senegal, were used for flood and drought mitigation (Tamagnone et al., 2020).

3.1.3. Scale of implementation

NBS in SSA were implemented over local (n=14), national (n=20), regional (n=3), and international scales (n=2), as indicated in Fig. 4. Some papers did not specify the implementation scale of the reported NBS (n=6) for diverse reasons, including that they were systematic reviews (e.g., Adegun et al., 2021; Choi et al., 2021) or conceptual papers (e.g., Kalantari et al., 2018).

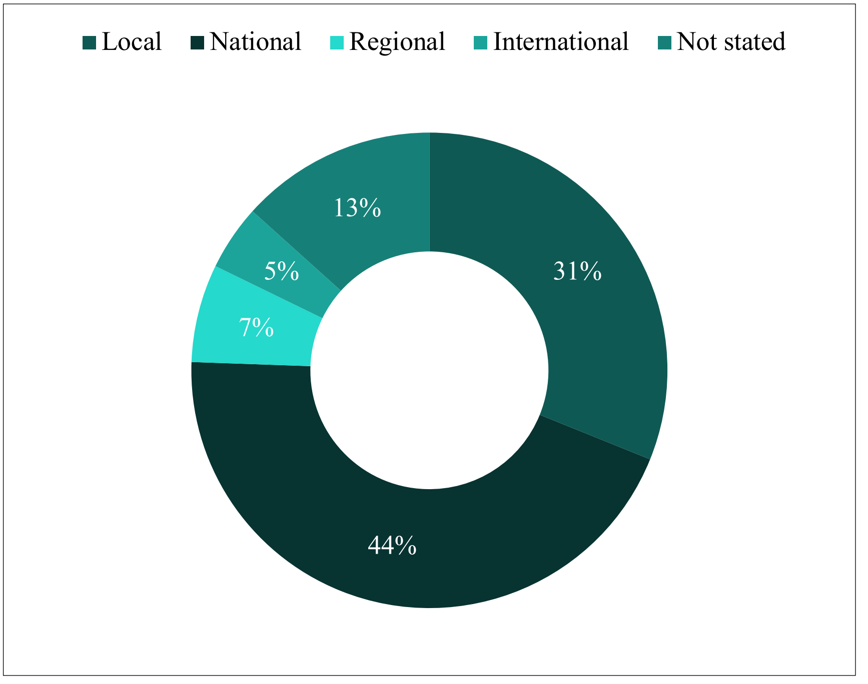

Figure 4. Implementation scale of NBS. Local-scale NBS are conceived as those implemented in specific local communities in a country, often by local actors, including non-profits (NGOs), community-based organisations (CBOs), local government administrations or the community. National NBS are implemented in different locations within the same country and are often advanced or coordinated by national agencies. Regional NBS refer to those that transcend two or more SSA countries. Lastly, international-scale NBS are conceived as those implemented in SSA and countries on other continents.

Identified local NBS include reforestation and organic farming efforts in Obudu, Nigeria, used for addressing droughts and floods (UNDP, 2017) and several rainwater harvesting technologies used by communities in Burkina Faso, Chad, Mali, Mauritania, Niger, Senegal and Sudan, where drought and flash floods are major concerns (Tamagnone et al., 2020). Other examples are Accra (Ghana), Dar es Salaam (Tanzania) and Kampala (Uganda), where urban agriculture was used to slow runoff and address flooding (Lwasa et al., 2014).

Local Action for Biodiversity is an example of a national NBS (ICLEI, 2010). This project was implemented at many locations across South Africa, including Cape Town, Durban and Cape Winelands and involved wetland conservation and restoration. The use of natural retention ponds and wetland conservation in Dakar, Senegal, to address floods advanced by the World Bank is also an example of a national NBS (Jongman et al., 2019).

Regarding regional NBS, the Great Green Wall is a good example (Turner et al., 2021). The project cuts across the entire width of Africa and spans 8,000 km of drylands in Burkina Faso, Chad, Djibouti, Eritrea, Ethiopia, Mali, Mauritania, Niger, Nigeria, Senegal and Sudan. The project seeks to rehabilitate lands through multifaceted afforestation, reforestation and revegetation measures, and sustainable agriculture. It is also expected to help mitigate climate change and address extremes such as drought and extreme heat. Another example is the Urban Natural Assets for Africa by ICLEI, which used practices like mangrove restoration, river restoration and green conservation to mitigate floods in locations across Tanzania, Mozambique, Uganda, Malawi, Kenya and Ethiopia.

Two international-scale NBS were identified. One is the Gazi Mangrove Restoration Project, implemented in Kenya and Bangladesh to mitigate floods through mangrove restoration (Taylor & Oluoch, 2012). The other is the Ecosystem-Based Adaptation in Marine, Terrestrial and Coastal Regions Project, implemented in South Africa, Brazil and the Philippines (CIFOR, 2013), which explores the effectiveness of wetland restoration, rangeland rehabilitation and the restoration of degraded lands for flood mitigation.

3.2. Relationship between the location of NBS and the location of risks

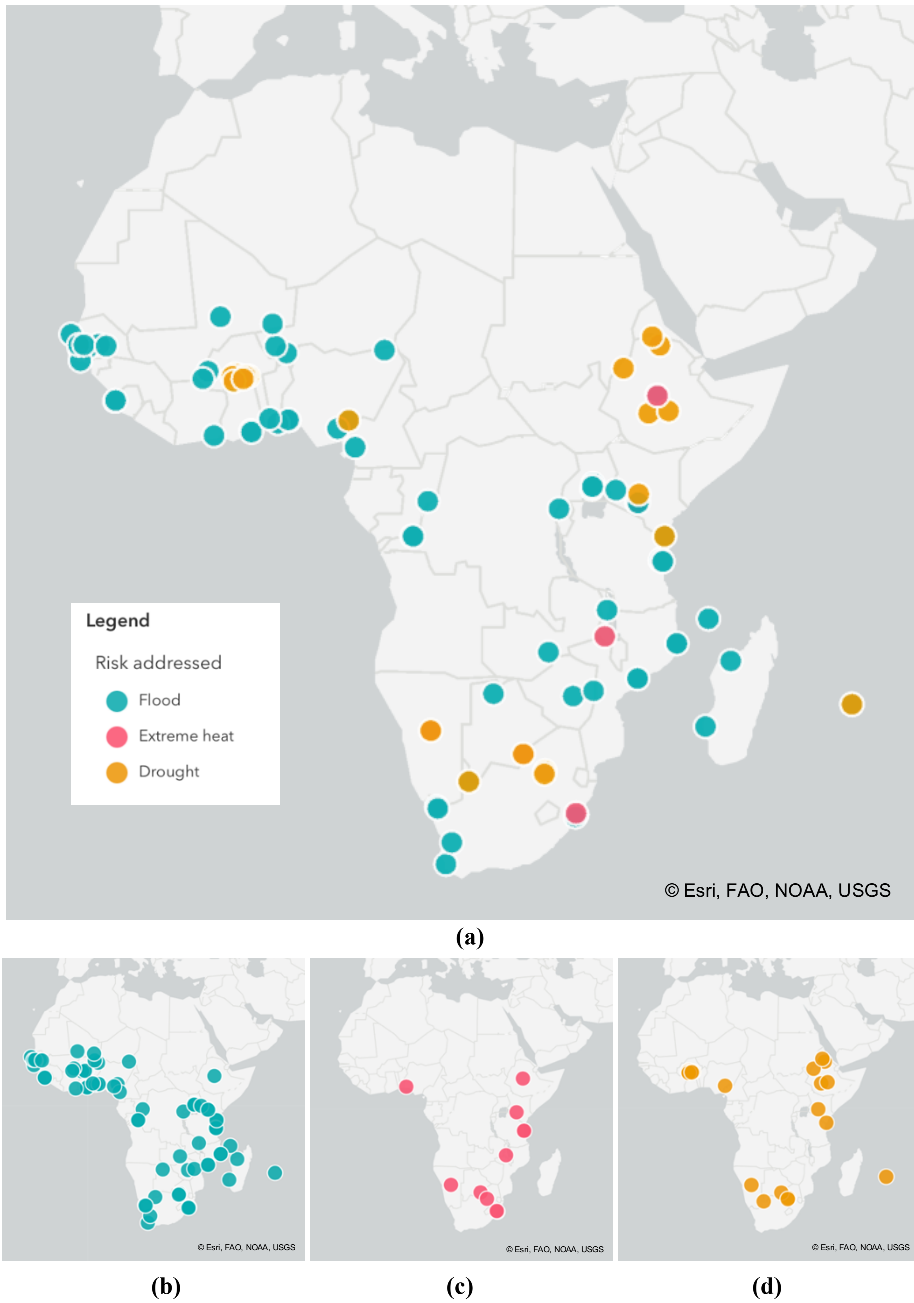

Figure 5. Map of the locations of all the reported NBS in SSA to mitigate hydro-meteorological risks. (a) Locations of all risks studied; (b) Locations of papers studying floods only; (c) Locations of papers studying extreme heat only; and (d) Locations of papers studying drought only.

For floods, the most NBS were implemented in Dar es Salaam (n=4) and Kampala (n=3), both located in East Africa. Two NBS were implemented in Nairobi and Gazi Bay, both in Kenya in East Africa; Accra in Ghana and Lagos in Nigeria in West Africa; Durban and Johannesburg in South Africa and Nacala and Quelimane in Mozambique in Southern Africa.

Regarding extreme heat mitigation, most NBS (n=6) were implemented in Southern Africa. Three NBS were implemented in East Africa, with most in Dar es Saleem (n=2). There was only one NBS in West Africa, in Lagos, Nigeria, and none were reported in Central Africa.

For drought mitigation, the city of Johannesburg in South Africa was reported to have the most NBS implemented (n=2). Only one NBS was implemented in each of the remaining cities. However, the majority of the NBS were clustered in West Africa (n=9), followed by East Africa (n=8) and then Southern Africa (n=3). Fig. 5 presents the locations where the NBS were implemented.

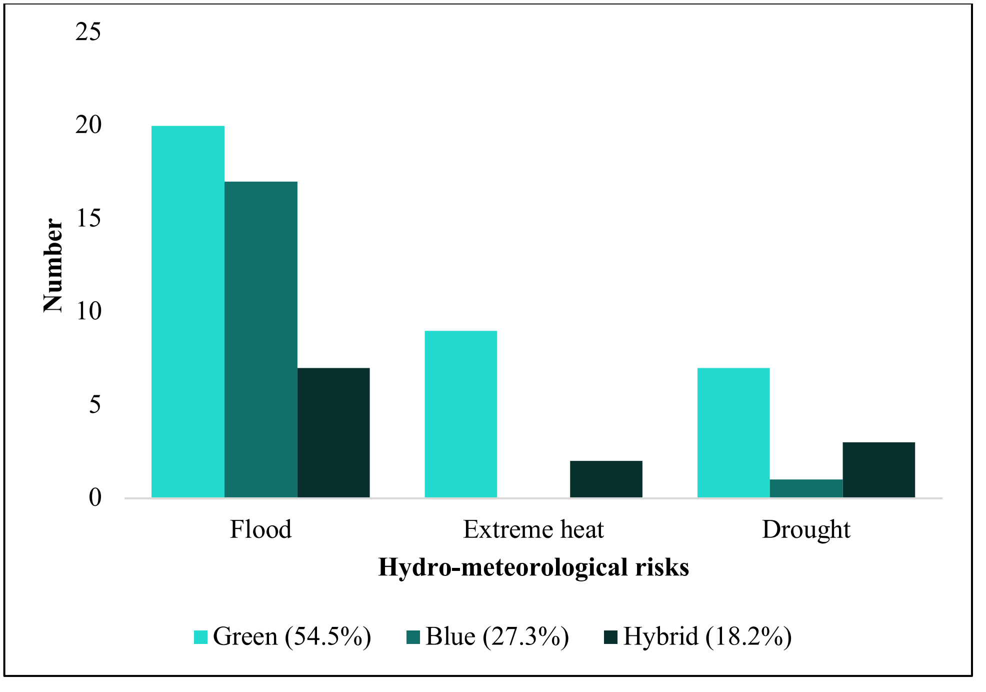

Figure 6. The link between NBS type and risks addressed.

Green NBS (n=20) were the most widely used for flood mitigation, followed by blue NBS (n=17). Hybrid NBS (n=7) were the least used. For extreme heat mitigation, most NBS were green (n=9), while a couple were found to be hybrid. There were no recorded blue NBS. Seven green NBS, three grey measures and one blue NBS were reported for drought mitigation. Figure 6 presents the link between NBS types, and the hydro-meteorological risks addressed.

3.3. Specific NBS types and practices in use in SSA

A total of 36 green, 18 blue and 12 hybrid NBS practices were reported for mitigating floods, extreme heat and drought in SSA. They summed up to 66 different NBS practices, with 44 deployed for addressing floods, 11 for addressing extreme heat and 11 for mitigating drought.

In terms of flood mitigation, the most reported NBS practices were mangrove restoration (n=10), wetland restoration (n=7), urban agriculture (n=5) and marine conservation (n=5). For extreme heat mitigation, reforestation (n=10), urban forests (n=8) green conservation (n=7), gardens (n=6) and green/open spaces (n=6) were the most reported practices. For drought, the most common practices reported were agroforestry (n=3), conservation agriculture (n=2), integrated soil management (n=2) and sustainable agriculture (n=2). Table 3 presents a detailed list of NBS types and practices used for hydro-meteorological risks mitigation in SSA.

Table 3. List of NBS types and practices used for mitigating floods, extreme heat and drought in SSA, their frequency and sources. (Green NBS are vegetation-based, blue NBS are water-based, and hybrid NBS combine green and blue NBS within constructed/grey structures).

Hydro-meteorological risk addressed	NBS practice	NBS type	Frequency	Reference
Flood	Bamboo planting	Green	1	Mulligan et al. (2020)
	Constructed wetland	Blue	1	Mulligan et al. (2020)
	Coral reef restoration	Blue	1	García (2019)
	Cross-cutting theme	Hybrid	1	Adegun et al. (2021)
	Floodplain conservation	Blue	3	Douglas (2018) Thorn et al. (2021) Turner et al. (2021)
	Floodplain restoration	Blue	2	Douglas (2018) Turner et al. (2021)
	Grass strips	Green	1	Kalantari et al. (2018)
	Integrated approach	Hybrid	1	Ajibade (2017) Kihara et al. (2020)
	Mangrove conservation	Green	4	Fischborn & Herr (2015) ICLEI (2020) Kalantari et al. (2018) Thorn et al. (2021)
	Mangrove restoration	Green	10	Fairhurst et al. (2012) Fischborn & Herr (2015) García (2019) ICLEI (2020) Kalantari et al. (2018) Laros et al. (2013) Ravenholt (2021) Taylor & Oluoch (2012) UN Environment (2019b) Washbourne (2022)
	Marine conservation	Blue	5	Fairhurst et al. (2012) Fischborn & Herr (2015) Kalantari et al. (2018) Thorn et al. (2021) Washbourne (2022)
	Meso-scale vegetation	Green	1	Adegun et al. (2021)
	Natural fountain	Blue	1	Thorn et al. (2021)
	Natural retention ponds	Blue	1	Jongman et al. (2019)
	Parks	Green	3	Adegun et al. (2021) Thorn et al. (2021) Washbourne (2022)
	Peatland conservation	Green	1	Kopansky et al. (2020)
	Peatland restoration	Green	1	Kopansky et al. (2020)
	Permeable surfaces	Hybrid	1	Fairhurst et al. (2012)
	Pervious paving	Hybrid	1	Mulligan et al. (2020)
	Planted infiltration pits	Blue	1	Mulligan et al. (2020)
	Planted revetment	Green	1	Mulligan et al. (2020)
	Rain gardens	Green	1	Mulligan et al. (2020)
	Rainwater harvesting	Blue	4	García (2019) Mulligan et al. (2020) Tamagnone et al. (2020) UN Environment (2019a)
	Rangeland rehabilitation	Green	2	CIFOR (2013)

				Reid et al. (2018)
	Recycled and planted tyres	Green	1	Mulligan et al. (2020)
	Resettlement	Blue	3	Douglas (2018) Kita (2017) Thorn et al. (2021)
	Restoration of degraded forests	Green	1	Global Landscapes Forum (2021)
	Land restoration	Green	1	CIFOR (2013)
	Revegetation of degraded slopes	Green	1	Doswald et al. (2021)
	River conservation	Blue	1	Laros et al. (2013)
	River restoration	Blue	4	Douglas (2018) ICLEI (2020), Thorn et al. (2021) World Bank (2020b)
	Sand dune	Blue	1	Thorn et al. (2021)
	Sewer connection	Hybrid	1	Mulligan et al. (2020)
	Soil remediation	Green	1	Mulligan et al. (2020)
	Springwater collection	Blue	1	Mulligan et al. (2020)
	Stone dykes	Hybrid	1	UN Environment (2019a)
	Swales	Green	1	Mulligan et al. (2020)
	Underground detention/infiltration	Hybrid	1	Mulligan et al. (2020)
	Urban agriculture	Green	5	Douglas (2018), Habtemariam et al. (2019) Lwasa et al. (2014) Mulligan et al. (2020) Thorn et al. (2021)
	Vegetated open areas	Green	1	Mulligan et al. (2020)
	Vegetative waterways	Green	1	Turner et al. (2021)
	Watershed rehabilitation	Blue	1	World Bank (2013)
	Wetland conservation	Blue	3	ICLEI (2010), Jongman et al. (2019) Weise et al. (2021)
	Wetland restoration	Blue	7	Benchwick (2019) CIFOR (2013) Douglas (2018) ICLEI (2010) Reid et al. (2018) UN Environment (2016) Weise et al. (2021)
Extreme heat	Gardens	Green	6	Adegun et al. (2021) Etshekape et al. (2018) Mugure (2020) Mulligan et al. (2020) Thorn et al. (2021) UN Environment, 2019b)
	Green roof	Hybrid	1	Adegun et al. (2021)

	Green conservation	Green	7	Etshekape et al. (2018) Fischborn & Herr (2015) ICLEI (2020) Laros et al. (2013) Mauvais (2018) Washbourne (2022) World Bank, 2014, 2014)
	Green/open spaces	Green	6	Habtemariam et al. (2019) ICLEI (2010) Laros et al. (2013) Thorn et al. (2021) World Bank (2020b, 2021)
	Green space conservation	Green	1	Kalantari et al. (2018)
	Reforestation	Green	10	Doswald et al. (2021) Fischborn & Herr (2015) GIZ (2021) ICLEI (2010) Ravenholt (2021) UN Environment (2019b) UNDP (2017) World Bank (2014, 2019, 2020a)
	Soccer field/playground	Green	1	Thorn et al. (2021)
	Tree-planting	Green	1	Doswald et al. (2021)
	Urban forest	Green	8	Adegun et al. (2021) Choi et al. (2021) Etshekape et al. (2018) Moyo et al. (2021) Mulligan et al. (2020) Schäffler & Swilling (2013) Thorn et al. (2021) Washbourne (2022)
	Urban greening	Green	2	Fairhurst et al. (2012) Laros et al. (2013)
	Vertical greening system	Hybrid	1	Adegun et al. (2021)
Drought	Agroforestry	Green	3	Doswald et al. (2021) Etshekape et al. (2018) Lwasa et al. (2014)
	Anti-fire corridors	Hybrid	1	UN Environment (2019a)
	Climate-smart agriculture	Green	1	World Bank (2020a)
	Composting toilet	Hybrid	1	Mulligan et al. (2020)
	Conservation agriculture	Green	2	Kihara et al. (2020) Laros et al. (2013)
	Organic farming	Green	1	UNDP (2017)
	Retaining walls	Hybrid	1	UN Environment (2019a)
	Integrated soil fertility management	Green	2	Ajibade (2017) Kihara et al. (2020)
	Protection of water sources	Blue	1	Kalantari et al. (2018)
	Restoration of degraded land	Green	1	ICLEI (2010)

	Sustainable agriculture	Green	2	Fischborn & Herr (2015) World Bank (2020a)

NB: Definitions of each NBS type and practice can be found in Table S4.

3.3.1. Green NBS practices

Mangrove restoration (n=10) and conservation (n=4) are used for mitigating floods, especially in coastal areas and are a very popular NBS practice in SSA. Mangroves serve as natural buffers against tidal pressure and storm surges. They also provide a range of ecosystem services, including sediment stabilisation, and prevent saltwater intrusion into up-shore ecosystems like wetlands and provide breeding grounds for various fish, crustaceans and birds. Evidence of these benefits has been seen in Douala (Cameroon) (Lwasa et al., 2014). The potential of mangroves to capture and store carbon is being demonstrated through the restoration of mangrove areas in Cape Winelands and other locations in South Africa through the Local Action for Biodiversity project (ICLEI, 2010). Our study revealed that urban agriculture (n=5) is being used in some locations in SSA, including Accra (Ghana), Dar es Salaam (Tanzania) and Kampala (Uganda), to mitigate floods (Douglas, 2018). Urban agriculture has been found to help slow runoff by 15-20%, depending on the type of soil and amount of rainfall (Lwasa et al., 2014).

Reforestation was the most reported NBS practice for extreme heat mitigation (n=10). Reforestation refers to the intentional restocking of depleted forests and woodlands. Many such efforts were found across different locations in SSA (GIZ, 2021). Urban forests are a comprehensive assemblage of trees within urban contexts. Urban forests were found to be a widely reported green NBS practice in SSA (n=8) (e.g., Adegun et al., 2021; Choi et al., 2021; Etshekape et al., 2018). Green conservation involves activities that help to protect existing trees and other forms of vegetation. Several green conservation efforts (n=7) were found in this review, with cases reported in Kinshasa (DR Congo) (Etshekape et al., 2018) and many cities in South Africa (Washbourne, 2022). Within domestic settings, studies by Adegun et al. (2021), Thorn et al. (2021), Etshekape et al. (2018) and others revealed the increasing use of gardens (n=6) for addressing many risks and providing co-benefits, including food and herbs.

There are reports of local people and urban farmers adopting agroforestry (n=3) to cope with the changing climate and associated drought events (Etshekape et al., 2018). Conservation agriculture (n=2) has also become important in Muttare, Zimbabwe, due to water scarcity (Kihara et al., 2020). Other practices identified were integrated soil fertility management (n=2) and sustainable agriculture (n=2). Integrated soil fertility management refers to a range of practices in cropping and fertiliser application, especially on small farms that seek to maximise production, while sustainable agriculture aims to bring innovation and recycling into agriculture to make it more circular. Climate-smart agriculture that seeks to adapt crop cultivation and animal rearing to the changing climate and reduce emissions from agriculture, was found in Ethiopia (n=1) (World Bank, 2020a).

3.3.2. Blue NBS practices

In terms of flood mitigation, wetland restoration (n=7) was the most reported blue NBS. The restoration of wetlands involves the manipulation of degraded wetlands' physical, chemical and biological characteristics to return them to their natural condition. In contrast, wetland conservation (n=3) aims to protect existing wetlands from degradation. Marine conservation encapsulates efforts to protect oceans and ecosystems in and around them from pollution and over-exploitation through planned management efforts. As revealed in this study, such efforts focused on preventing the degradation of marine ecosystems for flood protection, such as pioneering marine protected area management in Madagascar (Kalantari et al., 2018). The study by Kalantari et al. (2018), which observed the effectiveness of rainwater harvesting technologies, showed the possibility of addressing flooding and drought concurrently in urban areas. Others have focused on the ecological restoration of rivers (n=4) under diverse pressures (e.g., Douglas, 2018; ICLEI, 2020; Thorn et al., 2021).

The studies by Thorn et al. (2021), Douglas (2018) and Turner et al. (2021) found many efforts across SSA relating to floodplain conservation (n=3) and restoration (n=2), also widely used for flood mitigation. These studies found that floodplain conservation and restoration initiatives within urban settings could be challenging because of the presence of informal settlements that often made dwellings in these places and which depended directly on natural resources for their livelihoods. Closely related to such efforts is the resettlement of people living in the buffer zones, which also emerged in the review (n=3). In such instances, after relocation, floodplains are either conserved or restored to their natural state if degraded.

On drought mitigation, one practice, the protection of water sources, was reported in Kenya. This aimed to enhance water availability by providing more watering points in national parks and community areas (Kalantari et al., 2018). No blue practices were found for extreme heat mitigation.

3.3.3. Hybrid NBS practices

Each of the 12 hybrid NBS practices identified was reported only once. They ranged from quite traditional practices, such as the use of stone dykes and retaining walls in Comoros for flood mitigation (UN Environment, 2019a) and composting toilets in Kenya, to more widely accepted practices like green roofs and vertical greening systems in Nigeria (Adegun et al., 2021) for extreme heat and flood mitigation, and pervious paving in Kenya for flood mitigation (Mulligan et al., 2020).

3.4. Ecosystem services and economic benefits provided

Ecosystem services are either provisioning, regulatory or cultural. Intrinsically, NBS used for mitigating hydro-meteorological risks provide regulatory ecosystem services, whether flood control, reversing the impact of extreme heat or addressing drought. However, we also explored if other ecosystem services were provided beyond the hazard mitigation services studied (Fig. 7).

Twenty-four different ecosystem services made up of five different provisioning services (20.8 %), 15 regulatory services (62.5%) and four cultural services (16.7 %) were identified. In all, 88.9% (40 papers) reported at least one type of ecosystem service, while 11.1% (five papers) reported none. Furthermore, 13.3% (six papers) reported on only one type of ecosystem service, 46.7% (21 papers) reported on two types of ecosystem services, and 28.9% (13 papers) reported on all three types of ecosystem services.

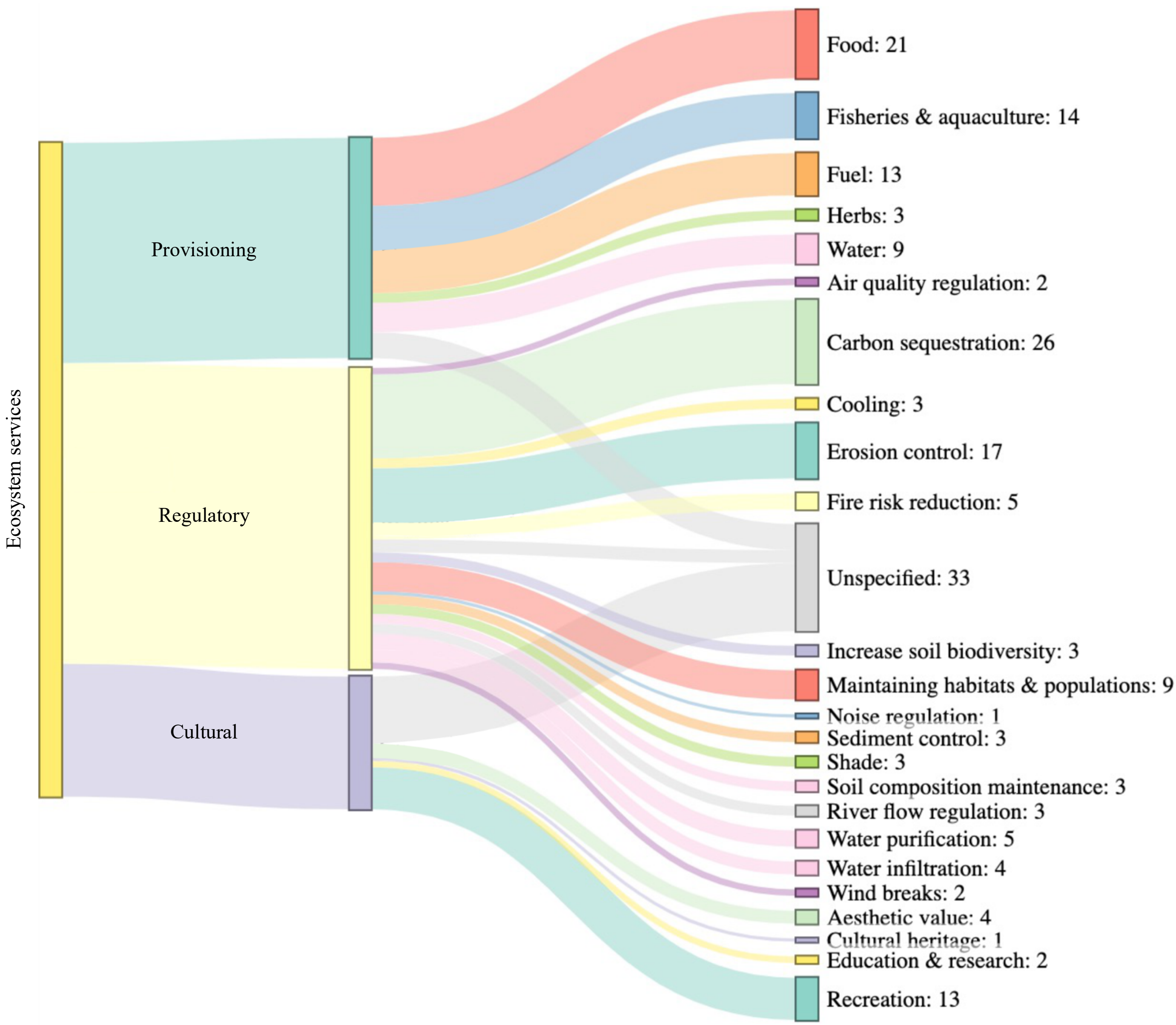

Figure 7. Ecosystem services provided by NBS initiatives beyond the hazard mitigation studied.

3.4.1. Provisioning services

Provisioning services provide direct benefits to urban residents, such as water, food, fuel and herbs. It was found that poor households in many informal settlements in cities depended directly on these provisioning services for their subsistence and livelihoods. In coastal areas and floodplains, fisheries and aquaculture were found to be more popular (e.g., Douglas, 2018; Ibe & Sherman, 2002; Turner et al., 2021), while food crops, fuel and herbs were found to be more common inland (Kihara et al., 2020; Lwasa et al., 2014; Schäffler & Swilling, 2013). For instance, in Obudu, Nigeria, the community is reported to have planted over 4,000 threatened *afang* vine and bush mango seedlings as part of reforestation efforts, providing edible non-timber forest products such as nuts and fruits (UNDP, 2017).

3.4.2. Regulatory services

The predominant regulatory service reported was carbon sequestration (n=26). In Durban, the Buffelsdraai Landfill Site Community Reforestation Project was conceived before the 2010 FIFA World Cup and aimed to see over 500 thousand indigenous trees planted. This restoration project was anticipated to help "absorb event-related greenhouse gas emissions while enhancing the capacity of people and biodiversity to adapt to the inevitable effects of climate change" (Douwes et al., 2015, p.6). The Great Green Wall project, roughly 15% underway, is expected to sequester 250 million tonnes of CO_2 by 2030 (Turner et al., 2021). Some studies acknowledged the importance of urban green areas for providing shade, reducing fire risk, increasing soil biodiversity and serving as windbreaks, among others (e.g., Etshekape et al., 2018; Kihara et al., 2020; Moyo et al., 2021). Other authors studied how urban greens help control erosion (n=17) both along the coasts (e.g., Fischborn & Herr, 2015; Ibe & Sherman, 2002; ICLEI, 2020) and inland (e.g., Adegun et al., 2021; Kalantari et al., 2018). Furthermore, restoration programmes are helping to maintain habitats and populations (n=9), especially in monitoring the loss of threatened species, ecosystems and critical habitats (Doswald et al., 2021). Weise et al. (2021) found that wetland conservation and restoration programmes are helping to protect thousands of bird and fish species across Botswana and Burkina Faso.

3.4.3. Cultural services

The cultural services provided were recreation (n=13), aesthetic value (n=4), education and research (n=2) and cultural heritage (n=1). In South Africa, the reforestation efforts under the Buffelsdraai Landfill Site Community Reforestation Project and the construction of the Buffelsdraai Reforestation Hub, which was an educational centre, provided recreation for residents and tourists. A review in Nigeria found similar benefits for green spaces (Adegun et al., 2021). Also, studies by Habtemariam et al. (2019) and Thorn et al. (2021) found that different NBS had aesthetic values that helped improve the image of cities. Papers describing various NBS projects in Ethiopia (ICLEI, 2020), Botswana, Zimbabwe, Tanzania and others found the same (Laros et al., 2013). In the Succulent Karoo in South Africa, the restoration of wetlands for flood mitigation also led to the creation of sites of value in the wetland areas for education and research purposes (Reid et al., 2018). A similar outcome was found in Lagos in Nigeria, where the Lekki Urban Forest and Animal Sanctuary helped to address extreme heat (Mauvais, 2018).

3.4.4. Livelihood and income generation

Ecosystem services provide a range of benefits, including social benefits such as improved human health and wellbeing, social cohesion and reduced crime, and economic benefits such as job creation and income generation. Thirty-four (75.6%) of the papers included reported on livelihood generation. Notably, most livelihood generation opportunities created were green jobs in disciplines like horticulture, forestry and market gardening. Cases from Kenya show that NBS for hydro-meteorological risks mitigation could create employment in the designing, planning, implementation and post-project phases (Mulligan et al., 2020). According to Doswald et al. (2021), restoration programmes can promote small businesses and increase household incomes.

For NBS with an international implementation scale, the Gazi Mangrove Restoration Project in Kenya is reported to employ dozens of people and attract over 300 eco-tourists each month (Taylor & Oluoch, 2012). The jobs created through the project were reserved for women, in order to address gender inequalities.

With regional NBS, the Great Green Wall across the width of Africa had created 350 thousand green jobs as of 2018 following its inception in 2007, mainly through land restoration activities, employment of rangers and nature guards and the production and sale of non-timber forest products. About $89.9 million was generated in revenue through these activities over the same period. The green job potential of the project is expected to reach 10 million by 2030 (UNCCD, 2020).

In the context of national NBS, Moyo et al. (2021) report that the Buffelsdraai Landfill Site Community Reforestation Project in South Africa created employment during the planting period between 2008 and 2016. Specifically, 50 full-time, 16 part-time and 389 temporary jobs were created. Over 600 tree-pruners were also reported to be supplying seedlings to the project in exchange for vouchers to buy food and bicycles, and pay for school fees and vehicle driving lessons, especially during the planting phase. In addition, these livelihood benefits can be improved by utilising invasive species such as *Chromolaena odorata, Melia azedarach* and *Eucalyptus*, which invaded the project site. For instance, there is the opportunity to use these species for medicinal purposes, including *Chromolaena odorata* to treat skin ailments, *Melia azedarach* to control diabetes and gastrointestinal disorders and *Eucalyptus* as an antioxidant and insect repellent. In Uganda, a wetlands restoration project advanced by the United Nations Development Programme is expected to help improve the lives of over 500 thousand people, including providing them with livelihood options (Benchwick, 2019). A tree-planting programme in Freetown, Sierra Leone, also helped to create 550 short-term jobs focused on women, youth and marginalised groups (Ravenholt, 2021).

At the community level, the rangeland rehabilitation and wetland restoration initiative in the Succulent Karoo of South Africa accentuates the potential of NBS for green job creation. It is reported that "937 jobs were created through two public works programmes funded by the DEA Expanded Public Works Programme Natural Resource Management Programme and building on CSA project activities (De Villiers 2013) – 611 jobs under the 'Working for wetlands' programme activities (implemented by South African National Parks), and a further 326 jobs under the 'Working for water' programme implemented by CSA between 2014 and 2017" (Reid et al., 2018, p. 12-13). These green jobs were mainly in restoration activities.

4. Discussion

4.1. Extent of reported NBS for hydro-meteorological risks mitigation uptake in SSA

After conducting this systematic review, we find that SSA is critically understudied in the area of NBS for hydro-meteorological risks mitigation. Du Toit et al. (2018) found that only 38% of cities in SSA had any research carried out on them on green infrastructure and ecosystem services. Choi et al. (2021)'s review of green infrastructure found that only 1% of the papers included were from Africa. Nevertheless, there may be more NBS initiatives in SSA, although they are unreported or were not captured within the search terms used in this study. Such unreported NBS most likely draw on local knowledge and are community-based, which makes documenting them challenging as a result of the ineffective data management culture in SSA (Malgwi et al., 2020; Manteaw et al., 2022). It is also likely that those locations in which NBS are reported in the scientific literature are places where research funds have been made available for their investigation. What is more, there may be other activities that could qualify as NBS but are not so described. For example, African farmers have been using NBS-like practices such as agroforestry, stone bunds, grass strips and sustainable land use through techniques like observing fallow periods for generations without calling them NBS (Keesstra et al., 2018). As such, it is unclear where a fine line should be drawn between age-old traditional practices and NBS or whether they should be considered NBS at all. Adopting the jointly-created citizen science approach, which brings lay people and experts together for knowledge co-creation (Gill et al., 2021), could help incorporate such practices, which are effective, into NBS and promote inclusivity and sustainability. The present study, therefore, affirms the assertions that literature on NBS and hydro-meteorological risks mitigation in SSA is scant, though this may be due in part to a lack of documentation and the use of different terminologies.

The results show that most papers were from South Africa, Kenya, Nigeria and Tanzania. This could be because these countries are among the biggest economies in SSA - South Africa and Nigeria, in particular, are the two biggest economies in SSA (Kamer, 2022) - and are basically leaders in their respective sub-regions. The four countries have also been forerunners in incorporating concepts like green infrastructure in urban planning, especially South Africa (e.g., Frantzeskaki et al., 2019; Russo et al., 2017; Venter et al., 2020). Furthermore, they boast some of the best educational and research institutions, which places them in an excellent position to advance research on urbanisation, climate change and concepts like NBS and ecosystem services.

Most reported NBS were implemented on a national scale. This is likely because major climate funds like Global Environment Facility and Climate Fund are more easily accessible to national governments than to non-profit and community-based organisations. Nonetheless, local scale NBS are the second most common. Such initiatives are often grassroots-driven, so enabling local people to maximise benefits. However, many challenges often constrain local governance in SSA; decentralisation mechanisms may be ineffective, local-level capacity may be weak and financial resources may be limited (Hjerpe et al., 2014). For many SSA countries, development and climate adaptation often occur only when they are grassroots-driven by non-state actors or when local institutions are robust enough to lead or coordinate initiatives (Mubaya & Mafongoya, 2017). The Local Action for Biodiversity project advanced by ICLEI (which focused on improving the capacity of local governments and political actors, including mayors, on biodiversity and ecosystems) presents a good case study of how national, even regional and international projects can support local communities to develop more sustainably. International and regional NBS also promote knowledge-sharing, which is essential, especially in applying a novel concept like NBS and in the context of the shared climate crisis that confronts all regions of the world.

4.2. Relationship between the location of NBS and the location of risks

Somalia, South Sudan and populations along the coast of Mozambique are identified as the most vulnerable to hydro-meteorological risks due to poor household and community resilience, high population densities and weak governance systems (Busby et al., 2014), even though they are not located in the areas the IPCC predict will receive the harshest climate impacts in SSA. In this review, only Mozambique, among these most vulnerable countries, reported NBS.

Based on the total deaths recorded from climate-related disasters, Somalia, Mozambique, and Nigeria have been the most affected (CRED, 2019) (Table 4). However, only Nigeria, third on the list, is among the countries most studied in this review.

Table 4. Top countries impacted by weather-related disaster deaths in SSA against top sources of papers by country in this review.

Country	Total deaths
Somalia	20,739
Mozambique	3,777
Nigeria	1,696
Madagascar	1,644
Ethiopia	1,639
Kenya	1,572
Sierra Leone	1,289
DR Congo	1,072
Malawi	985

Source: CRED (2019).

The factors behind very few papers from the countries most at-risk could be attributed to political instability. Somalia, in particular, is third globally and first in SSA on the Global Fragile States Index (Nasri et al., 2021). South Sudan, fourth globally and second in SSA on the Global Fragile States Index, is a relatively new country. Other reasons may be a lack of capacity for developing winning proposals for accessing climate funds and dwindling climate finance globally. The exclusion of papers published in Portuguese—because the language is not as widely spoken as English and French—could have also led to the low identification of papers in countries like Mozambique, Sao Tome and Angola. Therefore, the reported NBS for hydro-meteorological risks mitigation in SSA is in areas where risks are, but not where they are most severe.

In SSA, blue NBS have been the most used when addressing floods, while green NBS are more popular for extreme heat and drought mitigation. However, in Europe, hybrid practices are the most popular when addressing floods, while green NBS are more prevalent when responding to heatwaves and droughts. Blue NBS are used the least (Sahani et al., 2019). NBS implementation often demands land (e.g., river restoration), which is often unavailable due to urbanisation (Pugliese et al., 2022). In Europe, 90% of floodplains have been ecologically degraded (Entwistle et al., 2019), and the sections of urban areas vulnerable to floods increased by 1,000% between 1870 and 2016 (Paprotny et al., 2018). These factors have hampered the uptake of blue and green NBS, which is why practitioners have had to settle for hybrid NBS practices. In SSA, the rapid rate of urbanisation often makes it challenging for city officials to keep up with urban environmental change, which is characterised by green depletion and environmental degradation (Cobbinah et al., 2019). Much of the Global North went through this period, especially between the 18th and 20th Centuries, which saw the depletion of green spaces (Colding et al., 2020; Paprotny et al., 2018) and the degradation of several water-related ecosystems (Wantzen et al., 2019), which is why much attention has been on restoration even through NBS uptake (EC, 2016). In 2018, Europe was 4.2% built-up (EUROSTAT, 2021) compared to 0.16% in SSA (Karamage et al., 2018). A study on the extent of development in and around protected areas from 1975 to 2014 found that built-up areas were highest in Europe and Asia and lowest in Africa and Oceania (De La Fuente et al., 2020). Thus, the proliferation of blue and green NBS in SSA implies that decision-makers can structure urbanisation using lessons from the Global North to avoid counterproductive practices and develop in a climate-resilient way. In particular, lessons can be drawn from NBS like the Isar River Restoration in Germany (Pugliese et al., 2022) and the implementation of constructed wetlands, bio-swales, permeable pavements and other NBS in the sponge city concept in China (Li & Zhang, 2022), both for flood mitigation; as well as ambitious greening efforts across Europe (Pauleit et al., 2019), Singapore and Hong Kong to improve thermal comfort (Aflaki et al., 2017).

4.3. Specific NBS types and practices in use in SSA

Out of 66 NBS practices identified, most were implemented for flood mitigation. Earlier studies have found that 64% of hazard events in Africa from 2000 to 2019 were flood-related (CRED, 2019). Many identified NBS were reported to address multiple risks (Fig. 3). This demonstrates the multifunctionality of NBS and highlights their relevance for SSA in addressing the variety of challenges in the sub-region within the context of limited climate adaptation funds. Comparatively, Sahani et al. (2019) found 205 NBS used for addressing floods, heatwaves and drought in Europe. In a review in the German Alps, Zingraff-Hamed et al. (2021) also found 156 NBS used to address floods and landslides. While NBS are gradually becoming popular in SSA, it has not seen the level of wide uptake in the Global North, despite being the most vulnerable to hydro-meteorological risks.

Regarding flood risk mitigation, the most reported NBS were mangrove restoration and wetland restoration. For extreme heat mitigation, reforestation, urban forests and green conservation measures were the most reported NBS. In Europe, NBS like river and floodplain restoration (Zingraff-Hamed et al., 2021) and natural water retention measures (Hartmann et al., 2019) are more widely used for flood mitigation, while different green infrastructure types are used for heatwave mitigation (Pauleit et al., 2019). In this review, the most reported NBS for drought mitigation were agroforestry, conservation agriculture, integrated soil management and sustainable agriculture. Consequently, there may be many similarities between NBS practices used in SSA and Europe. However, food production appears to be a critical necessity for many SSA locals, even in the uptake of NBS for hydro-meteorological risks mitigation. Indeed, the agricultural sector is one of the most sorely affected by climate change in SSA (Stringer & Dougill, 2013), and it is predicted that yields could drop to up to 50% by 2100 (FAO, 2009). This could explain why communities often lend more support to NBS projects that provide provisioning ecosystem services like fruits from tree crops (Etshekape et al., 2018).

NBS practices that are not common in SSA but are more widely used in the Global North were identified in SSA. These include green roofs, vertical greening, constructed wetlands and soil remediation. Green roofs are building rooftops where plants are grown in extensive or intensive ways. The review showed the increasing use of green roofs in many locations in Nigeria (Adegun et al., 2021). Vertical greening systems are plants grown along the vertical axis of buildings, either on the façade or in the interior. Studies in Nigeria found the practice to improve thermal conditions and provide edible and medicinal plants (Akinwolemiwa et al., 2018; Oluwafeyikemi & Julie, 2015). Soil remediation is the process through which soils are returned to their original form of ecological stability before being disturbed. In Kenya, this method was used to help address floods through reduced runoff and improved access to co-benefits such as agricultural lands (Mulligan et al., 2020). These buttress the assertation that there may be many similarities between NBS practices used in Europe and those used in SSA.

4.4. Ecosystem services and economic benefits provided

SSA's most critical challenges include food and water insecurity, poverty, unemployment and climate change (World Economic Forum, 2019). Fifty percent of people in SSA live in urban areas (Kelsall et al., 2021), and over 43% of this urban population live below the poverty line (Du Toit et al., 2018). Most of these people live in informal spheres and lack access to decent and affordable housing, food and water and other necessities of life (Güneralp et al., 2017). Provisioning ecosystem services such as food, water and fuel are therefore necessary. This explains the popularity of NBS, which are closely related to food provision—agriculture already employs most of the labour force—such as agroforestry and climate-smart agriculture. Also, the urban poor are the most vulnerable to climate change impacts, and the fact that NBS can provide livelihood options is welcomed by locals. For decision-makers, the evidence that NBS can promote climate action through carbon sequestration, mitigate heat and beautify cities, among others, are significant benefits and drivers of adoption (Lupp et al., 2021; Thorn et al., 2021). Aside from delivering hazard mitigation services, NBS could help address some of SSA's developmental challenges concurrently.

Cultural ecosystem services provide non-material benefits such as recreation, education and intellectual appreciation, physical and mental benefits, aesthetic significance, spiritual and symbolic appreciation and enjoyment (Roux et al., 2020). Many of the papers did not report on cultural ecosystem services. This paper then adds to a long list of studies highlighting how cultural ecosystem services are little researched (e.g., Jones et al., 2022; Milcu et al., 2013). The lack of data in this sense makes it challenging to demonstrate the full spectrum of the benefits and disadvantages of NBS. It reiterates calls by earlier authors to scientists to produce ecosystem services assessment frameworks, especially for cultural ecosystem services, to improve reporting (Christie et al., 2019; Schäffler & Swilling, 2013).

Most of the papers included in the review reported that NBS created livelihood opportunities. Creating livelihood opportunities, mainly green jobs, which are more sustainable, is essential for a youthful region like SSA, where 60% of the population is 25 years or younger (Mo Ibrahim Foundation, 2019). This is also relevant in addressing crime and insecurity, which is often rife among the 50% and over people who reside in informal spheres in urban SSA due to a lack of economic opportunities. Improving life standards may also reduce the destruction of natural habitats and enhance natural restoration. Despite this, livelihood generation needs to be studied in detail, especially in river conservation and restoration projects, because, in some instances, NBS have led to the loss of local people's livelihoods. These have often occurred where risk responses have required the resettlement of populations; an NBS found to be used in SSA in this study. While its consideration as an NBS on its own may be contestable, Douglas (2018) indicates that relocation of informal settlements within riparian zones is a significant part of conservation and restoration initiatives in many locations in SSA, such as in Nairobi, Kenya. When such informal settlers were offered compensation and alternative livelihood options and relocated, they preferred to move back to these riparian areas, even if they were at risk of being impacted by floods because their livelihoods were tied to these areas. When river corridors have also been improved, it increased the value of such riparian lands, becoming more attractive to developers and displacing the original informal settlers. This mirrors concerns with conventional engineering solutions like wastewater treatment plants, raises critical social justice concerns, and could lead to a critique of the NBS concept.

5. Conclusions

This review presented an overview of NBS for hydro-meteorological risks mitigation in urban areas of SSA. First, regarding the extent of NBS uptake for hydro-meteorological risks mitigation, after analysing the 45 selected papers, we found at least one reported NBS in 71% of urban areas of SSA countries. However, this does not tell the whole story, as more than half of the NBS were based in only four countries. Hence, the reported uptake of NBS for hydro-meteorological risks in SSA is low even though there could be more unreported ongoing NBS, especially at the community level. Second, on whether reported NBS were implemented where risks are located, we found NBS to be implemented where risks occur but not where they are most severe, with only Mozambique reporting NBS among the countries most at risk. Third, regarding the specific NBS types and practices being used, mangrove restoration and wetland restoration, reforestation and urban forests, agroforestry and conservation agriculture were most commonly identified for floods, extreme heat and drought mitigation, respectively. We also found that food provision is, in most cases, a key objective of NBS in SSA even in hazard mitigation, with NBS like agroforestry and gardens being used quite significantly. There are many similarities between the NBS practices used in SSA and Europe, since practices like green roofs, vertical greening and constructed wetlands, which are more often used in the Global North, are emerging in the sub-region. More broadly, we also conclude that the proliferation of blue and green NBS in SSA indicates that the sub-region can advance urban development in a greener way and avoid repeating counterproductive practices in the Global North that led to the depletion and dwindling of green and blue spaces. Fourth, we found many benefits reported to accrue from these NBS through ecosystem services provision and livelihood generation, including 24 different ecosystem services. At the same time, four out of every five NBS created livelihood opportunities. Thus, NBS could help address some of the major developmental challenges that confront SSA, such as water and food insecurity, unemployment and poverty, aside from climate change and the associated hydro-meteorological risks.

Other conclusions were derived from the study regarding the concept of an NBS itself and its application. First, the concept of NBS needs to be further debated to clarify its scope, including its principles and use within different regional contexts. Apart from considering conservation efforts as NBS, this review also showed that the use of traditional methods like grass strips, which fit the definition of NBS, hundreds of years ago in SSA, raises the question of whether such age-old traditional practices should also be considered NBS. Designing NBS inclusively can also help to address challenges that confront localities more head-on since many SSA countries have difficulties with centralised governance and ineffective local government systems. Furthermore, if not inclusively designed, planned and implemented, NBS can affect livelihoods, as seen in the case of resettlement as part of efforts to conserve or restore floodplains and other vital ecosystems. This may raise crucial social justice concerns about the NBS concept.

From a policy perspective, we recommend that the concept of NBS be incorporated into urban planning in SSA to help address socio-ecological challenges associated with urban sprawl, such as greenspace depletion, water-related ecosystems degradation and pollution while helping to build resilience against hydro-meteorological risks. Adopting a co-created citizen science approach which will help increase knowledge on NBS and incorporate local knowledge into NBS interventions, is also recommended. Furthermore, given that food production, which is threatened by climate change, is a key objective for locals even during the roll-out of NBS for hydro-meteorological risks mitigation, we recommend that decision-makers prioritise NBS that promote urban and peri-urban agriculture. Furthermore, we propose that knowledge exchange opportunities on NBS be explored between SSA countries where the concept is still emerging with Europe and other regions where there has seen widespread uptake.

For future studies, we recommend research assessing the success or failure of NBS projects to document lessons by collecting empirical data. We propose that surveys and interviews be used to reduce dependence only on reported NBS, which was one of the limitations of this study. We also suggest more quantitative research to produce or update risk and vulnerability maps, to assess the effectiveness of individual NBS and study the multifunctionality of NBS in terms of ecosystem services and social and economic benefits. Research studying conventional engineering solutions and NBS comparatively, using, for instance, experimental set-ups, modelling or expert interview approaches, is also encouraged. Understanding the ecosystem disservices of NBS, such as the increased abundance of diseases caused by insects like mosquitoes that carry malaria, and increased harassment in green corridors, can also be advanced to fully understand the pros and cons of NBS.

Data availability

No datasets were used in this article.

Author contributions

KBE, AZ-H and MAR conceived the research, its design and analysis. AZ-H and SP led in the structuring and organisation of the paper. KBE led in the data collection and analysis. AZ-H, MAR and LCS contributed to the analysis. KBE led in authoring the manuscript. LCS contributed to writing the discussion section of the manuscript. SP reviewed and streamlined the draft manuscript.

Conflict of interest

We wish to confirm that this publication has no known conflicts of interest. In addition, we confirm that the manuscript has been read and approved by all the authors named and that there are no other persons who satisfied the criteria for authorship but are not listed.

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