Nature-Based Solutions for Flood Mitigation and Resilience in Urban Areas

Carla Sofia Santos Ferreira, Kristina Potočki, Marijana Kapović-Solomun, and Zahra Kalantari

Contents

C. S. S. Ferreira (✉)
Department of Physical Geography and Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden

Navarino Environmental Observatory, Costa Navarino, Navarino Dunes, Messinia, Greece

Research Centre of Natural Resources, Environment and Society (CERNAS), Polytechnic Institute of Coimbra, Coimbra Agriculture School, Coimbra, Portugal

K. Potočki
Department of Hydroscience and Engineering, Faculty of Civil Engineering, University of Zagreb, Zagreb, Croatia

M. Kapović-Solomun
Faculty of Forestry, University of Banja Luka, Banja Luka, Bosnia and Herzegovina

Z. Kalantari
Department of Physical Geography and Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden

Navarino Environmental Observatory, Messinia, Greece

School of Architecture and the Built Environment, KTH Royal Institute of Technology, Stockholm, Sweden

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Abstract Urban areas face several environmental problems and risks related to water management, such as floods and degradation of water quality, enhancing population vulnerability and threatening urban sustainability. These problems are expected to be exacerbated with increasing urbanization and climate change, which leads to higher frequency and intensity of hydrometeorological extremes. Moving towards more flood resilient cities has proven a major challenge, particularly considering the high concentration of population and economic activities and, thus, high pressure on limited available space. Nature-based solutions (NBS) in urban areas favour stormwater retention, infiltration, and filtration, contributing to flood mitigation and enhancement of water quality. The effectiveness of different NBS on stormwater management, however, is influenced by design and placement aspects, but a network of connected NBS elements can improve flood mitigation and enhance urban resilience. Stronger evidence of the advantages of NBS, however, is still required to overcome the current challenges and barriers impairing their wider implementation in urban areas.

Keywords Flood mitigation, Nature-based solutions, Urban areas, Urban resilience, Water pollution

1 Introduction

Urbanization has increased considerably over the last century, driven by the increasing urban population [1]. Today, 55% of the world's population lives in cities and the United Nations projection indicates that by 2050 this share will increase to 68%, and urban population will reach 6.7 billion people [2]. Physical expansion of urban areas is even faster than expansion of urban populations, due to the occupation of nearby land (peri-urban areas) motivated by the lower living costs than recorded in urban centres, easy mobility/transport, and the demand for improved quality of life [3]. The occupation of nearby rural areas involves an increasing consumption of natural resources, habitat loss, and environmental degradation and consequent decrease in ecosystem services supply, including water and climate regulations [4–6].

Number of floods in the world is rising since 1950s and this is associated with the changes in hydrological cycle and more frequent occurrence of hydrometeorological extremes [7]. Combined effects of more frequent occurrence of extreme events together with the development of urban settlements result in increasing occurrence of urban floods [8]. Removal of vegetation and expansion of sealed surfaces in urban areas additionally disrupts the hydrological cycle, i.e. reduces rainfall interception, evapotranspiration, and infiltration and thus increases runoff [9]. Urban water management practices based on nature-based solutions (NBS) are promising strategies to maintain the urban hydrological cycle as close as possible to the natural state. While reducing floods, NBS improve mitigation and adaptation to global changes (including both land-use and climate change) and provides services for maintaining and restoring ecological functions [10, 11].

Urban green infrastructure is a broad concept that supports NBS through integration of green and blue spaces in urban areas, thus sustaining water resources together with maintenance of biodiversity and ecological functions [12]. In the context of urban water management and mitigation of urban floods, similar concepts and solutions based on elements of green infrastructure can be found in the literature and differing in terminology depending on the part of world where they are developed. Some examples are Sustainable Urban Drainage Systems (SUDS), Runoff Best Management Practices (BMP), Low-Impact Development (LID), Water-Sensitive Urban Design (WSUD), Integrated Urban Water Management (IUWM), and Sponge city (SC) [13, 14]. NBS therefore contain solutions from specific techniques in urban drainage to the broad principles, such as sustainable development of urban areas [13]. Ecosystem restoration and climate change adaptation achieved by multiple functions of NBS contribute to the implementation of UN 2030 Agenda for Sustainable Development Goals and lead to enhanced development of circular economy [15]. However, the increasing extent and complexity of the urban systems pose major challenges for water management, and particularly to the implementation of NBS and to foster urban resilience [16, 17].

This chapter aims to present and discuss the main approaches used in urban flood risk management, and the most widely NSB measures implemented for flood mitigation in urban areas, based on literature review. Additionally, this chapter discusses the role of NBS to improve urban resilience and the main advantages and barriers to implement NBS in urban environments.

2 Urban Flood Risk Management Approaches

The urban water cycle is disrupted due to the extensive impervious surfaces, and their associated impacts on increasing flood hazard have been recognized for decades [18]. The traditional paradigm of *flood protection* founded on structural measures has been abandoned due to the high costs and inherent uncertainties regarding their effectiveness. Thus, a new approach based on flood risk management was slowly introduced in water management legislation at the turn of the century. For example, European Union has adopted the Water Framework Directive [19] and subsequent Floods Directive [20]. Water Framework Directive introduced an approach to integrated river basin management through development of River Basin Management Plans and commits EU member states to achieve good qualitative and quantitative status of all water bodies. Steps for assessment and management of flood risks are prescribed in Floods Directive. Measures focused on prevention, protection, and preparedness are proposed in Flood Directive through the development of Flood Risk Management Plans. Flood Risk Management Plans need to be coordinated with the River Basin Management Plans, together with the implementation of all the relevant environmental objectives from the Water

Directive. Flood risk management is therefore an integral part of integrated river basin management and incorporates the concept of *living with flood risk* [21].

Flood risk is defined as "a 'product' of the probability of flood and their consequences", or, as the "product of flooding hazard and society's vulnerability to flood hazard" [22]. Quantification of flood risk in urban areas presents a challenge due to the complex interrelationships of different flood sources and the effectiveness of management measures, so an integrated approach for flood risk management is needed [23]. The main phases included in the design and implementation of an integrated Flood Risk Management plan include (1) flood risk assessment, including risk perception and risk tolerance; (2) risk reduction through implementation of adaptative strategies and measures [22]; (3) emergency management; and (4) short- and long-term recovery [24, 25]. Development and implementation of the Flood Risk Management approach requires trans-sectoral governance, cross-sectoral cooperation and planning, interdisciplinarity, and inclusion of different stakeholders. Although this adds complexity to the Flood Risk Management, this wide integral approach enables coordination between social, hydrological, and ecological systems providing framework for better adaptation to climate change and sustainable development of urban areas [21, 25].

In urban areas, flood mitigation is performed through a series of structural and non-structural measures. Typically, structural measures rely on "grey" solutions, i.e. hard-engineering structures for flood defence such as channels, pipelines, and storage tanks included in urban stormwater drainage systems, which provide quick conveyance and drainage of stormwater runoff. The application and maintenance of these conventional methods have proved costly and insufficient to cope with challenges of more frequent precipitation extremes and consequent floods in urban areas, driven by climate changes [26]. Urban drainage systems are designed so that they can accept runoff caused by design rain, i.e. rain of a certain duration and recurrence period (usually 1–5 years). Design rain is determined by statistical analysis of historical rain events and does not consider changes caused by climate change recorded after the construction of the system. Therefore, the drainage system in circumstances of higher frequency and intensity of rain events, although designed and dimensioned according to the rules of the profession, can no longer successfully care excess water resulting from more frequent flooding [27]. Land-use changes during urbanization process are characterized by an increased share of impervious surfaces, resulting in reduced infiltration which ultimately leads to an accelerated and increased volume of surface runoff to be managed. Previous studies have shown that an increase in impermeable surfaces by 30% compared to the state before urbanization results in a twofold increase in flooding over a 100-year return period [28]. Also, complex interactions between urban and natural system present challenges to modelling urban flood processes, since hydrological models are usually based on simplified surface runoff processes and hydraulic models on simplified piped systems [29].

The transition from traditional urban water management system towards nature-based urban flood management intends to reestablish hydrological conditions before urbanization, i.e. reducing and delaying runoff, through the incorporation of green

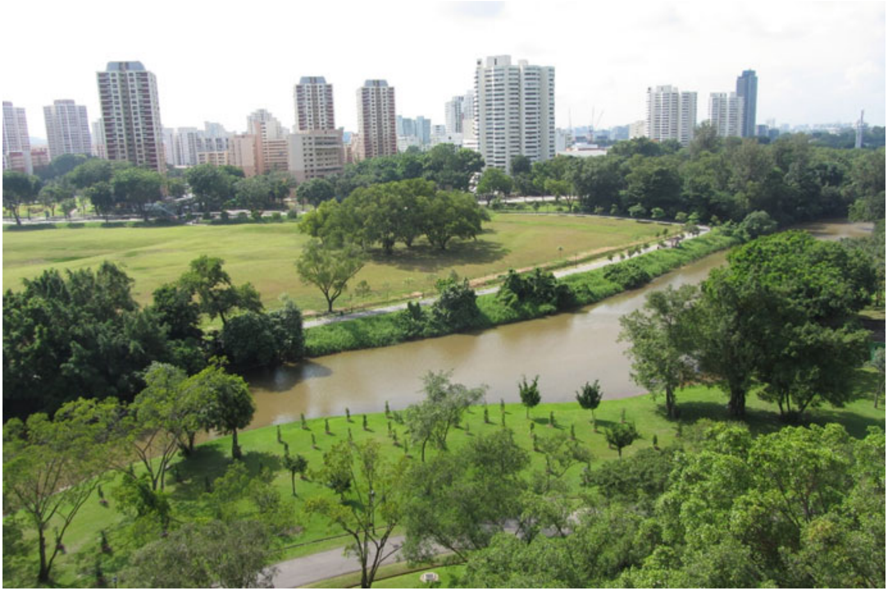

Fig. 1 Integration of green infrastructure in Singapore (Photo by: Ana Sović Kržić)

elements that increase infiltration, evaporation, and retain water [30]. An increasing number of cities all around the world have been implementing green solutions, regulations, programmes, and incentives enabling flood protection based on NBS. Singapore (Fig. 1), Berlin, and several cities in China present good examples of NBS for stormwater management [31–33].

NBS applications for Flood Risk Management in urban areas, however, must consider specific local conditions and a multidisciplinary approach, in order to implement economically, environmentally, technologically, and socially sustainable solutions. Operationalization of NBS for floods and other hydrometeorological hazards can be established through a set of principles that describe co-design, co-development, co-deployment, and demonstration of the NBS effectiveness. Research should be conducted with impact/scenario modelling together with the incorporation of related policy frameworks. Achieving these steps is possible through shared knowledge and skills of stakeholders, researchers, experts, and end-users from different fields, including engineering, hydrology, urban planning, landscape architecture, ecology, economics, law, and other professions [34].

3 Nature-Based Solutions for Urban Flood Mitigation

Water management in urban areas is established to mitigate the impacts of development on water cycling by means of NBS, namely through the implementation of Green Infrastructures. The Green Infrastructure concept appeared in the last decade

[35] as a result of the urbanization pressure and the shortage of green and blue spaces within urban areas. Green Infrastructure can be described as a system of natural areas, features, and green spaces in rural and urban, terrestrial, freshwater, coastal, and marine areas [36]. It includes a network of natural and designed landscape components with important role on water regulation and flood risk mitigation and management [37], as well as reduction of water pollution [2]. In the context of urban water management, Sustainable Urban Drainage Systems have been also presented as water management elements, based on natural hydrological processes. However, whereas Sustainable Urban Drainage Systems are devoted to more specific techniques on smaller spatial and functional scales, Green Infrastructure is used on larger scales and involves a multitude of stakeholders, such as local authorities and private landowners [13].

There are many permeable vegetated surfaces integrating Green Infrastructure in urban areas, such as green corridors, urban parks, urban gardens, urban forests, urban grasslands, and other recreation zones [38, 39]. The water elements integrating urban Green Infrastructure include rivers, lakes, canals, ponds, and floodplains, which provide an additional capacity to cope water during rainfall events [40]. In turn, Sustainable Urban Drainage Systems, which are incorporated into urban drainage systems, include green roofs, retention and detention ponds, wetlands, infiltration tranches, bioretention basins, rain gardens or swales, and impervious pavements (Fig. 2). These structures are mainly implemented as source control techniques, to reduce the amount but also improve the quality of stormwater at or near its source [41].

Sustainable Urban Drainage Systems and Green Infrastructure can be designed for temporary water storage and runoff reduction, but also to provide additional ecosystem services such as regulation of water quality and cultural services for citizens (e.g. aesthetics and recreation). Regarding water regulation, they provide infiltration, detention attenuation, conveyance, and water harvesting as the main management options for runoff quantity control and peak flow reduction. The use of vegetation in the NBS measures (e.g. green roof, infiltration gardens, and urban forests) additionally provides rainfall interception and evapotranspiration, enabling water to return to the atmosphere [42].

Some of the most widely used NBS to mitigate runoff and address issues of poor surface water quality include wetlands and runoff ponds (e.g. retention ponds, flood storage reservoirs, shallow impoundments), which contain water during dry weather and are designed to hold extra water when it rains [43]. While wetlands restoration has been performed to renew their natural functions (e.g. by removing underground drainage tiles), constructed wetlands have been also implemented to improve food mitigation and surface water quality. Typically, constructed wetlands are created through excavation of upland soils to elevations that will support the growth of wetland species, but they can involve also dyke installations [2]. Constructed wetlands establish a hydrological regime which mimic the functionality of natural wetlands and facilitate filtration of polluted stormwater runoff and pollutant absorption [43].

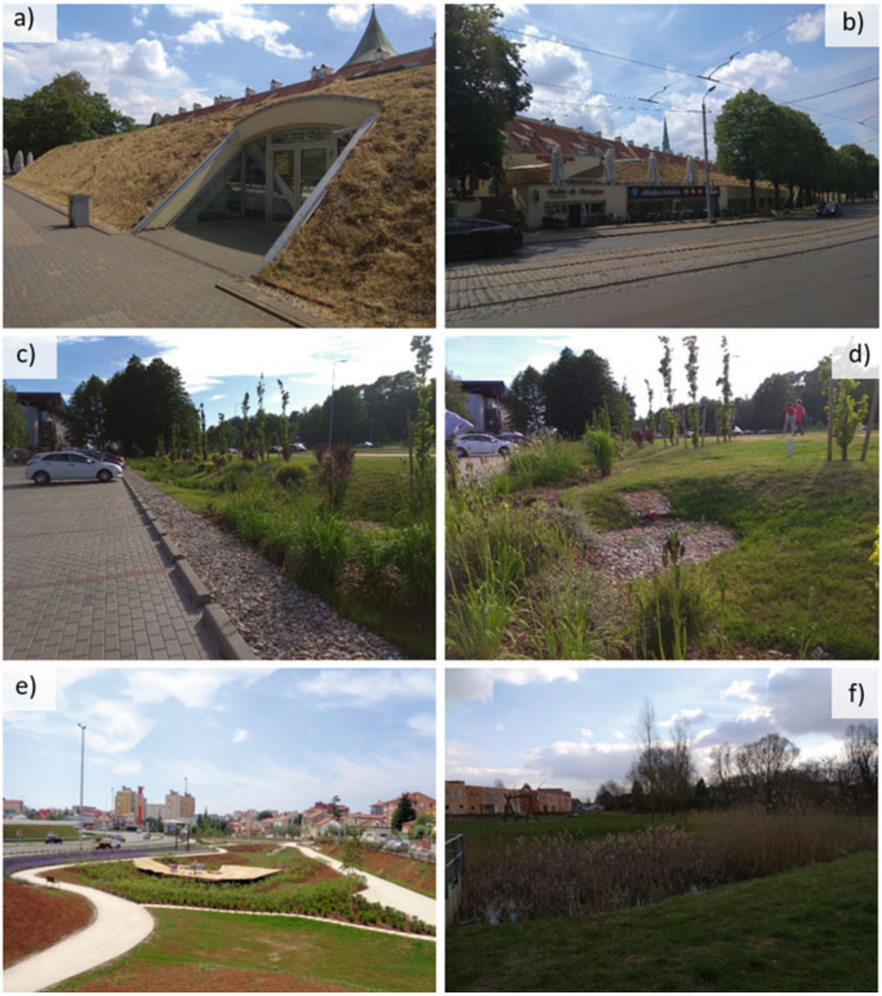

Fig. 2 Examples of NBS in urban areas: (**a**) green facade and (**b**) green roof in Riga, Latvia, (**c**) bioretention basin and (**d**) infiltration trench in Riga, Latvia, (**e**) detention basin in Pula, Croatia, and (**f**) wetland in Ghent, Belgium

Detention basins, which are grassed depressions or basins created by excavation into which runoff generated during rainfall events is channelled, are designed to temporarily detain and facilitate the slow filtration of runoff. They play important roles in regulating water flows and maintaining water quality by retaining sediments and reducing nutrient and metals, as a result of settling of particulate pollutants and uptake by vegetation [43, 44]. Additional bioretention structures, such as pits backfilled with soil, mulch, and/or vegetation used to retain and infiltrate runoff, also rely on biophysical processes within the soil matrix to reduce the volume of stormwater and pollutant characteristics [2].

The performance of NBS on flood mitigation, however, is highly dependent on rainfall return periods [45]. Based on field and laboratory studies, for example, porous pavements showed better performance in respect of peak runoff reduction than green roofs and bioretention cells under different storms [46]. Bioretention cells, in turn, revealed more effective in the reduction of runoff volume [42]. In general, filter trenches, soakaways, and green roofs are typically designed to cope with moderate rainfall events, whereas elements such as retention ponds, swales, and detention basins can cope with heavier rainfalls [45].

As presented above, several studies have shown the positive impacts of NBS on water infiltration, retention, interception, transpiration, evaporation, and mitigation of surface runoff, and thus their role in managing flood risk [39, 47]. However, the performance of different NBS in flood protection is strongly linked to different spatial allocations and to different patterns of their installation. Small-scale examples of several NBS showed better performance in surface runoff reduction than single NBS [48] and that was also the case with NBS that were spatially distributed but with good hydrological linkages [49]. Spatial allocation tools are therefore used to estimate optimal hydrological functioning and perform spatial analysis [50]. Mapping of Green Infrastructure is considered a prerequisite to improve its functionality, but consensus is still lacking about using appropriate typology, mapping methods, and tools for specific applications [39].

Some researchers argue better effectiveness of NBS over the grey infrastructures [51, 52]. Others, however, have found that although NBS provide flood reduction gains, under intensive rainfalls and in cases when only green measures are applied, its performance is questionable [11]. Grey infrastructures provide rapid conveyance and transport of runoff into downslope areas [53], particularly relevant in dense urban areas, and can be designed and constructed to manage large volumes of stormwater (e.g. driven by 50-year floods [54]). Nowadays, this grey approach is considered to offer low sustainability, while NBS provide numerous complementary benefits, such as climate regulation and supporting biodiversity [55]. Thus, a combination of NBS and grey measures has been advocated as the best option for stormwater management and urban flood mitigation [54, 56].

4 The Role of NBS to Improve Urban Resilience

4.1 Sustainability and Urban Resilience Principles

Urban resilience can be defined as the ability of a system to develop the resources, skills, and capacities needed to maintain or rapidly return to desired functions in the face of a disturbance (e.g. flood and climate change) and limit its negative impacts [57]. It enables the urban system to prepare and plan for (pre-disaster actions to mitigate hazards by reducing their frequency, intensity, and duration), absorb (minimize potential damages and losses), rapidly recover from, and adapt to stressors and adverse events (Fig. 3) [58].

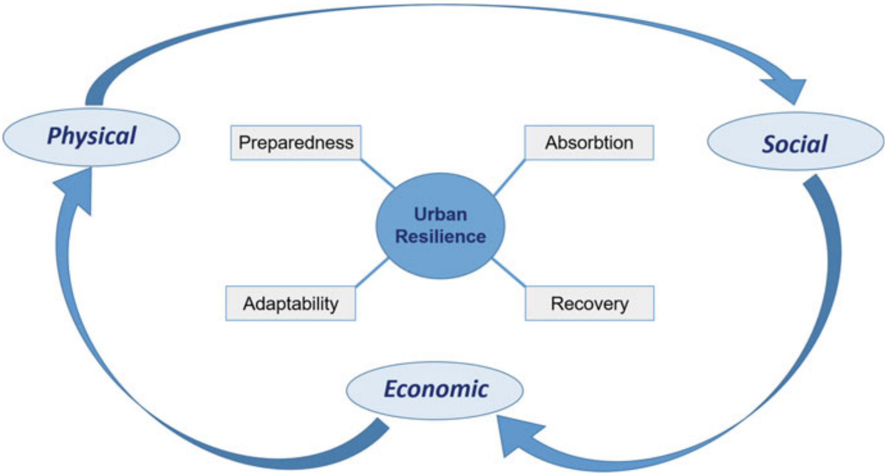

Fig. 3 Three dimensions and four principles of urban resilience

In order to plan and prepare for disturbance (e.g. flood event), it is important to assess the consequences based on past experiences, namely by building knowledge about previous disturbance, exposure, vulnerability, and monitoring of critical slow variables. Absorbing disturbances requires robust infrastructures, and creation of buffer capacity to dynamically cope with disturbance and maintain the desired functions of the urban system. Urban systems must provide diverse responses, ensured by different spatial diversity, to recover from disturbances. Adaptability involves changes driven by institutional learning capacity and reflectivity, which requires innovative and transdisciplinary practices, and flexibility in spatial planning, to quickly modify and transform the urban system and maintain the desired functions into the future [59]. Besides the physical component of urban resilience, the social networks that connect resources to vulnerable social groups (social resilience) and the economic recovery of the urban areas (economic resilience) are important aspects to include in resilience thinking [60]. The need for urban resilience has been reinforced by the European Commission, the World Bank, and the United Nations and has become a major focus for guiding planners and decision-makers [58] and to support the achievement of Sustainable Development Goals [15].

4.2 NBS Contribution for Urban Resilience

Governments and local authorities are increasingly involved in resilience-building strategies, seeking to design and implement sustainable solutions, which combine the maximization of tradeoffs between positive and negative effects of, for example, urbanization and climate change, with sustainable development and environmental concerns, to guarantee liveable conditions in urban areas [58]. Towards this end, there is a perspective change in the conception, planning, and development of the built, infrastructural, operational, and functional forms of urban areas [61]. NBS have been identified as a promising approach to enhance urban resilience by providing flexible and adaptable solutions, based on the delivery of ecosystem services [43, 60]. In terms of flood risk management, for example, "re-naturing" urban areas reestablish some natural hydrological processes (e.g. water infiltration and purification), providing clear departing from the traditional resistance-based approach focused on flood-safe solutions (e.g. dams) [17].

Depending on their type, function, design, and configuration, NBS may contribute to urban resilience by integrating properties such as diversity, efficiency, flexibility, modularity, multifunctionality, and redundancy into urban planning and design [58]. Protecting, restoring, and enhancing green and blue infrastructures across spatial and temporal scales in urban areas enhance resilience of urban systems to disturbances. For example, vegetation buffers in riparian zones provide flood protection and reduce the occurrence of extreme urban heat events, identified as two key socio-natural disasters requiring preparation, recovery, and resilience [62]. Wetlands are known for their provisioning of ecosystem services, and thus constructed wetlands have great potential for use as NBS to address a variety of environmental, social, and economic challenges. Common multi-beneficial ecosystem services derived from wetlands include water quality protection [63], groundwater level and soil moisture regulation [64, 65], flood regulation and sediment retention [66], and biodiversity support [76]. As the frequency of natural extreme events increases, it is becoming increasingly important to deploy NBS such as wetlands, both locally and at larger scales, in flood risk mitigation measures that strengthen the resilience of the urban landscape [2]. Wetlands are often described as natural sponges, due to their long hydraulic residence time combined with their vegetative features, which play an important role in reducing downstream peak flows, erosion rates, and nutrient retention [67, 68]. However, despite their importance, there has been a rapid and sustained decline in wetland areas globally. The absolute scope of global wetland losses is uncertain, and the rate of loss has slowed substantially in some regions of the world, such as the USA and Europe, in recent decades [69]. Nevertheless, many regions worldwide are still experiencing rapid wetland loss [70, 71].

According to the domino effect concept, based on a chain reaction causing changes in a territory, some urban areas may be affected by floods even if they are not located directly in the risk area. Indeed, in the interconnected space of urban areas, risks have impacts beyond spatial municipality boundaries [57]. Since most urban catchments begin prior to and continue beyond municipal boundaries, different approaches to impervious cover regulation and water management strategies may marginalize the benefits of a municipality's effort to implement NBS. Because of the spatial and institutional mismatch, NBS strategies requires collaborative or polycentric governance approaches. As a result, a growing emphasis on NBS as a significant contributor to urban resilience necessitates a more thorough understanding of the institutional fit between the social infrastructure for governance [62].

The links between NBS and urban resilience, however, should also consider the resilience (or vulnerability) of ecosystems themselves. For example, climate change impacts ecosystems and may affect their capacity to function and provide services. The extent to which urban ecosystems, as isolated green spaces within the urban areas, can themselves be resilient may be limited, but could be supported with active management, by selection of temperature-adapted species, creation of connected networks, and control of habitat disturbance and destruction processes [72].

5 Challenges and Barriers to Implement NBS in Urban Areas

5.1 The Role of Urban Planning in NBS Implementation

Urban planning can play a substantial role to support the implementation of NBS, in response to the challenges of attainting urban resilience and environmental sustainability [73]. Urban resilience from NBS applications, however, must consider the interconnectivity of the urban green spaces at local, regional, or even national scales, to better assess the mitigation of floods. Connectivity refers to the physical connection between green elements (structural connectivity), but also the connection between natural and ecological processes, such as water and geochemical cycles (functional connectivity) [74]. Thus, although one small NBS may (partially) lose functionality during a rainfall event, a larger connected network of NBS can have the potential to function as a decentralized stormwater management infrastructure and thus ameliorate flood risks [2]. As a decentralized approach to stormwater management, NBS are usually inherently more resilient than large, centralized grey infrastructures [60]. According to WWAP/UN Water [2], climate change adaptation will not be possible without a range of NBS that deal with increasing water variability and extremes induced by changing climate. Furthermore, open spaces provided by NBS have a potential for disaster management, since they can be utilized for emergency evacuation and as shelters [58].

The planning and implementation of NBS can be supported by policy approaches. For example, regulation of impervious cover within a city and mandates that new buildings or developments must include green spaces [62]. Some urban areas, in turn, are incentivizing NBS through subsidies for rainwater harvesting or relied on grant programs for the adoption of green roofs [60]. Cities such as New York and the already mentioned Singapore have adopted an NBS approach based on urban green infrastructure to combat climate change and associated problems such as urban floods and to achieve overall socio-economic resilience by delivering ecosystem services [73].

Successful implementation of sustainable NBS to cope with a range of current and future challenges requires the involvement of all relevant sources of expertise and interests in the planning and decision-making process, due to the multidimensionality and complexity of NBS [75, 76]. The involvement of a wide range of stakeholders and actors in turn requires deployment of different communication tools and methods. Successful implementation of NBS in urban planning relies on a proactive approach where implementation early in the planning process is key [77, 78].

5.2 *Effectiveness of NBS*

In order to compare the effectiveness of NBS with that of technology-based grey solutions in urban areas, further research and onsite monitoring are needed to capture the diverse co-benefits that NBS can provide [79, 80]. Multiple social, environmental, and economic co-benefits can be associated with NBS, in addition to their direct benefits, and the challenge is to link and capture these co-benefits in evaluations [77]. The current evidence on NBS performance is largely imbalanced and mainly focuses on a few ecosystem services. Most previous studies addressing the ecosystem services provided by NBS have focused on local climate regulation (40%) and recreation (20%), while only 8% have focused on water regulation [81]. There is thus a major knowledge gap in the evidence based on NBS performance. Consequently, there is an urgent need to investigate a wider range of aspects and to develop assessment models that can be applied at different locations, thus helping to reduce the geographical bias in the literature [81].

To evaluate the economic effectiveness of NBS, Potschin et al. [82] suggest validation methods such as “avoided costs” from, e.g. damage or problems that would arise if NBS were not implemented. Cost–benefit analysis can also be used to help decision-makers choose between different NBS [83]. It should be stressed that additional methods may be required to assess the full economic effectiveness of NBS. For instance, Raymond et al. [84] argue that cost–benefit analysis can be insufficient for evaluating the economic effectiveness of NBS, since it cannot account for the long-term cumulative benefits provided by NBS, and suggest combining it with methods such as participatory assessments, group modelling, and integrated sustainability assessment.

Data availability is currently one of the main factors preventing full-scale implementation of NBS [79]. This lack of data can be overcome by widespread onsite monitoring [77]. Future monitoring efforts need to cover both the process of implementing NBS and the outcomes, including the final benefits of a particular NBS, how it is perceived and how it responds to the challenge for which it was implemented [84]. In order to enable effective monitoring of these aspects, indicators of NBS performance covering a range of social, economic, and technical aspects must be developed [77, 83]. Raymond et al. [83] suggest working with measurable indicators to assess, monitor, and communicate the effectiveness of different NBS. However, it remains unclear the effectiveness of NBS over a longer temporal scale, which NBS would be most effective in the long run and which would produce effective results immediately after implementation. Therefore, when assessing the effectiveness of a given NBS, it is important to consider the possible time lapse between its initial effect and the point when it reaches full effectiveness.

5.3 Advantages and Disadvantages of NBS

There are four main advantages of NBS: (1) *sustainable systematic and integrative approach,* (2) *resource efficiency,* (3) *long-term cost-efficiency,* and (4) *co-benefits.* The systematic and integrative approach is a strong advantage of NBS [75]. NBS applied in a suitable manner can, in an innovative way, use natural elements to achieve environmental and societal goals [10]. More specifically, NBS can provide energy- and resource-efficient measures that combat climate change and, at the same time, support and protect natural capital [85]. For example, green roofs and walls provide thermal insulation of buildings [86], and pervious pavements can reduce surface temperatures up to 4°C, due to lower reflection and evaporation [87].

In many cases NBS have been proven to be more cost-effective and multifunctional over the long term than grey solutions [88]. This is a consequence of their often-low maintenance costs and flexibility of application [89]. In addition, NBS provide a variety of multiple benefits, often including socio-cultural values such as recreation, increased biodiversity, and cultural heritage [90]. Pollution control and opportunities for enhancement of human well-being are other co-benefits provided by NBS [89, 91]. Green roofs and walls, for example, provide air pollution reduction and carbon sequestration [92], and habitat for different species [36].

There are four main disadvantages of NBS: (1) *longer time frame compared with grey solutions,* (2) *space-consuming,* (3) *ecosystem disservices,* and (4) *segregation and environmental injustice.* A particular disadvantage of NBS is the generally longer time frame before reaching full potential and effects compared with grey solutions [77]. Solutions based on ecosystem services require a significant time frame to create or restore a habitat, which can be an obstacle in fast-growing urban areas and a reason for choosing conventional grey solutions [10]. In addition, local conditions have to be well understood in transdisciplinary ways, in order to choose the most beneficial NBS to exploit the full potential at a specific site. This requires expertise and experience in relevant areas, which may be costly [75]. Finally, NBS in urban planning and policy development processes can be time-consuming, unless clear strategies are established. The multidisciplinary process related to NBS involves different stakeholders with multiple different interests and assets [75, 84]. Many NBS projects in an urban context, e.g. open stormwater management, require more space than grey solutions such as underground systems. Therefore, a potential conflict between NBS and the global goal of increased urban compactness can be regarded as a drawback [90]. Apart from the multiple benefits provided by NBS, they can also supply “ecosystem disservices” (EDS) [93]. For instance, NBS involving open water surfaces, such as wetlands and stormwater handling systems, in combination with increased temperatures, could enhance the risk of infection by vector-borne infectious diseases, including malaria and dengue fever [94]. Therefore, it is important to use modelling tools to evaluate multiple benefits of SUDS [95, 96]. Implementation of NBS in urban areas may also not be beneficial for all citizens. It can even lead to segregation, through displacement of population groups that cannot afford the higher rents and land prices resulting from the higher reputation and living standards brought about by NBS [77].

6 Final Considerations

Most people in the world live in urban areas; therefore, it is important to develop resilient cities and ensure adequate proportion of green and blue urban spaces for human well-being. NBS provide sustainable water management, since it relays on natural processes to manage stormwater quantity and quality. Based on vegetated surfaces, NBS provide opportunities for water interception, evapotranspiration, infiltration, and filtration, and thus, reduced surface runoff and water pollution. Besides the relevant contribution for flood risk mitigation and to support water quality within urban areas, NBS comprise multifunctional spaces able to deliver a wide array of ecosystem services beyond water management, such as climate regulation, improving air quality, provision of habitat and support to biodiversity, and contribution to human satisfaction. However, development of a stronger evidence based on NBS is a key aspect for successful NBS implementation, particularly empirical evidence demonstrating the effectiveness of NBS [77]. Since NBS for water management depend on many factors, improving the knowledge in different hydrological, environmental, socio-economic, and management conditions, and providing well-established historic evidence of their positive impacts, will be relevant to support increasing NBS applications.

Several NBS have been implemented at different scales within the urban areas, such as urban forests, gardens, wetlands, infiltration trenches, and green roofs. The effectiveness of NBS for water management varies with their design, size, and local conditions. Nevertheless, it is rather a network of connected NBS than small isolated elements that can effectively mitigate urban floods and thus contribute to enhance urban resilience, namely through adaptation to climate changes. Nevertheless, relatively limited knowledge is available to compare the effectiveness of NBS with conventional alternatives. Filling this information gap is key to better assess the advantages of combining NBS and grey infrastructures in water management plans and to enhance the urban resilience. This will be useful to promote private sector investment in NBS and to advocate for policy changes supporting NBS and promoting NBS to political leaders [2].

Implementing NBS in urban areas, however, is inherently complex, due to increasing environmental, social, and economic challenges and the limited space to fulfil a wide range of needs. Urban planning can play a substantial role to support the implementation of NBS and to manage tradeoffs and conflicts while assuring social equity. Governance systems must improve and legitimize the delivery of ecosystem services by reinforcing the means to prioritize and implement NBS and thus enhance sustainable development and urban resilience.

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