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Nature-based solutions for water management: insights to assess the contribution to urban resilience

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ABSTRACT

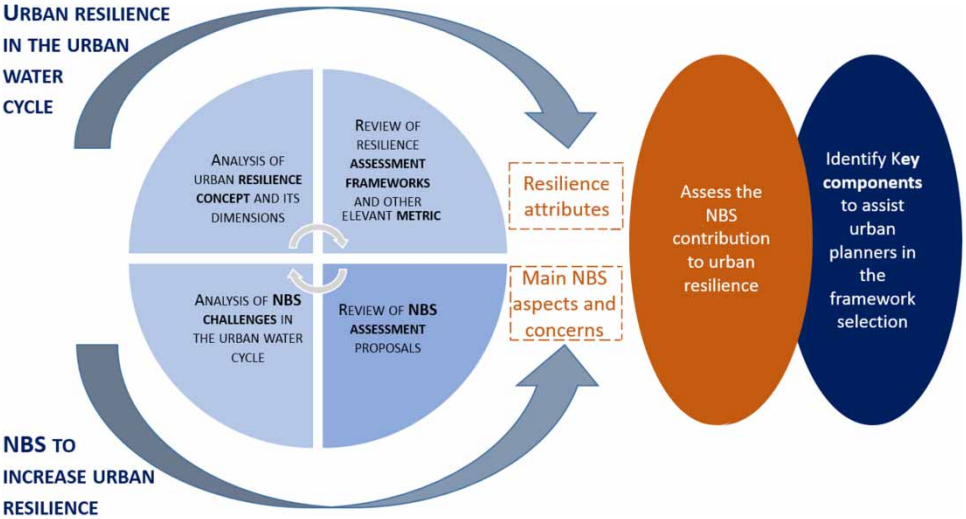
Assessing the Nature-Based Solutions (NBS) contribution to urban resilience, along with developing tools capable of demonstrating their long-term value, comprises a most needed step forward. Nevertheless, the NBS contribution to urban resilience has been yet slightly explored. Given the urban resilience complexity and multiple NBS capabilities, specific needs for a robust assessment should be investigated. This paper identifies the requirements for a comprehensive assessment of the NBS contribution to urban resilience and analyses the main assessment frameworks focused on resilience and NBS for urban drainage. First, the evolution of the resilience concept and relevant resilience assessment frameworks (RAF) are presented. Secondly, NBS challenges to enhance resilience and NBS assessment proposals are analysed. Thirdly, the attributes for assessing urban resilience and aspects to assess the NBS contribution are analysed. To conclude, a critical analysis of the assessment approaches is presented. Important challenges across the RAF have been identified, especially regarding their feasibility of application. Based on the performed analysis, most RAFs are not feasible for city benchmarking and assessing the resilience evolution over time, neither for assessing comprehensively the NBS contribution. Regarding specifically the NBS assessment proposals, just one focused on urban resilience was developed to date, which allows evaluating their contribution over time, between cities, or between different NBS.

Key words: cities, nature-based solutions (NBS), resilience assessment framework (RAF), urban resilience, water drainage sector

HIGHLIGHTS

- Assessing NBS contribution to urban resilience represents a crucial need.
- Specific needs for a robust assessment were studied to support NBS implementation.
- Most RAFs are not feasible for city benchmarking and assessing resilience over time, as well as assessing NBS contribution.
- Just one NBS proposal assesses specifically urban resilience, evaluating the NBS contribution over time, between cities, or between different NBS.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Climate change has raised multiple challenges in urban areas, with larger cities being particularly vulnerable to climate change expected impacts and to the anticipated urban population growth in the coming decades (UN-Habitat 2017). The need to face these challenges while maintaining environmental sustainability has led urban planning into including resilience concepts in the design practice (Coaffee 2008).

The concept of resilience emerged in the 1960s from the growing interest in ecology to determine population stability (Folke 2006). Initially, resilience only considered a single point of view and a single state of equilibrium, to which the system returned after the disturbance. The concept evolved under the works of Holling (1973), to describe the ability of a system to maintain its function when exposed to possible shocks or disturbances, which does not necessarily return to its initial state. The system can evolve and improve its functioning, reaching a new state of equilibrium. Resilience should, therefore, be analysed from multiple perspectives, considering the several existing subsystems and analysing the interconnections between them. Several works have addressed different perspectives, focusing on the capabilities, drivers, and tensions to be considered in social, ecological, and complex systems (Davoudi *et al.* 2012; Francis & Bekera 2014).

Resilience in urban areas is commonly understood as the ability of human settlements to withstand and recover quickly from any plausible hazards (UN-Habitat 2017). In this regard, resilience pertains to more than maintaining a system working, as it comprises its adaptive capacity, when facing stresses and changes, into more desirable states (Milman & Short 2008). The Organisation for Economic Co-operation and Development (OECD) identified resilient cities as those with the capacity to absorb disruption, learn from the past, adapt, transform, and prepare for the future (Sayaas 2016). The need for improvement of urban resilience is recognized worldwide through Sustainable Development Goal (SDG) 11 'Make cities and human settlements inclusive, safe, resilient and sustainable', establishing resilience in cities as a critical issue.

To improve urban resilience, policymakers and city managers aim to address underlying risk factors and reduce the exposure and vulnerability of people and assets (Coaffee 2008). Water plays a major role in cities. Water provides not only multiple functions, such as drinking purposes and as an amenity, but also poses risks to human populations due to floods. Historically, urban drainage systems started to be implemented mainly for sanitary and public health purposes during the 19th century. As cities grew and multiple roles were recognized within the city, the functions of urban drainage also changed. Nowadays, these include flood control, pollution management, ecological concerns, and recreational uses (Brown *et al.* 2009; Shutes & Raggatt 2010).

In the last decade, the application of the resilience concept to the urban water sector sought to understand its capacity to adapt to climate change, both from a global water management perspective (Muller 2007; Milman & Short 2008) and from specific water and wastewater treatment technologies (Luh *et al.* 2017).

A widely used Integrated Urban Water Management (IUWM) approach is the Water-Sensitive Urban Design. This approach to urban planning and design originated and was applied in Australia. It aims to integrate into

urban design the various disciplines of engineering and environmental sciences associated with the provision of water services (Wong & Brown 2009).

The Water-Sensitive Urban Design (WSUD) and other IUWM applications have included Nature-Based Solutions (NBS) in the design of water systems. NBS have been emerging as sustainable solutions that contribute to urban resilience while addressing climate change challenges in the water sector. NBS provide an umbrella concept for other nature-based approaches, such as green infrastructures and forest landscape restoration. NBS can be defined as living solutions inspired by, continuously supported by, and using nature, which are designed to address several societal challenges from a resource-efficient perspective and to provide simultaneously economic and environmental benefits (European Commission 2015).

The NBS concept goes beyond the traditional biodiversity conservation and management principles. It focuses on its relevance to social co-benefits, such as human well-being, socio-economic development, and governance principles (Eggermont *et al.* 2015). NBS may also contribute to the maintenance, enhancement, and restoration of biodiversity and ecosystems in urban areas while addressing societal challenges and promoting sustainable and resilient urbanization (Wendling *et al.* 2018). Regarding urban water drainage, some examples of NBS are infiltration basins, green roofs, vegetated swales, infiltration trenches, or porous pavements.

The importance of NBS to address water availability and management in urban areas has been highlighted by UNESCO (2018) and also by the European Commission (EC). NBS are a crucial component in the EU policy strategy for Re-Naturing cities, given their ability to address multiple societal challenges (European Commission 2015). Regarding its direct contribution to urban water management, NBS assessment should consider not only the infrastructure capability to deal with acute shocks (e.g. floods) but also the continuous stresses occurring over longer time scales (e.g. ground water level changes due to climate change) (UNESCO 2018).

In the last years, NBS have been positioned as solutions for enhancing urban resilience in the face of the social challenges associated with climate change and urbanization (Sarabi *et al.* 2019). However, recent studies highlight that the adoption of the NBS concept and its integration into urban policies, planning, and development has been limited (Bush and Doyon 2019; Sarabi *et al.* 2019; Snep *et al.* 2020; Tyllianakis *et al.* 2022). Despite the recognized opportunities and benefits of city re-greening, the systematic NBS operationalization and implementation is still an unsolved challenge. This is due to the lack of tools to determine their long-term value and to quantify the NBS contribution to urban resilience. As mentioned by Lehmann (2021), the integration of NBS as a strategy for the city's urban planning would make it possible to strengthen urban resilience and slow down the decline in biodiversity. The systematic assessment of the NBS implementation in cities and their contribution to urban resilience by urban planners and decision-makers is a current need. In line with this, analysing the requirements to assess the NBS contribution to urban resilience and the capabilities of the existing assessment framework is an essential step forward.

The main objectives of the present paper are to (i) address the required resilience attributes for a comprehensive assessment of urban resilience, (ii) identify the main NBS aspects and concerns for assessing the NBS contribution to urban resilience; and (iii) analyse the main existing assessment frameworks for urban resilience and NBS and the evaluation of the NBS contribution within every framework. Accordingly, the key components are analysed to assist urban planners in the selection and application of the most suitable framework, namely, the assessment scope and structure, the proposed metrics, and the feasibility of application.

Section 2 analyses the several resilience dimensions and presents the more relevant projects on the topic and the existing resilience assessment frameworks (RAFs). Section 3 analyses the role of the NBS umbrella concept and its contribution to urban resilience, the main projects, and the existing NBS assessment proposals, namely those related to the water cycle. In the discussion section, a critical analysis is presented, identifying the resilience attributes and the relevant NBS aspects and existing gaps, focused on NBS contribution to urban resilience.

The main novelty corresponds to, namely, (i) the identification of the main resilience *attributes* for a comprehensive assessment of urban resilience and the main NBS *aspects* and *concerns* required to assess the contribution of these solutions to urban resilience; (ii) the systematic characterization of the main RAF and the existing NBS assessment proposals. Moreover, this systematic characterization aims to assist in the selection and application of the most suitable framework.

2. MATERIAL AND METHOD

Figure 1 presents a flow chart of the process for collecting information and performing its analysis in the study, identifying also the specific objectives, required information, and research results. The main RAF at the urban

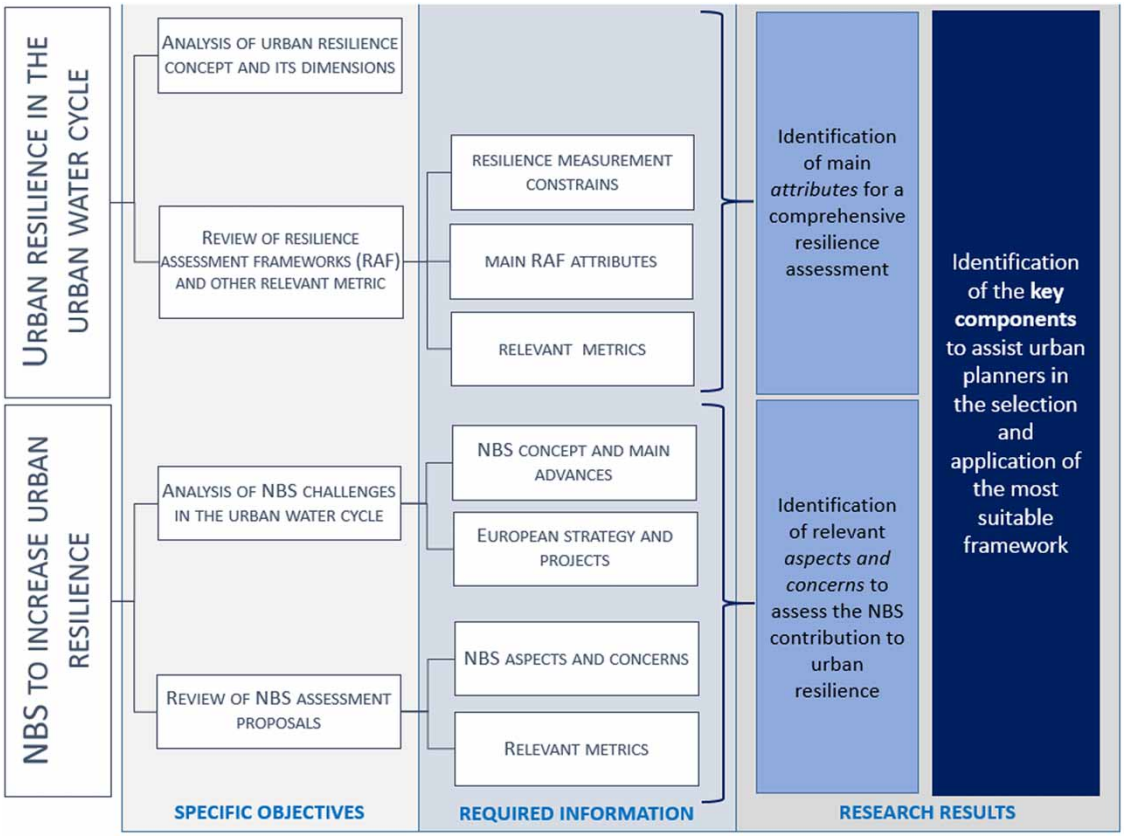


Figure 1 | Methodology for collecting information and its analysis.

scale and the existing NBS assessment proposals were analysed based on a set of predefined key components. For assisting urban planners and decision-makers in the selection and application of the most suitable framework, the adopted key components were (i) assessment scope and structure; (ii) proposed metrics; and (iii) feasibility of application.

3. RESILIENCE AND THE URBAN WATER CYCLE

3.1. Urban resilience dimensions

Resilience emerged as an interesting perspective on cities, often theorized as highly complex adaptive systems (Meerow *et al.* 2016; Van der Jagt *et al.* 2019; Cardoso *et al.* 2020). In the urban water cycle, the evolution of the drainage systems followed the evolution of the resilience concept. First, from one single point of view (e.g. economic or social resilience), and nowadays a more inclusive definition, encompassing the multiple dimensions of urban resilience.

Urban resilience aims to integrate the social, economic, governance, and environmental components, which before were analysed separately, as the four main dimensions that contribute to resilience. A resilient city must have the capacity to absorb, recover, and prepare for future shocks, promoting sustainable development, well-being, and inclusive growth (Sayaas 2016). Cities should adopt social and ecological approaches, including ecological and social feedback, to improve urban resilience (Calderón-Contreras & Quiroz-Rosas 2017). Table 1 presents several resilience concepts, considering different research perspectives, that are considered the main dimensions of urban resilience.

In the global context, several organizations from multiple sectors (e.g. public and private) have developed programmes and projects focused on sustainable development, city resilience, and climate change. Involving multidisciplinary organizations and actors is a common point in the various agendas for urban development. Resilience, as a contribution to urban sustainability, attracts a wide variety of stakeholders at the global, regional, and local levels (UN-Habitat 2017; Sellberg *et al.* 2018). Organizations with high relevance such as the EC, the United Nations, and the Rockefeller Foundation are involved in numerous collaborations and projects focused on

Table 1 | Resilience concepts adopted as urban resilience dimensions

Resilience	Definition	Key-properties	Reference
Organizational	Inherent ability to keep or recover a steady-state, thereby allowing to continue normal operations after a disruptive event or in the presence of continuous stress.	Recovery	Sheffi (2005), in Hosseini *et al.* (2016)
Economic	Ability of the system to withstand either market or environmental shocks without losing the capacity to allocate resources efficiently.	Adaptationcsbarline Persistence	Francis & Bekera (2014)
Ecological	Ability of the system to absorb a disturbance, persist in its functions, and adapt.	Absorptioncsbarline Persistencecsbarline Adaptation	Davoudi *et al.* (2012)
Social	Ability of groups or communities to cope with external stresses and disturbances as a result of social, political, and environmental change.	Adaptation	Hosseini *et al.* (2016)

urban resilience. In this complex network, organizations such as the OECD, the World Bank, and the International Organization for Standardization (ISO) are also participating, among others. Moreover, two ISO technical commissions, namely, the 'ISO/TC 268 for Sustainable Cities and Communities' and 'ISO/TC 292 for Security and Resilience', are working on sustainability and resilience standards for cities.

Overall, urban resilience can be understood as a city's ability to absorb disturbances, learn from the past, adapt, transform, and prepare for the future (Sayaas 2016). In this light, addressing different urban scales (from a single building, neighbourhood, or the whole city), contexts (regarding previous resilience maturity and the available information in a city), and time frames (from acute shocks to continuous or chronic stresses) is essential for a better understanding of the complexity of urban resilience. Droughts, floods, and heat waves are the main common stress shocks that cities must be prepared for (IPCC 2022). Regarding the continuous stresses, which occur over a longer time scale, groundwater level changes or the decrease of annual rainfall due to climate change are some examples.

3.2. Resilience metrics for cities

Resilience has to be tangible for cities. Cities that understand and measure resilience are more capable of identifying adequate strategies and of prioritizing investments with resilience as a focus. Today, a large number of tools and models for assessing some aspects of resilience, based on metrics such as parameters, indexes, or metrics, have been developed. Nevertheless, existing metrics are often not standardized, comparable over time or across cities (ISO 2014), or are not associated with reference values. Moreover, the risk, cost, and performance analysis, recommended for service performance evaluation in the European Standard EN752:2008 (CEN 2008), is usually not ensured, focusing most metrics mainly on the performance dimension.

A performance assessment framework is an adequate base for the diagnosis of the current situation of a city, as well as for the selection of solutions to the identified problems, aiming at resilience improvement. In line with this, the identification of metrics and their respective reference values is essential for comparing cites and evaluating their evolution over time.

A comprehensive assessment of urban resilience should consider specific attributes (e.g., using qualitative and quantitative metrics or defining reference values), allowing to identify main challenges and consolidate aspects in the city and evaluate the resilience development over time. In the present study, resilience attributes are understood as the essential characteristics to be considered in a RAF for a comprehensive assessment of urban resilience, which will be analysed and identified throughout the manuscript. Another example of an attribute might be considering both subjective and objective information.

Resilience is by nature dependent on the specific context. In this sense, cities need to consider their own set of metrics, depending on their major concerns and most probable scenarios, and which shocks and stresses require further exploration in their respective context. The OECD highlights the need for each city to adopt its own metrics, taking into consideration the local characteristics and challenges (Sayaas 2016). Despite the efforts carried out by researchers and several organizations, there is still a significant gap regarding resilience operationalization from theory to practice (Marana *et al.* 2019).

In line with this, several frameworks to assess urban resilience were developed by international organizations and research institutions, such as the Disaster Resilience Scorecard for cities (UNISDR 2015), the ARUP and Rockefeller City Resilience Framework (100 Resilience Cities project, ARUP 2014), and the U.S. EPA Resilience Assessment Framework (U.S. EPA 2017), among others. Much focus is placed on environmental drivers, natural, and manmade hazards, mainly because the discussion on resilience itself started as resilience to natural disasters and climate change.

On a global scale, in the context of the New Agenda, the UNHABITAT III metrics framework aligns with the city level for each SDG (UN-Habitat 2017; Wendling *et al.* 2018). For the urban resilience SDG, a set of metrics was proposed along with a specific target. It should be noticed that reference values or targets for each indicator have not been proposed and the global application is not yet feasible due to the lack of clarity in definitions for the metrics (Wendling *et al.* 2018). Likewise, the technical commission ISO/TC 268 proposed a set of metrics for a holistic and integrated approach to sustainable development and resilience in the ISO 37120:2018, including metrics for city services and quality of life, for smart cities and resilient cities (ISO 2014). Aligned with the UNHABITAT III metrics framework and the SDG, the City Resilience Profiling Tool (CRPT) was proposed (UN-Habitat 2018). The CRPT allows for the identification of strengths, weaknesses, capacities, and vulnerabilities in a city and defines actions for enhancing its resilience and sustainability. Initially, this self-assessment tool was developed in the context of the City Resilience Profiling Programme based on the Millennium Development Goals. Afterward, the CRPT was fully updated to incorporate mandates and resolutions of the SDG and the New Agenda, among others (Diaz-Sarachaga & Jato-Espino 2019). It should be noticed that the proposed metrics are not available for public access, representing an important disadvantage for its application.

From the point of view of risk management, the Local Government Self-Assessment Tool (LG-SAT) was developed by the UNISDR in the Making Cities Resilient Campaign. This tool allows calculating a set of metrics focused on 'Ten Essentials for Making Cities Resilient', where risk is a major concern (Johnson & Blackburn 2014). More recently, the Disaster Resilience Scorecard for cities was developed and structured around these 10 essential aspects, updated to support the implementation of the Sendai Framework for Disaster Risk Reduction: 2015–2030 (UNISDR 2015). Moreover, the City's Resilience Index (CRI) was developed in the 100 Resilient Cities project. This index enables cities to assess and monitor the multiple factors that contribute to their resilience, providing an accessible tool to assess their resilience and develop guidelines for urban planning, practices, and investments (ARUP 2019). The UNISDR Scorecard and the CRI consider variables for measuring resilience at the city scale, helping to understand gaps and challenges in risk reduction and providing means to assess and monitor how a city is progressing towards resilience (OECD 2016).

With the main focus on climate change, the United States Environmental Protection Agency (U.S. EPA) developed a climate resilience assessment system to capture changes in resilience over time (U.S. EPA 2017). This system includes a set of qualitative and quantitative metrics where weight is applied depending on its relevance for resilience. Within the EC, a comprehensive resilience assessment framework (RESCCUE RAF) was proposed, with a focus on water at the city, service, and infrastructure level (Cardoso *et al.* 2020). This RAF analyses city management, the interdependencies between city services and infrastructure, and the structural and non-structural implemented and planned solutions. The RAF allows highlighting where the cities, and respective urban services, are today concerning resilience to climate change, and to identify critical aspects, based on the assessment of the reference situation and future climate change scenarios.

Table 2 presents the main available RAF related to the water sector, identifying the more relevant information, the RAF structure, the key information, and the approach for NBS assessment adopted. Moreover, Table 3 provides a systematic characterization of the RAF, identifying the key components considered in every assessment approach, regarding the scope and structure, metrics, and application.

The analysis of NBS contribution assessment across the explored RAF allows for identifying how the NBS assessment is considered in the RAF. As can be observed, the NBS contribution to urban resilience is mostly indirectly assessed in the RAF; consequently, it is slightly considered or even not considered. A holistic assessment of the NBS contribution to urban resilience, considering their multiple benefits and synergies, is not ensured by any RAF, representing a significant shortcoming.

Cities need metrics to evaluate their performance (ISO 2014). At present, there is a high interest to harmonize the several resilience metrics through the development of generic structures that can be adapted to each city. On the other hand, the lack of quantitative information, and the unfeasibility to quantify certain components of urban

Table 2 | Main available urban RAFs related to the water sector

RAFs	Description	Structure	Key information	NBS assessment
ARUP and Rockefeller City Resilience Framework (ARUP 2014, 2016)	• Focuses on risk management. • Enables cities to assess resilience at a city scale. • Allows identifying strengths, weaknesses, and priorities for action.	• Structured in 4 categories and 12 goals, which are complemented by resilience qualities. • Proposes a final assessment, CRI. • Considered categories: health and well-being, economy and society, infrastructure and environment, leadership and strategy. • Considered goals: minimal human vulnerability; diverse livelihood and employment; effective safeguards to human health and life; collective identity and community support; comprehensive security and rule of law; sustainable economy; reduced exposure and fragility; effective provision of critical services; reliable mobility and communications; effective leadership and management; empowered stakeholders; integrated development planning.	• Allows comparing the city's resilience over time. • Does not allow for comparison between cities. • Integrates qualitative and quantitative metrics. • Includes a final assessment. • Proposed metrics are not available for public access. • Evaluates some NBS-specific aspects (not a NBS comprehensive assessment).	• A specific category or goal focused on assessing the NBS contribution to urban resilience is not included. • Some proposed metrics assess NBS aspects. • Example of NBS-related proposed metric: ○ 'Effectively managed and protective ecosystems (NA)' metric in the reduced exposure and fragility goal. • *Note*: Metrics are no access publicly, so, metric units are unknown.
Disaster Resilience scorecard for cities (UNISDR 2015)	• Focuses on disaster risk reduction. • Allows local governments to monitor and review progress in the implementation of the Sendai Framework for Disaster Risk Reduction 2015–2030.	• Structured around Ten Essentials for Making Cities Resilient. • Proposes two assessment levels: preliminary and detailed level. • Considers three dimensions: governance and financial capacity; planning and disaster preparation; disaster response and post-event recovery. • The Ten Essentials are: organize for resilience; identify, understand and use current and future risk scenarios; strengthen financial capacity for resilience; pursue resilient urban development; safeguard natural buffers to enhance strengthen the institutional capacity for resilience; strengthen the institutional capacity for resilience; understand and strengthen societal	• Does not allow for comparison of cities over time or between cities. • Integrates qualitative and quantitative metrics. • Proposes reference values for the metrics. • Scores are not standardized. • Proposed metrics are available for public access. • Assesses acute shocks and continuous events. • Evaluates some NBS-specific aspects (not a NBS comprehensive assessment).	• A specific Dimension or Essential focused on assessing the NBS contribution to urban resilience is not included. • Some proposed metrics assess NBS aspects. • Example of NBS-related proposed metric: ○ 'Integration of green and blue infrastructure into city policy and projects (–)' metric in the Safeguard Natural Buffers to Enhance the Protective Functions Offered by Natural Ecosystems Essential (Essential 05).

(*Continued*.)

Table 2 | Continued

RAFs	Description	Structure	Key information	NBS assessment
		capacity for resilience; increase infrastructure resilience; ensure effective disaster response; expedite recovery and build back better.		
RESCCUE Resilience Assessment Framework (Cardoso *et al.* 2020)	• Focuses on climate change. • Focused on the water cycle, at the city, services, and infrastructure level. • Evaluates and identifies opportunities to improve the city's resilience.	• Structured into objectives, criteria, and metrics. • Metrics assign a development level to each criterion, supporting the setup of clear targets and the monitoring of the results. • Proposes three assessment levels: essential, complementary, and comprehensive • Includes a city profile and a service profile. • Based on UNHABITAT resilience dimensions: organizational (focus on the city, governance relations, and stakeholders), spatial (focus on urban space and environment), functional (focus on the strategic services in the city), physical dimension (focus on the assets and infrastructures).	• Allows comparing cities or the same city over time. • Integrates qualitative and quantitative metrics. • Proposes reference values for the metrics. • Assesses acute shocks and continuous events. • Evaluates some NBS-specific aspects (not a NBS comprehensive assessment).	• A specific Objective or Criteria focused on assessing the NBS contribution to urban resilience is not included. • Some proposed metrics assess NBS aspects. • Example of NBS-related proposed metric: ○ 'Availability of green and blue infrastructures (m^2/inhabitant)' metric in the provision of protective infrastructures and ecosystems Objective.
UNHABITAT III SDG 11: Make cities and human settlements inclusive, safe, resilient and sustainable (United Nations General Assembly 2017)	• Focuses on sustainable development. • Proposes a set of metrics and targets for SDG 11.	• Structured in SDG, targets, and indicators. • The SDG 11 is desegregated in seven target, which are detailed for the horizon year 2030, from the 2030 Agenda for Sustainable Development. • For every target, some metrics are proposed, without a clear definition of the metrics.	• Does not allow for comparison between cities. • Does not provide a clear definition of the metrics. • Indicators do not provide a judgement of the results, a threshold, or a target numerical value. • Does not assess acute shocks and continuous events. • Does not evaluate any NBS aspect.	• A specific Objective or Criteria focused on assessing the NBS contribution to urban resilience is not included. • Proposed metrics do not assess any NBS aspects.
UNHABITAT City Resilience Profiling Tool	• Focused on sustainable development	• Considers five critical and interdependent dimensions, common to	• Assesses acute shocks and	• Not possible to be analysed due to metrics

(*Continued.*)

Table 2 | Continued

RAFs	Description	Structure	Key information	NBS assessment
(UN-Habitat 2018)	(natural disasters and manmade threats). • Provides a transversal diagnosis and pathway to resilience-based sustainable urban development.	all human settlements, namely, Spatial, Organizational, Physical, Functional, and Time abilities. • Data collection is divided into four SETs that, collectively, provide an in-depth picture of the city and its stakeholders and provide the basis of the Actions for Resilience. • There is no specific public information regarding the resilience assessment.	continuous events. • It was not possible to analyse the main key information.	definition is not public access.
U.S. EPA resilience assessment framework (U.S. EPA 2017)	• Focuses on climate resilience. • Establishes a base for metrics needed for assessing resilience and its evolution. • Considers exposure, sensitivity, and response capacity of urban vulnerability, across sectors.	• Indicators are structured around the following eight municipal management sectors: water, energy, transportation, people, economy, land use and land cover, natural environment, and telecommunications. • Includes qualitative and quantitative indicators, which are weighted depending on the resilience relevance.	• Allows comparing the city's resilience over time. • Not allow comparing between cities. • The RAF does not provide a clear definition of the metrics. • Proposes qualitative and quantitative metrics. • Assesses acute shocks and continuous events. • Evaluates some NBS-specific aspects (not a NBS comprehensive assessment).	• A specific management sector focused on assessing the NBS contribution to urban resilience is not included. • Some proposed metrics assess NBS aspects. • Example of NBS-related proposed metric: ○ 'Does zoning encourage green roofs or other practices that reduce urban heat? (–)' in the municipal sector Land use and Land cover.
ISO 37120:2014 (ISO 2014)	• Focused on sustainable development, regarding city services and quality of life. • Allows monitoring city progress performance, measuring the city services performance and life quality over time.	• Indicators are divided into core indicators (required) and supporting indicators (recommended). • Includes profile indicators (basic statistics and background information). • The indicators are structured around themes. • The 17 themes are: economy, education, energy, environment, finance, fire and	• Does not allow for comparison of cities over time or between cities. • Proposes only an indicative list of some indicators. • Indicators do not provide a judgement of the results, a threshold, or a target numerical value.	• A specific Objective or Criteria focused on assessing the NBS contribution to urban resilience is not included. • Proposed metrics do not assess any NBS aspects.

(*Continued.*)

Table 2 | Continued

RAFs	Description	Structure	Key information	NBS assessment
		emergency response, governance, health, recreation, safety, shelter, solid waste, telecommunication and innovation, transportation, urban planning, wastewater, water and sanitation.	• Metrics are available for public access. • Does not assess acute shocks and continuous events. • Does not evaluate any NBS aspect.	

resilience, implies the need for qualitative metrics. According to the EPA, developing a methodology that integrates objective and subjective information on a single scale represents a critical challenge (U.S. EPA 2017).

In addition, many studies have proposed several metrics focused on the assessment of a specific resilience capability (Diao *et al.* 2016; Platt *et al.* 2016; Gonzales & Ajami 2017; Barreiro *et al.* 2021). A common practice in resilience metrics is the measurement of specific characteristics of the system (Milman & Short 2008; Mugume *et al.* 2015) or of impacts and sectors that contribute to resilience (Sayaas 2016). For instance, focused on how communities can make more resilient to disasters, the Community Disaster Resilience Index was proposed by Yoon *et al.* (2016). The index combines the human, social, economic, institutional, physical, and environmental dimensions. These are assessed by quantitative metrics, providing an overall index score to the local municipality. Communities should be prepared to respond to the occurrence of simultaneous multiple hazards, to reduce related impacts from the disaster, and to minimize recovery periods afterward (Yoon *et al.* 2016; Cardoso *et al.* 2020). Another example of aggregated index corresponds to the integrated urban resilience index focused on flooding occurrence (e.g. volume overflowed, flooded area, and building affected), proposed by Barreiro *et al.* (2021).

With a special focus on flooding occurrence, a scalable flood resilience index for measuring climate change adaptation in urban systems was proposed by Leandro *et al.* (2020). This index highlights the importance of considering different urban scales for assessing resilience from the city or district to the household level. At the household level, the index is focused on the physical, coal, and economic dimensions. At the city or district scale, the index considers five main dimensions, namely, natural, physical, economic, social, and institutional.

Moreover, even though urban resilience is not the direct focus, several assessment approaches and indexes, which examine several aspects essential for assessing urban resilience, were developed. One example is the City Blueprints project's metrics system, aiming to assess the water cycle and the sustainability of water resource management (Leeuwen & Frijns 2012). Likewise, the Water-Sensitive Cities Index (WSCI) was proposed, grounded in three pillars, namely, (i) cities as water-sensitive communities and networks; (ii) cities as water catchments; and (iii) cities as ecosystem service providers (Platt *et al.* 2016).

Operationalizing the resilience concept by considering specific cities or urban service constraints, regarding the specific political, economic, geographical, climatic, and cultural context, is a current need (Cardoso *et al* 2020). In response, the European Resilience Management Guidelines and the Resilience Maturity Model were developed, with a focus on evaluating the implementation progress of resilience policies (Marana *et al.* 2019). Seeking to classify policies and the city's stakeholders at different stages, several metrics were proposed. These identify positive behaviours and support the continuous development of resilience-building policies.

4. NBS TO INCREASE URBAN RESILIENCE

4.1. The challenges of NBS in the urban water cycle

NBS are essential to achieve the goals of the Paris Agreement on Climate Change (UN-Climate Action 2019). The NBS potential to face climate change and other existing challenges is being analysed. The goals are to promote knowledge exchange and experience sharing, while enhancing the regulatory instruments, the greening transition, and upscaling local-scale solutions. Setting of NBS's implementation across different and interconnected scales of application is also a goal. Recently, the NBS's importance to deal with climate change was also recognized by the European Water Association as one of the current challenges for water management in Europe (EWA 2020).

Table 3 | Systematic characterization of the main RAF related to water sector regarding the key components

	Scope and structure				Metrics							Application				
RAF	**Urban scale**	**Urban resilience dimensions**	**Objectives and criteria**	**Context information**	**Public access**	**Clear definition**	**Qualitative and quantitative information**	**Performance, risk and cost analysis**	**Reference values**	**Final assessment**	**Resilience capabilities**	**Assessment levels**	**Evolution over time**	**City benchmarking**	**Acute shocks and continuous events**	**NBS assessment and benchmarking**
ARUP and Rockefeller City Resilience Framework (ARUP 2014, 2016)	✓	✓	Partially	X	X	–	–	–	✓	✓	✓	X	✓	X	–	Some NBS aspects
Disaster Resilience scorecard for cities (UNISDR 2015)	✓	✓	Partially	X	✓	✓	✓	✓	X	X	X	X	X	X	✓	Some NBS aspects
RESCCUE Resilience Assessment Framework (Cardoso *et al.* 2020)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	Some NBS aspects
UNHABITAT III. SDG 11: Sustainable communities and cities (United Nations General Assembly, 2017)	✓	✓	Partially	X	✓	X	X	X	X	X	X	X	X	X	X	X
UNHABITAT City resilience Profiling Tool	✓	✓	X	✓	X	–	–	–	–	–	–	–	–	–	✓	–
U.S. EPA resilience assessment framework (RAF) (U.S. EPA 2017)	✓	✓	X	X	✓	X	✓	✓	✓	X	X	X	✓	X	✓	Some NBS aspects
ISO 37120:2014 (ISO 2014)	✓	✓	X	✓	✓	✓	✓	✓	X	X	X	X	X	X	X	X

✓ – Considered in the RAF; X – Not considered in the RAF; (-) – Not possible to be analysed due to documents are not public access.

Evaluating and enhancing urban resilience in the water cycle is a crucial step toward more sustainable urban water management (Diao *et al.* 2016). In this sense, NBS have emerged as sustainable solutions to contribute to city resilience. While addressing the climate change challenges, NBS are an essential element for stormwater management (Oral *et al.* 2020).

In essence, NBS correspond to actions inspired and supported by nature that encompass other closely ecosystem-based approaches (Potschin *et al.* 2014). NBS directly link with concepts such as bio-economy, green infrastructures, and natural capital, among others (Balian *et al.* 2014; Eggermont *et al.* 2015). With a greater focus on the environmental dimension, the International Union for Conservation of Nature (IUCN) describes NBS as actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (Cohen-Shacham *et al.* 2016). Upscaling NBS will be central to achieving the 2030 Agenda for Sustainable Development (UNESCO 2018).

The EC's policy agenda for research and innovation in the field of 'NBS and Re-Naturing Cities' aims to place the EC as a leader in 'Innovation with Nature' for more sustainable and resilient societies (European Commission 2015). The EC defines NBS as actions that aim to help societies address a variety of environmental, social, and economic challenges sustainably. NBS involves actions for the conservation or rehabilitation of natural ecosystems, as well as the improvement or creation of natural processes in modified or artificial ecosystems (UNESCO 2018). Some examples of NBS for stormwater management are infiltration basins, green roofs, constructed wetlands, or swales with vegetation cover, among others. There are several nature-based opportunities for adaptation and mitigation of climate change, both through the implementation of NBS and also through the establishment of synergies between different sectors (European Commission 2015).

The EC highlights the importance to develop integrated and holistic nature-based approaches to adapt and mitigate climate change. These approaches ought to be applicable to different sectors and challenges, such as the integration of grey, green, and blue infrastructures. NBS can offer synergies to reduce multiple risks, such as droughts and floods, and meet the objectives of different regulations in force in Europe. In this way, NBS can play an important role in city resilience, in particular concerning stormwater management. Adequate monitoring and performance assessment of these solutions may highlight their added value and their input to city resilience.

The European Research and Development (R&D) Programme promotes a large number of projects related to NBS. These aim to increase knowledge and to create technical, political, and other conditions for cities renaturalization. These R&D projects will analyse several objectives and perspectives, such as the improvement of regulatory instruments, the increase of natural capital through NBS, or the capacity to obtain a more sustainable and resilient urban ecosystem. One of these projects is the ThinkNature platform that includes a set of projects focused on NBS (EKLIPSE, Inspiration, NAIAD, Nature4Cities, Naturvation, among others). This platform aims to promote NBS in research, policy, non-governmental organizations, and business areas. This will be accomplished by improving regulatory instruments, sharing business practices, and demonstrating the long-term value of these solutions. Table 4 presents a summary of some undergoing European NBS projects in the framework of the EC policy agenda for R&D on NBS and Re-Naturing Cities.

In addition, the NBS application and concerns from several perspectives have been explored across several studies, focused mainly on planning and design issues (Liquete *et al.* 2016; Martínez 2016; Lafortezza *et al.* 2018), political perspective (Maes & Jacobs 2017), social changes, and health benefits (Cariñanos *et al.* 2017), and the identification of barriers and opportunities for NBS implementation (Rizvi *et al.* 2015; Kabisch *et al.* 2016; Faivre *et al.* 2017). This set of studies allowed to conclude and highlight the need to compile more information on NBS to create an evidence base to promote the implementation of this type of solution. The NBS practical implementation may be challenging due to the existing differences from traditional systems (Blackburn *et al.* 2021). In the context of urban resilience, some NBS studies were carried out focusing on some Ecosystem Services (ES) enhancement, or specific challenges. Examples of these challenges are urban heat island mitigation (Zölch *et al.* 2016; Panno *et al.* 2017), air quality improvement, climate mitigation and adaptation (Naumann *et al.* 2014; Calliari *et al.* 2019), and water quality improvement (Hancz *et al.* 2018; Lim *et al.* 2021), among others.

Particularly for stormwater management, the NBS regulating role for urban surface runoff (Zölch *et al.* 2016) and the benefits of NBS for water pollution control (Liquete *et al.* 2016) were analysed. To date, the NBS capabilities to build resilience have only been analysed from the standpoint of addressing climate shocks or increasing

Table 4 | Examples of projects, focused on urban areas, in the EC policy agenda for R&D on NBS and Re-Naturing Cities

Project (Reference)	Main objectives	Main concerns
ThinkNature (Somarakis *et al.* 2019)	• This platform is an umbrella for all projects on NBS funded by the EC H2020 program. • The objective is to support the understanding and promotion of NBS.	• Knowledge sharing and communication. • Improvement of regulatory instruments and share best commercial practices. • Fostering collaboration at local, regional, national, and EU levels. • Development of synergy between NBS projects.
EKLIPSE (Raymond *et al.* 2017b)	• Aims to create a way of knowing, networking, and learning about biodiversity and ES. • Aims to devise an impact evaluation framework that can guides the design, development, implementation, and assessment of NBS projects in urban contexts.	• Benefits for ES and biodiversity. • Assessment of NBS projects at the level of the infrastructure. • Infrastructure design and implementation. • Monitoring and maintenance processes.
TURAS (Collier 2011)	• Aims to bring urban communities and businesses together with local authorities and researchers. • Aims to co-create working links with communities at the centre.	• New technical solutions for a more sustainable and resilient urban area. • Spatial and land use planning. • Infrastructure management, implementation, and design. • Communities sharing.
OpenNESS (Braat *et al.* 2015)	• Aims to translate the concepts of Natural Capital and ES into operational frameworks. • Provide solutions for integrating ES into land, water, and urban management and decision-making.	• Spatial and land use planning. • Existing relation between NBS, ES, and Natural Capital. • Infrastructure's implementation and design. • Improvement of regulatory instruments.
Connecting Nature (Dushkova & Haase 2020)	• Aims to measure the impact NBS projects on climate change adaptation, health and well-being, social cohesion, and sustainable economic development in participating cities. • Create a community of cities.	• Climate change, health and well-being, social cohesion, and economic development. • Spatial and land use planning. • NBS monitoring and maintenance processes. • Knowledge sharing, capacity building, and communication.
UNALAB (Eisenberg & Polcher 2019)	• Aims to use the experience of partner cities • Create easy-to-use manuals, models, and tools • Guide cities in the development and implementation of NBS.	• Spatial and land use planning. • Knowledge sharing and communication. • Improvement of regulatory instruments.
URBAN GreenUp (O'Sullivan *et al.* 2020)	• Replicate the development of Re-Naturing Urban Plans in several partner cities • Disseminate the use of innovative NBS.	• Climate change, air quality, and water management. • Spatial and land use planning. • Service and infrastructure management. • Performance under normal conditions
Nature4Cities (Nature4Cities 2019)	• Create a comprehensive reference platform for NBS. • Offer technical solutions, methods, and tools for urban planning decision-making.	• Technical solutions, methods, and tools. • Spatial and land use planning. • Knowledge sharing and communication.

(*Continued.*)

Table 4 | Continued

Project (Reference)	Main objectives	Main concerns
GREEN SURGE (Hansen *et al.* 2008)	• Aims to identify, develop and test ways of linking green spaces, biodiversity, people, and the green economy.	• Spatial and urban decision planning. • Benefits for biodiversity, people, and green economy. • Climate and demographic changes.
NATURVATION (Davis *et al.* 2018)	• Realize the potential of NBS to respond to urban sustainability challenges. • Examine how innovation can be fostered. • Working with communities and stakeholders.	• Benefit for biodiversity, Natural Capital and ES. • Knowledge sharing and communication. • Improvement of regulatory instruments.

ES in urban areas (UNEP 2014; Staddon *et al.* 2018). The current global situation encourages experts to create an evidence base that helps to understand the NBS contribution to urban resilience.

4.2. NBS assessment

Researchers and practitioners need to recognize the importance of the assessment process that includes qualification, quantification, and standardization (Raymond *et al.* 2017a). Metrics help to systematically evaluate NBS projects' implementation, compare between projects, and follow along with a system over time. The study of metrics to assess NBS contribution to urban resilience is still in an early stage.

UNESCO highlighted the existence of a lack of awareness, communication, and knowledge (at all levels, from communities to regional planners and national policymakers), of what NBS can offer (UNESCO 2018). To promote the use of NBS to increase urban resilience, tools that demonstrate the value of this type of solution over the long-term are required. Kabisch *et al.* (2016) analysed the existing gaps in methods to evaluate NBS, highlighting the potential use of metrics. Among the existing barriers, several authors underline the lack of (i) evidence base of the social, environmental, and economic capabilities; (ii) information on NBS efficiency; (iii) technical knowledge for integrating NBS in traditional structures; (vi) information on legal instruments and requirements; and (v) processes for stakeholder involvement (Rizvi *et al.* 2015; Kabisch *et al.* 2016; Calliari *et al.* 2019; Wihlborg *et al.* 2019).

Despite the growing attention NBS have been receiving, only four NBS assessment proposals were published to date. These NBS assessment proposals are focused on climate change and social co-benefits (Kabisch *et al.* 2016), on NBS environmental, economic, and social challenges (Raymond *et al.* 2017a), on NBS urban challenges (Nature4Cities 2019), and the NBS contribution to urban resilience, focused on stormwater management and control. In essence, only the RAF for NBS developed by Beceiro *et al.* (2020) is focused on urban resilience. Even though most referred NBS assessment frameworks are not directly focused on urban resilience, they may contribute to a specific assessment framework focused on NBS contribution to urban resilience.

From the point of view of NBS effectiveness, a group of 34 experts from research, municipalities, policy, and society proposed examples of potential metrics to assess the climate change adaptation and mitigation, and associated co-benefits. This was done in the 'NBS to climate change mitigation and adaptation in urban areas' workshop carried out in the context of the BIOCLIM project (Kabisch *et al.* 2016). The metrics are structured around four dimensions, namely, integrated environmental performance, health and well-being, citizen involvement, and transferability and monitoring. The proposed metrics are only examples, without a clear definition and methodology. However, some of them, such as 'decrease in air pollution in temperature and CO_2 emissions' or 'number and share of people with access to a green or blue space', might present a suitable base for NBS assessment. Several dimensions that are critical for an adequate NBS assessment, such as governance or NBS infrastructure performance, were not, or partially, considered. The proposed indicator should be taken as the first approach to a detailed NBS assessment, particularly related to health, well-being, and citizen engagement aspects. Table 5 presents some examples of metrics defined in the NBS assessment proposals.

A more comprehensive NBS approach was analysed by the EKLIPSE Expert Working Group on NBS to Promote Climate Resilience in Urban Areas. The EKLIPSE project proposed an impact evaluation framework to support the planning and evaluation of NBS projects, focusing on providing information about environmental, economic, and

Table 5 | Some examples of metrics considered in the NBS assessment proposals

NBS assessment proposals (references)	Metrics	Reference
Climate change and adaptation metrics system	• Decrease in air pollution (%) • Increase in species number (%) • Number of people using green space (*n*)	Kabisch *et al.* (2016)
EKLIPSE impact evaluation framework	• Decrease in mean or peak daytime local temperatures (°C) • Energy and carbon savings from reduced building energy consumption (kWh/y) • Flood peak reduction (%) • Temperature reduction in urban areas (°C)	Raymond *et al.* (2017a, 2017b)
Nature4Cities integrated performance metrics system	• Potential of areas likely to host biodiversity (–) • Sustainable practices indicator (%) • Normalized Difference Vegetation Index (–) • Connectivity of green spaces (–)	Bouzouidja *et al.* (2021); Nature4Cities (2019)
RAF for NBS	• NBS plan or strategy alignment with ES (–) • NBS financial support to community involvement (–) • Citizens' engagement with NBS (%) • Carbon sequestration and storage (t/ha)	Beceiro *et al.* (2020)

social challenges related to climate resilience. This framework defines actions and proposes a few quantitative and qualitative metrics, considering 10 climate resilience challenges, as well as a range of methods for assessing each indicator (Raymond *et al.* 2017a). It should be noticed that this framework does not provide a clear definition of metrics and reference values. The metrics are examples and not exhaustive. For water management, the authors underline that the metrics should comprise the impacts of runoff, flood risk, water quantity, and water quality.

The Nature4Cities project proposed integrated multiscale and multi-thematic urban performance metrics for assessing urban challenges and NBS. These were focused on climate, environment, resources, social, and economic topics. The classification of challenges is slightly different from the EKLIPSE classification. Most of the challenges in EKLIPSE are linked between them or with sub-challenges in this classification (Nature4Cities 2019). The alignment between the EKLIPSE and the Nature4Cities was a starting point for developing the Nature4Cities proposal. This proposal adapts the EKLIPSE urban challenges, focused on climate resilience, at the urban scale. It should be noticed that this framework, like the EKLIPSEs, does not provide a clear definition of metrics and reference values for assessing NBS impacts. The authors highlight that this NBS assessment approach intends to be a comprehensive book of reference of urban performance metrics for the assessment of urban challenges and NBS. Table 6 presents the alignment between the EKLIPSE and the Nature4Cities assessment proposals.

As observed, the alignment between the EKLIPSE and the Nature4Cities assessment proposals was ensured by the authors. However, some climate resilience concerns, such as the coastal resilience, of the EKLIPSE proposal, were not considered sufficiently relevant for all cities and were not included in the Nature4Cities proposal. Similarly, the Nature4Cities proposal identified the resource efficiency as a relevant urban challenge, although this was not considered relevant for climate resilience in urban areas. The alignment between proposals aimed to facilitate the exchange of information between both initiatives.

With a focus on stormwater management and control, recently, a comprehensive and multidimensional RAF to assess the NBS contribution to urban resilience was developed, driven by specific resilience objectives, assessment criteria, and metrics (Beceiro *et al.* 2020). The resilience objectives defined were governance and stakeholder involvement; economic sustainability; social involvement and co-benefits; environmental resilience; spatial planning; service management; resilience engaged service; infrastructure safety and robustness; infrastructure preparedness; infrastructure dependence and autonomy. The integration of the NBS at the city level and the operation and service of the NBS, with special attention to the hydraulic performance, are assessed in this RAF.

Table 6 | Alignment between the EKLIPSE and the Nature4Cities assessment proposal

Nature4Cities		EKLIPSE
Topics	**Urban challenges**	**Urban challenges**
CLIMATE	1 | Climate issues	1 | Climate mitigation and adaptation
	2 | Water management and quality	2 | Water management
Environment	3 | Air quality	5 | Air/ambient quality
	4 | Biodiversity and urban space	4 | Green space management (including enhancing/conserving urban biodiversity|
	5 | Soil management	6 | Urban regeneration (partially)
Resource	6 | Resource efficiency	This topic is not assessed.
Social	7 | Public health and well-being	9 | Public health and well-being
	8 | Environmental justice and social cohesion	8 | Social justice and social cohesion
	9 | Urban planning and governance	6 | Urban regeneration (partially)
		7 | Participatory planning and governance
Economy	10 | People security	
	11 | Green economy	10 | Potential for new economic opportunities and green jobs
	This topic is not assessed.	3 | Coastal resilience

The relevant governance, environmental, social, and economic concerns and the main aspects of the city (e.g., NBS planning at the city level and public finances), service (e.g., NBS integrated management and service articulation), and infrastructure (e.g., NBS hydraulic performance and NBS water quality) required to assess this contribution are considered in the proposed resilience objectives.

Table 7 presents the main available NBS assessment proposals, identifying the main characteristics, the RAF structure, the key information, and the main focus and assessment constraints. Table 8 presents a systematic characterization of the NBS assessment proposals based on the identified key components, regarding its scope and structure, the proposed metrics, and the feasibility of the application.

5. RESULT AND DISCUSSION

5.1. Relevant attributes

Urban resilience aims to integrate social, economic, governance, and environmental dimensions, which were usually analysed separately, as the main areas that contribute to resilience. In this regard, resilience should be analysed from multiple perspectives, considering not only every dimension but also the different urban systems and the interconnections between them.

The analysis of the main RAF at the urban scale in the water sector allowed identifying the main relevant attributes for a comprehensive assessment of urban resilience, such as identifying resilience objectives and criteria or the need to consider subjective and objective information, allowing to measure urban resilience on one scale.

The main resilience attributes for a comprehensive assessment of urban resilience have been identified, based on the analysis of the urban resilience concept and its dimensions (Table 1), the complexity of resilience measurement, the existing main RAF at the urban scale, and other existing relevant metrics.

In this sense, a RAF needs to (i) propose a multi-dimension methodology that includes subjective and objective information, allowing to measure urban resilience on one scale; (ii) identify resilience objectives and criteria (points of view that allow the evaluation of the objectives); (iii) use qualitative and quantitative metrics addressing performance, cost, and risk; (iv) define reference values that allow metric classification; and (v) identify the urban resilience capabilities associated with the proposed metrics. Moreover, as the metrics are inter-related, it is necessary to understand how they provide comprehensive information on the degree of resilience, enabling to compare a city over time or eventually different cities. Comparing cities is not consensual, as every city has its own specific context, so a different interpretation of the same metric results in two cities may occur. Additionally, there is a need for the RAF to consider and allow the assessment of short- and long-term changes, thus evaluating the impacts related to acute shocks (e.g., heat waves or floods) and to continuous or chronic stresses occurring over longer time scales (e.g., climate change) (U.S. EPA 2017).

Table 7 | Description of the main NBS assessment proposals published to date

Assessment proposal (reference)	Description	Structure	Key information	Focus and assessment constraints
Climate change and adaptation metrics system (Kabisch *et al.* 2016)	• Focuses on assessing the NBS effectiveness for climate change adaptation and mitigation and associated co-benefits. • Helps to understand (i) feasibility and opportunities for enhancing and implementing NBS; (ii) NBS effectiveness; (iii) potential barriers and opportunities.	• Urban resilience is not the focus of the assessment. • Considers the social, environmental, economic, and governance dimension of urban resilience. • Objectives and criteria are not identified. • Proposed metrics are grouped in four areas, namely: (i) urban scale integrated environmental performance; (ii) health and well-being; (iii) transferability and monitoring; (iv) citizens' involvement.	• Proposes only an indicative list of some metrics. • Integrates qualitative and quantitative metrics. • Metrics do not provide a judgement of the results, a threshold, or a target numerical value. • Does not allow for comparing NBS over time or between cities. • Does not allow for assessing the impact related to acute shocks and continuous/chronic events.	• Main focus • Focuses on related health, well-being, and citizen engagement aspects. • Assessment constraints. • Several critical dimensions for an adequate NBS assessment (e.g., governance or infrastructure performance) are slightly considered.
EKLIPSE impact evaluation framework (Raymond *et al.* 2017a, 2017b)	• Focuses on climate resilience and NBS design, development, and implementation. • Establishes a base of metrics to support NBS planning and evaluation of projects, providing information about environmental, economic, and social challenges.	• Urban resilience is not the focus of the assessment. • Proposed metrics are grouped in 10 climate resilience challenges, namely, (1) contribution of NBS to climate resilience; (2) water management; (3) coastal resilience; (4) green space management; (5) air quality; (6) urban regeneration; (7) participatory planning and governance; (8) social justice and social cohesion; (9) public health and well-being; (10) potential for new economic opportunities and green jobs. • For every challenge, examples of metrics for assessing the impact of climate mitigation actions along the macroscale, mesoscale, and microscale are proposed.	• Does not provide a detailed definition of the metrics. • Metrics do not provide a judgement of the results, a threshold, or a target numerical value. • Integrates qualitative and quantitative metrics. • Does not allow for comparing NBS over time or between cities.	• Main focus • Focuses on climate resilience. • Proposes an extensive list of examples of metrics and available methods for assessing each indicator. • Assessment constraints. • Proposed metrics represent the first approach without a clear definition or reference values. • The framework application is not direct. The user has to construct its framework, selecting the impact in each city.

(*Continued.*)

Table 7 | Continued

Assessment proposal (reference)	Description	Structure	Key information	Focus and assessment constraints
Nature4CIties integrated performance metrics system (Nature4Cities 2019; Bouzouidja *et al.* 2021)	• Focuses on climate, environment, resources, social, and economic aspects. • Proposes multiscale and multi-thematic performance metrics for assessing urban challenges and NBS. • Intends to be a comprehensive book of reference of performance metrics for assessing urban challenges and NBS.	• Urban resilience is not the focus of the assessment. • Proposed metrics are structured around 5 topics and 11 urban challenges. • Every urban challenge is disaggregated into sub-challenges. Considered topics are climate, environment, resource, social, economy, and multi scales. The analysed challenges are: (1) climate issues; (2) water management and quality; (3) air quality; (4) biodiversity and urban space; (5) soil management; (6) resource efficiency; (7) public health and well-being; (8) environmental justice and social cohesion; (9) urban planning and governance; (10) people security; (10) people security; (11) green economy.	• Does not provide a clear definition of the metrics. • Proposes qualitative and quantitative metrics. • Metrics do not provide a judgement of the results, a threshold, or a target numerical value. • Does not propose a final assessment. • Does not identify the resilience capabilities associated with the proposed metrics. • Does not propose different assessment levels. • Does not allow to compare NBS over time or between cities.	• Main focus • Focuses on climate, environment, resources, social, and economic aspects. • An extensive review of possible metrics, potential actions, and expected impacts in the urban context is provided. • Assessment constraints. • Proposed metrics represent the first approach without a clear definition or reference values.
RAF for NBS (Beceiro *et al.* 2020)	• Focuses on assessing the NBS contribution to urban resilience, regarding stormwater management and control. • Supports the NBS diagnosis, decision-making, implementation, planning and management, and the identification of NBS with the potential to contribute to city resilience.	• Urban resilience is the focus of the assessment. • Structured into resilience objectives and criteria. Proposed objectives are grouped in two dimensions ('Integration of NBS in the city' and 'Operation and services of NBS'). • Objectives considered are: (1) governance and stakeholders' involvement; (2) economic sustainability; (3) social involvement and co-benefits; (4) environmental resilience; (5) spatial planning; (6) service management; (7) resilience engaged to service; (8) infrastructure safety and robustness; (9) infrastructure preparedness; (10) infrastructure dependence and autonomy.	• Integrates qualitative and quantitative metrics. • Provides a clear definition of the metrics. • Proposes reference values for the metrics and a metrics classification, regarding the resilience development level. • Allows comparing cities or the same city over time. • Allows for assessing the contribution of all existing NBS in the city, of a group of NBS, or a specific NBS.	• Main focus • Focuses on governance, environmental, social, and economic concerns, and the NBS contribution to city, service, and infrastructure. • Focuses on hydraulic performance. • Predefined to assess flooding scenarios. • Assessment constraints. • Focuses on specific NBS for stormwater management and control (e.g., infiltration basins, green roofs).

(*Continued.*)

Table 7 | Continued

Assessment proposal (reference)	Description	Structure	Key information	Focus and assessment constraints
		• Proposes different analysis degrees according to the resilience maturity and available information in the city. • Includes a complementary profile to identify city and NBS characteristics. • Three metrics types were proposed regarding the information's complexity and metric determination.	• Allows to assess impact related to acute shocks and continuous/chronic events.	• NBS water quality performance is evaluated in an aggregated and qualitative way.

Table 8 | Systematic characterization of the main NBS assessment proposals regarding the key components

	Scope and structure					Metrics							Application				
Assessment proposal	Urban resilience focus	Urban scale	Urban resilience dimensions	Objectives and criteria	Context information	Public access	Clear definition	Qualitative and quantitative information	Performance, risk, and cost analysis	Reference values	Final assessment	Resilience capabilities	Assessment levels	Evolution over time	City benchmarking	Acute shocks and continuous events	NBS assessment and benchmarking
Climate change and adaptation metrics system (Kabisch *et al.* 2016)	X	✓	✓	X	X	✓	X	✓	✓	X	X	X	X	X	X	X	X
EKLIPSE impact evaluation framework (Raymond *et al.* 2017a, 2017b)	X	✓	✓	X	X	✓	X	✓	✓	X	X	X	✓	X	X	X	X
Nature4CIties integrated performance metrics system (Nature4Cities 2019; Bouzouidja *et al.* 2021)	X	✓	✓	X	X	✓	X	✓	✓	X	X	X	✓	X	X	X	X
RAF for NBS (Beceiro *et al.* 2020)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	✓	✓

5.2. Analysis of the main RAF at the urban scale

To support the analysis of the main RAF, their description and systematic characterization are detailed in Tables 2 and 3, respectively. The analysed RAFs are specifically focused on the urban scale and urban resilience.

All RAFs consider the main urban resilience dimensions, namely, the environmental, social, economic, and governance dimensions. In this sense, the resilience concept and its different dimensions can be identified as a concept already ensured in these assessment approaches.

Regarding the RAF structure, most analysed frameworks present a resilience objective-driven assessment. The remaining RAF aggregates the proposed metrics attending other factors, such as the city sector or the area that will be assessed. Although most RAFs have identified resilience objectives to drive the assessment application, only one RAF establishes assessment criteria, as proposed in the ISO 24500 standards structure (ISO 2007a, 2007b, 2007c) for water supply and wastewater system management. The definition of assessment criteria allows for guiding the resilience assessment by covering several aspects or points of view in every objective. Although defining criteria presents several related advantages (e.g., assessment oriented towards specific resilience aspects, easier metrics aggregation, and better global understanding), this practice is uncommon among these RAF structures.

A systemic collection of the context information (e.g., city and existing urban service characteristics) represents an important step for assessing urban resilience, helping in the RAF application and adaptation of the proposed metrics to the own city's context. In this light, a predefined and structured collection of the context information, oriented to metrics determination, can help to encourage cities to assess city's resilience and achieve a successful assessment. Three RAFs define the collection of the context information, in a more or less aggregated manner, in the assessment approaches, namely, the UNHABITAT City Resilience Profiling Tool, the ISO 37120:2014, and the RESCCUE RAF.

Regarding the proposed metrics, most RAF metrics are available for public access and include a clear definition of them. Only the ARUP and Rockefeller City Resilience Framework and the UNHABITAT City Resilience Profiling Tool do not provide this information. In this sense, the adequacy of the metrics' definition could not be analysed. Considering the RAF with metrics available for public access, the incorporation of qualitative and qualitative information for assessing urban resilience represents a consolidated aspect across the analysed RAF. Moreover, the risk, cost, and performance analysis recommended for service performance evaluation, as detailed in the European Standard EN752:2008 (CEN 2008), is ensured in most RAFs.

Defining reference values is essential for assessing urban resilience, allowing to measure resilience on one scale, monitoring the resilience progress over time, and cities benchmarking. Furthermore, reference values allow for identifying adequate strategies and prioritizing investments. Nevertheless, most RAFs do not propose any judgement of the results, a threshold, or target numerical value. In this sense, most assessment frameworks are not prepared to monitor the resilience progress over time and for city benchmarking.

With the proposed metrics, a clear identification of the urban resilience capabilities associated with the proposed metrics and the definition of an overall final assessment are quite uncommon. Only ARUP and Rockefeller City Resilience Framework identified the urban resilience capabilities which are evaluated in every metric. For example, metrics related to the flexible, robust, inclusive, and integrated capabilities of resilience are considered for assessing the 'Minimal human vulnerability' goal.

As previously referred, most assessment approaches are not feasible for city benchmarking and assessing the city resilience evolution over time mainly because resilience is not measured based on a normalized scale through defining reference values. Even when a RAF is able for city benchmarking, comparing cities is not consensual and needs to be made with caution (Cardoso *et al.* 2020). In this light, a final assessment of urban resilience is not proposed in most assessment approaches. Instead, it is recommended to compare the metrics results aggregated at the criterion or objective level. Lastly, only a few RAF proposals assess both the acute shocks and chronic stress impacts.

For RAF application, just one RAF proposes several assessment levels in the function of resilience maturity and the available information in a city. Assessment levels, along with a systemic context information collection, can significantly help cities in the RAF application, guiding the metrics' determination and the collection of the required information. Assessing urban resilience is a complex and time-consuming process that requires a significant amount of information. In this sense, tools or guidance to simplify and help cities in the resilience assessment represent an important step forward, encouraging cities for working on this aspect. For instance,

the RESCCUE RAF guides cities in the resilience assessment, allowing to identify the main challenges and consolidated aspects in the cities. Moreover, this approach allows identifying measures to upgrade the resilience level in the city and the required information to apply the next assessment levels.

Regarding the NBS contribution to urban resilience, these solutions are mostly indirectly assessed in the analysed RAF. In this sense, just some NBS aspects are considered. The ARUP and Rockefeller City Resilience Framework, the Disaster Resilience scorecard for cities, the RESCCUE RAF, and the U.S. EPA RAF consider the assessment of some NBS aspects. Moreover, some RAFs do not consider the NBS contribution to urban resilience directly or indirectly (UNHABITAT III. SDG 11, ISO 37120:2014). For example, in the Disaster Resilience Scorecard for cities, some NBS aspects, such as the integration of green and blued infrastructures into city policies and projects, are assessed in the Essential 05 'Safeguard Natural Buffers to Enhance the Protective Functions Offered by Natural Ecosystems'. In the same alignment, the U.S. EPA RAF proposes some metrics to assess specific NBS aspects mainly regarding the land use/land cover and the natural environment sectors.

5.3. Main NBS aspects and concerns

The NBS concept goes beyond the traditional principles of biodiversity conservation and management. It focuses on individual and social co-benefits, such as human well-being or socio-economic development. This concept is directly related to other ecosystem-based approaches such as ES or natural capital, among others. The NBS umbrella concept aims to integrate social, environmental, and social concerns with more traditional approaches. This concept emphasizes NBS's relevance for humans and promotes solutions inspired and supported by nature. Identifying the specific aspects and concerns for assessing the NBS potential is an important step forward.

Given the complexity of the urban resilience measurement and the multiple NBS capabilities, specific needs for a robust assessment have been investigated. A comprehensive literature review was done to identify the NBS's role, particularly for stormwater management and control, in building urban resilience and how it can be assessed. In this sense, the main NBS aspects and concerns have been identified based on the analysis of the NBS concept, the European strategy and projects, and the main existing NBS assessment proposals. Relevant NBS aspects and concerns, such as the importance of including them in spatial and land use planning or the need to explore NBS benefits for biodiversity, people, and green economy, were identified.

The analysis of main NBS challenges in the water sector and the main available NBS assessment proposals allowed identifying essential NBS aspects and concerns for a comprehensive assessment of the NBS contribution to urban resilience, such as the evaluation of the infrastructure implementation and design. In essence, the assessment of the NBS contribution to urban resilience should consider the following aspects: (i) social, environmental, economic, and governance dimensions; (ii) spatial and land use planning at the city level; (iii) service and infrastructure management; (iv) potential capabilities to provide ES and to enhance natural capital and biodiversity; (v) impacts on the surrounding area (e.g. population or critical locations); (vi) infrastructure implementation and design, including adequate monitoring and maintenance processes; (vii) infrastructure performance under normal and stressing condition, considering acute shocks and continuous stresses; and (viii) infrastructure interdependencies with other urban services.

5.4. Analysis of the main NBS assessment proposals

To support the analysis of the NBS assessment proposals developed in this section, their description and systematic characterization are detailed in Tables 7 and 8, respectively. All NBS assessment proposals are focused on the urban scale, with only the RAF for NBS (Beceiro *et al.* 2020) being specifically developed to assess the NBS contribution to urban resilience. It is noteworthy that the remaining NBS proposals can be understood as a valuable first approach, in which a large number of metrics and methods for its determination were proposed, as identified by the corresponding authors. Regarding the definition of objectives and criteria, just one assessment proposal is aligned with the structure proposed in the ISO 24500 standards for water supply and wastewater system management.

In terms of the proposed metrics, most NBS assessment proposals do not provide a clear definition of the metrics. For example, an exhaustive description or a single response of the metric is not provided, recognizing the need for further development and identifying different possibilities for development in the respective assessment proposal. On the other hand, the incorporation of qualitative and quantitative information, and the risk, cost, and performance analysis, as detailed in the European Standard EN752:2008 (CEN 2008), are consolidated aspects of the NBS assessment proposals.

The main challenge of most NBS assessment proposals corresponds to the definition of reference values due to their relevance for benchmarking and assessing the NBS contribution over time. Aligned with this lack of reference values, most NBS assessment proposals are not able to assess the evolution of the NBS contribution over time, to compare their contribution between cities or between different NBS. However, while these proposals have several limitations, they represent an important step forward and provide a valuable basis for cities to select and adapt the proposed metrics to assess urban resilience considering their constraints and existing NBS.

The identification of a final assessment and the resilience capabilities evaluated in every metric is an uncommon practice as expected. This situation is primarily due to the fact of comparing resilience in cities represents some difficulties (e.g., different interpretations of the same metric result may occur), as identified for the RAF at the urban level. Therefore, it is recommended to compare the metrics results at a more disaggregated level (e.g. at the criterion or objective level), avoiding summarizing the resilience of a city in a unique global metric. Secondly, due to several NBS proposals represent the first approach, an exhaustive definition of every metric and the corresponding reference values is not available.

Lastly, three NBS assessment proposals (Raymond *et al.* 2017a; Nature4Cities 2019; Beceiro *et al.* 2020) propose different assessment levels regarding the resilience maturity and available information or the NBS impacts at different urban scales (e.g., macroscale, mesoscale, and microscale), respectively. In this framework, the macroscale corresponds to the global and international level, the mesoscale represents the regional to metropolitan and urban scales, and the microscale includes from the neighbourhood to the single building (Raymond *et al.* 2017a). The proposed assessment levels aim to guide and help planners, decision-makers, and practitioners in the NBS assessment.

6. CONCLUSIONS

This paper highlights the importance to evaluate the contribution of NBS to urban resilience, by considering a more comprehensive definition of urban resilience and by addressing the environmental, social, and economic capabilities of NBS to face acute shocks and continuous or chronic stresses occurring over longer time scales.

First, this paper analysed the evolution of urban resilience, with a focus on the urban sector, and identified the main efforts performed to assess urban resilience in cities, by analysing the most relevant resilience assessment frameworks. Secondly, this paper investigated the existing challenges of the NBS umbrella concept and the main advances developed regarding the water cycle, and the assessment of its contribution to urban resilience. Thirdly, this paper identified the main attributes required for a comprehensive assessment of urban resilience, the common NBS aspects, and concerns for evaluating the NBS contribution to urban resilience. Lastly, this paper analysed the main existing assessment frameworks for urban resilience and NBS, and the evaluation of the NBS contribution within every framework. This was done based on the pre-identified key components, identifying the most consolidated aspects and existing challenges.

Important differences and challenges across the analysed RAF at the urban scale have been identified, especially regarding its feasibility of application (e.g., lack of reference values and systemic collection of the required information). The most relevant lack corresponds to the fact that most RAFs are not feasible for city benchmarking and assessing the city resilience evolution over time, which are essential aspects for a city to monitor the city resilience progress and assess the impact of the actions over time. Moreover, the NBS contribution to urban resilience is not fully evaluated in most RAFs, considering just some NBS aspects.

Regarding the NBS assessment proposals, just one NBS assessment proposal is focused on assessing urban resilience and can evaluate the evolution of the NBS contribution over time, to compare their contribution between cities or between different NBS. The other proposals are comprehensive first approaches, in which a large number of metrics and methods for their determination are identified. However, it should be noted that the proposed metrics do not include a clear and unequivocal definition, or a single response, requiring further development to be used. In this sense, these proposals can be understood as a valuable basis for cities to select and adapt the proposed metrics to assess urban resilience considering their constraints and existing NBS.

Overall, this paper aims to support urban planners and decision-makers in the NBS implementation and resilience assessment process. It assists the selection and application of the most suitable framework. This assistance is based on the identification of the requirements for a comprehensive assessment of the NBS contribution to urban resilience, and on the systematic analysis of the main assessment frameworks focused on urban resilience, at the city level and NBS level.

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CONFLICT OF INTEREST

The authors declare there is no conflict.

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