npj | urban sustainability

Article

Published in partnership with RMIT University

https://doi.org/10.1038/s42949-024-00162-z

Urban flood risk management needs nature-based solutions: a coupled social-ecological system perspective

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A growing number of Nature-based Solutions (NbS) has been advocated for urban flood risk management (FRM). However, whether NbS for FRM (NbS-FRM) achieves both social and ecological co-benefits remains largely unknown. We here propose and use a conceptual framework with a coupled social-ecological perspective to explore and identify such “win-win” potential in NbS-FRM. Through a scoping-review we find that ecological FRM measures are unevenly distributed around the world, and those solely targeting flood mitigation may have unintended negative consequences for society and ecosystems. In elaborating this framework with evidence from the reviewed studies, we find that NbS-FRM has the potential to provide both social and ecological co-benefits, with remaining gaps including a lack of resilience thinking, inadequate consideration of environmental changes, and limited collaborative efforts to manage trade-offs. The proposed framework shows how to move forward to leverage NbS for equitable and sustainable FRM with improved human well-being and ecosystem health.

Flooding is one of the most severe climate-related disasters worldwide, and associated with profound societal and environmental challenges[1]. By 2050, current 100-year flood events are projected to occur at least twice as frequently as today across 40% of the globe[2]. In urban areas, extreme flood disasters exacerbate impacts on both people and nature, as increasing urban populations are exposed to flooding, which intensifies damage losses and welfare reduction[3]. Additionally, the major flooding also disrupts hydrological processes and associated biotic communities, affecting flood mitigation function and service from natural ecosystems[4].

Flood risk to human society and ecosystems comprises three elements, *viz.* flood hazard, exposure, and vulnerability of the affected systems[5,6]. To reduce flood damage and impacts, urban flood risk management (FRM) is aimed at improving the capacity of infrastructure to accommodate excessive floodwater, mitigate population exposure to flood hazards, and enhance adaptation of vulnerable individuals and communities[7]. Green and blue spaces have been widely adopted as ecological measures in urban FRM. However, ecological measures that solely aim at flood mitigation may create unintended consequence in ecosystems and/or vulnerable societal groups. For instance, site selection of rain gardens may disturb or maladapt habitats for amphibious animals or fauna[8]; and failure to involve local stakeholders in restoration programs for flood risk mitigation may displace and marginalize poor and vulnerable communities[9]. To avoid such negative consequences, Nature-based Solutions (NbS) could harness the natural services of local ecosystems to potentially both mitigate flood hazards and enhance biodiversity and adaptation to future climates[10], thereby addressing a chain of climate, societal, and biodiversity challenges[11].

The nature and extent of applied NbS determines whether multiple benefits can be provided and for whom[12], as various NbS involve different direct and indirect links between human society and ecosystems[13]. For example (see Fig. 1): mangrove restoration can reduce coastal protection costs while also limiting future ecosystem loss[14]; actions to increase biodiversity and connectivity in floodplain vegetation can provide the regulation

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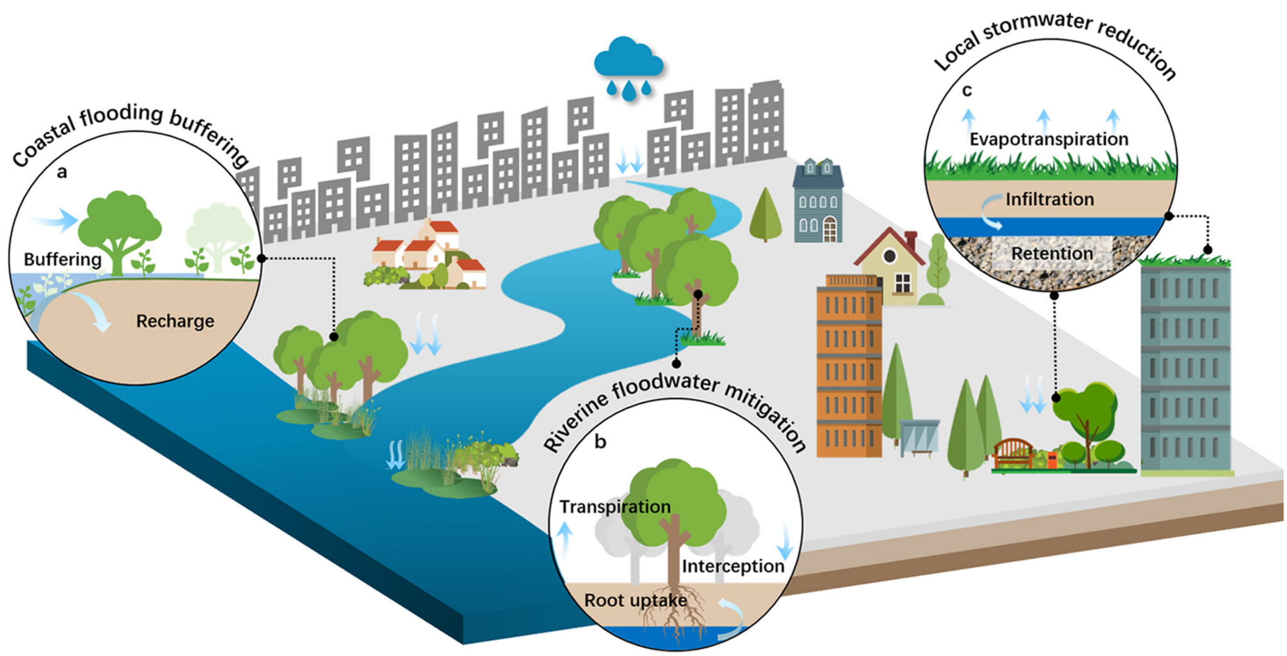

Fig. 1 | NbS interventions to tackle different types of flooding. **a** mangrove protection to buffer coastal surges; **b** tree planting in riparian areas to mitigate floodwaters; **c** rain gardens and green roofs to regulate local stormwater runoff.

service of buffering riverine overflow in adjacent settlements[15]; and rain gardens and green roofs can jointly mitigate stormwater runoff and thermal exposure for local communities[16,17]. Given the urgent need for flood risk management, it is critical to further explore whether the use of NbS can provide co-benefits for both people and nature, and face barriers to such achievement related to the prevailing design, implementation, and governance frameworks in urban regions[18].

Cities are complex social-ecological systems (SESs) with particularly intense interactions between human society and ecosystems[19]. A number of studies have developed coupled social-ecological frameworks that enable NbS interventions to foster resilience thinking and tackle a wide range of challenges, such as, optimizing social and ecological components that are crucial at different stages of NbS planning and implementation in urban environments[13], centering human well-being and biodiversity as both outcomes and drivers of NbS interventions[20], and enhancing NbS' resilience based on social-ecological interdependences to sustain climate adaptation outcomes[21]. By including NbS in the SES framework, it may thus be possible to enhance positive feedbacks between human well-being and biodiversity, and motivate the use of NbS towards sustainable urban development[20]. However, the use of NbS for urban flood regulation has so far rarely achieved the dual goals of social and ecological co-benefits, for example, improvement of wellbeing for local stakeholders has been inadequate, measurable benefits for biodiversity have been limited, and spatial-temporal upscaling to achieve immediate cost-effectiveness has been lacking[22–24]. Such shortcomings may be due to insufficient accounting of the socio-ecological interactions involved when leveraging NbS for urban FRM.

A general and classificatory SES framework, as proposed by Ostrom (2009)[25], paves the way to facilitate multidisciplinary efforts for a better understanding of complex interactions in SES. This framework divides a focal SES into four sub-systems (Governance system, Users, Resource system, and Resource units), among which a set of variables are captured to describe the influence or process relationships that then induce multiple outcomes in society and the ecosystem. Considering that NbS concepts are framed to benefit both people and nature, the extension of the SES framework into NbS research and practice is indispensable to reinforce frameworks and tools that can couple social and ecological perspectives in urban FRM[26]. By transferring the SES framework into the context of urban FRM, the NbS-FRM are correspondingly interpreted into four sub-systems (NbS Decision-making and Rules, Citizens and Stakeholders, NbS-related Ecosystem, NbS Hydrological Performance). When leveraging NbS interventions in urban FRM, these sub-systems can be envisaged as interacting reciprocally among three dimensions that are dependent on social and biophysical factors, mediated by human activities and relevant hydrological responses, and that drive multiple effects (e.g., social equity, biodiversity, and flood mitigation), respectively[27–29]. Therefore, a coupled social-ecological perspective enables NbS in the aims of urban FRM to realize synergistic "win-win" outcomes for society and ecosystems.

In this study, we aim to answer two main research questions, which emerge as important from the above-discussed needs for and inadequacies of NbS use for urban flood regulation with both social and ecological co-benefits: (1) What are the current research trends and gaps in this context, regarding NbS-related ecological measures for urban FRM? (2) How can urban FRM better leverage NbS to achieve synergistic "win-win" outcomes for the urban coupled SES? Overall, the main study objective is to provide a holistic tool for broadly embedding NbS interventions into a coupled SES perspective in future research and strategies, thereby enabling an equitable and sustainable paradigm for urban FRM in general.

Results

Through the scoping review, we generalize the features of ecological measures in the reviewed FRM studies, and elaborate the social and ecological perspectives considered for the NbS following our proposed conceptual framework for SES interactions.

Ecological measures in the FRM studies

The distribution of ecological FRM measures is imbalanced around the world (Fig. 2a). From all FRM studies reported for 96 countries, we note the highest concentration of ecological measures in the United States (39%), China (19%), Australia (9%), and the United Kingdom (8%). The results suggest that, even though many countries in the Global South (particularly tropical and small island countries) face significant exposure to coastal flooding and sea-level rise, fewer studies for these countries address ecological measures compared to the Global North. These disparities in distribution of research studies highlight the importance of further research to address flood-vulnerable regions in the Global South and to incentivize nature-based projects and enhance awareness for guidance of local FRM strategies.

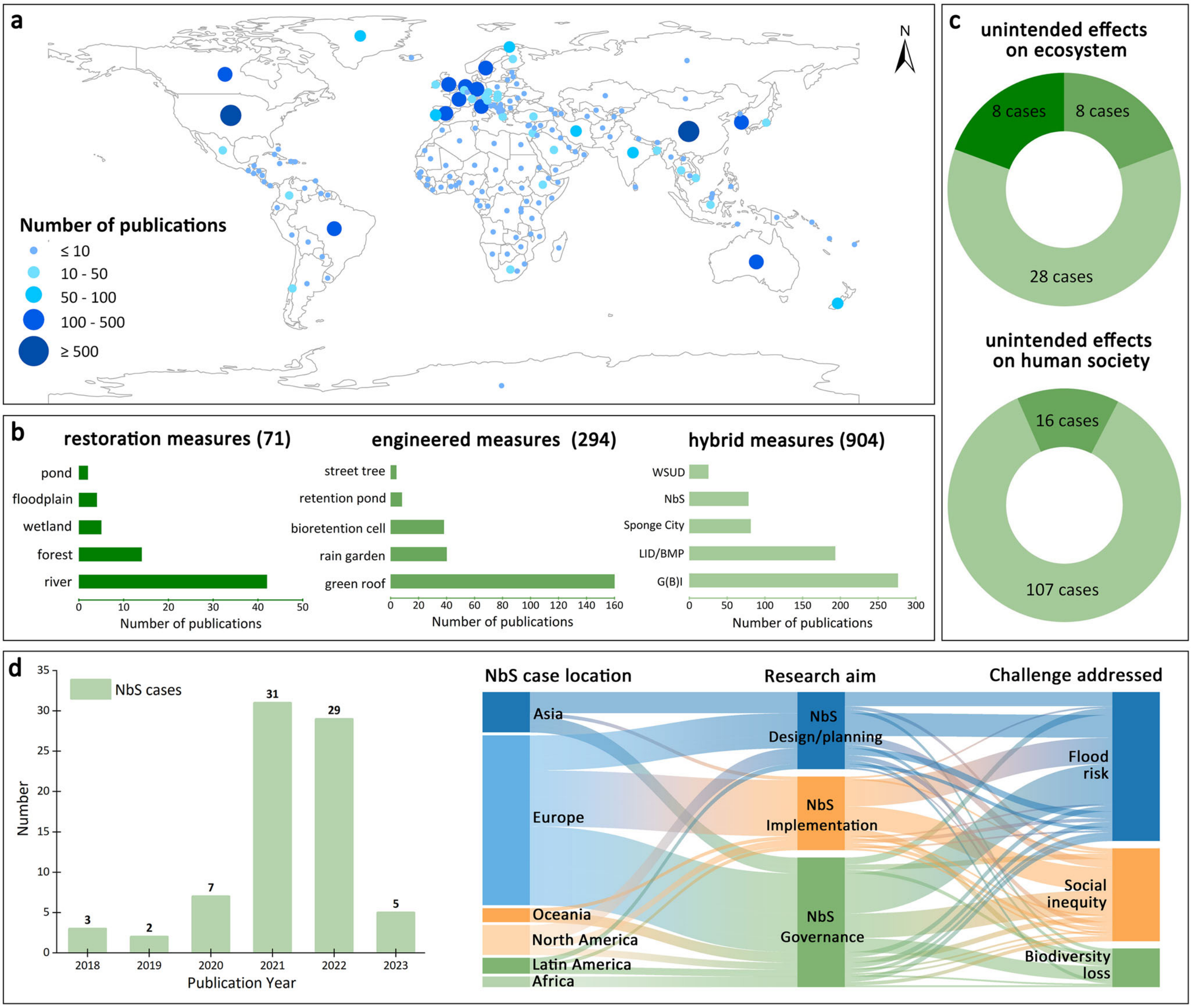

Fig. 2 | Key features of ecological measures in urban FRM studies. **a** Global distribution of numbers of publications. **b** Type of ecological measures in urban FRM studies. **c** The frequency of different measures that reported unintended effects on social and ecological systems. **d** The numbers and features of NbS cases in urban FRM studies to tackle social and ecological challenges.

There is still a considerable bias in the numbers of restoration, engineered, and hybrid measures within the reviewed FRM studies (Fig. 2b). The analysis reveals that the frequency of restoration measures is notably less than the other two types, although they are proved to offer wider-ranges of co-benefits, espectially on habitat quality improvement and flood loss reduction[30,31]. There is a significant number of cases employing hybrid measures (904), and engineering measures are recorded in more than one fourth (297) of the studies, which is four times more than those focusing on restoration measures (71) (Fig. 2b). Our analysis shows that various other concepts, besides NbS, are widely included in hybrid measures (including mainly: Low Impact Development/Best Management Practice, LID/BMP; Water-sensitive Urban Design, WSUD; and Green(-Blue) Infrastructure, GBI). Overall, combined GBI measures emerge (276) as key NbS strategies to cope with urban flood risks.

When solely targeting flood regulation, ecological measures may also have unintended effects on ecosystems and/or society that need to be considered and managed (Fig. 2c). The reviewed studies reported negative effects on ecosystems, including eight cases of restored and engineered measures respectively, and 28 cases of hybrid measures. For example, bioretention cell projects that overlook runoff thermal treatment may prove harmful to instream biota in receiving waterbodies[32]. In other examples, rain gardens and stormwater ponds demonstrate commendable performance in reducing runoff, but may inadvertently lead to water eutrophication and poor tree growth[33]. Urban GBI measures, however, may also have negative societal effects, such as enhanced mosquito prevalence with increased infection transmission and nuisance impacts[34]. As influenced by demographic and institutional factors, the benefits derived from ecological measures are further distributed unevenly within[35] or between cities[36], thereby exacerbating social inequality and environmental injustices[37].

Unintended societal effects were found among the reviewed studies for 16 engineered measure cases and 107 hybrid measure cases (Fig. 2c). For instance, younger, wealthier, more highly educated inhabitants have greater motivation to adopt ecological measures in their neighborhoods, such that more projects are planned and implemented in these areas[38]. Meanwhile, varying perceptions of policymakers, differences in institutional structure, and limited cross-sectional collaboration may result in disparities with inequitable funding to implement ecological measures for different social groups[39,40]. These disparities may lead to the phenomenon of "climate green gentrification", which can escalate land values and in turn displace low-income families[41]. Given this, most ecological measures are designed to maximize flood regulation capacities, failing to adequately address actual demands and needs of vulnerable communities[42]. As a result, there is often a

Table 1 | Main aspects of the social-ecological interactions considered in the reviewed studies, and relevant approaches and tools provided to support NbS-FRM

		Main aspects of social-ecological interactions [1]	Tools and approaches for NbS-FRM [2]	
D1	S	- risk awareness - investment scheme - stakeholder knowledge	- risk perception assessment - public and private sector co-design - demography investigation	**Design/Planning** evaluation, modeling, and analyzing approaches that provide knowledge to support NbS-FRM policy or research.
	E	- plant trait - soil performance - habitat quality	- vegetation structure assessment - soil performance evaluation - biodiversity investigation	
	S+E	- NbS placement suitability • local demography, flood exposure; • surface slope, land permeability.	- multi-criteria evaluation - weighting analysis	
D2	S	- voluntary behaviors to adopt NbS - land use development	- social learning - participatory decision - cross-sector collaboration	**Implementation** the processes and actions on how agencies and stakeholder adopt NbS-FRM practices.
	E	- total runoff volume reduction - peak flow attenuation	- ecosystem restoration - imperviousness disconnection - stormwater source control	
	S+E	- ecosystem service flow • demands of vulnerable groups • supply of hydrological functions	- NbS scenario analysis - service flow investigation	
D3	S	- cost-effectiveness - social equity	- performance evaluation - social disparity assessment	**Governance** strategies and tools for evaluating, monitoring, and managing performance of implemented NbS-FRM.
	E	- biodiversity gain - ecosystem connectivity	- baseline condition assessment - long-term monitoring	
	S+E	- synergized effects • low costs and avoided flood damage • nutrient cycling and carbon storage	- watershed-level management - transboundary governance	

[1]literature database has been reviewed by authors according to the proposed framework, to identify which aspects of social and ecological variables, processes, and outcomes have been considered in FRM studies.
[2]tools and approaches in the reviewed literatures are preliminarily extracted as potential strategies for future NbS-FRM to bridging social and ecological perspectives.

spatial mismatch between the supply and demand of flood regulation services[43], making it difficult to target at-risk groups and communities, and indirectly reducing their social well-being[44]. Accordingly, it is important to find a balance between flood reduction, ecological benefits, and social implications in urban FRM.

Recently, NbS to tackle both social and ecological challenges are emerging in urban FRM (Fig. 2d). Among the reviewed studies, 77 cases explicitly report effectiveness of NbS in coping with flood risks and related SES issues (**see details in Supplementary**). Notably, these studies were all published after 2018, following the global advocacy of NbS as a key strategy for climate adaptation since the Paris Agreement (2015) and the UN Climate Action Summit (2019). Based on these studies, we found that integrating social and ecological perspectives throughout the stages of NbS design/planning, implementation, and governance can contribute to flood risk mitigation and adaptation while simultaneously tackling wide ranges of challenges.

By optimizing the configuration and composition of city-wide NbS, ecosystem functions can be maximized to reduce flood risks. As for at-risk individuals and communities, NbS that are implemented following proper public engagement, continuous maintenance and monitoring schemes, and flexible funding mechanisms can achieve more equitable benefits[45]. Interestingly, NbS that achieve runoff reduction can also mitigate social health deprivation, as reported from an equity-based Gini index evaluation[46]. Studies have also noted that improvement of human wellbeing by NbS requires decision-making processes that consider stakeholder preferences and participatory design[47].

The principle of benefitting both people and nature is a distinguishing feature of NbS compared to other ecological measures[48]. Design of more biodiverse NbS, with multiple ecological functions beyond flood regulation, can also provide higher values of ecosystem services to beneficiaries[49]. For instance, constructing green roofs with diverse plant species can enhance the provision of substrate cooling and stormwater retention[50]; reconnecting streams and vegetation in floodplain can improve habitat quality and facilitate species migration, while buffering people and assets in downstream settlements from flooding[51].

Leveraging NbS-FRM from a coupled social-ecological system perspective

The three dimensions and associated sub-categories based on the content of reviewed studies and the proposed NbS-FRM framework were outlined in Table 1, including coupling of social and ecological factors (D1), linking of human activities with hydrological responses (D2), and balancing of potential tradeoff effects (D3). Each dimension is summarized in terms of social, ecological, and coupled social-ecological aspects, which can inform NbS-FRM approaches to address trade-offs between social wellbeing, ecosystem and biodiversity benefits, and flood management across the stages of NbS design/planning, implementation, and governance.

Dimension 1: coupling social and ecological factors. From the reviewed FRM studies, we identified key variables which affect the hydrological performance in NbS-related ecosystems as well as influence the engagement of stakeholders in NbS decision and rules. There is an ample evidence in the reviewed studies that biophysical factors are considered in FRM studies, as they affect the hydrological performance of NbS and associated ecosystem function and service. Most of these studies take variations in precipitation and evapotranspiration across climate zones into account, as suitable choices for vegetation and soil properties are fundemental factors in designing the NbS[52]. Main considered NbS traits include plant height, canopy density, leaf area, and species richness, as they closely interact with the urban hydrological cycles[53,54]. Several studies note the importance of these traits for evapotranspiration in retention-based NbS[55], but record only limited contributions to rainfall interception during large storm events[54]. Soil hydrological performance is another key factor for the infiltration capacities of NbS, as soils with high unsaturated and saturated hydraulic conductivity can facilitate greater groundwater recharge instead of surface runoff[56]. Additionally, habitat quality is an important factor influencing ecosystem regulation services of NbS, because it determines if the NbS can sustain suffiecient local biodiversity (e.g., establishing spontaneous species, enhancing native species, or introducing invasive speices) to provide ecosystem functions that be resilient to climate extremes[57].

Risk awareness, investment schemes, and stakeholder knowledge are key factors that can significantly increase flood risk adaptation in society, but they are less frequently reported in comparison to the biophysical factors. Prior experiences of flooding by individuals and groups leads to heightened risk awareness[58]. Besides social status (such as income, house ownership, and education leve), high risk awarenesshas also has great potential to lead to public acceptance of NbS[59]. The latter can increase willingness to pay (WTP) for ecosystem services on NbS to compensate the installation costs of NbS on private lands[60], assisting with lowering the incentive costs from local governments[61]. In this context, local stakeholder knowledge and accurate perceptions of flood risk can influence the understanding of actual benefits that NbS may bring, toward successful uptake of NbS design and planning in flood risk management[62].

There are much fewer scientific studies of urban NbS-FRM that consider coupled social and ecological factors than those evaluating social or ecological domains separately. The coupled studies often apply multi-criteria assessment tools to weigh each factor and develope NbS planning scenarios. First, the environmental variables, like land permeability, surface slope, and density of stream networks, are used to determine suitable sites for general NbS (not specific types)[63], while the biophysical factors, especially plant traits and local climate factors that influence NbS functions and services are less commonly considered. Next, social vulnerability metrics based on local demography (i.e., education, age, gender, race) are often used to indicate priority locations for NbS that can reduce flood exposure[63], while risk awareness, investment schemes, and stakeholder knowledge are not well accounted for in the local context. Moreover, although multiple factors are weighted to determine NbS suitability and priority, the coupled social-ecological studies typically fail to consider the dynamics of NbS capacities to withstand flood hazards. This means that there is often insufficient knowledge about which types and what traits of NbS as well as where the NbS should be placed to ensure flood resilience.

Dimension 2: linking social processes with hydrological responses. Most of the reviewed studies report NbS effectiveness in mitigating and adapting flood risks. They include ways that social processes may influence the hydrological responses of NbS-related ecosystems, and they also consider how affected ecosystems contribute to society through hydrological functions and services. Land use change and urban development are the most studied social processes in our literature database. In urban areas, existing blue and green spaces become increasingly occupied or fragmented by the growth of impervious surfaces, leading to less capacities in canopy interception, vegetation infiltration, and water storage[64]. Therefore, activities to reconnect pervious green or blue surfaces may play a key role in increasing positive hydrological functions and services[65]. A case of the City of Paraty, Brazil, illustrated that, improving connection between urban parks and ponds, as well as rivers and floodplain vegetation can directly increase surface permeability and mitigate flood risks[66]. Besides, drainage infrastructures around impervious surfaces can be replaced by vegetation to facilitate natural flow conveyance, such as disconnecting roof gutter downspouts from the impervious surfaces and directing the roof runoff to lawns, thereby achieving reduction in runoff volume in the range of 57-99% over nine months[67].

Meanwhile, inclusive NbS implementation, such as collaboration activities and knowledge co-production, is an important social process for obtaining ecosystem service synergies (e.g., combining cultural and flood regulation services) in several FRM studies. It is evident that such processes should be transparent and just so as to facilitate knowledge exchange between public and government, which can underpin a bottom-up perspective to NbS implementation that enlarges the extent of beneficiaries. A study reported that, when social networking, opinion dissemination, and diffusion of innovations are captured in adoption of green stormwater infrastructure (GSI), market-based incentives can enhance support from private property owners with the potential to retrofit 20% or more of existing impervious surfaces to GSI in urban areas[35]. Thus, incorporating the views of citizens and stakeholders, as well as improving community education and outreach, can positively encourage voluntary restoration efforts and improve the effectiveness of NbS. Several examples show that residents' "green behavior", such as homeowner landscaping practices[68], citizen stormwater governance[69], and everyday nature experiences[70], can increase the adoption of NbS in private lots (e.g., backyard spaces, home gardens, and roofs) and contribute to effective runoff reduction. A study in the City of Syracuse reported that, if 58 ~ 64% of households were to participate with rain gardens and/or rain barrels, an additional 5.3% reduction of peak runoff and 6.3% reduction in total runoff can be obtained[69]. Such contributions affect the pattern and capacity of *in-situ* NbS, so that their hydrological as well as cultural services (e.g., aesthetic enjoyment, social cohesion, and spiritual experience) can directly benefit the residents who, in turn, can further boost public commitment to the adoption of more NbS in neighborhoods.

Changing environments in cities, including urban growth and climate extremes, introduce uncertainties and complexities with regard to the effectiveness of NbS for flood risk mitigation and adaptation, e.g., under varying rainfall conditions, the provision of hydrological functions from green roofs could not always equitably match the demands of vulnerable residents[71]. It is notable, however, that few studies address how NbS-related ecosystems react to flooding, through the fundemantal hydrological processes in urban areas (e.g., precipitation interception and redistribution, evaporation and transpiration, infiltration and soil water transport, as well as groundwater recharge). This can lead to limited knowledge on how to maintain the effectiveness of NbS in sustaining essential ecosystem functions under different climate and urban growth conditions.

Dimension 3: balancing trade-offs. Studies on evaluating, monitoring, and managing implemented measures for FRM have revealed the trade-offs among social, ecological and hydrological benefits, and discussed how these may be balanced over the long term. In the studies reviewed, performance evaluation is often used to quantify the NbS trade-offs between hydrological benefits and economic costs. As a case study showed, centralized NbS have greater flood regulation capacities but be more expensive in terms of investment and maintenance than distributed NbS[72]. Such evaluations may promote cost-effective measures but fail to account for ecological benefits and social well-being. Indeed, there are several important non-financial aspects to consider, such as the unintended consequences of social inequity and biodiversity loss from implemented measures, which may not appear initially but develop in the long term, and are uncertain and difficult to evaluate. We noticed that monitoring and detecting such unintended social or ecological effects can offer a sound footing for evaluating the performance of NbS projects. Acknowledging the possible inequitable benefits of NbS between different social groups is necessary to develop long-term governance actions for addressing trade-offs and safeguarding benefits for various stakeholders. For example, a newly-built stormwater park, located in the City of Atlanta, U.S.A, was designed to mitigate flooding and provide recreational space, but resulted in social displacement after implementation[73]. This was generated by higher lease prices for low-income and ethnic groups who were renters, thus forcing them to move out from these neighborhoods. With regard to ecosystems, it is difficult to fully restore biodiversity to pre-development conditions through localized FRM measures alone. For instance, in a project monitoring the long-term (eight year) effects of an urban river intervention for both habitat conservation and flood risk management, riparian revegetation and gravel back-fill increased aquatic diversity as expected, but species composition and density did not fully recover to baseline conditions[30].

Few of the existing actions were taken based on governance for both social and ecological effects of the NbS interventions, and such governance is needed to systematically monitor and manage potential trade-offs. By treating the FRM as a network of interacting and co-evolving NbS interventions, rather than focusing solely on individual projects, synergy effects within broader extends may be accumulated to sustain both the local ecosystem and improve human well-being[74]. There are good examples of NbS projects that emphasize ecosystem connectivity and transboundary governance. A case study from Belgium proved that, reconnecting rivers to floodplains, "zero management" on riparian vegetation, and retaining overflows in natural floodplain can link locally-restored NbS to watershed-level ecosystems beyond the intervention sites, providing flood control with lower costs and mitigating flood losses for society[51]. Additionally, these projects alter biotic components (e.g., species abundance and community composition of invertebrates) by adapting abiotic components (e.g., climate conditions, soil properties, and vegetation types), leading to the restored invertebrate communities driving further direct and indirect effects (e.g., nutrient cycling and carbon storage)[75]. Since flood risks do not respect administrative boundaries, transboundary collaboration between municipalities and regions can greatly assist NbS governance and upscale co-benefits of NbS[29]. Collaborative actions among departments, experts, and local residents can also enhance coherency and consistency of FRM strategies across different socioeconomic and institutional contexts[76]. These findings combine in indicating great potential to synergize flood mitigation, habitat quality, and human well-being; thus, more collaborative and interconnected approaches are needed to advance governance and balance trade-off effects associated with NbS.

Dicussion

Leveraging NbS with coupled social-ecological interactions paves a way to achieve sustainable urban FRM which can benefit both people and nature. But, this is still challenging due to limited understanding of the NbS dynamic capacity to withstand flood impacts, inadequate consideration of changes in climate, environment and society, and the lack of practical tools for managing trade-off effects. Technological developments offer new opportunities for leveraging NbS to tackle a range of challenges[20], opening up new interdisciplinary paradigms for incorporating social and ecological system perspectives in NbS-FRM studies and actions. Here, we put forward future steps needed to enhance these social-ecological system perspectives at planning, design, implementation, and governance stages to develop a "win-win" NbS-FRM for human wellbeing and ecosystems (Fig. 3).

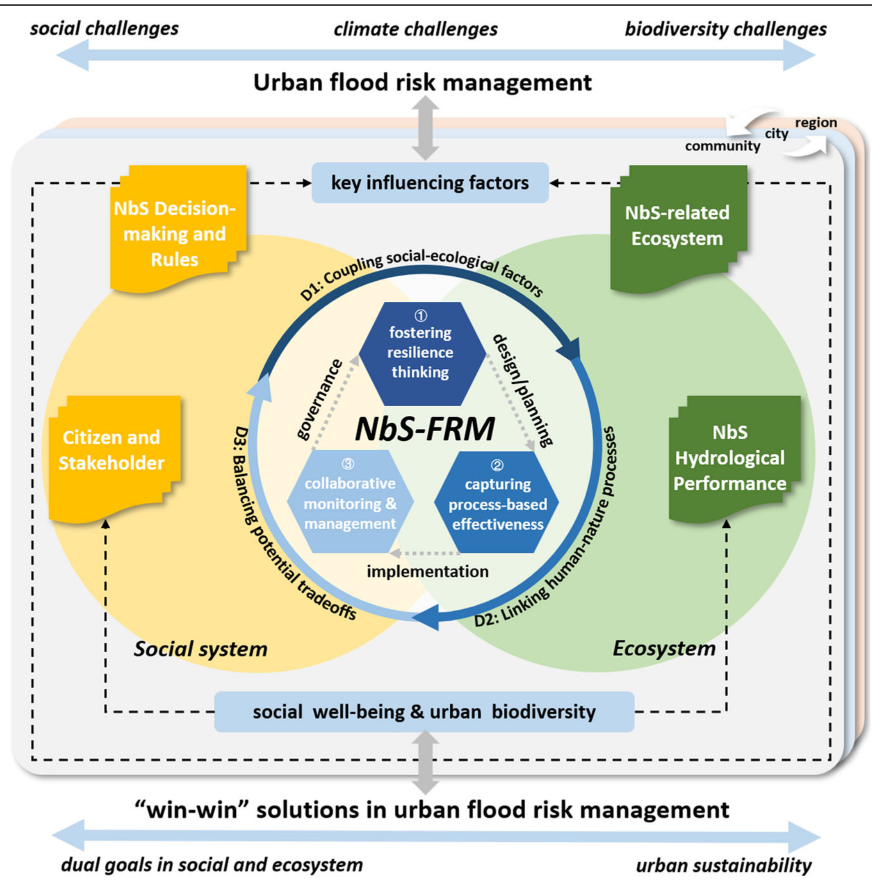

Fig. 3 | Priority steps for a "win-win" NbS in urban flood risk management. The steps correspond to three dimensions of social-ecological interactions, including (1) harnessing flood resilience thinking to level up adaptative NbS planning for local society and ecosystem; (2) developing comprehensive tools to capture the linked dynamics of social behaviors, human activities and ecological processes in a changing environment, and (3) enhancing collaborative approaches to monitor and manage "win-win" solutions for long-term co-benefits in urban FRM.

Fostering resilience thinking in NbS design/planning

Coupling of social and ecological perspectives is still lacking in designing and planning NbS, as few approaches and tools have been reported to reveal the key variables affecting the NbS dynamic capacities to mitigate and adapt flood risks. Resilience is a theoretical concept that encompasses the capacity of a system to absorb shocks, adapt to changing conditions, and maintain or enhance their functioning[77]. Fostering resilience thinking in NbS design/planning will be benifial both to social and ecological system. For example, when affected by extreme floods, NbS with high resilience may assist the local SES to withstand and recover, by shifting possible tipping points for systematic failures, reducing the time needed to bounce back to pre-disaster states, and adding to the capacities to maintain key functions and buffer flood impacts. The ongoing climate change leads to hotter and, in some places also wetter climates[78], therefore, resilient NbS are needed to keep pace with increasing flood risks and contribute to climate adaptation for local communities[78,79]. This means that resilience capacities should be considered for both society and ecosystem, for which further SES research is needed to support such resilience thinking and practice in NbS design and planning[21].

One way for policy-makers and researchers to address this current gap, is to consider NbS that foster both ecosystem stability and local preparedness[48]. To start with, the baseline conditions in local ecosystems need to be fully assessed to understand the characteristics that influence ecological capacity before and after flooding. Such characteristics include species richness, plant traits, river structure, etc., and are important for quantifying resilience of the NbS-related ecosystem[79]. In addition to the biophysical component of NbS' resilience, the societal resilience enabling preparedness and recovery of vulnerable social groups is also important to include in resilience thinking for NbS planning[79]. These capacities also need to be evaluated for public acceptance of and exposure to nearby NbS, in order to identify actual beneficiaries and degree of adaptation in local communities[80]. In combing the above factors, a comprehensive indicator system is necessary to measure local resilience with and without NbS interventions. Such an indicator system should cover the full risk stages before, during, and after flood events. Thereby, it may systematically predict the NbS capability to affect potential future regime shifts in the urban system, and indicate key thresholds and tipping points that a network of NbS could shift to enhance flood resilience for both the local ecosystem and vulnerable social groups.

Capturing process-based NbS effectiveness in changing environments

Incorporating NbS can provide local residents with improved hydrological benefits, however, as both climate and land use change, potentially increasing the frequency and magnitude of flooding, existing NbS may not be able to mitigate future flood impacts that exceed their design conditions. Furthermore, public acceptance and engagement also vary with social, economic, and political developments, so that social support for NbS may not remain constant over time. In order to capture NbS effectiveness under such variations and changes, more research is needed on the interaction dynamics of human activities, social behaviors and hydrological responses involved in urban NbS-FRM under different conditions of climate and environmental change and social development.

Different types of process and system modeling can provide valuable tools for evaluating the outcomes and effectiveness of NbS and has been used in recent FRM studies[81]. Such a modeling toolkit requires wide-ranging data based on social surveys, field investigation, remote sensing, etc., to link the influencing factors of public engagement, policy decisions, and ecosystem services. These various datasets are needed to provide necessary information for researchers to accurately model the patterns of human activities and ecosystem responses before and after NbS and other urban FRM initiatives. Using such datasets, for example, System Dynamics (SD) models, can be developed to describe the complex interactions and feedbacks of society and ecosystem. Such models, integrating interdisciplinary knowledge from social and natural sciences, should be able to simulate and predict NbS effectiveness in regulating flood risks in various urban and climate scenarios. In particular, SD modelling can couple hydrological processes and management decisions in urban FRM. In recent studies, participatory modelling[82] and cognitive maps[83] have been linked with SD modelling and flood simulation to predict NbS performance taking social-ecological interactions into account. Introducing policy and climate scenario analysis in SD models, such as land use change and Shared Socioeconomic Pathways (SSPs), can further indicate if and how NbS functions and services can be maintained in a warming climate under parallel other environmental and societal changes, and how NbS effectiveness for flood mitigation and adaptation may develop in the long term.

Enhancing collaborative approaches for NbS monitoring and management

Our scoping review suggests that challenges remain in monitoring and managing NbS trade-offs, particularly in relation to hydrological performance and social-ecological effects (eg., financial cost, social disparity, and biodiversity loss). For the social domain, trade-off effects between social equity and flood adaptation may stem from low engagement of vulnerable groups, knowledge and perception challenges, and limited funding availability, leading to social inequity for people with low incomes. Moreover, trade-offs between ecosystem and flood mitigation effects may result from a lack of measurable ecosystem and biodiversity targets, such that decision-makers and optimization efforts cannot rationally and readily consider the effects of NbS refinements for reaching such targets over time.

Consequently, to achieve long term co-benefits, it is crucial to adopt collaborative approaches to monitoring and managing NbS that can provide "win-win" outcomes. The collaborative approaches need to develop context-based policy instruments for NbS uptakes[84]. These instruments may be of regulatory (top-down policies or bottom-up agreements with stakeholders), financial (incentive or disincentive rules), and/or supportive types (information sharing and public education), tailored as policy mixes for mainstreaming NbS and overcoming existing barriers[85]. Multi-stakeholder involvement, beyond just property owners and renters, is further required to successfully implement these collaborative approaches. Throughout the NbS governance stage, it is vital to consider both stakeholder demands for flood risk mitigation and their shared responsibilities for NbS maintenance. Co-development of monitoring indicators and procedures between stakeholders, including researchers and experts, is thus essential. Through such co-development, communities are able to proactively and regularly review and update monitoring databases for NbS performance, and provide feedbacks on either trade-off effects associated with NbS can lead to positive or negative outcomes for the local ecosystem and society. For example, a Bayesian Belief Network model (BBN), may be applied to support co-development by offering a systematic means of diagnosing tradeoffs/ synergies and link learning-by-doing decisions based on observed NbS performance for prediction of future outcomes[86,87]. With the aid of such collaborative approaches, adaptive management can be enhanced between local communities and agencies for more inclusive and equitable FRM desicions.

In summary, this study reveals the co-benefits of NbS along with flood risk mitigation and adaptation, and improves the systematic understanding of the social-ecological interactions during NbS design, planning, implementation, and governance to support urban FRM. On the basis of a scoping review covering the period 2000-2023, notable gaps emerge from existing FRM studies that reflect the uneven global distribution of studies, and biased ecological measures that have unintended societal and ecosystem impacts. These gaps call for more research on NbS in the context of urban FRM, in particular since emerging NbS studies and practices, especially since 2018, reveal the possible multiple benefits that NbS may provide in addressing flood risks, social inequity, and ecosystem degradation including biodiversity loss. Based on the proposed conceptual NbS-FRM framework that considers social-ecological interactions, our results highlight the need for

Table 2 | Search term strategy used in scoping the literature

Scoping		Search terms
Types of ecological measures for urban FRM	Restoration measures	("floodplain" OR "wetland" OR "forest" OR "stream" OR "river" OR "riparian" OR "open space" OR "blue-green" OR "park" OR "protected area" OR "natural reserve") AND "urban"
	Engineered measures	"rain garden" OR "constructed wetland" OR "green roof" OR "blue roof" OR "bioswale" OR "bioretention" or "stormwater pond"
	Hybrid measures	"green infrastructure" OR "natural infrastructure" OR "eco* infrastructure" OR "ecosystem-based adaptation" OR "ecosystem-based solution*" OR "nature-based solution" OR "green stormwater infrastructure" OR "low impact development" OR "low impact design" OR "sustainable urban drainage" OR "sustainable stormwater" OR "best management" OR "source control" OR "sustainable urban stormwater" OR "sponge city" OR "water sensitive" OR "water sensitive planning" OR "blue-green infrastructure" OR "green-blue infrastructure"
Urban flood risk aspects mitigated by ecological measures		"flood risk" OR (flooding* OR flood* OR rainwater OR rainfall OR "stormwater runoff" OR runoff OR waterlogging OR "water logging") OR ("flood hazard" OR "flood exposure" OR "flood vulnerability")

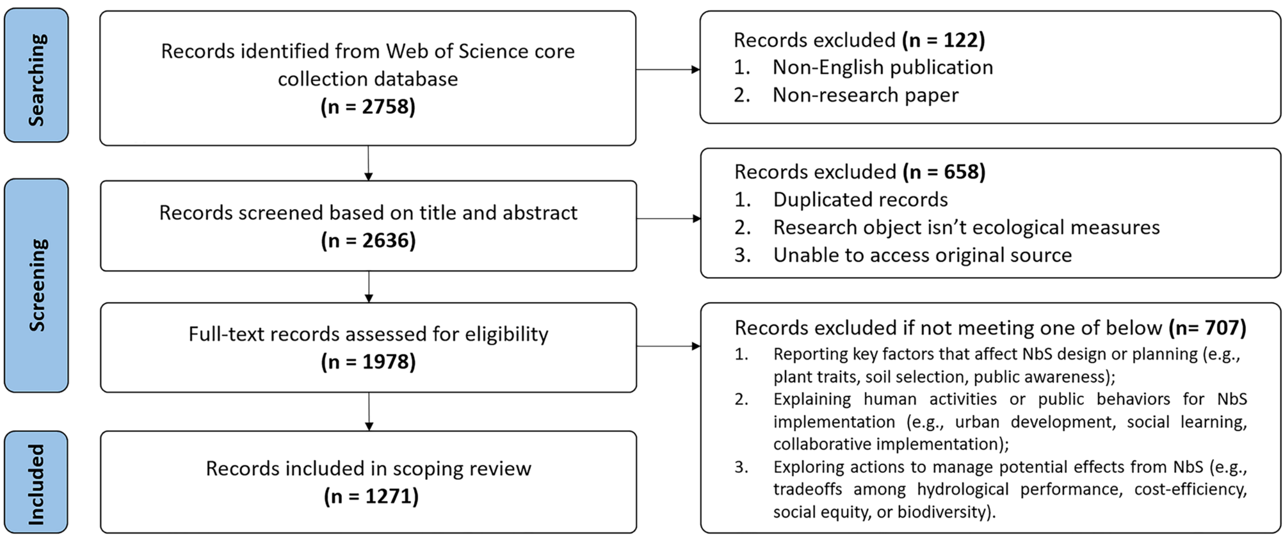

Fig. 4 | Literature screening workflow. The procedures are conducted according to the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA).

further NbS-FRM research to address: (1) the resilience of NbS' dynamic capacity to mitigate and adapt to flood risks under various and changing climate, environmental and social conditions; (2) the linked urban hydrological responses and human activities related to NbS interventions, considering the uncertainties and complexities of their coupled change effects; and (3) the trade-off effects and balances associated with NbS, with collaborative stakeholder evaluation, monitoring and management across sectors and administrative boundaries to enhance possible NbS synergies. Overall, in the face of combined climate, societal, and biodiversity and other environmental challenges, future research needs to further and more systematically explore the potential and effectiveness of NbS interventions to mitigate flood risks while also achieving dual goals of social equity and ecosystem health toward a more sustainable urban future.

Methods

Scoping review

To address the first research question, we searched for studies (including case studies and review articles) on ecological measures in urban FRM, and established a comprehensive associated database of literature published during 2000-2023. To structure the reviewed studies, we first classified the types of studied ecological measures for urban FRM into three groups: restoration measures, engineering measures, and hybrid measures[12]. Then, the flood risk aspects addressed by these ecological measures in urban areas were further classified according to the risk components and key causes of urban flooding. The search terms for these two classification are presented in Table 2, and final results were obtained by overlapping the findings from both scopes.

Following the workflow of the PRISMA protocol (Fig. 4), the literature search initially returned 2758 studies from the Web of Science (WoS) Core Collection. These studies were first checked to select peer-reviewed papers written in English and exclude non-research papers. Based on this, 2636 studies remained for review. Title and abstract were further screened to exclude duplicate records and irrelative topics, yielding 1978 studies for further analysis. The full texts of these studies were further carefully reviewed by the authors, and a total of 1271 studies were finally deemed eligible for inclusion in the scoping review.

From the included studies, we extracted the key study features for additional analysis and visualization. The first feature reflects the general characteristics including the country of publication and the type of FRM measures. We further mapped the global distribution of these studies, and identified the most studied or applied FRM measures in them. The second feature refers to these different types of measures and their identified unintended social/ecological effects along with flood regulation. The third feature finally addresses research on emerging NbS concepts, considering the publication year, the intervention stage, and the challenge addressed.

Conceptual framework

To develop the conceptual framework as a guidence for answering the second research question, we depart from noting that FRM represents a complex decision-making system, in which both social and ecological perspectives determine decision outcomes[26]. For example, based on urban FRM studies, mostly from the United States and Australia, Flynn and Davidson (2016)[27] emphasized that the arrangements of social and biophysical factors affect the outcomes of green stormwater infrastructure implementation with

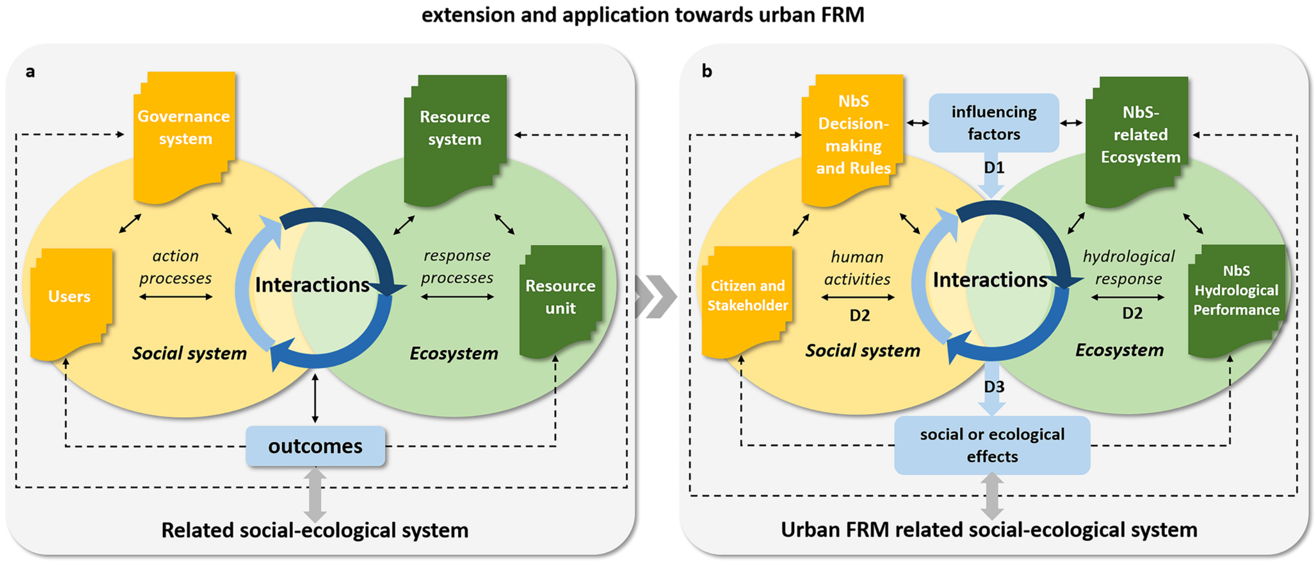

Fig. 5 | Schematic representation of the social-ecological system (SES) framework. The solid arrow links represent the processes of multiple variables shaping the outcomes through their interactions, while the dashed arrows represent feedback from the outcomes to the social and ecological system domains. **a** Social-ecological interactions revised from Ostrom (2009)[25]. The interactions among key social and ecological variable are mediated by the broader actions and responses in SES and can result in various ecological and social outcomes. **b** Conceptual framework showing how NbS-FRM can bridge the social and ecological system domains. This framework illustrates the social-ecological interactions induced by NbS interventions, including coupling of social and ecological factors (D1), linking of human activities with hydrological responses (D2), and balancing of potential tradeoff effects (D3) in the NbS-FRM related social-ecological system.

regard to the additional benefits that can be provided to the community beyond flood regulation. Chang, et al. (2021)[88] further proposed a framework for evaluating social learning based on spatial-temporal changes of the social, ecological, and technological elements, noting that integration of socio-ecological elements into urban FRM (e.g., floodplain restoration, green infrastructure, and public education) can contribute to urban flood resilience. Overall, these examples illustrate that decision-making for equitable and sustainable FRM in cities requires a coupled socio-ecological system perspective.

Ostrom (2009)[25] has developed a SES framework to disentangle the dynamics of system interactions. In that framework, a focal SES is divided into four core sub-systems (Governance system, Users, Resource system, and Resource units) (Fig. 5a). By doing so, ecosystem management can be conceptualized as an interacting system, where the two key social components are the governance system (i.e., decision-making system and rules) and the users (i.e., stakeholders and their attributes), while the key ecosystem components are the resource system (i.e., water, forests, pasture) and the resource units (i.e., economic value and spatial distribution of ecosystem products or services)[25,89]. Reciprocal interactions between the social and ecological components drive various SES outcomes (e.g., in terms of social equity and biodiversity), mediated by processes including societal activities and ecological responses[90].

For a SES framework to support equitable and sustainable FRM decisions, the associated social-ecological interactions need to be specifically understood in terms of their key factors, processes and outcomes as basis for appropriate FRM decisions to be made. By adapting and extending the general SES framework to the key interaction mechanisms for urban FRM, we interpret the NbS-FRM into four sub-systems (NbS Decision-making and Rules, Citizens and Stakeholders, NbS-related Ecosystem, NbS Hydrological Performance) (Fig. 5b). We here consider that various citizens and stakeholders (e.g., local residents, indigenous people, water experts, non-government organizations or voluntary groups, private sectors, as well as FRM-related government ministries, departments and agencies) are critical actors for an NbS Decision-making and Rules system, while hydrological performance and relevant functions are the main resource aspects that contribute to the NbS-related Ecosystem. In this focal FRM-related SES, when human activities alter the hydrological responses through NbS interventions, the social system and the ecosystem interact, thereby adjusting the severity of flooding. These interactions, determined by the human-driven hydrological performance of the NbS, may lead to a range of social and ecological outcomes that can benefit different stakeholders (Fig. 5b).

As it is currently largely unknown if, or to what degree, FRM research and practice related to NbS have considered social and ecological system perspectives, we here use the mechanism of SES interactions as a basis to answer the second research question. In this way, the content of the reviewed studies is structured into three dimensions, based on the main focus of each study in terms of one (or more) of the following dimensions (outlined in Fig. 5): D1 - "social and ecological factors" - investigating the key design or planning variables for NbS interventions; D2 - "social processes affecting hydrological responses" - explaining important human activities or public behaviors for NbS adoption to modify hydrological processes in an urban context; and D3 - "trade-off effects between hydrological benefits and social-ecological consequences" - exploring actions to manage potential effects from NbS practices. Reviewed studies of these three dimensions are further sub-categorized into social, ecological or coupled social-ecological domains and, additionally, identified approaches and tools in the design/planning, implementation, and governance stages of NbS interventions for urban FRM studies or practices. In so doing, we also identify key knowledge gaps that constrain achievement of dual goals of social well-being and ecosystem health.

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The datasets used and/or analyzed during the study are available in supplementary document.

Received: 13 November 2023; Accepted: 8 April 2024;
Published online: 22 April 2024

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Acknowledgements
This study is supported by the National Key R&D Program of China (No. 2022YFE1303102) and the Global Engagement for Strategic Partnership project of Nanjing University.

Author contributions
K.Z. and F.K. conceptualized and designed the work, K.Z. and F.K. conducted the analysis and wrote the original draft, F.K., H.Y. and G.D., helped to intepret the results. G.D., M.M., E.A. and L.C. contributed to the review and editing of the manuscript and to strengthening the paper quality. Z.L, J.S. and B.C. contributed to develop the literature databse amd give comments to refine the figures. All authors approved the manuscript for submission.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s42949-024-00162-z.

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