Nature-based solutions for water management: Pluridisciplinary state-of-the-art and research needs

Freddy Rey, Jean-Luc Bertrand-Krajewski, Sara Fernandez, Joana Guerrin, Cécile Hérivaux, Michel Lafforgue, Philippe Le Coent, Marie-Noëlle Pons, Bénédicte Rulleau

Ecological Engineering 225 (2026) 107887

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Nature-based solutions for water management: Pluridisciplinary state-of-the-art and research needs☆

Freddy Rey [a,*], Jean-Luc Bertrand-Krajewski [b], Sara Fernandez [c], Joana Guerrin [d,e], Cécile Herivaux [e,j], Michel Lafforgue [f,g], Philippe Le Coent [e,j], Marie-Noëlle Pons [h], Bénédicte Rulleau [i]

[a] *Univ. Grenoble Alpes, INRAE, UR LESSEM, F-38402 Saint-Martin-d'Hères, France*
[b] *Univ. Lyon, INSA Lyon, Laboratoire DEEP UR 7429, 3-5-7 promenade Jeanne Barret, F-69621 Villeurbanne cedex, France*
[c] *Univ Toulouse, Toulouse INP, ElP, INRAE, AGIR, Castanet-Tolosan, France*
[d] *Université de Strasbourg, INRAE, CNRS, ENGEES, SAGE UMR 7363, F-67000 Strasbourg, France*
[e] *G-eau, UMR 183, INRAE, CIRAD, IRD, AgroParisTech, Supagro, BRGM, 34000 Montpellier, France*
[f] *Suez Consulting, SAFEGE SAS, Le Bruyère 2000, Bâtiment 1, Zone du Millénaire 650, Rue Henri Becquerel - CS79542, Cedex 2, 34961 Montpellier, France*
[g] *A-IGECO 12 Rue de l'Industrie, 92400 Courbevoie, France*
[h] *Université de Lorraine, CNRS, Laboratoire Réactions et Génie des Procédés, 54000 Nancy, France*
[i] *INRAE, UR ETTIS, 50 Avenue de Verdun, 33610 Cestas, France*
[j] *BRGM, Université de Montpellier, 1039 rue de Pinville, 34000 Montpellier, France*

ARTICLE INFO

Keywords:
Water-related natural risks
Ecological restoration
Ecological engineering
Biodiversity

ABSTRACT

Nature-based Solutions (NbS) offer a way to preserve, manage and restore ecosystems so as to better meet today's societal challenges, by combining benefits for society and the environment, including biodiversity. They are a response to current climate change-related challenges for water management. However, various barriers exist to the implementation of NbS, such as a lack of appropriation of the concept, as well as needs for knowledge and know-how. Focusing on societal challenges linked to water, we highlight the importance of implementing pluridisciplinary and transdisciplinary projects when trying to implement NbS projects. This requires new approaches in research, practice, and governance. This discussion allows identifying levers for a widespread use of NbS for water management.

1. Nature-based solutions for water management with benefits for environment and society

Nature-based Solutions (NbS) are actions aimed at protecting, sustainably managing and restoring ecosystems, as well as answering both societal challenges and biodiversity conservation issues (IUCN French Committee, 2019). They are actions incorporating natural features and processes into applied projects in order to ensure their sustainable development. The NbS concept has been defined at the end of the 2000 decade, at the global scale by institutions such as the International Union for the Conservation of Nature (IUCN) and lately the European Commission (EC). Since then, many countries have been implementing NbS projects (Cohen-Shacham et al., 2019). The latter rely on methods and techniques also associated with other concepts such as ecological engineering, soil and water bioengineering, or green/blue infrastructures (Nesshöver et al., 2017). However, they differ from approaches and methods developed in the field of biomimicry (Benyus, 1997; Dicks et al., 2021).

In the field of water management, NbS correspond to a variety of actions: protecting or improving the quality and/or quantity of water resources and ecosystems; reducing the impact of natural hazards (floods and droughts), urbanisation and pollution from anthropic activities; preserving or improving biodiversity (Fig. 1; Rey et al., 2023). Some of them were promoted before the development of the NbS concept, while the latter adding a systemic perspective to handle together climate adaptation, biodiversity restoration and equity matters of concerns. For instance, wetlands can be restored and reduce the risk of flooding or scarcity, secure water supplies, and combat climate change

☆ This article is part of a Special issue entitled: 'IEES 2023' published in Ecological Engineering.

* Corresponding author.
E-mail address: freddy.rey@inrae.fr (F. Rey).

https://doi.org/10.1016/j.ecoleng.2025.107887
Received 7 May 2024; Received in revised form 29 September 2025; Accepted 19 December 2025

impacts through carbon sequestration, while providing benefits for ecosystems and society. Such projects aim at holding together the protection of people, economic activities, and properties with gains for biodiversity and ecosystems. Another example is the restoration of a channelled river in a stream with meanders, with the aim of allowing it to function more naturally (improving exchanges with underground aquifers, biodiversity, and ecosystem resilience), while slowing the flow velocity and reducing the impacts of potential flooding (Fig. 2). The revegetation of civil engineering structures on riverbanks can also be considered as a NbS.

NbS also have many applications in urban water management (Ramirez-Agudelo et al., 2020). Indeed, nature in cities can help mitigate runoff, as well as reduce drought impacts, by improving infiltration, temporary water storage, evapotranspiration, and biodiversity. Moreover, they can also contribute to reducing the heat island effect (shade, cooler areas, evapotranspiration), and to improving landscape quality and citizens' well-being including social and health issues (Choe et al., 2020). One of their key applications is the management of rainwater, through the promotion of water retention, infiltration, evapotranspiration, and reuse. This limits further development of hydraulic structures and expensive water collection or drainage networks. NbS provide a natural treatment of rainwater and sustain aquifer and stream recharge. They allow to reduce the size of the collection and transfer systems and of the associated wastewater treatment plants, and their costs. The combination of soil, vegetation and root systems, associated with mycorrhizae, can fix and/or treat numerous pollutants (Lafforgue, 2016a). Heavy metals can be fixed in the superficial part of the soil, a better situation than in the sediments of the watercourses, where they could be remobilized. Among existing NbS (Fig. 1), we can mention: surface-flow constructed wetlands, which allow for a complementary purification of wastewater thanks to bacteria attached to plants and sediments; vegetated swales and rain gardens, which are islands of vegetation installed in cities to promote water infiltration into the soil and contribute to protect against heat island effects; or vegetated retention ponds, retaining water during heavy rainfalls and allowing infiltration of water (Boano et al., 2020; Penru et al., 2017; Simperler et al., 2020). For their part, vegetated roofs promote evapotranspiration of rainwater as well as thermal and sonic isolation of buildings.

Thus, NbS participate in a better integrated and global water management (Zölch et al., 2017; Jessup et al., 2021). They overcome the traditional opposition between water management for human uses and ecological preservation, in that they promote "design with nature" instead of "design against nature" (McHarg, 1967). When implemented with full consideration of the local context, they could prompt positive changes, help to reframe policy debates about climate change adaptation, increase the participation of citizens into risk management policy and planning, while reconciling responses to societal challenges and biodiversity conservation strategies under a common framework.

However, numerous barriers exist to the implementation of NbS (e.g., Seddon et al., 2020). Local governance has also critical effects on how NbS are applied and operated (Guerrin et al., 2023a). While NbS have been embraced at international scale, they are implemented in very different local contexts. Knowledge on how they are actually implemented remains partial and site dependant, while the NbS umbrella concept can lead to a variety of interpretations (Guerrin et al., 2023a). Local authorities worldwide are now investing in NbS projects. However, little is known about how the latter are understood and handled in different institutional, geographic, and socio-political contexts, especially when implemented by actors with different and sometimes conflicting goals, values, representations and sources of legitimacy (Guerrin et al., 2023a, 2023b; Drapier et al., 2024).

Therefore, water professionals are currently raising several

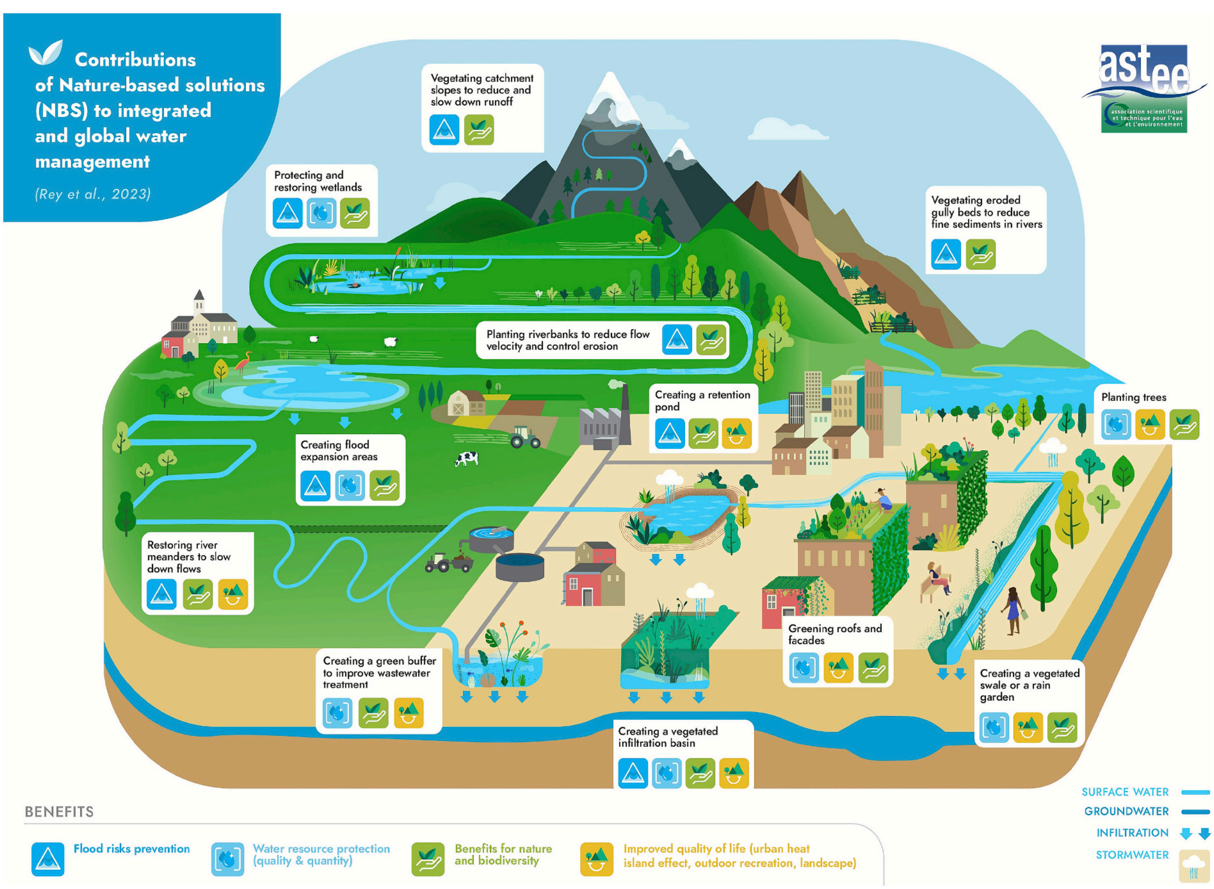

Fig. 1. NbS for preventing and mitigating water-related natural hazards (from Rey et al., 2023).

Fig. 2. Restoration of a degraded stream through meanders, in 2021 (a), 2022 (b) and 2023 (c) (Olon River, France; pictures by F. Rey).

questions, among which: How effective are NbS and what is the adequate scale of implementation? What is their range of effectiveness (e.g., from moderate to extreme climatic events?) and how can they be combined with existing or new grey infrastructures? How should they be designed to account for climate change? What kind of monitoring do they require before, during and after their implementation to ensure their long-term adaptive management and maintenance? What specific skills and governance are required for this? How can the appropriation process (i.e., by local authorities and citizens) be facilitated?

Ultimately, the question today is of seeing how, in their design and operational implementation, NbS can help better support the relationships between quantitative and qualitative issues related to water cycle, i.e., between the management of hydrological extremes (floods, low flows) and their effects, and the management of pollutants (suspended solids, pesticides, fertilizers, metals, hydrocarbons, etc.) or sediment flows. In such a context, the question concerns the interaction between climate change, water and ecosystems, and requires anticipation and adjustment of practices. Researchers must be involved in the discussions. They can report scientific results, experiences and case studies, analyse challenges and positive changes, and identify research gaps. To this end, we consider that pluridisciplinary and transdisciplinary approaches are of utmost importance in applied water-related projects maximising both benefits for biodiversity and benefits for society. This should allow identifying barriers and levers for a widespread use of NbS in the water sector.

2. Considering pluridisciplinary approaches for water management

Pluridisciplinary approaches are required to design effective and sustainable NbS actions for water management. Their application to aquatic environments entails investigations in the field of ecology, geosciences, economics, health sciences and human and social sciences. Such a pluridisciplinary approach should allow improving both resilience of ecosystems and water management, at adapted territorial scales (Rey, 2021).

For a large part, work on the concept of NbS has been developed in the field of ecology. In particular, research is regularly questioned in fields such as ecological engineering (Bergen et al., 2001), and soil and water bioengineering (Preti et al., 2022). For instance, climate change leads to new strategies aimed at preventing flood and drought. Threshold values, such as those characterizing the resistance of vegetated protection structures preventing flooding, may be adjusted. Species showing resistance today could not remain resilient in the future, and uncertainties are increasing. Alien species invasion and pest infestation are likely to occur and have tremendous impact on biodiversity, ecosystem resilience and human health. Control measures are therefore necessary, as improving biodiversity should not lead to uncontrolled detrimental consequences (Rey et al., 2019). Besides, through socio-ecological viewpoints, the application of NbS raises the question of the relevant spatial scales for NbS implementations (Guerrin et al., 2014; Babi Almenar et al., 2021). Local projects should also be understood as the successive steps of a longer-term process, where each step may contribute to a global and multi-annual project: the overall consistency in space and time is thus required. In addition, an increasing number of models allow to design and position vegetated structures more judiciously (Tardio and Mickovski, 2023). At the urban scale, as in more natural environments, where should these solutions be placed, with which technicity or should them be massified? The integration of surface-flow constructed wetlands used for water pollution treatment for instance involves a variety of fields and actors (Penru et al., 2017). Is it possible to quantify the potential of NbS by vegetation type (e.g., soil water retention during droughts, water quality and/or air quality protection, aquifer recharge, air temperature regulation, interactions with fauna, etc.)? The temporal scales are another key aspect of NbS, especially regarding ecology. Indeed, an ecosystem evolves with time and is not a static system, unlike grey infrastructures. In such a context, the medium to long term impacts of climate change jeopardise the capacity of species to develop and survive, and adaptation strategies should be considered in both the design and operation stages (Lafforgue, 2016b). Moreover, maintenance, ageing and rehabilitation of NbS for water management are also emerging concerns that require methodologies different from those applied to grey infrastructures (Langemeyer and Baro, 2021). This highlights the key issue of the maintenance of NbS. It is even more critical than for grey infrastructures since NbS are based on living species that have complex cross interactions between themselves and with their environment. Invasive species, pest infestations, climate change, soil properties evolutions, progressive contamination of NbS soils and substrates are examples of issues that can strongly impact the NbS performance. It is then essential to build relevant NbS monitoring and survey methods, allowing to adapt their operation and maintain their long-term efficiency. For this, when trying to maximize both benefits for biodiversity and benefits for society in the global water cycle, practitioners need methods and tools for assessing effectiveness and predict capability of NbS. Statistical approaches can be a good solution for relevant critical appraisal of provided solutions (Bouzouidia et al., 2021; Gómez et al., 2021).

Some questions relate more specifically to the regulation of water resources and their flows. Indeed, one of the goals of researchers today is to provide evidence of the roles played by aquatic and terrestrial ecosystems in preserving water resources (Gutry-Korycka, 2019). This includes the triptych “collect, store and use” rainwater, which must be considered in substitution of drinking water for certain uses. Which NbS can help meet this challenge? And what is their link with groundwater recharge or with the functioning of waterways? What is their impact on water quality? In particular, which natural water retention measures contribute to slowing the flow of water through the restoration of ecosystems or the modification of agricultural and silvicultural practices? As discussed previously, while NbS are increasingly used to address certain societal challenges, the issue of the most appropriate scale of action often remains unresolved for water management. The scales of imbricated watersheds seem to be the most consistent for a better management of the water cycle. However, decision-making is usually not structured according to hydrological categories (Guerrin et al., 2014; Fernandez et al., 2014). Different territorial scales, entities and levels of responsibilities can create difficulties in the implementation of NbS aimed at preventing flooding, limiting the impact of droughts, restoring biodiversity/ecosystems and preserving – or even increasing – the services provided by ecosystems. This is the reason why the implementation of NbS for water management requires institutional, human and financial innovations like new instruments of public or collective actions that better articulate hydrological and ecological issues (Lafforgue, 2018; Drapier et al., 2024).

NbS can be used for sustainable groundwater management, influencing groundwater recharge and quality. Adapted treatment processes may be necessary depending on the quality of the water to be infiltrated. The preservation and/or restoration of ecosystems in the recharge zone of surface aquifers can influence the quantitative and qualitative states of groundwater. It thus makes it possible to preserve or even improve several aquifer-dependent services, such as the storage and natural production of quality water, the supply of water to associated downstream ecosystems, and flood control. More recently, NbS have also been envisaged to improve the quantitative management of groundwater, by promoting stormwater infiltration, from natural recharge options to more technical solutions for controlled recharge (Herivaux and Marechal, 2021).

Another goal of researchers is to assess the effectiveness of NbS for water management associated with agro-ecological practices (Wynberg et al., 2023): diversification rather than intensification of cropping and livestock systems (longer crop rotations, plant associations, agroforestry, genetic diversity within species, etc.), and more broadly diversification of rural landscapes (grass strips, hedgerows, agroforestry, etc.). Their aims include regulating water and nutrient cycles (carbon, nitrogen, phosphorus), preserving habitats, or limiting the development of harmful and invasive species, leaching inputs and finally controlling pests, erosion and soil depletion. The objective is also to better assess the capacity of soil management to retain water in response to changes in vegetation cover and/or tillage techniques, for instance. Thus, how to optimize the management of water in agricultural environment, through adapted agro-ecological practices? This will highlight the effectiveness of NbS to contribute to the preservation of water, soil and biodiversity in agroecosystems, as well as in freshwater ecosystems.

In order to understand the double ecological and social dimensions of the management of water and biodiversity, questions on the rise of the concept of NbS, its origin, its appropriation, its implementation, its development modalities, and its consequences on the relationship of

Man to Nature must be addressed (Wang et al., 2022). The purpose of current and future research is to contribute to better conduct and support organisations in the implementation of NbS for water management. One possible way is by integrating the contours and the meanings of this concept, in relation to research and management practices that may or may not rely on it. Furthermore, such an integrated approach needs to consider not only environmental and social aspects, but also economic ones (Drapier et al., 2024). Another key point is the public perception of NbS and how people interact with them. It is a wide topic that must be investigated and promoted to avoid misunderstanding, wrong practices, and even loss of diversity and equilibrium. This interaction with the public must be included at the early stage of any NbS project, then accompanied during the first years, but also throughout mid- and long-term management (Anderson et al., 2021). Large local public involvement through participation would allow favoring local appropriation and fair practices related to NbS.

Economic approaches are particularly required to assess the relevance of NbS projects, guide their spatial and chronological implementation, and identify relevant policy instruments to promote and support their development. Economic rationale is a required step for public investment in NbS development projects in many contexts. Although guidelines for the economic assessment of NbS for water management have recently emerged through European funded projects (NAIAD, Nature4Cities, Regreen…), there is still limited evidence on the economic performance of NbS projects as compared to traditional grey strategies, implemented at the right scale and taking into account their breadth of co-benefits. Most existing evidence focus on urban contexts and rarely includes an explicit assessment of the reduction of water related risks generated by NbS scenarios (Herivaux and Le Coent, 2023). In addition, several authors point out the limitations of NbS for water management in the backdrop of financial implications and social issues (Teo et al., 2023). For example, Wübbelmann et al. (2022) demonstrate the limitations of NbS both under physical parameters (extreme rainfall events) and financial considerations (demand and supply budget approach to support practitioners). Finally, most policy-mandated economic assessment methods such as the one for flood mitigation projects in France (CGDD, 2018) account for benefits in terms of water risk reduction but fail to consider the contribution of NbS to an array of important policy objectives at the territorial scale. This may be particularly problematic since NbS may perform well only when all benefits are considered (Herivaux and Le Coent, 2023; Ruangpan et al., 2024), requiring to revisit the traditional economic assessment approaches.

The importance of NBS in economic activities remains under-emphasized. Chausson et al. (2024) conducted a systematic review of 66 articles on the economic impact of NBS. The study concerned in particular the security of water supply, as well as flood protection. The results are enlightening on the latest advances in NBS dealing with economic issues related to environmental issues. They showed positive results in terms of income and employment, influenced notably by factors such as the balance between short- and long-term benefits. It showed, as we will detail further in this article, the importance of citizen consultation, this population being then the first to benefit from the implementation of NbS projects, sources of job creation at different levels of competence.

The monetarisation of benefits promoted in some of these methods may provide some answers on the welfare impacts of NbS projects. This economic valuation toolbox can be enriched with methods allowing to account for the diversity of values associated with NbS benefits (Jacobs et al., 2016) as well as potential trade-offs among them. These tools should nevertheless not overlook the importance of integrating citizen demand as well as their spatial heterogeneity (Hérivaux and Le Coent, 2021), and especially their relation with spatial environmental inequalities (Herivaux and Marechal, 2021). Indeed, beyond their technical effectiveness, the capacity of NbS for water management to be socially just rather than generating negative effects and creating or exacerbating existing inequalities is still contested (Kotsila et al., 2021). Stakeholders may be more or less involved in the design and implementation of NbS programs (empowerment approach), more or less affected by the positive and negative effects of these solutions, and their preferences and values more or less considered. This heterogeneity of effects and potential inequalities can limit the societal acceptance of NbS and affect their implementation and long-term sustainability. Accounting for environmental and social justice in the design and assessment of NbS is a growing field of research.

In order to prioritise investments and design spatially explicit NbS upscaling pathways, decision support tools that consider spatial heterogeneity of costs and benefits need to be designed. Some promising decision support tools currently under development (see Farina et al., 2024) still need to be tailored to a diversity of contexts and turned into practical planning tools for planners. Innovative policy instruments ensuring that land owners (farmers, foresters, urban dwellers) receive effective incentives to modify their practices and land use for the implementation of NbS still need to be evaluated. Payment for environmental services programmes have been used in Europe mainly for the improvement of water quality but may be strategically tailored to the development of NbS aiming at reducing water-related risks. This is crucial when water use (such as drinking water supply) occurs downstream the place where NbS are developed. Indeed, they can be used for providing funds for NbS operational costs, promoting the long-term stability of the NbS efficiency (Lafforgue, 2018).

Policy and governance approaches are fundamental to achieve the effective implementation of NbS for water management given the prominence of institutional barriers (Nesshöver et al., 2017). If NbS are expected to be more participative and to enable cross-sectoral governance at the scale of territories, these characteristics must be analysed in practice. This involves conducting research on stakeholder systems and governance modalities of NbS, with the view of improving the resilience of territories to climate change impacts. This would include a better understanding of imposed, wanted or potential institutional changes within organisations (local authorities, socio-professional and inter-professional organisations, etc.) that seek or wish to seek to implement NbS that must, or will, adapt to resource management constraints. This research should also seek to analyse potential tensions and conflicts raised in the definition and the actual implementation of NbS, and of unexpected socio-political effects of NbS (such as gentrification or potential environmental injustices).

As NbS are not “one-size-fits-all” solutions, three dimensions are essential for them to be effective, sustainable, and socially accepted: planning, monitoring, and consultation. Planning ensures coherence and effectiveness. Monitoring before, during, and after the works, as well as long-term maintenance, guarantee performance and adaptability, as well as adaptative management of NbS. They are essential for NbS for water management because they ensure that the interventions meet their both ecological and hydrological objectives, properly adapt to local conditions, quickly detect any issue, and secure lasting environmental and social benefits over time. Finally, co-construction between planners and local communities would favor legitimacy and long-term sustainability. These three pillars are essential for NbS to deliver on their ecological and societal promises (Fig. 3) (Chrysoulakis et al., 2021). Planning, monitoring and consultation should allow simplifying the inherent complexity of the pluri-disciplinary approach in addressing success of water management considering environmental and societal issues with time. They are a good way to overcome the difficulties related to taking into account several types of benefits, environmental on one side and societal on the other. Success can be evaluated through different criteria such as: i) coherence of planned actions and optimized water resource allocation, considered through a long-term storage due to water surfaces, or phosphorus and nitrogen and their link with the eutrophication of aquatic environments; ii) various actions linked to local communities for inclusive governance, such as workshops, committees and consultations on water management (Fig. 3) (Frantzeskaki, 2019; Van Lierop et al., 2024).

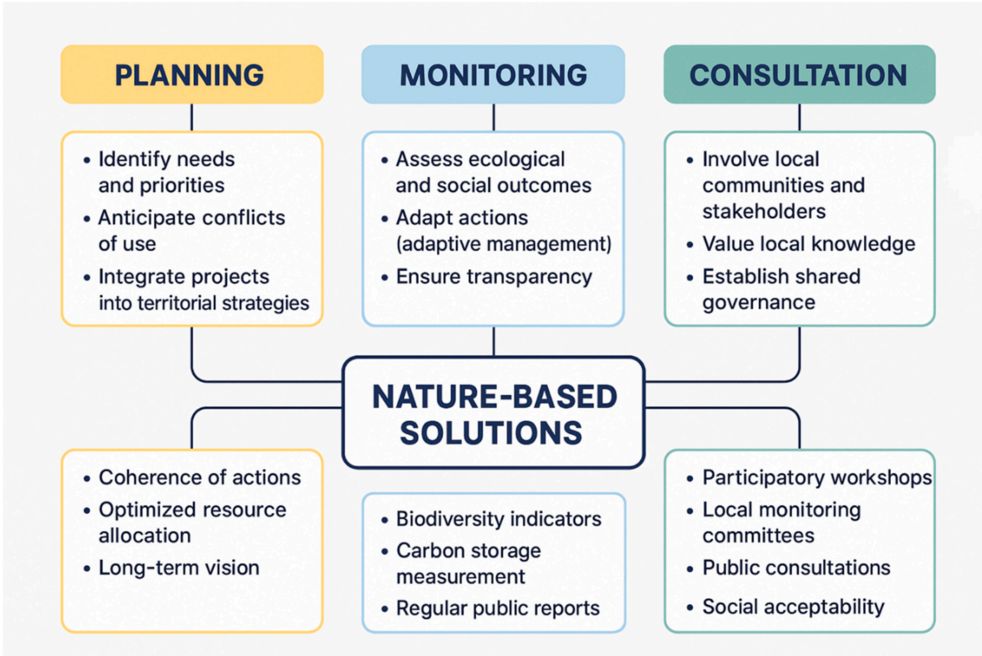

Fig. 3. For NbS to be effective, sustainable, and socially accepted, three key dimensions are essential: planning, monitoring, and consultation with local communities (upper part of the figure). They allow addressing success of water management considering environmental and societal issues with time (lower part of the figure).

Finally, whatever the scientific disciplines, limitations of NbS include different aspects on adaptability, effectiveness against extreme events, implementation time, cost, biodiversity and co-benefits, social acceptability, regulation and standards, and durability. Water management is particularly concerned considering their effectiveness facing extreme rainfall events or drought, conflicts due to different uses of water supply, and lack of regulation and standards leading to lack of clear reference frameworks for sharing water.

3. Transdisciplinary approaches to find the balance between gains for biodiversity and gains for society in the global water cycle

Transdisciplinary approaches should enable building dedicated frameworks for the application of NbS for water management. They must associate engineering and research, including civil society and stakeholders, for a connection and integration of knowledge and practices. A particular challenge is to characterise or evaluate the governance modes associated with NbS. This would involve answering the following questions, co-constructed between the different academic disciplines and the stakeholders: what type of governance is preferred, or should be sought, in the implementation of NbS? What should be the implication of civil society/ private actors/ local authorities? What institutional arrangements are favoured? What should be the integration of NbS in local public policies? Do NbS promote reworking in an effective and coordinated way the relations between environmental conservation policies and water policies? Finally, which methods for financial investments and operations should be adopted (Venkataramanan et al., 2020)?

A specific question deals with the obstacles presented by the implementation of NbS by practitioners, and the main consequences of these obstacles (Duffaut et al., 2022). Levers to activate the promotion of NbS could be: i) disseminate knowledge on aquatic and terrestrial ecosystems and NbS among practitioners; ii) strengthen governance around the implementation of NbS projects, for greater solidarity between the upstream and downstream parts of catchments (when preventing water-related natural risks), or at larger scales for questions around biodiversity; iii) facilitate the implementation of NbS through strong, appropriate and legitimate political decisions, enshrined in law, with dedicated and meaningful financial channels; iv) support socio-economic actors in setting up NbS by developing financial instruments; v) communicate on the multiple services provided by ecosystems to better involve and coordinate stakeholders in their actions of protection; and vi) identify governance models for application of NbS at the catchment scale, from transdisciplinary approaches (Young et al., 2019).

A relevant application of NbS requires adapted governance but also specific policies (Cohen-Shacham et al., 2019). How are NbS integrated into local public policies? Do NbS make it possible to effectively rework the relationship between environmental conservation policies and the ones dedicated to the sustainable management of water resources (see Guerrin et al., 2023a)? For this, an analysis of the actors' systems of territories related to catchments is necessary. It corresponds to actors and their decision criteria, as well as the modalities of governance of NbS, crossing considerations at the catchment level (i.e., scale of NbS application for preventing water risks and restoring biodiversity and ecosystems functioning, through ecological measures) and at the level of administrative or project territories (decision making scale).

Concerning management and recommendations, which methods should be applied for funding investments and operations? A larger decision-making system should ensure that the proposed solutions are feasible and that all co-benefits of a project are reachable and compatible, while also considering negative effects. It should facilitate going beyond the accommodation of different objectives, such as the reduction of damage and the preservation of biodiversity, so that the key challenge of integrating aquatic environment management with response to societal challenges can be met. An expected outcome could be to allow practitioners and engineers to find truly integrated solutions based on nature and maximize both benefits for biodiversity and benefits for the society in the global water cycle. This could be in the form of recommendations for defining NbS long-term maintenance, improving territorial organisation, providing increased resilience to climatic perturbations and more broadly to natural hazards related to water (erosion, runoff, floods, drought…), improving multi-stakeholders participation, and combining city and inter-city management (Lupp et al., 2021; Dumitru and Wendling, 2021). It is also essential to include the public participation and how they will interact with the NbS and will sustain/use them.

An attempt could be made to simplify the inherent complexity of both transdisciplinary and pluridisciplinary approaches in addressing success of water management considering environmental and societal issues with time (Ruggerio et al., 2024). Whether it is natural or anthropized, drinkable or worn out, dripping or rain-fed, we must (re) consider water within a systemic integrated way, that is borrowing it from the natural environment and restore it as clean as possible. This requires to have a renewed social contract to define which water uses are worth sustaining and which ones should be accompanied and transformed. Re-unifying the water cycle, by combining its natural part (rivers and aquatic environments) and its anthropized part (drinking water, sanitation and urban stormwater systems) appears as most advantageous for decision-makers and communities. Maintaining a distinction or even a full separation between natural and anthropized parts indeed leads to a compartmentalization of issues and skills. A truly integrated water management can thus better incorporate the unavoidable complexity of water ecosystems, connect the issues, their understanding and management, between opportunities and constraints. Floods, droughts, aquatic environments, water resources: there are ways to think globally about managing the common denominator that is water. More broadly, there are multiple examples of co-benefit actions that allow the security of water supply, while providing benefits for nature. These are often even "triple effects" actions, for those that also contribute to reducing the flood risks (Fig. 1). Among them, we can cite the preservation and restoration of wetlands, the development of flood expansion zones at the level of alluvial forests, or even the creation of vegetated infiltration basins.

4. Conclusion

NbS, seen as multi-benefits solutions, can allow envisioning a more integrated management of water considering jointly environmental and societal issues. Scientists occupy a prominent place in the design and the implementation process of these solutions. Research aims overall to better understand the structure and functioning of ecosystems affected or potentially affected by NbS projects. Relevant approaches must depart from traditional siloed approaches and become multidisciplinary, and even interdisciplinary. Very diverse as highlighted in this article, such approaches allow to evaluate the relevance of solutions, to identify and quantify the benefits by means of cost-benefit approaches and multicriteria decision aid methods, and even to ease their appropriation by public authorities and citizens. The scientific added value of this article lies mainly in the multidisciplinary approach inherent to the field of water, but which has rarely been addressed in such a comprehensive manner. We tried to bring together approaches from different scientific disciplines, going so far as to summon interdisciplinarity. But also presented things from the perspective of transdisciplinarity, to favour a more inclusive and effective implementation of NbS locally. However, this kind of approach calls for new, much more global research, whose results should become the knowledge base for engineers, managers, and decision-makers. These thoughts could pave the way for more disciplinary and transdisciplinary research since they combine approaches in several scientific disciplines, and involve various kinds of actors. Furthermore, interdisciplinarity has to be strongly promoted. It means associating knowledge from various disciplines that are often built separately, to enrich water representation and management which, in turn, can change the ways in which the disciplines are solicited or represent processes linked to water. For this, research should further come at the crossroads of ecology (structure and functioning of the initial ecosystem and its possible evolutions, associated ecosystem services, biotic and abiotic stresses of the site, integration of the transformed sites in the green/blue/brown/black frames, etc.), hydrology and hydrogeology (modelling of the height of the water line, runoff, infiltrated and evapotranspired flows, design of facilities for given positive impact, quantification of pollutant flows received, intercepted and released, etc.), social studies of water (perceptions and appropriation of populations, cultural aspects related to water, etc.), economics and management sciences (recognition and optimization of services provided, coupling of functions and uses, cost sharing, gentrification issues related to urban greening, etc.), geography (spatial integration, quality of landscapes, etc.), (micro)biology (impact on pathogens, etc.), political science, and public health and well-being. NbS are grounded on pluridisciplinary approaches and have multiple benefits using nature in development projects, whether in urban, peri-urban or rural areas. They respond to a major community issue, that of "ecological transition" using ecological engineering. Such a transition cannot be envisaged without considering many other areas such as agriculture, urbanism, mobility, climate change adaptation… Research must therefore be intensively developed, which means that it must produce and enhance knowledge to guide public policies, improve the know-how of managers and facilitate decision-making by stakeholders.

CRediT authorship contribution statement

Freddy Rey: Writing – original draft. **Jean-Luc Bertrand-Krajewski:** Writing – original draft. **Sara Fernandez:** Writing – original draft. **Joana Guerrin:** Writing – original draft. **Cécile Herivaux:** Writing – original draft. **Michel Lafforgue:** Writing – original draft. **Philippe Le Coent:** Writing – original draft. **Marie-Noëlle Pons:** Writing – original draft. **Bénédicte Rulleau:** Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank OFB for financial support through the Research Committee of ASTEE. This research was also partially funded by the DAPP of INRAE through the SONADES project.

Data availability

No data was used for the research described in the article.

References

Anderson, C.C., Renaud, F.G., Hanscomb, S., Munro, K.E., Gonzalez-Ollauri, A., Thomson, C.S., Pouta, E., Soini, K., Loupis, M., Panga, D., Stefanopoulou, M., 2021. Public acceptance of nature-based solutions for natural hazard risk reduction: survey findings from three study sites in Europe. Front. Environ. Sci. 9. https://doi.org/10.3389/fenvs.2021.678938.

Babi Almenar, J., Elliot, T., Rugani, B., Philippe, B., Navarrete Gutierrez, T., Sonnemann, G., Geneletti, D., 2021. Nexus between nature-based solutions, ecosystem services and urban challenges. Land Use Policy 100, 104898. https://doi.org/10.1016/j.landusepol.2020.104898.

Benyus, J., 1997. Biomimicry: Innovation Inspired by Nature. Harper Perennial, New York.

Bergen, S.D., Bolton, S.M., Fridley, J.L., 2001. Design principles for ecological engineering. Ecol. Eng. 18, 201–210.

Boano, F., Caruso, A., Costamagna, E., Ridolfi, L., Fiore, S., Demichelis, F., Galvao, A., Pisoeiro, J., Rizzo, A., Masi, F., 2020. A review of nature-based solutions for greywater treatment: applications, hydraulic design, and environmental benefits. Sci. Total Environ. 711, 134731. https://doi.org/10.1016/j.scitotenv.2019.134731.

Bouzouidia, R., Cannavo, P., Bodenan, P., et al., 2021. How to evaluate nature-based solutions performance for microclimate, water and soil management issues – available tools and methods from Nature4Cities European project results. Ecol. Indic. 125, 107556.

CGDD, 2018. Analyse multicritère des projets de prévention des inondations - Guide méthodologique 2018. Report, MTES, 785.

Chausson, A., Smith, A., Reger, R.Z.-Z., O'Callaghan, B., Mori Clement, Y., Zapata, F., et al., 2024. Harnessing nature-based solutions for economic recovery: a systematic review. PLOS Clim. 3 (10), e0000281. https://doi.org/10.1371/journal.pclm.0000281.

Choe, E.Y., Kenyon, A., Sharp, L., 2020. Designing Blue Green Infrastructure for Water Management, Human Health, and Wellbeing: Summary of Evidence and Principles for Design, 2020. University of Sheffield, Sheffield, UK. Available at https://orda.shef.ac.uk/articles/report/Designing_Blue_Green_Infrastructure_BGI_for_water_management_human_health_and_wellbeing_summary_of_evidence_and_principles_for_design/13049510/1 (accessed 03 July 2025).
Chrysoulakis, N., Somarakis, G., Stagakis, S., Mitraka, Z., Wong, M.-S., Ho, H.-C., 2021. Monitoring and evaluating nature-based solutions implementation in Urban areas by means of earth observation. Remote Sens. 13, 1503. https://doi.org/10.3390/rs13081503.
Cohen-Shacham, E., Andrade, A., et al., 2019. Core principles for successfully implementing and upscaling nature-based solutions. Environ. Sci. Pol. 98, 20–29.
Dicks, H., Bertrand-Krajewski, J.-L., Ménézo, C., Rahbé, Y., Pierron, J.-P., Harpet, C., 2021. Applying biomimicry to cities: the forest as model for urban planning and design. In: Nagenborg, M., Stone, T., González, Woge M., Vermaas, P.E. (Eds.), Technology and the City - Towards a Philosophy of Urban Technologies, vol. 36. Springer Nature Switzerland, Philosophy of Engineering and Technology, Cham (Switzerland), pp. 271–288. https://doi.org/10.1007/978-3-030-52313-8_14.
Drapier, L., Barbier, R., Bonnefond, M., Brochet, A., Fernandez, S., Fournier, M., Guerrin, J., Heitz, C., Kondolf, G.M., Pelet, J., Serra-Llobet, A., Rey, F., 2024. Les solutions fondées sur la nature pour la gestion des risques liés à l'eau : quelle institutionnalisation du concept en France ? Hydrosci. J. 1–23.
Duffaut, C., Frascaria-Lacoste, N., Versini, P.-A., 2022. Barriers and levers for the implantation of sustainable nature-based solutions in cities: insights from France. Sustainability 14, 9975. https://doi.org/10.3390/su14169975.
Dumitru, A., Wendling, L. (Eds.), 2021. Evaluating the Impact of Nature-based Solutions: A Handbook for Practitioners. European Commission EC. https://doi.org/10.2777/244577.
Farina, G., Le Coent, P., Neverre, N., 2024. Multi-objective optimization of rainwater infiltration infrastructures along an urban–rural gradient. Landsc. Urban Plan. 242, 104949. https://doi.org/10.1016/j.landurbplan.2023.104949.
Fernandez, S., Bouleau, G., Treyer, S., 2014. Bringing politics back into scenarios for water planning in Europe. J. Hydrol. 518, 17–27. https://doi.org/10.1016/j.jhydrol.2014.01.010.
Frantzeskaki, N., 2019. Seven lessons for planning nature-based solutions in cities. Environ. Sci. Pol. 93, 101–111. https://doi.org/10.1016/j.envsci.2018.12.033.
Gómez, Martín E., Máñez, Costa M., Egerer, S., Schneider, U.A., 2021. Assessing the long-term effectiveness of nature-based solutions under different climate change scenarios. Sci. Total Environ. 794 (10), 148515.
Guerrin, J., Bouleau, G., Grelot, F., 2014. Functional fit" versus "politics of scale" in the governance of floodplain retention capacity. J. Hydrol. 519, 2405–2414. https://doi.org/10.1016/j.jhydrol.2014.08.024.
Guerrin, J., Fernandez, S., Drapier, L., Llobet, A.S., Roche, C., 2023a. Que font les solutions fondées sur la nature aux politiques de gestion des risques liés à l'eau ? Dev. Durab. Territ. 14, 22771. https://doi.org/10.4000/developpementdurable.22771.
Guerrin, J., Serra-Llobet, A., Barbier, R., Bonnefond, M., Brochet, A., Drapier, L., Fernandez, S., Fournier, M., Heitz, C., Kondolf, G.M., Pelet, J., Rey, F., 2023b. Que sont les solutions fondées sur la nature pour la gestion du risque inondation ? Appropriations d'un concept international en France et aux Etats-Unis. Tech. Sci. Méthodes. 10, 97–119.
Gutry-Korycka, M., 2019. The influence of hydro-climatological balances and nature-based solutions (NBS) in the management of water resources. Meteorol. Hydrol. Water Manag. 8, 110415. https://doi.org/10.26491/mhwm/110415.
Hérivaux, C., Le Coent, P., 2021. Introducing nature into cities or preserving existing Peri-Urban ecosystems? Analysis of preferences in a rapidly urbanizing catchment. Sustainability 13, 587. https://doi.org/10.3390/su13020587.
Herivaux, C., Le Coent, P., 2023. Inégalités environnementales et hétérogénéité des préférences pour les solutions fondées sur la nature. Dev. Durab. Territ. 14, 23149. https://doi.org/10.4000/developpementdurable.23149.
Herivaux, C., Marechal, J.-C., 2021. Services écosystémiques et solutions fondées sur la nature: quelle place pour les eaux souterraines et pour les hydrogéologues? Géologues 207, 76–84.
IUCN French Committee, 2019. Nature-Based Solutions for Climate Change Adaptation and Disaster Risk Reduction. Paris, France.
Jacobs, S., Dendoncker, N., Martín-López, B., Barton, D.N., Gomez-Baggethun, E., Boeraeve, F., McGrath, F.L., Vierikko, K., Geneletti, D., Sevecke, K.J., Pipart, N., Primmer, E., Mederly, P., Schmidt, S., Aragão, A., Baral, H., Bark, R.H., Briceno, T., Brogna, D., Cabral, P., De Vreese, R., Liquete, C., Mueller, H., Peh, K. S.-H., Phelan, A., Rincón, A.R., Rogers, S.H., Turkelboom, F., Van Reeth, W., van Zanten, B. T., Wam, H.K., Washbourne., C.-L., 2016. A new valuation school: integrating diverse values of nature in resource and land use decisions. Ecosyst. Serv. 22 (B), 213–220. https://doi.org/10.1016/j.ecoser.2016.11.007.
Jessup, K., Parker, S.S., Randall, J.M., Cohen, B.S., Roderick-Jones, R., Ganguly, S., Sourial, J., 2021. Planting stormwater solutions: a methodology for siting nature-based solutions for pollution capture, habitat enhancement, and multiple health benefits. Urban For. Urban Green. 64, 127300. https://doi.org/10.1016/j.ufug.2021.127300.
Kotsila, P., Anguelovski, I., Baro, F., Langemeyer, J., Sekulova, F., Connolly, J.T., 2021. Nature-based solutions as discursive tools and contested practices in urban nature's neoliberalisation processes. Environ. Plann. E Nat. Space. 4 (2), 252–274. https://doi.org/10.1177/2514848620901437.
Lafforgue, M., 2016a. Impact of forests on water quality. In: Lachassagne, P., Lafforgue, M. (Eds.), Forest and the Water Cycle: Quantity, Quality, Management. Cambridge Scholars Publishing, pp. 204–265.
Lafforgue, M., 2016b. Climate change impacts on forest-water interactions and on forest management. In: Lachassagne, P., Lafforgue, M. (Eds.), Forest and the Water Cycle: Quantity, Quality, Management. Cambridge Scholars Publishing, pp. 612–649.
Lafforgue, M., 2018. Protéger la qualité des eaux des captages en bassins versants forestiers. TSM 5 (2018), 55–66.
Langemeyer, J., Baro, F., 2021. Nature-based solutions as nodes of green-blue infrastructure networks: a cross-scale, co-creation approach. Nat.-Based Solut. 1, 100006.
Lupp, G., Zingraff-Hamed, A., Huang, J.J., Oen, A., Pauleit, S., 2021. Living labs—a concept for co-designing nature-based solutions. Sustainability 13, 188.
McHarg, I.L., 1967. Design with Nature. John Wiley and Sons Inc., New York (USA), 25th anniversary edition 1992. 198 p. ISBN 978-0471-11460-4.
Nesshöver, C., Assmuth, T., et al., 2017. The science, policy and practice of nature-based solutions: an interdisciplinary perspective. Sci. Total Environ. 579, 1215–1227.
Penru, Y., Polard, T., Amalric, M., Cirelli, C., Bacchi, M., Lafforgue, M., Shuehmacher, J., Chambolle, M., Lebas, M.A., Prohin, P., Mehdi, L., Di Pietro, F., Larrue, C., Sellier, A., Cadiere, A., Som, P., Tapie, N., Budzinski, H., Martin, Ruel S., Perridy, L., 2017. L'ingénierie écologique appliquée aux zones de rejet végétalisées: élimination de micropolluants, biodiversité et intégration socio-territoriale. TSM 12 (2017), 157–186.
Preti, F., Capobianco, V., Sangalli, P., 2022. Soil and water bioengineering (SWB) is and has always been a nature-based solution (NBS): a reasoned comparison of terms and definitions. Ecol. Eng. 181, 106687.
Ramirez-Agudelo, N.A., Anento, R.P., Villares, M., Roca, E., 2020. Nature-based solutions for water management in peri-urban areas: barriers and lessons learned from implementation experiences. Sustainability 12, 9799. https://doi.org/10.3390/su12239799.
Rey, F., 2021. Harmonizing erosion control and flood prevention with restoration of biodiversity through ecological engineering used as co-benefits Nature-based solutions. Sustainability 13, 11150.
Rey, F., Bifulco, C., Bischetti, G.B., Bourrier, F., De Cesare, G., Florineth, F., Graf, F., Marden, M., Mickovski, S., Phillips, C., Peklo, K., Poesen, J., Polster, D., Preti, F., Rauch, H.P., Raymond, P., Sangalli, P., Tardio, G., Stokes, A., 2019. Soil and water bioengineering: practice and research needs for reconciling natural hazard control and ecological restoration. Sci. Total Environ. 648, 1210–1218.
Rey, F., Fernandez, S., Rulleau, B., Pons, M.N., Bertrand-Krajewski, J.-L., Lafforgue, M., 2023. Les solutions fondées sur la nature: quelles recherches pour répondre aux défis de la gestion de l'eau? Tech. Sci. Méthodes. 9, 59–69.
Ruangpan, L., Vojinovic, Z., Plavsic, J., Curran, A., Rosic, N., Pudar, R., Savic, D., Brdjanovic, D., 2024. Economic assessment of nature-based solutions to reduce flood risk and enhance co-benefits. J. Environ. Manag. 352, 119985. https://doi.org/10.1016/j.jenvman.2023.119985.
Ruggerio, C.A., Cisneros, R.L., Mendez-Lemus, Y., 2024. A complex transdisciplinary approach to achieve water sustainability: lessons from a case study in Morelia, Mexico. Sustain. Sci. 19 (3), 1–13.
Seddon, N., Chausson, A., Berry, P., Girardin, C.A.J., Smith, A., Turner, B., 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philos. Trans. R. Soc. B 375, 20190120. https://doi.org/10.1098/rstb.2019.0120.
Simperler, L., Ertl, T., Matzinger, A., 2020. Spatial compatibility of implementing nature-based solutions for reducing urban heat islands and stormwater pollution. Sustainability 12, 5967. https://doi.org/10.3390/su12155967.
Tardio, G., Mickovski, S.B., 2023. A novel integrated design methodology for nature-based solutions and soil and water bioengineering interventions: the Tardio & Mickovski methodology. Sustainability 15, 3044. https://doi.org/10.3390/su15043044.
Teo, F.Y., Aziz, F., Di Francesco, F., Förster, K., 2023. Editorial: potential and limitations of nature-based solutions (NbS) to global water challenges. Front. Water Sec. Water Resour. Manag. 5. https://doi.org/10.3389/frwa.2023.1278462.
Van Lierop, M., Dobbs, C., Flores, C., van der Jagt, A., Skiba, A., Maselli, Locosselli G., Duarte, D., Buijs, A., Zingraff-Hamed, A., Pauleit, S., 2024. Monitoring and assessment in the context of governance of nature-based solutions. Shared challenges and opportunities in CELAC and EU cities. Nat.-Based Solut. 6, 100170. https://doi.org/10.1016/j.nbsj.2024.100170.
Venkataramanan, V., Lopez, D., Mccuskey, D.J., Kiefus, D., Mcdonald, R.I., Miller, W.M., Packman, A.I., Young, S.L., 2020. Knowledge, attitudes, intentions, and behavior related to green infrastructure for flood management: a systematic literature review. Sci. Total Environ. 720, 137606. https://doi.org/10.1016/j.scitotenv.2020.137606.
Wang, X., Wang, J., Wang, B., Burkhard, B., Che, L., Dai, C., Zheng, L., 2022. The nature-based ecological engineering paradigm: symbiosis, coupling, and coordination. Engineering 19, 14–21.
Wübbelmann, T., Bouwer, L., Förster, K., Bender, S., Burkhard, B., 2022. Urban ecosystems and heavy rainfall—a flood regulating ecosystem service modelling approach for extreme events on the local scale. One Ecosyst. 7, e87458. https://doi.org/10.3897/oneeco.7.e87458.
Wynberg, R., Pimbert, M., Moeller, N., Mcallister, G., Kerr, R.B., Singh, J., Belay, M., Ngcoya, M., 2023. Nature-based solutions and agroecology: business as usual or an opportunity for transformative change? Environ. Sci. Policy Sustain. Dev. 65 (1), 15–22. https://doi.org/10.1080/00139157.2023.2146944.
Young, A.F., Marengo, J.A., et al., 2019. The role of nature-based solutions in disaster risk reduction: the decision maker's perspectives on urban resilience in Sao Paulo state. Int. J. Disaster Risk Reduct. 39, 101219.
Zölch, T., Henze, L., Keilholz, P., Pauleit, S., 2017. Regulating urban surface runoff through nature-based solutions – an assessment at the micro-scale. Environ. Res. 157, 135–144. https://doi.org/10.1016/j.envres.2017.05.023.