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REVIEW

The potential for nature-based solutions to combat the freshwater biodiversity crisis

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Abstract

Enthusiasm for and investments in nature-based solutions (NBS) as sustainable strategies for climate adaptation and infrastructure development is building among governments, the scientific community, and engineering practitioners. This is particularly true for water security and water-related risks. In a freshwater context, NBS may provide much-needed "win-wins" for society and the environment that could benefit imperiled freshwater biodiversity. Such conservation benefits are urgently needed given the ongoing freshwater biodiversity crisis, with declines in freshwater species and their habitats occurring at more than twice the rate of marine or terrestrial systems. However, for NBS to make meaningful contributions to safeguarding freshwater biodiversity, clear links must be established between NBS applications and priorities for conservation. In this paper, we link common water-related NBS to six priority actions for freshwater life established by the conservation science n community, and highlight priority research and knowledge that will be necessary to bring NBS to bear on the freshwater biodiversity crisis. In particular, we illustrate how NBS can play a direct role in restoring degraded aquatic and floodplain ecosystems, enhancing in-stream water quality, and improving hydrological connectivity among freshwater ecosystems. System-level monitoring is needed to ensure that freshwater NBS deliver on their promised benefits for ecosystems and species.

Introduction

Interest and investment in nature-based solutions (NBS) is growing rapidly worldwide, motivated by the promise of economically viable climate change adaptation strategies that can simultaneously deliver social and environmental co-benefits [1,2]. The term NBS encompasses naturally occurring, restored, and artificial ecosystems that deliver ecosystem services to address key societal needs; it also includes management actions taken to protect or enhance those ecosystems and their services. These services include flood control, water quality improvement, the provision of economic and recreational opportunities, and the replenishment of water supplies, among others. NBS have been promoted as "win-wins" for society and the environment because they can restore or protect habitats while ensuring the sustainable delivery of key ecosystem services. Decision-makers are increasingly looking to NBS to meet rising global infrastructure needs for flood risk management, erosion reduction, and water, sanitation, and hygiene (also known as WASH) [3–6].

At the same time, freshwater species are declining at rates greatly exceeding terrestrial and marine taxa, due to multiple stressors including invasive species, river flow modification, water abstraction, pollution, and overharvest [7,8]. More than half of all freshwater megafauna assessed by the International Union for the Conservation of Nature are threatened [9], and the World Wildlife Fund's index of freshwater vertebrate populations indicates an 83% decline over the last fifty years–more than twice the rates of decline observed in terrestrial or marine realms [10]. Furthermore, since freshwater biodiversity provides critical ecosystem services to human communities [11], a collapse in freshwater biodiversity has alarming implications for human well-being, particularly for indigenous and marginalized populations. The freshwater biodiversity crisis continues largely unchecked due to the extreme under-funding of conservation actions and pervasive management of freshwater resources for human needs via conventional infrastructure, often to the direct detriment of freshwater ecosystems and wildlife [12,13]. In this context, NBS have been highlighted as alternatives to meet human infrastructure needs while turning the tide for freshwater life [14].

However, the question remains: can NBS actually deliver on promises for biodiversity conservation while providing essential infrastructure and climate adaptation services? Presently, much of the ecological and biodiversity-specific language around NBS is vague and general, referring only to the creation of habitat or restoration of ecological functions that support biodiversity. The excitement surrounding NBS runs the risk of outpacing the evidence and understanding needed for their implementation, a problem faced by other popular sustainability concepts [1,15]. If NBS are to be a successful tool for safeguarding freshwater biodiversity, more robust links must be established between individual NBS approaches and concrete, ecological conservation objectives (e.g., changes in the demographic rates of species of concern, restoration of ecosystem functions). Explicit connections between freshwater NBS and specific biodiversity conservation goals will facilitate the leverage of infrastructure investments toward combating the ongoing freshwater diversity crisis. Here, we highlight key linkages between widely implemented freshwater NBS and the six priority actions for freshwater biodiversity conservation identified by Tickner et al. [13] (Table 1). For each of these priority actions, we conducted a targeted review of available peer-reviewed and gray literature to assess whether commonly-implemented water-related NBS directly, indirectly, or did not affect those conservation goals. Finally, we discuss the critical knowledge gaps and challenges that require assessment to improve our understanding of the linkages and tradeoffs associated with NBS and biodiversity-based outcomes.

Table 1. Tickner et al. [13]'s 6 priority actions for freshwater biodiversity conservation.

1. Accelerate implementation of environmental flows
2. Improve water quality
3. Protect and restore critical habitats
4. Manage exploitation of species and riverine aggregates
5. Prevent and control non-native species invasions
6. Safeguard and restore freshwater connectivity

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Methods

Our interdisciplinary team conducted a targeted literature search of peer-reviewed and gray literature on NBS, including U.S. Army Corps of Engineers technical reports and presentations. A complete list of search terms used in Google Scholar and Web of Science™ can be found in (S1 Text). We organized our search around specific types of freshwater management NBS and investigated whether they had documented or perceived potential impacts on each of Tickner et al. [13]'s six priority conservation actions. Our list of water-related NBS was assembled using the freshwater case studies described in the U.S. Army Corps of Engineers Engineering With Nature initiative's EWN Atlas Volumes 1 and 2 [16,17].

Given that monitoring data and evidence for assessing the biodiversity impacts of NBS are extraordinarily scarce [18], we restricted our analysis to a qualitative rating system of the degree of connection between NBS and conservation actions. We classified the potential pathways for influence of NBS on conservation goals as Direct, Indirect, or Not Applicable. We called linkages *Direct* where the primary or planned outcome of a nature-based solution resulted in conservation gains for a given action, *Indirect* where conservation gains might be possible through some intermediary ecological or hydrological process, and *Not Applicable* where we perceived no mechanism by which a given nature-based solution could contribute to a given conservation goal.

Nature-based solutions for freshwater management

A multitude of infrastructure and ecosystem management strategies might be considered NBS. We establish a working definition for this paper based on that of the U.S federal government, which states that NBS include ". . . actions to protect, sustainably manage, or restore natural or modified ecosystems as solutions to societal challenges," [19], with the caveat that we also consider artificial or created habitats like stormwater retention ponds as a form of NBS. Importantly, we view NBS as one integral part of a broader approach to nature-positive civil infrastructure management. For a list of NBS and other infrastructure management actions considered in this paper and their relevant categorization, see Table 2.

Connections between NBS and the priority actions for freshwater biodiversity

Safeguard and restore freshwater connectivity

The hydrological connectivity of freshwater systems across multiple dimensions (channel-floodplain, surface-groundwater, upstream-downstream, and temporal) is crucial for supporting biodiverse freshwater ecosystems [20]. Longitudinal (upstream-downstream) connectivity in riverine systems allows for migratory species to complete their life cycles and maintains population connectivity in aquatic habitats, while lateral (channel-floodplain) connectivity provides nesting and rearing areas for aquatic taxa and maintains terrestrial wetland habitats and their disturbance regimes. Vertical (surface-groundwater) connectivity stabilizes base flows during dry periods and supports species that are dependent on hyporheic habitats [21,22]. Our literature synthesis suggests that NBS actions may have excellent potential to enhance freshwater connectivity across each of these dimensions.

One prominent example for longitudinal connectivity is river restoration via the removal of dams, weirs and culverts. Barrier removals comprise an important catchment management and restoration action that can result in societal benefits, and can hence be considered a NBS. For instance, the removal of aging or obsolete dams can not only address important safety and economic concerns, but can also generate societal and environmental co-benefits including,

Table 2. Examples of conventional and natural infrastructure management actions relevant to freshwater biodiversity conservation in the Anthropocene.

Freshwater Infrastructure Management Action	Examples
Habitat protection, including strategic conservation planning	• Conservation land purchases* • Payment for watershed ecosystem services* • Riparian buffer management* • Land use planning and zoning*
Strategic impact avoidance	• Dam and levee siting • Routing of linear infrastructure (e.g., roads, power grids, pipelines)
Habitat restoration and enhancement	• In-stream restoration* • Invasive species removal* • Streambank restoration* • Floodplain reconnection*
De novo infrastructure construction	• Stormwater retention ponds, rain gardens, and other forms of green infrastructure* • Urban forests* • Drainage swales*
Altered operations of existing infrastructure	• Environmental flows & dam releases • Water withdrawal strategies • Port and channel maintenance via dredging operations
Modification of existing infrastructure	• Levee setbacks* • Dike and weir notching* • Fish bypasses, ladders, and other appurtenance structures*
Removal of aging infrastructure or replacement of services	• Dam removals* • Levee decommissioning
Natural asset management	• Ecological monitoring of NBS • Community-based management

Nature-based solutions (NBS) are marked with an asterisk (*).

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but not limited to, floodplain and delta restoration through sediment redistribution, improved water quality, and recreational fisheries. Given the high costs of repairs, safety concerns, and environmental impacts of aging infrastructure, barrier removals are gaining popularity in industrialized countries. For instance, of the ~1,900 dams removed in the U.S. since 1912, 57 were removed in 2021 alone, cumulatively reconnecting 2,131 miles of upstream river length [23]. Despite potential short-term disruptive effects of barrier removals, evidence suggests that fragmentation-threatened taxa recover rapidly following dam removals; this is particularly true of anadromous species [24,25]. The restoration of riverine ecosystems via barrier removal can influence biodiversity outcomes via several pathways including increased in-stream and floodplain habitat diversity and availability, access to spawning grounds, and increased productivity [24].

Spatial prioritization tools can identify critical barriers whose removal maximizes gains in connectivity and benefits targeted biodiversity outcomes [26–28]. Alternatively, in regions where dam building is ongoing, new construction can be strategically planned to reduce impacts on freshwater connectivity via optimization analyses [29,30] and impact-level classifications of proposed dams [31,32] in basins with high freshwater biodiversity. This systematic infrastructure management and planning can be used in conjunction with NBS to improve conservation outcomes when managing for multiple societal benefits.

Levee setbacks and floodplain restoration projects can improve lateral and vertical connectivity by reuniting a river with its former floodplain [33,34]. Although primarily implemented for flood risk reduction, these projects restore floodplain habitat by relocating levees further from the river channel, creating more space for channel migration and inundation during high flows. Levee setbacks thus enhance lateral connectivity, typically improving in-stream water quality and increasing species diversity [35,36]. This may include the recovery of flood-tolerant riparian vegetation communities [37], creation of feeding, spawning, and nursery habitat for native fishes [38], and enhanced habitat for other aquatic taxa such as macrophytes, mollusks, odonates, amphibians, and waterbirds [36,39].

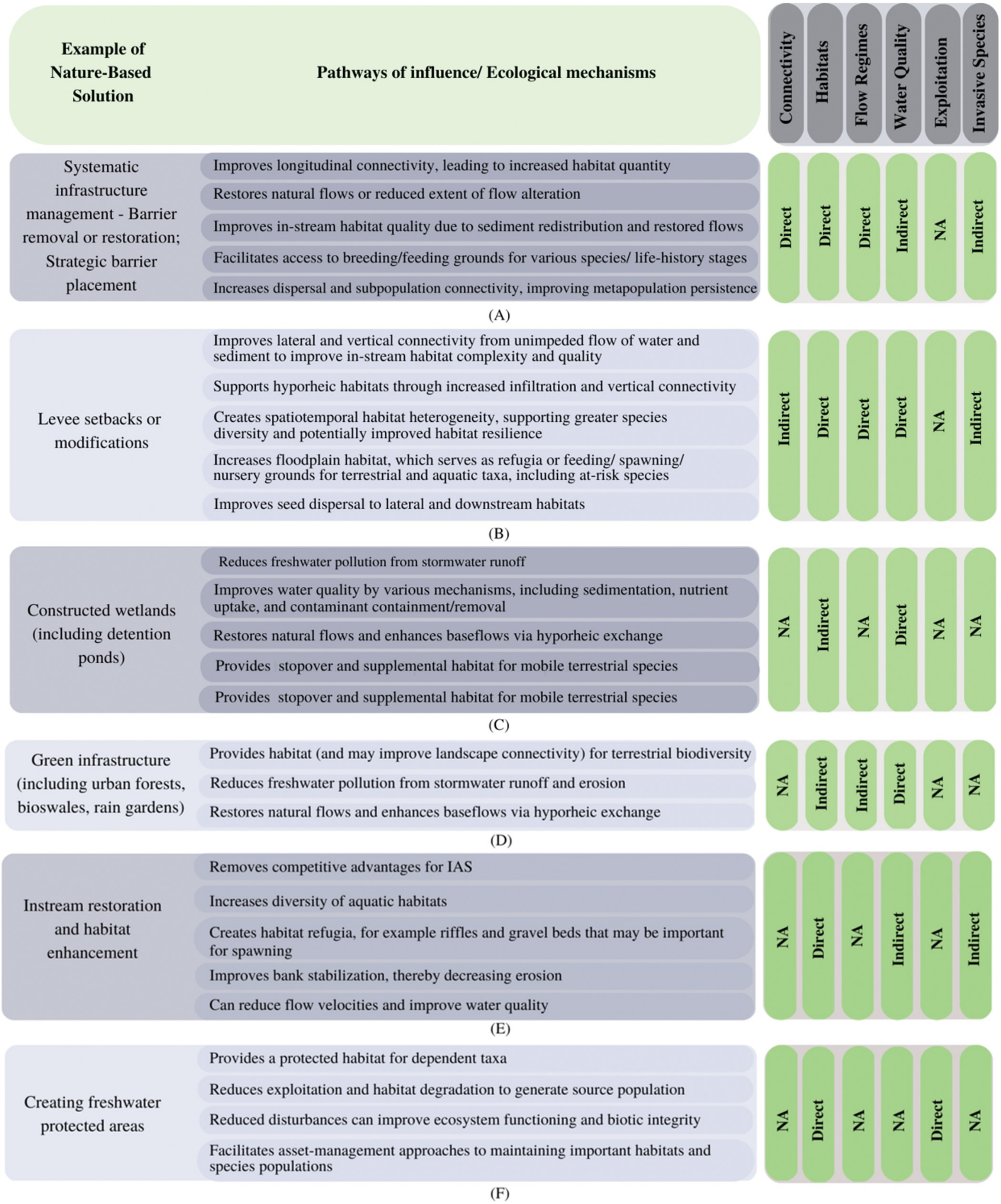
In cases where NBS restore riparian corridors for societal goals like flood or water quality management, such as via reforestation programs, they may enhance population connectivity for terrestrial and semi-aquatic species, including birds, bats, insects, herpetofauna, rodents, and wide-ranging mammalian species [40–44]. Floodplain restoration also increases vertical connectivity, promoting enhanced groundwater recharge, base flows during droughts, and biogeochemical cycling, which increase the resilience of the local ecological community to climate stressors [34].

Protect and restore critical habitats

NBS projects that create, restore and protect habitats as part of multi-purpose landscapes can support freshwater biodiversity while also providing other climate-related, economic, and socio-cultural benefits [45]. Framing or justifying ecosystem protection as an investment in NBS could greatly increase opportunities for safeguarding valuable and biodiverse freshwater and terrestrial habitats where ecosystem services are aligned with infrastructure needs. This sort of non-traditional pathway to habitat protection might be a key tool in achieving the ambitious protected area goals being set for the coming decade (e.g., the 30x30 initiative) [46]. Viewed in this light, protected areas managed as NBS are a form of “Other Effective area-based Conservation Measures” (better known as OECMs), an essential complement to protected areas needed to reach area-based conservation goals [47]. In other words, they provide an excellent alternative to potentially problematic “fortress conservation” practices around establishing protected lands, which might exclude or disenfranchise local communities [48]. Such issues of conservation equity are hugely important for sustainable conservation outcomes, yet remain poorly recognized and studied. Where legal frameworks are in place, conservation easements can leverage private land for conservation, be tailored for specific landowners, and strategically acquired to improve connectivity [49–51].

Funds in support of NBS can also increase available habitat for freshwater biodiversity by driving habitat restoration, enhancement, and creation outside of protected areas, for example in agricultural and urban landscapes (Fig 1). By dint of their multiple objectives, NBS projects can bring funding directed toward other societal goals (e.g., water supply or flood control) to bear on conservation goals where other societal objectives can be achieved. This framing increases available financial support for projects that increase habitat quantity and quality for local biodiversity [6].

Floodplain and in-stream restoration can increase habitat diversity and provide refugia for aquatic biota [52,53], while also providing a range of services, including flood protection and water quality enhancement. Levee setbacks are one such restoration-based NBS that provides flood control services while avoiding the rising maintenance costs of aging or poorly sited levees and simultaneously providing conservation benefits [35]. This type of restoration is especially critical, given steep historical losses of floodplains and the diverse and specialized biota that they support [54]. Given the ability for levee setbacks, barrier removals and e-flows to restore hydrology within river channels, these NBS and infrastructure management strategies may contribute to aquatic habitat availability across entire riverscapes. For example,



	Example of Nature-Based Solution	Pathways of influence/ Ecological mechanisms	Connectivity	Habitats	Flow Regimes	Water Quality	Exploitation	Invasive Species
(A)	Systematic infrastructure management - Barrier removal or restoration; Strategic barrier placement	Improves longitudinal connectivity, leading to increased habitat quantity Restores natural flows or reduced extent of flow alteration Improves in-stream habitat quality due to sediment redistribution and restored flows Facilitates access to breeding/feeding grounds for various species/ life-history stages Increases dispersal and subpopulation connectivity, improving metapopulation persistence	Direct	Direct	Direct	Indirect	NA	Indirect
(B)	Levee setbacks or modifications	Improves lateral and vertical connectivity from unimpeded flow of water and sediment to improve in-stream habitat complexity and quality Supports hyporheic habitats through increased infiltration and vertical connectivity Creates spatiotemporal habitat heterogeneity, supporting greater species diversity and potentially improved habitat resilience Increases floodplain habitat, which serves as refugia or feeding/ spawning/ nursery grounds for terrestrial and aquatic taxa, including at-risk species Improves seed dispersal to lateral and downstream habitats	Indirect	Direct	Direct	Direct	NA	Indirect
(C)	Constructed wetlands (including detention ponds)	Reduces freshwater pollution from stormwater runoff Improves water quality by various mechanisms, including sedimentation, nutrient uptake, and contaminant containment/removal Restores natural flows and enhances baseflows via hyporheic exchange Provides stopover and supplemental habitat for mobile terrestrial species Provides stopover and supplemental habitat for mobile terrestrial species	NA	Indirect	NA	Direct	NA	NA
(D)	Green infrastructure (including urban forests, bioswales, rain gardens)	Provides habitat (and may improve landscape connectivity) for terrestrial biodiversity Reduces freshwater pollution from stormwater runoff and erosion Restores natural flows and enhances baseflows via hyporheic exchange	NA	Indirect	Indirect	Direct	NA	NA
(E)	Instream restoration and habitat enhancement	Removes competitive advantages for IAS Increases diversity of aquatic habitats Creates habitat refugia, for example riffles and gravel beds that may be important for spawning Improves bank stabilization, thereby decreasing erosion Can reduce flow velocities and improve water quality	NA	Direct	NA	Indirect	NA	Indirect
(F)	Creating freshwater protected areas	Provides a protected habitat for dependent taxa Reduces exploitation and habitat degradation to generate source population Reduced disturbances can improve ecosystem functioning and biotic integrity Facilitates asset-management approaches to maintaining important habitats and species populations	NA	Direct	NA	NA	Direct	NA

Fig 1. Linkages between common freshwater nature-based solutions (NBS) and priority actions derived from Tickner et al. [13]'s emergency recovery plan for freshwater biodiversity. D stands for Direct effects on conservation outcomes via the linkage, I stands for Indirect, and NA indicates no effect or Non-Applicable.

https://doi.org/10.1371/journal.pwat.0000126.g001 declining terrestrial species like neotropical migratory songbirds and insectivorous bats typically prefer riparian habitats for foraging and nesting, ostensibly relying on nutritionally important exports of emergent aquatic insects [55,56]. Given the potential for restored floodplains to greatly increase food availability for such threatened taxa, the conservation benefits of levee setbacks may extend well beyond the river channel [57].

Accelerate implementation of environmental flows

Flow is a key factor in the maintenance of aquatic ecosystems, providing necessary aquatic habitats throughout species' life stages, cues for reproduction, migration, and dispersal, and access to floodplain and off-channel habitats [58]. Environmental flows (hereafter e-flows), the deliberate management of flow regimes for ecological outcomes via dam and reservoir operations, are an essential tool for freshwater biodiversity conservation [14,59] with growing evidence for effective implementation [60]. NBS can contribute indirectly to the broader implementation of environmental flows, and to the creation of ecological conditions envisioned by e-flows implementation. (Fig 1).

Stakeholder buy-in is a major limiting factor in global e-flows implementation [12,61,62]. The multi-purpose and service-focused framing of NBS could contribute to overcoming this barrier and accelerating the implementation of e-flows, with the ultimate goal of enhancing flow regimes and biodiversity in riverine systems. Where the hydrological and ecological functions of biodiverse riverscapes can be aligned with societal infrastructure needs, NBS approaches might provide compelling motivation toward restoring and managing flows, indirectly supporting this conservation action.

For example, levee setbacks and the resulting reconnection of floodplains can provide space for ecological flows to build complex in-stream habitats that support biodiverse communities. While they do not directly affect flow regimes, levee setback projects reduce constrictions on the river channel, allowing erosion-accretion dynamics leading to meanders, cutoffs, point bars, pools, riffles, and other valuable in-stream habitat features which are often among the end-goals of e-flows implementation [62–64]. Where such NBS projects can be implemented in river reaches managed via e-flows, the biodiversity benefits of flow allocations may be greatly enhanced. Dam removals, when viewed as a large-scale infrastructure management decision, contribute directly to e-flows by eliminating some controls on river flow within a basin.

Green infrastructure such as bioswales, constructed forests, rain gardens and detention ponds in urban areas can improve the timing and quality of flow as well as support groundwater recharge and base flows [65,66]. Urban streams tend to have flashier hydrographs, impaired water quality, lower biotic richness, and degraded channel morphology [67]. In areas that rely on surface water for water supply, green infrastructure can be a valuable tool that supports more stable water quality and quantity that can lead to more biodiverse and resilient ecological communities in urban areas. These NBS have been growing in popularity for their multiple benefits of flood control, improving water quality, and providing green spaces for local residents [68–70].

Improve water quality

Water pollution is a pervasive pressure on freshwater systems, putting physiological stress on aquatic organisms via reduction in oxygen levels, increased temperatures, excessive algal growth, and increased turbidity, and driving system-scale eutrophication of freshwater habitats 71,72]. The capacity for NBS to enhance water quality, especially in urban and agricultural contexts, is well-studied relative to other forms of NBS implementation [3,73,74]. Where they can be strategically implemented to improve the condition of impaired aquatic ecosystems while delivering other services, NBS could be an indispensable tool for addressing this threat to freshwater biodiversity (Fig 1).

NBS such as constructed wetlands, restored floodplains, detention ponds, and barrier removals can improve freshwater quality through various mechanisms including sedimentation, denitrification, and anaerobic ammonium oxidation [75,76]. For instance, constructed wetlands remove pollutants and excess nutrients, such as nitrogen and phosphorus, from stormwater runoff by increasing residence time and providing conditions for the metabolism and settling [77,78]. These nutrients are absorbed by the soil and taken up by plants and microorganisms [79]. In Nevada (United States), pilot-scale constructed wetlands removed an estimated 62% nitrogen, 38% phosphorus, and 84% sediment [77], from non-point sources combating eutrophication. Constructed wetlands also efficiently remove biologically harmful compounds like pharmaceutical and personal care products and linear alkyl benzene sulfonates from wastewater [80,81], reducing their ecotoxicological effect on aquatic organisms [82]. Even small, isolated ponds constructed for water quality can provide valuable habitat for urban biodiversity [83,84].

Levee setbacks and e-flows can greatly improve within-channel water quality [75,85]. These NBS practices reduce erosion and excess sediment influx on the river and improve downstream water quality by reducing flow velocity, dissipating the energy of flood peaks, and increasing the residence time of water in the floodplain, where pollutants can settle out or be metabolized [76,86]. The restoration of flooding dynamics by levee setbacks provides ideal conditions for denitrification (low oxygen and abundant organic carbon), by local bacterial assemblages, leading to the removal of bioavailable nitrogen from the water column and improvements in water quality [87]. This is especially important in agricultural catchments where fertilizer runoff can trigger algal blooms and other disruptive pressures on aquatic life [88].

Green stormwater management practices are another important NBS approach for reducing water pollution effects on freshwater biodiversity [89]. These contribute substantially to freshwater quality improvement by reducing sedimentation and nutrient influx to local waterways. This practice has been formalized in the "sponge cities" concept in China, where urban greenspaces and restored wetlands are being used to address a variety of water security and water management issues in densely populated areas [90]. Green stormwater infrastructure practices also create urban freshwater habitats that support local wildlife [91,92]. In Hawai'i, urban stormwater NBS like drainage swales and ditches provide not only habitat, but facilitate landscape-scale movements and enhanced population connectivity in an endangered waterbird [93]. Such contributions not only to total habitat but also landscape connectivity could support biodiversity in urban wetlands.

Manage exploitation of species and riverine aggregates

The exploitation of freshwater ecosystems for fish and other wildlife harvest, as well as sand and gravel mining, are major drivers of ecological decline, where the former results in direct reductions in wildlife populations, and the latter degrades important riparian ecosystems [71]. The capacity of NBS to directly address this issue appears limited, largely because extractive activities from freshwater ecosystems are often undertaken by different stakeholder groups than those in charge of implementing NBS. However, there are indirect pathways by which NBS and their management could reduce the impacts of exploitation.

The creation of community-based freshwater protected areas with enforced regulatory mechanisms is a commonly-cited solution for species and ecosystem overexploitation [94].

Community-led efforts have resulted in the creation of several communal freshwater conservation zones, 'no-fish' zones, or sanctuaries across parts of South and Southeastern Asia [95,96] and the Amazon [97]. By regulating or safeguarding against resource exploitation and harmful activities, such freshwater protected areas have been shown to host communities of relatively higher species richness, density and biomass [98], become refuge habitats for species of high conservation importance [99], and potentially serve as source populations for adjacent river reaches.

Where freshwater protected areas are managed both for biodiversity and for provisioning ecosystem services like food supply, they can be viewed as natural assets; that is, natural capital investments to be managed and protected analogously to conventional infrastructure [100–102]. In other words, minimally altered rivers are themselves a form of NBS. Such framings could encourage investment and management of such shared resources in ways that better ensure the long-term prospects of local ecological communities, so long as societal benefits were protected and distributed equitably [1,102]. Strategic NBS investments in the form of restored, created, or protected habitats could be monitored and managed using the population trends and demography of exploited species as an indicator [18]. Such practices, where implemented in conjunction with NBS, could synergize with and potentially catalyze the establishment and management of community-based freshwater protected areas.

Prevent and control non-native species invasions

The potential applications of NBS to address invasive alien species (IAS) remain poorly studied, especially for freshwater systems. Generally speaking, wherever ecological restoration—for example, of benthic, wetland, or riparian vegetation communities—is involved in actions to maintain or optimize ecosystem services, the removal of invasives can potentially be made a synergistic benefit of NBS projects and heir management. This is especially relevant where ecosystem services are strongly contingent on native species assemblages, and thus reduced by invasion (e.g., [103]). However, given that IAS may in some cases provide comparable ecological services to native communities, there may arise management conflicts where reducing IAS comes at an additional economic cost with no major increase in function [104].

Flow modification by dams and water withdrawals, as well as floodplain disconnection via levees facilitate the invasion and establishment of aquatic and terrestrial IAS [58,105]. NBS like barrier removals, levee setbacks, and stream restorations could thus potentially tip the scales in favor of native aquatic species assemblages. However, in cases where dams act as barriers to the spread of invasive species, as in the case of invasive sea lampreys in the Great Lakes [106] or invasive crayfish in Europe [107], dam removals could facilitate their spread, adversely impacting native biodiversity.

The urgent need for empirical and monitoring data for proactive IAS management and NBS implementation present an important opportunity for synergistic and strategic monitoring. Where monitoring data are critical to NBS research and development [18], they are also a key part of modeling and predicting the spread of IAS [108]. Consequently, from a logistical point of view, funding for IAS management could be leveraged to finance necessary monitoring of the outcomes of different NBS projects, where existing support for mandatory performance monitoring may fall short [18]. In either case, citizen science efforts supported by mobile apps could make substantial contributions to such biodiversity monitoring at potentially lower cost [109].

Knowledge gaps and research priorities

Our review has found that many NBS applications can support and synergize with freshwater biodiversity conservation goals, but the empirical data needed to assess the actual degree of contribution are often lacking. Indeed, very few NBS projects in any context have been quantitatively evaluated for their impacts on, or benefits to, biodiversity [18]. This represents a major knowledge gap and research priority, and simultaneously a major opportunity: as enthusiasm and investment for NBS builds worldwide, biodiversity scientists must seize the opportunity to collaborate with civil and environmental engineers, landscape architects, and other practitioners to collect meaningful biodiversity data on these applications.

This is no doubt easier said than done; several factors make such research difficult. First, water-related NBS are typically implemented in a piecemeal fashion, making systematic monitoring difficult, since different projects will be enacted at different times, interacting in complex ways within a catchment and confounding isolation of an individual projects' benefits or impacts. This complexity complicates the robust Before-After-Control-Impact framework normally employed for understanding the effects of civil and environmental infrastructure projects. Furthermore, performance assessments and monitoring of infrastructure projects are typically funded and implemented at the project scale, meaning that watershed-scale and ecosystem-scale benefits may be missed or misunderstood. Finally, the temporal scales at which ecological processes and species populations change and interact are misaligned with the timeframe for most infrastructure monitoring. More flexible, deliberate, and learning-based frameworks [18] will be necessary to glean useful information from the coming wave of water-based NBS implementation at the correct scales and levels of organization. The links between water-related NBS and different freshwater biodiversity conservation goals established in his paper may provide a helpful context for choosing what ecological variables to monitor in different NBS projects. For example, biodiversity monitoring for levee setback studies should include both terrestrial habitats and temporary aquatic habitats created during flood events.

Conservation goals pursued to the exclusion of equity and social justice will ultimately be ineffective [110], and these factors must be considered as NBS applications enter the mainstream for water resources management applications [102]. Social impacts like environmental gentrification [70,111] and conservation imperialism [112] have nontrivial implications for the success, performance, and sustainability of NBS, that bear equal consideration to their potential for protecting nature. Without interdisciplinary synthesis including knowledge from social science and integrated conservation, any contributions to biodiversity goals made by NBS may lack sustainability.

Conclusion

As the momentum and support for widespread NBS implementation grows, it is increasingly important to be explicit about the pathways by which biodiversity "wins" can actually be achieved. The prior sections establish conceptual links between commonly cited freshwater NBS and key objectives for biodiversity conservation. Table 2 provides an example of how specific NBS can be qualitatively linked to Tickner et al.'s [13] six conservation outcomes. Our goal was to match NBS and specific biodiversity targets, and encourage planning and dialogue beyond broad, abstract statements about benefiting biodiversity.

We hope that this paper will encourage a deliberate approach to NBS implementation that explicitly considers what different methods can and cannot achieve for freshwater biodiversity. While there remains an urgent need for quantitative evidence to assess the efficacy of NBS for contributing to key conservation actions [18], this paper should provide a general framework for where results might be reasonably expected. Practitioners have the unenviable task of navigating a complex landscape of trade-offs between infrastructure services and other outcomes, and this work may offer guidance in navigating these trade-offs with respect to freshwater biodiversity.

Supporting information

S1 Text. List of search terms used in targeted literature searches for each conservation goal considered in this manuscript.
(DOCX)

S1 Graphical abstract.
(TIF)

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