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Review

Selection, Planning, and Modelling of Nature-Based Solutions for Flood Mitigation

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Abstract: The use of nature-based solutions (NBSs) for hazard mitigation is increasing. In this study, we review the use of NBSs for flood mitigation using a strengths, weaknesses, opportunities, and threats (SWOT) analysis framework for commonly used NBSs. Approaches reviewed include retention and detention systems, bioretention systems, landcover and soil management, river naturalisation and floodplain management, and constructed and natural wetlands. Existing tools for identification and quantification of direct benefits and co-benefits of NBSs are then reviewed. Finally, approaches to the modelling of NBSs are discussed, including the type of model and model parameterisation. After outlining knowledge gaps within the current literature and research, a roadmap for development, modelling, and implementation of NBSs is presented.

Keywords: flood mitigation; co-benefits; green infrastructure; nature-based solution; detention systems; bioretention; floodplain restoration; wetlands 0026

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1. Introduction

The International Union for Conservation of Nature (IUCN) described nature-based solutions (NBSs) as 'actions that protect, sustainably manage, and restore natural or modified ecosystems, to address societal challenges such as climate change, human health, food and water security, and disaster risk reduction, while simultaneously benefiting human well-being and biodiversity' [1–3]. The United Nations Environment Assembly (UNEA-UNEP) subsequently adopted a resolution that provided the first multilaterally agreed definition of NBSs [4] as actions to protect, conserve, restore, sustainably use and manage natural or modified ecosystems and which address social, economic, and environmental challenges to provide human well-being, ecosystem services, resilience, and biodiversity benefits, and called for the development of common criteria, standards, and guidelines among member states to support their implementation. The World Bank defines NBSs in terms of the environmental processes and functions that enhance biodiversity while providing a range of associated benefits, often referred to as ecosystem services (ESs).

In the last ten years, NBSs have increasingly been used to reduce the risk of flooding in rural and urban areas [5–8]. However, while natural environment systems can be used to mitigate flood impacts (similarly to traditional engineering infrastructure), they may also exacerbate the problem if conceived, designed, or implemented without reference to scientifically based guidelines [9]. International guidelines for the use of NBSs for flood management state that flood risk assessment should consider flood hazard, exposure, and vulnerability, and that potential solutions should be understood in terms of their wider environmental, ecological, and social benefits [10]. Moreover, the cost-effectiveness of NBSs for flood management should also consider the wider cost reductions afforded by any co-benefits of NBSs [11]. NBSs for flood mitigation, therefore, need to be designed, tested, and evaluated using both quantitative and qualitative criteria.

This paper aims to review the existing knowledge, methodologies and tools that can be used to select, plan, and model NBSs for flood mitigation to further enable their implementation. More specifically, NBSs that can be used to reduce the extent and impact of fluvial and pluvial flood risk are reviewed, and an assessment of their strengths, weaknesses, opportunities, and threats (SWOT) is provided. Benefit and co-benefit assessment methods, factors that affect implementation and maintenance, and approaches to modelling different NBS types are also reviewed. Finally, a high-level roadmap for decision-making and planning of NBSs for flood mitigation is outlined.

2. NBS Options for Flood Mitigation

Generally, much of the drive towards implementation of NBSs in both rural and urban landscapes over recent decades has been to improve water quality, although in urban areas, they have also been used to reduce nuisance inundation of roads and sewer overflows following medium-intensity rainfalls. However, their ability to capture and store runoff means that they may also be useful for flood risk management as an alternative to hard-engineered flood protection infrastructure. Conceptually, the success of an NBS for flood risk management will lie in its ability to attenuate peak flow volumes; this ability will vary by type of NBS and its size, design, and location within the surrounding landscape. The UK Environmental Agency [12] project 'Working with Natural Processes' provided guidance for the use of landscape-scale features (e.g., natural dams, lakes, ponded areas, woodland, wetland areas) to attenuate flow or sediment transport. Such features can be applied in the upper, middle, or lower catchment, in river corridors, floodplains, and coastal areas (Figure 1), to reduce or retain runoff, and thus reduce the frequency and magnitude of downstream discharges. The capture of larger storm events may only be possible if additional areas of low-risk or -value 'sacrificial land' are created, into which excess runoff can be temporarily diverted. As proposed for Sustainable Urban Drainage Systems (SUDS) [13], it is useful to conceptualise an integrated hierarchical 'Surface Water Management Train'. Using this approach, runoff mitigation measures are developed locally first for 'source' areas in the middle and upper catchment before they are considered for downstream areas. In this way, the quantity of runoff water requiring management downstream is already reduced. Risk of sediment or contaminant mobilisation can be managed in the same way.

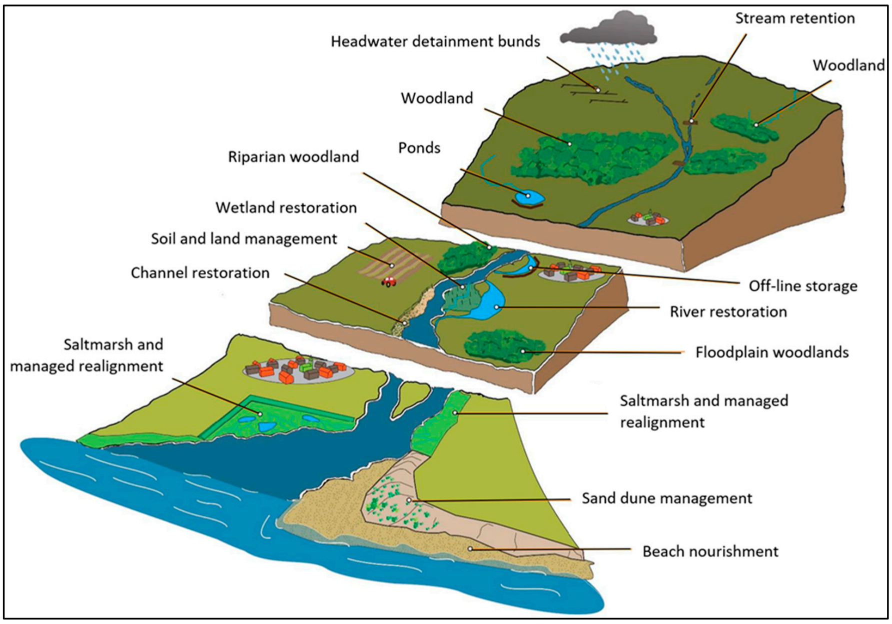


Figure 1. Use of different landscape features in upper, middle, and lower catchments (Source: [12]). Note that many of these mitigation measures can be used in multiple locations of the catchment, e.g., riparian buffers, constructed and natural wetlands, improved soil and land management, and channel restoration. Reprinted with permission from [12] Environment Agency—February 2018.

In this study, we adopt the World Bank-defined NBS categories of retention and detention features, bioretention systems, landcover and soil management, river naturalisation and restoration, and natural and constructed wetlands [14]. Each NBS type is reviewed separately, and an assessment of the strengths, weaknesses, opportunities, and threats (SWOT) is completed for each category.

2.1. Retention and Detention Systems

Retention and detention systems are structures either designed to retain surface runoff permanently or detain and slowly release it over a period of usually a few days. Retention systems hold water in permanent pools but allow temporary storage of runoff that discharges via an outlet structure. Detainment systems include dry ponds, bunds, leaky barriers, and filter strips that are designed to empty and dry out between runoff events. Both types of system can include overflow structures to bypass peak runoff volumes in excess of the storage capacity.

Retention and detention systems are found in rural and urban landscapes and are commonly designed to treat runoff by trapping sediment and associated particulate contaminants [15–17]. For example, McDowell et al. [18] recommended placing settling ponds or sediment traps in zero-order catchments to capture sediment and associated particulate contaminants. They suggest that the area covered by the systems be around 1–5% of the upstream catchment area, with catchment areas ranging from 100 to 500 ha. Similarly, Smith and Muirhead [19] reviewed the effectiveness of sediment traps (and detainment bunds) in agricultural landscapes and endorsed a 120 m^3/ha minimum storage volume. They noted highly variable sediment removal, ranging from 30% to 98%, with a mean of 59%. On-farm dams and retention ponds can store water for irrigation or stock watering, and, if located near forest, provide water to control forest or brush fires. They can also provide habitats for fish, waterfowl, and game birds. In many European agricultural landscapes, ponds and dams are also seen as a means for promoting increased biodiversity [20,21].

In addition to stormwater management, urban detention and retention systems can be part of blue-green corridors bringing nature back into towns and cities and can help cool urban climates [22]. In New Zealand, detention systems based on infiltration have a special cultural role for Māori, as flow through soil spiritually purifies rainwater for human use [23]. While end-of-pipe stormwater ponds are fairly common in urban areas, the construction of multiple smaller retention or detention structures at source can improve urban resilience through the provision of system modularity and redundancy [24,25]. Multiple smaller systems in rural catchments could likewise improve resilience.

However, there are some potential problems associated with these systems: they can require large areas to provide adequate storage, which can reduce the availability of productive land and may be prohibitively expensive in urban areas with high property costs. Discharges and bypasses from large end-of-pipe systems following extreme events can lead to remobilisation of settled sediments and particulates within the basin and deposition of these in the stream network, which can result in smothering benthic stream communities. Furthermore, shallow retention ponds can increase the temperature of stored water, which may already be elevated due to stormwater flowing over heated surfaces like roofs and roads and needs to be carefully managed to facilitate water cooling [26,27]. For example, Maxted et al. [28], studying in-stream ponds, reported that a lack of shading and the effects of accumulated organic and nutrient-rich sediments contributed to elevated water temperatures and depressed water quality, with negative impacts on downstream aquatic life.

Care must be taken in urban areas when siting and sizing urban infiltration systems that drain to aquifers to avoid groundwater contamination [29,30] and, where there is shallow groundwater, to prevent negative impacts such as damage to building foundations, basement flooding, rising dampness in building and groundwater surface inundation, and sewer infiltration [31]. However, where imperviousness in urban areas has led to reduced stream baseflow [32,33], such features can provide meaningful aquifer recharge as a co-benefit.

With respect to flood management, the placement of multiple small water-detention structures in headwaters has the potential to reduce downstream flooding [20,21]. Placement of off-line farm ponds adjacent to streams has been recommended in the UK by national and local agencies [34–36] to divert flood water away from vulnerable downstream areas. However, constructing ponds that have sufficient storage capacity for this purpose can result in loss of productive agricultural land. An advantage of detainment bunds over ponds is that they are designed to dry out between events so that land can be kept in cultivation. These are earth embankments typically located across small gullies and ephemeral streams designed primarily for water quality control in rural areas. While detainment bunds are effective at reducing hydrograph peaks locally, strategic placement of multiple bunds within the upper catchment would be needed to contribute meaningfully to downstream flood control. Levine et al. [37,38] investigated the ability of two detainment bunds to treat agricultural runoff. The bunds represented 1.5% and 2% of their catchment areas and were able to remove an estimated 51% and 59% of the total annual sediment loads, 47% and 68% of annual TP loads, and 57 and 72% of annual TN loads, respectively. They also reduced annual surface discharge volumes, largely through infiltration, by 43% and 31%, respectively.

In urban areas, the sponge-city concept to reduce the impact of pluvial flooding is based around the construction of retention and detention basins to reduce and attenuate peak flows [39,40], but, to be effective, they need to be adequately sized to store peak runoff volumes and designed to drain completely between rainfall events [41,42]. Stormwater retention and detention systems designed for stormwater treatment are usually sized to capture the 90th or 95th percentile storm event [43,44] (often equivalent to rainfalls with a recurrence interval of ~2 years) and are often installed with overflow structures to by-pass high runoff volumes following more extreme rainfalls. These systems can also be sized to retain runoff generated by storms with recurrence intervals of 10 years to reduce incidents of nuisance surface flooding and combined sewer overflows. This means that while they can be used for day-to-day stormwater runoff control [45,46], they have limited potential for flood risk attenuation at a catchment scale if not part of a wider flood mitigation strategy. The land costs and lack of suitable land can be prohibitive for larger flood detention basins; however, there are exceptions, especially where large detention basins can be incorporated into existing parkland, as in the upper Heathcote Valley in Christchurch (https://ccc.govt.nz/services/water-and-drainage/stormwater-and-drainage/stormwater-projects/heathcote-catchment (accessed 9 February 2024)) and Greenslade Reserve detention basin in Auckland (https://ourauckland.aucklandcouncil.govt.nz/news/2023/02/rain-drain-northcote-s-new-stormwater-infrastructure-tested-to-the-max/ (accessed 9 February 2024)).

The common strengths, weaknesses, opportunities, and threats discussed above are summarised in Tables 1 and 2.

Table 1. Summary of strengths and opportunities identified for NBSs for flood management.

	Retention and Detention Systems	Bioretention Systems	Landcover and Soil Management	River Restoration and Floodplain Management	Wetlands
STRENGTH: Cost effectiveness	Relatively low cost of implementation.	Relatively low cost of implementation.	Low cost if natural regeneration of vegetation is sufficient for purpose. Moderate cost if replanting and weed management required.	Can become self-maintaining and contribute to carbon sequestration.	Relatively low cost to maintain or restore existing wetlands. Natural landscape features such as swales and gullies can facilitate construction of wetlands. Relatively long operation life and low maintenance costs.

Table 1. *Cont.*

	Retention and Detention Systems	Bioretention Systems	Landcover and Soil Management	River Restoration and Floodplain Management	Wetlands
STRENGTH: Water related benefits	Can achieve both water quantity and quality (reduced sediment, particulate and faecal microbe) control. Can be targeted to manage localised gullying, bank erosion, and flooding.	Bioretention and remediation of contaminants. Reduced sediment loads and transport. Pluvial flood regulation through volume and peak flow attenuation.	Landcover change can increase infiltration, canopy interception, and evapotranspiration, and thus reduce magnitude and temporal response of flood peaks.	Increase stormwater storage and conveyance capacity in flood plain, stream courses. Floodplain connection can decrease the magnitude and duration of downstream floods and improve water quality	Can achieve both water quantity and quality (reduced sediment, particulate, and faecal microbe) control.
OPPORTUNITY: Socio-economic benefits, Community engagement and Indigenous knowledge	Detention systems enable productive land use between events. Retention systems provide water for stock drinking, firefighting, irrigation.	Job creation, recreational and educational opportunities.	Green spaces increase amenity value. Planting opportunities can be used to introduce culturally significant plant species.	Aesthetic value increases to open mixed-use options.	Maintain greenspace and associated cultural and aesthetic values. Restoration and construction provide job creation, recreational, cultural, and educational opportunities.
OPPORTUNITY: Other environmental benefits	Can provide water for non-potable uses in urban areas such as for passive urban cooling.	Can improve biodiversity in urban areas. Can provide heat regulation, air quality improvement, carbon storage.	Forest cover can provide carbon sequestration. Green corridors and similar can lead to habitat creation (for birds and fish) and improvements in water quality (e.g., biodiversity, visual clarity, etc).	Opportunities to increase biodiversity and improve habitat integrity.	Opportunities to maintain or enhance biodiversity and improve habitat integrity.
OPPORTUNITY: Implementation and integrated planning	Can be linked with constructed wetlands to improve performance across a wider range of contaminants and provide a wider range of ecosystem services.	Opportunity to develop and document guidance.	Increased vegetation cover is particularly useful in upper catchments areas or strategically targeted to areas of known high runoff and/or erosion.	Can assist flood plain wetland restoration programmes.	Opportunity to strengthen protection, restore and supplement natural wetland assets.

Table 2. Summary of weaknesses and threats identified for NBSs for flood management.

	Retention and Detention Systems	Bioretention Systems	Landcover and Soil Management	River Restoration and Floodplain Management	Wetlands
WEAKNESS: Limits on efficiency	Limited relative storage capacity in very large events.	Fully efficient only after a "start-up" period (e.g., 8 months to 2 years). Performance of mature systems is subject to change as the systems age (e.g., clogging can happen after several years, e.g., 5–6 years).	Long start-up time related to vegetation growth period, during which space may be more vulnerable to flooding.	Susceptible to damage in the first two to four years after implementation.	Efficiency can be limited due to poor vegetation establishment; for example, in highly permeable soils (require lining) or if prolonged flood or drought conditions occur in the first year after implementation.
WEAKNESS: Space requirement/scale	Require large numbers distributed across the landscape to moderate widespread flooding.	Can be part of a flood mitigation strategy but may not be sufficient on its own to manage flooding at a catchment scale.	Land acquisition can be challenging. Initial capital costs could be prohibitive to private landowners.	Land acquisition may be required to extend river and riparian areas. Effectiveness depends on floodplain-to-catchment size ratio	Effectiveness depends on wetland-to-catchment size ratio. Lost opportunity value of other potential land uses.
WEAKNESS: Limited applicability	Require rolling but not-too-steep landscapes that facilitate sufficient ponding with minimal earthworks.	Potential for maladaptation if limited availability of expertise or guidance materials.	May be limited options where soil, climatic, and topographic conditions dictate.	Creation of new riverscapes can be expensive and take time to stabilise. Need surface and channel data and floodplain roughness data critical for planning.	Can be relatively expensive to construct and plant in low-gradient landscapes and where natural plant regeneration cannot be relied on. Vegetated wetlands generally require large areas of relatively shallow water (0.3–0.4 m) but will survive short periods (days) of deeper inundation.

Table 2. *Cont.*

	Retention and Detention Systems	Bioretention Systems	Landcover and Soil Management	River Restoration and Floodplain Management	Wetlands
WEAKNESS: Maintenance and management	Require regular sediment removal to retain storage capacity and limit scouring and remobilisation of accumulated sediments during large storms.	Ongoing maintenance costs. Potential failure of the system if not properly maintained. Uncertain responsibilities for ongoing management.	Any change in land or soil management will likely come with an associated cost.	Maintenance costs for ongoing river widening, weed clearance, sediment removal, riverbank repair. Regular inspections required to check for erosion or damage.	Weed control likely needed during initial establishment. Bunds and water level control structures may be damaged by large flooding events, requiring repair.
THREAT: Water-related disbenefits	Can increase water temperature and/or cause groundwater contamination.	Can become clogged if fine sediment accumulates in system	Use of monoculture plant assemblages increases the risk of soil erosion and flooding after harvest.	Floodplain complexity in large catchments can make dynamics hard to predict. May behave unpredictably in very large floods.	On-line constructed wetlands may impact fish passage. Wetlands may exacerbate flood risk where there is high groundwater.
THREAT: Environmental and socio-economic disbenefits	Capture of small ephemeral flows may reduce downstream low flows and associated ecological values.	May increase vector breeding in case of stagnant water (i.e., system failure).	Forestry can be at cost of carbon-rich and biodiverse native ecosystems, and land rights. Monoculture plant assemblages could have negative impact on local biodiversity.	Increased risk of invasive species within created environments.	Risk of invasive and pest species. Open water may increase vector breeding risks in some situations (e.g., mosquitos and midges).

2.2. Bioretention Systems

Bioretention systems are stormwater management systems composed of vegetation planted on top of a specific media or substrate allowing infiltration, retention, and treatment of the stormwater runoff [47–49], such as raingardens, bioswales, and vegetated infiltration strips. They have been reported to efficiently remove suspended solids, metals, nitrogen, and organic and microbial pollutants [50]. They also provide volume and peak flow reduction, even in low-permeability soils. Winston et al. [51] measured up to 59% runoff reduction. This was mainly attributed to infiltration and evapotranspiration which was increased by the presence of a storage zone at the bottom of the bioretention cell. However, insufficient function or failure of these systems can occur due to lack of maintenance, often resulting in clogging [52]. Insufficient communication, unclear responsibilities, lack of knowledge, financial barriers, and decentralised measures were reported by the authors as probable reasons for failure.

Liu et al. [53] suggested that bioretention systems' performance varies over their life cycle and is partly dependent on the establishment period, the design, the local conditions, and maintenance frequency. The establishment period involves vegetation growth and spread, and the time it takes for the root network and microbial community to colonise the media. Eight months to two years have been reported as being sufficient for the bioretention systems to be effective [53,54]. The performance of mature systems is also subject to change as the systems age. The filter media can be prone to clogging and therefore less efficient over time. Clogging can happen in the early stage of the implementation and/or later on due to improper discharge (e.g., construction activities or overloading of undersized systems) or lack of maintenance [55,56]. While some systems showed no significant decline in hydraulic conductivity after six years [57], others exhibited a reduction in hydraulic conductivity to less than half the initial value after a seven-year period [58]. It is thought that selecting plants with thick roots (e.g., Melaleuca) could help in maintaining permeability over time [56].

While current guidelines recommend bioretention systems to cover 2% to 5% of the catchment area [43,59] to provide a hydrological function and avoid media clogging, specific models have been used over the past decade to further investigate the design and placement of NBSs (including bioretention) specifically for flood risk attenuation [60]. Mei et al. (2018) [61] developed an evaluation framework based on the Storm Water Management Model (SWMM) and life cycle cost analysis (LCCA) to assess 15 scenarios of NBS implementation for flood. Simulations suggested that a combination of bioretention cells and vegetated swales covering 6% of the catchment surface area was the most cost-effective option per unit investment and could reduce the flood volume (volume in excess of the channel capacity) by ca. 20–50% depending on the storm event return period (2–100 years). Wu et al. [60] developed a catchment-based planning framework to identify optimal NBS designs and their placement in different sub-catchments to effectively reduce flood damage cost in Australia. The results of the framework applied to urban catchments in Sydney suggested that implementation of bioretention systems accounting for 12% of the catchment area would reduce the annual average flood damage of a 20-year return period storm event by approximately AUD$ 1.2 million.

Co-benefits of bioretention systems include heat regulation, air quality improvement, carbon storage, improved local economies and job creation, recreational and educational opportunities, and increased biodiversity [14]. Heat regulation is primarily attributed to the presence of trees that directly (via shading) or indirectly (via evapotranspiration) reduce urban heat island effects [62]. Creating tree-planted bioretention corridors could therefore be an opportunity to improve human thermal comfort, where it is an issue. Carbon storage can be promoted in the soil and vegetation compartments of bioretention units. Kavehei et al. [63] estimated that an average annual carbon storage of 2.4 kg/m^2 is possible in bioretention areas. The number of species, species richness, and diversity have also been found to be higher in bioretention swales, compared to garden and lawn spaces [64]. However, such areas may also increase vector breeding [65], such as mosquitoes, where system failure leads to ponding of stagnant water. When implemented close to air-pollutant emission sources (e.g., roads), bioretention areas can also improve the air quality [66], especially if sufficient height, density, and foliage coverage are obtained [67]. Dense roadside vegetation containing bushes/trees promoted the reduction of ultrafine particles (50%), black carbon (BC) (27%), and gaseous pollutants, including NO_2 (20%) and CO (carbon monoxide) (19%) [67]. From a socio-economic perspective, bioretention areas can create opportunities for educational and recreational activities, thereby promoting social interaction [14,68]. They can also provide economic benefits by increasing the market value of nearby real estate and creating green jobs [14,69].

2.3. Landcover and Soil Management

Forests are also increasingly recognised for their role in managing runoff, although the extent to which individual forests impact downstream flooding is difficult to quantify due to the complexity of mixed land-use catchment hydrology [70]. Marapara et al. [71] found that forests can be most effective for flood mitigation when appropriate species are grown on gentle or moderate slopes, and on shallow-to-medium-depth soils, over permeable bedrock. They were least effective on shallow soils over impermeable bedrock in steep sloping areas.

Generally, extensive monoculture forestry is practiced in upland areas, whereas in middle and lower catchments, forestation tends to be smaller in scale and involve targeted pockets of diverse trees, shrubs, and grasses. While the introduction of both natural and cultivated forests can help reduce downstream flood risk, monoculture planting can have negative impacts on ecosystem diversity [72]. Commercial forests are also harvested over 30–40-year periods, resulting in periodic exposure of land and soil and production of forestry slash, both of which increase downstream impacts. Previous work on the East Cape of New Zealand, which is an area prone to high soil erosion, earthflows, and landslides, suggests 2–3 years post-harvest in which soil erosion risk is exacerbated due to exposure of bare soils [73–75]. In addition, road cutting can take place 1–2 years prior to harvesting.

In addition to providing a range of commercial products (wood, fiber, biofuel) and habitat for wildlife, planted forests can help prevent extreme temperatures and reduce the impacts of heatwaves by as much as 4 °C (in urban green space) and 3.5 °C (in parklands) [5]. Forests have also been shown to reduce air pollution in urban areas [76]. When integrated with ponds or wetlands, tree-cover can reduce localised flooding [77]. Green corridors, parklands and recreational spaces in urban areas also provide designated flow pathways for flood flows, hence alleviating otherwise flooded areas.

By contrast, pasture management practice and intensive grazing can lead to soil compaction and cracking, which promotes increased runoff and sub-surface drainage. Flow from boundary ditches, animal tracks, and reduced riparian corridors, can also increase runoff and sediment transport [78,79]. Restoring and maintaining vegetation can reduce the extent of erosion during flood events. Drainage improvement, the use of debris dams, ground recontouring, and stream bank strengthening can also be used [80–82].

Zero-tillage farming aims to further increase organic matter retention and water infiltration into the soil to produce an improvement in soil biological fertility, making soils more resilient [83]. Tillage reduction aims for 30% crop residues as soil cover to aid rainfall infiltration and preserve soil structure [83]. The resulting gradual increase in soil, carbon stock, and soil adhesion increases water stable aggregates [84] and macropore connectivity, which in turn increases the soil water storage [85].

A report commissioned by the World Wildlife Fund—Cymru [86] in Wales (UK) showed that farmers who adopted NBSs or regenerative farming practices enhanced their land resilience, enabling them to better mitigate and adapt to the impacts of climate change and droughts and floods. Activities such as improving soil health to enable better water absorption/retention during floods/drought, tree planting to absorb carbon and provide shelter to livestock during extreme weather, and improvement of on-farm water management (including better water storage during periods of drought) all had the potential to provide beneficial impacts on farm productivity in the face of changing climate. However, it was also stated that such measures would likely require central government assistance with capital costs.

In New Zealand, the Tīmata Method [87] is a low-cost way of returning productive land to native forest. The method involves restoration of native forest on marginal lands that is susceptible to soil erosion by planting low-density scrub to act as a nursery crop for successional trees to establish. Full regeneration of complex ecosystems may take up to 100 years or more, but the method is based on the Te Ao Māori (Māori worldview: https://nzarm.org.nz/resources/knowledge-hub/te-ao-maori#:~:text=Te%20Ao%20M%C4%81ori%20offers%20a,complexities%20of%20the%20modern%20world, accessed 14 June 2024) principles [88] of long-term thinking. Reductions in runoff and sediment production also occur at a natural pace, along with improved water quality, reduced greenhouse gas emissions, and more economic land management.

2.4. River Naturalisation and Floodplain Management

Growing appreciation of NBSs, ESs, and biodiversity is leading to a paradigm shift in river management, of which re-naturalisation and restoration are a part. These are encapsulated in the often-used phrases of 'making room for rivers' or 'working with water'. There are several NBS approaches which form part of this approach, including stream 'daylighting' [89], re-establishment of riparian corridors, removal of concrete embankments, and riverbed and bank revegetation. River and stream re-naturalisation aims to slow river flow and thus reduce downstream flood risk by increasing water retention and infiltration [8,90]. Slowing stream and river flows (increasing pathlength and hydraulic roughness) can, however, contribute to localised "flooding" where the floodplain has been commandeered for agricultural or urban uses.

Several bioengineering techniques can also be used to recreate a more natural river course and re-connect the river floodplain with riparian corridor revegetation to achieve riverbank stabilisation and riverbed restoration. Plants, rocks, and other natural elements can be used in combinations with geotextiles to create ecologically rich and structurally stable environments [91]. Similarly, embankments can be stabilised with geotextile matting [92].

River channels can also be re-profiled laterally to initiate channel dynamics for flood plain enlargement. Pool-and-riffle sequences for example, may also be initiated in this way [93]. Similarly, rocks, tree trunks, or branches can be used to redirect, disturb, deflect, or divert river flow to re-direct river current to prevent or initiate riverbank erosion. In addition to stock exclusion, riparian planting and forest buffers can strengthen banks and trap fines, thereby reducing erosion rates long-term [94–101].

Finally, wooded riparian buffers can provide shade for stream habitats which will cool temperatures and reduce periphyton and macrophyte biomass [102,103].

River floodplain restoration is a similar process of returning modified river channels and floodplains to a more natural state such that they become self-regulating and exist in a more stable state [89]. More regular inundation of the floodplain from the channel is not discouraged, so that the river utilises additional storage space within the floodplain.

Methods of restoration include increasing the hydraulic roughness and morphological complexity of the river corridor and riparian area using landscaping and planting techniques. Other measures may include floodplain extension or excavation, lowering of the river channel bed, diverting river channel flows, converting pastures into wetlands, and the creation of additional water storage areas. These changes are designed to decrease river velocity and increase flood plain area and storage and can only be achieved by active removal of previously introduced management structures or by passive gradual promotion of natural processes.

Methods used to better understand the extent of a natural floodplain, within which the river can be managed, include identification of the maximum erodible floodplain and defining the river management envelope based on past river behaviour (which helps define flood risk levels and vegetation management regimes).

Floodplains, rather than upland wetlands, have been found to be better at attenuating flood flows [104,105]. However, landscape configuration, soil, topography, moisture status, and management all influence the capacity of wetlands to provide flood attenuation. For example, if a wetland is poorly connected with a river, then it will have little impact on downstream flows, regardless of its location. Knowledge of groundwater and surface water interactions are also important when managing floodplain dynamics, especially when they have permeable geology substrates [106].

2.5. Wetlands

2.5.1. Natural Wetlands

Natural wetlands in the landscape can retain and buffer flows and sustain downstream base flows [107,108]. As well as providing storage volume and space to accumulate flood flows, vegetative resistance slows flows passing through wetlands. However, recent estimates show a net global wetland loss of 21% since the 1700s [109], predominantly associated with agricultural development. Regional variability is high, with wetland losses exceeding 70% in some European countries, midwestern states of the USA, and New Zealand. Protection and restoration of natural wetlands can help to recover their natural hydrological dynamics [108] and enhance associated ecosystem services [110].

There are a wide range of different wetland types, each with different hydrology, connectivity, and ecological values [108,111,112]. Rain-fed peatlands and bogs can act as giant sponges, soaking up and slowly releasing captured rainfall [113]. Fens, swamps, and marshes generally receive a mix of groundwater and surface waters from their surrounding catchments, while riverine swamps form part of river floodplains. The use of natural wetlands for flood control and contaminant management in agricultural and urban landscapes has the potential to impact their ecology and biogeochemical functioning in both positive and negative ways, by modifying their hydrology and/or nutrient status [114–116].

Even though natural wetlands and riparian zones may make up only a proportion of a catchment, they can have a significant effect on overall water and nutrient balances [117–119]. Kurki-Fox et al. [120], using the Soil and Water Assessment Tool (SWAT) model ([121,122], swat.tamu.edu), found that on a per-hectare basis, wetlands sized and designed strategically for flood control had a greater impact on peak flow reduction than reforestation and produced substantial nutrient and sediment-load reductions. Javaheri and Babbar-Sebens [123], studying the effects of wetlands in central Indiana (USA), used SWAT modified to simulate sub-daily flows. They reported that wetlands were able to reduce peak flows by up to 42%, flood areas by up to 55%, and maximum flows by up to 15%, with wetland depth a key determinant of flow-buffering performance. Reductions in peak flows of 15–20% were predicted under future climate scenarios for this watershed [124]. Wetland restoration in a North Dakota watershed was predicted using SWAT to reduce peak flows by 32% in wet years and 25% in dry years [125]. Collectively, these papers show that wetlands and other natural infrastructure can realise significant flood reductions at local scales, but that substantial areas are required to provide flood reduction benefits at the catchment scale.

2.5.2. Constructed Wetlands

Constructed wetlands (CW) are engineered systems designed to treat wastewaters, agricultural runoff and drainage, and/or urban stormwater by mimicking the processes that occur in natural wetlands. Utilising the natural functions of plants, soil, and organisms, CWs remove pollutants such as suspended solids, organic matter, and nutrients [126]. There are a wide range of different designs of CW, categorised into surface or subsurface flow types. Surface-flow (or free-water surface) CWs are most commonly employed for surface waters. They generally comprise extensive areas of shallow water vegetated with emergent wetland plants (Figure 2), often including deeper open water areas at the inlet, to settle and retain sediment [127]. The planted zones disperse flow, promote sedimentation, and remove a proportion of the nutrient load. Plants provide surfaces for the growth of microbial biofilms and decomposing organic matter for microbial conversion of dissolved nitrate into nitrogen gas that is returned to the atmosphere. Deep zones may also be interspersed throughout the wetland to increase storage capacity, allow for mixing and redistribution of flow, enhance habitat diversity, and provide refuges for aquatic life during dry periods. Extended detention of water can be accommodated, providing for increased wetland depths by limiting the outlet flows from the wetland. The depth of the water and the duration of flooding needs to be controlled to maintain the viability of the wetland plants. Generally, it is recommended that the effective water depth (normal water level plus the extended detention depth) must not exceed half the plant height for more than 20% of the time [128]. Greater depths may be accommodated for short periods of time (a few days).

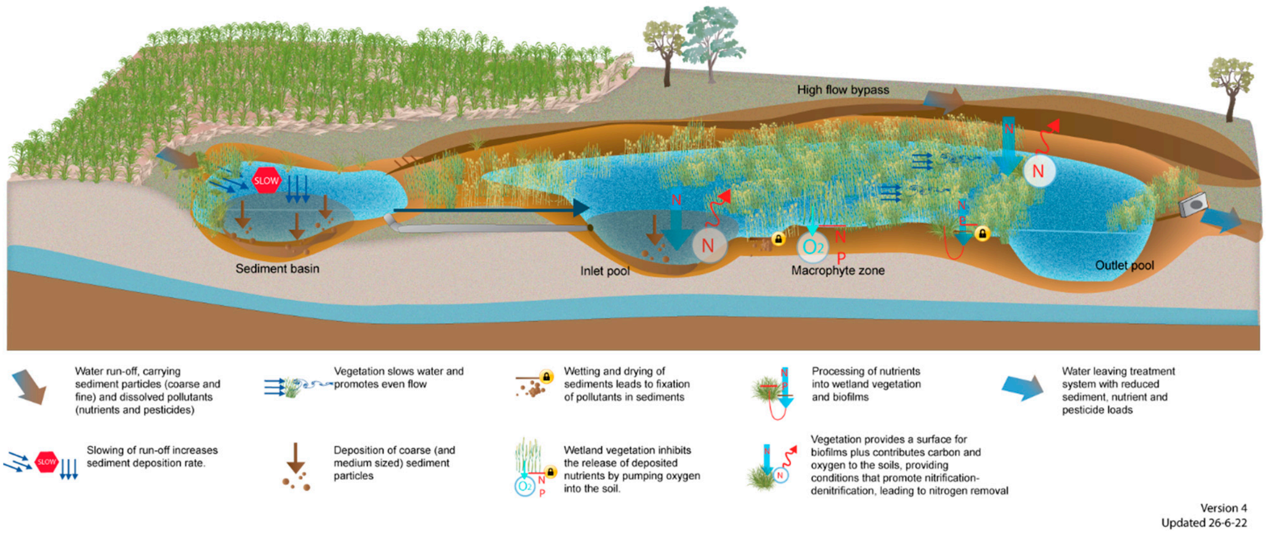


Figure 2. Surface-flow constructed wetland intercepting agricultural run-off, showing key contaminant removal processes. (Reprinted with permission from Queensland Government [129]. Copyright content licensed under a Creative Commons Attribution 4.0 International licence (CC BY 4.0).

CWs can be employed in a wide range of different situations within a catchment, including where surface and sub-surface drains flow into stream channels, and in headwaters, the middle, or at the bottom of catchments. CWs are ideally located in natural depressions and gullies that provide a pathway for water flow yet require minimal excavation and earthmoving and are of lower agricultural value. CWs can be built either in-stream (on-line) or off-stream (off-line). On-stream wetlands will generally require a high-flow bypass that diverts a proportion of extreme flows around the wetland (Figure 2) or include a suitably armored short-circuit channel through the wetland. Off-stream wetlands generally only receive a proportion of the streamflow and, depending on relative elevation, may only connect with the stream and fill when flows are elevated.

2.6. Summary of NBSs' Strengths, Weaknesses, Opportunities, and Threats

The common strengths, weaknesses, opportunities, and threats discussed in previous sections are summarized in Tables 1 and 2. It should be noted that the contents of Tables 1 and 2 represent general rather than case-specific guidance, and that more detailed quantitative information is available from the sources referenced. More detailed SWOT analysis matrices compiled for each NBS category are also available as supplementary data (Supplementary Materials).

3. Assessing Benefits, Costs, and Performance

Several tools and assessment frameworks have been developed over the past decade [130–134] with the overall aim of providing a comprehensive assessment of environmental, social, cultural, and economic benefits. The results from this type of assessment can be used to guide and inform decision-makers and developers for planning, (co)design, (co)implementation, and monitoring of NBSs [132,133].

To objectively assess NBS performance, it is necessary to first define key expected outcomes [135]. This step should involve relevant stakeholders (i.e., co-benefit beneficiaries), as differences in perception and valuation of benefits and outcomes can lead to post-project conflict [136,137]. NBS performance assessment methods and tools, to measure agreed outcomes, include numerical models, expert judgment, and life cycle costing. They provide metrics for comparison of different NBS strategies or can be used to compare NBS performance against traditional engineering approaches [136,137]. Most of the existing frameworks allow consideration of a range of co-benefits (environmental, economic, social, and cultural) and also provide a monetary (or equivalent) valuation. For example, Ira and Simcock [138] describe both project and wider environmental benefits as 'avoided costs' and 'cost effectiveness' factors (Table 3).

Table 3. Environment and project 'avoided costs' and 'cost effectiveness' (after Ira and Simcock [138]).

	Cost Effectiveness	Avoided Costs
Project	Housing affordability Development yield Public infrastructure delivery Health and wellness affordability	Earth working costs Hard infrastructure/pipes costs Impervious area costs Landscaping costs Property operation costs
Environment	Water quality cost effectiveness Hydrology cost effectiveness Aquatic habitat quality cost effectiveness Terrestrial habitat quality cost effectiveness	Environmental remediation costs Property remediation and storm damage costs (flooding) Future proofing costs (climate change; resilience)

Commonly reported NBS benefits span a wide range of issues that can be broadly classed as environmental or social (Table 4). It is noted that some NBSs can yield both benefits and disbenefits depending on their implementation. For instance, large tree-planting can provide carbon sequestration but could also deteriorate local air quality by reducing air pollutant dispersion if implemented in a street canyon environment [76].

Hydrological benefits of NBSs can be assessed in the same way as traditional flood infrastructure, i.e., by assessment of flood risk and impacts before and after development, and with reference to different design event criteria. Co-benefits, however, need to be assessed with reference to some measure of ecosystem services (ESs), i.e., the 'goods or services provided by ecosystems' [139]. For example, wetland restoration projects are routinely assessed for their ability to buffer floods, but should also be assessed for their contribution to local fish population, biodiversity, economic, cultural, and amenity values [140].

Table 4. Commonly reported NBS environmental and social benefits [132,135,141].

Environmental Benefits	Social Benefits
Water and air quality	Noise attenuation
Erosion/landslide attenuation	Food and raw materials
Temperature regulation	Recreation
Habitat connectivity	Tourism
Soil health	Health and well-being
Biodiversity	Job opportunities
Carbon storage	Energy saving
Groundwater recharge	Property values
Flood management	Social cohesion
Water supply	

There is currently no single tool that can be applied to the complete range of benefits and disadvantages that might arise from different NBSs. However, several tools are tailored to specific types of environmental challenges such as climate resilience [142], flood risk management [143], urban runoff management [144], ecosystem services [145,146] and accounting [147]. Several such tools that are available online are presented in Table 5 and briefly described below. Up to twenty environmental, social, and economic benefits are usually investigated, and are either qualitatively or quantitatively assessed, depending on the input data requirements. When quantitative assessment is possible, the benefits are often monetised to evaluate trade-offs associated with alternative management choices and to identify areas where investment in NBSs produces the best economic, social and environmental outcome. When economic values for specific ecosystem services or benefits are not available for a specific project, the method of 'benefits transfer' is commonly used (in which economic values for ecosystem services or benefits are estimated by transferring information from previously completed studies).

Table 5. Co-benefits and cost assessment tools for NBSs.

Tool Name *	Developer	Assessment Scale	Benefits Assessed	Type of Assessment	Monetisation of Benefits
Green Values Calculator (online)	Center for Neighborhood Technology, Chicago, IL, USA (greenvalues.cnt.org (accessed 9 February 2024))	Small neighbourhood to large watershed	22	Qualitative for 16 benefits Quantitative for 6 benefits	Yes, for the 6 quantified benefits (life cycle valuation of the benefits)
B£ST (2019 version)	Susdrain, London, UK (susdrain.org (accessed 9 February 2024)))	Neighbourhood to small watershed	20	Quantitative	Yes
INFFEWS BCA Tool (2021 version)	Monash University, Melbourne, Australia. (crcwsc.org.au (accessed 9 February 2024)))	Neighbourhood to city scale	20	Quantitative	Yes
InVEST (version 1)	Stanford University, California, CA, USA (naturalcapitalproject.stanford.edu (accessed 9 February 2024)))	Large watershed	20	Quantitative	Yes, for some of the benefits
Nature Value Explorer (online)	Environment Department of the Flemish government, Brussels, Belgium (natuurwaardeverkenner.be (accessed 9 February 2024)))	Small neighbourhood to large watershed	19	Qualitative and Quantitative	Yes, for 17 benefits

Table 5. *Cont.*

Tool Name *	Developer	Assessment Scale	Benefits Assessed	Type of Assessment	Monetisation of Benefits
i-Tree (v. 2024_6.1.51)	USDA Forest Service, Washington, DC, USA (itreetools.org (accessed 9 February 2024)))	1 tree to forest	5	Quantitative	Yes
More Than Water tool (2019)	Ministry of Business, innovation and Environment, Wellington, New Zealand (landcareresearch.co.nz (accessed 9 February 2024)))	Neighbourhood	25	Qualitative	No

* hyperlink inserted in the tool name gives access to the tool webpage.

The Center for Neighborhood Technology (CNT) and United States Environmental Protection Agency (USEPA) developed the web-based Green Values Calculator (GVC) [148] to assess the performance, costs, and benefits of NBSs compared to conventional stormwater structures. The tool is applicable for small urban developments to large watersheds, and performance is based on assessment of total annual runoff volume. The tool allows the user to evaluate runoff reductions under a range of NBS configurations. Twenty-two benefits are covered by the GVC, which provides a generic description for each of them, and specific quantified evaluation using benefit transfer from relevant studies for six co-benefits (reduced air pollution, CO_2 sequestration, tree value, groundwater replenishment, reduced energy use, and reduced stormwater treatment). The GVC provides cost estimates for each scenario, including construction, maintenance, and lifecycle costs.

The Benefits Estimation Tool (B£ST) [149] was developed by the UK's Construction Industry Research and Information Association (CIRIA) to assess twenty-two types of NBS benefits via an online tool. An initial qualitative assessment helps users decide which benefits to value in detail. Monetized estimates of the benefits are calculated as Net Present Value (NPV) using analyses conducted specifically for the project in question or where these estimates are not available, from a 'values library' (i.e., benefit transfer). The developers encourage the user to think about the level of confidence they have in the data they have used, and the value assigned to the benefits in the context of the project. Given the potential for uncertainty, the tool is best used for comparing project alternatives (including business-as-usual scenarios), rather than to produce absolute values [149,150].

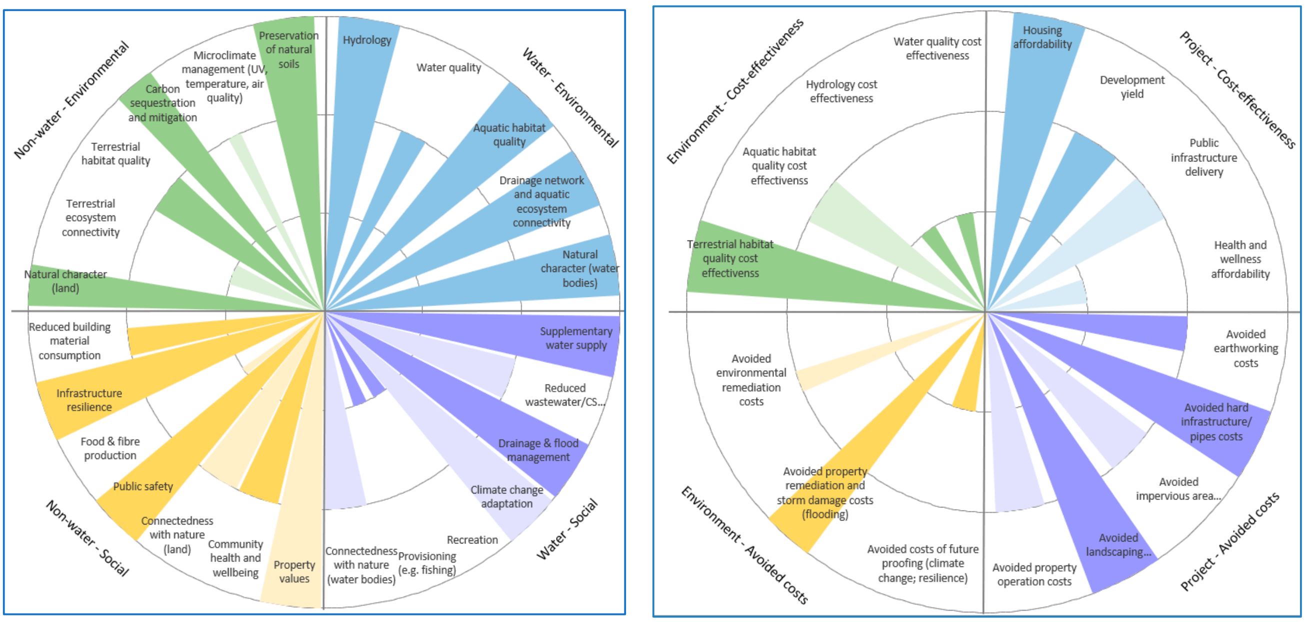
The Benefits-Cost Assessment (BCA) tool provides estimates for twenty types of benefits (including water consumption, ecological improvement, improved air quality, reduced flood risk, reduced risk of poor water quality due to fire, improved aesthetics, and reduced mortality). It relies on established methods for monetising benefits that cannot be bought and sold in markets, such as non-market valuation (NMV). Data for benefit transfer is taken from a library of relevant valuation studies. Value estimates can also be imported from external projects. With enough data from relevant studies or project-specific analyses, detailed cost-benefit analysis for each project alternative can be generated.

InVEST is a suite of models used to value and map the goods and services from nature that sustain and fulfil human life [151]. It provides information about how changes in ecosystems can lead to changes in benefits by exploring the outcomes of alternative management and climate scenarios and evaluating trade-offs between sectors and services. Co-benefits are divided into supporting ESs (habitat risk assessment, habitat quality, pollinator abundance) and direct ESs (forest carbon edge effect, carbon storage and sequestration, coastal blue carbon, crop production, annual water yield, nutrient delivery ratio, sediment delivery ratio, unobstructed views, scenic quality provision, visitation, recreation and tourism, wave energy production, offshore wind energy production, crop production, seasonal water yield, urban cooling, urban flood risk mitigation, urban nature access, urban stormwater retention). Individual models are used for each type of ES, each of which employs different analysis methods and input data accordingly. All InVEST model benefit calculation methods can be found at http://releases.naturalcapitalproject.org/invest-userguide/latest/en/index.html#invest-models (accessed on 1 June 2024).

The Nature Value Explorer (NVE) tool [152] assesses ES values (biological value, food production, water supply, materials, energy, waste reduction, regulation of water and land flows (groundwater recharge and protection against flooding), regulating the environment, green space, cultural identity and sense of place, physical and mental health effects relating to green space, and social cohesion) based on an international classification system (CICES 5.1 [153]), adapted to also include 'nature's contributions to people'. The generated results provide qualitative, quantitative, and monetary values (for current and future scenarios) for indicators such as avoided runoff, carbon sequestration, and filtration of fine particles. The NVE allows the user to visualise existing projects or create new ones. The study area can be drawn on an interactive map, and a specific NBS location and type added to it. Additional data such as the number of inhabitants living close to the study site, yearly rainfall, and other socio-environmental aspects are required.

i-Tree is a software suite from the USDA Forest Service [154] that provides analysis and benefits-assessment tools for urban and rural forestry. The tools help strengthen forest management and advocacy efforts by quantifying the environmental benefits that trees provide. The main quantified and monetised benefits include carbon sequestration, air pollution removal, stormwater mitigation, energy savings, and avoided energy emissions. Input parameters include location, number, species, size, and condition of trees.

The More Than Water (MTW) tool was developed to provide a "quick win" method to assess the wide-ranging benefits of NBSs [144]. MTW qualitatively assesses a set of water- and non-water-related benefits (e.g., micro-climate management, carbon sequestration, terrestrial habitat, infrastructure resilience, community health and well-being), project cost effectiveness, and avoided cost. It provides graphical output showing benefits and cost outcomes and can be run for different scenarios for comparison (Figure 3). It can be used at a screening level and as a communication tool for both technical or non-technical audiences. While the current tool is tailored to the urban context, a similar approach could be developed for rural areas.



(**a**) (**b**)

Figure 3. The 'More Than Water' benefits (**a**) and costs (**b**) assessment tool. The length, width, and intensity of color of each slice represent the level achieved, importance from a stakeholder perspective, and reliability of the assessment, respectively, for each benefit or cost assessed (Reprinted with permission from [144], with approval from the authors).

Most of the tools in Table 5 rely on generic or bespoke models specific to each considered benefit and sometimes geographical areas (e.g., NVE primarily developed for benefits assessment in Belgium). There are therefore multiple ways to assess the co-benefits provided by NBSs, which mainly depend on the amount of available data, computing time, and effort. Table 6 presents some common approaches and quantification methods for some co-benefits. Additional methods can be found in the Urban Nature Navigator (https://naturvation-navigator.com/ (accessed on 1 June 2024)).

Table 6. Performance Indicators and quantification methods for some co-benefits (adapted from [132,155]).

Co-Benefits	Performance Indicators and/or Quantification Methods
Flood mitigation	Percentage of rainfall leaving a site as runoff; Runoff and volume for high flow events (>20-year event); Runoff and volume during low flow; Impacts on pre-existing and neighbouring hydrology; Efficiency of site drainage; Exceedance event capacity of site; Flexibility of design to accommodate change
Air quality Proxies: NO_2, PM_{10}, SO_2, O_3	Changes in air quality by vegetation based on air pollutant deposition and estimation of leaf area index [154,156,157] or using the i-Tree tool [154].
Carbon Storage by vegetation	Sequestration by vegetation can be estimated based on vegetation biomass as done by the i-Tree tool.
Carbon Storage by soil	Land cover and land use (LULC), climate regions and soil types, and urban-rural areas influence carbon storage in soil. The InVEST tool can be used to estimate such storage for different land uses/covers.
Increased biodiversity	Extent, significance, and quality of local habitats; Extent of integration with existing biodiversity objectives; Connectivity with neighboring habitats; Resilience and sustainability of created habitats
Noise Attenuation	Noise reduction can be estimated with average leaf biomass and canopy area of trees and hedges (i.e., Noise Attenuation Potential [157]).
Water quality Proxies: Nitrogen, phosphorus	Stormwater pollutant retention depending on LULC can be estimated with InVEST.
Soil health Proxy: bulk density	Bulk density, which can be a proxy for soil quality (e.g., 1.47–1.8 g/cm^3 can restrict root growth [158]), is dependent on the soil type and land cover. Vandecasteele et al. [159] provides some estimates of bulk density changes due to LULC changes.
Recreation and increased amenity value	The size of the area, the proximity to population, the accessibility in terms of transportation and the quality and aesthetic of the space all contribute to the attractiveness of a space for recreational purposes. Usage can be estimated with the travel cost method or the Recreational Opportunity Spectrum (ROS). ROS is based on recreation potential (which can be reflected by the naturalness and presence of protected areas or water bodies) and remoteness or accessibility [160]. Other aspects such as dual function of drainage for recreation, enhancements to visual character, improvements to public safety, improvements in environmental awareness, and education can be accounted for [155].
Job creation	Green-space maintenance can serve as a proxy for job creation. Average monthly/annual maintenance hours per unit of green space could be used as indicator. Job and/or business creation for the implementation of an NBS would also contribute to this co-benefit and should be taken into account.
Property Values	Property costs are driven by many factors, including air quality, noise levels, thermal comfort, and the proximity to green/blue spaces. Cost can be calculated with the hedonic pricing method. Ira [69] reviewed 74 studies worldwide, including various type of NBS such as wetlands, riparian planting, river restauration etc, and reported a 6.04% average price increase for houses near NBSs/green spaces.

Table 6. *Cont.*

Co-Benefits	Performance Indicators and/or Quantification Methods
Social cohesion/inclusion	Feeling of ownership, social cohesion, and inclusion can be increased by NBSs, especially during the co-creation process. Once NBSs are implemented, they also promote social contacts and inclusion. The type of NBS can imply the possible interactions (e.g., dry infiltration basins close to a playground may offer more possibilities to interact with others than a wetland). The diversity of incomes of households in proximity to NBSs can give an estimate to "equal access to green spaces". The potential of co-creation of NBSs can be an indicator of the potential for cohesion and the feeling of ownership of the place.

Despite a vast amount of data and international research on the use of NBSs, there is a lack of common guidance for assessing the performance for specific purposes (e.g., flood mitigation), especially at the catchment scale. Performance indicators can be defined for minimum operational targets once construction has been completed. Such performance indicators can relate directly to flood mitigation, impacts on biodiversity, or increased amenity value [155]. Seddon et al. [161] warn against using only technical criteria and suggest full engagement and consent of indigenous peoples and local communities, in a way that respects their cultural and ecological rights. Nature-based solutions can be presented as 'place-based partnerships between people and nature', with the conservation and enhancement of biodiversity at its core [161]. Because NBSs occupy more space than 'grey' infrastructure and often overlap with private land, transdisciplinary approaches that recognise NBSs as local in scale and specific to the needs of a region, people, and situation have greater potential to equitably maximise environmental, social, and economic benefits [162,163].

4. Modelling NBS Hydrology

Flood modelling is used for a range of purposes including source area mapping, flood risk mapping, flood protection planning and design, and real-time flood forecasting. Proprietary modelling packages used for flooding usually have integrated hydrological models coupled to one or more hydraulic modules. Hydrological models determine the volume and timing of runoff to the stream network, while hydraulic models route flows down the stream network and across the flood plain. There have been several state-of-the-art reviews of flood modelling [164,165], including deep-learning techniques [166].

Hydrological and hydraulic models are regularly used to assess the feasibility of different NBS options at the site, reach, or catchment scale. Numerous modelling studies have shown that NBSs can reduce flood risk in both urban (e.g., [61,167–169]) and rural [170–172] catchments. The key findings of these studies are that:

- The efficacy of NBSs for flood risk management is dependent on the placement of NBSs in relation to water sources and the drainage network, and the individual and cumulative storage of the structures prior to and during flood events.
- NBSs can be effective for reducing the impacts of localised minor floods, but they generally lack the cumulative capacity required to prevent catastrophic flooding associated with extreme rainfall events.

Modelling can also be used to compare the performance of different NBS options or NBSs against more traditional or hard engineering options. For example, Iacob et al. [173] (Figure 4) showed how models can be used to illustrate potential changes in flood risk over time in response to both traditionally engineered and NBS mitigation options within the context of long-term climate change. Their figure illustrates the immediate reduction in flood risk that is associated with the completion of traditionally engineered flood schemes (top left). In contrast, flood risk may undergo a more gradual decrease after the implementation of an NBS scheme is introduced (top right). Under climate change, flood risk response is more complex. As a result, the traditionally engineered scheme's immediate flood risk reduction may be moderated and eventually nullified by ongoing climate change (bottom left). The impact of the NBS scheme under climate change conditions is less certain because of the potentially complex interaction between climate conditions and ecosystem-based components within the scheme. The uncertain nature of the long-term environmental impact of the NBS under changing climate is therefore represented by a response envelope (bottom right). Similarly, changes to land cover and land use and management practices not related to the NBS can both increase and reduce flood risk. For example, modelling by Semadeni-Davies et al. [174] of the Helsingborg drainage network in Sweden suggested that increased imperviousness can have an impact on runoff generation on the same order of magnitude as climate change. They found that increased storage in the drainage network can mitigate this impact.

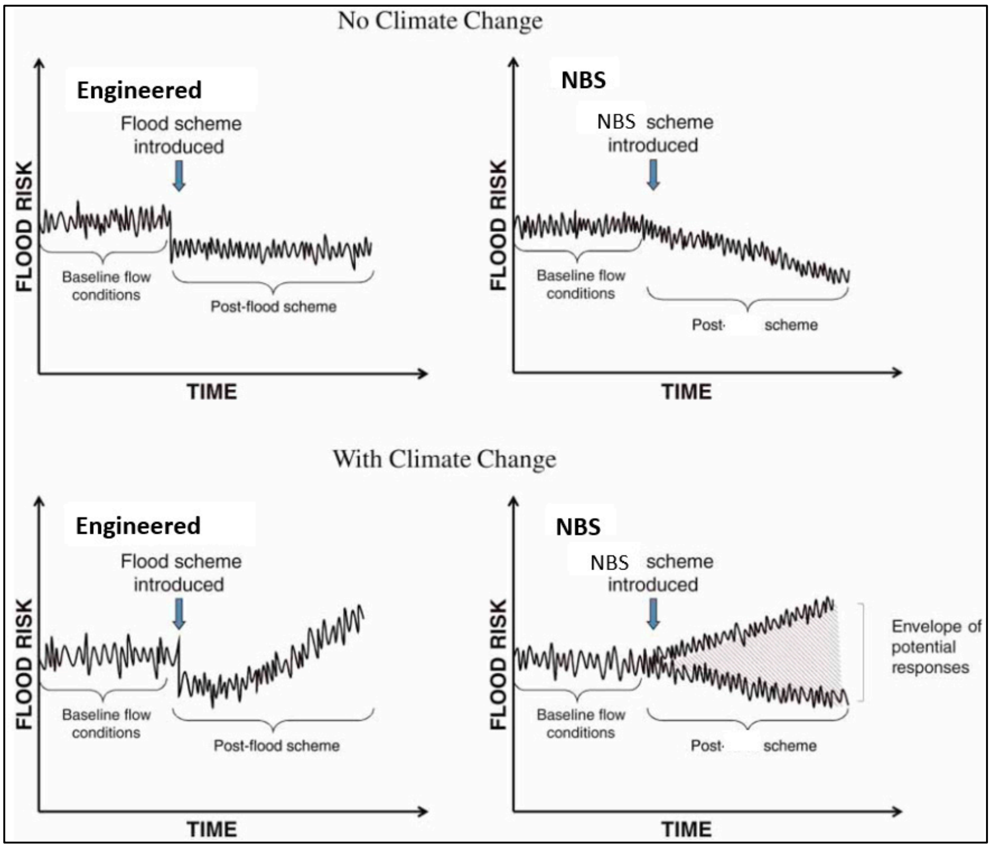


Figure 4. Potential outcomes of engineered and NBS strategies under no climate change (**top**) and climate change (**bottom**) conditions. (Reprinted with permission from [173], IWA Publishing, 2014).

The complexity of NBS systems and their interaction with each other and the wider environment alongside climate change results in a need for multidisciplinary models and estimates of likely uncertainty associated with single-disciplinary models where the stationarity of the system is not guaranteed. Elaboration of the implications of this uncertainty for climate change planning is described by Wübbelmann et al. [175], Gómez Martín et al. [176], and Kõiv-Vainik et al. [177].

4.1. Model Choice

The choice of modelling approach and model is predominantly guided by the proposed model purpose, i.e., which algorithms are needed to represent NBSs and produce outputs that can be used in the assessment of the hydrological response. Other key considerations include data availability, model resolution, reliability, uncertainty, track record, and resources needed to build, test, and run the model at the scale and extent required.

For example, the model best suited to determining the number and volume of stormwater overflows required for a small urban catchment (i.e., nuisance flooding) will be quite different from the model best suited to quantifying riverine flood hazard in a rural catchment with mixed land use. Although both tasks require hydrological and hydraulic modelling, the processes represented, and the level of detail required, are different. The former case requires a hydraulic model of the stormwater system but only needs to simulate surface runoff. The latter requires a catchment model capable of coupling separate urban and rural drainage networks, possibly at different scales, using a simplified pipe network. In addition, the former case may only require extreme rainfall values, whereas the latter would require continuous rainfall timeseries. The spatial scale and model resolution will also differ with the former covering perhaps only a few city blocks and the latter covering the wider catchment.

A review of models used for NBS intervention in the UK, described by the Environment Agency (Accessible here: https://assets.publishing.service.gov.uk/media/6036b795e90e0740b33891e3/Working_with_natural_processes_using_the_evidence_base_appendix_1_flood_risk_matrix.xlsx, accessed 1 June 2024) [12], indicates no one dominant model. This suggests that case-specific factors (local environment, data availability, project objectives) determined model choice rather than intervention type alone (Table 7).

Table 7. Model and model combinations used for NBS types (after the Environment Agency [12]).

NBS Intervention	Types of Models Used	Examples
Headwater drainage management	Hydraulic models Hydrological models	Jflow
Catchment woodland	Opportunity mapping Catchment hydrological models Multiscale models	
Soil and land management	Catchment hydrological models	WaTEM/SEDEM; SWAT; Hype; INCA; Fieldmouse.
Retention and detention	Desk-based studies Catchment walkovers Catchment hydrological models Hydraulic models Hydrological–hydraulic models Pond network model	HEC-RAS; Flood Modeller; Overflow; Topmodel; Topcat; 1D flood modeller; Flood modeller; Tuflow; SCIMap; CRUM4
Runoff pathway management	1D and 2D models Hydraulic models	Flood modeller; Tuflow; TopModel; Jflow.
River restoration	1D and 2D models Hydraulic models	Flood modeller; Tuflow; Jflow; 1D Flood modeller
Off-line storage areas	1D and 2D models Hydrologic and hydraulic models	Excel; Flood modeller; Tuflow
Floodplain woodland	1D and 2D models	HEC-RAS; River2D; Overflow
Floodplain restoration	1D and 2D models Hydrological-hydraulic models Lumped rainfall runoff models	MIKE SHE/MIKE 11

4.2. Parameterising NBSs

There are three ways of representing the influence of NBSs within standard hydrological models:

1. By changing model parameters and boundary conditions to represent different land cover, drainage pathways, or land use practices as determined by the NBS design (e.g., imperviousness, soil drainage properties, roughness/Manning's n).

2. By changing the topology of streamlines within the drainage network to represent adjustments to stream or river water courses [170,171].
3. By adding modules to represent NBSs in existing flood modelling software. This involves adding nodes to detain or retain runoff from one or more modelled flow pathways.

The hydrology of NBSs can be most simply modelled using 1D stream polylines connected by nodes at stream confluences. Water flow within these networks can be simulated by application of simple attenuation factors to reduce flow rates, or more complex physically based algorithms that simulate the hydrological or hydraulic processes operating within the NBS being modelled (e.g., infiltration and percolation to groundwater, detention, or retention). For example, a reservoir node can be placed within the drainage network to represent the storage of water in ponds or flood basins and its subsequent release via outflow structures. Complexity can be increased by the introduction of 2D and ultimately 3D processes within the same framework.

Table 8 illustrates how different model types can be parameterised to represent the inclusion of NBSs for flood mitigation. The NBS categories used in Table 8 are the same as those used in Tables 1 and 2, which have been mapped against the categories used in the Environment Agency (UK) guidance materials [12]. Parameter selection is made after specification of an NBS relative to the characteristics of the environment in which it is applied.

Table 8. Representative parameterisation strategies for different NBS options for 1D, 2D, and distributed models (after Environment Agency [12]). Light grey indicates 1D models, medium grey indicates 2D models, and dark grey indicates catchment models.

	1D Physics-Based cross-Section Analysis	1D Routing Model with Limited Survey	1D Hydrodynamic Model with Limited Survey	1D Model and Survey	2D Model	2D Model with Sub-grid Hydraulic Properties	1D-2D Linked Model	Lumped Parameter Catchment Model	Semi-Distributed Hydrological Model	Fully Distributed Model
Landscape retention and detention features	Adjust frictional losses per cross-section	Increase attenuation parameter	Increased Manning's *n* or reduce inflows	Increased Manning's *n* roughness	Increase Manning's *n*, or in-line storage			Change time constants in linear cascade	Adjust wave speed and treat as time constant storage	
Bioretention systems										
Landcover		Reduce wave speed in routing model	Increase overbank Manning's *n* roughness		Increase distributed Manning's *n* roughness and hydrological losses		Represent Manning's *n* roughness in more detail in 2d areas and hydrological losses	Change maximum soil moisture, storage, Cmax, and quick flow time constants	Change transmissivity, canopy storage, evaporation, overland flow speed, and antecedent wetness.	
Soil management	not applicable	Reduce inflow boundary			Modify losses: reduce rainfall inputs, increase infiltration, and surface roughness.			Changes to Cmax	Increase transmissivity	Vary soil parameters
River naturalisation		Reduce inflow boundaries	Reduce inflow boundaries, represent increased friction		Modify DTM to increase storage			Change time constants in linear cascade	Increase root-zone or other storage	
Natural wetlands										
Constructed wetlands										
River floodplain and estuary management	Different shear stresses	Increase attenuation parameter in Muskingum unit	Increase storage area capacity	Modify lateral weirs and roughness overbank	Modify DTM to add storage / roughness	Modify DTM to add storage / roughness. Add / remove break-lines			Increase complexity of floodplain representation	Link with detailed hydraulic model

In catchments where flood mitigation measures are already in place, it is important to know their location and how they are operated so that an accurate baseline can be created, against which future-state scenarios can be compared. It is also important to know how long the mitigation measures have been in place, so that identified trends in monitored data can be attributed to previous mitigation efforts. In this way system performance metrics can be adjusted to account for existing conditions.

When using models to optimise the position and operation of NBSs, the following questions should be considered:

- Are NBSs placed in the optimal position for maximum performance (e.g., slope, soil drainage, flow pathway, or position or in the drainage network)?

- Are NBSs correctly sized for the upstream area, and are sufficient NBSs operating to provide flood mitigation for all downstream areas?
- Design can greatly affect NBS performance, particularly peak flow volumes and flow rates [178–180]. Therefore, it is important to consider the shape and bathymetry of wetlands and ponds, and the use of islands, baffles, and planting to increase detention time.
- How will mitigation performance change with time (e.g., due to clogging or maturation of vegetation), and how will operation and level of maintenance influence performance?

Modellers often assume that hydrological systems operate under optimal conditions, and algorithms are calibrated against data collected at experimental sites or laboratory studies. In practice, however, the implementation and operation of mitigation measures may be sub-optimal, leading to poorer performance than was predicted by models during the design and planning phases. Challenges related to closing the gap between theoretical and actual performance of mitigation measures are discussed below.

5. Discussion: Challenges and Opportunities

While extensive literature on the potential use of NBSs for flood mitigation exists, significant gaps in knowledge about performance at a range of spatial and temporal scales remain. There is a need, therefore, for more empirical evidence about the short- and long-term effectiveness of current NBS designs. More specifically, better understanding of NBS functioning during extreme events, and the degree to which large scale events can be mitigated by NBSs at the catchment scale, are required. Such evidence will help build the scientific foundation for ongoing improvement in the performance and modelling of such measures.

5.1. Monitoring Hydrological Impacts for Model Validation

It can take years for vegetated solutions to become established, so a long-term monitoring plan is essential to ensure that changes in performance over time are captured. Perceived uncertainty in NBS effectiveness over longer time scales is one of the greatest barriers to adoption of NBSs [11,181]. To date, evaluation of the hydraulic and hydrological performance of NBSs has been predominantly for individual devices at the site or neighbourhood scale. The few studies that have looked at catchment-scale impacts have relied on modelling rather than monitoring. To characterise both the site- and catchment-scale impacts of NBSs, it is necessary to validate their performance by monitoring landcover or hydrological parameters that have been directly influenced by the introduction of one or more NBSs.

The hydrological response following the introduction of one or more NBSs can be monitored using traditional hydrometry techniques. The comparison of observed and modelled flows for conditions before and after installation of the NBS schemes will be of particular interest. Although a change in observed conditions may take some time to emerge, it is critical for modellers to be able to predict the length of time that it will take for the scheme to become effective. This will require the use of transient parameters identified in Table 8. It is equally important to monitor the hydrological effects of the installed NBS to refine model parameterisation, validate model predictions, or refine expectations of the specific NBS.

5.2. Evidence of Co-Benefits

In addition to improved hydrological performance, environmental and socio-economic co-benefits should be monitored to provide evidence of the cost and overall benefits of NBSs in the long term [11]. This is crucial to unlock their wider adoption. Buckley et al. [162] provided a list of spatial and temporal methods used for monitoring ecosystem and biodiversity indicators in response to agroecosystem restoration. These included three-times-a-year to 5-yearly monitoring of vegetation, soil and/or fauna (e.g., invertebrates, birds, worms) for various parameters (e.g., richness, relative abundance, composition, chemistry, compaction, moisture). While this list is not exhaustive, it provides candidate metrics that should be considered for monitoring at the start of any NBS project to provide information and metrics for similar future work. Iacob et al. [173] conclude from their meta-analysis of 25 Natural Flood Management (NFM) studies that, due to the complex processes involved and the dependency on pre-existing conditions, future studies should be framed as ecosystem-based assessments, with trade-offs considered on a case-by-case basis. Their study was able to relate species type to resulting impact on ecosystem services metrics (provisioning, regulating, cultural and supporting) for combinations of forestation, drainage management, and wetland and floodplain management.

5.3. Research Needs

Areas for future research focus, identified from the literature, for different NBSs for flood mitigation are summarised in Table 9.

Table 9. Challenges and research needs for specific NBSs used for flood mitigation.

NBS Intervention	Research Gaps
Retention and detention features	• Assessment of NBS efficiency and development of empirical data to link feature size with downstream impact. • Sensitivity of catchment flood response to the type, number, placement, design, and operation of storage areas in the upper catchment. • Impact of historic woodland reduction in upper catchment streams and rivers on hydrology and ecosystem services. • Potential impact of multiple small-scale storage measures on groundwater, the risk of flood, and stream low-flow regimes. • Difference between engineered flood storage areas and naturally functioning storage areas.
Bioretention areas	• Evaluation of water quality and quantity mitigation impact at the catchment scale, depending on location, size, and number of bioretention areas. • Performance over the long term, depending on operational conditions and maintenance. • Assessment of co-benefits such as air pollution and temperature control, depending on vegetation characteristics (foliage coverage, height, density).
Landcover and soil management	• Impacts of woodland in small-to-medium catchments (<50km^2) on flood flows. • Selection of representative processes in numerical models, and appropriate parameter values. • Monitoring of flood flows from woodland areas during extreme events. • Sensitivity of flood risk to area and location of different soil and land management measures.

Table 9. *Cont.*

NBS Intervention	Research Gaps
River naturalisation	• Conveyance capacity of restored rivers compared to degraded or managed rivers. • Estimation of flow attenuation and water storage that results from restoring natural river processes and landforms. • Type, location, and spatial and temporal scale of river restoration needed to reduce downstream flood risk. • Methods for phasing of flow attenuation features and synchronisation of attenuated flood peaks. • Better representation of floodplain hydraulics in numerical models.
Wetlands	• Effectiveness of different types and configurations of wetlands for flow regulation. • Determination of wetland and floodplain roughness, and parameterisation of associated drag coefficients. • Consideration of groundwater in wetland and floodplain restoration for flood attenuation.

6. Conclusions: Roadmap for Decision-Making for NBS Planning

A roadmap to guide the development of NBSs for flood mitigation at the feasibility stage was derived by the authors based on the reviewed literature and feedback from stakeholders (as illustrated in Figure 5). The first stage of the procedure is to define the nature of the flooding problem in terms of existing flood risk; related environmental processes (rainfall-runoff, soil moisture storage, groundwater recharge); current environmental controls (e.g., land use, slope, rainfall frequency and duration, rainfall intensity); the spatial and temporal scale of interest; and stakeholder impacts. This stage is critical for defining which NBS will be most applicable.

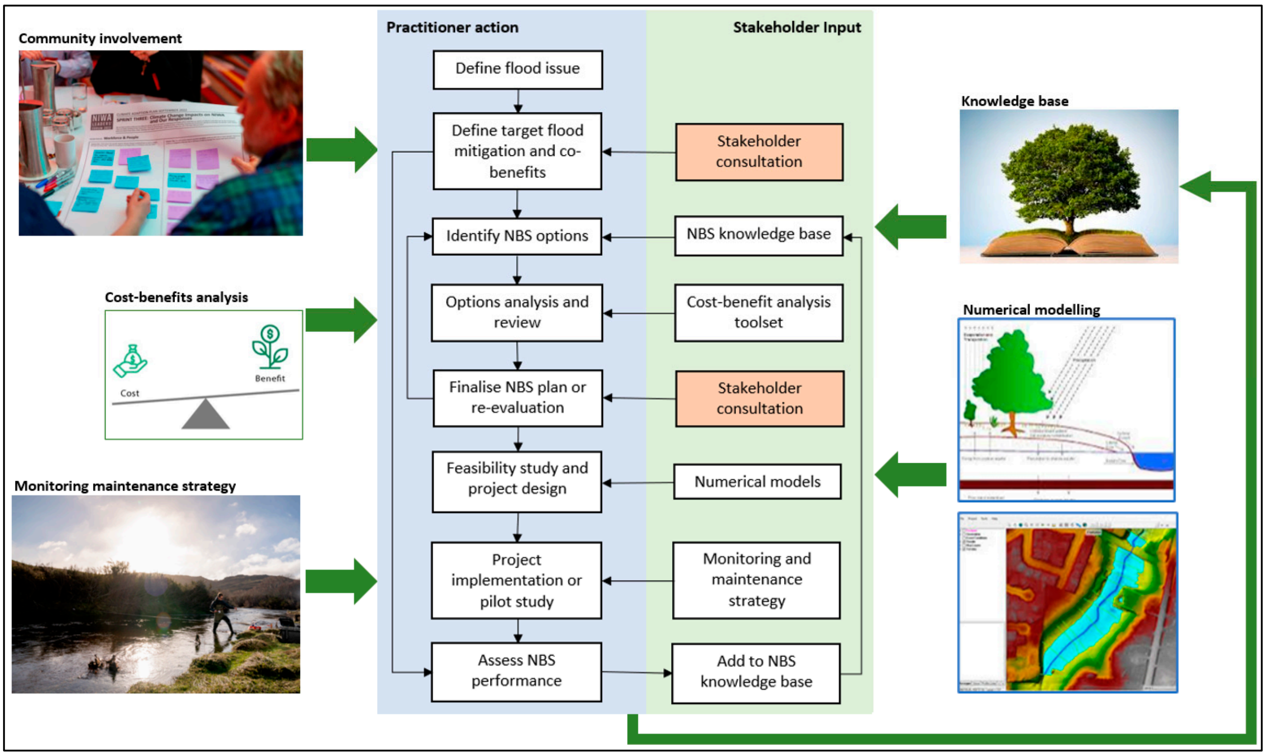


Figure 5. Flowchart of decision processes needed in planning NBSs for flood mitigation.

After the flood issue has been defined, target outcomes from the successful adoption of remedial measures can be set (e.g., reduced hydrograph peaks, reduction time of flooding, reduced impact to property, etc.). Stakeholder consultation should be sought at this stage to agree on and prioritise mitigation aims and identify environmental linkages that could create co-benefits (in addition to direct benefits). This information is used to compare the performance of different NBS options during model simulation at the design feasibility stage, and for performance assessment after implementation.

The definition of NBS mitigation options should be made with reference to the existing national and international knowledge bases. Consideration of co-benefits and direct benefits, and capital and operational costs should also be made at this stage (using tools of the type described in Section 3). The choice of which tool is used perform cost-benefit analysis will depend on the specific NBS under review. Which measures of performance are given priority by the stakeholder groups and project planners (i.e., social, cultural, economic, or environmental) will also influence this decision.

Before the commencement of a feasibility or pilot study, a clear monitoring plan should be formulated to allow measurement of model input parameters, performance variables, and co-benefit metrics. This will ensure accurate model simulation and subsequent mitigation performance after implementation, and that any learning outcomes can feed back into the existing knowledge base.

Given the procedure described above, it is clear that opportunities to develop location-specific NBS pilot or feasibility studies is an opportunity for systematic analysis of the use of NBSs for flood mitigation using location-specific parameters. However, to draw conclusions from multiple such studies, a common theoretical framework is needed to provide common aims, performance metrics, and measurable outcomes. Such a framework could also form the basis of experimental design specifically for the purpose of informing future national guidance and government policy (such as in Barkved et al. [182]).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16192802/s1, Table S1: SWOT analysis—retention and detention systems; Table S2: SWOT analysis—bioretention systems; Table S3: SWOT analysis—landcover management; Table S4: SWOT analysis—river naturalisation; Table S5: SWOT analysis—river floodplain restoration and estuary management; Table S6: SWOT analysis—natural wetlands; Table S7: SWOT analysis—constructed wetlands.

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