Nature-based solutions for flood management

Literature Review

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Executive summary

This literature review, independently commissioned by the Ministry of Business, Innovation and Employment (MBIE), was undertaken to inform 21 flood mitigation feasibility studies being undertaken by 15 regional or unitary councils. The aim of the review was to provide an up-to-date and in-depth analysis of the existing literature, case studies, and best practises related to the use of nature-based approaches for mitigating and managing fluvial floods. This report aims to avoid duplication of effort between local government authorities when evaluating the benefits (improved flood resilience) and co-benefits (environmental, cultural, social, economic improvements) of proposed nature-based solutions (NBS) schemes.

A key aspect of this study involved a review and analysis of the strengths, weaknesses, opportunities, and threats (SWOT) of NBS categories most often used by international literature and consisting of:

- Retention and detention systems
- Bioretention systems
- Landcover and soil management
- River naturalisation
- Natural wetlands
- Constructed wetlands
- River floodplain restoration and estuary management.

A summary of the strengths, weaknesses, opportunities, and threats matrices developed for the above categories is provided the table below. Challenges to implementation of NBS are also summarised in the main body of the report.

Despite a vast amount of international research on the use of NBS for water management, there is relatively little quantitative guidance for decision support at the design stage of NBS implementation for flood mitigation. In the absence of specific NBS design engineering standards, or performance measures, metrics used in grey infrastructure optioneering can be utilised. However, while grey infrastructure metrics can be effectively used to represent flood peak and volume attenuation, NBS impacts on biodiversity, socio-economic and cultural values are less well represented. To address this potential shortfall, several methods for identification and quantification of both hydrological (direct benefits) and non-hydrological performance (co-benefits) are reviewed.

Finally, the use of hydrological and hydraulic models for simulation of NBS performance are reviewed. Examples are used to illustrate how such models can be used with multiple landcover and climate scenario data to identify optimal location of single or multiple NBS at the catchment scale. A range of key parameters that can be used within numerical models, of differing complexity and for representation of different NBS, are identified from the literature. Data requirements, model uncertainty and error, and performance representation of different modelling approaches are also discussed.

Although this report can represent only a snapshot of the existing peer-reviewed and grey literature on the topic of NBS for flood mitigation, the summary section presents a roadmap derived from commonly occurring components of NBS implementation projects found in that literature, including definition of problem, option identification, costs-benefit analysis, project design, monitoring strategy and performance assessment.

Summary SWOT analysis of NBS that can be used in flood mitigation:

Strengths	Weakness
Ecosystem Services: NBS harness the natural functions of ecosystems, such as wetlands, floodplains, and riparian zones, to provide valuable ecosystem services like flood regulation, water filtration, and habitat provision. **Cost-Effectiveness**: Compared to traditional engineered solutions, NBS often require lower initial investment and maintenance costs, offering a cost-effective approach to flood risk reduction. **Resilience and Adaptation**: NBS enhance the resilience of communities and ecosystems to climate change impacts, supporting adaptation to changing hydrological conditions. **Multiple Benefits**: NBS offer a range of co-benefits beyond flood risk reduction, including improved water quality, enhanced recreational opportunities, and biodiversity conservation.	**Limits on applicability**: NBS may not be suitable for all flood risk scenarios, particularly when there is limited space available or areas with steep terrain. **Uncertainty and Risk**: There may be uncertainties associated with the effectiveness and performance of NBS, particularly in extreme or unpredictable flood events. **Time and Scale**: Implementing NBS requires time, careful planning, and coordination among multiple stakeholders, which can be challenging, especially when scaling up to address larger flood risk areas. **Maintenance and Management**: NBS are by nature cross-sectoral implying split responsibilities across their life span making their implementation and maintenance more difficult than grey infrastructure. They require ongoing management to ensure their effectiveness and sustainability, which may require resources and expertise.
Opportunities	**Threats**
Policy Support: There is increasing recognition and support for NBS from government agencies, policymakers, and the public, creating opportunities for their widespread implementation. **Innovation and Research**: Continued research and innovation in NBS technologies and practices can further enhance their effectiveness and address existing limitations. **Community Engagement**: NBS provide opportunities for community engagement and involvement in flood risk management, fostering local ownership and resilience. **Integrated Planning**: NBS can be integrated into broader land use planning and watershed management strategies, promoting synergies with other environmental and development goals. **Indigenous knowledge**: NBS provide a unique opportunity to include mātauranga Māori within flood planning and mitigation. Māori values and knowledge are already coincident with the approach taken by many NBS.	**Land Use Pressures**: Competition for land use and development pressures may limit the availability of suitable areas for implementing NBS, particularly in urbanized or rapidly growing regions. Achieving consensus between multiple property owners may also prove to be a challenge. **Climate Change Impacts**: Increasing frequency and intensity of extreme weather events associated with climate change may challenge the effectiveness of NBS and exacerbate flood risks in some areas. **Funding Constraints**: Limited funding and resources for NBS implementation and maintenance may hinder their widespread adoption, particularly in regions with competing priorities. **Regulatory Barriers**: Existing regulatory frameworks and permitting processes may pose barriers to the implementation of NBS, requiring streamlined approaches and policy reforms to facilitate their uptake. Clear process pathways that rely on evidence-based materials would help.

1 Introduction

The International Union for Conservation of Nature (IUCN) described nature-based solutions (NBS) 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, whilst simultaneously benefiting human well-being and biodiversity (Cohen-Shacham et al. 2016; Kabisch et al. 2017; IUCN 2020). The United Nations Environment Assembly (UNEA-UNEP) subsequently adopted a resolution that provided the first multilaterally agreed definition of NBS[1], and called for the development of common criteria, standards, and guidelines among member states to support their implementation. The World Bank define NBS in terms of the environmental processes and functions that enhance biodiversity whilst providing a range of associated benefits, often referred to as ecosystem services (ES).

In the last ten years, NBS have increasingly been used to reduce the risk of flooding in rural and urban areas (Brillinger et al. 2020; Browder et al. 2019; Debele et al. 2023; Ruangpan et al. 2020). However, whilst natural environment systems can be used to mitigate flood impacts (similar to traditional engineering infrastructure), they may exacerbate the problem or become prematurely degraded if conceived, designed, or implemented without reference to scientifically derived guidelines (Lallemant et al. 2021). It is within this context that this report presents a review of existing literature on the design and implementation of fluvial and pluvial flood mitigation measures that utilise NBS. A review of methods used to assess the benefits and co-benefits of different NBS types, and factors that need to be considered during their implementation and subsequent maintenance is also made. Finally, a review of how models can be used to represent the impact of NBS on flood risk is made.

1.1 Background

The Ministry for the Environment (MfE) has provided funding to 15 Regional and Unitary Councils to undertake 21 flood mitigation feasibility studies across New Zealand. The studies (listed in Appendix A) will employ numerical models to assess the benefits of incorporating NBS into flood mitigation designs. This literature review was independently commissioned by the Ministry of Business, Innovation and Employment (MBIE), to avoid duplication of effort between local government authorities when evaluating the benefits (improved flood resilience) and co-benefits (environmental, cultural, social, economic improvements) of NBS. Access to a common, widely available background literature review will improve the cost efficiency of these (and subsequent) projects. The report defines a common vocabulary and knowledge base for NBS used to improve flood resilience, and which can be used to describe different NBS methodologies and modelling approaches. Common strategies related to NBS design, implementation, and performance assessment are identified from national and international literature.

1.2 Aims and objectives

International guidelines for the use of NBS 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 environmental, ecological, and social benefits (World Bank 2017). NBS therefore, need to be designed, tested, and evaluated using both quantitative and qualitative

[1] https://wedocs.unep.org/bitstream/handle/20.500.11822/39864/NATURE-BASED%20SOLUTIONS%20FOR%20SUPPORTING%20SUSTAINABLE%20DEVELOPMENT.%20English.pdf?sequence=1&isAllowed=y

criteria. However, in the absence of nationally or internationally agreed standards for NBS, a review of existing numerical modelling and performance assessment methods is helpful to inform their use and application. This study focussed predominantly on NBS that i). reduce the magnitude of the flood hydrograph (flood peak) by increasing the rainfall storage capacity in the catchment, and ii). increase the resilience of drainage network infrastructure, farmland, and property to medium and large floods (>10-year return period).

This report aims to provide:

- a review of current national and international literature on the use of NBS in flood mitigation and management, and
- review of existing guidance and case studies for how such measures may be implemented in New Zealand.

To do this the following objectives were defined:

1. Present an overview of the state of knowledge and concepts of **NBS for flood mitigation and management**, including definitions, principles, and key components, within a New Zealand context.
2. Provide a literature-based evaluation of the **strengths, weaknesses, opportunities, and threats** (SWOT) associated with different NBS approaches, as they apply in New Zealand.
3. Identify **environmental, social, cultural, and economic co-benefits** associated with NBS and examples of where traditional knowledge has been incorporated in NBS.
4. Review methods used to **quantify benefits and costs** of NBS.
5. Review **best practice for modelling** to determine the efficacy of NBS on reducing flood flows. This includes assessment of **spatial and temporal scales** at which different NBS can be applied and are likely to function effectively (for moderate flood flows), and review of surrogate parameters used to represent the efficiency of different NBS.
6. Describe **New Zealand based case studies** that demonstrate successful implementation of NBS, as well as strategies that reflect the environments of the 21 funded projects (i.e., rural upper catchment areas, riparian areas, river flood plains, and freshwater and coastal environments).
7. **Report** the findings of this review in a manner that is suitable for both technical and non-technical audiences.

1.3 Structure of report

Section 2 describes different NBS options available for flood mitigation using the nomenclature described by the World Bank (World Bank 2021) and shown in Appendix B. For each defined approach, consideration of the spatial impact is made so that associated performance can be assessed in terms of reductions in peak flow or improvement in other environmental values. Consideration of impacts at the catchment scale help identify overall benefits and potential negative impacts downstream. The temporal scale of potential impacts is also considered through assessment of long-term ecosystem evolution in response to mitigation measures.

Section 3 presents a review of measures that can be used to assess the performance NBS. Different types of benefits and co-benefits produced by NBS are defined, i.e., benefits in flood mitigation as well as a range of socio, economic, cultural and amenity values. Tools that have been developed to provide quantitative or comparative assessment of benefits are then described. Related policy and guidance and policy that may influence their implementation is also described.

Section 4 provides a short review of different modelling approaches that can be used to quantify the impact of NBS on flood risk and mitigation. Issues related to data requirements, model scale, and uncertainty are discussed. An approach to modelling NBS is then suggested which includes model choice, identification of key parameters, and a strategy for estimating hydrological benefits and co-benefits. Pertinent site management and operational issues are also discussed. A review of key case studies which apply or investigate NBS application is made in **Section 5**.

2 NBS options for flood mitigation

The World Bank describes NBS according to their component physical processes, functions, derived benefits, and suitability of the location in which they are to be applied (World Bank 2021). This is useful because selection of an optimal performing NBS will depend on how these factors influence the outcome of a project. For example, in this study we focus on NBS that can be used to reduce flood risk and impacts, so meteorological and hydrological processes and functions are of most interest (though soil, vegetation, and topographical factors are also important factors).

In this section we describe different NBS types with respect to World Bank defined categories (listed in Table B-1, World Bank 2021). Each NBS can be used to reduce flood risk, improve flood resilience, and provide opportunities for net gains in biodiversity and socio-economic factors, to an extent that depends on local conditions. A review of literature for each NBS type was made, and an analysis of strengths, weaknesses, opportunities, and threats (SWOT) completed for each category. In practice, location-specific SWOT analysis will help determine the preferred NBS option for implementation (before modelling and feasibility assessments).

2.1 Spatial distribution of NBS

Kirby (2005) suggests the of the ‘Surface Water Management Train’ (CIRIA 2000) for development of Sustainable Urban Drainage Systems (SUDS). In this approach, runoff mitigation measures are developed first locally 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.

The UK Environment Agency (2018) project ‘Working with Natural Processes’ also provides guidance for the development of landscape-scale features (e.g., natural dams, lakes, ponded areas, woodland, wetland areas) that can be applied for flow or sediment transport attenuation. Such features can be applied to emulate natural hydrological functions in the upper middle or lower catchment, and in river corridors, floodplains, and coastal areas (Figure 2-1), 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 areas of ‘sacrificial land’ can be created, into which excess runoff can be temporarily diverted.

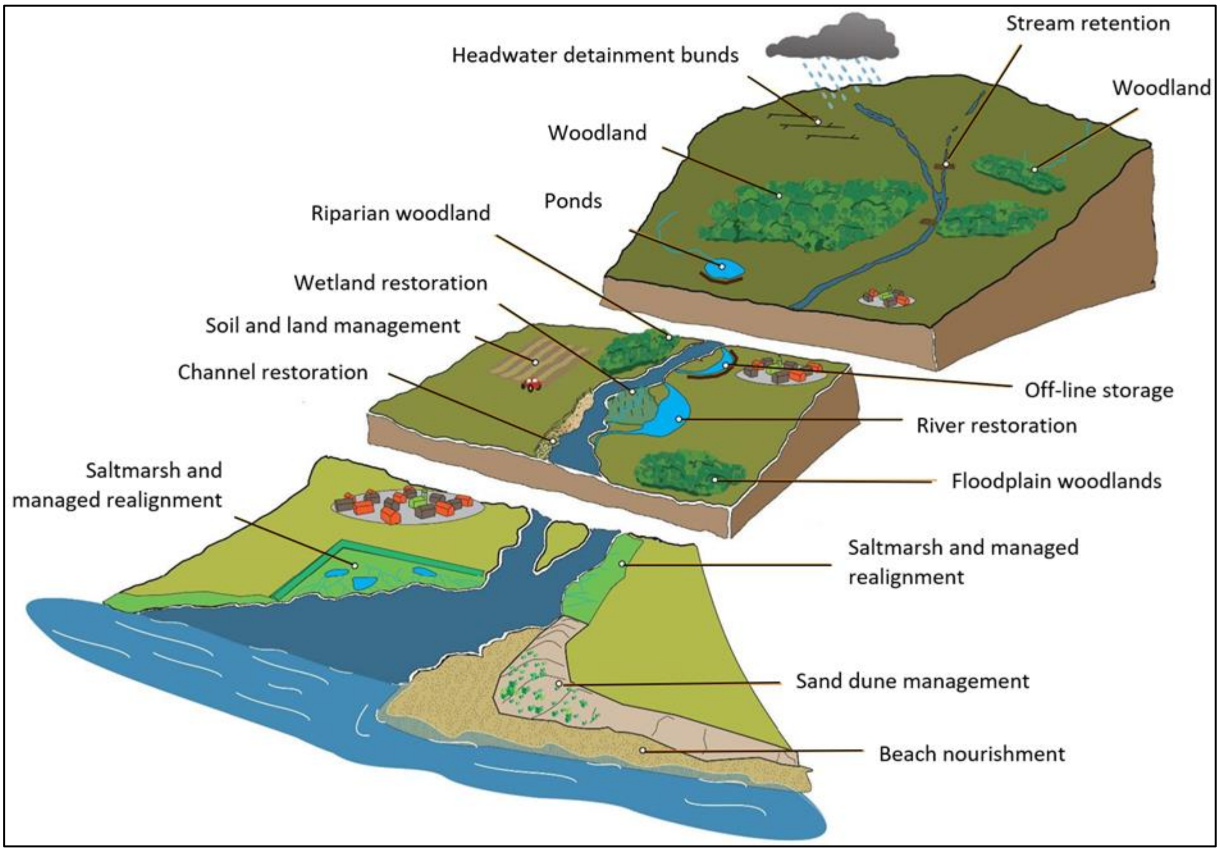

Figure 2-1: Use of different landscape features in upper, middle and lower catchments. (Source: UK Environment Agency 2018). Note that many of these mitigations can be used in multiple parts of the catchment, e.g., riparian buffers, constructed and natural wetlands, improved soils and land management and channel restoration.

2.2 Retention or detention systems

Retention systems (ponds, lake, and reservoirs) hold water in permanent wet storage areas whilst **detention systems** refer to storage areas that dry-out between runoff events (detainment bunds, swales, and dry ponds). Both retention and detention systems are designed to reduce flow volumes and peak flow. There is also wide range of other small-scale, soft-engineered, water-detention structures that can be deployed in headwaters to ameliorate downstream flooding (bunds, micro-dams, leaky barriers, buffer zones, peak run-off control and off-line ponds (Marttila et al. 2010; Roberts et al. 2022)).

In New Zealand, rural and urban detention systems are often designed and constructed to control water quality which means that they are typically designed to hold runoff from rainfall events with recurrence intervals of just one to two years. Good examples of exceptions to this are the larger detention basins in the upper Heathcote Valley in Christchurch[2] and Greenslade Reserve detention basin in Auckland[3], which are designed to hold 800,000 m^3 and 12,000 m^3 respectively.

Numerous modelling studies have shown that urban retention and detention systems can be effectively used to for prevent 'nuisance' or localised flooding of roads or stormwater outflows (Villarreal et al. 2004), and river flooding (Emerson et al. 2005; Ravazzani et al. 2014). The success of these systems depends on their location, and individual and cumulative storage capacity.

[2] https://ccc.govt.nz/services/water-and-drainage/stormwater-and-drainage/stormwater-projects/heathcote-catchment
[3] https://ourauckland.aucklandcouncil.govt.nz/news/2023/02/rain-drain-northcote-s-new-stormwater-infrastructure-tested-to-the-max/

Fassman-Beck et al. (2013) noted that in addition to runoff, groundwater recharge and evapotranspiration rates should be considered when estimating required storage capacity for NBS. They also note that operating NBS in series can be more effective for runoff control than traditional end-of-pipe systems. The use of multiple NBS would also add modularity and optional redundancy to stormwater networks, thereby increasing their long-term resilience (Ahern 2011; Ahern 2013; Moores et al. 2014; Moores and Semadeni-Davies 2015). Design rainfall return periods of 2 and 10 years were recommended for stream and flood protection respectively.

Tomer and Nelson (2020) described rural water and sediment control basins (WASCOBs) in the US (ISU, 2018), and calculated the cumulative water storage capacity of WASCOBs across three catchments and reported potential storage volumes from 10 mm to 1,000 mm. The effectiveness of these relatively small NBS options for flood management was assessed across multiple catchments to reflect total available runoff storage. In a similar manner, Ayalew et al. (2017) simulated the effect of 133 small headwater dams within a 660 km^2 catchment in Iowa. The volume of the resulting ponds ranged from 23,436 m^3 to 15,591,201 m^3. Collectively the dams could reduce peak discharge in the main river channel by between 20–70%. Modelled impact of the dams on peak flows was negligible for high frequency, low discharge events (2-year recurrence interval) due to low surface runoff. For lower frequency events, high magnitude events (1000-year recurrence interval) the dams had less influence on peak flows.

Detainment bunds are earth embankments typically located across small gullies and ephemeral streams. They are designed to store and slowly release runoff over several days following rainfall. During the detention time, sediment and contaminants from the runoff are removed through settling and infiltration. Paterson et al. (2019) differentiate between detainment bunds and other on-farm structures for removing sediments (such as ponds, dams, or sediment traps) using two criteria: 1) they are constructed within the landscape, and 2) they are designed to hold water for up to three days before being drained. This means that pastures are maintained and can continue to be used as productive land between storm events.

The placement of the bunds is critical to their function. Bunds are best placed on ephemeral flow paths with undulating to rolling slopes: the location should be large enough to accommodate a ponded area that is at least 1.2% of the upstream drainage area (120 m^3 of potential pond volume per ha of catchment area) (Figure 2-2).

In the Bay of Plenty region detainment bunds are being effectively used to reduce flooding generated by high intensity storms and help control sediment and phosphorus transport to the Rotorua Lakes[4]. The results of monitoring the hydrology and water quality of two bunds located upstream of Lake Rotorua over a 12-month period were published by Levine et al. (2021 a, b). The bunds were installed following local design guidance to treat agricultural runoff from dairy farms. Their upstream catchment areas were 20 ha and 55 ha, and the ponded area was ca. 1.5% and 2% of these catchment areas, respectively. Sampling was undertaken during and following storm events that led to upstream ponding. It was found that the two bunds reduce annual surface discharge volumes, largely through infiltration, by 43% and 31%, respectively. They 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. A key removal process was found to be soil infiltration rather than sedimentation, in the free-draining volcanic soils where they were studied.

[4] https://www.rotorualakes.co.nz/detainment-bunds (date of access 18 January 2024)

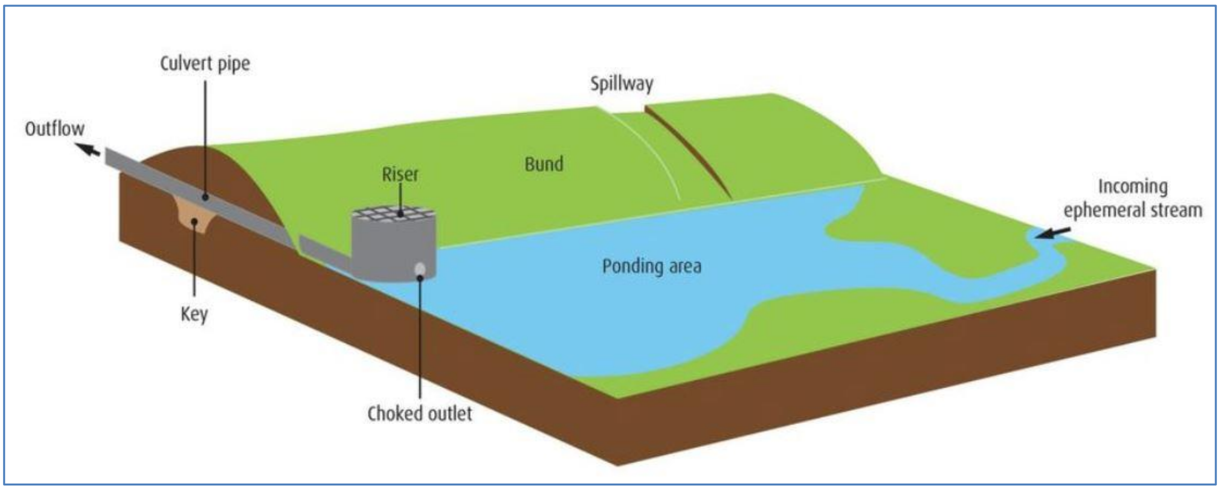

Figure 2-2: Example of a decanting earth bund (Source: Paterson et al. 2019)

'Living Water' trialled two detainment bunds in the Wairua River catchment in Northland (Moscrip Farm on Umuwhawha Road, and Roberts Farm on Riponui Road)[5]. The bunds acted like instream-dams with permanent ponds and were sized to optimise peak flow reduction and sediment removal. Both bunds had an outlet pipe below the bund crest to allow slow release. The Roberts Farm bund (catchment area of 112.5 ha) saw a reduction in nutrient load but suffered from overtopping during heavy rainfall which resulted in increased sediment load downstream. The Moscrip Farm bund (catchment area of 5.5 ha) however, was able to detain around 70% of high flow volumes and effectively remove sediment (95%), TN (45%) and TP (81%). Preliminary results from research by NIWA in Northland and Otago to access performance of bunds in landscapes with heavier, lower permeability soils indicate similar levels of sediment and nutrient reduction despite lower infiltration rates[6].

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. Generally, they are better suited to rolling rather than steep landscapes to facilitate cost-effective bund construction which are compatible with other farm activities and infrastructure. Assuming a ponding volume of 120 m^3/ha, detainment bunds can provide storage for between 4–11 mm of stormwater run-off (depending on soil type) (Paterson et al. 2019; Smith 2023). They can also provide significant downstream protection from high intensity rainfall events by reducing erosive outflows to protect roads and other infrastructure. As a result, the New Zealand Transport Agency (NZTA) has funded their construction at several sites around Lake Rotorua (John Paterson, PMP, pers. comm., Feb. 2023).

On-farm sediment traps, in the New Zealand context[7], take the form of shallow ponds or reservoirs in natural or man-made depressions. They are constructed at the outlet of a zero-order catchments and are designed to slow surface water flows to allow settling of sediment (McDowell et al. 2013). Their sizing (1–5% of upstream catchment area, with catchment areas ranging from 100 to 500 ha), location, and function, are similar to detainment bunds, but they may have a permanent rather than temporary pool. They can remove up to 80% of sediment transported via surface water flows (Basher et al. 2020; Phillips et al. 2020). Perrin Ag Consultants Ltd (2022) determined that there is a potential

[5] Living Water is a partnership between Fonterra and the Department of Conservation, https://www.livingwater.net.nz/what-were-up-to-nga-mahi-kei-te-haere/#stories-about-our-work Date of access 30 May 2024
[6] Andrew Hughes, National Institute of Water and Atmospheric Research (NIWA), pers. comm. Jan. 2024.
[7] Not to be confused with open check dam sediment traps used in alpine areas or constructed settling basins or hollows excavated at the inlet of culverts or drains installed as part of earth works (e.g, road or landing construction in plantation forest ahead of harvest).

for sediment traps also to be used on steep land. Smith (2023) reviewed the effectiveness of sediment traps (and detainment bunds) for use in New Zealand agricultural landscapes and endorsed the 120 m^3/ha minimum storage volume as appropriate for effective sediment removal. They noted highly variable performances ranging from 30% to 98%, with an average reported annual sediment trapping efficiency in agricultural catchments of 59%. Infiltration may also occur from sediment traps (depending on substrate) and they will require maintenance over the long-term.

Retention or wet ponds are common in both European and New Zealand's urban and rural landscapes (see Figure 2-3). On-farm retention ponds[8] can be either natural (e.g., ox-bow lakes) or constructed by excavation or damming of minor flow paths. Their primary purpose is to store water (for irrigation and stock watering) or to provide habitats for waterfowl and game birds (Ministry for the Environment 2001). Depending on seasonal inflows and corresponding water levels, wet ponds will generally provide less flood-water storage than dry retention structures. Other co-benefits of farm ponds include promotion of biodiversity, if planted near or within forested areas, and water supply for control of brush or forest fires. Placement of off-line farm ponds adjacent to streams has been recommended in the UK (Scotland's Rural College (SRUC) 2019; Yorkshire Dales National Park 2018) 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.

Eutrophication is a particular risk when nutrient levels in runoff are high, but this risk can be offset with the introduction of climate-appropriate nutrient-processing plant assemblages. Maintenance of a minimum flow through a pond, using inlet and outlet sumps, can also offset this risk. Ponds can be sized for water treatment, settling, stream protection and flood mitigation – usually for storms events up to 10% annual exceedance probability (AEP). If ponds are draining to streams, they must be sized to detain the volume from the 90th or 95th percentile storm events for release over 24 hours to provide erosion protection. Ponds for flood protection should be designed to 1% AEP rainfall.

Retention ponds can trap significant quantities of sediment and associated particulate contaminants (Brainard and Fairchild 2012; Robotham et al. 2021; Smith et al. 2002) which require periodic mechanical removal. Automated methods have been developed to determine optima locations for bunds and dams and estimating reservoir yields over large areas (e.g., Petheram et al. 2017). In rural landscapes Ayalew et al. (2017) simulated the impact of multiple small dams in the Soap Creek watershed in Iowa, finding that peak discharges could be reduced between 20% and 70%, with the effect declining as drainage area increased. The effect influence of distributed detention structures is also significantly affected by soil storage capacity and antecedent soil wetness (Thomas et al. 2016).

Capture of small ephemeral flows reduces downstream intermittent and perennial flows (Thompson 2012) and can reduce the ecological values these provide. Maxted et al. (2005) studying dams in the Auckland region reported that a lack of shading and the effects of accumulated organic and nutrient-rich sediments contributed to elevated water temperatures, depressed water quality and negative impacts on downstream aquatic life. In contrast, in a global review of the effects of small impoundments on stream habitat Mbaka et al. (2015) reported minimal effects on downstream water quality and variable effects (positive and negative) on macroinvertebrate communities. Also, in many European agricultural landscapes ponds and dams are seen as providing valuable biodiversity values (Cereghino et al. 2010; Williams et al. 2004).

[8] This discussion does not include enhanced pond systems or oxidation ponds intended for effluent treatment.

Figure 2-3: Wet retention ponds in Tampere, Finland (top) (pictures from Eisenberg and Polcher (2019)) and Auckland (lower). (picture from Dr Annette Semadeni-Davies).

While end-of-pipe stormwater retention ponds are common in New Zealand towns and cities, smaller on-sited NBS are increasingly being used for stormwater management as part of Water Sensitive Urban Design initiatives. Their benefits in the urban landscape include evaporative cooling (Spronken-Smith et al. 2000; Winker et al. 2019), non-potable use (Coutts et al. 2013), aesthetics, and as elements, in conjunction with other NBS, within blue-green corridors.

Swales are engineered channels that are used to convey surface water. They are generally linear, shallow, and wide in shape. They are most usually used as open drainage alongside roads or between other drainage structures (e.g., between ponds or wetlands arranged in series) in both rural and urban settings. Depending on the treatment and drainage requirements of the site, they can consist of standard vegetation cover (usually grass) or may include a specific media (for water detention and filtration), the latter, known as bio-swales are discussed in Section 2.3. The surface of the swale will be dry in fair weather but may contain shallow surface water flow during heavy rainfall. The wide and shallow shape of the swale means that it can facilitate evapotranspiration and infiltration of runoff (if required) and filter surface waters for solids and pollutants (Figure 2-4). Whilst most swales are sufficiently low gradient to reduce the velocity or surface water flow, check dams may be built across a swale to increase this capability (and reduce the risk of erosion). Swales can be used in place of kerbsides on highways, and whist they require some maintenance (mowing and trimming) they should reduce overall capital and operating costs.

Figure 2-4: Dry detention pond and infiltration basin (top left) (Source: susdrain.org) and vegetated swale (top right) (sudswales.com) in United Kingdom; and vegetated swale in Christchurch New Zealand (Source: niwa.co.nz).

Dry ponds and infiltration basins, which again are used in predominantly urban locations, are shallow basins in which excess runoff water can be stored and gradually infiltrate to sub-surface soils. The performance of such features depends on the infiltration capacity of soil and the depth to water table. Depending on the contributing catchment (typically up to 0.1 km^2) and space available, the basin may require an overflow pathway for larger rainfall events. Both infiltration trenches and basins are susceptible to sedimentation and detritus accumulation such that a pre-filter is usually used to reduce maintenance costs. Overflows from both features may require a filter-strip or sump to reduce mobilisation of sediment during high flow events (see Figure 2-5).

Soakage infiltration is widely used in parts of Auckland where stormwater is allowed to drain to underlying basalt aquifers. Infiltration of poor water quality, however, can result in ground water contamination. Soakage and infiltration systems can also exacerbate flood risk in groundwater fed areas (Graeme Smart, pers. comm. 2023), causing subsidence and undermine building foundations in built-up areas. Where groundwater resources are scare however, such features could produce meaningful aquifer recharge as a co-benefit.

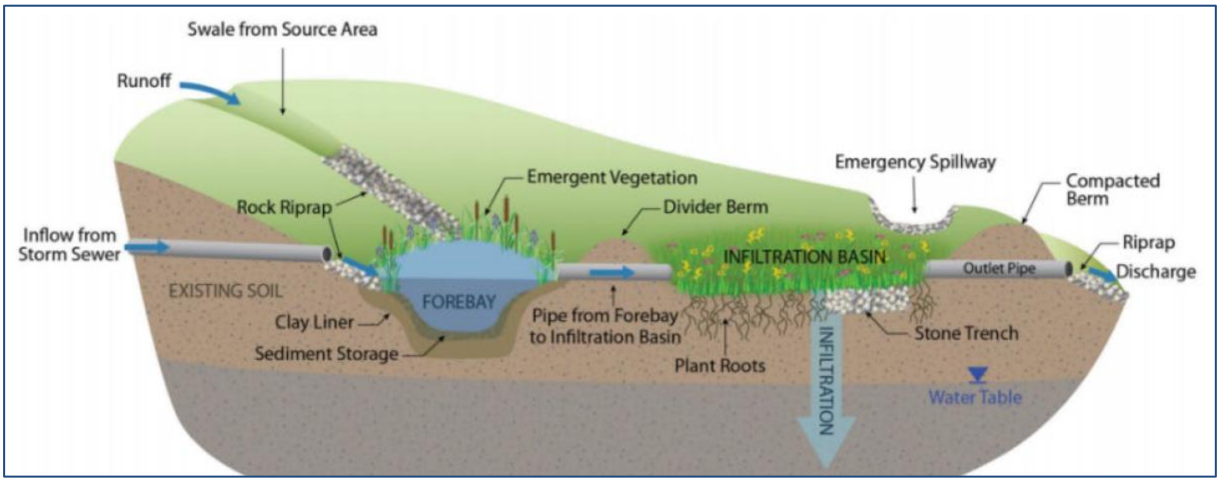

Figure 2-5: Schematic of typical infiltration basin (source: geosyntec.com).

2.2.1 SWOT analysis – retention and detention systems

Strengths	**Weakness**
▪ Relatively low-cost structures which can often be constructed without needing resource consents (e.g., bunds <3 m high, catchment <50 ha). ▪ Enable productive land-use between events. ▪ 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. ▪ Can provide water for stock drinking, firefighting and irrigation in rural areas. ▪ Can provide water for non-potable uses in urban areas such as for passive urban cooling.	▪ Limited relative storage capacity in very large events. ▪ Require large numbers distributed across the landscape to moderate widespread flooding. ▪ Require rolling but not too steep landscapes that facilitate sufficient ponding with minimal earthworks. ▪ Take areas of land out of production. ▪ Require regular sediment removal to retain storage capacity and limit scouring and remobilisation of accumulated sediments during large storms.
Opportunities	**Threats**
▪ Can be linked with constructed wetlands to improve performance across a wider range of contaminants and provide a wider range of ES and benefits. ▪ Can be used networked within catchment and provide aquifer recharge. ▪ Promotion of biodiversity, reduction of forest fire risk if retention ponds are sited in forests. ▪ Can support biodiversity. ▪ Can be used as exemplars when established (e.g., Te Arawa Lakes).	▪ Can increase water temperatures and reduce downstream water quality and aquatic biodiversity. ▪ Capture of small ephemeral flows reduces downstream intermittent and low-order stream length and the ecological values these provide. ▪ Infiltration practices in urban areas can cause groundwater contamination and, where there is high groundwater, can exacerbate flood risk.

2.3 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 (Auckland Council; USEPA 2021; Vijayaraghavan et al. 2021) (Figure 2-6). They vary in sizes from few square meters to few hundred square meters. However, some isolated examples of larger systems exist, such as the one implemented by Port of Vancouver reaching approximately 2,000 m², to collect and treat the runoff from a 20 hectares catchment (Vancouver 2013).

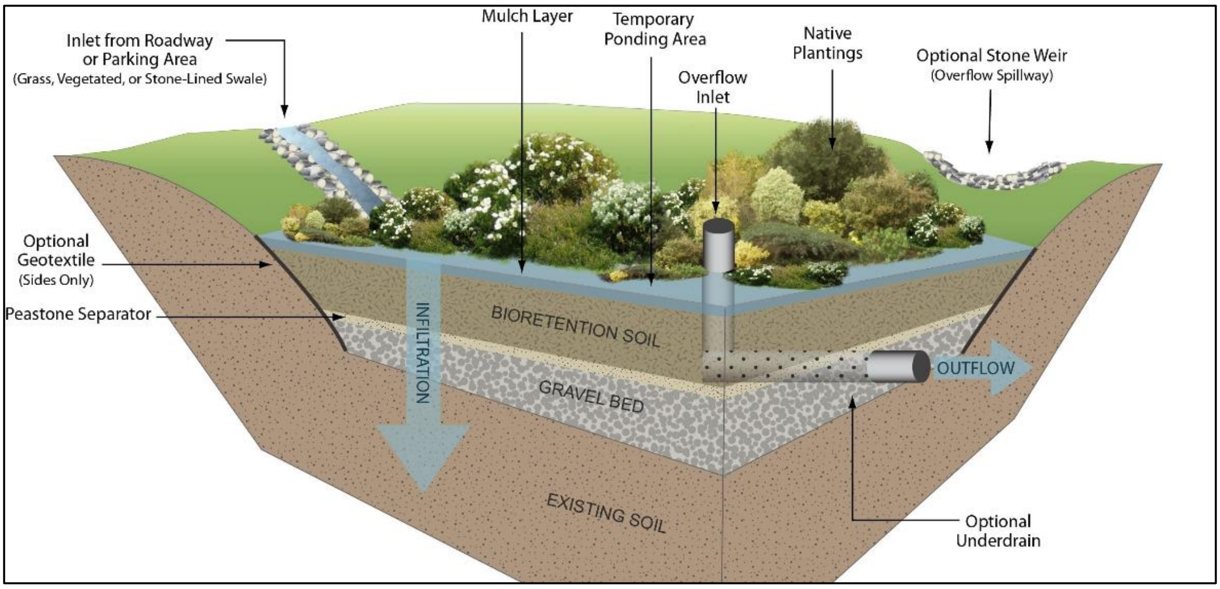

Figure 2-6: Example of a bioretention basin. (Source: Massachusetts Department of Environmental Protection).

Bioretention areas provide water quantity and quality control functions. While their design may differ from one jurisdiction to another, they generally rely on:

- A ponding zone above planted media, providing a water detention area
- Planted vegetation (shrub like vegetation or trees), whose roots help to maintain the hydraulic conductivity of the filtration media and provide pollutant removal mechanisms (plant uptake, rhizofiltration and bioremediation)
- A filtration zone composed of a mix of soil, sand and/or other reactive/sorbing material: providing pollutant removal mechanisms and water detention
- An optional underdrain where the *in-situ* soil does not allow for infiltration
- An optional storage zone located under the underdrain outlet to provide storage and further infiltration in to *in-situ* soil.

While most bioretention systems are landscaped depressions collecting surface flow runoff in urban or semi-urban areas, such as rain gardens, bioretention basins or bioswales, systems such as planter boxes receiving runoff from rooftops are also considered as bioretention systems as they provide similar functions (except infiltration to *in-situ* soil) and serve the same purpose of regulating stormwater runoff. The most commonly used bioretention areas are rain gardens and bioswales. The main difference between these NBS is that in addition to providing water storage and treatment like raingardens, bioswales are also used to convey water runoff in lieu of a stormwater pipe. While raingardens can accommodate shrubs and trees, bioswales are usually only planted with grass.

Bioretention areas have been reported to efficiently remove suspended solids, metals, nitrogen, organic and microbial pollutants (Mosley and Peake 2001; Vijayaraghavan et al. 2022). They also provide volume and peak flow reduction - even in low permeability soils. Winston et al. (2016) measured up to 59% of 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 (Blecken et al. 2015). Insufficient communication, unclear responsibilities, lack of knowledge, financial barriers, and decentralised measures were reported by the authors as probable reasons for failure.

Co-benefits of bioretention system include heat regulation, air quality improvement, carbon storage, improved local economies and job creation, recreational and educational opportunities, and increased biodiversity (World Bank 2021). Heat regulation is primarily attributed to the presence of trees that directly (via shading) or indirectly (via evapotranspiration) reduce urban heat island effects (Endreny 2007). 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. When trees are present, as opposed to smaller plants, long-term carbon sequestration and storage is increased (Vito et al. 2021). Kavehei et al. (2018) estimated an average annual carbon storage of 2.4 kg/m^2 is possible in the bioretention area.

Another co-benefit of bioretention areas is increased biodiversity (Kazemi et al. 2011). The number of species, species richness and diversity has been found to be higher in bioretention swales, compared to garden and lawn spaces. The presence of mid-stratum vegetation, flowering plants, higher slope, and lower soil pH are thought to have increased refuge and food resources for invertebrate species in bioretention swales. However, such areas may also increase vector breeding (World Wildlife Fund 2016), such as mosquitoes, in case of system failure leading to stagnant water.

When implemented close to air pollutant emission sources (e.g., roads) bioretention areas can also improve the air quality (Biswal et al. 2022). In Woodside (California), 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%) (Deshmukh et al. 2019). The authors stipulated that the roadside vegetation is required to be of sufficient height, density, and foliage coverage to obtain a high pollutant reduction.

From a socio-economic perspective, bioretention areas can increase opportunity for educational and recreational activities hence increasing potential for social interaction (Kim and Song 2019; World Bank 2021). They can also provide economic benefits by increasing the market value of real estate and creating green jobs (Ira 2017; World Bank 2021).

Liu et al. (2018) 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 mainly depends on the vegetation establishment and the time it will take for the roots' network to colonise the media. Maturity might take longer when trees are present than only shrubs or grass (for bioswales) for instance. The microbial community responsible for the biodegradation of some pollutants (e.g., nitrogen, organic pollutants such as Polycyclic aromatic hydrocarbons (PAHs)) will also develop during this establishment period. While Liu et al.

(2018) considered an eight-month period (one growing season + two months) to be sufficient for the bioretention to be effective, Spraakman et al. (2020) suggested a period of two years.

Performance of mature systems is also subject to change as the systems ages. 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 (Hečková et al. 2022; Le Coustumer et al. 2012). While some systems showed no significant decline in hydraulic conductivity after six years (Jenkins et al. 2010) others exhibited a hydraulic conductivity more than half the initial value after a seven-year period (Le Coustumer et al. 2009). It is thought that selecting plants with thick roots (e.g. Melaleuca) could help in maintaining permeability over time (Le Coustumer et al. 2012).

In the past decades many different amendments (e.g., biochar, water treatment residuals, fly ash) were used as part of the filter media to increase pollutant (especially metals, organic micropollutants and phosphorus) sorption (Qiu et al. 2019; Xiong et al. 2022). While the durability of the sorption capacity is highly variable depending on the intrinsic properties of the material and the environmental conditions it is exposed to, it will most probably decrease over time while sorption sites become saturated (Vogel et al. 2021), potentially reducing its treatment efficiency.

Bioretention areas are usually implemented as part of a suite of NBS that collectively mitigate stormwater runoff impacts in a specific catchment. They are commonly implemented at the neighbourhood or city scale (World Bank 2021) but can also be effective at the floodplain scale in improving drainage and enhancing resistance to damage (World Wildlife Fund 2016). While current guidelines recommend bioretention systems to cover 2% to 5% of the catchment area (Cunningham et al. 2017; FAWB 2009) 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 NBS (including bioretention) specifically for flood risk attenuation (Wenhui Wu et al. 2023).

Mei et al. (2018) 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 (including green roofs, permeable pavements, vegetated swales, and bioretention cells) for flood mitigation in a 651 km^2 urban watershed. Simulations were performed for storm events with return periods of 2–100 years. Results suggest that the NBS scenarios could mitigate the flood risk (between 10% and 80% reduction of the peak flow depending on the scenario) but could not eliminate it. Highest and lowest reductions were achieved with NBS covering 37% (comprising all investigated NBS) and 6% (only vegetated swales) of the catchment surface area, respectively. 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 by c.20–50% the flood volume (volume in excess of the channel capacity) depending on the storm event return period.

Wu et al. (2023) 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 first step of the approach, which can be applied to both rural and urban catchments, is to set damage reduction targets defined by historic flood volume and damage relationships. The framework also explores eligible flood reduction scenarios to set sub-catchment runoff volume reduction targets and required sizes and placement of NBS. The results of the framework applied to the urban catchment of Sydney suggested that the 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.

2.3.1 SWOT analysis – bioretention systems

Strengths	**Weakness**
▪ Bioretention and remediation of contaminants. ▪ Reduced sediment loads and transport. ▪ Pluvial flood regulation through volume and peak flow attenuation. ▪ Relatively low cost of implementation. ▪ Well documented guidance available. ▪ Improve biodiversity in urban areas.	▪ Potential failure of the system if not properly maintain. ▪ Can be part a flood mitigation strategy but will not suffice on its own. ▪ Ongoing maintenance costs. ▪ Potential for maladaptation.
Opportunities	**Threats**
▪ Co-benefits could include. ▪ heat regulation, air quality improvement, carbon storage. ▪ Job creation, recreational and educational opportunities. ▪ Increased biodiversity.	▪ May increase vector breeding if case of stagnant water (i.e., system failure). ▪ Financial barriers and uncertain responsibilities for ongoing management and maintenance.

2.4 Landcover and soil management

Whilst there is multiple evidence to suggest that landcover and soil management measures can reduce local peak flows after moderate rainfall. There is limited evidence that such measures can influence flooding from extreme events and at larger scales. Longer term monitoring of land-use change at the catchment scale would be needed to conclude this. The main landcover and management approaches used for flood mitigation are described below.

MEA (2005) considers forest ecosystems to be better providers of ecosystems services compared to other ecosystems (e.g., marine, coastal, island, mountain etc). **Forests** are also increasingly recognised for their role in managing runoff, though the extent to which individual forests impact downstream flood is difficult to quantify due to the complexity of mixed land-use catchment hydrology (Bathurst et al. 2020). Despite this, modelling can help navigate different forest design specifications related to species type, location, extent, planting, and harvesting; all of which are important to consider when planning forest and woodland NBS that can take decades to reach maturity and to become fully effective. Marapara et al. (2020) found that forests can be most effective for flood mitigation when the appropriate species is grown on gentle or moderate slopes, on shallow to medium depth soils, over permeable bedrock. Similarly, they were least effective on shallow soils over impermeable bedrock in steep sloping areas.

It is important to distinguish between the impact of **native and exotic forest species**. The removal of indigenous forest and its replacement with pasture-based agriculture started just 180 years ago in New Zealand (Cao et al. 2009; Clark and Wilcock 2000) and has resulted in significant increases in runoff (Hughes et al. 2021). Sediment mobilisation has also increased and has become a significant contributing factor to flood damage. Generally, mono-culture forestry is used in upland catchment areas, whereas in the middle and lower catchment forestation tends to be smaller in scale and involve targeted pockets of trees, shrubs and grasses. Whilst the introduction of both natural and cultivated forests can help reduce downstream flood risk, monoculture planting can have negative impacts on ecosystem diversity (Ma et al. 2022).

Commercial forests which are harvested over 30 to 40 years periods result in periodic exposure of land and soil, and production of forestry slash; both of which increase downstream impacts. Previous work in the East Cape (Eyles and Fahey 2006; Fahey et al. 2003; Fahey and Marden 2006) suggest a six-year post-harvest period in which soil erosion risk is exacerbated. In addition, road cutting can take place 3 to 5 years prior to harvesting. This means that for a 30-year growth cycle, the land is in a vulnerable state for up to a fifth of the time.

Planted forests provide a range of provisioning, regulating, cultural and supporting services (Figure 2-7). Whilst provisioning services (wood, fibre, biofuel) are more easily converted to equivalent monetary value, regulating, cultural and supporting services require further investigation as to their total net benefits on societal health, security and cultural values (Yao et al. 2013).

Co-benefits of forest cover include prevention of extreme temperatures and reduction of the impacts of heatwaves by as much as 4 °C (in urban green space) and 3.5 °C (in parklands) (Debele et al. 2019). Forests have also been shown to reduce air pollution in urban areas (Abhijith et al. 2017). When integrated with ponds or wetlands, tree-cover can reduce localised flooding (Green et al. 2021). Green corridors, parklands and recreational spaces in urban areas also provide designated flow pathways for flood flows, hence alleviating otherwise flooded areas.

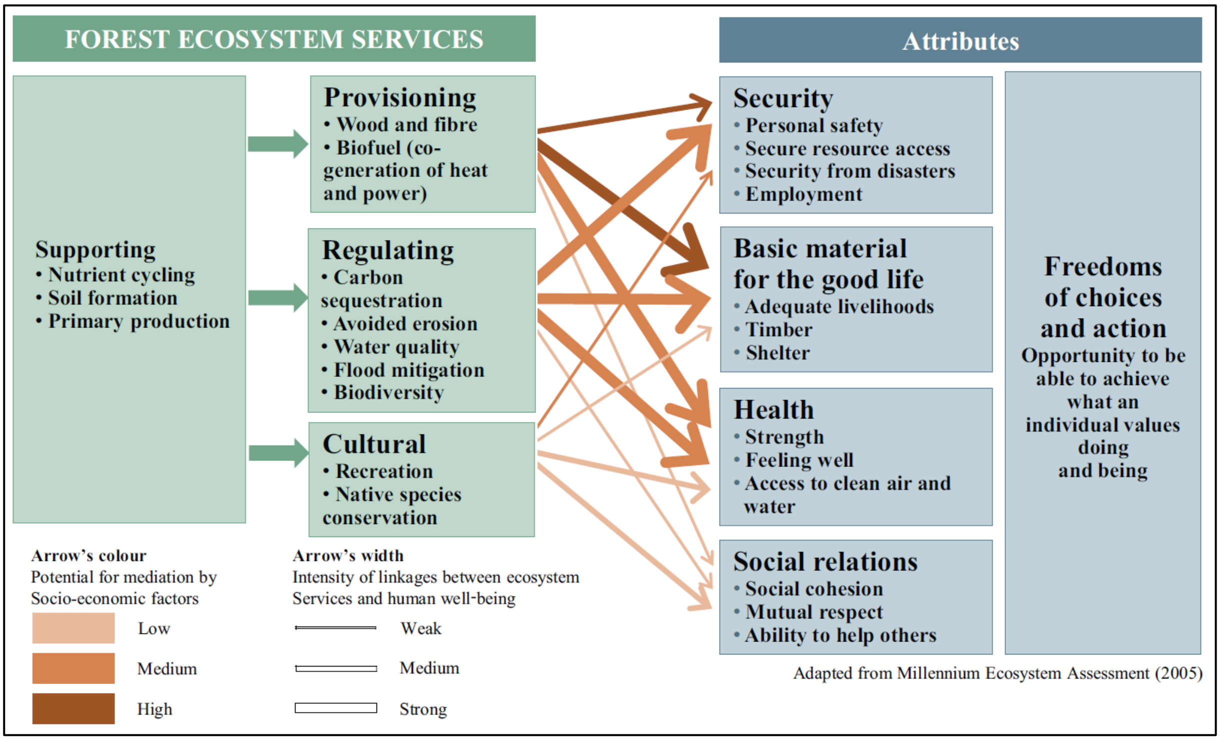

Figure 2-7 Ecosystem services provided by planted forests. (Source: MEA 2005; Yao et al. 2013).

As a low-cost way to retire farmland into native forest, the Tīmata Method (Dewes et al. 2022) is a good example of how traditional knowledge can be used to develop NBS. The method involves restoration of native forest on marginal lands that is susceptible to soil erosion by planting low density kānuka and mānuka to act as a nursery crop for succession trees to establish. Full regeneration of complex ecosystems may take up to 100 years or more to arise, but the method is based on the Te Ao Māori principles of long-term thinking. The guiding philosophy of the method is to harness the healing powers of Papatuanuku (Earth Mother) to protect the whenua and awa, attract manu (birds) and allow natural reversion to mature ngahere. Resulting reductions in runoff and sediment production will also occur at a natural pace, along with improved water quality, lower greenhouse gas emissions, and more economic land management.

Restoring and maintaining vegetation can reduce the extent and magnitude of erosion that occurs during flood events by trapping sediments and reducing mobilised sediment load. Less commonly used approaches include drainage improvement, use of debris dams, ground recontouring and stream bank strengthening. Table 2-1 presents a summary of erosion sediment control measures in New Zealand and their sediment removal efficiency (grouped by erosion type). Additional guidance on implementation is given in Basher et al. (2016) and summarised in Phillips et al. (2020). Table 2-2 highlights the key costs and benefits for different land-use types (Haddadchi et al. 2022).

Table 2-1: Runoff and erosion controls in New Zealand. (after Basher et al. 2016; Haddadchi et al. 2013; and Phillips et al. 2020).

Process	Control principles	Features
Surface erosion	Runoff control to reduce flow rates and sediment generation Sediment control to settle or trap sediment before discharge	Wetlands and sediment traps Detention and retention settling ponds Silt fences (urban earth works) Riparian grass buffer strips Wheel-track ripping and diking Cover crops (horticulture) Continuous dense, improved pasture
Mass movement (landslides and earthflows)	Control of slope hydrology and soil strength to maintain slope stability.	Space-planting (full cover) and afforestation / reversion to scrub Debris dams
Gully erosion	Runoff control to reduce flow rates and sediment generation	Space-planting (full cover) and afforestation / reversion to scrub
Streambank erosion	Maintain bank stability to reduce undercutting and lateral migration.	Riparian fencing Riparian fencing and planting

Pasture management practice and intensive **grazing** in New Zealand promote soil compaction and cracking, which leads to increased runoff and sub-surface drainage. Flow from boundary ditches, animal tracks, and reduced riparian corridors, promote increased runoff and sediment transport. Localized flooding can therefore be attributed to changes in land management and land cover.

Tillage reduction approaches that preserve soil structure, and thus aid more effective infiltration of rainfall to the root zone, aim to leave a minimum of 30% of the soil surface covered with crop residues (Soane et al. 2012). The gradual increase in soil cover, carbon stock and soil adhesion, increases the amount of water stable aggregates (Keretsz et al. 2010) and macropores connectivity through the action of earthworms, which in turn increase the soil water storage (BIO Intelligence Service and HydroLogic 2014). 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 (Soane et al. 2012).

Table 2-2: Costs and benefit of different NBS to reduce on erosion susceptibility.

Risk	Controls	Costs	Benefits
Cropland erosion	Cover crops	Sowing	Nutrient and sediment removal
	Detention and retention ponds	Excavation and construction	Nutrient and sediment removal
Grassland erosion	Wetlands and sediment traps	Opportunity cost of retired grazing Excavation and construction Planting, weed and pest control	Wetland co-benefits (habitat enhancement, nutrient and sediment removal)
	Detention and retention ponds	Excavation and construction	Nutrient and sediment removal
	Riparian buffer strips	Fencing Maintenance	Nutrient and sediment removal
	Improved pasture	Re-sowing Stand-off pads	Pasture productivity benefits
Streambank erosion	Riparian fencing	Fencing	Pathogen reduction
	Riparian planting	Planting and weed control	Co-benefits (habitat enhancement, nutrient removal, pathogen reduction, carbon sequestration)
Gullying	Space planting	Planting	Carbon sequestration
	Afforestation	Opportunity cost of retired grazing Fencing Planting, weed and pest control	Forest co-benefits
Mass-movement	Space-planting	Planting	Carbon sequestration
	Afforestation	Opportunity cost of retired grazing Planting, weed and pest control	Forest co-benefits

A report commissioned by the World Wildlife Fund - Cymru (Farmlytics 2023) in Wales clearly shows that farmers who adopt NBS or regenerative farming practices enhance 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 have the potential to provide beneficial impacts on farm productivity in the face of changing climate. However, it was also stated that such measure will likely require central government assistance with capital costs.

2.4.1 SWOT analysis – landcover management

Strengths	**Weakness**
▪ Landcover change can be used to increase infiltration, canopy interception and evapotranspiration and thus reduce magnitude and temporal response of flood peaks. ▪ Forest cover can provide carbon-sinks for carbon sequestration. ▪ Green corridors and similar can lead to habitat creation and passage for birds and fish and improvements in water quality (e.g., biodiversity, visual clarity, etc).	▪ Long-start-up time related to vegetation growth period, during which space may be more vulnerable to flooding. ▪ Land acquisition can be challenging. ▪ Initial capital costs could be prohibitive to private landowners.
Opportunities	**Threats**
▪ Increased vegetation cover is particularly useful in upper catchments areas or strategically targeted to areas of known high runoff. ▪ Increased green space has co-benefits for amenity value and biodiversity. ▪ Planting opportunities can be used to introduce culturally significant plant species.	▪ Use of monoculture plant assemblages could have negative impact on local biodiversity and increases the risk of soil erosion and flooding after harvesting. ▪ Expansion of forestry for flood risk mitigation could be at cost of carbon rich and biodiverse native ecosystems, and local land rights.

2.5 River naturalisation

Over time, large sections of rivers and streams in New Zealand have become 'denaturalised' by either urban or rural development. In particular, the construction of embankments, culverting, and filling in of tributaries increases risk in flood prone areas. Growing appreciation of NBS, ES and biodiversity is leading to a paradigm shift in river management, of which renaturation and restoration are a part. These are encapsulated in the often use phrases of 'making room for rivers' or 'working with water' There are several NBS approaches which form part of this approach including stream 'daylighting' (Brierley et al. 2022), re-establishment of riparian corridors, removal of concrete embankments, and riverbed and bank revegetation. River and stream renaturation aims to slow river flow and thus reduce flood risk by increasing water retention and infiltration (Ozment et al. 2019; Soar and Thorne 2001).

River naturalisation aims to increase the volumetric capacity of a catchment and restore the natural hydrodynamics of watercourses, riverbanks, riparian corridors, buffer zones, and floodplain. River and stream renaturation projects can lower flood height and flood velocity in surrounding areas and thereby reduce structural damages to properties and infrastructure. Passive (or indirect) river management focuses on connectivity along the river network from upstream to downstream, laterally between the river and its floodplain, and vertically with the underlying alluvial aquifer (Kondolf et al. 2006) (see Figure 2-8). Methods include land use change to reduce the flow of water to the river network anywhere in the catchment, and removal of barriers within the river network. Direct management intervention involves removal of bank and bed reinforcements to allow the form and position of the river to adjust to the surrounding environmental conditions.

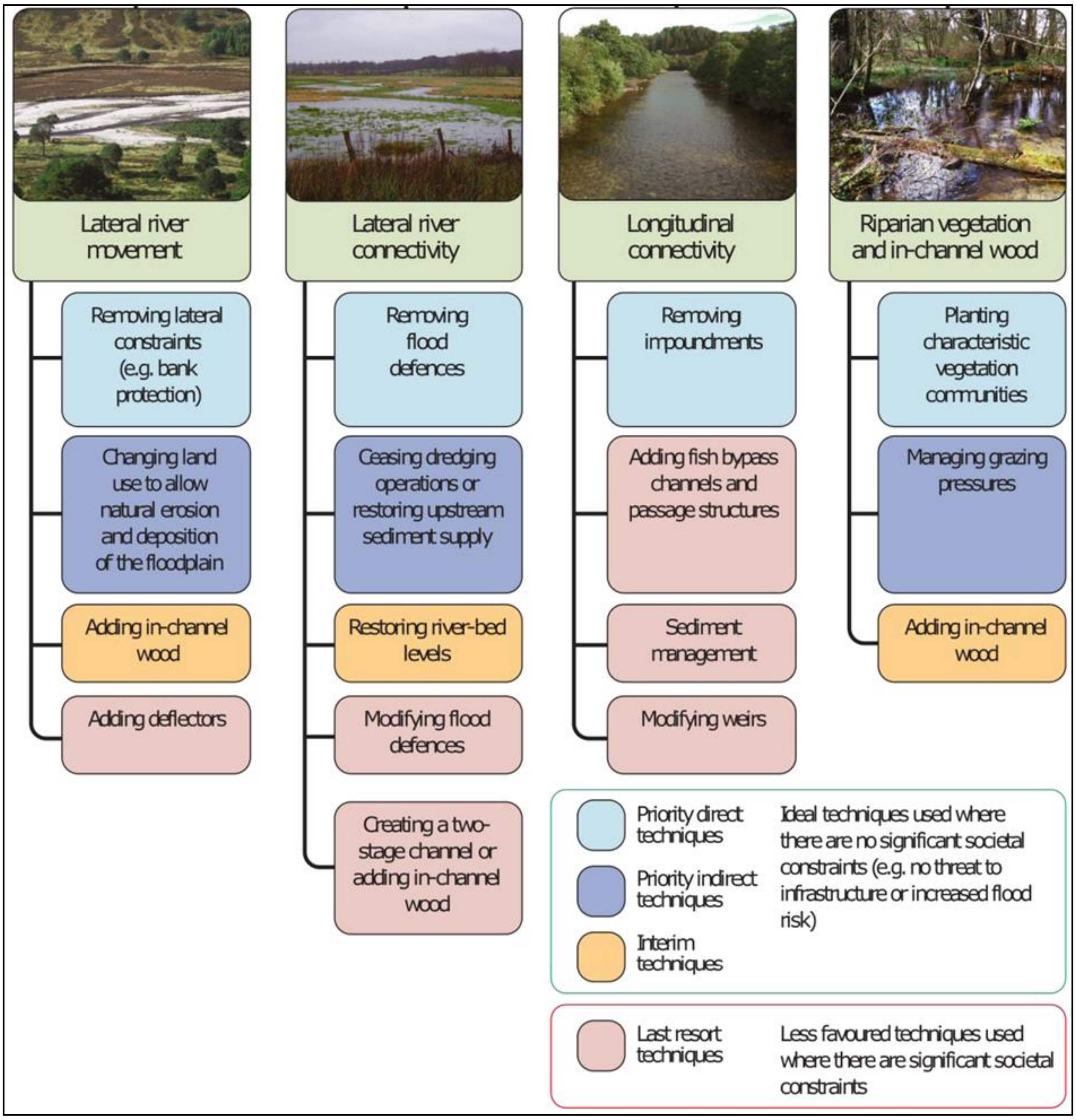

Figure 2-8 Targeted long term restoration aims (natural river movement and connectivity, and dynamic riparian area) and associated techniques to achieve them. (Source Addy et al. 2016; Environment Agency 2017).

Riverbank and bed renaturation is achieved by recreating natural structures to restore the natural river shape and reconnecting it to its floodplain, thus reducing erosion, and providing greater habitat space for aquatic species. Similarly, stream daylighting is achieved by removing closed concrete channels to recreate the shape and dynamics of natural streams, resulting in a less regulated stormwater drainage system (Eisenbert and Polcher 2020). 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 (Eisenbert and Polcher 2020).

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 (Prominski et al. 2017). Similarly, rocks, tree trunks, or willow branches can be used to redirect, disturb, deflect, or divert river flow to re-direct river current to prevent or initiate river-bank erosion (Figure 2-9).

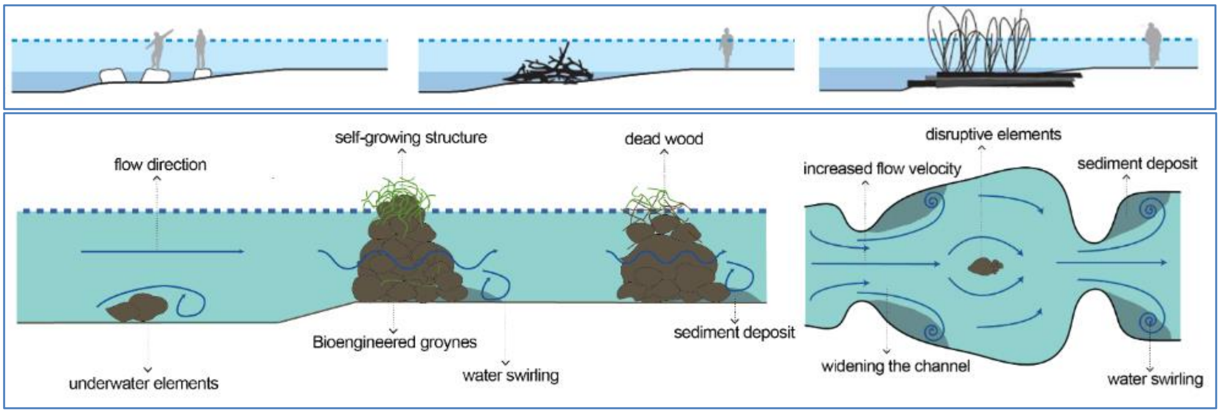

Figure 2-9: Large single rocks, dead wood, bioengineered groynes (top), and placement of disruptive elements above and under water level (bottom). (Source: Prominski et al. 2017).

Bio-engineering techniques can also be used to promote NBS as they used predominantly natural products and promote habitat creation. In the river corridor, natural materials can be used to provide bank stabilisation and protection to flood events including ‘living fascine’ or revetment with cuttings (Figure 2-10). Similarly, embankments can be stabilised with geotextile matting.

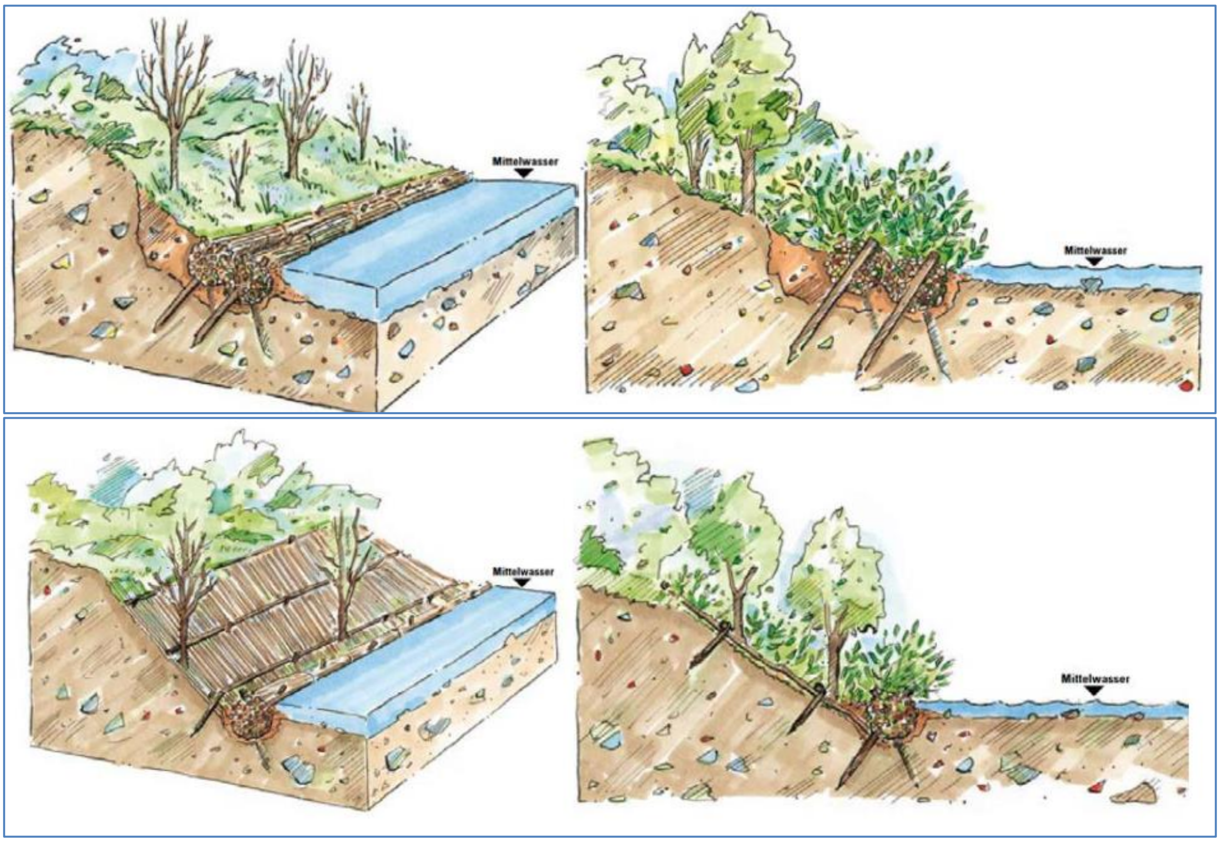

Figure 2-10: Living fascine after implementation (top left); after stabilisation (top right); and revetment with cuttings after implementation (bottom left) and stabilisation (bottom right). (Source: Jany und Geitz 2013).

Brierley et al. (2022) describe the effects of engineering solutions for flood management in New Zealand (e.g., levees, channelisation, dredging) and its detrimental effects on rivers. They also describe strategies to allow rivers greater space to move (rewilding, managed retreat) and environmental, cultural, social, and economic barriers. Both fencing and riparian planting will reduce bank erosion by stopping stock trampling on banks and wading in channels and may also affect other sediment generating mechanisms. For example, stock exclusion setbacks can act as a vegetated buffer to reduce sediment loads from slopes reaching streams as well as reducing bank erosion.

Riparian planting and fencing are key mitigation strategies nationally (Ministry for the Environment 2018; New Zealand Government 2020)[9], and regionally. Their primary purpose for stock exclusion is reduce nutrient and microbial loads from cattle and to reduce soil and bank erosion (e.g., trampling / pugging) and bed erosion. Guidelines for planting riparian buffers in New Zealand have recently been published by NIWA (McKergow et al. 2022). The guidelines contain a method for estimating the removal efficiencies sediment, and particulate nitrogen and phosphorus that as a function of sediment loss. They note that the efficacy of riparian planting to reduce sediment loads (and nutrient loads) is dependent on the buffer width as a ratio of the hillslope width, channel slope and hillslope slope, stream morphology, peak flow rates, soil clay content, and the maturity of planting. The type and composition of planting (e.g., grassed vs mixed herbaceous and wooded vegetation) and the age / maturity of vegetation can also impact on the success of riparian planting.

In addition to stock exclusion, riparian planting and forest buffer can strengthen banks and trap fines thereby reducing erosion rates long-term (Boothroyd et al. 2004; Micheli and Kirchner 2002; Quinn 2005; Quinn et al. 2004; Zaimes et al. 2019), however, shade from dense woodland planting can lead to the loss of undergrowth and bank-armouring vegetation, such as grasses, leading to bank erosion as the stream channel widens. This widening is essentially a return to the natural stream morphology, and the process has a timeframe in the order of 20 years or more depending on local flow conditions and storminess. Finally, wooded riparian buffers can provide shade for stream habitats which will cool temperatures and reduce periphyton (McKergow et al. 2022).

Semadeni-Davies et al. (2020) modelled the water quality effects of **fencing and riparian planting** for stock exclusion on sediment and *E. coli* loads. *E. coli* was modelled using the Catchment Land Use Sustainability Model (CLUES) (Semadeni-Davies et al. 2016), whereas sediment was modelled using the New Zealand Sediment Yield Estimator (NZSYE) (Hicks et al. 2019). Both models are catchment-scale, steady state models for predicting mean annual yields and do not include hydrology. The reduction of sediment loads was based on a statistical relationship between set-back width and catchment sediment reduction determined by Sweeney and Newbold (2014) using removal efficiencies reported in literature. The Australian SedNet model (Wilkinson et al. 2014; Wilkinson et al. 2009), and SedNetNZ model (Dymond et al. 2016), which model mean annua sediment yields from different erosion processes (bank, gully and surface erosion, landslides, and earth flows), assume an arbitrary 10-fold reduction in sediment from bank erosion where riparian planting in place. Like CLUES and NZSYE, the SedNet and SedNet NZ models are steady state and do not include hydrology. Semadeni-Davies et al. (2020) reduced *E. coli* using removal estimates taken from local and international literature (Muirhead 2019). Muirhead surmised that there was not enough evidence to show a difference between the removal for fencing alone and fencing with riparian planting. For this reason, an arbitrary 10% increase in reduction based on expert knowledge was applied where there

[9] The lastest version of the regulations were updated in 2023 (https://www.legislation.govt.nz/regulation/public/2020/0175/latest/whole.html#LMS379869, date of last access 18 April 2024)

is fencing and riparian planting. The same *E. coli* removal efficiencies for stock exclusion were used for earlier model applications (Semadeni-Davies et al. 2018).

River naturalisation projects are susceptible to damage in the first two to four years after implementation (DEP 2006). Regular inspections are required to check for erosion or damage. Stability increases as new vegetation becomes established but there is then a risk of invasive species.

2.5.1 SWOT analysis – river naturalisation

Strengths	**Weakness**
▪ Increased stormwater storage and conveyance capacity in system (flood plain, stream courses). ▪ Encourages greater biodiversity. ▪ Can become self-maintaining. ▪ Aesthetic value increased. ▪ Possible improvements to water quality and ecosystem health.	▪ Land acquisition may be required to extend river and riparian areas. ▪ Creation of new riverscapes can be expensive (if engineering required) and take time to stabilise ▪ Maintenance costs for ongoing river widening, weed clearance, sediment removal, riverbank repair.
Opportunities	**Threats**
▪ Can provide multiply opportunities to increase biodiversity via increasing the integrity of existing habitat and the creation of new habitat types.	▪ May behave unpredictably in very large floods.

2.6 Natural wetlands

Natural wetlands in the landscape can retain and buffer flows and sustain down-stream base-flows (Baker et al. 2009, Mitsch and Grosselink 2007). As well as providing storage volume and space to accumulate flood flows, vegetative resistance slows flows passing through wetlands. In New Zealand we have lost over 90% of our original wetland cover and the hydrological buffering they can provide. Restoration and protection of our natural wetlands can help to recover the natural hydrological dynamics of wetlands and the surrounding landscape (Mitsch and Grosselink 2007) and enhance associated ES (Clarkson and Peters 2010; Clarkson et al. 2013).

There are a wide range of different wetland types in New Zealand (Clarkson and Peters 2010; Johnson and Gerbeau 2004) each with different hydrology and ecological values (Gilvear and Bradley 2009; Grootjans and van Diggerlen 2009; Mitsch and Grosselink 2007). They may intercept just rainwater or be connected to groundwater and/or surface waters. Rain-fed peat bogs can act as giant sponges soaking up and slowly releasing captured rainfall. Some also become connected to surface waters during large floods, either naturally or because of flood control works (e.g., Whangamarino wetland in the Waikato), which may cause significant ecohydrological alteration and negative ecological impacts in the wetland (Blyth 2011). Fens, swamps, and marshes generally receive a mix of groundwater and surface waters. Riverine swamps are often connected to flood flows and form part of river floodplains. 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 (Hefting et al. 2013; Strand and Weisner 2013; Verhoeven et al. 2006).

Even though natural wetlands and riparian zones may make up only a small proportion of a catchment they can have a significant effect on overall water and nutrient balances (Hansen et al. 2018; Hatterman et al. 2006; Knox et al. 2008). Kuri-Fox et al. (2022) using the Water and Soil

Assessment Tool (SWAT) model (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. Javari and Babbar-Sebens (2014) studying the effects of wetlands in central Indiana (USA) also used SWAT modified to simulate sub-daily flows. They reported wetlands were able to reduce peak flows by up to 42%, flood areas up to 55%, and maximum flows up to 15%, with wetland depth a key determinant of flow buffering performance. 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 catchment scale.

2.6.1 SWOT analysis – natural wetlands

Strengths	**Weakness**
▪ Integral part of the natural landscape. ▪ Provide a wide range of regulatory and provisioning and cultural ES, including flow moderation, contaminant retention and transformation, wildlife habitat and mahinga kai. ▪ Historical wetland areas are generally located where water preferentially flows and are often amenable to hydrological restoration. ▪ Relatively low ongoing maintenance requirements. ▪ Will regenerate themselves with low level of effort if previous wetland area is retired from productive land use.	▪ Restoration of historical wetland water levels can impact on drainage, flooding and the productivity and viability of surrounding farmland. ▪ Wetland boundaries need to be able to expand to accommodate flood flows. ▪ Past agricultural development and weed invasion can make it difficult to restore historical wetland values, e.g., elevated nutrients can leach from inundated agricultural fields.
Opportunities	**Threats**
▪ Can integrate with the wide range of co-benefits from wetland restoration (social, economic, cultural, environmental).	▪ Increased protection of natural wetlands may limit opportunities to optimise flood storage and increase consent requirements and compliance costs.

2.7 Constructed wetlands

A constructed wetland (CW) is an engineered system designed to treat wastewaters, agricultural runoff and drainage, and urban stormwater by mimicking the natural processes of natural wetlands. Utilizing the natural functions of plants, soil, and organisms, CWs remove pollutants such as suspended solids, organic matter, and nutrients (Kadlec and Wallace 2009). There are a wide range of different designs of CW, categorized into surface or subsurface flow types. Surface flow (or free-water surface) CWs are most common employed for surface waters. They generally comprise extensive areas of shallow water vegetated with emergent wetland plants (Figure 2-11 and Figure 2-12), often including deeper open water areas at the inlet, to settle and retain sediment. The planted zones disperse flow, promote sedimentation, and take up a proportion of the nutrient load. However, their greatest benefit is providing surfaces for growth of microbial biofilms and organic matter for microbial conversion of dissolved nitrate into nitrogen gas that is returned to the atmosphere. Deep zones may also be interspersed through 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 depth 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 (Water 2017). Greater depths may be accommodated for short periods of time (a few days).

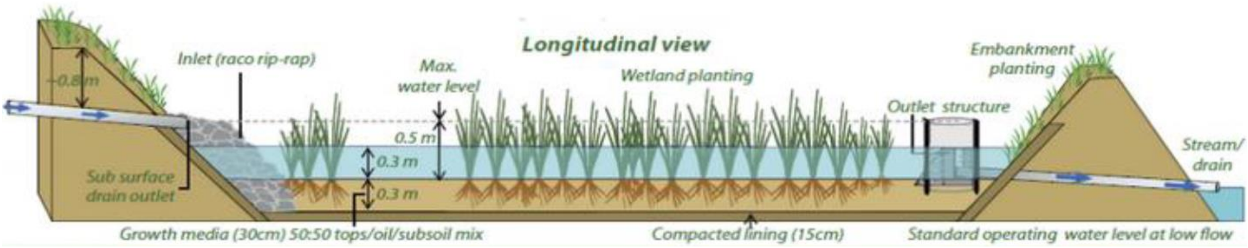

Figure 2-11: Surface-flow constructed wetland intercepting subsurface agricultural drainage. (Tanner et al. 2009).

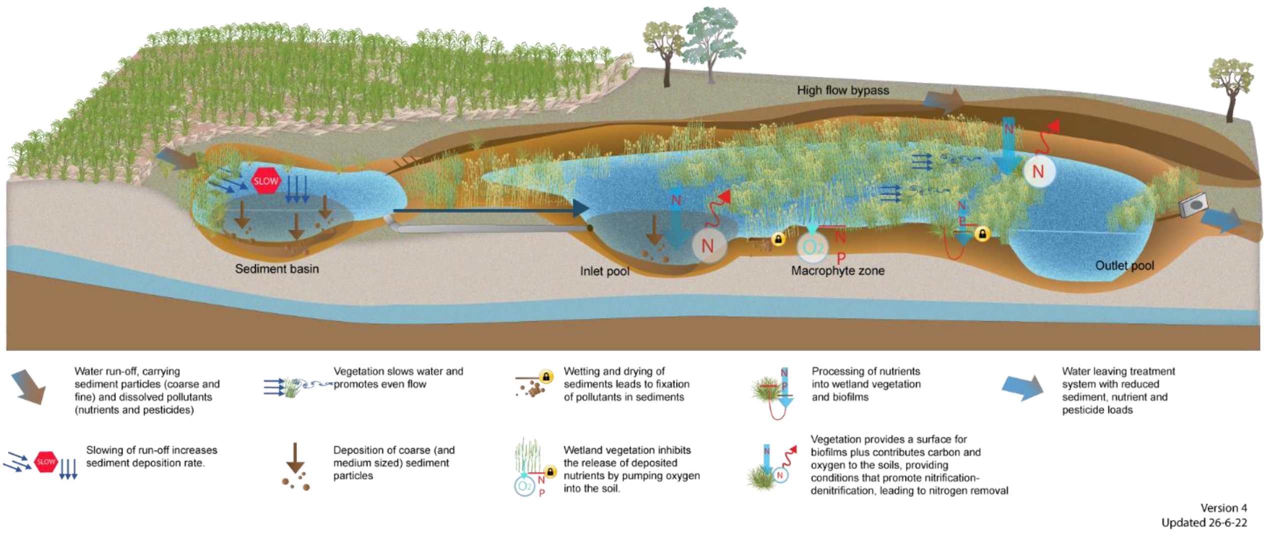

Figure 2-12: Surface flow wetland constructed wetland intercepting agricultural run-off, showing key contaminant removal processes. (Source: Queensland Government 2022).

CWs can be employed in a wide range of different situations within a catchment (Figure 2-13), including where surface and sub-surface drains flow into stream channels, in headwaters, the middle, or at the bottom of catchments, and be either in-stream (on-line) or off-stream (off-line) (Figure 2-14). Locations are shown relative to riparian buffers, sedimentation ponds, natural wetlands, and tile drains.

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. CW 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 2-12) or include a suitably armoured 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. Thus off-stream CWs allow very high flows to bypass down the main channel. They also have the benefit of maintaining fish passage via the natural stream channel rather than through the wetland.

Wetland construction is best undertaken in late spring or summer when soils become dry enough for earthmoving and plants can be sown in the optimal growing season (though watering may be necessary to ensure survival) (Tanner et al. 2022).

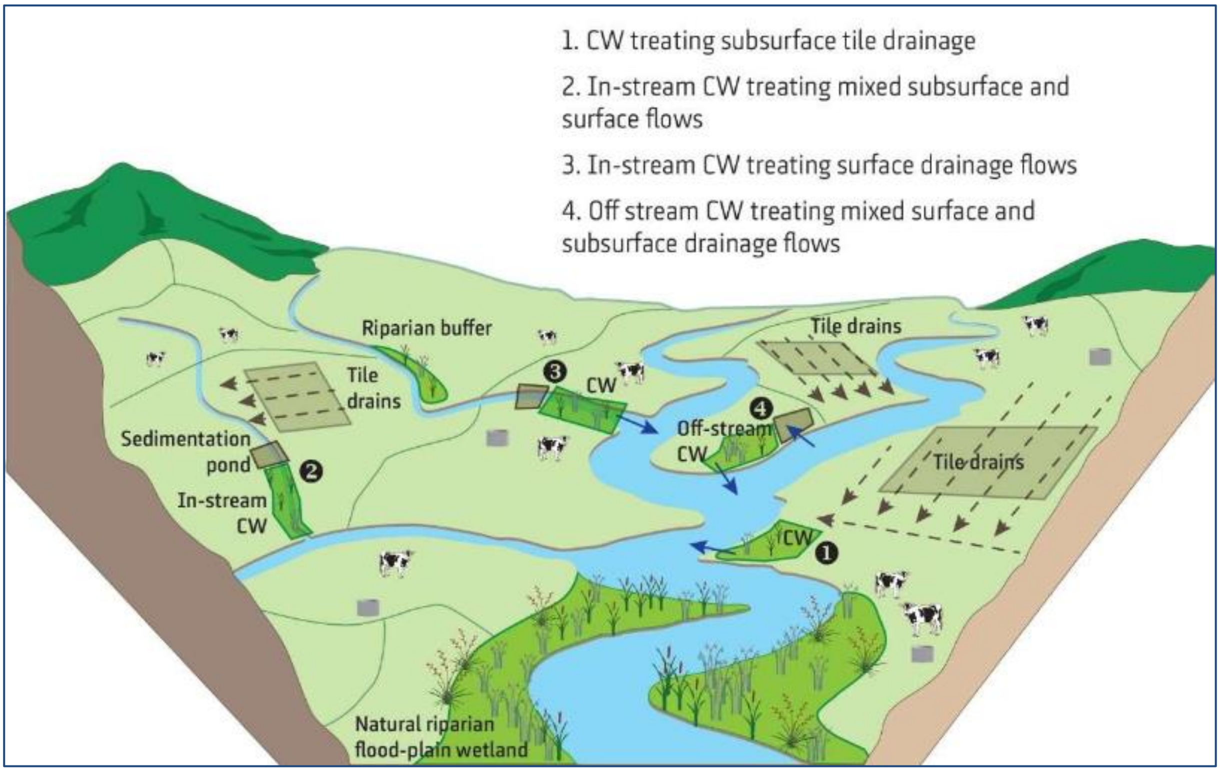

Figure 2-13: Potential locations for constructed wetlands (CW) to intercept run-off and drainage flows. (Source: Tanner et al. 2021).

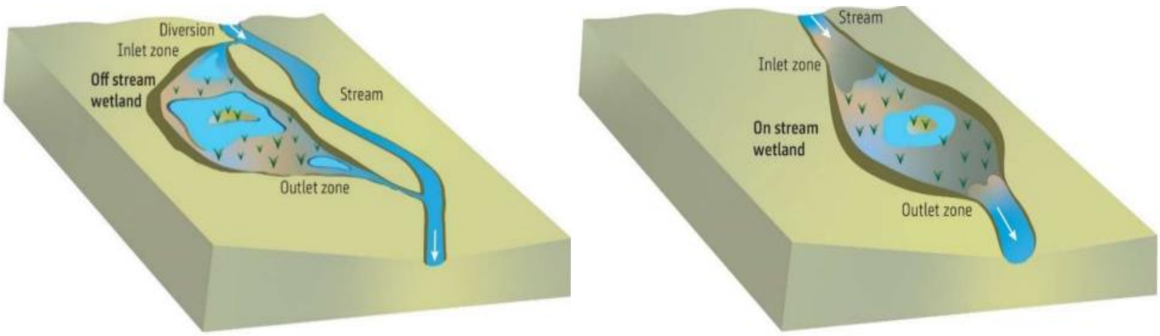

Figure 2-14: Comparison of off-stream (left) and on-stream (right) constructed wetlands. (Source: Tanner et al. 2021).

2.7.1 SWOT analysis – constructed wetlands

Strengths	Weakness
▪ Potential to design for specific storage targets. ▪ Can be sited in strategic locations. ▪ Provide wide range of co-benefits, including contaminant reduction, habitat, and biodiversity, mahinga kai, aesthetics, cultural. ▪ Less expensive than conventional wastewater treatment options.	▪ Vegetated wetlands generally require large areas of relatively shallow water (0.3–0.4 m) but will survive short periods (days to weeks) of deeper inundation. ▪ Risk of maladaptation or poor design. ▪ Risk of exceedance in severe events.
Opportunities	**Threats**
▪ Rolling landforms provide lower-cost construction opportunities. ▪ Combine with detainment bunds to increase temporary detainment.	▪ May be damaged by large flooding events, requiring repair.

2.8 River floodplain restoration and estuary management

River floodplains lie in the bottom of river valleys and evolve over long time periods, through cycles of river flood and sediment aggradation and erosion. A combination of channel and river-bank erosion and construction allows the river to move within the valley bottom building new areas of floodplain as it does so (Nanson and Croke 1992). Many floodplains however no longer function naturally as their natural course is increasingly restricted by human activity.

River **floodplain restoration** is the 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 (Brierley et al. 2022). More regular inundation of the floodplain from the channel is not discouraged, so that the river utilises additional storage space within the floodplain. The process is well described by Christensen Consulting (2023) in their description of the 'Room for Rivers' concept and includes:

- Reconnecting floodplains, paleochannels, oxbows and back water areas
- Removing or retreating stop banks, and
- Creation of offline storage areas including wetlands.

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 to wetland and 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, defining the river management envelope based on past river behaviour (Figure 2-15), which help define flood risk levels and vegetation management regimes.

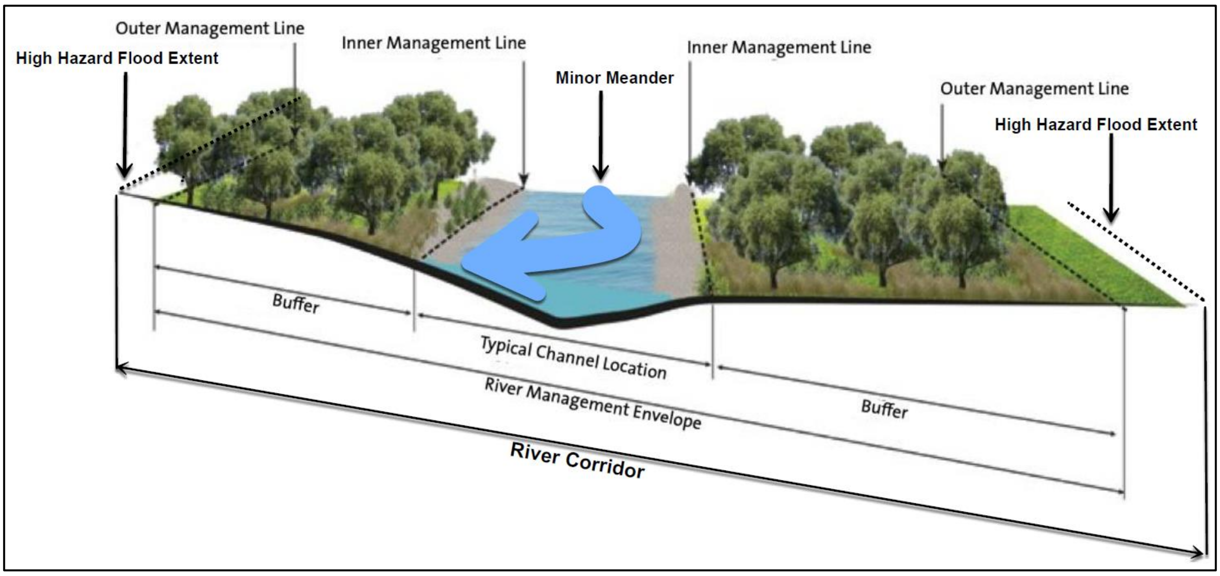

Figure 2-15: River management envelope indicating floodplain management boundaries either side of the river. (Source: Christensen (2023), adapted from Te Kāuru Upper Ruamāhanga Floodplain Management Plan (2019)).

Acreman and Holden (2013) found that floodplains rather than upland wetlands were better at attenuating flood flows. However, landscape configuration, soil, topography, moisture status and management all influenced 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 (House et al. 2016).

Saltmarsh and mudflats lie between river floodplains and the coastal zone and play a valuable role in flood and coastal defence as well as ecosystem conservation. Saltmarsh maintenance, restoration or enhancement is increasingly considered as a way of managing flood risk in estuaries as they gradually accrete sediment to provide wave attenuation and surface erosion resistance. Techniques for managing saltmarsh can be divided into three main groups:

- Marsh restoration through grazing management, vegetation planting, pollution source control, freshwater input and drainage management.
- Managing marsh erosion/accretion using sedimentation fields, intertidal recharge, vegetation planting, sediment source control, and hard engineering techniques such as breakwaters or groynes (or erosion management techniques such as brushwood and drainage furrows).
- Creating new saltmarsh to landward through managed realignment and regulated tidal exchange systems.

2.8.1 SWOT analysis – river floodplain restoration and estuary management

Strengths	**Weakness**
▪ Floodplain connection can decrease the magnitude and duration of downstream floods. ▪ Multiple co-benefits associated with habitat creation.	▪ Impact depends on floodplain to catchment size ratio. ▪ Need surface and channel data. ▪ Floodplain roughness data critical for planning.
Opportunities	**Threats**
▪ Can assist flood plain wetland restoration. ▪ Can contribute to carbon sequestration.	▪ Floodplain complexity in large catchments can make their dynamics hard to predict.

2.9 Challenges for NBS implementation

The UK Environment Agency (2018) study, mentioned at the start of this section, also identified barriers that hinder wider adoption and implementation of NBS for flood mitigation. They identify the need for more empirical evidence of the short and long-term effectiveness of existing NBS designs. In addition, documented evidence of proven flood regulation and ecosystem services provided by NBS will help provide a firm scientific foundation required for ongoing improvement in the performance of such measures. More specifically, better understanding of NBS functioning during extreme events and the degree to which large scale events can be mitigated by either singular or multiple NBS at the catchment scale is required. Their option-specific challenges for different NBS types that are most relevant to (and sometimes overlapping) this study are provided below.

Retention and detention features

- Knowledge gaps remain about the effectiveness of retention and storage features for mitigating flood peaks at the catchment scale.
- The influence of creating storage areas within 1st order sub-catchments to mitigate flood volume and peaks at the catchment scale is still uncertain.
- The impact of historic reductions of woodland debris from upper catchment streams and rivers on hydrology and ecosystem services has not been quantified. Management of natural woodland debris within rivers needs attention due to risks of debris mobilisation and downstream snagging.
- A consistent methodology for assessing the impact of using multiple small-scale offline storage measures distributed across large catchment areas has not be developed.
- Questions remain about how offline storage features impact groundwater if present, and whether there is increased risk of flood.
- The impact of offline storage areas on low flows could be better quantified.
- The difference between engineered flood storage areas and naturally functioning storage areas is not clearly defined.

Landcover and soil management

- There is limited evidence about the impacts of woodland created at small to medium catchment scale on flood flows.

- Improvement is needed in the way that hydrology and hydraulic models represent relevant processes (evaporation, soil infiltration, surface roughness and ideally sediment interactions) and the selection of appropriate parameter values.
- Technological development in sensor design is required to improve estimation of flood flows during extreme events and woodland impact on flood generation and conveyance.
- Limited direct study of relative influence that soil and land management measure can have on flood risk relative to their area and location in the catchment.

River naturalisation

- There is limited field-based empirical evidence on the flood attenuation benefits of river restoration or naturalisation.
- There is limited study relating to the conveyance capacity of restored rivers compared with degraded or extensively managed rivers.
- Methods for estimation of the extent of flow attenuation and water storage change that results from restoring natural river processes and landforms are not consistent and often highly uncertain.
- The type, location and spatial and temporal scale of river restoration needed to cause significant attenuation of downstream flood risk is difficult to ascertain because of the complexity of the system being described.

Natural and constructed wetlands

- There is limited guidance on the effectiveness of different types of wetland for flow regulation.
- Improved techniques for predicting habitat formation are needed.
- Improved methodologies are needed for determining attenuated floodplain roughness, and parameterisation of drag coefficients.
- improved techniques and data are needed for ecosystem services valuation.

Floodplain restoration and estuary management

- Further research on phasing of sub-catchment flow attenuation and catchment-scale benefits is needed.
- A method to assess synchronisation of flood peaks attenuated by large-scale floodplain restoration works is required.
- Improved methodologies are needed for determination of attenuated floodplain roughness, and parameterisation of drag coefficients.
- Better understanding of floodplain hydraulics is needed to better represent them in models.
- The role of groundwater in floodplain restoration is often not considered.
- More evidence is needed on the role of intertidal habitat for improving water quality.

3 NBS performance and selection

Despite a vast amount of data and international research on the use of NBS, there is a lack of common guidance for their implementation and monitoring. There is even less guidance on assessing the performance of NBS when employed for specific purposes (e.g., flood mitigation), especially at catchment scale. This section outlines approaches used to compare benefits, co-benefits and potential costs of different preferred NBS options before more detailed numerical analysis of their impact on flood risk.

In the absence of specific NBS design standards, existing engineering standards can be used for the hard structural components of NBS designs. In addition, performance indicators can be defined that equate to minimum operational standards once construction has been completed. Such performance indicators can relate directly to flood mitigation, impacts on biodiversity, or increased amenity value (Table 3-1). However, Seddon et al. (2021) 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, should also be ensured.

Table 3-1: Potential performance indicators for flood management NBS (after Griffiths and Chan 2022).

Benefits	Performance Indicators
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
Increased biodiversity	Extent, significance, and quality of local habitats
	Extent of integration with existing biodiversity objectives
	Connectivity with neighbouring habitats
	Resilience and sustainability of created habitats
Increased amenity value	Dual function of drainage for recreation
	Enhancements to visual character
	Enhancements to flood resilience
	Improvements to public safety
	Allowances for climate change
	Improvements in environmental awareness and education

In New Zealand the performance of any NBS should specifically address the concept of Mātauranga Māori. Nature-based Solutions can be presented as 'place-based partnerships between people and nature', with the conservation and enhancement of biodiversity at its core (Seddon et al. 2021). This phrase suggests an understanding of NBS as local in scale and specific to the needs of a region, people, and situation (Buckley et al. 2023). For example, the AUT Living Laboratories program sought to understand nutrient cycling and soil health, soil erosion, biological interaction webs, connectivity and maintenance of native plant and animal populations, suppression, or enhancement of weed and pest-animal spread, changes in water quality (nutrient run off) and quantity (water capture) and change over time at different locations. As such the project involved partnerships with Indigenous communities, such as Ngāti Whātua Ōrākei, Ngāti Manuhiri, and Ngāti Pāoa, to value and embed mātauranga Māori as Indigenous knowledge.

Also in New Zealand, Water Sensitive Urban Design (WSUD) evolved as a land planning and engineering approach to surface water management which sought to reduce environmental degradation by making use of natural environmental processes. WSUD also promotes the use of NBS for predominantly urban stormwater flood management but is increasingly being implemented with reference to catchment scale processes. Figure 3-1 illustrates WSUD measures that employ so-called 'green water management technologies', which reduce built environment footprints and retain and restore natural environments and green spaces. The resulting environmental benefits include more 'natural' hydrological regimes and associated gains in water quality and aquatic habitats. The social benefits, which Moores et al. (2019) indicated generally receive less recognition, range from recreational opportunities to increased connectedness of communities with nature.

Ommer et al. (2022)[10] reviewed common approaches to quantify co-benefits (Table 3-2). Although they related predominantly to an urban context, most ecosystem services and benefits calculation methods are transferable to rural environments (e.g., the methodology for calculating carbon sequestration by trees will be the same in both urban and rural environments).

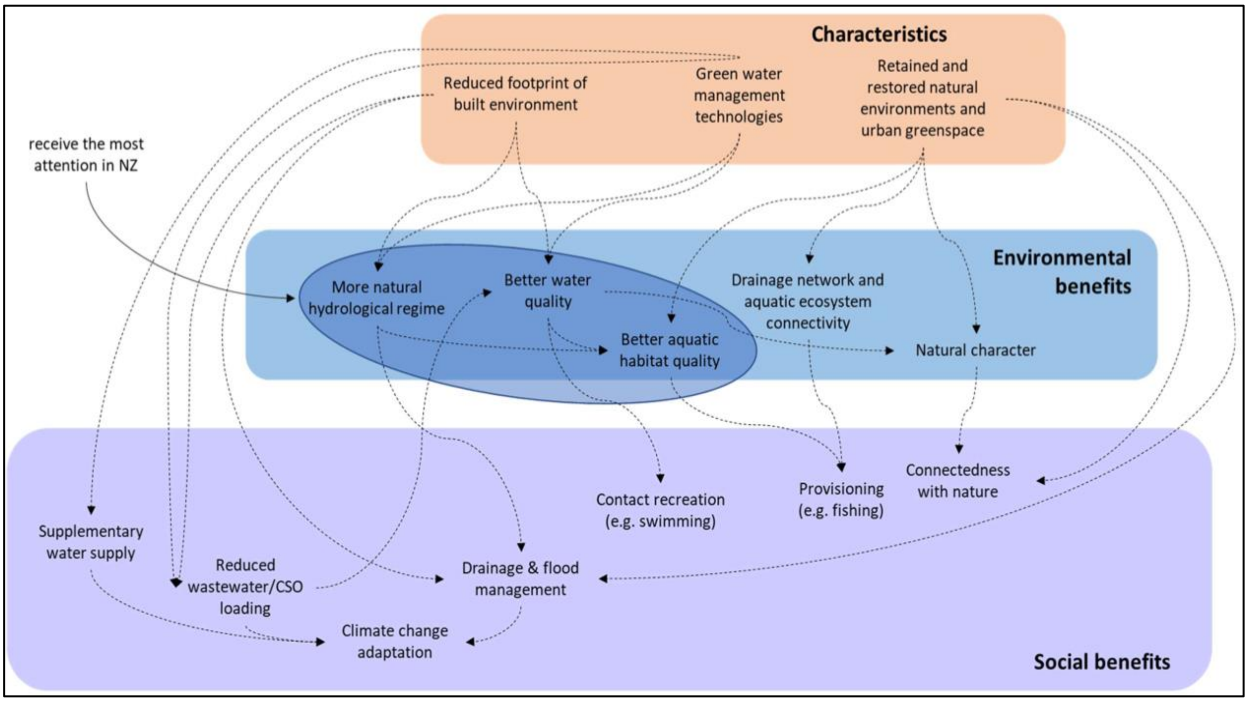

Figure 3-1: Hydrological characteristics and environmental and social benefits of WSUD. (Source: Moores et al. 2019).

[10] See also Urban Nature Navigator (naturvation-navigator.com)

Table 3-2: Indicators and quantification methods for some co-benefits. Adapted from Ommer et al. (2022).

Co-benefits	Performance Indicators and/or quantification methods
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 (Nowak et al. 2006; Tiwary et al. 2016) or directly with i-Tree tool[11] (USDA Forest Service et al. 2006).
Carbon Storage by vegetation	Sequestration by vegetation can be estimated with allometric equations based on vegetation biomass as applied by the i-Tree tool.
Carbon Storage by soil	Carbon stocks in soils are dependent on land cover and land use (LULC), climate regions and soil types, and urban-rural areas. InVEST provides estimates for different land uses/covers (see description of the tool in 3.1)
Noise Attenuation	Noise Attenuation Potential by Tiwary et al. (2016) can be used to estimate noise reduction with average leaf biomass and canopy area of trees and hedges.
Water quality Proxies: Nitrogen, phosphorus	Stormwater pollutant retention depending on LULC can be estimated with InVEST.
Soil health Proxy: bulk density	Bulk density can be used as a proxy for soil quality. Bulk density is dependent on the soil type but also the land cover. Vandecasteele et al. (2018) reports on examples of bulk density changes due to LULCC. Bulk densities of 1.47–1.8 g/cm3 can restrict root growth (Correa et al. 2019).
Recreation	The attractiveness of a space for recreational purpose is depending on the size of the area, the proximity to population, the accessibility in terms of transportation but also the quality and aesthetic of the space. Usage can be estimated in different ways, for instance, the travel cost method or with the Recreational Opportunity Spectrum (ROS). ROS is based on recreation potential (which can be reflected by the naturalness, presence of protected areas or water bodies) and remoteness or accessibility (Paracchini et al. 2014).
Job creation	Green space maintenance can function as a proxy for job creation. However, this co-benefit also includes job and/or business creation for the implementation of an NBS. Estimations could be based on average monthly/annual maintenance hours per unit of green space or from reported impact in NBS case studies.
Property Values	Air quality, noise levels, thermal comfort, and the proximity to green/ blue spaces are influencing property prices which can be calculated with the hedonic pricing method. Ira (2017) reviewed 74 studies worldwide including from NZ, including various type of NBS such as wetlands, riparian planting, river restauration etc, and reported a 6.04% average price increase for houses near NBS/green spaces.
Social cohesion/inclusion	Social inclusion can be enhanced by green spaces promoting social contacts and the feeling of inclusion. The co-creation of NBS can also increase social cohesion and feeling of ownership of the place. Equal access to green space can be estimated by assessing households in proximity and the diversity of incomes. Other estimates of the cohesion and the feeling of ownership of the place can be made based on the potential of co-creation of the NBS. The type of green/blue space can imply the potential interactions (e.g., playgrounds may offer more possibilities to interact with others than a wetland).

[11] See Section 3.1 for i-Tree tool description.

3.1 Related environmental policy and guidance

Selection of specific NBS will also be influenced by current environmental policy and guidance. Whilst a full review of current national level policy is outside the scope of this study, McFadgen (2023) and Christensen Consulting (2023) identified several regulatory levels and guidance documents as important for consideration at the planning stage of NBS. These include:

- **Common law** - which applies to the management of watercourses in New Zealand (unless modified by legislation) and gives property owners responsibility for managing flooding and erosion risks. For multiple owned properties, this responsibility is ceded to regional or district (or unitary) councils.

- **Soil conservation and rivers control Act 1941** – includes general discretionary functions and powers of regional councils who have taken on the responsibilities of Catchment Boards, the function of which is to minimise and prevent damage by floods and erosion (Section 126 General Powers of Catchment Boards).

- **Local Government Act 2002** – outline District and Regional Council responsibilities to avoid or mitigate erosion and flooding and identify appropriate protection works (as outlined in Long-Term Plan, Annual Plan and Asset Management Plan documents).

- **Resource Management Act 1991** - requires regional authorities to control the use of land to avoid or mitigate natural hazards. The Resource Management (Energy and Climate Change) Amendment Act 2004 further requires local authorities to have particular regard to the effects of climate change.

- **Civil Defence Emergency Management Act 2002** - focuses on the sustainable management of hazards, resilient communities and ensuring the safety of people, property, and infrastructure in an emergency. Recommends risk reduction, readiness, response, and recovery.

- **New Zealand Standard NZS 9401:2008 – Managing Flood Risk –** whilst there is no legislated process for managing flood risk in New Zealand, this standard outlines a best practice approach. It includes guidance on quantifying natural, social and cultural values; quantifying flood risk and identifying options to manage it; implementing solutions.

- **NZ Coastal policy statement[12] 2010** – Policy 26 (Natural defences against coastal hazards) advocates the 'provision of protection, restoration or enhancement of natural defences that protect coastal land uses or sites of significant biodiversity, cultural or historical heritage or geological value, from coastal hazards'; and 'recognition that natural defences include beaches, estuaries, wetlands, intertidal areas, coastal vegetation, dunes and barrier islands'. Policy 15 (Natural features and natural landscapes) is also relevant.

[12] https://www.doc.govt.nz/about-us/science-publications/conservation-publications/marine-and-coastal/new-zealand-coastal-policy-statement/new-zealand-coastal-policy-statement-2010/

- **ANZ Biodiversity strategy 2020** – Objective 13 'Biodiversity provides nature-based solutions to climate change and is resilient to its effects', highlights the potential for carbon storage, restoration of indigenous ecosystems, and for indigenous NBS to be better understood and included within the planning process.

- **The NZ National Adaptation Plan 2022** - promotes the greater use of NBS for improving resilience of housing stock and infrastructure in urban areas. Includes objectives that support working with nature to build resilience, inclusion of NBS in planning and regulatory system where possible and protection and restoration of indigenous ecosystems.

- **Emissions reduction plan 2022** – Action 14 focusses on laying the foundation for 2050 vision for forestry by growing the forestry industry, maintaining existing forestry, and encouraging native forestry as long-term carbon sinks.

It is noted that each region in New Zealand is responsible for its own stormwater management and a number of guidance documents are available including Auckland Regional Council (1999); Greater Wellington Regional Council (2021); and Waikato Regional Council (2018).

At an international scale, the need to advance nature-based approaches is endorsed by a multitude of international agreements and initiatives (Reguero et al. 2020) including the Sendai Framework for Disaster Risk Reduction (2015–2030)[13], the Sustainable Development Goals (SDGs)[14], the Kunming-Montreal Global Biodiversity framework (UNEP)[15], and the Paris Climate Agreement[16].

3.2 Quantifying NBS benefits and costs

One of the challenges of adopting NBS for flood mitigation is objective measurement of benefits and co-benefits (Ommer et al. 2022; van Zanten et al. 2023; Wishart et al. 2021). Hydrological benefits of NBS can be assessed in the same way as the benefits of 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 ecosystems services (ES), i.e., the 'goods or services provided by ecosystems' (Wilson et al. 2004). Wetland restoration projects for example, are routinely assessed for their ability to buffer flood hydrographs, however, they should also be assessed for their contribution to local fish populations, biodiversity, economic, cultural, and amenity values (van den Belt et al. 2013 for example).

To objectively assess NBS performance it is necessary to first define key expected outcomes (van Zanten et al. 2023). 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 (Giordano et al. 2020; Liquete et al. 2016). NBS performance assessment methods and tools, to measure agreed outcomes, include numerical models, expert judgment, and life cycle costing.

Several assessment frameworks have been developed worldwide to provide metrics for comparison of different NBS strategies or to compare their performance against traditional engineering approaches (Giordano et al. 2020; Liquete et al. 2016). Most of these frameworks allow consideration of a range of co-benefits (environmental, economic, social, and cultural) and also provide a monetary (or equivalent) valuation, that can be used to inform decision-making during

[13] United Nations Office for Disaster Risk Reduction (UNISDR) - UNISDR/GE/2015 - ICLUX EN5000 1st edition.
[14] https://www.worldbank.org/en/programs/sdgs-2030-agenda
[15] https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf
[16] https://www.un.org/en/climatechange/paris-agreement

project design, planning, implementation, and subsequent monitoring (European Commission 2021) (Borne et al. 2022; Ommer et al. 2022). Ira and Simcock (2019) for example describe a range of environment- or project-specific 'avoided costs', and 'cost effectiveness' factors that can be considered (Table 3-3).

There is currently no single tool that can be applied to the complete range of benefits and disadvantages that might arise from different NBS. However, several tools are tailored to specific types of environmental challenges such as climate resilience (Raymond et al. 2017), flood risk management (van Zanten et al. 2021), urban runoff management (Moores et al. 2019), ecosystem services (Dang et al. 2021; Veerkamp et al. 2023) and accounting (United Nations 2022). Several such tools that are free to download or use online are presented in Table 3-4 and briefly described below.

Most of these tools have been developed overseas, they are therefore not readily applicable to New Zealand, due to uncertainty in benefit transfer from one jurisdiction to another, monetisation of environmental benefits, and lack of representation of Māori values (Moores and Batstone, 2019). To cope with these challenges, the More Than Water (MTW) tool was developed by NIWA, Manaaki Whenua-Landcare Research, Batstone Associates and Koru to provide a "quick win" method to assess the wide-ranging benefits of NBS (Table 3-4). 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 (Moores et al. 2019). It provides graphic demonstration of benefits and cost outcomes and how these might vary under different scenarios. It is suited to screening level assessments and communication for both technically familiar and lay audiences. While the current tool is tailored to the urban context, a similar approach could be developed for rural areas.

Table 3-3: Environment and project 'avoided costs' and 'cost effectiveness'. (after Ira and Simcock 2019).

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

Table 3-4: Co-benefits and cost assessment tools for NBS.

Tool name*	Country	Assessment scale	Benefits assessed	Type of assessment	Monetisation of benefits	Free or licensed
Green Values Calculator	USA	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)	free
B£ST	UK	Neighbourhood to small watershed	20	Quantitative	Yes	2019 version free
INFFEWS BCA Tool	Australia	Neighbourhood to city scale	20	Quantitative	Yes	free
InVEST	USA, Sweeden, China	Large watershed	20	Quantitative	Yes, for some of the benefits	free
Nature Value Explorer	Belgium	Small neighbourhood to large watershed (rural or urban)	19	Qualitative and Quantitative	Yes, for 17 benefits	free
i-Tree	USA	1 tree to forest	5	Quantitative	Yes	free
More Than Water tool	New Zealand	Neighbourhood	25	Qualitative	No	free

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

The Center for Neighbourhood Technology (CNT) and United States Environmental Protection Agency (USEPA) developed the web-based **Green Values Calculator (GVC)** (Center for Neighbourhood Technology 2006) to assess the performance, costs, and benefits of NBS 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. The GVC provides information on twenty-two benefits, which are covered by generic narrative statements, except for six which are quantified by benefit transfer from relevant studies (reduced air pollution, CO_2 sequestration, tree value, groundwater replenishment, reduced energy use and reduced stormwater treatment). The GVC provides costs estimates for each scenario including construction, maintenance, and lifecycle costs.

The Benefits Estimation Tool **(B£ST)** (CIRIA 2019) was developed by 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 a business-as-usual scenarios), rather than to produce absolute values (CIRIA 2019; Moores and Batstone 2019).

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 monetizing benefits such as non-market valuation (NMV).

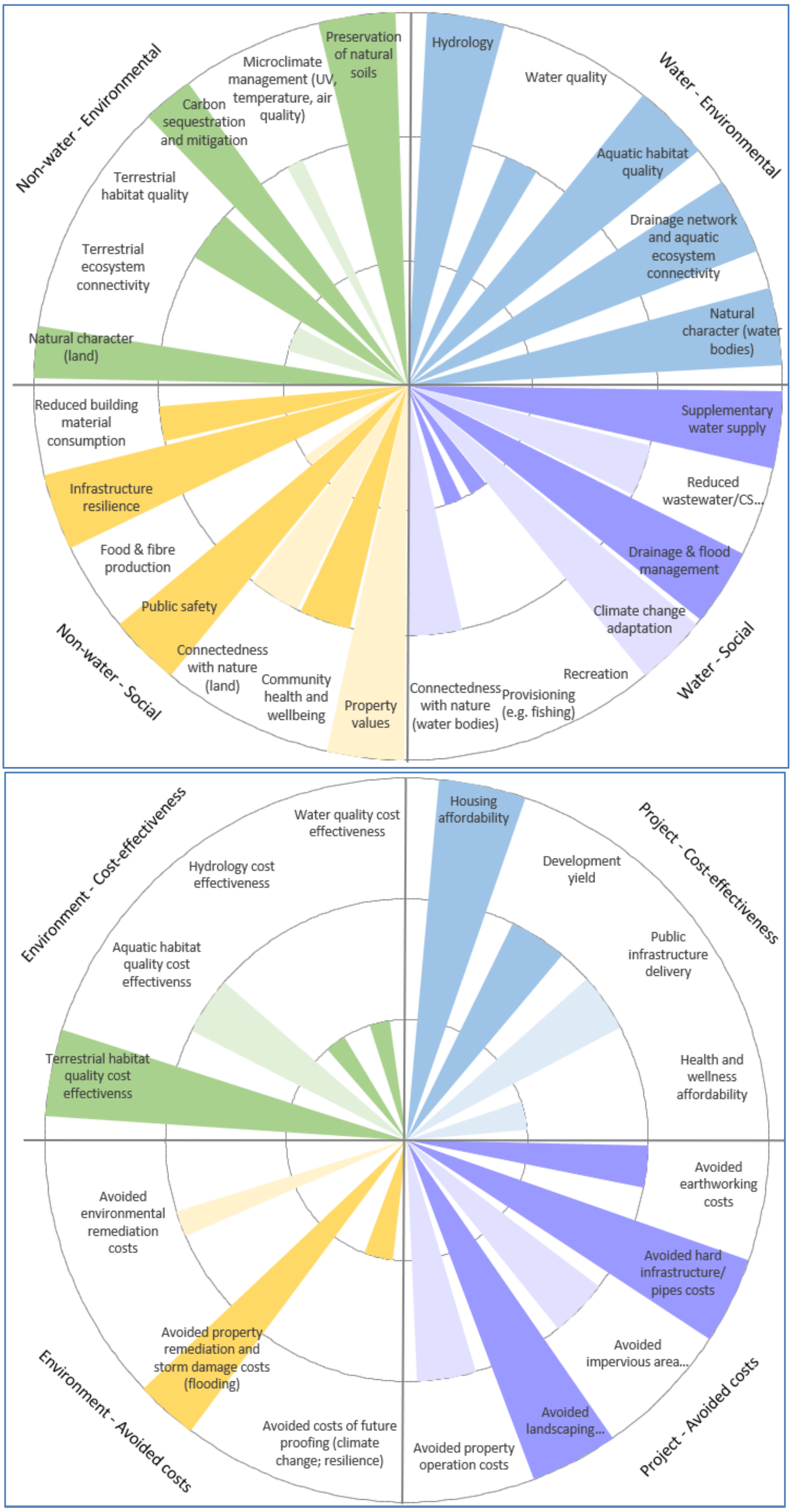

Figure 3-2: The 'More Than Water' benefits (top) and costs (bottom) assessment tool. (Source: Moores et al. 2021).

Data for benefit transfer is taken from a library of relevant Australian valuation studies. Value estimates can also be imported from external project-specific analyses. With enough data from relevant studies or project-specific analyses, the tool can be used to provide a detailed benefit-cost analysis of project alternatives. Where specific data is absent, the tool can be used by specialists in WSUD and economics to make informed judgements on the relevance and degree of confidence of data from other studies, to arrive at a screening-level or comparative assessment of options (Moores and Batstone 2019).

InVEST is a suite of models used to value and map the goods and services from nature that sustain and fulfil human life (Natural Capital Project 2018). 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 ES (habitat risk assessment, habitat quality, pollinator abundance) and direct ES[17]. Individual models are used for each type of ES, each of which employ 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.

The **Nature Value Explorer (NVE)** tool (Vito et al. 2021) assesses ES values[18] based on an international classification system (CICES 5.1 2017), 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 visualize existing projects or create new ones. The study area can be drawn on an interactive map and 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 (USDA Forest Service et al. 2006) 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. 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.

Most of the tools described above were developed to assess the benefits of NBS implemented in an urban context but some (InVEST, Nature Value Explorer, i-Tree) can now be applied to large watersheds and rural environments. 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 NBS produces the best economic, social and environmental outcome. When economic value for specific ecosystems services or benefits are not available for a specific project, the method of 'benefits transfer' is commonly used (in which economic values for ecosystems services or benefits are estimated by transferring information from previously completed studies).

[17] 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.

[18] 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.

4 Modelling flood and NBS

Whilst there is a wealth of literature available relating to the use, application and development of flood modelling techniques, literature relating to the incorporation of NBS for flood mitigation is relatively sparse. This is partly because traditional flood alleviation is still largely associated with the development of conventional hard engineered solutions. However, in recent years there has been a paradigm shift, in which the integration of 'soft' engineering approaches (including NBS) has gained more widespread interest from academia (Dadson et al. 2017), government institutions (Environment Agency 2018; Ministry for the Environment 2022), and industry (Mercier 2023).

Despite a growing evidence base that NBS can contribute meaningfully to flood mitigation there is still uncertainty around the use, longevity, and compatibility of such measures at the catchment scale (Iacob et al. 2014). The main challenge for any NBS feasibility study is to provide evidence that the developed NBS approach can reduce flooding and exhibit resilience at both the local and catchment scale. Most studies on NBS to date, certainty in New Zealand, have focused on individual, often small NBS at the site scale, so that there is less information regarding the impact of multiple NBS (operating in series or parallel) at the catchment scale. This is where modelling can be a valuable tool for assessing the effectiveness of NBS for flood mitigation (Hill et al. 2023; Ruangpan et al. 2019).

4.1 Flood models

Proprietary modelling packages used for flood simulation, such as TUFLOW [19], MIKE FLOOD[20], InfoWorks ICM[21] and HEC-RAS[22] 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.

Hydrological models simulate processes related to runoff generation (e.g., infiltration, evaporation, percolation, throughflow) and are used to calculate the rate, volume, and timing of rainfall-runoff within a receiving drainage network. They vary in complexity from empirically based models of rainfall - runoff, to semi-distributed physically based models that capture the spatial distribution of component processes across a catchment. Hydrological models can be used to calculate flow anywhere within the drainage network if so designed, and as a result can be used to predict flood level and extent of flooding. They can be used to represent NBS by altering landcover parameter values (to represent vegetation or landcover management change), or by making changes to the geometry of the catchment or drainage network (to represent more significant morphological changes such as river or floodplain naturalisation).

Hydraulic models apply the physical laws of fluid motion to varying degrees depending on their complexity. The choice between using 1D, 2D or 3D models depends on the purpose for which they will be used; the data available to build and run the model; and the system being modelled.

1D hydraulic models simulate the longitudinal movement of water in a river channel taking into account channel characteristics such as slope, shape, depth, width, roughness and morphology. They are adequate where channels are well defined and flood waters are not expected to flow significantly across the flood plain. For every node or section of the river network, these models simulate a single water level and flow rate. As such they can be used to model the effects of channel interventions

[19] https://www.tuflow.com/ (date of access 27 March 2024)
[20] https://www.mikepoweredbydhi.com/products/mike-flood (date of access 27 March 2024)
[21] https://www.autodesk.co.nz/campaigns/one-platform-for-every-catchment-infoworks-icm (date of access 27 March 2024)
[22] https://www.hec.usace.army.mil/software/hec-ras/features.aspx (date of access 27 March 2024)

such as levees and dams. The main advantages of 1D models over 2D models is that they are easier to set up and run, and have faster run times.

2D hydraulic models simulate the lateral movement of water in a river channel (as done by 1D models), as well as water movement across the flood plain that is represented by a grid. Water can move from grid cell to grid cell allowing vertical simulation of water level, taking into account terrain and barriers to flow (e.g., buildings). This means that 2D models can be used to capture the distribution of flood waters more accurately over the flood plain and therefore better predict the impact of flooding within the model domain. 2D models can provide more accurate flood mapping and impact assessment, particularly in urban areas and areas with complex terrain, but to represent the flood plain require more spatial data, longer build and run times, and greater computational power.

In flood modelling 3D hydraulic models, also known as computational fluid dynamic (CFD) models, are generally restricted to complex flow situations where extra detail is required. For example, they can be used to simulate the impact of flooding on buildings, dams, bridges and other infrastructure (Junyi and Chengcheng 2024; Velísková et al. 2018; Viccione and Izzo 2022). They can also be used to determine the hydraulic efficiency of NBS (Allafchi et al. 2021; Li and Sansalone 2021; Nuruzzaman et al. 2023), which can guide the development of models for specific NBS applications (e.g., stormwater detention ponds (Persson et al. 1999; Persson 2000; Persson and Wittgren 2003)).

A more comprehensive discussion of state-of-the-art flood models can be found in reviews by Kumar et al. (2023) and Teng et al. (2017). Kumar et al. (2023) note that there is a potential for Artificial Intelligence (AI), Machine Learning (ML) and Deep Learning (DL) techniques to increase the accuracy and reliability of flood models. However, they note that barriers to the use of such techniques include large data requirements, sensitivity to noise in the data, and high computation needs. The potential for application of these techniques for hydrological modelling has also been explored by Tripathy and Mishra (2024).

Flood models can be used for a range of purposes including:

- **Source area mapping** - this involves assessment of flood controlling processes and determination of flood contributing area. This approach can be used to define the type, location, and number of NBS that will be used to reduce catchment flood probability and impacts.
- **Flood risk mapping** - spatial distribution and extent of flood and their resulting impact on life, limb, infrastructure, and property. Flood risk maps can be produced pre- and post-implementation of NBS and can be created for a range of storm magnitude events.
- **Scenario modelling** – uses the model to assess the impact of a range of mitigation measures to support the planning and design of flood risk management plans. Scenario modelling also allows assessment of the relative benefits of traditional engineering and NBS relative to a base case scenario. Scenarios can also incorporate land-use changes (e.g., urbanization and intensification, conversion of forest to pasture, and afforestation of retired pasture) that may occur as part of the planned NBS.
- **Flood forecasting and real-time modelling** - used to predict and then coordinate emergency response to flood events. These models need to be able to incorporate NBS if they are incorporated within flood mitigation systems.

- **Modelling specific historical or synthetic rainfall** – this can yield information about likely flood response that can be used to design systems able to mitigate and withstand floods. Design information is derived from the historic rainfall intensity, duration and frequency (IDF) data. For example, the NIWA High Intensity Rainfall Design System (HIRDS)[23] provides rainfall depths for climate stations across the country with frequencies ranging from recurrence intervals of 1.58 years (AEP of 0.633) to 250 years (AEP of 0.004), and rainfall durations ranging from 10 minutes to 120 hours. The rainfall data available for current conditions have also been adjusted for four climate change scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5)[24] and two time slices (2031–2050, 2081–2100).

- **Continuous rainfall-runoff models** – these allow modellers to understand flooding over time and to identify the climate, catchment and hydrological factors that lead to extreme flood events. Continuous models are also used for real-time flood forecasting.

Flood modelling within a Drivers-Pressure-State-Impact-Response framework (DPSIR) is overviewed in Appendix E. The DPSIR framework provides a simplified method of visualising the factors affecting environmental hazards and their interactions thereby aiding communication and understanding of flood risk.

4.1.1 Data requirements

Flood models generally require information relating to land cover, soil characteristics, topography, soil type, drainage characteristics, climate, stream network, and channel characteristics. Data required to calibrate and test models include synchronous climate and river flow data, and information on the depth and extent of past floods. Nationally available datasets that can be used for flood modelling are listed in Table 4-1. Other data, such as the S-map soil layer[25], the NIWA DN3 river network, Agribase[26], and LIDAR may not be available in some regions and may be subject to charges. Data from NIWA's virtual climate station network (VCSN) (Tait and Turner 2005; Tait et al. 2006) is gridded at a 5 km resolution and interpolated from climate station data using a thin-plane smoothing spline model. Stream network data may require additional processing to remove or add features such as roads, culverts, bridges, overhanging vegetation, depending on model requirements.

4.1.2 Scale issues

Scale issues have long been discussed with respect to hydrological modelling (Bergström and Graham 1998; Blöschl and Sivapalan 1995; Klemeš 1983). Model scale is defined as the characteristic time or space in which processes or observations are represented within a model. Process scale is defined as the spatial or temporal scale at which a specified process occurs. Generally, small-scale spatial processes tend to be associated with small temporal scales, while large-scale processes are associated with large temporal scales (Figure 4-1). In addition, at larger scales, the hydrological response to meteorological events represent an amalgamation of multiple small-scale processes over a large area, so that the overall response occurs across a longer period. A rainfall event leading to pluvial flooding in a small, impervious urban catchment for example, will have a fast response time (minutes to hours) and affect a smaller area (streets or neighbourhoods), when compared to riverine flooding in a large rural catchment for which the hydrological response may be measured in days.

[23] https://hirds.niwa.co.nz/ (date of access 28 March 2024)
[24] https://niwa.co.nz/our-science/climate/information-and-resources/clivar/scenarios (date of access 28 March 2024)
[25] https://smap.landcareresearch.co.nz/
[26] https://www.asurequality.com/services/agribase/

Table 4-1: Nationwide spatial data that can support flood modelling.

Dataset	Latest release	Description	Owner	Source
Elevation model	2023	This 8 m Digital Elevation Model (DEM) was originally created by Geographx (geographx.co.nz) and was primarily derived from January 2012 LINZ Topo50 20m contours (data.linz.govt.nz/layer/768). Spatial accuracy: ±22 metres horizontally and within ±10 metres vertically.	Land Information NZ (LINZ)	https://data.linz.govt.nz/
Digital River Network	Version 2 (DN2)	Topographically defined national surface water network based on digital elevation models. Derived from a 30 m DEM, based on 20 m contour data (LINZ). The network includes over 600,000 river reaches with an average reach length of 750 m.	NIWA	niwa.co.nz/freshwater/management-tools/
Fundamental Soil Layer (FSL)	2023	The FSL is a geodatabase consisting of soil orders and their physical, chemical and mineralogical characteristics including drainage properties. Separate layers exist for different soil data sets (e.g., drainage class, particle size class, profile available water), and are available as national shapefile. All attribute shapefiles are available for the North and South Island separately.	Maanaki Whenua / Landcare Research (MWLR)	https://lris.scinfo.org.nz/ (Search for FSL)
Land Cover Database (LCDB5)	2021 Version 5	LCDB identifies 33 mainland land cover classes. Land cover features are described by a polygon boundary, a land cover code, and a land cover name. Data are available for the following nominal time steps; summer 1996/97 (LCDB1), summer 2001/02 (LCDB2), summer 2008/09 (LCDB3), summer 2012/13 (LCDB4), and summer 2018/19 (LCDB5).	Maanaki Whenua Landcare Research	https://lris.scinfo.org.nz/ (Search for LCDB5)
Climate data	Continuously updated	Rainfall, temperature and other meteorological timeseries from the National climate database (data from approximately 6500 climate stations dating back to 1850). Approximately 600 stations are currently in operation and data can be obtained in ten minute, hourly and daily increments.	NIWA	cliflo.niwa.co.nz
VCSN	Continuously updated	National grid (~5 km^2) of daily spatially interpolated meteorological variables based on observed meteorological data from the New Zealand National Climate Database (Tait et al. 2006).	NIWA	cliflo.niwa.co.nz
High Intensity Rainfall Design System (HIRDS)	Version 4	High Intensity Rainfall Depth Surfaces (HIRDS) provides estimates of high intensity rainfall for a range of return periods and event durations. These surfaces can be used for design storm assessment and in the design of flood protection works. Includes design storm with climate change rainfall projections.	NIWA	hirds.niwa.co.nz/

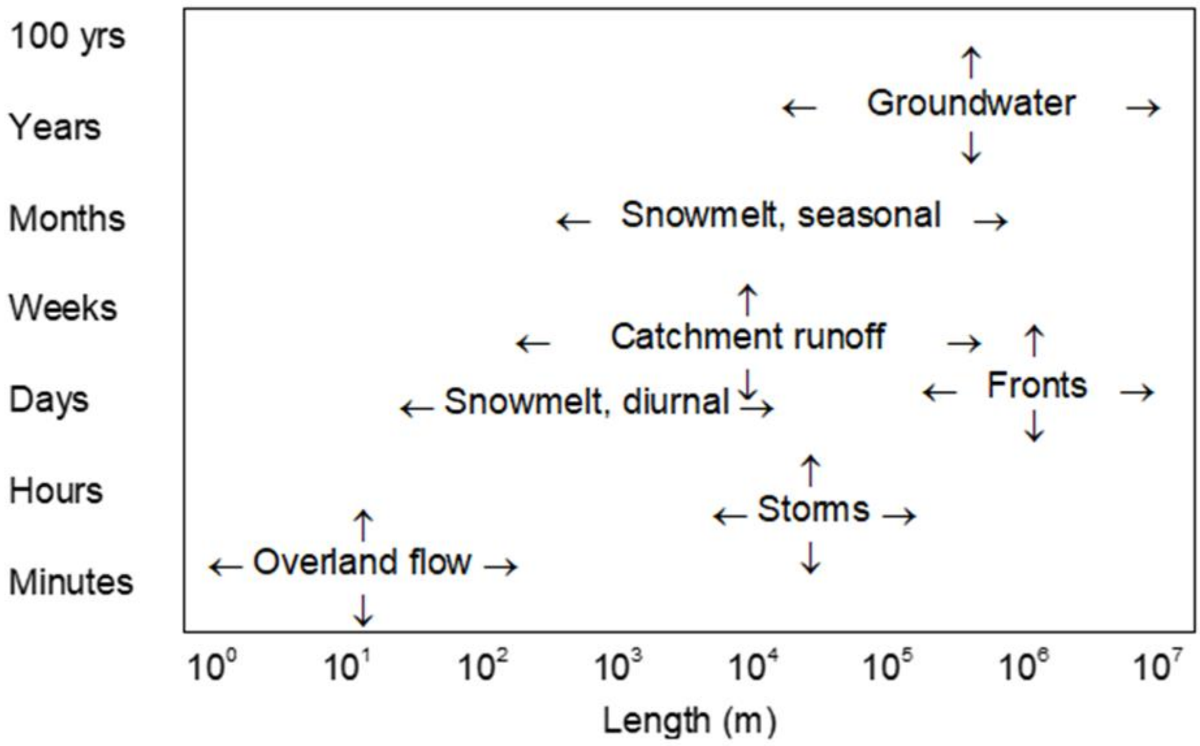

Figure 4-1: Spatial and temporal scales at which hydrological processes are typically represented within simulation models. Measurement scale refers to the scale at which observation data are available. This may be limited by the costs and logistics of data collection, the precision and accuracy of monitoring equipment, and the ability to process and store data. The model scale is the scale at which the model represents the processes and data within the model and may be limited by the level of model complexity, computational power, storage required to run models with large datasets, and the time required to build and run models.

Difficulties can occur when process, observation and model scales are not compatible and require re-distribution or aggregation. These steps may result in spurious spatial or temporal accuracy in resulting models. As computing power and remote sensing techniques improved from the 1980s, consideration of scaling issues related to both higher spatial and temporal resolution increased (Hellmers and Fröhle 2017; Sidle 2021). For example, whilst high resolution (c.1 m) LIDAR facilitates more precise drainage networks delineation, it becomes unfeasible when modelling large catchments due to the storage and computational power required to deal with extremely large datasets.

Hankin et al. (2019) also points out that while it may be possible to represent NBS intervention in small to medium catchments, it may be more difficult in larger catchments due to the resulting increase in model complexity. Such catchments may require an aggregated approach where a single node at the downstream point of mitigation represents the combined effect of multiple NBS, such as storage capacity and specific area (Elliott et al. 2006; Hellmers and Fröhle 2017). This view is echoed by McIntyre and Thorne (2013) who note that at the catchment scale, the spatial variability of both landscape parameters and rainfall increase, making evidence for the attribution of flood risk reduction to NBS measures difficult to obtain.

4.1.3 Uncertainty and error

Whilst it is recognised that NBS can contribute to improved ecosystem functioning, it should be noted that their implementation can also result in negative consequences (United Nations-Water, 2018). For example, river channel widening or diversion, conducted to produce greater river conveyance or storage in the riparian corridor, can lead to reduced water depth and increased water temperatures. This could produce a nett negative effect with respect to pre-existing ecosystems.

Due to the complexity of the processes represented flood model predictions often come with a high degree of uncertainty. Uncertainty and error have long been discussed in the literature relating to both hydrological models (Beven 2006; Beven and Alcock 2012; Grayson et al. 1992) and flood models (Beven et al. 2015; Freer et al. 2013; Merwade et al. 2008; Savage et al. 2016; Zhou et al. 2021). Uncertainty in model predictions can also result from the non-uniformity and sparsity of spatial and temporal representative data from within the model domain and associated complex calibration techniques. The dire consequences of inaccurately predicting flood depth and extent makes it imperative that modellers adequately estimate uncertainty and communicate the implications to stakeholders. To assist in this, model uncertainty can be broken down into a number of categories related to input data, model structure, parameter variability and measurement and calibration error propagation (Table 4-2).

Table 4-2: Model options that may result in uncertainty (after Moges et al. 2021).

Model uncertainty	Potential causes of uncertainty
Input data uncertainty	Measurement inaccuracies Spatial interpolations Missing values Temporal aggregation and disaggregation Assumptions in boundary and initial conditions
Structural uncertainty	Conceptualisation Numerical algorithms Discretisation Coupling and de-coupling process Scaling processes and parameters
Parameter uncertainty	Measurement uncertainty Natural variability Effective parameters Lack of observational data Optimisation and calibration techniques
Calibration and data uncertainty	Measurement inaccuracies Spatial and temporal interpolation Rating curves – structural and parameter uncertainty Rating curve extrapolation and interpolation

Model input and simulation errors can propagate at each step in the modelling chain so that initially small input errors can translate into significant error (and uncertainty) in model output. Model errors take three main forms:

Input errors – these are related to the accuracy and precision of input data. The magnitude of these errors is impacted by how data has been collected, collated, processed, and stored. Errors may also be related to how well input data is spatially and temporally representative, which may evolve from inappropriate sampling and interpolation methods. Noise may also be generated in the data collection process and influence model results if not recognised.

Calibration and validation errors – originate from data used to calibrate and validate the model. These errors may also occur if insufficient data are available.

Model structural or verification errors – structural errors may be produced if there are conceptual inaccuracies in understanding of processes being modelled. Verification errors may arise during coding of the conceptual model.

4.2 Modelling NBS hydrology

Hydrological and hydraulic models can be used to assess the feasibility of different NBS options at site, reach or catchment scale. In this section we provide guidance on how NBS can be represented within the numerical modelling process to allow accurate assessment of their expected impact. Often the performance of several NBS may need to be compared, or it may be necessary to compare NBS performance against the performance of traditional hard engineering options. Figure 4-2 illustrates what might be expected from such comparisons.

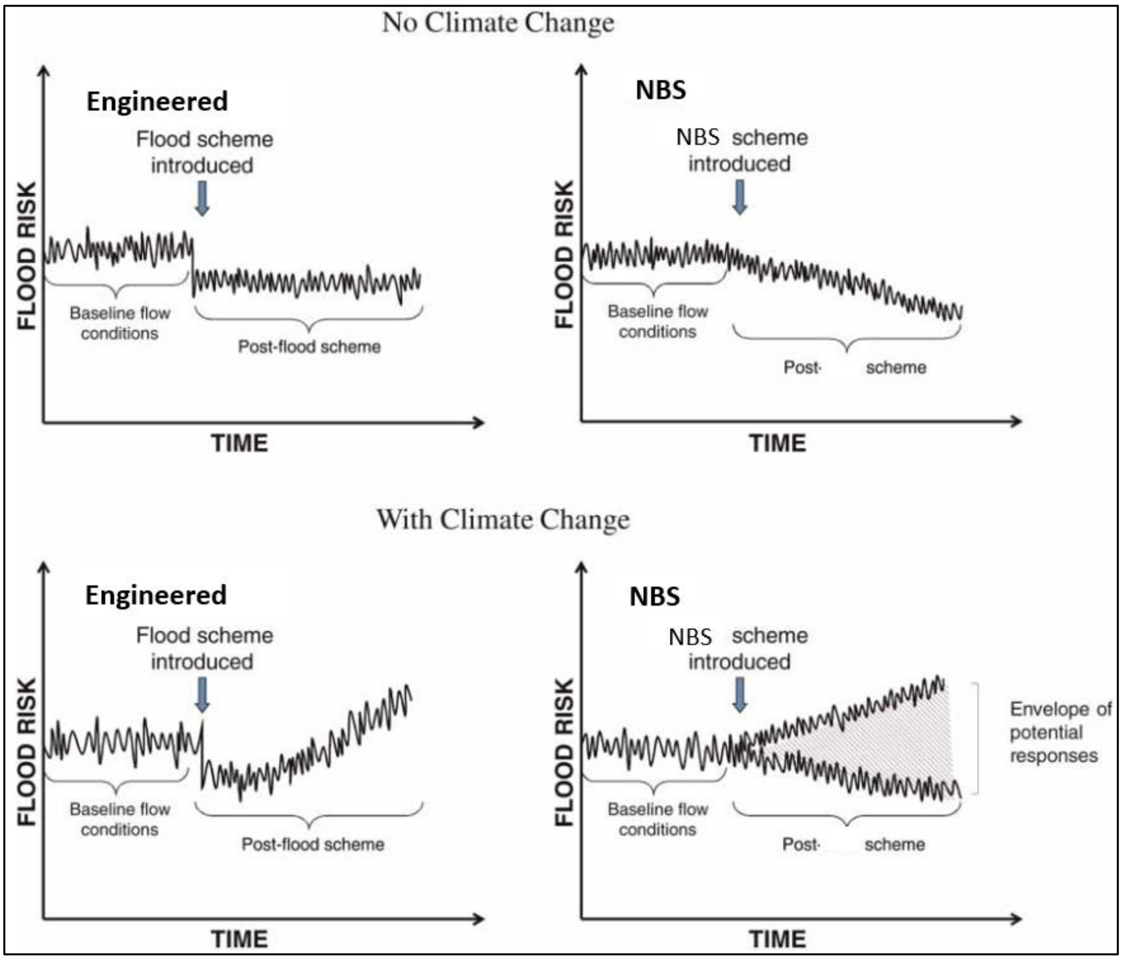

Figure 4-2: Expected outcomes of engineered and NBS strategies under *no climate change* (top), and *with climate change* (bottom) conditions. (Source: Iacob et al. 2014).

The figure illustrates changes in flood risk (over time) in response to a traditionally engineered mitigation option (top left). In this case flood risk is reduced when the flood scheme is introduced. By comparison, flood risk undergoes a more gradual decrease if an NBS scheme is introduced (top right). Under climate change, flood risk response is more complex. As a result, the traditionally engineered scheme's early impact (flood risk reduction) is mediated and nullified by ongoing climate change (bottom left). The impact of adopting a 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 (bottom right). The uncertain nature of the long-term environmental impact of NBS under changing climate is therefore represented by a response envelop. Elaboration of the implications of this uncertainty for planning is described by Kõiv-Vainik et al. 2022.

4.2.1 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 NBS and produce outputs that can be used in 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 (for 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.

A break-down of models used relative to different NBS intervention types, described by Environment Agency (2018) in Appendix C, indicates no immediate pattern. This suggests that case-specific factors (local environment, data availability, project objectives) determined model choice rather than intervention type alone (Table 4-3).

Table 4-3 Model or model combinations used for NBS types. (after Environment Agency, 2018).

NBS intervention	Models used
Headwater drainage management	▪ Hydraulic models ▪ *Jflow* ▪ Hydrological models
All woodland types	▪ Opportunity mapping ▪ Industry standard hydraulic models ▪ Multiscale models
Soil and land management	▪ *WaTEM/SEDEM* ▪ *SWAT, Hype and INCA* ▪ *Fieldmouse*
Leaky barriers	▪ Catchment simulation model. ▪ Hydraulic model. ▪ Coupled hydrological–hydraulic model: *Overflow* ▪ Desk based studies and catchment walkovers ▪ *HEC-RAS* hydraulic model. ▪ *Flood Modeller* model. ▪ Pond network model. ▪ *Topmodel*. ▪ *Topcat* ▪ 1D *flood modeller*. ▪ *Flood modeller* and *Tuflow* ▪ SCIMap and CRUM4 model
Runoff pathway management	▪ *Flood modeller* and *Tuflow* ▪ *TOPMODEL* ▪ *Flood modeller* ID model ▪ *Flood modeller* and *Tuflow* ▪ *Jflow*, *Flood modeller* and *Tuflow* ▪ 1D- Flood modeller
River restoration	▪ *Flood modeller*, *Tuflow* and *Jflow* ▪ 1D *Flood modeller*
Offline storage area	▪ 1D-2D Model. ▪ Hydrologic and hydraulic models ▪ *Excel* modelling tool. ▪ *Flood modeller* and *Tuflow* 1D-2D model
Floodplain woodland	▪ Standard 1D (*HEC-RAS*) and 2D (*River2D*) hydraulic models ▪ 1D-2D Model ▪ *Overflow* model
Floodplain restoration	▪ *MIKE SHE/MIKE 11* coupled hydrological/hydraulic model ▪ Detailed hydrological model ▪ Hydraulic model ▪ 1D and 2D model. ▪ Lumped rainfall runoff model

4.2.2 Modelling NBS

The previous section indicated that any drainage network can be represented by 1D stream polylines connected by nodes at stream confluences. Stream polylines and typologically linked sub-catchment polygons are connected to represent the larger catchment. These lines or nodes can be modelled by methods ranging from application of simple attenuation factors that reduce flow rates, to 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 retention in ponds or flood basins. Complexity can be increased by representing 2D and ultimately 3D processes within the same modelling framework.

Using the above numerical foundation to represent the flow of water through the catchment, there three ways of representing the influence of NBS within standard hydrological models:

1. **By changing model parameters and boundary conditions** to represent different land cover or drainage pathways (as determined by with specific NBS design) or land use practices (e.g., tillage).
2. **By changing the topology of streamlines** within the drainage network to represent adjustments to stream or river water courses (Hankin et al. 2019; Metcalfe et al. 2017).
3. **By adding modules representing NBS into the flood package.** This is usually done by adding a node to the flow hydrological model where the modelled runoff from one or more flow paths is used as the input to the module. This runoff is detained or retained at the node load location.

Table 4-4 illustrates how a range of model types typically employed within hydrology can be parameterised to represent the inclusion of NBS to mitigate flood risk. The NBS categories of options in Table 4-4 are the same as those used within Section 2 of this report and have been loosely matched (and slightly adjusted) with the categories used in the Environment Agency (UK) guidance materials (Environment Agency 2018). Optimal parameter(s) selection should be made after considering the exact specifications of the NBS option chosen and the characteristics of the environment in which it is applied.

4.2.3 Measuring hydrological impacts

Whilst extensive literature on the potential use of NBS for flood mitigation exists, significant gaps in the information about their performance, both with regards to single measures and the use of NBS generally at a range of spatial scales (e.g., site vs catchment) and temporal scales (single events or long-term averages) remains. As illustrated in Figure 4-2 it can take years for plant-based solutions to become established, so a long-term monitoring plan is essential to ensure any change in performance is captured over time.

Perceived uncertainty in their effectiveness over longer scales is one of the greatest barriers to adoption of NBS (Keech et al. 2023). Most previous evaluation of the hydraulic and hydrological performance of NBS has been for individual devices at the site or neighbourhood scale. The few studies that have looked at catchment-scale impacts have relied predominantly on modelling rather than monitoring. To characterise both the site and catchment scale impacts of NBS it is necessary to validate their performance by monitoring landcover or hydrological parameters that have been directly influenced by introduction of one or more NBS (such as those described in the above section).

The hydrological response following introduction of one or more NBS can be monitored using traditional hydrometry techniques. 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 (as indicated in Figure 4-2), it will be critical for modellers to predict the duration of time that it will take for the scheme to become effective. This will require the use of transient parameters identified in Table 4-4. It is equally important to monitor the hydrological effects of the installed NBS to refine model parameterisation, validate model predictions, or refine expectations of specific NBS.

4.2.4 Measuring co-benefits

In addition to improved hydrological performance, environmental co-benefits should be monitored to provide evidence of the cost and overall benefits of NBS in the long-term. For example, Table 4-5 and Table 4-6 illustrate the spatial and temporal controls on methods for monitoring ecosystem and biodiversity indicators in response to agroecosystem restoration respectively. Whilst these tables are not exhaustive, they provide a list of 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. (2014) conclude from their meta-analysis of 25 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 are 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.

Table 4-4 Representative parameterisation strategies for different NBS category options for 1D, 2D, and distributed models. (Source: Environment Agency 2018).

<table>
<tr><th></th><th>1D physics-based cross-section analysis</th><th>1D routing model with limited survey</th><th>1D hydrodynamic model with limited survey</th><th>1D model and survey</th><th>2d model</th><th>2d model with intelligent sub-grid hydraulic properties</th><th>1d-2d linked model</th><th>Lumped parameter catchment model</th><th>Semi-distributed Hydrological model</th><th>Fully distributed model</th></tr>
<tr><td>Landscape retention and detention features</td><td rowspan="3">Adjust frictional losses per cross-section</td><td rowspan="2">Increase attenuation parameter</td><td rowspan="2">Increased Manning's n or reduce inflows</td><td rowspan="2">Increased Manning's n roughness</td><td rowspan="2" colspan="3">Increase Manning's n, or in-line storage</td><td rowspan="2">Change time constants in linear cascade</td><td rowspan="2" colspan="2">Adjust wave speed and treat as time constant storage</td></tr>
<tr><td>Bioretention systems</td></tr>
<tr><td rowspan="2">Landcover and soil management</td><td>Reduce wave speed in routing model</td><td colspan="2">Increase overbank Manning's n roughness</td><td colspan="2">Increase distributed Manning's n roughness and hydrological losses</td><td>Represent Manning's n roughness in more detail in 2d areas and hydrological losses</td><td>Change maximum soil moisture, storage, Cmax, and quick flow time constants</td><td colspan="2">Change transmissivity, canopy storage, evaporation, overland flow speed, and antecedent wetness.</td></tr>
<tr><td rowspan="4">not applicable</td><td colspan="3">Reduce inflow boundary</td><td colspan="3">Modify losses: reduce rainfall inputs, increase infiltration, and surface roughness.</td><td>Changes to Cmax</td><td>Increase transmissivity</td><td>Vary soil parameters</td></tr>
<tr><td>River naturalisation</td><td rowspan="3">Reduce inflow boundaries</td><td rowspan="3" colspan="2">Reduce inflow boundaries, represent increased friction</td><td rowspan="3" colspan="3">Modify DTM to increase storage</td><td rowspan="4">Change time constants in linear cascade</td><td rowspan="3" colspan="2">Increase root-zone or other storage</td></tr>
<tr><td>Natural wetlands</td></tr>
<tr><td>Constructed wetlands</td></tr>
<tr><td>River floodplain and estuary management</td><td>Different shear stresses</td><td>Increase attenuation parameter in Muskingum unit</td><td>Increase storage area capacity</td><td>Modify lateral weirs and roughness overbank</td><td>Modify DTM to add storage / roughness</td><td colspan="2">Modify DTM to add storage / roughness. Add / remove break-lines</td><td>Increase complexity of floodplain representation</td><td>Link with detailed hydraulic model</td></tr>
</table>

Table 4-5: Relevant spatial and temporal scales for methods used to measure ecosystem indicators of agroecosystem restoration. (Source: Buckley et al. 2023).

Ecosystem indicator	Methods	Spatial scale	Temporal scale	Implications/rationale
Late-successional tree seedlings	Alive, dead, resprouted, dieback, height, basal stem diameter	All seedlings are monitored	Initially yearly for 3 years, then every 3–5 years.	Spatio-temporal variability in tree survival, growth
Nurse tree seedlings	Tagged, measured and have introduced plant coverage estimated. Alive, dead, resprouted, height, basal diameter	At every fourth late-successional tree throughout the site, four associated nurse trees located using the PCQ method	Initially yearly for 3 years, then every 3–5 years.	Spatio-temporal variability in tree survival, growth
Soil chemistry (soil fertility, pH, toxicity)	500 g sample, 25 cm deep max; standard soil analysis techniques	20-m soil grid scale	Year 1 and every 3–5 years thereafter	Spatio-temporal variability in soil condition
Water quality	"Wai Care" New Zealand protocols for water quality monitoring.	All seasonal water sources; at least three repeated measurements from each water source	Three times per year, late summer, winter and spring; in year 1 and every 2 years thereafter.	Spatio-temporal variability in water chemistry and biotic indicators
Soil moisture–volumetric soil water content (%)	Handheld soil moisture probe	20-m sample grid and near late-successional trees	Three times per year, every year from year 1	Spatio-temporal variability in plant water availability
Soil compaction	Soil penetrometer	20-m sample grid and near late-successional trees	Year 1 and every 2 years thereafter	Spatio-temporal variability in soil compaction
Soil biological activity	Bait lamina probes	Treatment block scale	Year 1 and every 3–5 years thereafter	Spatio-temporal variability in soil micro-invertebrate activity
Decomposition	Teabag decomposition experiment	Treatment block	Year 1 and every 3–5 years thereafter	Spatio-temporal variability in decomposition rates/decomposer communities
Soil bulk density	100-cm^3 core	20-m sample grid, every fourth soil sample point	Every 3–5 years	Spatio-temporal variability in soil compaction
Fine woody debris	Collect all fine woody debris in 30 × 30-cm quadrat; samples dried, sorted, and weighed	Treatment block	2 years after planting and every 2 years thereafter	Spatio-temporal variability in woody litter deposition
Canopy closure	UAV imagery	Whole site	Three times per year	Spatio-temporal variability in tree canopy growth and closure

Table 4-6: Relevant spatial and temporal scales for methods used to measure biodiversity indicators of agroecosystem restoration. (Source: Buckley et al. 2023).

Indicator	Methods	Spatial scale	Temporal scale	Variables
Birds*	5-min bird counts	Conducted every 200 m moving away from adjacent forest patches	Yearly in spring	Richness, relative abundance, composition
Introduced plants *	Introduced plant survey and species list per site percent cover of introduced plant species in a 1 m^2 radius quadrat around seedlings.	Site scale, and around all late-successional seedlings and subset of nurse seedlings	Yearly for first 3, 3–5 years thereafter	Richness, relative abundance, composition
Woody seedling recruitment *	Count of recruits, by species	Treatment block scale	After initial planting, and every 2 years thereafter	Richness, abundance, composition
Invertebrates * (Aranae, Hymenoptera, Coleoptera)	Pitfall traps, malaise traps	Pitfall traps: treatment block scale Malaise traps: site scale, three per site, at distances from forest patches	Yearly, during summer, for the first 3 years, then 3–5 years thereafter	Richness, relative abundance, composition
Nematodes *	Extracted from 600 cm^3 soil sample *via* decanting and sieving; nematodes characterized *via* microscopy	Treatment block	Every 3–5 years	Richness, relative abundance, composition
Earthworms	Within a 30 × 30 × 10-cm volume of soil; total worm count and biomass, native or exotic species identified and confirmed *via* DNA sequencing	Treatment block	Every 3–5 years	Richness, relative abundance, biomass, composition
Soil microbes	Three soil core samples (2.5-cm radius × 10-cm depth); samples composited and frozen at —20°C for DNA extraction and subsequent sequencing	Every 20-m sample grid location	Three times per year; in first year and every 3–5 years thereafter	Richness, relative abundance, composition

4.2.5 Site and operational issues

Implementing NBS often requires specialised resources and careful planning (including possible resource consent application), as well as coordination among multiple stakeholders and landowners. Scaling up NBS to address larger flood risk areas or catchments may also present logistical challenges and require significant investment in land acquisition, restoration, and monitoring. Similarly, while NBS may have lower maintenance costs compared to engineered solutions, they may require longer start-up or large event recovery time for plant assemblages to grow or regrow. Ongoing management is also needed to ensure their long-term effectiveness and sustainability, and may involve activities such as vegetation management, sediment removal, and monitoring of ecosystem health.

The type, number, placement, design, operation, and maintenance of multiple NBS within a single catchment necessitates an integrated model to represent the combined efficacy (in addition to individual NBS feature performance). Modellers often assume that a hydrological system is operating under optimal conditions, with algorithms calibrated against data collected at experimental sites or laboratory studies. In practice, the implementation and operation of multiple mitigation measure may be sub-optimal leading to poorer performance than was predicted by models during the design and planning phases.

In catchments where mitigation is already in place, it is important to know where these are installed and how they are operating 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 mitigations have been in place to identify trends in monitored data that can be attributed to mitigation that needs to be considered in model calibration and testing. In this way the assumed modelled system performance can be adjusted to account for any such identified trends.

When representing NBS in models, it would be informative to ask questions related to site and operational issues such as:

- Are NBS placed in the optimal position for maximum performance (e.g., slope, soil drainage, flow pathway or position or in the drainage network)?
- Is a NBS correctly sized for its upstream area, and are sufficient NBS operating to provide flood mitigation for the catchment as a whole?
- Is the mitigation design optimal? For example, does the shape and bathymetry of wetlands and ponds and the use of islands, baffles and planting improve hydraulic efficiency (increasing detention times), or cause short-circuiting (reducing detention times)? Design can greatly affect NBS performance, particularly peak flow volumes and flow rates (Persson 2000; Persson and Wittgren 2003; Persson et al. 1999).
- How long has the mitigation been installed and how will its performance change during maturation, and how will operation and level of maintenance influence performance?

5 NBS case studies

Hankin et al. (2019) presented a framework for modelling NBS for flood protection, noting that advances in computer power, methods for spatial data analysis, and fast numerical equation solvers now permit complex whole of catchment modelling – at least for small to medium sized catchments. They also noted that simulation of the effects of NBS requires the modeller to understand NBS processes and downstream processes that may be indirectly impacted. For example, modelling afforestation or tree-planting requires changes to the parameters describing evapotranspiration, surface roughness and infiltration. Similarly, changes to flow pathways due to detention basins, will influence downstream attenuation.

Hankin et al. (2019) coupled a hydrological model (Topmodel) to a 2D hydraulic model (HEC-RAS 2D) to simulate outflow from an instream impoundment dam located in the uplands of a small (15 km^2) catchment in the UK. The catchment drainage network was delineated at a 2 m resolution and the model was run with a 15-minute timestep using historical data. The hydrological model was used to simulate hillslope processes while the hydraulic model was used to model flow over rough terrain and within the stream channel. Runoff attenuation features were represented by reducing the storage outflow, effectively damming the upper section of the catchment. The model was run with an ensemble of 1482 scenarios representing different boundary conditions – this allowed assessment of model sensitivity and uncertainty. The authors found that although the additional storage volume in the upper catchment reduced flow volumes in the rising limb of the hydrograph in the lower catchment, associated downstream peak flow rates however, were not significantly reduced.

In a later example, again using HEC-RAS 2D, Hankin et al. (2021) modelled the effect of flow diversions to connect marshland to a stream channel in a 2.5 km^2 catchment in Cumbria (UK). The model was applied with adjusted rainfall series to simulate the effect of climate change and with changing boundary conditions to represent mature trees in the marshlands and an associated increase in roughness. The authors used their experience from this modelling exercise to apply similar modelling strategies to two larger catchments (70 km^2 and 280 km^2) in which woody barriers were placed in the stream channel to push it into the flood plan. In both catchments, they predicted that the NBS could reduce peak flows by a modest extent (5-10%), but that this reduction was consistent over a range of design storm sizes. Extrapolating these benefits over time, they predicted considerable reductions in the costs arising from minor flooding. They concluded that a whole-of-catchment approach is particularly useful in larger catchments to represent the complex interactions between the channel, flood plains and NBS, and to represent sometimes hidden financial benefits.

Metcalfe et al. (2017) modelled two storms that occurred in Yorkshire (UK) from September and November 2012, to assess impact of multiple instream NBS features designed to attenuate flow (artificial log jams, debris piles, wooden screens, and barriers). The November storm had two peaks that occurred several hours apart. A hydrological model (used to estimate hillslope runoff) was coupled with a 1D hydraulic model (used to simulate flow through the channel network). The model configuration was run with a series of scenarios representing up to 59 instream barriers that were represented as weir nodes within the 1D model. The initial system configuration which had weir nodes of equal height for both the September and November flood events, resulted in under-utilisation of upstream weirs and exceedance of downstream weirs. When weir heights were optimised to maximise weir storage, it was found that the September flood event could have been prevented. Flooding still occurred in the November event however, when the second event peak occurred before the weirs had been after the first event. The authors noted that if they had not run the model for different event distributions, the exceedance of the system design would not have been identified.

In New Zealand, Hoang and Hughes (2024) used the SWAT model to assess the hydrological impact of afforestation of retired pastoral land in three neighbouring Waikato hill country catchments. Two of the catchments had undergone conversion of grazed pasture to pine plantations in the early 2000s, albeit with different percentage covers of forest (9% vs 57%), the third is a forested (regenerating native vegetation) catchment that was used as a reference. The catchments have been monitored as part of a 25-year Before-After-Control-Impact (BACI) study (Hughes et al. 2020) providing the unique opportunity to apply a model to better understand the hydrological response to afforestation. SWAT performed well for all three catchments for both the calibration (2004–2011) and validation (1995–2000 and 2012–2019) periods. SWAT was run for the two afforested catchments for a baseline pastoral scenario and with afforestation. The modelling suggests that afforestation results in reduced surface runoff, largely through increased evapotranspiration, leading to reductions in mean annual flow, seasonal flow and the annual maximum flow. There were also modelled reductions to groundwater recharge, but the groundwater estimates were uncertain. The catchment with 57% afforestation had a reduction in mean annual flow of almost 30% — which was consistent with monitored flow for this catchment (Hughes et al. 2020), while the catchment with 9% afforestation had a more modest reduction in mean annual flow of around 5%. While not focused on assessing or reducing flood risk per se, the work demonstrates that modelling can provide valuable insight regarding the hydrological effects of land use change. This is important because very little information of this type exists for New Zealand.

Bokhove et al. (2019) used stage/discharge relationships to estimate the threshold volumes of flood water above which flood damage occurred for floods in 2015 (River Calder, UK and River Brague, France). The amount of storage required to contain the flood volume was equated to a conceptual square lake with a fixed depth 2 m. The River Calder required storage equal to a 908 × 908 m square lake (c.82 ha), while River Brague would require a lake of 494 × 494 m lake (c.24 ha). The concept of a square lake In relation to the catchment size allowed stakeholders to picture the feasibility of using NBS to increase storage. The total cost of NBS that would be required to provide this storage was determined in relation to the number, size and extent of flood basins, tree planting and peat restoration. It was determined that mitigation of flood risk in the River Calder catchment would be expensive and inadequate to protect against a 100-year flood, because the catchment is largely urbanised and narrow, making it difficult to find adequate space for NBS. The authors concluded that although NBS can be effective at local scale for low return period events, it would be difficult to deploy them at the scale required for protection during large-scale extreme floods. It was suggested that hard engineering solutions, such as drawdown of upstream water supply dams, improved maintenance of existing dams, and river widening may be more effective in some catchments.

Ruangpan et al. (2020) provide a critical review of the literature concerning use of NBS to mitigate hydro-meteorological risk and identify current knowledge gaps and future research prospects. Their review summarises the hydrological benefits (expressed as reductions in run-off volume and peak-flow) drawn from 31 single, and 13 multiple NBS case-studies and based on empirical evidence (Table 5-1). Although NBS were predominantly applied in urban settings, they were found to reduce run-off volume by between 0.3% to 100%, and reductions in peak flow of 2.2% to 96% were possible.

Table 5-1: Summary of run-off volume and peak flow reductive effectiveness, co-benefits, and costs for small-scale NBS measures. (Source: Ruangpan et al. 2020).

Measures	References	Case studies	Area or volume covered by NBS	Effectiveness: Run-off volume reduction	Effectiveness: Peak flow reduction	Co-benefits	Cost per square metre*	Remark
Porous pavement	Shafique et al. (2018) Damodaram et al. (2010)	Seoul, South Korea Texas, USA	$1050\,m^2$ $2.99\,km^2$	~ 30 %–65 % –	– ~ 10 %–30 %	– Removing diffuse pollution – Enhancing recharge to groundwater	USD ~ 252	– More effective in heavier and shorter rainfall events
Green roofs	Burszta-Adamiak and Mrowiec (2013) Ercolani et al. (2018) Carpenter and Kaluvakolanu (2011)	Wroclaw, Poland Milan, Italy Michigan, USA	$2.88\,m^2$ $0.39\,km^2$ $325.2\,m^2$	– ~ 15 %–70 % ~ 68.25 %	~ 54 %–96 % ~ 10 %–80 % ~ 88.86 %	– Reducing nutrient loadings – Saving energy – Reducing air pollution – Increasing amenity value	USD ~ 564	– More efficient in smaller storm events than larger storm events
Rain gardens	Ishimatsu et al. (2017) Goncalves et al. (2018)	Japan Joinville, Brazil	$1.862\,m^2$ $34\,139\,m^2$	~ 36 %–100 % 50 %	– ~ 48.5 %	– Providing a scenic amenity – Increasing the median property value – Increasing biodiversity	USD ~ 501	More effective in dealing with small discharges of rainwater
Vegetated swales	Luan et al. (2017) Huang et al. (2014)	Beijing, China Hai He basin, China	$157\,m^3$ $1500\,m^3$	~ 0.3 %–3.0 % 9.60 %	~ 2.2 % ~ 23.56 %	– Reducing concentrations of pollutants – Increasing biodiversity	USD ~ 371	– More effective in heavier and shorter rainfall events – Not suitable in mountains areas
Rainwater harvesting	Khastagir and Jayasuriya (2010) Damodaram et al. (2010)	Melbourne, Australia Texas, USA	$1–5\,m^3$ $1.5\,km^2$	~ 57.8 %–78.7 % –	– ~ 8 %–10 %	– Improving water quality (TN – total nitrogen) was reduced around 72 %–80 %)	USD ~ 865 per m^3	
Dry detention pond	Liew et al. (2012)	Selangor, Malaysia	$65\,000\,m^2$	–	~ 33 %–46 %	– Providing recreational benefits		Delaying the time to peak by 40–45 min
Detention pond	Damodaram et al. (2010) Goncalves et al. (2018)	Texas, USA Joinville, Brazil	$73\,372\,m^3$ $9700\,m^3$	– 55.7 %	~ 20 % ~ 43.3 %	– Providing biodiversity benefits – Providing recreational benefits	USD ~ 60	
Bio-retention	Luan et al. (2017) Huang et al. (2014) Khan et al. (2013)	Beijing, China Hai He basin, China Calgary	$945.93\,m^3$ $1708.6\,m^3$ $48\,m^3$	~ 10.2 %–12.1 % 9.10 % ~ 90 %	– ~ 41.65 % –	– Reducing total suspended solids (TSSs) pollution – Reducing TP (total phosphorous) pollution	USD ~ 534	– Measure has a better reduction effectiveness in various rainfall intensities
Infiltration trench	Huang et al. (2014) Goncalves et al. (2018)	Hai He, China Joinville, Brazil	$3576\,m^3$ $34\,139\,m^2$	30.80% 55.9 %	~ 19.44 % ~ 53.4 %	– Reducing water pollutant – Improving surface water quality	USD ~ 74	
Green roof and porous pavement	Damodaram et al. (2010)	Texas, USA	$4.49\,km^2$	–	~ 10 %–35 %	– Saving energy – Increasing amenity value		– More effective in smaller events
Swale and porous pavement	Behroozi et al. (2018)	Tehran, Iran	–	5 %–32 %	~ 10 %–21 %	– Decreasing TSSs pollution 50%–60 %		– More effective in smaller events
Rainwater harvesting and porous pavement	Damodaram et al. (2010)	Texas, USA	$4.49\,km^2$	–	~ 20 %–40 %	– Removing diffuse pollution		– More effective in smaller events
Detention pond and rain garden	Goncalves et al. (2018)	Joinville, Brazil	$18\,327\,m^2$	70.8 %	~ 60.0 %	– Providing a scenic amenity		
Detention pond and infiltration trench	Goncalves et al. (2018)	Joinville, Brazil	$18\,327\,m^2$	75.1 %	~ 67.8 %	– Improving surface water quality		

* Cost of each measure is based on CNT (2009), Nordman et al. (2018) and De Risi et al. (2018).

6 Summary

The primary aim of this study was to provide a review of current national and international literature about the use of NBS in flood mitigation and management, and associated guidance for NBS implementation. This report can be used as a reference document and to provide guidance for feasibility assessment of NBS options for reduction of flood risk and impacts. The first part of this review provides basic definitions of NBS as understood by the international community. Examples of NBS commonly used in flood mitigation are then described with reference to World Bank defined NBS categories (Appendix B).

Based on the reviewed literature, a common procedure to develop NBS for hydrological objectives was derived by the authors. The first stage of this procedure is to define the flooding issue in terms of existing flood risk, related environmental processes (rainfall-runoff, soil moisture storage, groundwater recharge) and 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 in defining which NBS will be most applicable.

After the flood issue is defined, target outcomes from successful adoption of remedial measures are 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 and prioritise mitigation aims and identify environmental relationships that could create co-benefits as well as direct benefits. This information is used to compare the performance of different NBS options within model simulations, and after design implementation.

Definition of NBS mitigation options should be from the existing national and international knowledge base. Consideration of co-benefits (in addition to direct benefits), and capital and operational costs should also be made at this stage (using example tools described in Section 3). Before commencement of feasibility or pilot study, a clear monitoring plan should be formulated whereby identified model input parameters, target performance variables and agreed co-benefit metrics can be measured to ensure that the developed option is performing as expected, and so that learning outcomes can feed back into the existing knowledge base.

Given the procedure described above and summarised in Figure 6-1, NBS feasibility studies represent an opportunity for the systematic analysis of the use of NBS for flood mitigation and management. However, it is noted that for this to occur in consistent manner, 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 even government policy (for example see Barkved et al. 2024; McFadgen and Huitema 2016).

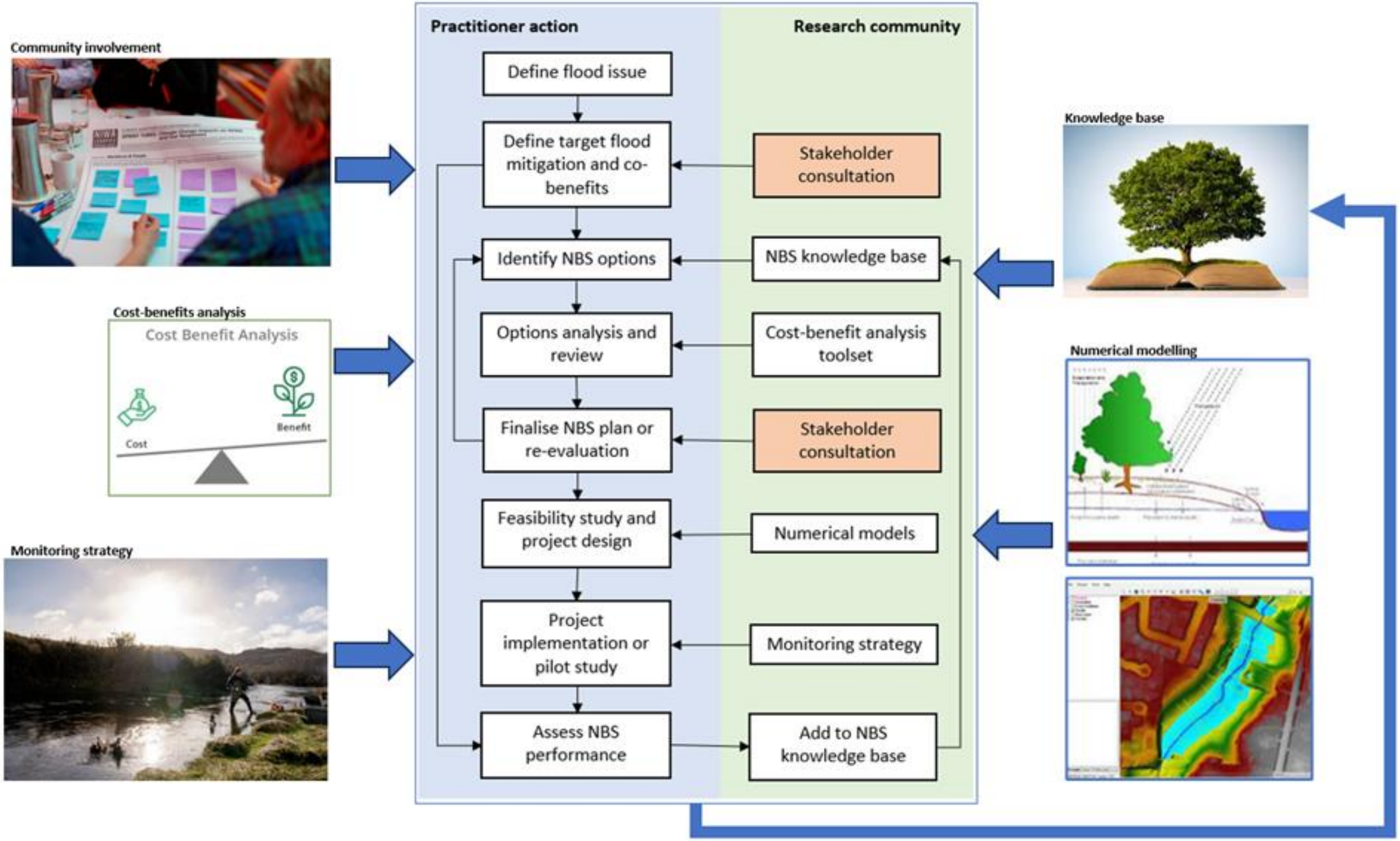

Figure 6-1: Flowchart of decision processes needed in planning NBS for flood mitigation.

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[27] https://www.gov.uk/government/organisations/flood-and-coastal-erosion-risk-management-research-and-development-programme
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8 Glossary of abbreviations and terms

AEP	Annual exceedance probability. For example, the 100-year return period flood can be expressed as the 1% AEP flood, which has a 1% chance of being exceeded in any year.
BI	Blue Infrastructure
Biodiversity	The variability among living organisms from terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part.
BRANZ	Building Research Association of New Zealand
CIRIA	Construction Industry Research and Information Association (UK)
ES	Ecosystem services. The benefits provided by ecosystems that contribute to human wellbeing (Millennium Ecosystem Assessment., 2005) Can be categorised as: 'provisioning' (e.g., food, timber and freshwater) 'regulating' (e.g., air quality, climate and pest regulation) 'cultural' (e.g., recreation and sense of belonging) and 'supporting' (e.g., soil quality and natural habitat resistance to weeds).
Flood resilience	Resistance to impact and damage from flooding. Often focuses on reducing risk to people and infrastructure by ensuring there is ample room for river adjustment to occur during flood.
Flood risk	Flood risk is product of the probability (likelihood or chance) of an event happening, and the likely consequences (or impact) of the event if it occurred.
Green-Blue infrastructure	Semi-natural and man-made green and blue features including agricultural land, green corridors, urban parks, forest reserves, wetlands, rivers, coastal and other aquatic ecosystem
Grey infrastructure	Term used to describe engineered water management structures such as reservoirs, embankments, pipes, pumps, water treatment plants, and canals.
IUCN	International Union for the Conservation of Nature
NBS	Nature-based solutions - umbrella term referring to "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits." (Cohen-Shechem et al. 2016.)
NIWA	National Institute of Water and Atmospheric Research Limited
NFM	Natural Flood Management
MWLR	Maanaki Whenua Landcare Research Limited
Resilience	The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance.

Risk	The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard (IPCC 2014).
Soft engineering	Expression used to describe when the natural environment is used to help reduce river flooding or erosion.
SuDS	Sustainable Urban Drainage Systems
Urban greening	A range of approaches designed to improve the sustainable management of stormwater, waste, energy, transport and ecosystem services
WSUD	Water Sensitive Urban Design - an approach used in urban greening which adopts nature-based solutions (NBS) and ecosystem-based adaptation (EbA).

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Appendix A Feasibility studies

Table A-1: Summary details of NBS feasibility studies funded by MBIE (2024).

Applicant and project name	Project description	Nature-based solution options
Auckland Council *Compaction of Urban Soils Feasibility Study*	This project will undertake a feasibility study that will enable development of an alternative rules framework to support spongy urban soils. The project will build on a previous study to understand the effect of soil compaction on run-off, undertake hydrological modelling, and engage with iwi to support the development of solutions with a Te Ao Māori lens.	TBD
Environment Canterbury *Coastal flood mitigation through protection and restoration of coastal freshwater and brackish wetlands*	The project will explore the feasibility of using/enhancing existing, or creating new, freshwater/brackish coastal wetlands and lagoons to mitigate the environmental and economic effects of severe coastal flooding. The study will look at the coast between Waitarakao Washdyke Lagoon and Orari River, and coastline between Rakaia River and Taumutu.	TBD
Environment Canterbury *Room for the River*	The project will investigate what would be required to implement a ‘room for the river’ upgrade to reduce the frequency of flooding in a river. The river is to be confirmed, but tentatively the Waihi River in South Canterbury. The project will use a hydraulic model to analyse ideal riverbed buffer, as well as other nature-based solutions to improve flood and erosion resilient. It will also analyse financial feasibility.	TBD
Environment Canterbury *Mātauranga Māori – Waitaha*	This project will explore the feasibility of using a mātauranga Māori framework to design, monitor and assess nature-based solutions for flood mitigation that deliver Papatipu Rūnanga aspirations in rivers across Waitaha/Canterbury.	TBD
Gisborne District Council *Maunga to Motu – Embracing the Waimata Awa*	Following the aftermath of Cyclone Gabrielle, the Waimata river confronts a range of challenges. Nature-based solutions will be explored to work with the natural characteristics of the river and it’s floodplain. Ministry funding will go towards project management, project governance, and technical analysis.	TBD
Hawkes Bay Regional Council *Heretaunga Plains nature-based solutions for flood management*	This project will undertake hydrological modelling for 3 catchments within the Heretaunga Plans to investigate how nature-based solutions may change the runoff coefficients at appropriate scales, and the impact of this on peak flows and flood potential. The outcomes of these to guide flood management in the region.	TBD

Applicant and project name	Project description	Nature-based solution options
Hawkes Bay Regional Council *Upper Tukituki Flood Resistance*	This project will undertake hydrological modelling for the Tukituki catchment to investigate how nature-based solutions may change the runoff coefficients at appropriate scales, and the impact of this on peak flows and flood potential. The outcomes of these to guide flood management in the region.	TBD
Horizons Regional Council *Oroua and Pohangina catchments nature-based flood mitigation solutions*	The project will conduct a feasibility study to explore the most effective flood mitigation solutions and management practices in the Oroua and Pohangina catchments through the concept development of a mobility corridor. The findings will support the councils existing resilience planning, safeguard important infrastructure while protecting the river catchment.	Assess channel symmetry Channel alignment Channel confinement
Marlborough District Council *Whole of catchment flood mitigation modelling in the Te Hoiere catchment*	The rivers and sub-catchments of the Te Hoiere/Pelorus river are regularly subject to major flooding events and no catchment-wide flood protection scheme is in place. The study will undertake whole of catchment hydrographic modelling based on a range of climate change scenarios, to assess the feasibility of flattening the hydrograph for flood events by intervening with a series of nature-based flood management techniques.	Increased Forest planting Wetlands Earthworks structures
Nelson City Council *Nature-based solutions for river management in North Nelson*	This project will a develop a hydrodynamic model for the Wakapuaka catchment using historical hydrological data to forecast average weather events, extreme rainfall events, and low river flows. The model will be used to identify areas where nature-based solution may have the greatest benefits to minimising the effects of flooding.	Increase infiltration Slow the flow of water Reduce channel erosion Detain flood water Hold back sediment
Northland Regional Council *Upper Kawakawa Catchment Detention*	The project will investigate capitalising on the natural detention of wetlands, which will slow water down and allow sediment to deposit in the upper Kawakawa catchment. It will explore options to provide better interaction between the road network and landscape to enhance flood detention and alleviate flooding impact to the local communities.	Wetland detention in upper catchment
Otago Regional Council *Analysis of nature-based solutions for flood and erosion mitigation in the Dart-Rees Floodplain to Inform the Head of Lake Wakatipu Natural Hazards Adaptation Strategy*	The project will be a workstream in the wider Head of Lake Wakatipu natural hazards adaptation programme. It will focus on nature-based interventions and river management to reduce the flood hazard and bank erosion. The project will undertake hydraulic modelling as well as determining cost-benefit constraints of these interventions.	Screening study braided rivers in an alpine environment

Applicant and project name	Project description	Nature-based solution options
Otago Regional Council *Modelling of the Te Hakapupu Catchment to investigate Flood Mitigation*	The project will investigate how wetlands/constructed wetlands (or other nature-based solutions) could contribute to flood mitigation in the Te Hakapupu catchment. Secondly, the project will investigate landowner perception and willingness to contribute land area for nature-based solutions.	Wetlands (natural or constructed)
Environment Southland *Slow the Flow Murihiku Southland*	The project will facilitate a co-design process between the councils of Murihiku Southland and Te Ao Mārama Incorporated. They will collectively identify and agree on where in Southland to identify pilot projects, and what science and information is required to test the feasibility of the nature-based solutions for flood mitigation at these sites.	TBD
Taranaki Regional Council *Kai manawaroa Waitōtara, kia whakaritea te tangata (Let Waitotara be resilient, let the people be adaptive)*	The project aims to incorporate a range of existing and new spatial modelling to identify, at the catchment scale, appropriate nature-based solutions to help reduce the effects of flooding and climate change on at-risk communities within Te Awa o Waitōtara (the Waitotara River catchment).	TBD
Tasman District Council *Hydrodynamic modelling of nature-based flood mitigation solutions – Motueka River, Tasman*	The project will utilise hydrodynamic modelling to evaluate a range of nature-based flood mitigation options aimed at reducing the risk of severe flooding in the Motueka River catchment. It will involve the consolidation of existing river models into a single catchment model, including extension into currently unmodelled areas.	Remediation of wetlands Land use change Reclamation of the floodplain Riparian corridor vegetation Pre-modification geomorphology
Waikato Regional Council *Understanding coastal wetland hydrology and the effects of extreme events on land-use transition and blue carbon storage*	This project aims to understand the role of costal wetland plant species in protecting adjacent farmland from extreme weather events and the sustainability of blue carbon storage credits through LiDAR data collection, waterway surveys and the development of a hydrodynamic model. The results of which will help understand the feasibility of land transition from farmland to coastal wetlands.	TBD
Waikato Regional Council *Waikato and Waipa River Nature Based Solutions Feasibility Investigations*	The project will undertake a feasibility study to understand the changes to peak flows through the Waipa and Waikato River catchments using existing hydrological models.	TBD

Applicant and project name	Project description	Nature-based solution options
Greater Wellington Regional Council *Feasibility assessment of nature-based solutions for addressing the flood risk in the Waipoua catchment, Masterton, Wairarapa*	This project will undertake a feasibility study that will assess and quantify the benefits of a suite of nature-based solutions (including mātauranga Māori practices) for managing risk under various flood event scenarios.	Re-establishment of wetlands Vegetative cover/afforestation Use of swales or bunds Land/soil management
West Coast Regional Council *Cobden Flood Attenuation and Wetland*	This project seeks to return the Cobden Domain to its previous state as a tidal lagoon with native habitat, and create upstream attenuation areas to reduce the impact of flooding on infrastructure and properties. The project includes establishment of project governance, data collection, hydraulic modelling, and feasibility design.	Topographical and drone survey Earthworks modelling
West Coast Regional Council *Multi-benefit approaches to building Westport's flood resilience*	Westport is recognised as one of Aotearoa's most flood -vulnerable communities and funding has been announced for structural flood protection of Westport's urban area. This project will investigate where there is opportunity for grey and green flood management infrastructure to work synergistically to achieve the best outcomes. Ministry funding will be used to identify candidate nature-based solutions and then undertake hydraulic modelling under various rainfall, sea level rise and climate change scenarios.	Storage of floodwaters Strategic revegetation Room for the rivers Reducing flood velocities Upstream planting of forest Biologically pumped tree swamp Land cover management

Appendix B Definition of NBS categories for flood mitigation

Table B-1: NBS defined for fluvial and pluvial flood mitigation (after van Zanten et al. 2021) Associated methods, functions, benefits, and suitability factors.

NBS categories	Methods	Process and functions	Benefits	Suitability factors
Retention and detention features	Vegetated gabions, Wattle fences, Slope changes and landscaping.	Pluvial flood regulation, soil erosion and landslide control; water quality control.	Flood, landslide, and erosion risk reduction Water quality and sediment management Resource production	Climate, soil, slope, and hydrology Construction methods and dimensions Existing land-use and applicability
Bioretention systems	Bioswales and raingardens, Detention and retention ponds.	Pluvial flood regulation, heat regulation, pollutant attenuation, infiltration.	Pluvial flood risk reduction Carbon storage and sequestration Biodiversity Water quality and sediment management	Climate, soil, slope, and hydrology Slope and substrate type Dimensions and existing infrastructure Plant assemblage planning
Landcover and soil management	Phytoremediation forests, Ecological forest corridors, Agroforestry, green corridors and green spaces	Intercept precipitation and recycle the water through evapotranspiration, root water uptake, and infiltration.	Pluvial and riverine flood risk reduction Heat stress risk reduction Resource production Human health Tourism, recreation, and economic benefits Carbon storage and sequestration Biodiversity	Climate, soil, slope, and hydrology Species selection and combinations Seedling and tree production Planting time and growing strategy
River naturalisation	Bank and bed renaturation, Stream daylighting, Bioengineering.	Pluvial and riverine flood regulation, heat regulation, pollution attenuation, erosion reduction.	Pluvial and riverine flood risk reduction Tourism, recreation, and economic benefits Human health Biodiversity Water quality and sediment management	Climate, soil, slope, and hydrology River dimensions Plant assemblages and growing strategy Natural resources and textiles available
Natural wetlands	Drainage, Improving lateral connectivity, Maintenance, and cleaning	Pluvial flood regulation, heat regulation, pollutant attenuation, groundwater recharge, slow water release, flood buffering.	Pluvial and riverine flood risk reduction Water quality and sediment management Biodiversity and resource production Carbon storage and sequestration Tourism, recreation, and economic benefits	Climate, soil, and hydrology Water sources, hydraulic connectivity, retention and cycling. Landscape integration Planting and growing strategy Existing infrastructure
Constructed wetlands	Surface constructed wetlands, Gravel wetlands, Floating wetlands.	Pluvial flood regulation, heat regulation, pollutant attenuation, groundwater recharge, slow water release, flood buffering.	Pluvial and riverine flood risk reduction Water quality and sediment management Biodiversity Resource production Carbon storage and sequestration Tourism, recreation, and economic benefits	Climate, soil, and hydrology Slope and landscape integration Planting and growing strategy Substrate and ecology choices.
River floodplain restoration and estuary management	Setting levees back, River bypass or oxbows, Re-activating river floodplains.	Riverine flood regulation, water quality and pollution attenuation, sediment management, river seasonality.	Pluvial and riverine flood risk reduction Water quality and sediment management Biodiversity Resource production Carbon storage and sequestration Tourism, recreation, and economic benefits	Climate, soil, and hydrology Floodplain profile, dimension, riverbanks, Planting and growing strategy

Appendix C Model types, NBS parameterisation, and uncertainty management

Table C-1: Parameters used to represent NBS options within different model types (after Environment Agency (UK))[31].

	Parameter to represent impact of each NBS type					Method to manage model uncertainty				
	Forest and tree-planting	**Surface runoff controls**	**Floodplain reconnection**	**Gully blocking**	**Soil structure improvement**	**Calibration**	**Scenario (parameter) test**	**Performance test**	**Resilience Test (extreme events)**	**Uncertainty Analysis**
Field survey only	Estimate upstream influence	Estimate storage from flood hydrograph data	Estimate storage from routing data	From flood risk maps and depth information	Estimate additional storage	None	None	Backwater calculation. Check culvert and upstream descriptors	None	Check culvert manual
1d physics-based cross-section analysis	Physics of increased frictional losses	None	Different shear stresses	Physics of frictional losses per cross-section	None	None	Sensitivity analysis of physics-based factors	Estimation of roughness and feed into hydrodynamic model	None	Useful for assessing frictional losses to more complex model
1D routing model with limited survey e.g., extracted from LiDAR	Reduce wave speed in routing model	Reduce inflow boundaries	Increase attenuation parameter in Muskingum unit	Increase attenuation parameter	Reduce inflow boundary	Compare with gauging data	Multiple return periods, real events, and parameter sensitivity analysis	If routing is simple such as KW or Muskingum, then only synchronisation can be tested	Modification of inflow boundaries	Care with simple routing units as key hydraulic effects cannot be modelled
1D hydrodynamic model with limited survey e.g., extracted from LiDAR	Increase overbank Manning's roughness	Reduce inflow boundaries, represent increased friction	Increase Storage Area capacity	Increased manning's or reduce inflows	Reduce inflow boundary	Compare with gauging data	Multiple return periods, real events + parameter sensitivity analysis	Can test all above, may require model domain extension	Modifications to inflow boundaries	May be worth building 2d model to estimate effect of culverts using screening approach. Use with uncertainty framework.
1D model and survey	Increase overbank Manning's roughness	Reduce inflow boundaries, represent increased friction	Modify lateral weirs and roughness overbank	Increased manning's roughness	Reduce inflow boundary	Compare with gauging data	Multiple return periods, real events + parameter sensitivity analysis	Can test all above, may require model domain extension	Modifications to inflow boundaries	May be worth building 2d model to estimate effect of culverts using screening approach. Use with uncertainty framework.
2d model (Tuflow/JFLOW/ISIS2d)	Increase distributed roughness and hydrological losses	Modify DTM to add storage	Modify DTM to add storage / roughness	Increase manning's or in-line storage	Modify losses: reduce rainfall inputs, increase infiltration, and surface roughness.	Compare with peak estimates; drive with real rainfall and losses.	Multiple return periods, real events + parameter sensitivity analysis	Can test all above, if 2d model permits culvert unit or some kind of equivalent	Create 2d rainfall fields using e.g. Theissen weighting or alternatives	Careful with sub-grid representation if use large cells - limits channel definition. Assess uncertainties e.g. GLUE.

[31] https://assets.publishing.service.gov.uk/media/6036b795e90e0740b33891e3/Working_with_natural_processes_using_the_evidence_base_appendix_1_flood_risk_matrix.xlsx

	Parameter to represent impact of each NBS type					Method to manage model uncertainty				
	Forest and tree-planting	Surface runoff controls	Floodplain reconnection	Gully blocking	Soil structure improvement	Calibration	Scenario (parameter) test	Performance test	Resilience Test (extreme events)	Uncertainty Analysis
2d model with intelligent sub-grid hydraulic properties (HEC-RAS 2d)	Increase distributed roughness and hydrological losses	Modify DTM to add storage	Modify DTM to add storage / roughness. Add / remove break-lines	Increase manning's or in-line storage	Modify losses: reduce rainfall inputs, increase infiltration, and surface roughness.	Compare with national flood estimates; drive with real rainfall	Multiple return periods, real events + parameter sensitivity analysis	Can test all above, if 2d model permits culvert unit or equivalent	Create 2d rainfall fields using e.g. Theissen weighting or alternatives	This type of model represents sub-grid detail in DTM through storing hydraulic properties of cell faces. Use e.g. GLUE
1d-2d linked model	Represent roughness in more detail in 2d areas and hydrological losses	Modify DTM to add storage	Modify DTM to add storage / roughness. Add / remove break-lines	Increase manning's or in-line storage	Modify losses: reduce rainfall inputs, increase infiltration, and surface roughness.	Compare with gauging data	Multiple return periods, real events + parameter sensitivity analysis	Can test all above	Create 2d rainfall fields using e.g. Theissen weighting or alternatives	Use with uncertainty framework like GLUE.
Lumped parameter catchment model (PDM, Catchmod, NAM, etc)	Changed maximum soil moisture, storage, Cmax, and quick flow time constants	Change time constants in linear cascade	Change time constants in linear cascade	Change time constants in linear cascade	Changes to Cmax	Compare with gauging data	Multiple return periods, real events + parameter sensitivity analysis	None	Theissen weighting and kriging of rainfall across domain	Use with uncertainty framework (GLUE)
Semi-distributed Hydrological model (e.g. Dynamic TOPMODEL, SWAT, HYPE)	Transmissivity, Wet Canopy Evaporation, Overland flow speed, Antecedent wetness.	Increase root-zone or other storage	Make more complex floodplain representation	Adjust wave speed and treat as time constant storage	Increase transmissivity	Compare with gauging data	Multiple return periods, real events + parameter sensitivity analysis	Synchronisation can be examined, backwater and culvert blockage require additional hydraulic routing model - diffusion wave	Theissen weighting and kriging of rainfall across domain	Use with uncertainty framework (GLUE)
Fully distributed model (e.g. MIKE SHE)	Transmissivity, Wet Canopy Evaporation, Overland flow speed, Antecedent wetness.	Increase root-zone or other storage	Link with detailed hydraulic model	Adjust wave speed and treat as time constant storage	Vary soil parameters	Compare with gauging data	Multiple return periods, real events + parameter sensitivity analysis	Link with detailed hydraulic model	Create 2d rainfall fields using e.g. Theissen weighting or alternatives.	Use with uncertainty framework (GLUE)

Appendix D Online resources and tools

Table D-1: Online resources and tools that can be used in development of NBS.

Auckland Design Manual Stormwater, WSUD2, Erosion control	https://www.aucklanddesignmanual.co.nz/regulations/technical-guidance
Benefits Estimation Tool Construction Industry Research and Information Association (CIRIA) (UK)	https://www.susdrain.org/resources/best.html
Benefits Cost Analysis Tool Excel-based tool for developing business case to deliver WSUD (Monash University).	https://shop.monash.edu/benefit-cost-analysis-tool.html
Catalogue of Natural Water Retention Measures European Commission project. Measures groups as agriculture, forest, hydro-morphology, and urban. Can be searched by required biophysical benefits.	http://nwrm.eu/index.php/measures-catalogue
CNT Green Values Stormwater management calculator tool	https://greenvalues.cnt.org/#calculate
Erosion and sediment control sizing tool (Auckland Council) – sediment and retention ponds and bunds sizing	https://tools.aucklandcouncil.govt.nz/erosion-sediment-control-device-sizing-tool/
Evidence base for natural flood management Environment Agency (UK)	https://prezi.com/view/0kkkS47snB1ah7gGMavN/
More Than Water WSUD assessment tool	https://www.landcareresearch.co.nz/WSUD/More-Than-Water.xlsx
Soakage Device Sizing Tool (Auckland Council) For rock-bores, stormwater and groundwater soak-pits	https://tools.aucklandcouncil.govt.nz/soakage-device-sizing-tool/#/
Stormwater Device Sizing Tool (Auckland Council) Retention and detention features, rainwater tanks, swales, check dams, and bioretention units.	https://tools.aucklandcouncil.govt.nz/storm-water-device-sizing-tool/#/
Rapid Assessment tool for Nature Based Solutions.	https://www.nature-basedsolutions.com/assessment
Resilient River Communities List of projects / case studies	https://www.resilientrivers.nz/projects-map
NBS Case Studies European Union	http://nwrm.eu/list-of-all-case-studies
Urban Forest Futures Talks Online	https://www.youtube.com/playlist?list=PLB292clS-IATNJqrJsdU5lTN2nKToxjaE

Appendix E Modelling within a DPIR framework

The Drivers-Pressure-State-Impact-Response framework (DPSIR) was first put forward by the OECD, Organisation For Economic Co-Operation and Development (1993) and has been adopted internationally by environmental reporting agencies (e.g., European Environment Agency, 1999; US Environment Protection Agency, 1995). The framework provides a simplified method of visualising the factors affecting environmental hazards and their interactions. This can aid communication and understanding of flood risk. The basic structure of the DPSIR framework with respect to rural and urban flooding are shown in Figure E-1, however, the identified factors will vary by location and flood phenomena. A more complex version that considers the interaction between water quality and water quantity is shown for stormwater in Figure E-2.

There have been several examples of flood modelling within a DPSIR framework in recent years. Karimi Sangchini et al. (2022) used the DPSIR framework to prioritise the driving forces and pressures in a flood prone catchment in Iran and to evaluate the efficacy of flood risk management in the catchment. Fang et al. (2023) coupled a flood model with a traffic model to assess the performance and resilience of the transport network in Shanghai, China, under severe rainfall and flood conditions. Hammond et al. (2018) developed a modified version of the DPSIR framework to help policy makers to evaluate strategies for improving flood management in urban areas. They found that while the framework was an effective approach for assessing and improving urban flood resilience, there are challenges, particularly in large cities, due to the complexity of urban systems. Kaur et al. (2020) used the framework to evaluate the effects of urban densification on buried urban drainage infrastructure with respect to urban water services (i.e., water supply, wastewater and stormwater management).

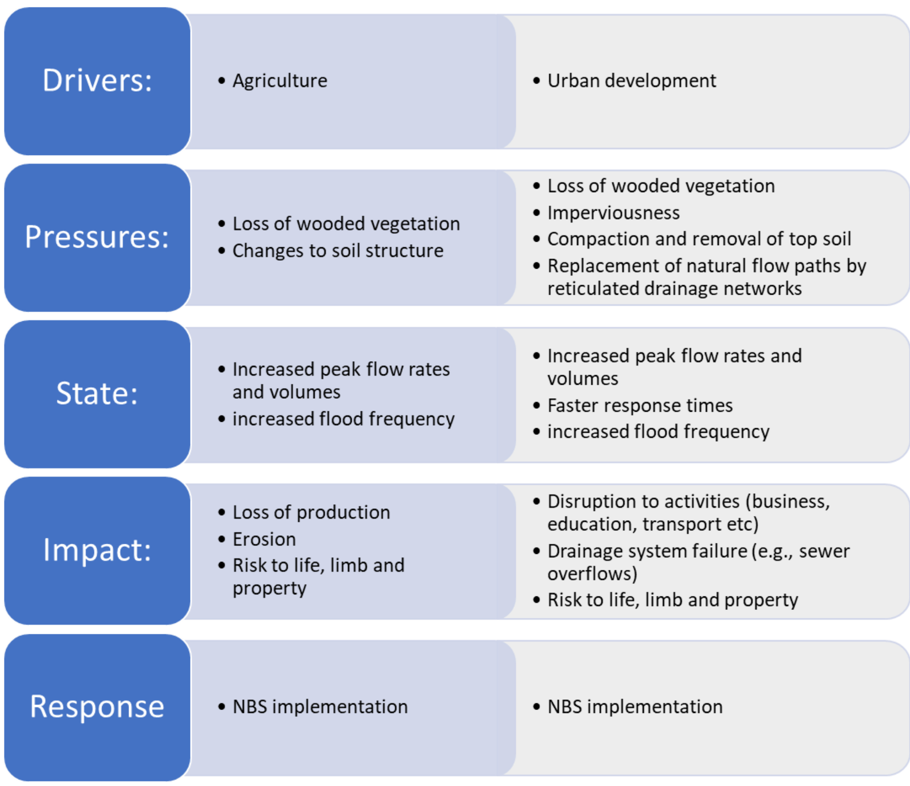

Figure E-1: Basic DPSIR frameworks for rural and urban flood rick assessment.

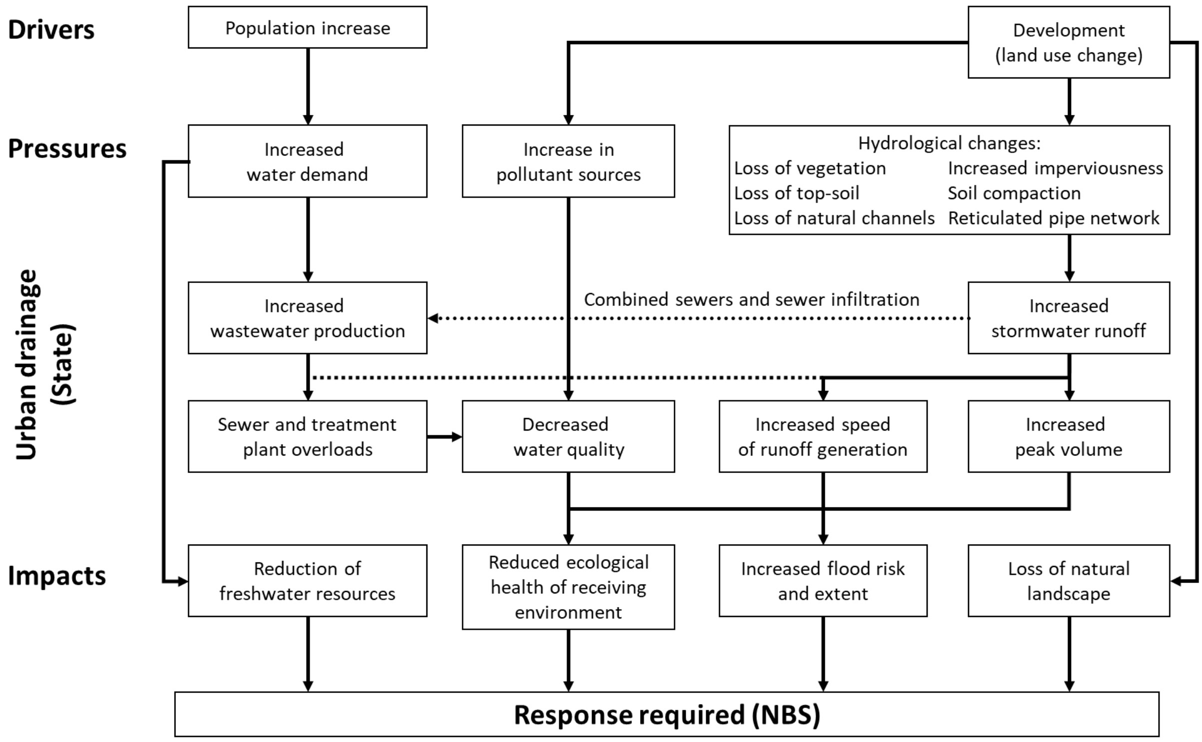

Figure E-2: DPSIR framework for urban drainage showing interaction between water quality and water quantity.