Assessing the potential for flood risk mitigation and salmon habitat restoration in the Lower Fraser

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Disclaimer

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Executive Summary

Soaring flood damages and inadequate infrastructure have created a crisis of unaffordable inundation in BC, undermining the right to a safe environment, driving people into distress and financial debt, and disproportionately affecting socially and economically marginalized people. In response to this challenge, under the Dike Maintenance Act, the BC government and regional alliance organizations recognize the responsibility to realign the strategy toward meeting provincial obligations for flood protection and safety, as well as planning for flood management through sustainable alternatives that ensure equal and affordable access to natural resources to various communities in the region. Hence, a movement has begun to shift away from traditional dike-based flood control and toward more sustainable nature-based solutions.

In contrast to the diking infrastructure, nature-based solutions (NBS) restore, retain, or enhance natural hydrological processes at a site or in a watershed, resulting to lower downstream flood peaks while providing numerous valuable ecosystem services. NBS is becoming increasingly popular due to its incredible versatility; it can be installed as completely 'green,' using only natural elements, or as a 'hybrid,' using a combination of natural elements and engineering structures. In addition, the cost of NBS construction and maintenance is significantly lower, making it a preferred choice over other options. Examples of NBS include tree planting, wetlands, riparian forests, setback dikes, and others. Previously, the successful implementation of NBS include the Dutch program 'Room for the River' and the Washington State project 'Floodplains by Design.' These observations pique intellectual curiosity about the steps involved in implementing NBS-based flood management and their suitability for Lower Fraser conditions. NBS appears to be a viable option to deal with the risk of increasing floods and disconnected floodplains from rivers. A key question regarding the NBS implementation is, therefore, whether the scientific evidence on decreased flood peaks is sufficiently reliable to steer the transition towards nature-based alternatives. In this regard, we aim to review scientific literature on NBS from the previous five years on NBS and examine if the various NBS measures can be used to cope with increasing flood risk in terms of water storage, peak discharge reduction, reconnecting floodplain, and other relevant attributes. Besides flood control, we intend to document NBS co-benefits that are particularly beneficial to indigenous communities and healthy ecosystems.

There are three main findings of this review are as follows:

1. Wetland and stream restoration, in particular, has been shown to reconnect floodplains and lower peak flows. However, because flood risk reduction is assessed using a range of

methods/approaches and the results are presented in a variety of metrics, it is challenging to compare claimed water storage capacity of nature-based solutions.

2. NBS is favored over conventional diking infrastructures because it offers a variety of ecosystem benefits such water purification, salmon habitat, wildlife preservation, carbon sequestration, and educational and recreational opportunities for local communities.
3. At the watershed level, a single nature-based infrastructure would be insufficient to address flooding problems; therefore, a suite of measures installed along hydrologic flow paths in the form of "treatment trains" are more likely to be successful.

Introduction

In 2021, November flooding in BC was the world's fifth most expensive climate disaster of the year, as well as the most expensive disaster in Canadian history (Kramer and Ware, 2021). These floods are the result of an atmospheric river that brought intense rainfall across southern BC, resulting in evacuations and property damage totaling $7.5 billion (Logan, 2021). This loss is not going to stop any time soon; climate-related risks to British Columbians are increasing and are expected to increase fivefold by 2050. Increased awareness of these issues has raised concerns about uncertainty in intensity and frequency of weather events, drawing our attention towards tipping point thresholds for existing flood control infrastructure in BC.

By far, flooding is one of the most common and costly natural disasters in BC, with the Lower Mainland particularly vulnerable to the direct or indirect effects of Fraser River flooding. Historically, all Lower Mainland communities have relied heavily on dikes and floodgates as primary means of structural flood protection. There are 200 regulated dikes and 400 flood boxes in BC which protect 160, 000 ha of valuable land and natural assets (Govt. of British Columbia, 2022). Although valuable, the majority of this infrastructure is reported to be old, inadequate, and undersized, requiring urgent upgrades to withstand climate-induced flood risks. According to recent reports, required flood control upgrades in seven BC communities are expected to cost over $2.6 billion in dike maintenance and flood protection to meet modern-flood standards and to account for climate changes (Hoekstra, 2021). Furthermore, existing diking infrastructure is responsible for cutting off 85% of the floodplain and 64% of the streams in that floodplain, resulting in significant losses for ecosystem connectivity and salmon population in the region (Finn et al., 2021). Clearly a new approach to flood management is required in this region.

Around the world, a popular alternative to traditional flood control focuses on reconnecting floodplains to rivers via a set of non-structural, sustainable measures known as Nature-based solutions (NBS). Typical examples of large-scale riverain NBS include bypass channels, setback dikes, large retention basins, lakes, wetlands, riparian forests, terraces, etc. Mangroves, mudflats, dunes, beach nourishment, and coral reefs are some examples of coastal NBS. Primarily, NBS mimic natural hydrological processes, allows water retention and percolation, leading to reduce floodwater depth, flood extent, and flood duration. They could also offer a variety of co-benefits by improving biodiversity, habitat characteristics, water chemistry variables, amenity, aesthetics, recreation, and human well-being. Successful examples of these measures have been shown in Dutch's Program, 'Room for the River' and Washington State's projects, 'Floodplains by Design'. Our main challenge now is to better understand the steps involved in implementing NBS-based flood management and adapt these measures to the Lower Fraser conditions.

Given the aforementioned flood control priorities, this report examines some of the key NBS that have the potential to alleviate the long-term problem of rising flood heights and reconnect floodplains to rivers. It also discusses the co-benefits and challenges of implementing a specific NBS. In the long run, these findings advance the research in burgeoning field of nature-based flood management in BC and assist decision-makers in taking appropriate steps toward sustainability. Furthermore, this work is unique in that it highlights the benefits of reconnecting floodplains through the lens of ecosystem services and First Nations, who are increasingly concerned about Fraser freshet flooding and loss of salmon population.

Research Approach and Results

In light of the goals of this study, literature searches on floodplain reconnection were conducted in ISI Web of Science over the last five years, from 2016 to 2022. Initial searches were done by combining the terms "floodplain reconnection" and "flood risk reduction" into one search string. The first field included keywords denoting common synonyms/ floodplain reconnection (“Floodplain restoration”, “River restoration”, and “River training”). The second topic field specified the terms related to floods (“flood retention”, “peak flow reduction”, “flood flows”, “flood mitigation”, and “flood frequency”). The initial pool of candidate studies included any studies that seemed to be pertinent to the reconnecting of the floodplain and the decrease of flood risk. After that, all of the studies were evaluated for eligibility using the following criteria:

Later, all the studies were assessed for eligibility based on the following criteria:

1. The study should provide details on the floodplain reconnection intervention;
2. It should provide estimates of the reduction in flood risk or change in flow regime;
3. The study may take any form, such as an experimental setup, literature review, or scenario-based modeling.
4. The study can be from anywhere in the world, with no geographical restrictions;
5. The study should be described in English; and
6. The study should be published in a peer-reviewed scientific publication.

The initial identification and removal of duplicate records resulted in a set of 30 articles. The identified articles were then screened to ensure they met the criteria. A single reviewer reviewed the titles, keywords, and abstracts to select the articles. Finally, only 24 articles were chosen for analysis. For data collection, all articles that met the eligibility criteria were collected in full-text PDF format and kept in a separate folder. The reviewer compiled information on ten characteristics from each of the selected studies, including location, scale, study approach, intervention employed, impacts on flood level reduction, contributory factors, co-benefits, and challenges.

The records from the selected articles revealed that among the various NBS, wetland restoration and water storage infrastructures are the most common (n=6) intervention used to improve floodplain connectivity. Stream restoration through natural channel design and vegetation development in floodplains has also yielded promising results in reconnecting floodplains and lowering flood levels. Research also supports the effects of levee setback and removal, which are said to have a favorable relationship with both the reduction of flood risk and the restoration of habitat. The details of each of these interventions are given in Table 1.

Table 1. A summary of the literature review and impacts of NBS on flood risk reduction.

Reference	Location	Scale	Study Approach	Intervention used
Hovis et al., 2021	North Carolina	Coastal Plain	Literature review	Wetland Restoration
Impacts on flood level reduction		A wetland built solely for flood storage is typically faster, and it can delay floodwaters and reduce downstream flow, resulting in a lower peak flood height. Restoring wetlands with herbaceous vegetation adds coarseness to the water, reducing stream velocity and sedimentation.		
Contributing factors		The impact of wetlands on flooding is determined by a variety of factors, including the location of the wetlands in the landscape, the surrounding topography, type of vegetation, and management decisions. The restoration time for a wetland varies; a wetland with marsh vegetation may take three to four years, whereas forests may take 30 years or more.		
Co-benefits		Wetland grasses and sedges have fast-growing and dense root systems that help capture pollutants and serve as important wildlife habitat. Wetlands also sustain biodiversity, sequester carbon, improve water quality, improve downstream aquatic habitat, recharge aquifers, and provide storm protection.		
Challenges		Restoration of wetlands is difficult. For example, not all landowners are always enthusiastic about it. A landowner may be permanently barred from using a portion of their land for uses other than recreation by designating that portion of the land for wetland restoration. The North Carolina Wetlands Restoration Program (NCWRP) advises collaborating with landowners to develop a thorough study of the watershed and topography for wetland decision-making and implementation in order to avoid some of these difficulties. Due to poor designs, inappropriate site selection, and a lack of maintenance follow-up, restored wetlands might not function as intended. It is important to be aware that the Dike Maintenance Act or other current regulations may make it difficult for communities to adopt these solutions.		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Bezak et al., 2021	Glinscica river catchment, Slovenia	River catchment	Case study	Wetland Retention Reservoir (Podutik)
Impacts on flood level reduction		The effect of the wet retention reservoir is smaller, with peak discharge reductions of around 30% and 5% for the 2- and 25-year return periods, respectively.		

Contributing factors		xxx		
Co-benefits		Wet retention reservoirs are well-known for their numerous benefits, including improved in-stream self-purification processes, increased biodiversity, recreation, and education. Water from retention reservoirs can also be used for a variety of purposes, including irrigation, resulting in more sustainable water management.		
Challenges		Retention reservoirs that are dry or wet can have major local effects but may not have much of an influence on broader scales.		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Wu et al., 2020	Duobukuli River Basin	River Basin	PHYSITEL/HYDROTEL modelling and simulation scenarios	Wetlands
Impacts on flood level reduction		Wetlands have a significant impact on basin hydrological processes by decreasing streamflow and changing the flow regime. Wetlands significantly reduced quick flow during flood season while slightly supporting daily, monthly, and annual baseflow. Wetlands' average quick flow attenuation and baseflow support were 5.89% and 0.83%, respectively.		
Contributing factors		xxx		
Co-benefits		xxx		
Challenges		xxx		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Kadykalo et al., 2016	xxx	Wetlands and their influence on flow	Meta-Analysis	Wetlands
Impacts on flood level reduction		Wetlands, on average, reduce the frequency and magnitude of floods while increasing flood return period, augmenting low flows and decreasing runoff and streamflow.		
Contributing factors		The variation in wetland drainage is affected by location. When compared to downstream wetlands, upstream wetlands are likely better suited to immediately (but temporarily) store floodwaters. However, in the absence of detailed site-specific information, estimates of the flow regulation services provided by wetlands, as well as any associated estimate of their economic value, will be subject to significant uncertainty.		
Co-benefits		xxx		

Challenges		xxx		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Spyrou et al., 2021	Central Greece	River basin	A series of hydrological and groundwater simulations via 1) the TUFLOW (hydraulic model and (2) the MIKE-SHE models.	Flood storage reservoir in combination with nature-based solutions (NBS)
Impacts on flood level reduction		The maximum depth of flooding remained constant (12.28 m) and occurred in the same location for this intervention. Following the addition of the NBS, the mean depth decreased from 1.27 to 1.24 m. Without and with the NBS, the flooded area was 35.28 km2 and 34.94 km2, respectively. The greatest flood depth reduction occurred immediately downstream of the NBS, with a maximum flood depth reduction of 0.45 m. The NBS made the three residential villages less prone to flooding. The NBS had a minor effect on groundwater storage, which increased to 125.9 mm from 125.5 mm for the simulated time period. Overall, the presence of NBS reduces the maximum depth of flooding, the maximum velocity, and the flooded area.		
Contributing factors		xxx		
Co-benefits		In all climate change simulations, the NBS reduced flood depth. The NBS caused only a minor change in velocity, indicating that it did not increase the risk of erosion. The NBS functioned as a stilling basin for the flow approaching the upstream structure. The mean spatially-averaged annual actual evapotranspiration without the NBS was 561.6 mm, while it was 564.8 mm with the NBS.		
Challenges		xxx		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Bezak et al., 2021	Glinsica river catchment, Slovenia	River catchment	Case study	Afforestation and the use of wet retention reservoirs
Impacts on flood level reduction		Using retention reservoirs rather than afforestation can result in a more significant reduction in flood risk. Although dry and wet retention reservoirs may provide greater peak discharge reductions, the results show that reservoir effects diminish rapidly with scale.		
Contributing factors		The availability of suitable locations and the scale of the reservoirs both contribute to the performance of dry and wet retention reservoirs. Cost-effective reservoirs could be implemented.		

Co-benefits		xxx		
Challenges		xxx		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Bezak et al., 2021	Glinsica river catchment, Slovenia	River catchment	Case study	Afforestation
Impacts on flood level reduction		Peak discharge reductions from afforesting floodplains as a flood risk management option were relatively small (i.e., less than 15%) for all three tested return periods.		
Contributing factors		xxx		
Co-benefits		Afforestation can be employed as a supplement due to the numerous ecosystems benefits that trees can offer.		
Challenges		In the case of afforestation, substantial areas are needed to achieve a noticeable reduction in peak discharge. Given their potential for multifunctionality and multiple uses, afforestation measures could come at a rather high cost, perhaps even exceeding their potential advantages.		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Kurki-Fox et al., 2022	Neuse River Basin of eastern North Carolina	Two sub watersheds of the river basin	Hydrologic modelling	Natural Infrastructure (NI) such as afforestation water farming, and flood control wetlands
Impacts on flood level reduction		Extrapolation of reductions to other sub watersheds resulted in a 4.4% reduction in peak flow for the 100-year storm at the river basin's outlet in Kinston as a result of 1.1% water farming, 5.7% wetlands controlling runoff, and 8.4% afforestation of the river basin.		
Contributing factors		For two sub watersheds in the lower portion of the basin, where there is less development and flatter land slopes, NI opportunity was greater, and associated modelled peak flow reductions were larger. Peak flow reductions varied spatially depending on the type and location of NI as well as the hydraulic and morphologic properties of the stream network. Peak flow reductions varied spatially depending on the type and location of NI as well as the hydraulic and morphologic properties of the stream network.		
Co-benefits		xxx		
Challenges		xxx		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Ahilan	Johnson Creek,	Urban creek	Hydro-morphodynamic	Restored floodplain

et al., 2018	the East Lents reach,		modelling	
Impacts on flood level reduction		According to simulation results, the restored floodplain reduces the upstream flood peak by up to 25% at the downstream.		
Contributing factors		Deposited sediment over the simulated period (1941-2014) accounts for approximately 0.1% of the basin's flood storage capacity; however, the reduction in storage does not compensate for the flood basin's overall flood resilience impact.		
Co-benefits		xxx		
Challenges		xxx		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Wyżga et al., 2018	Upper Vistula Basin, Poland	River basin	Literature review	An erodible river corridor as a river restoration measure
Impacts on flood level reduction		The peak discharge of the flood in the erodible corridor reach was 15% lower. The flow area in the river cross-section shown was 43% larger, indicating that the unmanaged channel had greater hydraulic roughness. As a result, the mean flow velocity at the flood peak was significantly lower, at 2.88 m/s. With the development of wooded islands in the widened, unmanaged channel in later years, the retention potential of the erodible corridor reach may significantly increase.		
Contributing factors		xxx		
Co-benefits		xxx		
Challenges		xxx		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Hovis et al., 2021	North Carolina	Coastal Plain	Literature review	Stream restoration via Natural Channel Design (NCD)
Impacts on flood level reduction		Rather than straightening stream channels in a watershed, restoring them to their natural meandering path can reduce high-water velocity and downstream flooding.		
Contributing factors		NCD also calls for planting riparian vegetation, which can stabilize the stream bank, slow down runoff, and remove pollutants. The establishment of sequenced riffles and pools maintains the channel's slope and stability. Water flows over the riffles at low flow, removing fine sediments and providing oxygen to the stream.		
Co-benefits				

		Water quality and wildlife habitats are improved by NCD. Re-meandering stream channels and increasing riparian vegetation, for instance, were positively connected to indices of habitat quality. Beyond flood mitigation, the ecosystem services offered by wetlands and streams can also reduce erosion, farm pesticide and herbicide pollution, animal or human waste in the water, improve fish and shellfish habitat, and improve drinking water quality.		
Challenges		The use of stream NCDs is expensive and has a minimal impact on flooding. In a recent stream restoration project, the Department of Biological and Agricultural Engineering at NC State University projected that practice establishment would cost around USD 738 per meter. In a 1997–2006 cost assessment of stream restoration projects conducted by the North Carolina Department of Environment and Natural Resources, it was found that the procedure cost, on average, USD 794 per meter. Additionally, substantial collaboration with federal and state regulatory organizations will be needed to get the required permits before changing a stream channel. As a result, this procedure can take a long time.		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
McMillan et al., 2017	Charlotte, North Carolina, The USA	Urban stream	Data collection followed by regression modelling	Urban stream restoration via Natural Channel Design (NCD)
Impacts on flood level reduction		In this study of restored urban stream-floodplain systems, we showed that continuous gradients of connectivity between the stream and floodplain influenced dissolved nutrient and sediment loading to the floodplain and subsequent nutrient transformations. NCD approaches slow down water velocity and spread floodwaters across the floodplain, potentially reducing the magnitude of downstream flooding.		
Contributing factors		The potential for effectively trapping sediment, nutrients, and associated pollutants is greater when restoration sites are located downstream of sources of impairment (e.g., eroding stream banks). The age of restoration stream was also a significant control on nutrient transformations, implying that as systems become more established with increasingly stable and robust vegetation, the quality and quantity of soil carbon increases, accelerating microbial activity. Organic matter and nutrient content in floodplain soils increased with time since restoration, emphasizing the importance of the recovery time required for restored systems to increase ecosystem functions.		
Co-benefits		xxx		
Challenges		xxx		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**

Walczak et al., 2018	Jeziorsko reservoir,Warta River, Poland	River floodplain	Data collection followed by scenario analysis	The development of floodplain vegetation (willow shrubs); change in diameter (vegetation grew on a cultivation plot) when density remained constant and the inverse model when there is uncontrolled growth of vegetation.
Impacts on flood level reduction		The shrub development to flow reduction could reach 45% if the only factor considered was the increase in diameter (at a constant density), and up to 70% if the density of vegetation increased.		
Contributing factors		Increases in average diameter and density, as measured by the average distance between branches, both have a significant impact on flow reduction.		
Co-benefits		xxx		
Challenges		xxx		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Long et al., 2022	My Tho City, Vietnam	Riverine urban area along the Mekong River	Case study	Ecological infrastructure (EI)
Impacts on flood level reduction		EI in delta cities is primarily based on a landscape system that connects land and water, including riparian ecological corridors, wetlands, rivers, and canals. The health of riparian ecosystems will determine EI's ability to play a role in flood adaptation and riparian ecosystem restoration. EI should be regarded as an effective and necessary design tool for the preservation of riparian ecological corridors and public open spaces, which is a significant challenge for urban areas in the context of increasing climate change impacts.		
Contributing factors		xxx		
Co-benefits		EI are crucial to the control of flooding, the preservation of wildlife, and tourism.		
Challenges		xxx		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Gunnell et al., 2019	Central Greece	Upstream watersheds	WaterWorld model	Natural infrastructure
Impacts on flood level reduction		The majority of city upstream basins rely heavily on green natural storage, which is primarily driven by canopy cover but also by soil storage. Because of the inclination toward green storage, major		

		sources of landscape level water storage are vulnerable to modification or removal, leaving cities vulnerable to increased flood risk.		
Contributing factors		The 'roughness' of the floodplain can also affect the rate of flow (known as conveyance), so the more 'rough' or disrupted the floodplain, the slower the runoff. Riparian woodlands and wetland vegetation provide important flood regulation services by acting as a roughness element to surface water flow, slowing it down and helping to prevent it from entering the channel too quickly, as well as through vegetation's normal evapotranspiration processes. During flood conditions, riparian zones also help to store water on upstream floodplains, reducing downstream impacts.		
Co-benefits		xxx		
Challenges		xxx		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Suttles et al., 2021	xxx	Natural infrastructure in upstream agricultural landscapes	Literature review	Natural infrastructure in upstream agricultural landscapes
Impacts on flood level reduction		The restoration of depressional wetlands and floodplains appears promising for both improving water quality and reducing flood risk. Depressional wetlands, floodplain restoration, cropland conversion to native vegetation-forest, and farm ponds are all likely to have a Medium to High impact on flood risk.		
Contributing factors		xxx		
Co-benefits		xxx		
Challenges		A single infrastructure would not yield the needed reduction in flood risk for large-scale installation.		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Hamed et al., 2021	xxx	Urban river	Literature review	Human-nature interactions at urban river sites
Impacts on flood level reduction		The research identified six key tenets for developing guidelines for Human-River Encounter Sites: health, safety, functionality, accessibility, collaboration, and awareness. The researchers present how these tenets can work together to balance the needs of citizens and biota, as well as to alleviate the current urban river crisis.		
Contributing factors		xxx		

Co-benefits	River corridors promote natural ecosystems and high-quality biodiversity because of their provisioning functions. In England's Norfolk River Wensum, for instance, 31 aquatic plant species and target fish species like bullhead and brown trout were detected after the meander loop was restored after a year. Reduce the existing risk of flooding for the locals by allowing flooding processes to take place as naturally as is doable within a specific scale. Urban river corridors benefit people on a cultural, educational, recreational, and aesthetic level.
Challenges	Rather than emphasizing functionality, many urban restoration projects concentrate on form. In order to boost recreational opportunities without recreating almost natural riparian and floodplain regions and processes, they attempt to green the floodplain by constructing parks. As a result, restoration efforts provide only modest benefits, and fragile native species might not recover. Even though cultural ecosystem services, such as recreation, serve vital societal purposes, they may conflict with other environmental functions, such as the maintenance of functional habitats for vulnerable species. For instance, restoring urban rivers may rebuild habitats for threatened species, but frequent recreational use may impair those species' chances of recovering. It is definitely beneficial to create green spaces along rivers to offer leisure places and ensure ecological corridors. However, necessary steps should be taken to balance accessibility for humans and biota rather than conflate these two goals. Additionally, the impact of light on biota in cities is extremely detrimental, particularly to the emergence of water insects. Although midnight lights might disrupt or even kill nocturnal birds, this issue has not yet been fully considered. Even though they are rare, invasive species are one downside of enhanced habitat connectivity.

Reference	Location	Scale	Study Approach	Intervention used
Nicholson et al., 2020	Belford Burn catchment, Northern England	Catchment scale	Experimental setup and modelling	Catchment-wide runoff attenuation features (RAFs), in-particular offline storage areas, as a means of mitigating peak flow magnitudes in flood-causing events.
Impacts on flood level reduction		Peak flow can be reduced by more than 30% at downstream.		
Contributing factors		xxx		
Co-benefits		xxx		
Challenges		xxx		

Reference	Location	Scale	Study Approach	Intervention used
Kabeja et al., 2020	Yanhe and Guangyuan, China	Two mountainous catchments	Used a series of Landsat images followed by hydrologic modelling	Changes in landuse and land cover (LULC)
Impacts on flood level reduction		In Yanhe, forest and urban land increased by 18% and 2%, respectively, while in Guangyuan, they increased by 16% and 8%. In contrast, agricultural land in Yanhe and Guangyuan decreased by about 30% and 24%, respectively.		
Contributing factors		xxx		
Co-benefits		xxx		
Challenges		xxx		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Guida et al., 2016	Illinois River, The USA	River floodplain	A novel hydrodynamic, geospatial, economic, and habitat suitability framework is used.	Levee setbacks and removals
Impacts on flood level reduction		Flood heights and environmental benefits are maximized at the highest costs through the most aggressive levee setbacks and removals. The middle and upstream districts are reconnected under the 1000-m scenario, which is the most favorable scenario for prioritizing flood reduction and habitat, because the districts in the middle and upstream reaches have the greatest potential habitat benefits.		
Contributing factors		xxx		
Co-benefits		xxx		
Challenges		Although the "no levees" scenario improves marsh habitat the most, it also causes the most harm, amounting to $90.1 million annually. Costs for carrying out extensive strategic floodplain reconnection estimate from $1.2-$4.3 billion.		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Serra-Llobet et al., 2022	Elbe River, Germany	River floodplain	Project-based followed by data analysis and project evaluation	Levee Setback
Impacts on flood level reduction		The levee setback provided a nearly 50 cm local decrease in flood peak level, and its impact on a city 25km upstream aided in the promotion of levee setbacks on a national scale.		

Contributing factors		xxx		
Co-benefits		The area that was reforested by the previous LIFE-project now includes around 80 ha of floodplain forest as a result of the initiative. In addition, 45 ha of shallow waterbodies were dug up to provide levee construction materials to restore aquatic and semiaquatic habitat. Numerous waterfowl and other bird species have returned, as well as a wide variety of habitat types, according to investigations into the project's performance.		
Challenges		xxx		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Serra-Llobet et al., 2022	Bear River, California, The US	River floodplain	Project-based followed by data analysis and project evaluation	Levee Setback
Impacts on flood level reduction		To reconnect 240 ha of floodplain habitat, nearly 3 km of levee along the Bear River and a levee along the Feather River at the confluence were set back. This design increased conveyance and is expected to reduce flood risk along the lower Bear River by 1 m during major floods.		
Contributing factors		The majority of the project area was allowed to grow into forest, but to ensure that the target conveyance is maintained throughout the project, a portion of the setback area was kept as grassland with low hydraulic roughness.		
Co-benefits		xxx		
Challenges		Hydraulic modelling shows that the majority of the reconnecting floodplain in the Bear River leeves setback project would only be submerged during a 2-year flood, preventing it from providing the regular, prolonged inundated habitat that has proven crucial for native fish.		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Serra-Llobet et al., 2022	Yolo Bypass, California, The US	River floodplain	Project-based followed by data analysis and project evaluation	Yolo Bypass, California is a 66 km long, 4.8 km wide area of floodplain now bounded by levees.
Impacts on flood level reduction		The Yolo Bypass protects Sacramento from flooding by allowing up to 14,000 m3/s of Sacramento River flow, which is four times the capacity of the mainstem river channel as it passes Sacramento.		
Contributing factors		xxx		

Co-benefits		When the floodplain bypass is flooded, adult salmon use it to move upstream to breeding sites, and juvenile salmon successfully use it for rearing throughout downstream migration to the Delta and Pacific Ocean. It has been discovered that regulated inundation of some of the bypass during dry years with minor floods can offer comparable rearing habitat conditions and matching similar growth rates to those observed during actual flood circumstances. Additionally, the Yolo Bypass Wildlife Area offers possibilities for both education (school visits) and leisure (bird watching and hunting). For both environmental and flood risk management, the Yolo Bypass is unquestionably a "win-win" situation. National media attention was given to the Yolo Bypass Wildlife Area Restoration project as a prototype for team-based restoration.		
Challenges		xxx		
Reference	**Location**	**Scale**	**Study Approach**	**Intervention used**
Wyżga et al., 2019	Upper Vistula Basin, Poland	River basin	Literature review	Construction of boulder ramps: Not only are such ramps passable for fish, but they also appeared highly efficient in entrapment of the material flushed out from the lowered check dam.
Impacts on flood level reduction		Water begins to be retained in the floodplain at lower flood discharges due to the entrapment of bed material following the construction of boulder ramps, and the retention potential at given discharges is significantly greater than in the former, deeply incised channel.		
Contributing factors				
Co-benefits		xxx		
Challenges		xxx		

Based on a review of selected studies, the following conclusions are reached about the impacts of NBS on flood risk reduction and ecosystem:

1. There is concrete evidence that NBS, particularly wetland and stream restoration, help reconnect flood plains and reduce peak flows. However, it is difficult to compare reported water storage capacity of nature-based solutions because flood risk reduction is measured using a variety of methods/approaches and the results are reported in a variety of metrics.
2. In comparison to traditional diking infrastructures, NBS is preferred because it provides a wide range of ecosystem benefits such as water purification, salmon habitat, wildlife preservation, carbon sequestration, and educational and community recreation opportunities.
3. At the watershed level, a single nature-based infrastructure would be insufficient to address flooding problems; therefore, a suite of measures installed along hydrologic flow paths in the form of "treatment trains" are more likely to be successful.
4. The main challenges to the effectiveness of NBS include the need for large areas for these installations, a lack of interest on the part of landowners, and the possibility that societal and recreational uses will conflict with the ecological functions of these infrastructures.

Future Actions

1. To assess the water storage capacity of multiple NBS, it is necessary to explore and identify methodological relationships among various models, as well as to facilitate the interconversion of various metrics. Since the current studies vary in terms of size and type of NBS, it is important to standardize these estimates as per unit area and at a given location.
2. Because the implementation of NBS involves a wide range of stakeholders with competing interests, guidelines for stakeholder participation and collaborative decision-making would enhance the benefits of NBS projects at both the local and national levels.
3. To ensure that NBS fulfil their ecological and societal purposes, it is necessary to develop integrated decision-making tools that rank different NBS in accordance with conflicting interests.

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