CDRI
Coalition for Disaster Resilient Infrastructure

Global Infrastructure
Resilience Working Paper

Nature-based Solutions

Partnering with the Environment

GIR NbS
2025 WORKING PAPER

This work is a product of the Coalition for Disaster Resilient Infrastructure (CDRI), as part of a working paper series under the ambit of the second Global Infrastructure Resilience Report (GIR 2025). This Working Paper on *Nature-based Solutions: Partnering with the Environment*, explores how Nature-based Solutions (NbS) can strengthen infrastructure resilience through hybrid approaches. It examines the key challenges associated with scaling, financing, and implementing NbS, while highlighting practical pathways for integrating these solutions into infrastructure planning, development, and post-disaster recovery efforts. It may be accessed at https://cdri.world/resilience-dividend/global-infrastructure-resilience-report-second-edition/.

This document is a launch edition and may undergo minor changes subject to updates in the analysis.

All papers under the GIR 2025 Working Paper Series are available on the CDRI website, accessible on the web link mentioned above. They provide detailed background material, methodologies, analyses, and case studies for each chapter of the report. The papers will be released sequentially starting November 2025 through 2026.

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Contents

List of Figures

List of Tables

Acronyms

ANR	Assisted Natural Regeneration
CDRI	Coalition for Disaster Resilient Infrastructure
CEDR	Conference of European Directors of Roads
CRIO	Climate-Resilient Infrastructure Officer
FEBA	Friends of Ecosystem-Based Adaptation
FORIN	Forensic Investigations of Disaster
GIR	Global Infrastructure Resilience
GRI	Global Resilience Index
IISD	International Institute for Sustainable Development
IUCN	International Union for Conservation of Nature
LMICs	Low- and Middle-Income Countries
LID	Low-Impact Development
LSF	Living Snow Fence
MnDOT	Minnesota Department of Transportation
MOOC	Massive Open Online Course
NbS	Nature-based Solutions
PFES	Payments for Forest Environmental Services
PPP	Public–Private Partnership
SAVi	Sustainable Asset Valuation
UNDP	United Nations Development Programme
WBCSD	World Business Council for Sustainable Development

Key Messages

Working with nature as an ally, rather than against it, is a core principle of nature-based solutions (NbS) for resilient infrastructure.

There is no strict definition of what constitutes NbS for infrastructure resilience. Hybrid solutions that combine grey, green, and blue approaches may maximize infrastructure resilience against climate and disaster risks. They combine the predictability and protective capacity of engineered infrastructure with the adaptability, regenerative qualities, and multiple co-benefits of natural systems. Policy and governance frameworks set the 'rules of the game' for infrastructure agencies, determining whether NbS move from pilot initiatives to mainstream infrastructure practice. Embedding NbS in master plans, sectoral strategies, and concession agreements ensures that they are considered from the outset of infrastructure planning rather than treated as optional add-ons.

To institutionalize the implementation of NbS at scale, infrastructure agencies should adopt integrated cost-benefit tools, update procurement guidelines, and standardize technical guidance and design manuals. The availability of adequate financial resources and well-designed financing instruments is essential for scaling up the use of NbS. Instruments such as blended finance, public-private partnerships (PPPs), and performance-based contracts can align incentives between public and private actors.

To mainstream NbS, infrastructure agencies need to acquire technical expertise in ecology and related disciplines alongside traditional engineering capabilities. In addition, the development of effective NbS requires engagement across multiple sectors—including water, biology, transport, environment, and disaster risk management—as well as collaboration with diverse stakeholders, including local communities and indigenous groups.

There are significant cost differences between grey resilience solutions and NbS. In many cases, NbS require low capital expenditure. However, maintaining long-term effectiveness and undertaking rehabilitation activities require different institutional arrangements from those used for grey resilience solutions. Additional benefits ranging from improved air quality to enhanced recreational opportunities make NbS even more attractive for strengthening infrastructure resilience.

Continuous public education and engagement are crucial for maintaining and monitoring NbS. In many cases, transparent agreements are required to compensate communities for maintaining and managing NbS on their lands. Avoiding gentrification and other adverse social impacts is also essential for the successful use of NbS to enhance resilience.

1 Introduction

Nature-based solutions (NbS) have traditionally remained at the margins of infrastructure planning, often limited to localized pilot projects focused on carbon sequestration or the creation of aesthetic green spaces. However, as climate-related hazards increase in both frequency and severity, there is an urgent need to re-conceptualize NbS as integral components of large-scale infrastructure systems. Beyond carbon offsetting and flood protection, the functional spectrum of NbS is significantly broader. In urban and regional contexts, a hybrid systems approach synthesizes the high-performance reliability of grey engineered assets (e.g. concrete seawalls and drainage pipes) with the adaptive and self-healing capacities of green, biotic systems. NbS act as primary buffers that absorb environmental shocks, mitigating the inherent risks associated with rigid, traditional infrastructure. When integrated into a city or region's broader network, NbS provide a scalable, cost-effective approach for enhancing the durability of both natural and built environments.

Despite a growing body of literature on NbS and their role in enhancing societal resilience, there is significantly less guidance on their specific contribution to infrastructure resilience. This working paper draws on global case studies to demonstrate why development planners and infrastructure agencies must systematically integrate blue, green, and hybrid frameworks. There is an unprecedented opportunity because much of the infrastructure that will serve the global community by 2050 has yet to be built (UN Climate Change, 2021). This provides a critical, time-sensitive window to embed ecosystem-based approaches in planning and design from the outset, thereby avoiding the high costs and technical complexities associated with retrofitting existing systems. Furthermore, the *Global Assessment Report on Biodiversity and Ecosystem Services* (IPBES, 2019) notes that the rate of global change in nature over the past 50 years has been unprecedented, with infrastructure expansion often occurring at the expense of vital forests, wetlands, and grasslands. Consequently, this working paper treats NbS as strategic assets rather than environmental add-ons—essential for risk reduction, cost-efficiency, and long-term sustainability. Integration across the infrastructure life cycle—from design to recovery—is no longer optional; it is the road map to a resilient future.

1.1 Scope of the Working Paper

This working paper focuses on how NbS can increase the resilience of institutional infrastructure systems. In addition to their primary resilience function—such as reducing heat, managing floods, and stabilising slopes—NbS provide environmental, social, and economic co-benefits. These benefits can improve the reliability and cost-effectiveness of infrastructure assets and strengthen the resilience of communities connected through infrastructure networks. Any form of infrastructure, NbS must be tailored to the needs of the local environment and the surrounding communities to avoid unintended negative consequences. Viewing NbS as stand-alone solutions overlooks their potential to be scaled within and across infrastructure systems. Balancing customization with scalable implementation requires engagement with local knowledge, community participation, and natural processes to increase the flexibility and resilience of infrastructure networks.

This guidance is intended for infrastructure practitioners responsible for delivering reliable, maintainable, and scalable solutions within existing institutional frameworks, regulatory environments, and budget constraints. The challenges are particularly pronounced in low- and middle-income countries (LMICs), where institutional capacity gaps can further complicate implementation. Moreover, in incorporating nature-based approaches into infrastructure systems often requires more extensive communication, coordination, and stakeholder engagement than in the case of conventional grey infrastructure. These requirements can slow implementation, creating both practical and institutional challenges that must be addressed to enable broader adoption. While existing research has extensively demonstrated the ecosystem services and climate resilience benefits of NbS, this report focuses on the technical and institutional prerequisites for infrastructure agencies to implement them.

This working paper first defines NbS in their various forms and applications before exploring how they can strengthen the capacity of infrastructure systems to absorb, respond to, and recover from the shocks of natural hazards. The discussion then addresses the systemic challenges and limitations associated with scaling nature-based approaches within infrastructure systems and goes on to highlight the key stakeholders involved in implementation. The working paper concludes with a discussion of NbS readiness and emerging trends in its use for resilient infrastructure. The focus is on NbS for making infrastructure less vulnerable to hazards. NbS can also help reduce risks associated with drought, air pollution, and heatwaves (The Nature Conservancy, 2023). These applications will be analysed in future editions of the Global Infrastructure Resilience (GIR) report series.

This paper uses a balanced, evidence-based approach that acknowledges practical constraints, including land acquisition, long-term maintenance, and financing mechanisms. Central to this approach is the requirement for institutional transformation: agencies must move beyond narrow 'technical fixes' and develop new competencies in ecosystem assessment and adaptive management.

The discussion focuses specifically on asset and service resilience—emphasizing the protection of physical infrastructure and the reliable service-continuity under stress—how infrastructure serves wider systemic resilience, which falls outside its scope.

Rather than categorizing solutions solely by infrastructure type, this working paper adopts a challenge-driven approach, linking specific hazards to appropriate hybrid solutions.

Infrastructure assets	Hazard categories
Linear: roads, railways, pipelines, transmission lines, canals	Hydrometeorological: floods, cyclones, droughts, heat waves, wildfires Geophysical and coastal: earthquakes, landslides, tsunamis, erosion, saline intrusion
Point-based: power plants, substations, water facilities, hospitals, ports	
Area-wide: urban drainage networks, multifunctional open spaces	

This working paper compiles global knowledge, case studies, and technical approaches and provides practical recommendations that infrastructure agencies, policymakers, and practitioners can apply across diverse contexts.

1.2 Primary Audience

This report is intended for the following stakeholders responsible for managing the life cycle of infrastructure systems:

- **Infrastructure lead agencies:** Public works departments, utility operators, and regulators.
- **Disaster risk management authorities:** Institutions seeking proactive strategies to strengthen resilience.
- **Policy and planning executives:** National and local authorities responsible for shaping planning frameworks.
- **Development finance institutions and partners:** Financiers and international organizations that set investment priorities.

1.3 Reading Guide

The working paper is structured to guide the reader from theory to systematic implementation:

- **Sections 2–3: Conceptual framework:** Describes the resilience dividend and technical definitions of NbS.

- **Section 4: Implementation examples and best practices:** Presents practical approaches and case studies, including a deep dive into the cost of NbS, that can help infrastructure agencies and disaster management authorities leverage NbS to enhance infrastructure resilience—its capacity to absorb, respond to, and recover from disasters.
- **Sections 5–6: Institutional enablers:** Establishes challenges and potential solutions, as well as cross-cutting elements such as governance and finance, for managers, policy and planning executives, and decision-makers.
- **Section 7: The road map:** Proposes a step-by-step guide for scaling NbS and assessing institutional readiness.

2 Resilience Cycle Framework

GIR 2025 uses a common framework to analyse infrastructure resilience. This section introduces the key concepts and definitions used throughout the main report and its accompanying working papers.

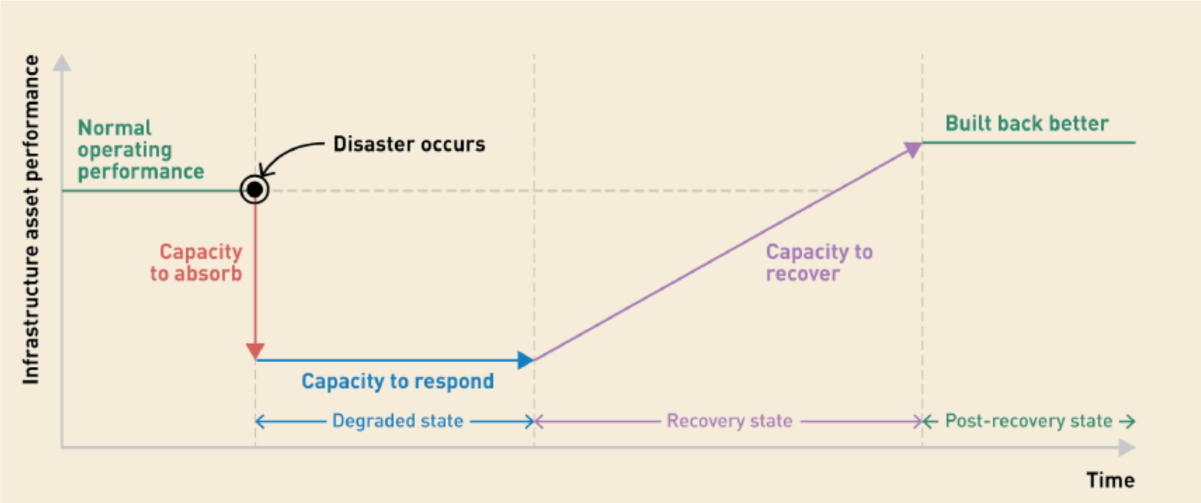
According to the Coalition for Disaster Resilient Infrastructure's (CDRI) *DRI Lexicon* (CDRI, 2023a), infrastructure comprises the 'individual assets, networks and systems that provide specific services to support the functioning of a community or society.' Disaster resilient infrastructure is defined as 'infrastructure systems and networks, the components, and assets thereof, and the services they provide, that can resist and absorb disaster impacts, maintain adequate levels of service continuity during crises, and swiftly recover in such a manner that future risks are reduced or prevented.' Thus, the resilience of infrastructure assets, networks, and services depends on their capacity to (i) resist and absorb the shocks caused by disasters; (ii) respond to the damage and maintain at least basic levels of service continuity during crises; and (iii) restore services as quickly as possible, incorporating lessons learned from the disaster to reduce future loss and damage.

It is also essential to consider the resilience of infrastructure service users. This depends on their ability to (i) be better prepared and utilize the information from early warning systems to reduce the impact of disasters; (ii) identify supplementary or alternative means when infrastructure services fail (e.g., back-up generators for electricity or alternative modes of transport); and (iii) learn from disasters, alongside infrastructure agencies, to improve preparedness for future events.

Resilience across three levels—infrastructure assets, services, and users—should be understood not only as the ability to withstand the next disaster but also as the capacity to respond to and recover from it. Building resilience in infrastructure assets and systems, therefore, requires a comprehensive understanding of the resilience cycle. Figure 2.1 illustrates the resilience cycle and the three capacities that an individual infrastructure asset should possess. In the figure, the vertical axis represents the performance level of the infrastructure asset, while the horizontal axis represents time. The asset's normal operating performance is indicated by the green line on the left-hand side of the graph.

When a disaster occurs, the normal operating performance of an infrastructure asset may drop to a lower state—even to zero, indicating a total failure of the asset, such as when a bridge is destroyed by a flood or a road blocked by a landslide. The magnitude of this drop depends on the asset's capacity to absorb disaster shocks, represented by the red line. The asset then remains in a degraded state for a period, represented by the blue line. During this period, emergency response and clean-up activities are undertaken alongside repair and reconstruction work. In some cases, the infrastructure agency also begins to partially restore basic services. The infrastructure asset then enters the recovery phase, represented by the purple line. The lessons learned from the disaster—including updated risk assessments that incorporate new hazard data and climate change projections—play a crucial role in guiding the repair and reconstruction phase. The reconstruction phase also offers an opportunity to incorporate NbS, adopt stronger resilience standards for the asset, and leverage new technologies to enhance resilience. The recovery phase can restore the asset to its normal operating performance or enable it to 'build back better,' as represented by the green line on the right-hand side of the graph.

Figure 2.1: The three capacities for resilient infrastructure



Source: CDRI (2025a)

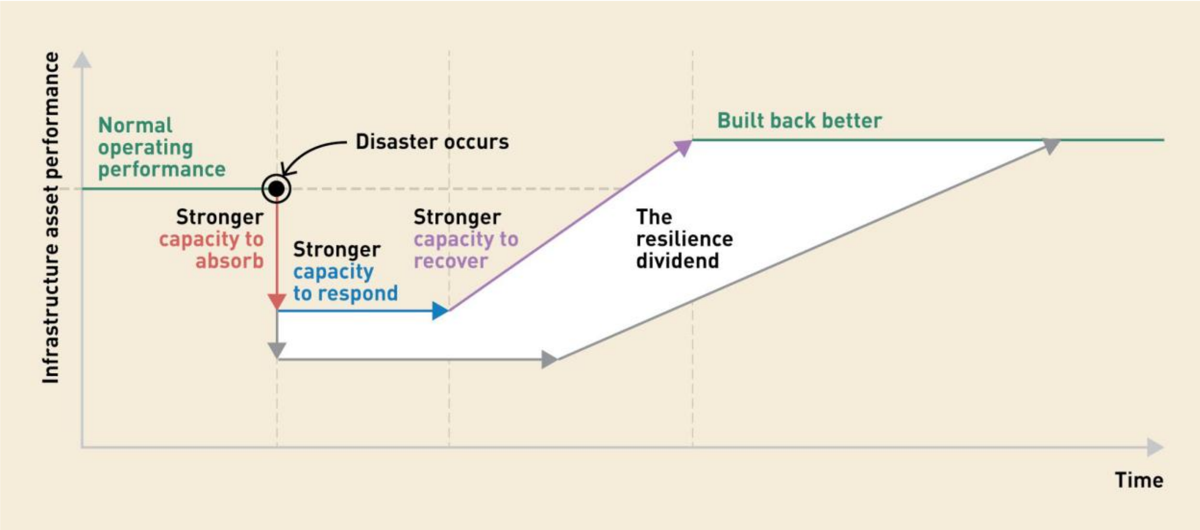
Many infrastructure agencies focus on enhancing the capacity to absorb by strengthening standards and regulations, implementing retrofit programmes for existing assets, and improving construction supervision for new, more resilient assets. They may also expand maintenance and repair programmes to strengthen assets in preparation for future disasters (e.g., during the cyclone season). However, focusing only on the capacity to absorb is insufficient. The duration and severity of disruptions to economies and livelihoods are directly proportional to the time it takes for the asset to return to its earlier (or an enhanced) level of operation. The longer an asset takes to respond and recover, the greater the impact on households, businesses, and communities. The capacity to recover services depends on network redundancy, while building back better requires a network-based analysis of vulnerabilities.

The capacity of users—whether individuals, households, communities, or businesses—to respond to infrastructure failures depends on effective communication with service providers and their ability to identify alternative means of accessing services.

As discussed earlier, building the resilience of infrastructure systems requires agencies and asset managers to strengthen not only the capacity to withstand disasters but also the ability to respond to shocks and recover quickly. Figure 2.2 shows the resilience-building process that could enhance the three capacities. An infrastructure agency or asset owner can implement several measures to strengthen the capacity to absorb (represented by the shorter red line on the left-hand side of the graph). These include developing enhanced maintenance, repair, and retrofit programmes or using systems that translate early warning notices sent by hydrometeorological services into preparatory actions to protect assets.

A stronger capacity to respond requires infrastructure agencies to be better prepared for disasters. Robust coordination plans with the national disaster risk management agency are essential, as well as with other emergency services and infrastructure agencies or utilities that provide interdependent services are essential, as failures in one system can trigger cascading disruptions after a disaster. Other actions that would boost preparedness include plans in place to remove debris from the asset; advance procurement of standby repair services, including strategic location of storing repair materials; and the use of new technologies such as drones for rapid assessment and evaluation of damage.

Figure 2.2: The resilience dividend obtained by strengthening the three capacities for resilient infrastructure



Source: CDRI (2025a)

Finally, infrastructure agencies or asset owners can improve the capacity to recover (represented by the purple line) by conducting post-disaster evaluation and learning activities. These activities include identifying new tools—such as NbS or emerging technologies—and incorporating them into repaired assets and enhancing resilience standards during repair and reconstruction.

Strengthening these three capacities will enhance resilience to damage and help protect assets from performance degradation. The response time in the event of a future disaster of similar magnitude can be improved by implementing more effective repair and reconstruction processes. It will also enable faster service restoration and, consequently, reduce the impact of disasters on livelihoods and the economy. The white area in Figure 2.2 represents the 'resilience dividend' resulting from these efforts.

This framework has been applied consistently throughout the main GIR 2025 report and working papers.

3 NbS types and Definitions

Unclear definitions create systemic risks for infrastructure reliability and complicate the development of technical standards and building codes. These standards and codes are essential for moving NbS from localized pilot projects into mainstream engineering practice. From a governance and financial perspective, clear definitions serve to ensure accountability, attract investment, and prevent greenwashing. For financiers and development partners, precise criteria are required to determine a project's eligibility for green bonds, climate finance, and resilience dividends. Furthermore, for policymakers, standardized definitions facilitate trans-boundary cooperation and equitable implementation. They ensure that resilience is not a vague catch-all term but a measurable objective that protects vulnerable communities and prevents maladaptation. Clear terminology, therefore, acts as a bridge between high-level policy goals and the detailed requirements of project procurement and legal contracting.

3.1 Definitions and Scope of NbS for Infrastructure Resilience

'Nature-based solutions' is an umbrella term encompassing a broad range of approaches that support infrastructure resilience. There is no single universally accepted definition for these solutions. However, NbS is widely described as 'actions to protect, sustainably manage and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, simultaneously benefiting people and nature.' CDRI's DRI Lexicon defines NbS as actions based on the protection, conservation, restoration, sustainable use and management of natural or modified terrestrial, freshwater, coastal and marine ecosystems. These actions address social, economic, governance and environmental challenges effectively and adaptively, while simultaneously, ecosystem services, disaster risk reduction, resilience and biodiversity benefits and supporting human well-being (CDRI, 2023a).

Although definitions of NbS vary, most of them concur that NbS use an integrated approach to address challenges such as risks and vulnerabilities to a variety of disasters such as flooding, soil erosion, and lack of water resources by harnessing natural processes—for example, using wetlands for flood control or urban parks to reduce heat.

To understand *NbS for infrastructure resilience*, it is useful to distinguish between different solution types. To enhance the resilience of these systems against climate and disaster risks, a variety of solutions may be applied, which are generally described as grey, green, blue, or hybrid.

Grey' infrastructure refers to conventional, human-made physical assets such as roads, railways, embankments, storm-water drainage systems, and telecommunication networks.

- **Grey solutions:** Traditional approaches to building infrastructure resilience have relied on grey or 'hard' solutions. These solutions consist of engineered structures and mechanical equipment (e.g., water retention basins, pipes, pumps, seawalls, transit shelters, permeable concrete, and solar canopies) that use hard construction materials (e.g., concrete, steel, and asphalt) to enhance the resilience of an infrastructure asset or its surrounding area. These solutions are often constructed for protective purposes and are typically rigid in both structure and function. In terms of resilience, grey solutions are commonly designed for current or near-term climate conditions and often lack the capacity to adapt to future changes.

- **Green solutions:** Green solutions are nature-based or ecosystem-integrated approaches that enhance resilience through terrestrial ecological processes. These solutions strengthen resilience by absorbing shocks, regenerating over time, and providing co-benefits such as biodiversity conservation, food security, and social well-being.

- **Blue solutions**: Blue solutions are water-centred interventions that leverage the ecological functions. of oceans and estuaries to enhance resilience by managing, storing, or redirecting water flows. Blue solutions enhance infrastructure resilience by reducing wave energy, mitigating storm surge impacts, and buffering climate extremes.

- **Hybrid solutions:** Hybrid solutions combine elements of grey, green, and blue approaches to maximize resilience to climate and disaster risks. They integrate the predictability and protective capacity of engineered solutions with the adaptability, regenerative qualities, and co-benefits of natural systems. Hybrid solutions generally address vulnerability more effectively than any single approach, hence they are frequently adopted. Examples include sea walls (grey) reinforced by mangroves (green), permeable pavements (grey-green) connected to engineered drainage systems (blue), and vegetated embankments (green) strengthened with structural barriers (grey). An example of a transition from grey to hybrid solutions for resilience is the grey-to-green storm-water management programme in Portland, USA (Box 3.1[1]).

BOX 3.1. The grey-to-green storm-water management initiative in Portland, USA

In Portland, the ageing of combined sewer infrastructure, together with rapid urbanization, has led to frequent flooding and sewer overflows into the Willamette River. To address these challenges cost-effectively, the city's Bureau of Environmental Services launched the grey-to-green initiative (2008–2018), investing $55 million to integrate green storm-water management with grey drainage infrastructure across the city.

The programme replaced parts of the traditional ‘pipe-and-drain’ system with distributed blue–green infrastructure (e.g., curb-side bioswales, rain gardens, eco-roofs, and street trees) to capture storm-water run-off at its source. More than 920 ‘green streets’ were constructed, 56,000 downspouts were disconnected, and 50,000 street trees were planted, collectively diverting 1.2 billion gallons of storm-water from the sewer system each year. These installations reduced combined sewer overflows from around 50 events per winter to an average of 4, while also improving water quality by filtering over 90 percent of suspended solids and heavy metals.

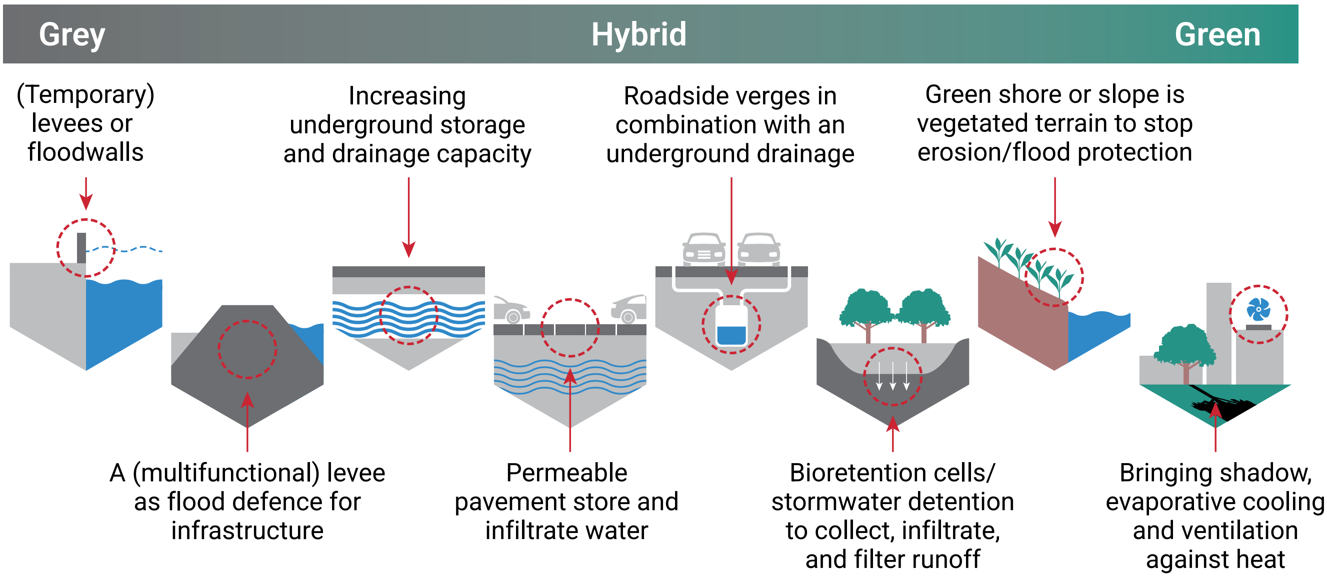
Beyond performance gains, the Green Stewards Program mobilized residents, businesses, and non-profit organizations to maintain local bioswales, reducing maintenance costs and fostering civic ownership. As of 2021, 238 stewards were caring for 590 facilities, demonstrating that distributed, community-managed, nature-based systems can sustainably extend the service life of grey infrastructure while enhancing urban resilience to increasingly intense rainfall.

For more information refer to City of Portland, Oregon.

There is no strict boundary defining what constitutes NbS, provided that green and blue solutions form part of the scheme. Working with nature as an ally, rather than against it, is at the core of NbS for resilient infrastructure, as seen in programmes such as Room for the River and Living with Water.

This framing positions NbS as a bridge between natural and built systems, demonstrating how they function across a range of hazards, scales achieved, and infrastructure types supported. Annexure A offers a comparative overview of the multiple definitions that exist in the field, together with a glossary of the terms used in this working paper. It also provides descriptions of selected NbS as well as the tools and catalogues discussed in Sections 5 and 6.

Figure 3.1: Grey, hybrid, and green solutions



Source: Authors' elaboration

Figure 3.1 illustrates a range of solutions across the spread from grey to green.

It is important to recognize that NbS are not the only available option. They should not be considered a 'silver bullet,' nor are they a 'one-size-fits-all' solution. Complementary approaches such as improved land-use planning, risk awareness campaigns, preparedness measures, and early warning systems are also essential. NbS should therefore be viewed as part of a broader portfolio of resilience measures, complementing rather than replacing other critical interventions.

The role of ecosystems in disaster risk reduction remains an area of active research. However, strong evidence indicates that NbS can reduce the adverse impacts of several hazards. Further research is needed in coastal, dryland, and watershed areas, particularly in the Global South (Sudmeier-Rieux et al., 2021).

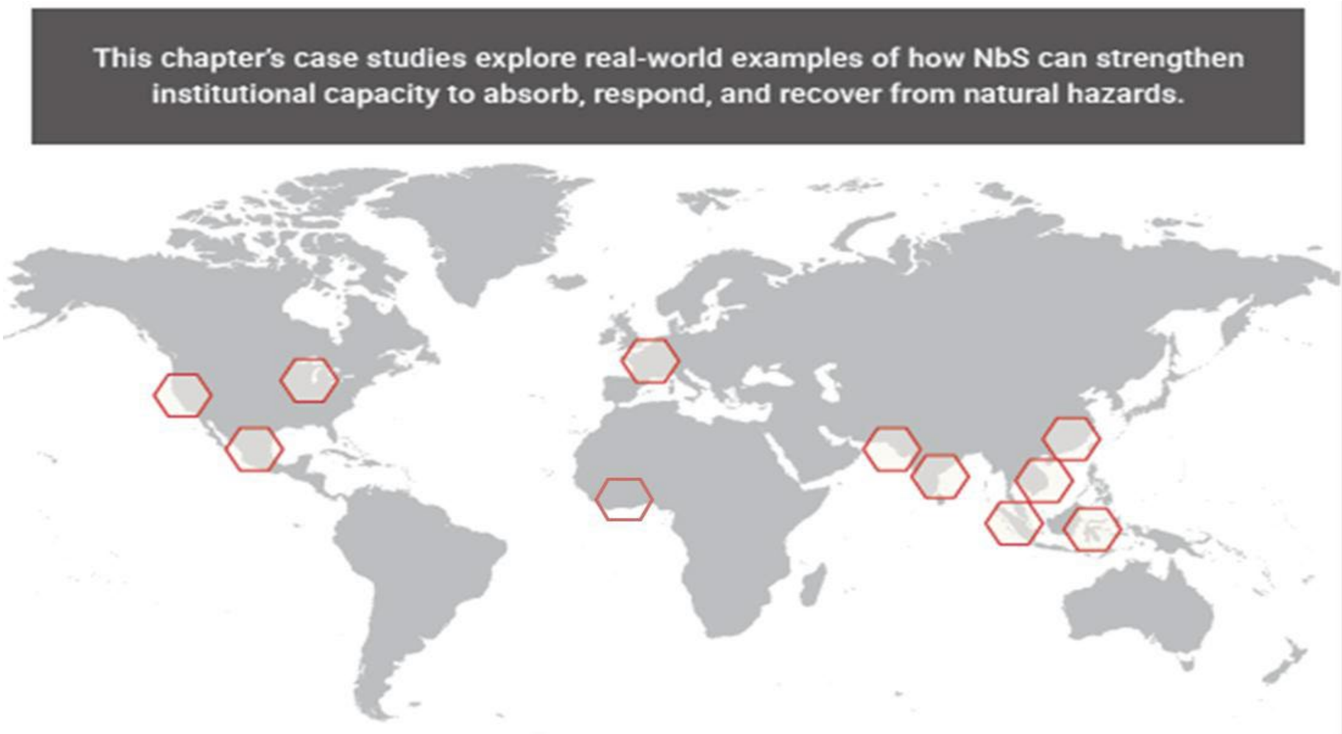
4 The NbS Opportunity for Resilience

NbS for infrastructure resilience are distinctive in their capacity to deliver multiple benefits simultaneously. These include environmental benefits (such as improved biodiversity and enhanced water and air quality), social benefits (including improved health outcomes, job creation, and recreational opportunities), and economic benefits (such as lower maintenance costs, increased tourism, and the stabilization of business operations during and after climate events). By viewing NbS as a strategic asset class, infrastructure planners can move beyond a narrow focus on risk mitigation towards a model of value creation in which natural capital actively supports the longevity and performance of built assets.

The core utility of NbS lies in their ability to strengthen infrastructure by enhancing its capacity to absorb, respond to, and recover from disasters. Realizing this resilience dividend requires shifting from viewing NbS as isolated pilot projects to implementing them strategically and systematically. When implemented strategically, NbS can make infrastructure more reliable, cost-effective, and beneficial to the communities it serves. Successful adoption depends on understanding the specific spatial and temporal scales at which nature-based interventions are most effective. When implemented alongside grey infrastructure solutions—for example, reducing the sediment load on a downstream hydroelectric dam through upstream reforestation—NbS can help ensure that infrastructure remains functional under stress while continuously providing essential services to the communities it was built to serve.

To establish a global evidence base, case studies were selected from diverse ecological and economic contexts based on measurable impact, data maturity, and evaluated effectiveness (Figure 4.1). Although many examples are drawn from coastal settings—where NbS have been most extensively piloted—the working paper reflects a broad global geographical distribution.

Figure 4.1: Case studies cited in this working paper



Source: Authors' analysis

The following sections demonstrate how nature-based and hybrid interventions can be integrated across the three pillars of the resilience cycle:

> **Section 4.1: Building the capacity to absorb shocks:** This section focuses on the lessening and dissipation of hazard energy. Here, NbS function as the first line of defence, utilizing modularity and ecological sponginess to help protect the physical integrity of grey assets.

Section 4.2: Strengthening the capacity to respond to disasters with NbS: This section focuses on operational agility and service continuity. It examines how ecosystems can function as emergency infrastructure—such as flood storage or evacuation corridors—and how monitoring ecological health can help provide real-time intelligence to disaster managers.

Section 4.3: Strengthening the capacity to recover after disasters through NbS: This section focuses on adaptive reconstruction. By leveraging natural regeneration and restorative hydrological design, NbS enable infrastructure agencies to 'build back better,' ensuring that the recovery phase results in a system that is more resilient to future shocks than its predecessor.

4.1 Building the Capacity to Absorb Shocks

Resilience measures across infrastructure sectors strengthen physical assets both individually and collectively within an interdependent system. Part of this capacity building involves improving preparedness and embedding structural redundancies and operational flexibility within infrastructure, enabling essential systems to continue functioning even under significant stress.

NbS increase the capacity of infrastructure to absorb shocks by providing ecological buffers that reduce the intensity of hazards before they affect critical components. NbS possess inherent properties, such as self-regulation, that make them particularly well suited to this function. They can offer a 'safe-to-fail' flexibility that delivers a multifaceted resilience dividend. By dissipating energy and managing volume at the source, strategically integrated NbS can significantly decrease risk and life cycle costs by lowering the physical vulnerability of assets exposed to recurring natural hazards.

Examples of how NbS can enhance the capacity of infrastructure to absorb shocks include the following:

1. **Reducing flood peaks through wetland and floodplain storage:** Wetlands and floodplains act as natural sponges, slowing water flow and lowering peak discharge during storm events. An example of flood peak reduction resulting from the use of NbS is the near-natural flood protection achieved in Germany (WWF Germany, 2020). When implemented using diverse, native plant species that are resilient to changing climatic conditions, these flood mitigation measures become more effective over time as the ecosystem matures. This provides a form of dynamic flexibility that traditional concrete structures cannot match.

2. **Reducing tidal flooding and coastal erosion using hybrid solutions**: Many coastal infrastructure assets located in low-lying areas are increasingly threatened by the combined impact of more frequent storm surges and long-term sea-level rise. Green and hybrid solutions, such as those implemented in the Sundarbans in India (Box 4.1) can help create a living shoreline that adapts to rising water levels while protecting critical buildings, agricultural land, and transport networks.

BOX 4.1. Protection of estuarine embankments in the Sundarbans, India

In the low-lying estuarine islands of the Indian Sundarbans, earthen embankments with a thick cover of mangroves—stretching to roughly 1,800 km—serve as the primary defence against tidal flooding and saline intrusion, enabling human settlement, agriculture, and local transport. Increasing erosion, strong tidal currents, and rising sea levels have contributed to embankment failures. Extensive foreshore areas lack sufficient mangrove cover, which would help enhance structural stability.

To reinforce embankment toes and promote foreshore sedimentation, WWF India and the Irrigation & Waterways Department of West Bengal introduced a living shoreline system that uses terracotta ring structures to trap sediment in front of embankments. These installations slow water flow, capture suspended sediment, and support annual elevation gains ranging from 1.42 to 16.51 cm across seven lower- and middle-estuary sites, exceeding the local rates of sea-level rise. As sediment accumulates, mangrove species such as *Porteresia coarctata*, *Suaeda maritima*, and *Avicennia marina* naturally colonize the area. In lower estuary installations, oyster species, including *Saccostrea cuculata* and *Crassostrea cuttackensis* also settle, reinforcing sediment retention and dissipating wave energy.

Suitability varies with local hydrodynamic conditions, and emerging vegetation may be grazed by livestock. This requires community cooperation or temporary protective measures. With the Sundarbans experiencing over 550 ha of land loss each year, the West Bengal Forest Directorate is testing modified terracotta structures to protect vertical embankment faces and potentially reverse shoreline erosion at high-risk locations.

A typical 1,000 × 6.5 m installation costs around $50,000, requires no maintenance, and offers a cost-effective, scalable alternative to repeated reinforcement with hard infrastructure. Larger anti-erosion installations designed for steep drops (e.g., 1.8 m) cost approximately $740,000 and aim not only to stabilize shorelines but also to rebuild lost land. Collectively, these living shoreline measures enhance embankment longevity, restore foreshore habitats, improve wave energy absorption, and strengthen the climate resilience of deltaic communities.

For more information, refer to WWF India (n.d.) and Chatterjee et al. (2025).

3. **Stabilizing slopes and embankments with deep-rooted vegetation:** Transportation infrastructure, such as roadways and railways in mountainous regions, is highly susceptible to landslides, often triggered by heavy rainfall. These hazards are often difficult to clear due to cascading risks and the terrain's inherent inaccessibility. Therefore, increasing the initial absorption of the shock is critical for maintaining connectivity. Deep-rooted vegetation effectively anchors the soil during extreme weather events, preventing movement. The application of Hong Kong's Slope Safety System illustrates the risk reduction benefits provided by mountain forests (Box 4.2) (Moos et al., 2018).

BOX 4.2. Reducing landslide risks through hybrid, nature-based slope protection in Hong Kong

Hong Kong's steep and densely urbanized terrain has long been susceptible to landslides triggered by rainfall. Major incidents in the 1970s prompted the creation of the Geotechnical Engineering Office (GEO) in 1977 to regulate slope safety. As extreme rainfall increase, deep-rooted vegetation and hybrid engineering-with-nature solutions have become essential for stabilizing hillsides and preserving transport connectivity in landslide-prone areas.

The Hong Kong Slope Safety System integrates vegetation-based slope treatments with engineered reinforcements to reduce risk. Landscape works retain or introduce vegetation to anchor soil and blend slopes into the urban environment, while engineering upgrades—enhanced drainage, soil nails, and flexible or rigid debris barriers—strengthen slope integrity. Groundwater-induced instability is addressed through the Po Shan Drainage Tunnel system, which uses horizontal drains, twin 500-m tunnels, and sub-vertical drains connected to real-time monitoring.

A citywide Landslip Warning System, supported by more than 120 rain gauges and slope data, provides timely alerts during periods of severe rainfall. Smart barriers detect debris accumulation and trigger rapid response measures. Public engagement initiatives—including the Bowen Road Slope Study Trail, augmented reality displays, STEM school workshops, and advisory services—help build slope safety literacy among residents and private slope owners.

The system delivers large-scale, measurable risk reduction. Approximately 150 man-made slopes are upgraded annually, along with assessments of around 100 private slopes and mitigation works on about 30 natural hillside catchments. A combination of engineering, vegetation management, monitoring, and early warning measures has significantly reduced landslide incidents and strengthened resilience during extreme weather events.

The hybrid approach enhances ecological integration, maintains continuity of transport and essential services, reduces emergency disruptions, and builds long-term public awareness and stewardship.

For more information, refer to Hong Kong Slope Safety (n.d.).

4. **Lowering urban heat stress on infrastructure services and users by erecting tree canopies and green roofs:** Extreme heat is one of the most prevalent hazards globally. It impacts the effectiveness of infrastructure by putting a strain on power grids due to the increased use of cooling systems. It can also disrupt transportation infrastructure. For example, rail services may be suspended when tracks become too hot for safe operation; vehicles may be unable to travel on heat-damaged roads; and aircrafts may be unable to take off due to high tarmac temperatures and the additional fuel required to cool the plane. The shade provided by tree canopies and green roofs cools sidewalks and public transport waiting areas. They also cool the surrounding air through evapotranspiration. Trees can provide support to urban ecosystems, including pollinators, birds, and other species. By incorporating biodiversity considerations into design, cities seek scalable ways to cool public spaces while strengthening social resilience. Paris's Oasis Schoolyard Programme (Box 4.3) demonstrates how nature-based design can transform the urban fabric at the neighbourhood level.

BOX 4.3. Cooling cities through hybrid solutions: Paris's Oasis Schoolyard Programme

Paris is increasingly facing urban heat island effects, limited permeable surfaces, and unequal access to cooling spaces. Schoolyards—typically paved, dark, and heat-absorbing—were identified as priority sites for climate adaptation and for delivering community benefits. In 2018, the city of Paris launched the Oasis Schoolyard Programme as part of its climate strategy, aiming to convert all schoolyards into cool, multifunctional spaces by 2050.

The re-design replaces asphalt with light-coloured, porous, low-carbon materials that remain significantly cooler during heatwaves. Rainwater retention and reuse—for evapotranspiration, gardens, and play—enhance natural cooling while improving storm-water management. Trees, gardens, and green walls provide shade and support biodiversity, while integrated educational features such as vegetable gardens help build children's environmental awareness. Additional installations such as shade structures, passive cooling features, and kinetic energy devices further regulate temperatures and reduce energy consumption.

By 2021, 10 Oasis schoolyards had been completed, reducing surface temperatures by several degrees and improving thermal comfort for students and nearby residents. Increased infiltration reduces run-off and contributes to urban flood resilience. When opened to the public outside school hours, these spaces function as inclusive local cooling refuges, strengthening neighbourhood cohesion. The programme demonstrates how nature-based design can foster climate resilience and social inclusion and deliver ecological benefits in dense urban areas.

For more information, refer to Climate-ADAPT (2022).

Buffering storm surges with mangroves and coastal dunes: In a closely integrated system of sub-littoral sediments, sandy beaches, and sand dunes act as coastal protection against strong waves and storm surges (Hanley et al., 2014). While dunes provide a solid landward barrier, mangroves offer a more permeable form of defence. They are natural obstacles that interrupt the momentum of waves, weakening the surge significantly once it has passed through these barriers. The weakened waves increase the overall infrastructure system's capacity to absorb strong and frequent storms. Infrastructure protected by these systems has a lower risk of severe flooding, which can damage power systems and buildings, as well as erosion, which can undermine transportation infrastructure. The Zephyr Power Limited wind farm and mangrove restoration project in the Indus River Delta in Pakistan is an example of NbS for resilient infrastructure (see Box 4.4). Similarly, the Sandbar Breakwater concept in West Africa (see Box 4.5) illustrates how embedding natural sediment transport in port design—using sand as a dynamic protective barrier—can create a more adaptive, climate resilient system.

BOX 4.4. Wind farm and mangrove restoration in Pakistan's Indus River Delta

Located in Pakistan's Indus River Delta—one of the world's largest yet most degraded mangrove ecosystems—the Zephyr Power Limited's (ZPL) 50-MW wind farm demonstrates how incorporating mangrove restoration into energy infrastructure design can enhance climate resilience. Pakistan's coastal region experiences accelerating sea-level rise, tidal flooding, erosion, and high exposure to storm surges, placing energy assets and the surrounding communities at significant risk.

During the development of the wind farm in Sindh Province (2017–2019), ZPL partnered with IUCN Pakistan and the Sindh Forestry Department to incorporate mangrove protection directly into civil works. Mangroves were planted and protected around turbine sites, creeks, drainage crossings, and access roads, transforming eroded mudflats into living green buffers. Initial offset commitments (14 ha to compensate for 1.2 ha of unavoidable impact) were later expanded to 64 ha and supported by a 91ha Habitat Monitoring and Management Plan. Community outreach included awareness campaigns on sustainable practices and plans to establish a mangrove nursery to generate local employment.

The restored mangroves now dissipate wave energy, stabilize soils, and filter run-off. Over a 25-year period, these functions are estimated to save approximately $7 million in flood and erosion damage. Annual maintenance savings of $35,000–$40,000 (equivalent to approximately $1 million over the project's lifetime) reflect the reduced exposure of access roads and cables. This protection helps safeguard critical infrastructure worth around $6 million. The improved nearshore water quality and habitat conditions also revitalized local fisheries. Daily shrimp catches have doubled from 5 to 10 kgs, and household incomes have increased proportionally. Across the community, these benefits contribute approximately $270,000 per year—equivalent to more than $6.7 million over 25 years—while also supporting direct employment for local workers.

For an investment of approximately $350,000—less than 1 percent of the total project cost—the intervention strengthened both the physical durability of the wind farm and the economic resilience of surrounding coastal communities facing recurring climate hazards.

For more information, refer to CDC Investment Works (2021).

5. **Slowing urban run-off and increasing infiltration through permeable landscapes:** Facilitating drainage into the ground through permeable surfaces—rather than allowing it to accumulate on impermeable surfaces—helps protect water and sanitation works and road infrastructure (see Box 3.1). This technique helps prevent sewers and drainage systems from overflowing, thereby reducing damage to infrastructure and the environment. Water and sanitation systems are grey infrastructure with limited capacity to withstand such hazards. Therefore, improving natural filtration in the surrounding landscape enhances these systems' capacity to absorb risk.

BOX 4.5. Sandbar breakwaters and natural sediment dynamics in West Africa

Traditional port infrastructure along the Gulf of Guinea—a region characterized by strong, predominantly eastward sand transport—often disrupts natural coastal flows, leading to sedimentation issues and the burial of expensive rock armouring. As rising sea levels and increased port traffic exacerbate coastal erosion, the need for cost-effective, nature-aligned protection led to the development of the Sandbar Breakwater concept.

During the pilot implementation at the Dangote port facilities in Lekki, Nigeria (2018), engineers leveraged "Building with Nature" principles to integrate natural dynamics into port design. Instead of relying solely on quarried rock, this approach uses strategic sand accretion updrift of the site to form a natural protective barrier. To manage downdrift erosion, the system incorporates a replenishable 'sand engine' that supplies sediment to sustain the wider coastal system.

The intervention has significantly reduced construction impacts, costs, and build time by decreasing reliance on traditional heavy materials. Post-construction studies across the Bight of Benin, including ports in Lomé and Lekki, demonstrate the system's performance, with updrift shoreline accretion of 10–23 m per year and sediment deposition reaching up to 700,000 m^3 per year. Ongoing morpho-hydraulic modelling and maintenance programmes ensure that the system maintains both navigability and ecological balance.

By embedding sedimentary processes in infrastructure design, the project demonstrates that nature-aligned systems can be more efficient and adaptive than rigid, traditional grey solutions. In coastal settings with similar morphological characteristics, this model offers a replicable pathway for climate resilient port development that works with, rather than against, natural cycles.

For further information, refer to van der Spek et al. (2020).

6. **Reducing wind Reducing wind speeds with shelterbelts and tree corridors:** Similar to the way mangroves and coastal dunes break the momentum of waves, –shelterbelts and tree corridors reduce wind speed. Wind can maintain high speeds over flat, uninterrupted surfaces, such as farmlands or large roadways. Shelterbelts and tree corridors form natural barriers that force airflow to pass around the vegetation, thereby lowering wind speed. This is particularly relevant for infrastructure such as above-ground power lines, which are highly vulnerable to strong winds. Introducing obstacles that slow the wind increases the capacity of power infrastructure to withstand such conditions. In Minnesota, USA, a project was implemented to block wind and snow from critical roadways, thereby improving the maintenance of services during severe storms (Box 4.6).

BOX 4.6. Living snow fences in Minnesota, USA

In Minnesota, drifting and blowing snow from open farmland has long created significant roadway hazards, increasing crash rates and raising the costs of snow removal and road maintenance. To address these risks, the Minnesota Department of Transportation (MnDOT) developed the Living Snow Fence (LSF) programme, which encourages landowners to plant trees, shrubs, and grasses—or leave rows of standing corn—to act as natural windbreaks that decrease wind speeds and reduce snow deposition on roads.

By interrupting wind flow, LSFs cause drifting snow to settle safely away from the road, thereby improving winter driving conditions. Participating landowners receive financial incentives to plant and maintain these barriers, though early adoption was limited. To refine the programme, researchers conducted extensive interviews and surveys with landowners and MnDOT staff, evaluated the environmental and safety benefits, and developed a Living Snow Fence Payment Calculator to tailor compensation based on avoided crashes, reduced maintenance costs, and emissions savings. Additional recommendations emphasized flexible contracts, updated payment structures reflecting crop and land values, enhanced outreach, and dedicated staff to support landowner engagement. GPS-equipped snowploughs were also introduced to gather location-specific data on snow drift and crash risk, enabling more targeted placement of LSFs.

Studies have found that LSFs can reduce snow- and ice-related crashes by up to 40 percent on roads with super-elevated curves. If implemented in just 40 percent of the identified high-risk sites, MnDOT could save approximately $1.3 million annually in safety and maintenance costs. Benefit–cost analyses across multiple locations revealed exceptional ratios ranging from 9:1 to 46:1, with an average of around 17:1, underscoring the economic value of incorporating vegetation-based windbreaks into transportation infrastructure. These results demonstrate how locally tailored, low-cost NbS can improve road safety, reduce operational costs, and enhance resilience to winter weather at scale.

For more information, refer to Minnesota Department of Transportation Research Services (2012).

7. **Reducing flood damage with riparian buffers:** Vegetated riparian zones along rivers and streams absorb excess rainfall and intercept run-off before it reaches and overwhelms nearby infrastructure. Their root systems bind the soil, reducing erosion and lowering the velocity of floodwaters as they move through the corridor. By slowing and filtering water, riparian buffers reduce the likelihood of storm-water systems backing up and help protect roads, bridges, and utilities near waterways. When designed with native, climate resilient species, these buffers become self-sustaining protective zones, lowering maintenance costs and providing ongoing protection against repeated flood events. A practical example of this approach is Singapore’s transformation of Kallang River at Bishan–Ang Mo Kio Park. The project has mitigated the impacts of intense rainfall and strengthened the surrounding infrastructure’s capacity to absorb floodwaters (Box 4.7).

BOX 4.7. Soil bioengineering and living river landscapes in Singapore

As an island city-state with a tropical rainforest climate, Singapore appears water-rich but lacks secure natural water sources, making water autonomy a national priority. Increasing climate volatility and rapid urbanization have intensified these risks. Longer dry periods followed by intense rainfall reduce the soil's capacity to absorb water, leading to stagnant pools that contaminate water supply and sanitation systems and create breeding grounds for mosquitoes and water-borne diseases. The city's predominantly concrete built environment further heightens flood risk and infrastructure damage while diminishing ecosystem services.

Against this backdrop, Singapore launched the Active, Beautiful, Clean Waters (ABC Waters) programme in 2006. A flagship project under this initiative was the transformation of Kallang River in Bishan–Ang Mo Kio Park. The former 2.7-km concrete canal was replaced with a 3 km meandering, naturalized river within a 62 ha park, designed to mimic a floodplain that narrows during dry periods and expands during heavy rainfall. Singapore pioneered the use of soil bioengineering techniques in its tropical context, employing vegetation, natural materials, and gabions to stabilize riverbanks and manage storm flows. The redesign incorporated flood safety measures, including water-level sensors, sirens, signal lights, and public announcements, while also integrating community amenities such as stepping-stone crossings, boardwalks, playgrounds, restaurants, lookout points, and Recycle Hill, constructed with concrete blocks salvaged from the former canal.

The naturalized river increased flood-handling capacity by about 40 percent, expanded the river's length and width, and significantly enhanced biodiversity. Species richness rose by around 30 percent, with 197 animal species recorded, including the return of smooth-coated otters, once thought locally extinct. Annual park visits doubled from 3 million to 6 million, demonstrating that ecological restoration can coexist with high levels of public use. The project cost SGD76.7 million (approximately $56 million), about 15 percent less than a grey infrastructure alternative, and earned international accolades, including the World Architecture Festival Landscape of the Year (2012) and the president's Design Award (2012).

For more information, refer to C40 Cities (n.d., 2018).

4.2 Strengthening the Capacity to Respond to Disasters

The potential of NbS to enable effective emergency response remains under-explored. Although natural systems are widely recognized for their preventive and protective functions, their ability to contribute directly to emergency response has received comparatively little attention. Ecosystems can provide immediate, actionable support during crises. Wetlands, for example, can function as temporary water retention zones that reduce peak flooding during response operations, while coastal vegetation can trap storm debris, thereby facilitating access for relief and evacuation.

Leveraging these functions requires reframing NbS not only as passive buffers but also as operational assets for emergency responders. This entails the following measures:

1. **Mapping ecosystems as emergency assets** (e.g., wetlands as staging or flood storage areas, forests as evacuation corridors): Recognizing ecosystems as a part of emergency infrastructure ensures that they can be utilized immediately when hazards occur. This identification and mapping could provide responders with reliable natural assets that can be activated during the critical window of emergency operations. Vallecillo et al. (2019) present a dataset that illustrates the potential of ecosystems to regulate water flows, along with fulfilling the socioeconomic need for protection against river floods.

2. **Training response agencies to monitor ecological indicators** (e.g., wetland water levels, vegetation health): Ecological indicators can provide real-time intelligence to anticipate potential infrastructure strain while hazards are still unfolding. By equipping responders to track indicators such as soil saturation, canopy stress, and water quality, agencies can gain real-time situational awareness of emerging risks. When these indicators are integrated with emergency response operations,

operators can dynamically redirect resources towards infrastructure and service areas facing the most imminent disruption. This enables a more targeted and timely deployment of response capacity, rather than reactive interventions after failures have occurred. Although guidelines and frameworks for monitoring ecological indicators are available, their practical application for infrastructure safety and continuity of service delivery remains under-explored (Deutsche Gesellschaft für Internationale Zusammenarbeit et al., 2020; United Nations Economic Commission for Europe, 2022).

3. **Embedding NbS in contingency and response protocols alongside engineered measures:** Institutionalizing NbS within emergency playbooks ensures that they are activated in tandem with grey infrastructure. For example, floodwaters can be routed into designated wetlands while drainage pumps are engaged. Similarly, as observed in Box 4.4, mangroves can be introduced or maintained for coastal hazard protection alongside sea walls. Embedding NbS in protocols ensures that responses are immediate, coordinated, and comprehensive, as demonstrated by the inclusion of temporary reservoirs (polders or agricultural areas) in the flood defence strategy for the Tisza River Basin, Hungary (Climate-ADAPT, 2022).

4. **Community-led ecosystem resilience during crises:** Communities that actively maintain riparian buffers, mangroves, or urban green corridors help ensure that these systems remain functional during a hazard event. Their stewardship enables immediate, context-specific use of these systems—for example, for safe passage, flood diversion, or cooling—thereby supporting service continuity before trained reinforcements arrive. A good example of local engagement in maintaining NbS for water and electricity resource management is Vietnam's Payments for Forest Environmental Services (PFES) programme (Box 4.8). Furthermore, locally governed NbS, such as flood channels or small wetlands, enable communities to take immediate action without waiting for central directives

BOX 4.8. Linking ecosystem stewardship to infrastructure services in Vietnam

Vietnam's nationwide PFES programme demonstrates how community-level stewardship of forests can directly support the resilience of water and energy infrastructure. First piloted in 2008 and mandated nationwide in 2011, PFES is based on the principle that hydropower plants, water supply companies, and tourism operators should compensate local communities for maintaining forest ecosystems that regulate water flow, reduce erosion and sedimentation, and protect watershed functions essential for downstream infrastructure.

Under the programme, buyers pay fixed rates—20 VND (Vietnamese Dong) / kWh ($0.00077/kWh) for hydropower generation, 40 VND/m³ ($0.0015/m³) for clean water supplied, and 1–2 percent of gross revenue for ecotourism. These payments are pooled and distributed per hectare to participating forest stewards after administrative and reserve contributions have been deducted. Between 2009 and 2012, PFES generated VND 1,782 billion (about $85 million), with hydropower plants accounting for nearly 98 percent of payments and water companies for the remainder. These funds support communities in protecting watershed forests that safeguard water supply and reduce sediment loads that threaten reservoirs, rivers, and infrastructure systems.

While the programme has mobilized substantial resources and strengthened forest management, several challenges persist. Only two of the four targeted ecosystem services have been fully implemented due to gaps in institutional guidance; forest tenure issues among owners limit community participation, and only 46 percent of collected revenues have been disbursed due to incomplete forest inventories, administrative complexity, and slow land allocation processes. Nevertheless, PFES demonstrates how legally structured, incentive-based NbS can link ecosystem protection with infrastructure resilience, provided that clear tenure arrangements, streamlined administration, and improved data systems are in place.

For more information, refer to Vietnam Forest Protection and Development Fund (2014).

(Box 3.1) (Flood Innovation Centre, n.d.). This decentralized capacity enables rapid, place-specific responses that help keep critical services functional in the immediate aftermath of hazards.

4.3 Strengthening the Capacity to Recover after Disasters

Post-disaster recovery extends beyond replacing damaged assets; it represents a pivotal opportunity to rebuild stronger, safer, and more resilient infrastructure. As governments and stakeholders move from emergency response to long-term reconstruction, their decisions carry lasting consequences. The success of recovery is therefore measured not only by how quickly services are restored but also by the resilience, inclusivity, and quality of the infrastructure assets and networks that emerge.

At the same time, post-disaster recovery unfolds against a deepening biodiversity crisis, making it critical that reconstruction choices do not further erode ecosystems whose degradation is already amplifying disaster risk. Post-disaster contexts can also present critical 'windows of opportunity' when urgent reconstruction needs coincide with the availability of financial resources. International frameworks such as the Strategic Plan for Biodiversity 2011–2020 and the Aichi Targets (Targets 5, 15, and 2) provide a clear justification for channelling recovery investments into NbS that simultaneously restore ecosystems, reduce hazard risk, and generate social benefits (Convention on Biological Diversity, 2010).

The European Commission's Climate-ADAPT platform highlights practical restoration strategies such as natural regeneration, assisted natural regeneration (ANR), diversified planting, and reforestation using climate resilient native species (Climate-Adapt, 2025). These approaches align closely with ecosystem-based adaptation principles by embedding ecological restoration within broader climate resilience strategies.

The reconstruction and rehabilitation of assets damaged by disasters provide a unique opportunity to reconsider legacy designs that rely exclusively on grey infrastructure solutions. Although the role of NbS in post-disaster recovery remains comparatively under-explored, it represents a promising dimension of resilience planning. By embedding ecological regeneration within recovery strategies, NbS can transform crises into opportunities to build back better by restoring ecosystem services, enhancing biodiversity, and strengthening long-term resilience.

Vegetation, soils, and hydrological systems often regenerate naturally after disturbances such as floods and droughts, gradually restoring functions such as flood buffering, slope stabilization, and erosion control without the need for extensive engineered reconstruction. This inherent regenerative capacity can reduce recovery costs and accelerate the restoration of protective functions—an especially valuable characteristic for infrastructure agencies operating under fiscal constraints in the aftermath of a disaster (see Section 4.4 for further discussion on the costs of implementing NbS). However, this must be managed effectively, as it takes time to implement NbS and to reap the benefits of the ecosystem services they provide (see Section 5.1 for further discussion on time considerations).

When systematically included in recovery plans—through rapid ecological assessments, dedicated financing, policy anchoring, and structured debris management—NbS can become operational assets for rebuilding safer, more adaptive systems.

Key approaches to leveraging NbS in post-disaster recovery include the following:

1. **Establishing financial mechanisms to accelerate response and recovery after disasters:** In Quintana Roo, Mexico, the Coastal Zone Management Trust used coral reef insurance to provide resources within days of a disaster, as part of support following a hurricane (Box 4.9).

BOX 4.9. Coral reef insurance in Mexico

Quintana Roo's Coastal Zone Management Trust demonstrates how conservation, financial innovation, and shared local governance work together to protect coastal infrastructure in one of the world's most tourism-dependent regions. Along Mexico's Caribbean coast—where reef-protected beaches underpin a $9 to $10 billion tourism economy—coral degradation, beach erosion, and increasingly intense storms have heightened risks to hotels, transport links, and local livelihoods. Recognizing that traditional disaster-response funding was too slow to prevent long-term reef decline, the State Government, hotel associations, TNC, NGOs, and academic partners created a public-private trust in 2018 to ensure immediate resources after hurricanes.

The trust reinvests revenue from tourism taxes and concessions into ongoing reef and beach maintenance. It also purchases a parametric insurance policy that pays out automatically when wind speeds exceed 100 knots within a defined reef polygon. This model accelerates post-storm response by delivering funds within days rather than months. Governance is supported by a technical committee representing the government, the tourism sector, and civil society, while a scientific committee provides guidance on restoration priorities. As part of this coordinated system, trained community Reef Brigades, composed of divers, fishers, and park rangers, stand ready to carry out rapid coral rescue and stabilization.

When Hurricane Delta struck in 2020, the insurance was triggered, releasing nearly $800,000. This funding enabled Reef Brigades to mobilize immediately and re-attach or rehabilitate more than 8,000 coral fragments within just 11 days. The rapid response helped preserve the reef structure, thereby maintaining natural coastal protection for beaches, hotels, and marine infrastructure. It also set a global precedent as the first insurance payout used for nature-based disaster recovery. By linking ecosystem stewardship with financial instruments and multi-stakeholder decision-making, the Quintana Roo model demonstrates how nature-based insurance can reduce risk of storm damage, safeguard economic assets, and strengthen long-term resilience in tourism-dependent communities.

For more information, refer to Tercek (2018) and The Nature Conservancy (2025).

As also observed in Box 4.9, when livelihoods reliant on tourism recover, communities are better able to maintain and repair infrastructure systems such as markets, roads, and energy grids.

2. **Enabling Quick Recovery such as Assisted Natural Regeneration (ANR):** ANR is a specific ecological restoration method that protects and nurtures existing growth, enabling vegetation to regenerate largely on its own. It focuses on conserving existing vegetation while reducing pressures from grazing, fire, and competing weeds. By removing invasive species, thinning overgrowth, and protecting seedlings, ANR accelerates the recovery of healthy vegetation following disturbances. Rapid restoration of tree cover and root systems helps stabilize slopes, reduces sediment flows onto roads, strengthens riverbanks, and creates natural buffers against storms and floods—functions critical for protecting infrastructure systems. Jong et al. (2021) evaluated the implementation of longitudinal training dams as an alternative to traditional groynes on Waal River in the Netherlands. The authors highlight the potential of this hybrid solution to maintain navigational depth in an important inland water transport corridor while also improving flood safety and supporting ecological recovery. Further, following disasters, soils are often compacted, eroded, or stripped of nutrients. Restorative measures improve water infiltration, rebuild soil fertility, and re-establish

natural flow regimes. This reduces long-term sedimentation, which clogs drainage systems and undermines roads, thereby creating a stronger foundation for infrastructure recovery.

BOX 4.10. Ecological corridors under transmission lines in Belgium and France

Across the forested regions of Belgium and France, the conventional management of high-voltage transmission corridors relied on frequent clear-cutting to maintain safety clearances, resulting in ecologically barren, costly-to-maintain strips that were widely unpopular with communities and environmental stakeholders. To address this issue, the LIFE Elia-RTE project (2011–2017) transformed 130 km of power line corridors—typically 50 m wide—into multifunctional ecological landscapes that maintained infrastructure safety while restoring habitat quality.

Within these corridors, project teams restored forest edges; revived heathlands, peat bogs, and nutrient-poor grasslands; created ponds; installed mowing and grazing infrastructure; and replaced invasive species with slower-growing native vegetation. In total, 528 ha were restored—exceeding the original targets for habitat restoration, grassland diversification, and infrastructure-friendly vegetation management. The intervention strengthened ecological connectivity, supported diverse flora and fauna, reduced fire-risk potential, and improved the aesthetic and recreational value of the landscapes surrounding transmission lines.

The cost–benefit analysis showed that this ecological approach was two to four times more cost-effective over time than traditional mechanical clearing, delivering both operational savings and substantial social and ecosystem benefits. Building on this success, Elia extended the intervention to an additional 375 ha between 2018 and 2023, supported by dedicated funding and the publication of practical toolkits. These include a detailed 'where to start' toolbox for transmission operators seeking to adopt alternative vegetation management methods, as well as a 30-year cost–benefit analysis comparing conventional and ecological management approaches, accounting for inflation and long-term ecosystem benefits.

For more information, refer to LIFE ELIA (n.d.) and Godeau et al. (2023).

3. **Diversified planting of trees, shrubs, and understory species for resilience:** Introducing a broad range of native species helps maintain ecosystem functions even if some species are lost due to pests, drought, or other future hazards. This biological redundancy strengthens the role of green systems surrounding infrastructure in supporting resilience, for example, by cooling heat-stressed cities and stabilizing riverbanks. Over time, these plantings reduce the vulnerability of rebuilt infrastructure to recurrent shocks. The importance of maintaining diversified planting to reduce wildfire risk and protect energy infrastructure is demonstrated in the LIFE Elia-RTE project (Box 4.10).

4. **Planning for debris management as part of post-disaster response:** The use of nature-based protection against multiple hazards may create operational challenges, particularly when vegetative debris (e.g. fallen branches or accumulated litter) obstructs drainage systems or delays access. Incorporating structured debris management, for example, with guidance from the United Nations Development Programme (UNDP), can help mitigate these trade-offs (UNDP, 2013). Managing debris to prevent drainage system obstruction and aiding vegetation recovery are important steps in strengthening the capacity to restore NbS functions.

5. **Integrating NbS with forensic investigations of disaster (FORIN):** This methodology entails examining social, environmental, infrastructural, and governance vulnerabilities to identify the underlying causes of disaster impacts and support targeted, evidence-based recovery strategies. FORIN can strengthen the effectiveness of NbS recovery interventions (Oliver-Smith et al., 2016). For example, FORIN can help identify which ecosystems or protective functions have been most compromised and require urgent regeneration; which areas are more vulnerable to repeated hazards and could benefit from hybrid or nature-based protective measures; and which socioeconomic factors influence recovery priorities—thereby helping to ensure equitable benefits from NbS interventions. FORIN can help identify the need for post-flood wetland restoration following drainage

system failure or define specific recovery actions, such as reforestation or dune restoration, where slope destabilization or coastal erosion has amplified disaster impacts. For example, Hong Kong uses smart management systems to monitor the Mai Po Nature Reserve, which serves multiple functions, from flood management to biodiversity conservation (Box 4.11).

While approaches such as FORIN help identify where and how NbS can most effectively support post-disaster recovery, translating these insights into implementable solutions ultimately depends on financial feasibility. Decisions on whether and how NbS are adopted for resilient infrastructure are strongly influenced by their cost structure, long-term value, and comparative performance relative to conventional grey alternatives. Understanding these cost differentials is therefore central to mainstreaming NbS in recovery and reconstruction processes.

BOX 4.11. Mai Po Nature Reserve: Smart wetland management for coastal resilience in Hong Kong

Located on the Hong Kong side of Deep Bay, the 380-ha Mai Po Nature Reserve protects one of the most rapidly urbanizing corridors in the region, situated between Hong Kong and Shenzhen. Managed by WWF Hong Kong in collaboration with the Agriculture, Fisheries and Conservation Department since 1983, Mai Po forms part of the internationally recognized Mai Po Inner Deep Bay Ramsar Site. It provides globally significant habitat for migratory birds while also functioning as a critical nature-based flood buffer for the surrounding communities and infrastructure.

Mai Po's mosaic of shallow and deep-water ponds, mangroves, reedbeds, and marshes functions as a dynamic natural defence system. The reserve's gently sloping mudflats can attenuate up to 80 percent of wave energy and 30 percent of storm surge energy, while coastal mangroves further reduce wave height by approximately 30 percent. These habitats collectively absorb storm surges and retain excess floodwater, thereby protecting nearby settlements, industrial areas, and future developments such as the Northern Metropolis. As climate threats intensify, this hybrid wetland system offers resilient, low-carbon, and self-sustaining protection.

To further strengthen resilience, Mai Po integrates smart management technologies into its operations. Intenet of Things–enabled devices, automated sluice gates, and remote sensors for monitoring water levels and water quality enable real-time monitoring and rapid response during extreme weather events. These technologies help maintain wetland functionality, prevent pollution impacts, and support adaptive water control strategies that are essential during typhoons and changing tidal conditions. Educational programmes, eco-tours, and corporate partnerships complement these efforts by fostering public stewardship and generating sustained financial support for conservation.

Through its combination of science-based adaptive management, multi-stakeholder governance, diversified funding, and innovative use of smart monitoring systems, Mai Po demonstrates how NbS can deliver biodiversity conservation, disaster risk reduction, and community benefits simultaneously within a densely urbanizing coastal region.

For more information, refer to Wen et al. (2024).

4.4 The Cost Differential of NbS for Resilient Infrastructure

There are important cost differences between grey resilience solutions and NbS. These differences should therefore be central to the options analysis and decision-making process when considering NbS for resilient infrastructure. Four key considerations should be addressed at the infrastructure project design stage: (i) differences in cost profiles between grey infrastructure and NbS; (ii) variations in costs across different NbS that provide the same level of resilience benefits; (iii) differences in depreciation profiles and indirect costs; and (iv) associated benefits.

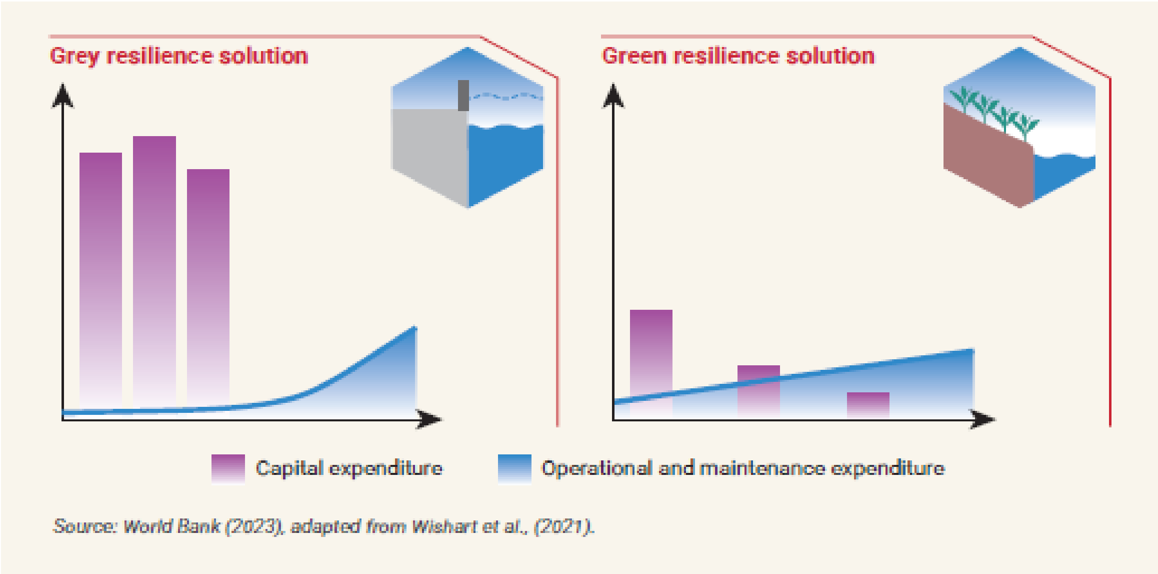
4.4.1 Cost Profiles

Cost considerations encompass both initial implementation costs (capital expenditure) and ongoing operations and maintenance costs which are often neglected (see Section 5.3 on 'maintenance'). The cost profile of NbS differs from that of grey solutions. The latter can involve high upfront capital expenditure but relatively low operating expenses in the initial years; however, these costs often increase significantly when major repairs or full reconstruction is needed. NbS, on the other hand, can have lower initial costs but may require greater effort and resources as the natural solution becomes fully established and requires protection from encroachment or damage.

The capital expenditure cost of NbS are highly dependent on land acquisition requirements, which may be larger in some cases, and may exceed those required for grey solutions that provide equivalent resilience benefits (van Zanten et al., 2023). At times, land may not be available for NbS due to encroachment into floodplains or designated future rights-of-way. Other times, purchasing the land may not be practical; instead, operations and maintenance contractual arrangements can be established with communities or landowners to provide resilience services. Even where land is available, its acquisition requires careful consideration of the social conditions and the potential impacts of gentrification. The different options will therefore result in varying capital costs for NbS.

Furthermore, operations and maintenance expenses for NbS can include the management of green areas (which sometimes would extend well beyond the immediate footprint of the infrastructure asset), maintenance of the natural elements of the NbS (which might require different procedures from what the infrastructure agency is used to), monitoring environmental quality, removing invasive species, fertilizing, and engageing with communities when they are contracted to maintain and preserve the NbS. The study of maintenance costs in NbS is an active area of research (Cherqui et al. 2024; Vicarelli et al., 2024). Figure 4.2 illustrates the differences in the typical cost profiles of grey solutions and NbS.

Figure 4.2: Illustrative cost timelines for green and grey infrastructure solutions



Source: World Bank. Adapted from (Wishart, et al., 2021)

Costs are highly dependent on the context, including the type of infrastructure and materials used, dimensions, implementation location, intended use, and maintenance requirements. Grey infrastructure typically involves higher upfront capital costs, driven by the need for materials, engineering inputs, and construction complexity. These costs are relatively predictable but often exclude long-term environmental externalities. In contrast, NbS tend to have lower initial investment costs, especially when leveraging existing ecosystems or community-based implementation. Recent Sustainable Asset Valuation (SAVi) assessments indicate that NbS typically cost about 50 percent less upfront than built alternatives while delivering equal or greater benefits, particularly where existing ecosystems can be leveraged (Bassi et al., 2021).

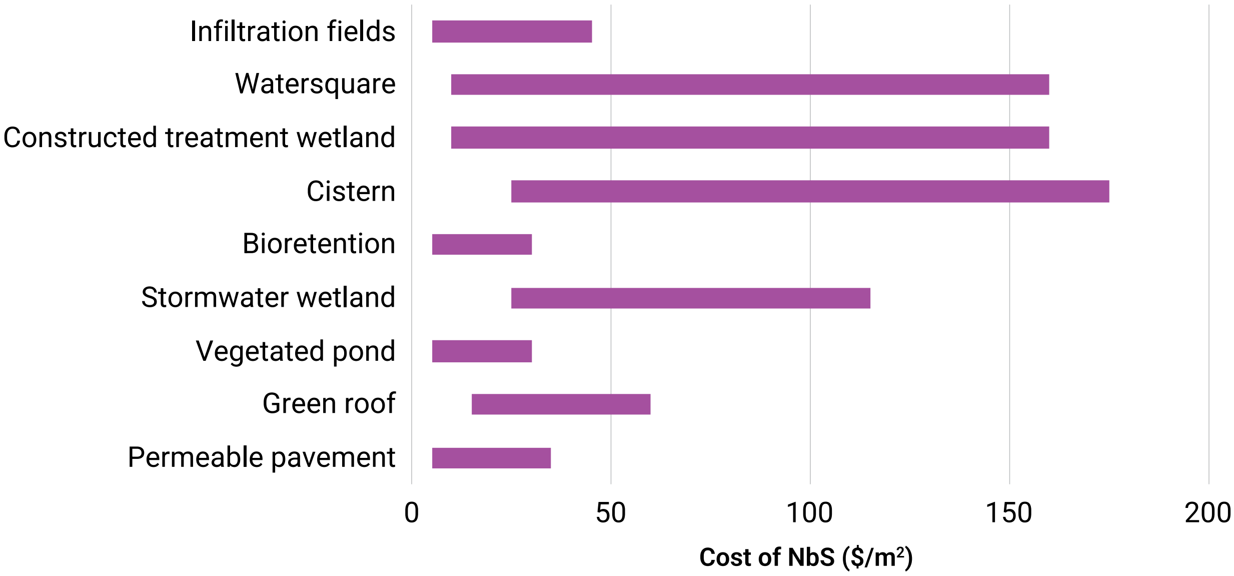
The cost analysis of options should also consider a range of possible hybrid solutions. In many resilience assessments, greater use of green or blue solutions can reduce the scale of the grey infrastructure required. This can result in hybrid approaches that are less costly, deliver quick resilience benefits from the grey components, and optimize the combination of natural and built solutions for greater effectiveness at lower cost.

4.4.2 Cost Variations

As discussed, capital expenditure can vary significantly across seemingly similar NbS options. Figure 4.3 illustrates this variation among small-scale NbS for urban water management, based on data from Europe and North America. The range varies from about $30/m^2 for vegetated ponds and bioretention to around $150/m^2 for cisterns or (green) water squares. Thus, a robust cost analysis is required when considering NbS options.

Similar variations are observed in mangrove NbS, where the cost of plantation can vary from a few hundred dollars to over $700,000 per hectare, with a global median cost of around $9,000 per hectare. These costs are strongly influenced by site-specific factors, including the degree of degradation, materials used, type of mangroves, local labour rates, and need for sediment trapping or hydrologic restoration.

Figure 4.3: Indicative cost range for small-scale water management NbS in Europe and North America



Source: Authors' analysis

It is important to note that implementation experience is limited in most regions of the world; consequently, there is insufficient detailed data on the costs of construction, input materials, and maintenance for NbS at specific locations. This gap requires infrastructure agencies to refine cost estimates during the feasibility stage, develop pilot projects specifically designed to gather cost and maintenance data, and work with contractors to fine-tune cost estimates for promising NbS applications. Figure 4.3 shows considerable variation in the costs of multifunctional systems, reflecting differences in the materials used and the dimensions. Examples include water squares—multifunctional areas with recreational features such as skate ramps—and constructed wetlands, which can be designed for horizontal or vertical flow.

4.4.3 Depreciation and Other Indirect Costs

An important distinction between grey solutions and NbS is their depreciation profile. NbS generally require an initial lead time to build up full performance capacities, depending on the extent to which existing ecosystems are utilized. However, the distinct characteristics of NbS—such as adaptability, self-repair, and the provision of ecosystem services—can result in non-linear growth in asset value over time. Unlike grey infrastructure, which depreciates steadily and requires reinvestment or reconstruction, NbS can increase in value as ecosystem health and resilience improve.

NbS can involve additional indirect costs compared to grey infrastructure. These include higher transaction costs due to the need for specialised ecological expertise in design. Costs may also arise from engaging communities through consultations for implementation, maintenance, and repair. While these processes can increase upfront costs, they can also lead to co-benefits such as reduced long-term costs, greater community participation, increased awareness, and stronger social cohesion. These approaches often differ from standard infrastructure procedures, which can further contribute to higher transaction costs.

The additional land required for NbS entails opportunity costs, as landowners may no longer be able to cultivate the land or construct buildings on it. Resource extraction from an existing ecosystem may also need to change to capture the resilience benefits of NbS. Fair compensation for these opportunity costs is integral to the success of NbS.

4.4.4 Benefits

In many situations, the indirect benefits of NbS influence their selection. In addition to resilience benefits, NbS provide a range of multifunctional co-benefits, including improved ecosystems, better air and water quality, recreation, mental health benefits, and enhanced urban quality of life.

Some studies have shown these indirect benefits can be substantial. Bassi et al. (2021) reported that NbS can deliver about 28 percent of additional value compared with grey solutions. Designing NbS to maximize these indirect benefits (see Figure 4.4) can often be done at modest incremental cost while creating significant opportunities to enhance environmental services for the surrounding communities.

Figure 4.4: Co-benefits of NbS options

	Green roofs	Tree planting	Bioretention & infiltration	Permeable pavement	Water harvesting
Reduces stormwater runoff					
Reduces grey infrastructure needs	Yes	Yes	Yes	Yes	Yes
Reduces water treatment needs	Yes	Yes	Yes	Yes	Yes
Reduces flooding	Yes	Yes	Yes	Yes	Yes
Drought					
Increases available water supply	No	No	Maybe	No	Yes
Increases groundwater recharge	No	Maybe	Maybe	Maybe	Maybe
Reduces soil use	No	No	No	Yes	No
Heat					
Reduces urban heat island	Yes	Yes	Yes	Yes	No
Mitigation					
Reduces energy use	Yes	Yes	No	Maybe	Maybe
Reduces CO_2	Yes	Yes	Yes	Yes	Maybe
Improves air quality	Yes	Yes	Yes	Yes	Maybe
Improves community liveability					
Improves aesthetics	Yes	Yes	Yes	No	No
Increases recreation	Maybe	Yes	Yes	No	No
Reduces noise	Yes	Yes	Maybe	Yes	No
Improves community cohesion	Maybe	Yes	Maybe	No	No
Urban agriculture	Maybe	Maybe	No	No	No
Education opportunities	Yes	Yes	Yes	Yes	Yes
Biodiversity					
Improves water quality	Yes	Yes	Yes	Yes	Yes
Improves habitat	Yes	Yes	Yes	No	No

Source: Adapted from SKINT water series (Ashley, et al., 2012) (Beer, Christensson, & Boogaard, 2012)

Biodiversity is often overlooked as an opportunity for enhancing the indirect benefits of NbS. Many NbS do not incorporate mixed species, rely on native species, or consider connections to ecological corridors that support broader ecosystem functions. The International Union for Conservation of Nature's (IUCN) guidelines for NbS are useful in this regard (IUCN, 2020).

An additional benefit of NbS is the flexibility they offer when the risk profile of hazards varies with climate change. Grey solutions are more rigid and difficult to adjust if flood or heatwave risks evolve over time. NbS are generally more flexible, adaptable, and cost-effective to expand or modify in response to changing climatic conditions. Figure 4.4 presents a range of indirect benefits associated with different NbS for urban flood management.

5 Challenges and Solutions in Applying NbS for DRI

NbS are increasingly recognized for their ability to enhance infrastructure resilience. However, implementing them presents challenges that are different from those associated with the grey resilience solutions commonly used by infrastructure agencies. Unlike grey infrastructure, NbS operate within living systems and therefore require adaptive management, long-term stewardship, and supportive governance to function effectively. These challenges are not insurmountable, but infrastructure agencies need to anticipate them and plan appropriate responses as they incorporate and scale up NbS in their operations. There can be variations in challenges depending on the context. Key challenges include the following:

- **Financing gap and business case:** As discussed in the GIR 2025 working paper on finance, governments and businesses need to urgently shift from reactive spending to proactive investment in resilience to unlock a 'resilience dividend'.
- **Standardization and evidence:** Traditional grey engineering solutions are often perceived as more reliable because they adhere to established building codes. In contrast, NbS face a shortage of skilled expertise and quantitative evidence regarding their long-term performance under extreme climate scenarios.
- **Governance and fragmentation:** Responsibilities for NbS are often distributed across multiple agencies (e.g., forestry, urban planning, and water management). The absence of coordinated, trans-boundary governance frameworks frequently lead to fragmented and less effective endeavors (see the GIR 2025 working paper on governance, Massive Open Online Course [MOOC]).
- **Time frames and permanence:** Natural systems such as mangroves or restored forests require more than a decade to reach full protective capacity, which may conflict with the typical three- to five-year cycles of political mandates and development donor financing. This aspect is also important for small-scale urban NbS such as rain gardens (Figure 5.1).

Figure 5.1: Temporal development of an urban NbS

Source: MOOC NbS (CDRI, 2025)

To better understand these dynamics, we now take a closer look at the key challenges associated with NbS implementation, including time considerations, potential maladaptation, maintenance and stewardship, and trade-offs with grey infrastructure.

5.1 Time Considerations

NbS have the potential for high performance, but this depends on proper design and implementation, and long-term monitoring. The benefits of NbS accrue at a progressive rate; as time passes, ecological systems mature, enhancing the solution's effectiveness. In contrast, grey infrastructure provides immediate resilience

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5.1 Time Considerations

NbS have the potential for high performance, but this depends on proper design and implementation, and long-term monitoring. The benefits of NbS accrue at a progressive rate; as time passes, ecological systems mature, enhancing the solution's effectiveness. In contrast, grey infrastructure provides immediate resilience benefits once operational, but these benefits can deplete as structures age. The gradual increase in benefits from NbS is not the standard expectation among infrastructure professionals. A successful shift in perspective can reveal this characteristic as a strength, with NbS complementing the decline of grey infrastructure and thereby ensuring that at least one component of resilience continues to perform. However, until such a shift occurs, this feature can remain a barrier to implementation when immediate, project-level results are prioritized over long-term, system results. However, until such a shift occurs, this feature can remain a barrier to implementation when immediate, project-level results are prioritized over long-term results.

NbS have attracted considerable interest in policy and research, yet their application at scale remains limited and often fragmented. Numerous pilot projects and demonstration initiatives have highlighted their benefits, but these successes typically occur in localized settings, without clear pathways for replication across broader networks and geographies. This so-called pilot trap arises because ecological, social, and governance contexts vary widely across regions. In addition, standardized methods, cross-sector coordination, and long-term financing models are rarely in place. Furthermore, the need for coordination across jurisdictions can present a significant impediment (Yuanita & Sagala, 2025). To move beyond isolated projects, integrative frameworks are needed to align interventions across multiple levels of infrastructure policy, planning, governance, and financing.

5.2 Maladaptation

Maladaptation refers to NbS producing adverse outcomes (Scheraga & Grambsch, 1998). Table 5.1 presents examples of maladaptation across different infrastructure asset categories and geographical contexts. Other potential negative impacts are related to land acquisition, restrictions on the use of natural resources in areas that support NbS, and gentrification. Avoiding maladaptation requires strong expertise at the design stage, multidisciplinary planning, targeted monitoring to anticipate unintended negative impacts, and compilation of the lessons learned from experience to support replication. Careful analysis of maladaptation risk is necessary from the early planning stages.

Table 5.1: Examples of maladaptation across asset categories and different geographies

Point-based assets (power facilities, treatment plants, ports, airports, social infrastructure)	
Context	**Examples of maladaptation**
Coastal	Installation of living shorelines to reduce wave energy along one berth can starve adjacent, unprotected shoreline segments of sediment, accelerating coastal erosion elsewhere.
Mountain/ slope hazard	Installing detention basins for storage of stormwater during highly intensive rainfall can prevent erosion at higher levels. However, by changing the natural dynamics of the water system there is a higher risk of drought-related slope hazards (oxidation of peat, subsidence).
Floodplain/riverine hazard/in-land	Installing stormwater infiltration systems in areas where the phreatic aquifer is used for drinking water may worsen water-quality risks due to the potential contamination of runoff.
Linear assets (roads, railways, pipelines, transmission lines, water networks)	
Context	**Examples of maladaptation**
Coastal	Planting dense dune grasses can prevent natural landward migration of sand under rising sea levels.
Mountain/ slope hazard	Increasing soil infiltration capacities on steep, unstable slopes to reduce runoff may result in increased risk of landslides in high rainfall events.
Floodplain/riverine hazard/in-land	Poor design and maintenance of a roadside bioswale may allow oils, heavy metals, and other automotive pollutants to accumulate in the planting media. Children playing on the grass adjacent to the feature can, in such situations, be exposed to contaminated soil and runoff, creating a direct health risk for the community.

Source: Authors' analysis

Poorly designed or maintained interventions can inadvertently lead to negative outcomes, including increased greenhouse gas emissions, long-term economic burdens, or disproportionate impacts on vulnerable communities. Examples include poorly designed storm-water infiltration systems contaminating drinking water aquifers, dense dune planting preventing natural sand migration, and roadside bioswales accumulating automotive pollutants. Preventing these outcomes requires standardized evaluation protocols, decision support tools, and careful design and maintenance practices that consider both intended benefits and potential unintended consequences.

5.3 Maintenance and Stewardship

Grey assets benefit from standardized maintenance protocols—including inspection cycles, material replacement schedules, and predictable deterioration models—that align with existing institutional frameworks and engineering practices. By contrast, NbS function through dynamic ecological processes that do not degrade linearly but instead fluctuate in response to seasonal, climatic, and ecological drivers. This creates uncertainty for operators accustomed to deterministic maintenance regimes and complicates the budgeting and accountability structures of infrastructure agencies.

Another challenge arises from the distributed and multifunctional nature of NbS. Unlike centralized grey assets, many NbS (e.g., bioswales, restored wetlands, and green roofs) are dispersed across urban landscapes and embedded within communities. Their performance depends not only on ecological upkeep but also on ongoing interactions with local actors, raising questions about ownership, responsibility, and capacity (Kabisch et al., 2022). Municipal agencies may be reluctant to assume responsibility for ecological maintenance, while community engagement strategies can be inconsistent or overly reliant on voluntary action. The resulting governance gap may lead to neglect, mismanagement, or piecemeal interventions that undermine system reliability.

Figure 5.2: Maintenance of a green wall by professionals in Indonesia

Source: Authors

Infrastructure resilience is determined as much by long-term stewardship as by the initial design. The stewardship of NbS also highlights a cost–recognition mismatch. Traditional infrastructure budgets often underestimate or overlook ecological maintenance because benefits such as biodiversity enhancement, heat mitigation, and social well-being do not fit neatly within financial reporting categories (Kurth et al., 2024). This invisibility contributes to chronic under-investment in upkeep, with maintenance often de-prioritized once construction is complete. Without innovative financing mechanisms, clear institutional mandates, and capacity for ecological management, *NbS risk being celebrated during the design phase but allowed to fail silently during operation.*

Infrastructure resilience is a function of both design and ongoing operation and maintenance. NbS require a different approach for their upkeep, emphasizing adaptive ecological management instead of the rigid repair cycles of grey infrastructure. Unlike grey assets with clearly defined maintenance regimes, NbS require adaptive management that accounts for ecological cycles, vegetation growth, and changing hazard conditions (see Figure 5.2). This approach brings both opportunities and challenges. Maintenance of NbS may involve multifunctional activities, but the payoff is the resilience of the infrastructure, which evolves with changing hazard conditions rather than deteriorating under them. The complexities of NbS management often lead to under-investment in upkeep. However, institutional mechanisms, multi-stakeholder partnerships, innovative financing, and emerging technologies such as remote sensing can help establish effective stewardship systems that sustain performance over time (refer to Box 3.1).

5.3.1 Debris Management

While NbS enhance infrastructure resilience through natural buffering, attenuation, and regenerative capacities, they also introduce unique challenges in debris management. During extreme events, ecological elements such as trees, shrubs, or restored wetlands can generate significant organic debris—fallen branches, accumulated sediment, and leaf litter—which may obstruct drainage systems, block access routes, or impair the functioning of other infrastructure assets. Unlike grey infrastructure, where failure modes and debris accumulation are well understood and standardized, the dynamics of NbS-generated debris are highly variable, context-specific, and often unpredictable, making routine planning and operational control more complex.

5.4 Trade-offs

Infrastructure agencies face trade-offs between rapid functionality restoration, ecological integrity, and long-term system resilience, which are rarely captured in conventional performance metrics or operational protocols. Without systematic monitoring and adaptive guidance, debris from NbS interventions can paradoxically undermine the very resilience these systems are designed to provide.

Institutional and capacity constraints often exacerbate these challenges. Agencies may lack the technical expertise, cross-sector coordination mechanisms, or financial resources required to integrate debris management effectively with NbS planning and maintenance. Standardized frameworks, rapid assessment tools, and multi-stakeholder protocols are needed to manage debris in ways that support reliability, recoverability, and resourcefulness, ensuring that NbS continue to deliver protective, adaptive, and regenerative functions under both normal and extreme conditions.

The implementation of NbS for infrastructure resilience must be understood as a cross-sectoral endeavour shaped by ecological, social, economic, and governance dimensions. success depends on multi-stakeholder collaboration, adaptive management, and long-term stewardship, along with careful attention to scale, time, and context. When designed and implemented effectively, NbS offer multifunctional benefits by enhancing resilience, biodiversity, and social well-being. At scale, they have the potential to contribute significantly to global agendas on climate adaptation, disaster risk reduction, and nature restoration. Achieving these outcomes requires ongoing research, systematic monitoring, and the establishment of governance, financing, and operational frameworks that enable NbS to move beyond pilot projects and into mainstream infrastructure planning and practice. The following are some key recommendations:

- **NbS are a long-term investment in resilience:** With coordinated funding, effective governance, and sustained maintenance, NbS mature over time, complement grey infrastructure, and contribute to climate adaptation, disaster risk reduction, and nature restoration.
- **Governance and maintenance are collective responsibilities:** Because NbS are dynamic, they need adaptive management. Clear roles, joint monitoring, and shared stewardship among public agencies, private actors, and communities help ensure continued performance through changing conditions.
- **Avoid maladaptation through shared expertise:** Poorly designed NbS can backfire. Multi-stakeholder planning—including input from private sector, academic, and community actors—reduces risk, ensures technical feasibility, and maximizes benefits.
- **Monitoring turns collaboration into learning:** Drones, sensors, and community feedback loops enable partners to track performance, improve designs, and strengthen the evidence base for scaling across regions and sectors.

Monitoring and adaptive management are central to the success of NbS. Performance monitoring provides feedback for improving designs, informs operational adjustments, and strengthens the evidence base for scaling interventions. Emerging technologies—including aerial and aquatic drones, sensors, and online platforms—complement traditional visual inspections by enabling more precise and multidimensional evaluation of NbS performance. Integrating these tools with national and local planning frameworks allows for alignment between ecosystem capacities and infrastructure protection objectives. Trans-boundary cooperation further highlights the importance of safeguarding critical ecosystem services across political borders.

Many of the challenges associated with scaling NbS—such as long time horizons, fragmented governance, uncertain performance, and underfunded maintenance—cannot be resolved through technical design alone. PPPs offer a mechanism to address these constraints by aligning long-term financing, risk-sharing arrangements, and stewardship responsibilities across public and private actors.

5.5 Public–Private Partnerships

The World Bank (2025) defines a PPP as a long-term contract between a private party and a government entity for the provision of a public asset or service, in which the private party bears significant risk and management responsibility and remuneration is linked to performance. The typical duration of these contracts ranges from 10 to 30 years. Common models include build–operate–transfer, in which the private party builds and operates a facility before transferring it to the government; design–build–finance–operate, where the private sector manages the project from design through operation; and concession agreements, in which a company is granted the right to operate a public asset for a fixed period.

The *Climate-Resilient Infrastructure Officer (CRIO) Handbook* (Global Center on Adaptation, 2021) provides comprehensive guidance on integrating NbS across all stages of project development through PPPs. Large-scale hybrid infrastructure projects demonstrate how PPPs can be structured to manage uncertainty while integrating nature-based and grey measures (Box 5.1).

BOX 5.1. The Fargo–Moorhead Area River Diversion Project (USA) and the Broadland Flood Protection Project (UK)

The Fargo–Moorhead Area River Diversion Project (USA) and the Broadland Flood Protection Project (UK) both employed PPP models to address complex flood risks. The Fargo–Moorhead project used milestone-based availability payments to incentivize timely delivery, while the Broadland project incorporated a two-year survey phase with an exit clause, allowing the private partner to assess technical and environmental feasibility before making a full commitment. These mechanisms reduced delivery risk and increasedimproved confidence in project implementation.

Both projects also achieved notable cost efficiencies. The Fargo–Moorhead PPP reportedly saved approximately USD $330 million and accelerated project delivery by nearly a decade., while, the Broadland Flood Protection Project was projected to be more cost-effective than traditional public procurement. The projects further illustrate the flexibility of PPP financing structures. The Fargo–Moorhead project combined federal grants, bonds, and private equity, with payments linked to performance milestones, whereas the Broadland project relied on national budget funding delivered through a performance-based contract. Together, these cases demonstrate that PPPs can be adapted to different fiscal and institutional contexts while maintaining accountability and delivering long-term value.

For more information, refer to CIRIA (2011) and U.S. Department of Transportation, Federal Highway Administration (n.d.).

An ongoing example is NL2120 (2024), in which national government bodies, regional water boards, and private sector engineering firms collaborate to restore floodplains along major rivers. The initiative creates space for floodwaters during peak flows while enabling private investment in eco-tourism and sustainable agriculture. Public actors provide regulatory frameworks and funding for ecosystem restoration, while private partners contribute technical expertise, implementation capacity, and long-term maintenance services.

6 Scaling Up NbS: From Pilots to Practice

Pilot projects demonstrate the potential of NbS. However, their long-term effectiveness depends on systemic change that embeds these approaches within the core practices of infrastructure agencies. Moving beyond isolated demonstrations requires a deliberate shift towards structural integration. This integration requires five strategic levers.

6.1 Institutional

Scaling up NbS requires more than demonstrating successful pilots—it demands internal transformation within infrastructure agencies. Institutional systems, mandates, and routines ultimately determine whether NbS become part of the core infrastructure portfolio or remain peripheral experiments. Agencies must therefore evolve from organizational structures built around fixed, engineered assets towards models that accommodate dynamic, multifunctional natural systems. This shift begins with internal alignment: updating Strategies, project pipelines, standards, and processes so that NbS are consistently considered as viable, credible, and investable options (Xie, et al., 2020). Once these foundations are in place, institutional measures can embed NbS into everyday practice and move agencies from treating NbS as experimental add-ons toward incorporating them as a standard, proactive approach to infrastructure service delivery.

Achieving this transition also requires organizational arrangements that sustain NbS over time. This may involve establishing new roles or dedicated units with ecological expertise, embedding NbS requirements into PPPs and concession agreements, and adapting procurement and maintenance regimes to the specific dynamics of nature-based assets. Regulatory flexibility—particularly in relation to land tenure, permitting, and concession management—is equally important, as agencies refine contracting models and operational processes to support effective NbS implementation (U.S. Environmental Protection Agency, 2025).

Several resources support agencies in embedding NbS within internal systems and organizational routines. *Nature-Based Solutions for Resilience: Infrastructure Pathways* (Arup & Global Centre on Adaptation, n.d.) provides life cycle–based guidance that identifies decision points, roles, and process reforms across planning, procurement, delivery, and asset management. This helps organizations translate strategic intent into operational practice. *The Practical Guide to Implementing Green–Grey Infrastructure* (Green–Gray Community of Practice, 2020) complements this guidance by consolidating methodologies and case experience for hybrid ecological–engineering solutions. It also supports updates to internal standards and maintenance regimes.

6.2 Policy and Governance

Scaling NbS requires a policy and governance environment that establishes clear mandates, incentives, and coordination structures necessary for widespread adoption. While institutional reforms determine what agencies can change internally, policies and governance frameworks establish the enabling conditions that guide how NbS are considered, approved, financed, and managed across sectors. Because NbS intersect with land use, environmental regulation, community engagement, and long-term stewardship, coherent governance systems are essential. Such systems align actors, prevent fragmentation, and ensure that NbS are considered early and consistently in planning and implementation. A few specific policy mechanisms and governance arrangements that create this enabling environment are outlined below.

Policy and governance frameworks set the ‘rules of the game’ for infrastructure agencies and determine whether NbS move from pilot initiatives to mainstream infrastructure practice. Embedding NbS in master plans, sectoral strategies, and concession agreements ensures that they are considered from the outset of infrastructure planning rather than treated as optional add-ons. Broader initiatives such as federal mandates and policy guidelines that recognize NbS as legitimate, investable, and scalable options also provide clarity for regulators, financiers, and contractors. Alignment with global commitments such as the Paris Agreement and the Sustainable Development Goals further strengthens both legitimacy and funding opportunities (United Nations Environment Programme Finance Initiative, 2024).

Equally important are governance mechanisms that institutionalize stakeholder engagement. Because NbS often rely on land availability (Castelo et al., 2023), community stewardship, and ecological co-benefits, ad hoc outreach alone is insufficient. Instead, formalized processes—such as statutory consultation requirements, participatory design protocols, or co-management agreements—are required to ensure that citizens, local communities, and private landholders are involved in decision-making. These governance provisions help surface co-benefits, reduce conflicts, and build the ownership needed to support long-term maintenance and sustainability (Box 6.1). Another example of engaging local communities in owning solutions for societal development can be observed in Medellín, Colombia. As part of the A Greener Medellín for You programme, several local residents from disadvantaged backgrounds were trained by Medellín's Joaquin Antonio Uribe Botanical Garden as city gardeners and planting technicians to plant and maintain the 30 Green Corridors as part of their full-time work (C40 Cities, 2019).

BOX 6.1. Multi-stakeholder engagement platform for NbS in Berlin, Germany

An example of an innovative governance mechanism that formally connects public and private stakeholders around NbS is the Berlin Rainwater Agency, established in 2018 through a collaboration between the state of Berlin and the Berlin Water Utility. Designed as a central interface for decentralized rainwater management, the agency provides structured, cross-sector coordination that enables a shift from ad hoc outreach to long-term, institutionalized stewardship of NbS.

The agency's overarching mandate is to support Berlin's transition to a 'sponge city' by reducing pressure on storm-water infrastructure, lowering heat island effects, and enhancing urban biodiversity. By bringing together policy, technical guidance, and stakeholder engagement on a single platform, the Rainwater Agency enables participatory design processes and provides clearer decision-making pathways for residents, landowners, and developers. Initiated by the Berlin House of Representatives and aligned with the European Water Framework Directive, the agency also supports the implementation of national and federal regulations, including the Water Resources Act, the German Building Code, and the Berlin Water Act. The agency provides practical information on requirements for managing rainwater discharge in construction projects, thus ensuring that regulatory expectations are transparent and accessible.

Beyond regulatory support, the agency plays a catalytic role in Berlin's transition to green infrastructure by supporting the delivery of the city's subsidy programmes, including 1,000 Green Roofs for Berlin and the GründachPLUS initiative. Through its coordinating function, the Berlin Rainwater Agency illustrates how formalized institutional platforms can accelerate the uptake of NbS, reduce governance bottlenecks, and build long-term ownership among diverse urban stakeholders.

For more information, refer to Berliner Regenwasseragentur (n.d.).

6.3 Technical

Standardized design guidelines, modelling tools, and performance metrics allow infrastructure agencies to plan, implement, and maintain nature-based projects with confidence. Design standards ensure reliability while providing flexibility to adapt to local ecological and social conditions, translating ecosystem variability into actionable project specifications (Qi, 2025). Several guidelines have recently been developed by a range of institutions. These are reviewed in greater detail in the accompanying working paper on NbS.

Modelling tools and simulations help agencies anticipate the performance of NbS under different environmental and climate scenarios (Voskamp et al., 2021). These tools can estimate flood reduction, water quality improvements, and biodiversity benefits, providing the quantitative evidence needed to integrate NbS alongside conventional grey infrastructure. When applied early in project planning, these tools inform site selection, sizing, and adaptive design strategies, reducing uncertainty and risk for both public and private stakeholders.

Monitoring and adaptive management close the feedback loop between design and performance. Continuous measurement of ecological, hydrological, and social outcomes builds an evidence base that strengthens institutional knowledge and supports replication.

Technical standards, modelling tools, and monitoring systems are most effective when aligned with regulatory requirements and strategic objectives. This ensures that NbS designs not only provide ecological and social benefits but also comply with legal mandates and integrate seamlessly with conventional infrastructure planning.

Several established tools exist that strengthen the technical foundation of NbS. The *IUCN Global Standard for Nature-based Solutions* provides a structure based on key performance indicators (eight criteria and 28 indicators) that agencies can adapt for project-level performance frameworks and contractual requirements (International Union for Conservation of Nature, 2020). The European Commission's *Technical Guidance on the Climate Proofing of Infrastructure* (2021) provides a step-by-step methodology for climate risk and vulnerability assessment and for incorporating adaptation measures into infrastructure design (European Commission, 2021). This approach can also be adapted for use beyond the EU.

Alongside these frameworks, *Making Ecosystem-Based Adaptation Effective: A Framework for Defining Qualification Criteria and Quality Standards* (Friends of Ecosystem-Based Adaptation [FEBA], 2022) provides a useful approach for evaluating the quality of NbS and ecosystem-based adaptation measures, particularly in pioneering or demonstration projects. The FEBA framework offers qualification criteria and quality standards that help practitioners verify whether an intervention is designed and implemented in accordance with recognized principles of ecological integrity, social benefit, and climate resilience. While grounded in technical assessment, these standards also support broader integration by defining what constitutes high-quality NbS, thereby offering a reference point that can be incorporated into monitoring frameworks, performance evaluation, and even policy and regulatory systems.

Modelling and co-design are supported by tools such as the Climate Resilient City Tool, which enables users to simulate the hydrological effects of measures, compare adaptation options, and estimate construction and maintenance costs through a map-based interface (Deltares, n.d.-a). These functions help align a variety of stakeholders during the initial stages of decision-making. In addition, digital platforms—including open-source and citizen science initiatives such as ClimateScan.org—play a complementary technical role (ClimateScan, n.d.). They enable practitioners to examine comparable NbS implementations globally, understand key design parameters, and assess performance under real-world conditions. Catalogues that provide detailed compilations of potential NbS include the *Catalogue of Nature-Based Solutions for Infrastructure Projects*, the *Nature-Based Solutions Database*, the *Catalogue of Nature-Based Solutions for Urban Resilience* and *Nature-Based Solutions for Ports* (Conservation International and IFC, 2024; Equator Initiative, 2024; World Bank, 2021, 2025).

6.4 Finance

The availability of financial resources and well-designed financial instruments is essential for scaling up the use of NbS for resilient infrastructure. Instruments such as blended finance, PPPs, and performance-based contracts help align incentives between public and private actors. By linking remuneration to ecological outcomes and resilience performance, these models create market signals that encourage long-term stewardship of NbS.

Monetizing co-benefits strengthens the business case for NbS, particularly where costs are high due to land acquisition. Integrated cost–benefit tools that account for both direct and indirect benefits—such as avoided flood damage, carbon sequestration, and social well-being—enable decision makers to compare NbS with conventional alternatives on a more holistic basis (The World Bank Group, 2025). These tools ensure that long-term value—rather than upfront costs alone—drives investment decisions. By embedding these valuations into planning, procurement, and PPP contracts, NbS can be positioned as financially viable, multifunctional infrastructure investments.

Financial appraisal and investment decisions can be strengthened by using tools that quantify resilience dividends and incorporate co-benefits into formal comparisons with grey infrastructure alternatives. The International Institute for Sustainable Development's (IISD) SAVi framework captures the long-term environmental, social, and economic value created by NbS, including avoided losses and reduced risk profiles (Contor, 2025), thereby improving the robustness of investment cases, particularly in data-scarce environments. The World Bank's *Cost–Benefit Analysis Guidelines* provide structured methodologies for comparing options across the complete life cycle, enabling decision makers to incorporate indirect benefits and long-term value creation (van Zanten et al., 2023). Private sector–oriented resources, such as the NbS Blueprint and the Nature-Based Solutions Map, developed by the World Business Council for Sustainable Development (2024), support companies in identifying NbS aligned with business challenges and in quantifying layered ecological and socioeconomic returns. These tools can be utilized in blended finance and PPP contexts. Sector-specific valuation approaches—illustrated by case work such as ecosystem services assessment and evaluation (Box 4.4; CDC Investment Works, 2021), long-horizon vegetation management (Box 4.10; Godeau et al., 2023), and snow management in transport (Box 4.6)—demonstrate how NbS can be appraised across a range of infrastructure settings.

6.5 Capacity

For infrastructure agencies to implement NbS at scale, technical expertise in ecology and related subjects is needed, along with traditional engineering knowledge (Frantzeskaki et al., 2025). Capacity development should also extend to management staff and decision makers, enabling informed choices on integration and trade-offs.

Cross-disciplinary collaboration and coordination mechanisms help ensure that diverse knowledge streams are effectively combined. NbS often require engagement across multiple sectors—such as water, transport, environment, and disaster risk management—as well as with a range of actors, including local communities and Indigenous groups. Structured coordination platforms, joint planning processes, and knowledge-sharing mechanisms can foster collaboration, reduce institutional silos, and improve efficiency.

Building operational and adaptive capacity helps ensure long-term sustainability. Training programmes, mentorship, and hands-on experience in pilot projects or living labs equip teams with the skills needed to monitor, maintain, and adapt NbS assets over time. The Water as Leverage City of 1000 Tanks Project, implemented at Little Flower Convent School for the Blind and Deaf in Chennai, India, exemplifies this approach (City of 1000 Tanks, 2023). By institutionalizing these capacities, agencies can ensure that NbS are not only implemented successfully but also evolve dynamically in response to environmental and social changes (Box 6.2).

Anchoring NbS knowledge within permanent institutions is critical for transitioning from short-term training to long-term practice. Multiple centres of excellence and NbS knowledge exchange platforms exist, as well as country-level forums that assist with knowledge management repositories such as the India Forum for Nature-Based Solutions (2022) and the Nature-Based Solutions Italy Hub (2024).

Box 6.2. The Building with Nature programme in Indonesia

Field-based training has proven far more effective than classroom instruction for equipping practitioners to work with nature-based coastal protection. Through Indonesia's Building with Nature programme, young engineers gained hands-on experience in mangrove rehabilitation and hybrid coastal defence by working directly on breakwater pilot sites. This practical exposure is critical in Northern Java, where coastal erosion and sea-level rise are already affecting communities and threatening aquaculture ponds. By 2030, more than 70,000 people and 6,000 hectares of ponds are projected to be impacted, with longer-term estimates suggesting up to 30 million people could ultimately be affected. Much of this vulnerability stems from the widespread conversion of mangrove belts for aquaculture, compounded by groundwater extraction and resulting land subsidence.

The programme applies hybrid NbS, combining mangrove and river restoration with land-use changes and small-scale engineering measures. Changing wave exposure, submersion time, and sediment conditions meant that traditional single-species mangrove planting was no longer feasible across much of the coastline. Instead, the intervention used a combination of temporary semi-permeable barriers—constructed from poles and brushwood to dampen wave energy and trap sediment—and gradual mangrove restoration, adapted to local ecological conditions along different stretches of coast. This approach restored natural sedimentation processes while creating the conditions needed for mangrove recovery.

These pilot sites functioned as "living laboratories", serving simultaneously as training grounds for flood-protection engineering and for community-based ecological restoration. Supported by the EcoShape programme—a multistakeholder collaboration focused on ecosystem-based intervention design—the initiative enabled engineers and planners to learn directly from applied case studies that mirror the complexity and constraints of their own work environments. This combination of practical training, stakeholder coordination, and hybrid NbS design has helped build long-term operational capacity for nature-based coastal resilience in Indonesia.

6.6 Bringing the Five Strategic Levers Together

Underlying all five levers is the principle of cross-sectoral collaboration. Engineers, ecologists, policymakers, communities, and the private sector must work together to co-design solutions that protect and restore ecosystems while ensuring that infrastructure systems remain robust, reliable, and equitable. Only through such collective efforts can NbS move from the margins to the mainstream of resilient infrastructure planning. Box 6.3 illustrates how these five levers have been applied in the Netherlands' Room for the River programme, the largest and longest running at-scale NbS initiative worldwide.

BOX 6.3: Room for the River programme—Netherlands

As a country whose name translates as 'lowlands,' the people of the Netherlands have long managed life in a delta where major rivers meet the sea. Without its extensive system of dykes, polders, and coastal dunes—as well as major storm surge engineering works such as the Maeslantkering (see Figure 6.1), Afsluitdijk, and Eastern Scheldt Barrier—nearly two-thirds of the country would be under water. These engineered defences, developed largely in response to the catastrophic 1953 North Sea Flood, significantly strengthened protection against coastal and storm surge hazards.

However, the river floods of 1993 and 1995 exposed a different vulnerability: rapidly increasing upstream discharges and increasingly constrained river corridors. With around 250,000 people evacuated, policymakers recognized that simply raising dykes along rivers was no longer sustainable. This insight triggered a strategic shift towards a nature-based, landscape-oriented approach—the Room for the River programme.

Launched in 2006, the programme implemented more than 30–39 major interventions along the Rhine and its distributaries, supported by €2.3 billion in national investment. Measures such as lowering groynes, excavating and lowering floodplains, creating side channels, and relocating embankments widened the river corridor and enabled it to accommodate high flows safely. By allowing controlled inundation, the programme reduced peak water levels and flow velocities, decreased the stress on hydraulic structures, and reduced flood duration and severity. Equally important, Room for the River enhanced spatial quality, ecological function, and multifunctional land use, demonstrating how working with natural processes can complement, rather than replace, engineered infrastructure.

Institutional transformation

The Room for the River programme required a major cultural shift within Dutch water institutions. Rijkswaterstaat and its regional partners moved away from a predominantly engineered, containment-focused paradigm towards one that incorporates river dynamics, landscape design, and ecological function into core decision-making. This transformation involved treating spatial and ecological quality as essential components of flood risk management; normalizing nature-based measures such as dyke setbacks and floodplain lowering as standard, rather than experimental, interventions; and embedding adaptive delta management principles to maintain long term flexibility while ensuring that immediate actions remain aligned with future climate scenarios.

Policy and governance

The programme's effectiveness relied on deliberate, multi-level governance arrangements. While national authorities defined the overarching safety and spatial-quality objectives, provinces, municipalities, and water boards were responsible for planning and implementation. This arrangement allowed interventions to be tailored to local conditions and community priorities. Governance evolved from hierarchical control to collaborative, multi-actor decision-making. Working-with-nature principles were incorporated directly into policy to support multifunctional land use and adaptive planning. An independent quality team provided oversight of hydraulic, ecological, and spatial dimensions, ensuring coherence across the programme. Basin-scale coordination with upstream countries further strengthened alignment across the wider Rhine watershed.

Technical tools and standards

Room for the River relied on a rigorous technical foundation that ensured nature-based interventions were both predictable and replicable. A standardized planning toolkit—comprising hydraulic and morphological models, scenario assessments, and cost-effectiveness analyses—enabled designers and policymakers to compare interventions based on the expected reduction in water levels per euro invested. Widely applied intervention typologies—such as dyke relocation, floodplain lowering, groyne lowering, and side-channel creation—provided scalable templates across the more than 30 project sites. Continuous monitoring strengthened the evidence base. Biodiversity assessments across 179 floodplains showed increases at 76–93 percent of the sites, while sediment-transport studies informed iterative design improvements. Adaptive pathway approaches were also used to accommodate ecological and hydrological variability and ensure long-term flexibility.

Figure 6.1: Maeslantkering—the storm surge barrier in the Nieuwe Waterweg

Source: Image by Han Bijleveld, Deltares.

7 Road Map and Checklist for Institutional Readiness for Adopting NbS

7.1 Introduction

A road map, in its simplest form, is a plan that outlines the current position, the desired destination, and the steps required to move from one to the other. It can serve as a high-level visual representation—similar to a map—that helps guide progress towards the desired outcome—namely, resilient infrastructure.

Several road maps outline pathways for transitioning from grey infrastructure to NbS but not specifically for infrastructure systems. Existing road maps range from those tailored to particular sectors to broader, more general frameworks. In this section, we outline a simplified road map for beginners. A more detailed road map is provided in Annexure A, including key questions and practical steps to guide the integration of grey solutions and NbS.

The objective of the NbS for infrastructure road map is to help infrastructure organizations/agencies or individuals undertake a simple self-assessment by answering a set of practical questions. This self-assessment should help the organization determine which elements are required to implement NbS for resilience, based on key technical and non-technical considerations. This assessment framework builds on the practical information presented in Sections 4–6. The key questions are addressed to determine the starting point, supported by best management practices drawn from the presented case studies and from global experience and lessons learned.

NbS enhance infrastructure resilience, protect assets, and sustain ecosystems. While pilot projects demonstrate their potential, achieving lasting impact requires systemic change. Change requires not only the design and implementation of innovative solutions but also alignment with existing strategic priorities and regulatory frameworks. Integrating NbS with agency mandates, sector strategies, and national or local regulations ensures that these solutions are recognized, adequately resourced, and legally supported, thereby creating a stable foundation for long-term implementation.

Scaling NbS depends on five strategic levers: institutional, policy and governance, technical, financial, and capacity related. These levers may operate independently or in combination, depending on local priorities, available resources, and environmental conditions.

Key takeaways

- **Institutional:** Embed NbS within organizational mandates and operational practices
- **Policy and governance:** Establish enabling policies and regulatory frameworks, and promote multi-stakeholder coordination
- **Technical:** Standardize designs, model outcomes, and monitor performance
- **Financial:** Use integrated valuation and innovative financing mechanisms to scale investment
- **Capacity:** Build interdisciplinary, field-ready teams to support long-term sustainability

Scaling NbS requires more than the implementation of green infrastructure; it requires systemic alignment across institutions, policies, technical tools, financing, and skills. When all five levers are activated, NbS move beyond pilot projects to become resilient infrastructure that strengthens communities, ecosystems, and cities worldwide.

When a road map is too abstract for assessing an institution, a checklist can also be used. A checklist can help align incentives among governments and their partners to mainstream NbS as reliable, scalable components of resilient systems.

NbS Checklist

Even when NbS designs are technically sound and pilot projects demonstrate success, institutional bottlenecks often hinder their mainstreaming. Infrastructure agencies need a structured approach to assess their readiness to support NbS and to create the enabling conditions for implementation at scale. A summary in the form of a checklist can be used for this purpose (Table 7.1). By applying the checklist, aligning incentives, and recognizing ecosystems as operational infrastructure, governments and their partners can mainstream NbS as reliable and scalable components of resilient systems.

Table 7.1: Categories and high-level questions on the agency-level NbS checklist

Pillar	High-level questions for infrastructure agency self-assessment
Strategic and regulatory alignment	» Are NbS included in national strategies, sectoral policies, or climate adaptation plans? » Do procurement frameworks allow for ecological criteria to be considered alongside engineering standards? » Are NbS are reflected in planning codes, investment appraisals, and procurement guidelines to enable the transition from discretionary choices to standard practice?
Decision-making and governance	» Does the agency have the tools and guidelines to evaluate NbS alongside grey options? » Can the agency access external expertise, and are financing systems supportive of hybrid approaches? » Does the agency have transparent criteria for comparing options, mechanisms to bring in external knowledge, and procurement systems flexible enough to accommodate NbS performance metrics?
Institutional and technical capacity	» Does the agency's staff have the skills to design, monitor, and maintain NbS? » Are there institutional champions driving cross-departmental coordination? » Do training programmes and knowledge-sharing mechanisms exist? » Does the agency have governance mechanisms that institutionalize stakeholder engagement?
Monitoring, evaluation, and adaptive management	» Does the agency track NbS outcomes across ecological, social, and engineering dimensions? » Are lessons documented and fed back into future planning? » Is adaptive management part of the institutional culture? » Is iterative learning, supported by clear indicators and feedback loops, part of the agency's standard operating procedures?
Finance and partnerships	» Does the agency have financial instruments specifically designed to support NbS implementation at scale? » Is the agency capable of mobilizing the financial resources needed? » Does the agency have a structured approach to partnerships with civil society, private sector, and academia to support NbS programmes?

Source: Authors' analysis

The checklist focuses not on project-level interventions but on the systems that enable them to succeed, including policies, governance structures, organizational capacities, and adaptive learning. For ministries, municipalities, and agencies responsible for funding, designing, and maintaining infrastructure, institutional readiness determines whether NbS remain isolated pilot projects or become part of the mainstream toolbox.

Additional questions provided in Annexure A (Table A.2) can be used at the project level to support a more operational and context-specific application of NbS across the infrastructure lifecycle.

8 Conclusion

NbS are not a niche alternative to conventional infrastructure but a core component of contemporary infrastructure resilience strategies. At the system level, NbS strengthen the capacity of infrastructure networks to absorb, respond to, and recover from climate hazards. They also deliver environmental and social co-benefits in adaptive ways, which conventional infrastructure assets cannot. However, this potential is realized only when institutions move beyond case-by-case experimentation and embed hybrid grey–green approaches within the rules and incentives that govern infrastructure planning, delivery, and operation.

This document sets out a practical pathway for achieving this shift. The readiness checklist emphasizes five pillars for institutionalizing NbS. The implications are straightforward and actionable. To leverage the potential of NbS at scale, infrastructure agencies can institutionalize NbS by updating procurement processes to value ecological performance, standardizing technical guidance while adapting it to local contexts, and allocating budgets for ecological maintenance and monitoring. They can formalize collaboration across sectors and governance levels, incorporate forensic learning from events into standards and design manuals, and publish performance data to reinforce an organizational culture of iterative improvement. In low- and middle-income contexts—where capacity and financing constraints may be significant—prioritizing hybrid solutions that deliver multiple benefits per unit of investment can accelerate resilience gains while strengthening legitimacy and public support.

Implementing NbS for infrastructure resilience requires coordinated governance and adaptive management across sectors. When supported by clearly defined roles, adequate maintenance, inclusive planning, and systematic monitoring, NbS can mature over time and complement grey infrastructure while delivering multiple ecological and social benefits.

Ultimately, the question is no longer whether NbS 'work' but rather if institutions are prepared to work differently. By applying the checklist, aligning incentives, and treating ecosystems as operational infrastructure, governments and their partners can mainstream NbS as reliable, scalable components of resilient systems.

To reinforce this shift, this working paper has also drawn on a global evidence base of case studies from diverse ecological and economic contexts. These were selected for their measurable impact, data maturity, and evaluated effectiveness. Together, they demonstrate that NbS deliver robust performance when supported by enabling institutions. Shared expertise from the presented case studies and continuous learning are essential to avoid maladaptation and to scale NbS effectively.

Annexure A

Definitions

Term	Definition
NbS definition by UNEA	At the 5th United Nations Environment Assembly (UNEA 5.2), NbS were defined as "actions aimed at protecting, conserving, restoring, and sustainably managing natural or modified terrestrial, freshwater, coastal, and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits" (United Nations Environment Programme, n.d.).
NbS definition by UNEP	Nature-based solutions (NbS) are actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature. They have the potential to make an essential contribution to reaching net-zero CO_2 globally by around 2050, alongside other decarbonisation strategies. Nature based solutions projects of high quality and integrity could have the mitigation of up to 10 gigatonnes of carbon dioxide ($GtCO_2$) per year, corresponding to approximately 27% of current global annual emissions. Investments in, and implementation of, Nature-based Solutions can help financial institutions mitigate risks arising from nature loss and climate change, thereby contributing to the successful achievement of the targets arising from the Paris Climate Agreement.
NbS definition by WB	Nature-based solutions are actions to protect, sustainably manage, or restore natural ecosystems, that address societal challenges such as climate change, human health, food and water security, and disaster risk reduction effectively and adaptively, simultaneously providing human well-being and biodiversity benefits. For example, a common problem is the flooding in coastal areas that occurs as a result of storm surges and coastal erosion. This challenge, traditionally tackled with manmade (grey) infrastructure such as sea walls or dikes, coastal flooding, can also be addressed by actions that take advantage of ecosystem services such as tree planting.
NbS definition by EU	"Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions.
NbS definition by IUCN	Nature-based Solutions leverage nature and the power of healthy ecosystems to protect people, optimise infrastructure and safeguard a stable and biodiverse future.
Grey infrastructure	Grey infrastructure refers to the traditional, built infrastructure using hard materials like concrete and steel. It encompasses engineered systems designed for specific functions like water supply, transportation, and wastewater treatment. Examples include roads, bridges, dams, and water treatment plants.
Green infrastructure	Green infrastructure refers to a strategically planned network of natural and semi-natural areas, alongside other environmental features, designed to deliver multiple ecosystem services and enhance human well-being. It encompasses a range of approaches, including utilizing plants, soil, and natural materials to manage stormwater, improve air and water quality, provide recreational

	spaces, and promote biodiversity. Essentially, it's about integrating nature into the built environment to address various environmental, social, and economic challenges.
Blue infrastructure	Blue infrastructure consists of bodies of water, water courses, ponds, lakes, and storm drainage systems that perform ecological and hydrological functions, including evaporation, transpiration, drainage, infiltration, and temporary storage and discharge of run-off.
Resilient infrastructure	Infrastructure systems and networks, the components, and assets thereof, and the services they provide, that can resist and absorb disaster impacts, maintain adequate levels of service continuity during crises, and swiftly recover in such a manner that future risks are reduced or prevented.
Critical infrastructure	The physical structures, facilities, networks, and other assets, which provide services that are indispensable to the social and economic functioning of society, and which are necessary for managing disaster risk.
Infrastructure maintenance	Maintenance is a cycle of activities designed and undertaken to preserve the optimal functioning of infrastructure, including in adverse conditions. It is a necessary precondition for the preservation of its operational capability, and to guarantee service continuity.
Disaster risk management	The concept and practice of reducing disaster risks through systematic efforts to analyse and manage their causal factors, including through reduced exposure to hazards, lessened vulnerability of people and property, wise management of land and the environment, and improved preparedness for adverse events.
Exposure	The location, attributes, and value of important community assets that are exposed to the hazard, such as people, buildings, agricultural land, and infrastructure.
Hazard	A natural or anthropogenic phenomenon that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation. Natural hazards relate to natural processes (such as floods, storms, droughts, earthquakes, and so on) and may be single, sequential, or combined in their origin and effects. They may differ in intensity or magnitude, scale, and frequency and are often classified by cause, such as hydrometeorological or geological. Anthropogenic hazards relate to hazards caused by human activity.

Long List of NbS Interventions

Table A1 presents a long list of NbS interventions by hazard type. Note that this long list can be seen as a selection, since for a single hazard such as drought, more than 50 measures can be identified. See also the tool Climatescan.org, which documents over 100 NbS interventions (Restemeyer & Boogaard, 2021; Tipping et al., 2015).

Table A1: Long list of NbS interventions for heat, drought and floods

NbS practice	NbS type	Description/function	Potential scale of implementation	Potential strategy
Planting of vegetation and trees	Green	Trees give shade and increase infiltration, slowing run-off and reducing discharge	Regional network	Prevention
Green roofs	Green	Increase drainage capacity on rooftops; provide insulation during high temperatures; reduce run-off in urban areas	Regional network; national network	Pro-active attitude
Swales and rain gardens	Green/blue	Permaculture installation working as temporary water storage/reservoir for run-off/storm water	Object—stretch	Upgrade/retrofitting /new construction
Water harvesting	Blue	Collection and retention of rainwater to reduce total run-off	Object—stretch—network	Preventive maintenance and replacement
Unpaved pavement and grass-filled grid pavers	Green/hybrid	Infiltration of storm-water through vegetated openings	Object—stretch—network	Upgrade/retrofitting /new construction
Sedimentation ponds, retention ponds	Blue	Temporary catchment of eroded and disturbed sediments during rain/flooding	Object—stretch—network	Pro-active attitude
Peatlands, wetlands, and constructed wetlands	Blue	Flood-water storage, water retention; reduce run-off and discharge	Regional network	Pro-active attitude
Ditches, swales, two-stage ditches, detention basins, and dry ponds	Green/blue	Temporary storage/reservoirs for run-off/storm waters	Object—stretch	Upgrade/retrofitting /new construction
Floodplain protection,	Green/blue	Maintaining the function of floodplains,	Regional network, national network	Pro-active attitude

NbS practice	NbS type	Description/functi on	Potential scale of implementation	Potential strategy
woodland restoration		increasing infiltration, reducing run-off and discharge in the floodplain		
River renaturation, re-meandering, and restoration	Blue	Restoring natural river pathways	Object—stretch — network	Pro-active attitude
Leaky barriers	Green	Slowing stream flow and increasing soil conductivity most effective for mitigating smaller flood events	Object—stretch	Upgrade/retrofitting /new construction
Excavation of floodplains	Blue	Increasing floodplain area to reduce stream flow and run-off	Regional network	Prevention
Dike and dike relocation	Green	Flood defence structures, physical barrier between land and water	National network	Pro-active attitude
Porous surfaces such as pavement	Hybrid/grey	Increasing drainage capacity in urban areas, reducing run-off	Object–stretch–network	Upgrade/retrofitting /new construction
Large woody debris and engineered logjams	Green	Flood regulation and increased hydraulic roughness of the channel, reducing downstream discharge	Object–stretch–network	Pro-active attitude
Floodplain restoration and reconnection	Hybrid	Restoring the natural extent of the floodplain, increasing discharge capacity	Regional network	Prevention
Dams and vegetated dams	Blue	Flood water storage/reservoir	Object—stretch—network	Upgrade/retrofitting /new construction
River and river bed widening	Blue	Increasing stream flow capacity, reducing flooding; past river channel	Object—stretch — network	Prevention
Room for the River	Blue	A Dutch initiative to lower floodplains, creating water buffers, increasing the depth of side channels, and relocating levees to increase river discharge capacity	Regional network	Prevention

NbS practice	NbS type	Description/functi on	Potential scale of implementation	Potential strategy
Rewilding and vegetation restoration	Green	Increasing infiltration, slowing run-off	Object—stretch — network	Pro-active attitude
Stone/soil bunds	Green	Restricting upstream flow, reducing downstream discharge	Object—stretch — network	Pro-active attitude
Natural water retention and retention landscapes	Blue	Retaining water upstream, reducing downstream discharge	Regional network	Prevention
Offline storage areas, buffer areas to retain water	Blue	Water retention upstream, reducing discharge	Object—stretch—network	Pro-active attitude
Geotextiles and mulches	Hybrid	Increasing capillarity, absorbing water, and increasing drainage	Object—stretch	Prevention
Barrier removal, clearing of blockages, and removal of recent accumulation of debris	Green	Removing obsolete dams, restoring the natural watershed system. Natural watershed systems, which reduce flood risk more effectively than undersized or poorly located barriers and dams	Object—stretch	Prevention
Chipped branches	Green	Increasing water absorption	Object—stretch	Prevention
Grassed waterways	Green	Stabilizing waterways with reduced erosion, stable discharge point. Only medium run-off threshold; paved catchments are recommended if water is to be collected and stored in dams	Regional network	Pro-active approach
Water harvesting	Blue	Collecting rainwater to retain water, reducing total run-off	Object—stretch—network	Preventive maintenance and replacement
Disconnected roof drains	Hybrid	Leading drained water to areas with high absorption and infiltration capacity, reducing surface	Object—stretch—network	Pro-active attitude

NbS practice	NbS type	Description/functi on	Potential scale of implementation	Potential strategy
		run-off and discharge		
Catchment woodlands	Green	Total area of woodland within a catchment or, more specifically, cross-slope, riparian or floodplain woodland; all increase infiltration and reduce stream flow velocity	Object—stretch — network	Pro-active attitude
Soil and land management	Green	A type of run-off management; physical barriers and infiltration	Object—stretch—network	Pro-active attitude
Cyclic floodplain rejuvenation	Blue	Restoring diverse floodplain vegetation. Increasing infiltration capacity, reducing stream flow velocity	Object—stretch — network	Preventive maintenance and replacement
Continuous-cover forestry	Green	Increasing infiltration capacity, reducing stream flow velocity	Regional network—national network	Pro-active attitude
Overland flow areas	Green	Semi-permeable dam, retaining water	Object—stretch — network	Pro-active attitude
Preservation of upstream forests	Green	Increasing infiltration, reducing run-off and downstream discharge	Regional network—national network	Prevention
Rain garden	Green/blue	Engineered garden: water storage/reservoir for run-off/storm water	Object—stretch	Upgrade/retrofitting /new construction
Watershed renaturation	Blue	Reestablishing the infiltration capacity and water retention in the natural watershed	Regional network	Pro-active attitude
Live crib walls and facings	Green	A low wall of living material to protect toe and grading of the soil, stabilizing steep slopes and protecting the banks of streams against erosion	Object—stretch — network	Upgrade/retrofitting /new construction

NbS practice	NbS type	Description/functi on	Potential scale of implementation	Potential strategy
Soil bioengineering structures, hydroseeding	Green	Introducing vegetation to steep slopes, e.g., hydroseeding: a slurry of seeds, sediments, nutrition, and water that is sprayed onto a slope in order to have roots and vegetation, stabilizing the sediments	Object—stretch — network	Upgrade/retrofitting /new construction
Biodegradable road embankment geotextiles	Green	Biodegradable liners used to cover man-made road embankment for erosion protection due to heavy run-off	Object—stretch	Biodegradable road embankment, geotextiles
Cover crops	Green	Add lower-growing vegetation in between higher-growing crops to increase infiltration and root systems, stabilizing and strengthening the soil	Object—stretch — network	Cover crops
Live pole drains	Green	Bundles of tree branches to form tubular structures to improve surface water drainage along a slope	Object—stretch	Live pole drains
Permanent grassing	Green	Grassing very effective for soil conservation	Object—stretch — network	Permanent grassing
Vegetative barriers and grass filters	Green	Narrow strips of stiff and densely growing vegetation planted perpendicular to the slope stabilizes soil and slope, reduces run-off	Object—stretch—network	Vegetative barriers and grass filters
Afforestation/reforestation, forest maintenance	Green	Forests dampen velocity and impact pressure of rockfall	Regional network—national network	Afforestation/reforestation, forest maintenance
Natural protection measures	Hybrid	Protective structures made from logs placed on unstable rocks to prevent release	Object—stretch	Natural protection measures

NbS practice	NbS type	Description/function	Potential scale of implementation	Potential strategy
Buffer strips, riparian forest buffers	Green	A vegetative buffer on the edge of a stream/river bank, intercepting, slowing run-off, and stabilizing the eroding banks	Object—stretch	Buffer strips, riparian forest buffers
Terraces	Green	Water retention upstream, reducing water discharge along a slope	Object—stretch — network	Upgrade/retrofitting /new construction
Debris deflectors	Green	Embankments or natural fences aimed at changing the debris flow path	Object—stretch — network	Upgrade/retrofitting /new construction
Grazing management	Green	Managing the grazing areas to maintain higher vegetation than short cut grass; better infiltration and reduced run-off, improving slope stabilization	Object—stretch — network	Pro-active attitude
Sustainable forest management	Green	Conservation and sustainable management of forests in steep terrain, plantation of new forests	Regional network	Prevention

Source: Adapted from (Paor & Connolly, Guidelines providing an overview of and characterisation of adaptation options, with recommendations on implementation., 2024), Boogaard et al. (2025), and Capobianco et al. (2024)

Road Map and Assessment for NbS—Additional Information

From global practices, a stepwise approach emerges for agencies seeking to integrate NbS. The previous sections have examined the transition from grey infrastructure to NbS (including hybrid approaches) and identified several crucial steps that together form a practical road map for implementation:

1. Hazard and risk assessment
2. Mapping existing assets, including infrastructure, ecosystem, and NbS
3. Screening NbS options across project life cycles
4. Alignment with strategic and regulatory frameworks
5. Detailed technical design and decision-making
6. Building institutional and technical capacity
7. Monitoring, evaluation, and adaptive management

Road maps enable decision-making for asset managers who recognize the value of incorporating NbS into infrastructure assets to enhance resilience. As discussed in previous sections, NbS for infrastructure are not a 'one-size-fits-all' package; therefore, the detailing of the approach, framework, checklist, or road map to implement NbS depends on the type of hazard and infrastructure and on several other factors (technical, social, environmental, governance) and location-specific characteristics such as geo-hydraulic circumstances.

Road Map for NbS Navigation at the Project Level

Incorporating NbS into infrastructure systems requires a clear, context-driven approach that balances technical, environmental, and social considerations. Begin by *analysing the current situation*. Then *set realistic and achievable ambitions,* taking into account constraints such as space, capacity, and budget. Most importantly, develop an *action plan* that aligns with the existing conditions and defined goals. It need not necessarily be in this order; starting with action as part of 'learning by doing'—to prevent staying in the 'analysing phase with reports' and showing progress with quick wins—is recommended.

Analysis

Step 1: The process can begin with a comprehensive vulnerability and risk assessment, in which engineers evaluate the threats posed by hazards and climate extremes to specific infrastructure systems. At this stage, it is essential to consider whether nearby or restored ecosystems can offer protective functions. Mapping natural assets and identifying how they interact with built infrastructure can reveal opportunities for NbS that align with the resilience goals.

Several questions (Table A2) should be addressed to determine the current situation (the starting point), including the current, already implemented, grey and green infrastructure assets related to the identified challenges and potential solutions. It is advisable to evaluate current grey infrastructure and NbS before upscaling to the action plan (see, for example, section on Challenges and Solutions in applying NbS for DRI).

In project management, similar questions and steps may arise as stated in the road map. These steps help clarify where one is in the process:

1. Define the situation and the problem (absorb, respond, recover).
2. Establish the project team, and define governance arrangements.
3. Define the project goals and objectives.
4. Identify a suite of potential solutions.
5. Conduct a multi-criteria analysis.
6. Undertake technical assessments.
7. Carry out an economic assessment.

Ambition

Following the assessment, identifying and evaluating suitable NbS options is a critical step, as discussed in Sections 2 and 4. Engineers must appraise potential interventions for their effectiveness in managing the identified risks while considering the site's biophysical conditions, land-use context, regulatory constraints, and available resources. NbS should be assessed against criteria such as cost-efficiency, technical feasibility, maintenance requirements, expected lifespan, and long-term resilience outcomes. It is also important to recognize that NbS may not always be the most appropriate stand-alone solution—some contexts may require conventional grey infrastructure or hybrid systems that combine both approaches.

Several questions (Table A2) should be answered to clarify the intended destination before defining the project's ambition and concrete goals. The key point to be decided is what one wants to achieve This could be about technical implementation but also about financial structuring, policy and permitting, and governance.

It is advisable to communicate as specifically and measurably as possible when engaging with multidisciplinary and cross-sector stakeholders.

Action

Once a viable set of interventions has been identified, the next phase involves designing, implementing, and embedding NbS within broader infrastructure planning processes. This stage includes integrating landscape-level, green and blue measures into infrastructure layouts, engineering specifications, and operational protocols. Engineers should develop tailored operation and maintenance plans that account for the dynamic nature of ecosystems. Engaging local stakeholders, securing long-term funding (including resources for the maintenance phase), and ensuring institutional support are essential for sustaining NbS performance over time.

Allocate resources before action, as discussed in the previous sections. Relevant levers and tools for securing these resources include budget and finance skills, technical support and innovation, and capacity building.

There are several key practical learning points for developing an action plan and identifying the steps required both before and during implementation. One important step is to break down the overall goal into smaller, manageable steps or milestones. Identify key tasks: What specific actions are required to achieve each climate-adaptive objective while minimizing damage to the infrastructure? Set a reasonable timeline for the implementation of NbS for infrastructure resilience. Establish a realistic time frame for each step of the process.

Action plans are needed to operationalize the initiative, including a design and implementation plan, an operations and maintenance plan, and a monitoring and evaluation plan where stakeholders are involved and their actions clearly stated.

Share the plan. Sharing the road map with others can improve accountability and support.

Monitor progress. Regularly review progress, and make adjustments as needed. Monitoring and adaptive management are essential to ensure that NbS continue to deliver the expected outcomes as conditions evolve. This involves establishing measurable indicators not only for risk reduction but also for broader co-benefits, such as improved air and water quality, biodiversity gains, and enhanced community well-being. A flexible, learning-oriented approach enables course correction and supports continuous improvement. Overall, the road map encourages engineers to adopt an integrated mindset—leveraging both green and grey measures—tailored to the local context and the specific performance needs of the infrastructure system.

Table A2: Optional self-assessment questions

1. **Hazard and risk assessment**

   Do you clearly understand the risks that NbS are intended to address?

   - Do you have access to long-term ecological, hydrological, and hazard datasets?
   - Are hazard and vulnerability assessments (e.g., 50- to 100-year climate event scenarios, GIRI, GRI) being used to identify risks to infrastructure?
   - Can digital tools such as geographic information systems, 3D modelling, and hydrological simulations be leveraged to assess hazards and test NbS scenarios?
   - Are performance metrics being redefined to capture key NbS attributes, including adaptability, redundancy, and regenerative capacity?

2. **Mapping existing assets (infrastructure, ecosystem, NbS)**

   Do you know what assets you already have?

   - Is there a baseline framework covering both grey infrastructure metrics (e.g., reliability, robustness) and key ecological processes (e.g., vegetation, soil, hydrology)?
   - Have ecosystem assets such as wetlands, forests, and floodplains been mapped within the broader infrastructure risk context?
   - Are past or existing NbS pilots or demonstration projects documented for potential replication?
   - Can NbS examples from other regions be adapted to the local ecological and social context?

3. **Screening NbS options across project life cycles**

   Do you systematically consider NbS alongside grey measures?

- Are NbS catalogues, case studies, or inventories being used to develop an options menu?
- Are multidisciplinary teams (engineers, ecologists, economists, planners, and community managers) engaged in the appraisal of options?
- Are pilot projects or 'living labs' being used to test and refine NbS designs throughout the planning, delivery, and operational stages?
- Can community-based monitoring or citizen science be integrated into the screening and evaluation of options?
- Are adaptive design principles in place to tailor NbS interventions to site-specific conditions?

4. Alignment with strategic and regulatory frameworks

Do NbS initiatives connect with wider policy, planning, and standards?

- Do staff have access to relevant guidance—such as climate adaptation plans, building codes, and regulatory standards—that supports NbS integration?
- Are NbS performance metrics aligned with, or linked to, conventional engineering standards?
- Is leadership committed to embedding NbS in planning codes, procurement frameworks, and investment appraisal processes?
- Are lessons learned—both successes and failures—systematically documented to inform updates to standards and national or sectoral policy?
- Can trade-offs between ecological integrity, social benefits, and infrastructure services be systematically evaluated?

5. Detailed technical design and decision-making

Can you design and fund NbS with confidence?

- Can your agency quantify both the upfront and the long-term benefits of NbS, including avoided damages, ecosystem services, and public health outcomes?
- Are valuation tools—such as IISD SAVi, the NbS Blueprint, or the WBCSD NbS Map—being applied?
- Can financing mechanisms, including green bonds, payments for ecosystem services, environmental impact bonds, or parametric insurance, be piloted?
- Have potential co-beneficiaries—such as utilities, insurers, communities, and the tourism sector—been mapped for potential cost-sharing?
- Can procurement or PPP contracts be structured to reward ecological outcomes and adaptive management?

6. Building institutional and technical capacities

Do staff and institutions have the skills and culture for NbS?

- Do staff possess skills in ecological monitoring, adaptive management, and hybrid engineering approaches?
- Can cross-disciplinary training be provided for engineers, ecologists, planners, and finance officers?
- Have institutional champions or focal points been identified to bridge grey–green approaches?
- Are staff able to dedicate time to learning, pilot initiatives, and peer exchanges?
- Are open-access learning platforms and exposure visits being leveraged?
- Is there awareness across departments of the shared responsibility for NbS implementation?

7. Monitoring, evaluation, and adaptive management

Are feedback mechanisms in place to refine NbS over time?

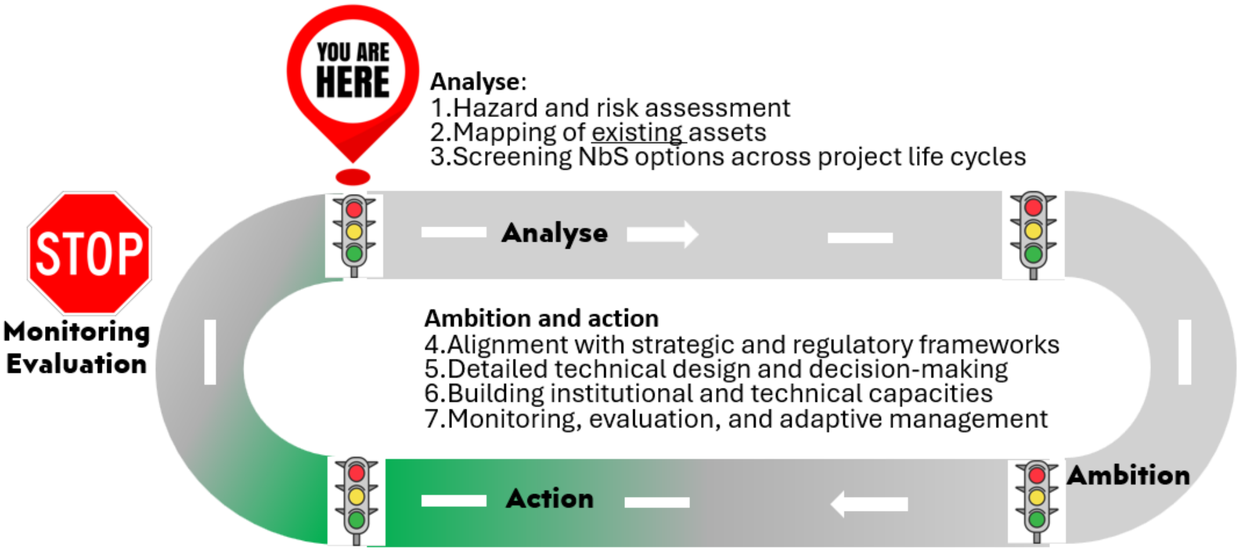
- Do monitoring frameworks track both engineering performance and ecological health?
- Do institutional processes support iterative learning and adaptation?
- Can lessons learned from pilot projects and operational experience be documented and shared internally and externally?
- Are integrated datasets and cross-institutional collaboration mechanisms in place to support monitoring?
- Are performance and scalability risks tracked and shared among public, private, and community stakeholders?
- Is adaptive management embedded to ensure that NbS can evolve in response to changing climate, ecological, and social conditions?

Source: Authors' compilation

Detailed Road Map with Pathways

The 'keep it simple' approach, using guiding questions throughout the pathway, can be visualized as a road map—a practical map that identifies the current position, the desired destination, and the steps required to reach it. This road map helps maintain direction and focus on achieving the intended outcome—resilient infrastructure.

Figure A1: Road map with pathways



Source: Authors' analysis

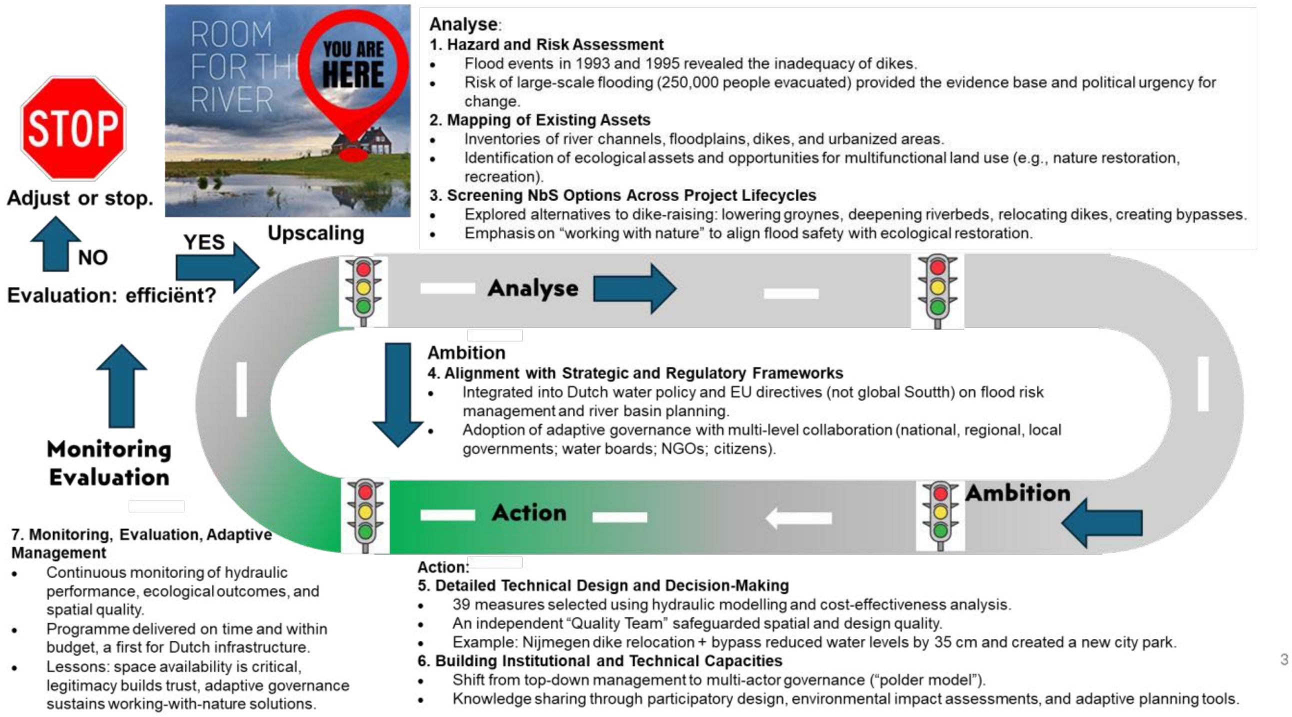
The road map is adapted from established resilience planning frameworks, including those developed by the European Commission (2021); the Global Center on Adaptation, Environmental Change Institute, University of Oxford, Resilient Planet Finance Lab (2025); and the Global Facility for Disaster Reduction and Recovery, World Bank Group, Program on Forests, & World Resources Institute (2018). Based on these frameworks, seven key steps have been identified:

1. **Hazard and risk assessment:** Begin with a systematic assessment of climate and disaster risks to understand infrastructure vulnerabilities and identify entry points for resilience.
2. **Mapping of existing assets (infrastructure, ecosystem, NbS):** Map both built and natural assets to recognize ecosystem functions and assess the potential contributions of NbS to infrastructure planning.
3. **Screening NbS options across project life cycles:** Evaluate and test a portfolio of NbS across project stages to identify context-appropriate, feasible, and high-impact interventions.
4. **Alignment with strategic and regulatory frameworks:** Integrate NbS into planning, investment, and regulatory frameworks to ensure that they are recognized as core components of resilient infrastructure.
5. **Detailed technical design and decision-making:** Develop standardized, context-sensitive technical guidelines and specifications for integrating grey, blue, and green infrastructure.
6. **Building institutional and technical capacities:** Strengthen institutional knowledge and technical skills to implement, manage, and scale NbS effectively within infrastructure systems.
7. **Monitoring, evaluation, and adaptive management:** Continuously monitor ecological and engineering performance to inform adaptive management and improve long-term resilience and co-benefits.

Infrastructure agencies can assess their readiness to implement NbS across these pathways by combining practical considerations from resources, governance, finance, capacity, and technology.

In several projects and road maps, education and knowledge exchange are treated as a distinct step within adaptive management, which in this road map is part of step 6: 'Building institutional and technical capacities.' This would entail knowledge exchange at both national and international levels, as CDRI is doing through its MOOC with workstreams related to this report: risk, governance, NbS, and finance.

Figure A2: Room for the River in the roadmap



Source: Author's analysis

The roadmap is used to interpret the Room for the River programme (Fig. A2), illustrating how its phases align with analysis, action, and long-term ambition. In doing so, the programme serves as a practical example of how the roadmap can be applied, progressing from risk assessment to implementation and adaptive ambition over time. It reflects a shift from traditional flood defence towards working with nature, embedding NbS across the project lifecycle. Through iterative decision-making that integrates technical assessment, spatial planning, and stakeholder engagement, the programme effectively operationalises the roadmap.

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[1] The dollar sign in Box 3.1 and the rest of the text refers to US dollars, unless specified otherwise.

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