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OneAquaHealth

Catalogue of measures for urban aquatic ecosystems rehabilitation

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OneAquaHealth

PROTECTING URBAN AQUATIC ECOSYSTEMS TO PROMOTE ONE HEALTH

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D2.4 Catalogue of measures for urban aquatic ecosystems rehabilitation

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Executive Summary

The current deliverable aims to review and compiles best practices that can be used in the rehabilitation or restoration of urban freshwater lotic ecosystems (i.e., rivers and streams). These measures ultimately aim their return to a good health, i.e., to good ecological conditions, which are a protective measure safeguarding the One Health in cities. It provides a brief diagnosis of the main pressures affecting urban streams and rivers and presents a structured set of measures addressing their morphological, hydrological, chemical, ecological, and social dimensions.

Special emphasis is placed on techniques that prioritise the reestablishment of natural ecosystem structure and processes, and the ecosystem resilience, promoting long-term sustainability and ecological integrity. The catalogue integrates a hierarchical approach to guide the selection of measures, from essential actions such as pollution control and riparian vegetation restoration to structural interventions, social measures, and complementary strategies adapted to the constraints of urban environments. Each measure includes its objectives, application scenarios, ecological benefits, limitations, and contribution to ecosystem services and human well-being.

To bridge theory and practice, the deliverable compiles real case studies from different cities worldwide, illustrating practical implementation, challenges, and lessons learned. A dedicated section highlights common limitations in urban settings and provides guidance for context-specific application. The catalogue also links rehabilitation measures to ecosystem services and human health, reinforcing their importance within a One Health framework.

This work provides essential input for the development of the OneAquaHealth Decision Support System and its Toolkit of solutions.

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Acronyms & Abbreviations

Term	Description
APA	Agência Portuguesa do Ambiente (Portuguese Environment Agency)
ARNET	Aquatic Research Network
BACI	Before-After-Control-Impact
BAG	Before-After-Gradient
CSOs	Combined Sewer Overflows
DIMFE	The Donors' Initiative for Mediterranean Freshwater Ecosystems
DSS	Decision Support System
EBC	Erosion Control Blanket
ENGO	Environmental Non-Governmental Organization
EGLV	Emschergenossenschaft (Emscher Cooperative)
GEOTA	Grupo de Estudos de Ordenamento do Território e Ambiente (*Study Group for Spatial Planning and Environment*)
MARE	Marine and Environmental Sciences Centre
MAVA	MAVA Foundation (Fondation MAVA pour la Nature)
NbS	Nature-based Solution
NGO	Non-Governmental Organization
OAH	OneAquaHealth project
RCC	River Continuum Concept
RR	ROLLIN' RIVERS: People, Knowledge and Action to Enhance River Restoration in Portugal
SMART	Specific, Measurable, Achievable, Realistic, and Time-bound
WFD	EU Water Framework Directive

1 Introduction

1.1 Overview

The scope of this deliverable is to review and compile current knowledge and solutions for the rehabilitation of urban freshwater lotic ecosystems, i.e., streams and rivers. The catalogue briefly identifies the main challenges affecting these ecosystems and presents detailed approaches and measures to address them, restoring or rehabilitating the ecosystems, considering is multiple ecological dimensions such as biological, morphological, hydrological, chemical, and social dimensions. It also emphasizes how these measures contribute to ecosystem services and human health. It provides the base-knowledge for the Toolkit of Solutions integrated in the OneAquaHealth Decision Support System, OAH DSS (D6.4, D6.5).

1.2 Relation to other tasks and deliverables

This deliverable is related to the following other OneAquaHealth tasks and deliverables:

Receives inputs from:

Table 1. D2.4 Input from other tasks and deliverables.

Deliverable	Due Date	Input for D2.4
D2.2	M36	Definition of Early warning indicators
D5.4	M36	Based on scenario analyses

Provides outputs to:

Table 2. D2.4 Output for other tasks and deliverables.

Deliverable	Due Date	Output from D2.4
D6.4	M36	Review of best practices and solutions for urban stream rehabilitation. These will be integrated into the DSS and the first version of the Toolkit, providing guidance on ecosystem rehabilitation/recovery measures that help prevent health risks under different urban conditions
D6.5	M42	The catalogue provides the foundational input for the second version of the DSS, which will include the final Toolkit. This input ensures that the DSS integrates validated, evidence-based measures to support ecosystem and biota rehabilitation and to reduce health risks in diverse urban scenarios

1.3 Structure of the deliverable

This deliverable aims to review, compile, and organise current knowledge and solutions for the restoration or rehabilitation of urban freshwater lotic ecosystems, i.e., running water ecosystems – rivers and streams. It provides a comprehensive diagnosis of the main pressures affecting these systems. It presents a structured set of morphological, hydrological, chemical, biological/ecological, and social measures designed to address the challenges in an integrated way.

Special emphasis is given to rehabilitation strategies that prioritise natural or nature-based approaches, removing and avoiding further artificialization, to promote the ecosystems resilience, ecological connectivity, and long-term sustainability. In addition to a literature review, the deliverable includes a dedicated section on practical implementation, outlining common challenges and limitations, and illustrating the application of selected measures through real case studies.

Overall, this catalogue serves as a key reference for the development of the Good Urban Stream Rehabilitation Practices Toolkit and provides essential input for the Decision Support System (D6.4 vs1, D6.5 vs2), supporting evidence-based decision-making for urban stream rehabilitation.

2 Urban Streams Restoration and Rehabilitation

2.1 Reference condition approach

The planning of the restoration process for a stream or river should, in principle, be based on a reference condition (**Reynoldson et al., 1997**), i.e., aiming as much as possible, to return the ecosystem to its natural state. It must also consider the river typology when determining the reference conditions, taking into account the natural characteristics and biodiversity of that specific ecosystem prior urbanization or impacts. This includes consideration of: i) the position of the stream or river within the catchment, following the River Continuum Concept (**Vannote et al., 1980**), such as headwaters, middle reaches, or lowland areas; ii) geology and sediment type (granulometry and geodiversity); iii) slope and discharge regime; iv) channel width and shape-morphology; v) riparian species composition and vegetation structure; among other site-specific features. In addition, vi) biomes, ecoregions, and the climatic conditions of the stream or river should also be considered.

For example, in mountainous area of temperate regions, a small stream meanders through a dynamic landscape, sometimes flooding its banks during wetter seasons and retreating during dry periods. Along its course, fallen trees, branches, and leaves create a mosaic of microhabitats and constitute a food source that support diverse communities of plants, animals (vertebrates such as fish, and invertebrates such as insects), and microorganisms. The accumulation of organic matter fuels decomposition processes that sustain species richness, and continuous nutrient cycling. The riparian vegetation also provides shade, stabilizes the banks, and connects aquatic and terrestrial habitats.

If we consider a stream in a lowland area of a catchment, they are typically characterized by gentle gradients and slow to moderate water velocities. These low-energy conditions promote sediment deposition rather than erosion, resulting in substrates dominated by fine-grained sediments with only sparse stones or boulders. Lowland streams naturally form meanders, broad bends, and oxbows, and tend to have wide, shallow cross-sections with gently sloping banks. They are often embedded within broad floodplains and associated wetlands.

A stream in the Mediterranean region, as an example, has a hydrology marked by strong seasonality, with flashy, high-energy flows in winter and low-flow or even ephemeral conditions during summer. These hydrological extremes shape the channel into a narrow, often deeply incised form, typically underlain by coarse substrates such as gravels and cobbles, which are regularly reworked by intense flood events. Riparian and in-channel vegetation tend to be sparser and highly drought-tolerant, while also capable of withstanding periodic flooding. Also, biological communities reflect these constraints. Mediterranean streams are colonized by specialized species adapted to rapid shifts in flow, temporary habitats, and prolonged dry periods.

Therefore, the reference approach is essential to prevent the design of measures that could improve some aspects but also promote more artificialization of a stream. In general the measures should consider as much as possible the re-naturalisation and techniques that let the system return to their **natural state with the less possible intervention**, and avoid techniques that imply the use of artificial materials, highly invasive techniques that further destroy the ecosystem (e.g., use of large machinery inside the channel or in the banks), or bringing species from other regions (in opposition, for example, to the propagation of species that already exist in the stream or catchment in a nearby area).

2.2 Potential limitations in the urban environment: restoration and rehabilitation concepts

Although the above should be the starting point of a restoration plan, urban settings may limit the possibilities of performing a full ecological restoration of streams due to the constructed environment, stress level, and social context.

Urban streams have often less floodplain available, have fragmented riparian zones, are surrounded by infrastructure or have highly modified or artificial channels and embankments. Due to such changes their hydrology is also modified, with frequent flash floods, changed baseflows, and fast runoff from impermeable surfaces. Stormwater, sewage overflows, and diffuse pollutants constitute mixed pollution sources that frequently degrade water quality. Culverts, weirs, and underground sections frequently break connectivity (both transversal and longitudinal). Furthermore, social and aesthetic pressures are strong in urban areas, where streams are expected to deliver multiple services such as recreation, landscape value, and public safety. These particularities of urban streams require specific restoration approaches.

Because of these constraints, ecological restoration in urban environments is often reframed as “rehabilitation” or “renaturalisation”, aiming not to recreate pristine conditions (which may be unknown or irreversibly altered in very dense cities), but to re-establish key ecological functions, such as hydrological regulation, habitat diversity, longitudinal and lateral connectivity, and water-quality improvement, within realistic constraints (**Figure 1**).

However, alternatives to full ecological restoration should be considered only when the **removal of built infrastructure or residential buildings is demonstrably impossible**. In this context, land reclamation for the ecosystem, including the recovery of space currently occupied by urban uses, should itself be regarded as a legitimate and necessary restoration measure. **It is also important to recall that most European water and environmental legislation recognise riparian zones as an integral part of river systems, requiring their protection and restoration even when they fall within private land**.

Therefore, the first step in stream or river rehabilitation requires the definition of clear ecological objectives, while also considering the social benefits that people obtain from the freshwater ecosystems in urban areas.

A realistic project should:

- depict a healthy ecosystem (e.g., healthy riparian vegetation, floodplain area, morphological diversity, transversal and longitudinal connectivity, ecological quality, biodiversity);
- be context-dependent;
- guide diagnosis, operational scale, and measurable objectives;
- ensure ecological improvement while delivering social benefits.
- serve as a communication tool among planners, citizens, and decision-makers;

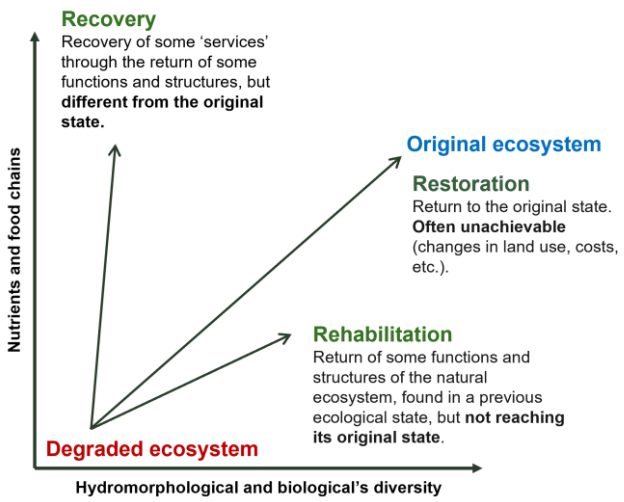


Figure 1. River recovery, restoration, and rehabilitation with the different aspects of the ecosystem structure and function considered to achieve distinct management goals. Based on **Cortes et al.** (**2019**)

2.2 Hierarchical approach: From Problem Diagnosis to Appropriate Measures

All restoration activities should be undertaken within an integrated project framework (**dos Reis Oliveira et al., 2020**). This framework should ensure there are sufficient baseline data to characterise the current status, identify causes of degradation, plan effective solutions, and set restoration targets.

Each action planned should be described by:

- **Objective:** what problem it addresses.
- **Examples:** practical cases from literature or partner experience.
- **Ecosystem services restored:** biodiversity, water purification, recreation, and health benefits.
- **Scale of application:** reach, catchment, city-wide
- **Limitations:** constraints in dense urban settings, costs, technical challenges.
- **Prioritization:** The European Centre for River Restoration (ECRR) emphasizes prioritization and the need to define what is essential and universal (e.g., riparian vegetation, water quality, river continuity) before investing in more costly and complex measures (e.g., floodplain reconnection). They highlight that barriers (even small ones) must be addressed early on, because otherwise they fragment the ecosystem and undermine other actions. They also stress that multiple problems require a package of hierarchical measures, it is not enough to just reshape the channel, nor is it enough to only plant trees.

In the context of restoration, mainly in urban areas, usually problems are multiple, and measures should be applied following a hierarchy, and tailored to specific urban contexts to achieve the best possible conditions (**Verdonschot and Verdonschot, 2023**). Thus, defining a first line (essential) of measures, followed by a second line (structural), and a third line (social) and a complementary line of measures.

First line (essential): Measures that address dominant pressures and secure minimum ecological conditions (water quality, riparian function and hydrological stressors), without which other interventions have low probability of sustained success:

- Riparian vegetation restoration, through the expansion and reconnection of riparian corridors, increased shading for temperature regulation, improved filtration of sediments and pollutants, and enhanced bank stability using native and locally adapted species. Well-functioning riparian zones also act as buffers that attenuate runoff, improve infiltration processes, and support microclimatic regulation.
- Improvement of water quality, including the control of point-source and diffuse pollution, as well as the reduction of contaminant inputs that limit biological recovery.
- Reduction of dominant physical pressures that directly undermine riparian function and water quality, where feasible, particularly those associated with altered surface runoff pathways and highly sealed urban surfaces.

Without these, the effectiveness of subsequent measures is greatly reduced. It is like fixing the leaks in a bucket before trying to fill it.

Second line (structural): Measures that restore physical habitat, morphology and connectivity to reinstate key ecological processes and associated ecosystem services, implemented once essential conditions are secured or, where urban constraints require, in parallel as part of an integrated delivery strategy.

- Morphological rehabilitation, including channel reconfiguration (e.g. re-meandering where feasible), substrate diversification, in-channel habitat complexity and local oxygenation processes;
- Floodplain reconnection, aimed at improving lateral connectivity and restoring space for flow, sediment deposition and ecological exchange;
- Barrier removal to restore longitudinal connectivity, or the implementation of fish passages in systems where barriers constitute the dominant limiting factor; in such cases, improving longitudinal connectivity becomes essential and should be prioritised at early stages of rehabilitation;
- Habitat improvement, through the creation of heterogeneous hydraulic and geomorphic conditions that support recolonisation and persistence of diverse biological communities.

These measures are considered structural because they reshape the physical architecture of the ecosystem and its functional connectivity. However, their effectiveness and persistence are strongly constrained if the chemical and riparian foundations of the system have not been at least partially secured.

Third line (social): Measures that strengthen long-term resilience by embedding river rehabilitation within governance frameworks, stewardship arrangements and socio-ecological systems. In urban contexts, these measures are essential to ensure continuity, legitimacy, maintenance and protection of restoration outcomes over time.

- Integration of riparian corridors into urban planning and land-use frameworks, ensuring that restored river corridors are recognised, protected and connected within broader ecological networks and public space strategies;
- Stakeholder engagement, co-design and stewardship, including public participation, citizen science initiatives, awareness-raising and shared responsibility mechanisms that support long-term care, compliance and social ownership of restored river systems.

Fourth line (complementary): Supporting measures that consolidate gains or manage secondary constraints/symptoms (e.g., invasive species control), and that are unlikely to succeed alone unless system-level drivers are addressed. These measures are supportive in nature and should be framed as part of an integrated package, rather than stand-alone solutions. These measures are valuable but cannot replace the others. They help consolidate gains, generate social and cultural benefits, and extend the effects of restoration.

- **Invasive species control**. In many cases, invasive species are better understood as symptoms of underlying habitat degradation rather than isolated causes and focusing only on their removal may neglect the drivers of ecosystem change (**Gaertner et al., 2012; Lapin et al., 2016**). This implies that invasive control alone won't succeed unless system-level stressors are

managed first; otherwise, invasives simply recolonize the restored sites. But without their control, renaturalisation may be feasible.

Compensatory (last-resort) measures (of several types): Constraint-driven, engineering-oriented interventions applied when process-based rehabilitation is not feasible, providing partial functional benefits but typically requiring continuous maintenance and offering **limited ecological self-sustainability**.

These measures involve a higher degree of artificialisation and are primarily designed to compensate for constraints that prevent the implementation of more natural or process-oriented solutions. They generally address the symptoms of degradation rather than its underlying causes, and are therefore targeted at achieving specific, often localized objectives, such as bank stabilisation, flood protection or infrastructure safety.

Compensatory measures are applied only when first-, second- and third-line measures are unfeasible due to severe spatial, technical or socio-political constraints, particularly in highly urbanised environments. While they can deliver short-term functional benefits, they often entail substantial financial investment, require continuous maintenance, and offer limited ecological sustainability over the long term.

For these reasons, compensatory measures should be regarded as options of last resort, to be implemented only when it is not possible to restore or re-establish self-sustaining ecological resilience and natural processes that support long-term river recovery. Rather than restoring ecosystem function, they compensate for its loss or mitigate impacts where more **nature-based solutions** (NbS) cannot be implemented.

Once restoration targets are established, they should be translated into clear SMART objectives, Specific, Measurable, Achievable, Realistic, and Time-bound, explicitly linked to project goals and expected outcomes. The absence of well-defined objectives, success criteria, or end points against which progress can be evaluated remains a major challenge in river restoration assessment (**Moore and Rutherfurd, 2017**).

2.3 Monitoring and evaluation

What should be monitored to evaluate restoration outcomes depends on both the river/stream type and the nature and scale of the intervention. Nevertheless, monitoring should always follow an integrated ecosystem approach that incorporates geomorphological, habitat, and biological assessments (**Lim and Do, 2023**).

Two broad categories of monitoring are commonly used in restoration: confirmatory and investigative (**England et al., 2021**). Confirmatory monitoring simply tests whether expected ecological responses occur, for example, checking for xylophagous (wood-feeding or wood-boring) invertebrates after large woody material is added. Confirmatory monitoring is simple but cannot address fundamental ecological questions or support prediction; these functions are the domain of investigative monitoring, which is more complex and involves measuring multiple related variables to understand the mechanisms and outcomes of habitat restoration.

Investigative restoration begins with collecting pre-restoration data to quantify baseline variability and establish appropriate target outcomes. It also involves identifying the factors driving that variability within the system (i.e., the catchment context) to guide the selection of suitable indicators, including consideration of multiple pressures. The frequency and duration of monitoring should align with the life histories of the target organisms and the expected timescale of their responses (i.e., the lag period) (**Figure 2**). Response times vary widely: algae often respond rapidly, fish show moderate response times, and riparian vegetation typically responds much more slowly.

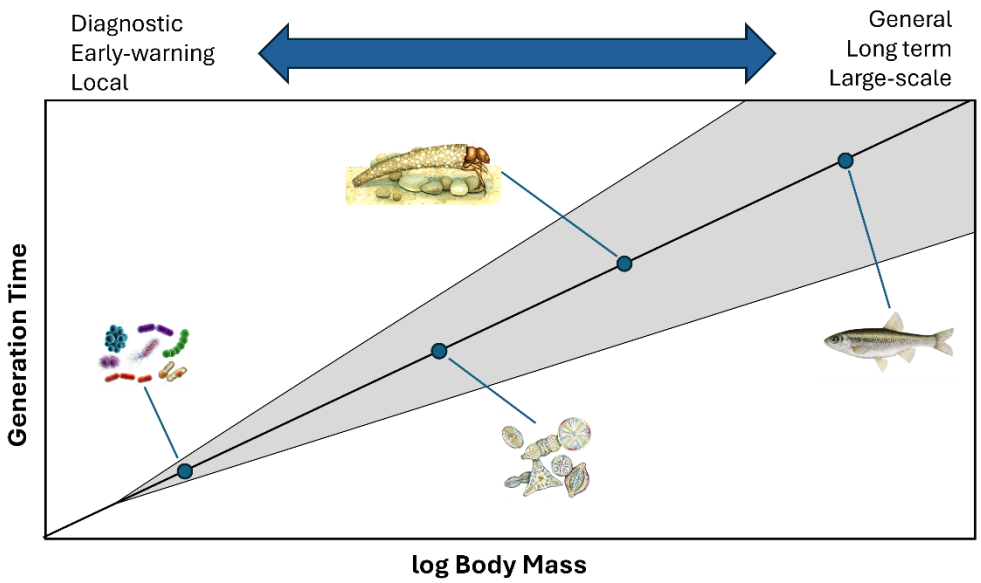


Figure 2. Biological monitoring indicators across body-size groups: small, short-lived organisms (e.g., bacteria, diatoms) detect short-term, localized changes with high stressor specificity, whereas larger, longer-lived organisms (e.g., fish) reflect broader-scale, long-term environmental change. Based on **England et al.** (**2021**).

The **Before-After-Control-Impact (BACI)** monitoring design, often combined with stratified random sampling, is widely regarded as best practice for detecting changes attributable to restoration

(**Underwood, 1994**). BACI designs are flexible and can be adapted to data limitations. For example, when control sites are unavailable, before-after studies must collect data for a sufficiently long period both before and after restoration to capture natural variability (e.g., periods of high and low flows). Conversely, when no "before" information exists, it is often assumed that Control and Impact sites were in comparable condition before the intervention. Control sites can be positive (the best example of what the restoration work is trying to achieve), negative (the state of a restoration site before the restoration intervention), or a combination of both. Without appropriate controls, it becomes difficult to determine whether observed changes result from restoration activities or from broader environmental variation.

An alternative is the **Before-After-Gradient (BAG)** design, which assesses ecological responses along spatial (lateral and longitudinal) and temporal gradients (**Underwood, 1994**). BAG approaches enhance understanding of the extent of restoration effects and typically offer higher statistical power than simple control-impact comparisons (**Methratta, 2020**).

Another alternative, to capture both local and system-wide effects, is **multi-scale monitoring**, which integrates data collected at different spatial scales (e.g., reach, sub-catchment, catchment; **O'Hare et al., 2020**). This data is potentially available presently in the European Member States due to the implementation of the ecological assessment of rivers after the European Water Framework Directive (WFD; 2000/60/EC; **European Parliament and Council, 2000**). Yet, in the case of urban streams this information may not exist, as often these water bodies were neglected from river monitoring programs. Nevertheless, **reference values** for similar river types should exist as they were established during the development of evaluation tools for the WFD (indices).

The main biological indicators used in the ecological monitoring of rivers and streams are:

- **Invertebrates.** Aquatic invertebrates respond sensitively to changes in habitat structure, water quality, and flow conditions (**Feio et al., 2023**). Because many taxa have short life cycles and specific environmental tolerances, they provide valuable indicators of ecological condition and restoration progress. Their community composition, abundance, and functional traits help reveal both short-term responses and longer-term shifts in ecosystem processes.
    - **Kick sampling**. Representative samples collected across multiple habitat types. Suitable for large-scale surveys but less effective for detecting fine-scale restoration responses. Works well in BACI designs and in situations expecting major habitat shifts, such as post-weir removal.
    - **Surber sampling**. Suction samplers that generate density estimates and support analyses of food webs, ecohydraulics, and habitat relationships.

- **Diatoms – microalgae.** Benthic diatoms respond rapidly to changes in water quality, hydrology, light availability, and substrate conditions. Because their silica frustules preserve well and taxa often show narrow ecological tolerances, diatom assemblages serve as sensitive and early-warning indicators of ecological condition and restoration progress. Their community composition, species turnover, and functional traits (e.g., motility, attachment strategy) reveal fine-scale changes in nutrient regimes, organic enrichment, hydromorphological alterations, and shifts in sediment dynamics (**Elias et al., 2015; Masouras et al., 2021; Pinto et al., 2020**).

- **Periphyton sampling** on natural or artificial substrates is usually performed, although diatoms can be collected also from the water column and sediments.
- **Diatom indices** (e.g., IPS, TDI, IBD) are especially effective for detecting improvements in water quality following restoration actions such as riparian shading, flow reconnection, or removal of pollution sources.
- **Diatom morphotypes** strongly reflect flow stability, sedimentation patterns, and light regimes. Shifts towards low-profile or adnate guilds can indicate increased shear stress or scouring, whereas motile and high-profile forms often proliferate in nutrient-enriched or depositional habitats, key signals of restoration efficacy or failure. Diatoms deformities (teratologies) can also be used as an indicator of stress (**Falasco et al., 2021**).
- **Microscopy-based counts, pigment analyses, and increasingly molecular techniques** (e.g., metabarcoding) provide robust assessments. Remote-sensing approaches can support large-scale detection of algal blooms or periphyton proliferation.

- **Macrophytes – aquatic plants.** Vegetation reflects water quality, conservation value, and geomorphological processes. Its influence on sediment stability and channel form means vegetation-geomorphology interactions are critical for understanding restoration trajectories (**Gurnell et al., 2020**). A few methods are valid for their evaluation, namely:
  - **Visual macrophyte surveys** over fixed river reaches provide semi-quantitative indicators of ecological quality; the surveys are at the basis of biological quality indices;
  - **Aquatic plant morphotypes** are strongly linked to hydraulic and hydrological conditions;
  - Monitoring of **Vegetation-Geomorphology Interactions** and vegetation alongside physical processes such as disturbance regimes or extreme events;
  - **Monitoring Tools** like field surveys, aerial photography, LiDAR, and remote sensing.

- **Fish.** Fish communities integrate ecological conditions over broad spatial and temporal scales due to their mobility, longer life cycles, and diverse habitat requirements. Their presence, abundance, and age structure provide key indicators of habitat quality, connectivity, and overall river health (**Van Andel and Aronson, 2012**). Because different species and life stages occupy distinct habitats, fish responses can reveal both reach-scale restoration effects and wider catchment pressures.
  - **Electrofishing**. A survey that uses controlled electric currents in the water to temporarily stun fish, allowing them to be netted, identified, measured, and released unharmed. It is used to assess fish populations, habitat use, and restoration outcomes in rivers and streams (**England et al., 2021**).
  - **Riparian vegetation.** The structure and composition of the riparian vegetation has proven to be a reliable indicator of restoration effectiveness but may take some time to manifest (**Arsénio et al., 2020**). Both quadrat and transect-based surveys are suitable monitoring practices. It is important to take account of zonation and succession patterns to ensure that the entire flora of the riparian zone is adequately

represented (**González Del Tánago and García De Jalón, 2006; González et al., 2015; Magdaleno and Martínez, 2014**).

In urban streams, where ecological conditions intersect closely with densely populated areas, monitoring may need to extend beyond the biological indicators established under the WFD. Due to the intensity of human-ecosystem contact, urban restoration frameworks should include broader assessments that include emerging pollutants (e.g., pharmaceuticals and other substances increasingly recognized as pollutants), bird communities that may act as reservoirs of pathogens, medically relevant Diptera that can function as disease vectors, invasive species whose dynamics often reflect urban disturbance, microorganisms from biofilms but others. Incorporating these complementary indicators strengthens a One Health approach by linking ecological restoration with public health safeguards and social well-being.

2.4 Maintenance and control

Grey engineering solutions used for river and stream management and often indicated as solutions for rehabilitation, such as concrete walls, riprap, gabions, sheet piling, culverts, and engineered channels, have relatively low short-term maintenance costs and their intervention needs are intensive but periodic (**Palmer et al., 2005**). However, these structures introduce further artificialization and alterations in the ecosystems, have limited adaptability, and their maintenance needs tend to increase over time. Structural fatigue, corrosion, undermining, and sediment imbalance progressively elevate repair requirements, and damaged or ageing elements frequently need expensive full replacement, typically involving heavy machinery such as cranes, excavators, or barges. Also, these rigid systems face additional pressure as extreme hydrological events are expected to become more frequent in the future, since they cannot adapt or self-repair.

Natural solutions for river and stream rehabilitation rely primarily on living materials and natural processes. As a result, their maintenance is generally low but continuous, focusing mainly on vegetation management, invasive species control, and ensuring successful plant establishment. Maintenance is therefore adaptive rather than corrective.

Rivers and streams are inherently dynamic systems, continuously adjusting their channel shape, banks, and flow pathways in response to changes in discharge, sediment transport, and vegetation growth (**Church and Ferguson, 2015**). During the early establishment phase (typically the first 2–3 years), bio-engineered structures and newly restored banks are still integrating into this dynamic system. Vegetation has not yet fully rooted or provided mechanical reinforcement, and flow paths may adjust as the river re-establishes its natural equilibrium. For this reason, close monitoring and occasional adjustments are essential during this period.

As vegetation matures and root systems develop, structural stability and ecological functions increase, maintenance requirements decrease, and restored elements become self-sustaining components of the ecosystem. In the long term, maintenance relies primarily on monitoring rather than repair. Regular ecological and hydraulic monitoring (e.g., vegetation cover, channel morphology, and bank stability) supports adaptive management, with most interventions being preventive rather than structural. In urban contexts, additional routine actions such as waste removal and inspections following major flood events are also commonly required.

Long-term maintenance should be ecosystem-supportive, enhancing the system's capacity to recover from disturbance while not compromising its long-term resilience. It should focus on four main aspects: selective pruning of riparian vegetation; maintenance of bank vegetation to ensure soil stability; preservation of the natural channel geometry, avoiding artificial reshaping; and selective removal of debris and waste from the channel.

Appropriate vegetation management enhances bank stability, filtration processes, nutrient cycling, shading, and overall habitat value. **Cleaning operations** in rivers and streams should therefore be carried out in a manner that preserves native, regionally adapted (local genetic pool) and non-invasive trees and shrubs along the banks, maintains herbaceous vegetation on the slopes, and protects the root systems of both shrub and herbaceous species. This approach reduces the risk of bank erosion and, consequently, limits excessive sediment input into streams or rivers.

In this context, “cleaning” refers to ecologically informed, selective channel stewardship rather than routine clearance. It primarily involves the removal of obstructions resulting from human activities, including:

- Removal of urban solid waste and anthropogenic debris;
- Highly selective removal of excessive vegetation biomass only where it poses a demonstrable risk to hydraulic infrastructure within the watercourse (e.g., bridges, weirs) or to public safety in recreational areas.

The objectives of these interventions are to:

- Ensure safe and sustainable use of water resources;
- Maintain adequate conveyance capacity for both liquid and solid fluxes (sand, fine sediments, organic matter) under normal and extreme hydrological conditions, without compromising natural dynamics;
- Minimise the risk of artificial bank destabilisation and subsequent excessive sedimentation.

Properly maintained streams and rivers should exhibit:

- Continuous riparian vegetation along the margins, where appropriate for the river type;
- Selective formative pruning that enhances shading over the channel (depending on the location in the RCC) while preserving structural diversity;
- Good ecological condition of both water quality and banks;
- A naturally irregular channel morphology (e.g., meandering or multi-thread patterns, where geomorphologically suitable);
- High structural and biological diversity.

Cleaning and maintenance activities should be carried out manually or using light equipment, and scheduled outside bird and fish breeding seasons, as well as outside peak rainfall periods. Ideally, interventions should occur every 2-3 years, allowing lighter and less invasive actions. Management should prioritise the preservation of native, regionally adapted vegetation and fauna, promote the establishment of local species where needed, and focus on the targeted removal of exotic and invasive species from the channel and its banks.

Excessive or frequent cleaning can be counterproductive, as it may disturb soils and root systems, increase light availability, and create bare substrates that favour the rapid establishment of opportunistic pioneer species, including nuisance or invasive plants. Such responses can ultimately reduce ecosystem stability, increase maintenance needs, and undermine the intended ecological and hydraulic benefits of the intervention (**Loo et al., 2009**).

2.5 Importance of long-term programme, governance and adaptive management

River restoration, particularly in urban contexts, requires a long-term programme that integrates maintenance, monitoring, governance and adaptive management, rather than being conceived as a one-off technical intervention. Evidence accumulated over several decades shows that many restoration projects fail to deliver sustained ecological benefits not because of inadequate design, but due to insufficient long-term maintenance, weak institutional arrangements, and limited learning from monitoring outcomes (**dos Reis Oliveira et al., 2020; Moore and Rutherfurd, 2017**).

Restoration measures follow different biophysical recovery trajectories, with some interventions progressively evolving towards **self-sustaining systems**, while others require continuous operational, post-disturbance or life-cycle maintenance. Failure to recognise these trajectories and their implications for management responsibilities and funding has been identified as a major barrier to long-term success (**Moore and Rutherfurd, 2017**). Long-term programmes should therefore explicitly acknowledge that maintenance is an integral component of restoration effectiveness and should be planned from the outset, rather than treated as an optional post-implementation activity.

Monitoring is a central pillar of long-term adaptive management, yet multiple reviews highlight that restoration projects are often evaluated over short timeframes and at limited spatial scales, constraining the capacity to detect delayed responses, cumulative effects, or mismatches between restoration goals and applied measures (**dos Reis Oliveira et al., 2020; González et al., 2015**). In particular, **dos Reis Oliveira et al. (2020)** demonstrate that, despite increasing restoration efforts driven by environmental legislation, monitoring programmes frequently lack sufficient duration and design to evaluate whether ecological objectives are achieved. Long-term monitoring frameworks should therefore be designed to support learning-by-doing, inform maintenance needs, and enable timely adjustments in response to system trajectories, disturbance events, or emerging pressures.

Effective long-term restoration also depends on appropriate governance arrangements, aligned with the cost, complexity, and maintenance requirements of the selected measures. Interventions that involve high costs or require ongoing maintenance typically demand robust institutional frameworks, stable funding mechanisms, and clearly assigned responsibilities. Whereas measures with greater potential for **self-sustainability (NbS)** may allow more flexible or voluntary arrangements, provided that effective oversight and accountability are ensured (**Moore and Rutherfurd, 2017**). Independent assessment and transparent reporting are repeatedly identified as critical elements to ensure that long-term commitments are fulfilled and that unsuccessful measures are adapted or discontinued.

Many of the ecological, hydrological and social benefits associated with river restoration (such as riparian forest development, enhanced flood attenuation, improved water quality, and delivery of multiple ecosystem services) emerge only over **medium to long temporal horizons**, often spanning decades. Conceptual frameworks developed at the river network and catchment scales highlight that restoration outcomes should be evaluated along explicit temporal trajectories, rather than **against short-term endpoints**, allowing cumulative benefits to be recognised and trade-offs to be managed transparently (**Gilvear et al., 2013**).

In urban river systems, where ecological processes are tightly coupled with land use, infrastructure and social dynamics, long-term programmes benefit from participatory and co-governance approaches that engage municipalities, water authorities and local stakeholders throughout the restoration cycle. Such approaches can strengthen institutional continuity, enhance social legitimacy, and support

sustained stewardship of restored river corridors as multifunctional socio-ecological systems delivering ecological, health and societal benefits over time (**Mohan et al., 2022**).

3 Stressors

The stressors impacting urban stream ecosystems, including their morphology, hydrology and biota, are varied and often act simultaneously. A stressor is any physical, chemical, or biological factor that alters the natural state of an ecosystem and causes a measurable negative impact on its structure, function, or ecological processes (**USEPA, 2017**). The measures to be proposed in a restoration plan should tackle these stressors that may be indicated by direct measurements or through their effects on the biological communities (as described in the OneAquaHealth deliverable D2.2 – Key ecosystem and biological health indicators). Therefore, before designing restoration or rehabilitation measures the stressors must be identified.

Below is a compressive list of common stressors (**Feio and Ferreira, 2019**) impacting the streams:

- Water pollution. Usually related with excessive concentrations of organic matter, nutrients suspended solids, but also heavy metals, plastics, pharmaceuticals, among other pollutants.
- Connectivity barriers. A total or partial alteration in the longitudinal connectivity of a lotic ecosystem (e.g., by culverts, weirs, grids, bridges, dams).
- Altered hydrological properties (e.g., increased runoff and flashiness, reduced baseflow, rapid flow variability).
- Geomorphological changes of the channel. For example, by channel incision or widening, bank erosion and instability, sediment imbalance, loss of natural channel complexity.
- Artificialization of the channel and banks. Using artificial materials in the riverbed (e.g., concrete, culverts, non-local materials – sand, stones, boulders, and metal grids) and banks (e.g., concrete, gabion and laid stones) leads to poor transversal connectivity, groundwater dysconnectivity and drives the ecosystem to a sterile state.
- Occupation of the floodplain. Constricts the natural available space for the riparian area, natural floods and infiltration (e.g., constructed areas such as buildings, roads or sidewalks - impervious areas; private gardens, vegetable garden – non impervious areas).
- Removal or degradation of the riparian vegetation (total or partial removal, alteration in the structure and species composition expected at the site; presence or invasion by exotic plant species; fragmentation of habitats and riparian corridors).
- Lack of expected aquatic habitats. Loss of pools, riffles, and woody debris; deposits of inorganic and organic matter, macrophytes disappearance).
- Linearization of the channel.
- Altered physico-chemical properties (e.g., low dissolved oxygen, high water temperature, acidification).
- Degraded biological communities (e.g., presence of invasive aquatic animals and plants, and altered food webs; **Haubrock et al., 2022**).
- Catchment pressures. (e.g., high impervious surface cover, intense urban land use, groundwater extraction).

4 Catalogue of measures for urban aquatic ecosystems rehabilitation

4.1 Essential riparian vegetation restoration: first line measures

Riparian vegetation is not an accessory feature of rivers and streams; it is a defining structural and functional component of their ecological identity. Riparian zones form the living interface between terrestrial and aquatic systems, regulating physical processes, sustaining biodiversity, and supporting the resilience of entire catchments. As such, the restoration and renaturalisation of riparian vegetation should be considered a first-line measure in any river or stream rehabilitation strategy (**European Commission final, 2025**).

A wide body of scientific evidence demonstrates that intact riparian vegetation underpins multiple ecosystem functions, including bank stabilisation, flow regulation, temperature control, pollutant filtration, and the provision of organic matter to aquatic food webs (**Gilvear et al., 2013; González et al., 2015; Mohan et al., 2022**). When riparian zones are functional, root systems bind soils and reduce erosion, vegetation buffers intercept surface runoff, and tree canopies moderate light and thermal regimes critical for aquatic biota.

Beyond their local effects, riparian corridors support high biodiversity and act as longitudinal and lateral ecological connectors, facilitating species movement and gene flow across landscapes, including highly urbanised environments. Their structural complexity provides refuge, breeding habitat, and trophic resources for birds, mammals, amphibians, and invertebrates, while contributing to the long-term ecological integrity of river networks (**Figure 3**).

Figure 3. Example of relatively well-preserved riparian vegetation along a headwater stream in the Mondego catchment, Portugal. **©Sónia Serra**

Because riparian vegetation underpins hydrological, geomorphological, and ecological processes across river networks, its restoration should be prioritised before more engineered or downstream interventions. In many cases, restoring space, vegetation, and natural dynamics offers greater long-term resilience than compensatory or purely technical solutions.

4.1.1 Passive riparian vegetation: allowing natural regeneration.

Where hydrological and morphological conditions remain favourable and pressures have been reduced or removed, passive riparian restoration should be the preferred approach. Passive restoration relies on the natural regenerative capacity (inherent resilience) of riparian systems, allowing vegetation to recolonise banks and floodplains without direct planting interventions (**González et al., 2015**).

This approach is particularly effective where seed sources remain available, soil structure is intact, and hydrological connectivity has not been irreversibly altered. Passive regeneration promotes locally adapted plant assemblages, preserves genetic diversity, and allows vegetation structure to develop in response to natural disturbance regimes.

Typical measures include the cessation of mowing, grazing exclusion, restriction of access by vehicles or heavy machinery, and the removal of pressures that prevent natural succession. When successful, passive restoration is cost-effective, low-impact, and results in riparian vegetation that is well integrated with local hydrological and geomorphological dynamics.

Passive riparian restoration should not be interpreted as inaction, but rather as a deliberate ecological strategy that prioritises process recovery over structural intervention. By restoring space, hydrological connectivity, and protection from disturbance, natural regeneration allows riparian systems to reorganise according to local environmental conditions, resulting in vegetation communities that are more resilient, genetically adapted, and functionally integrated with river dynamics. Nevertheless, passive restoration requires long-term safeguarding, monitoring, and adaptive management to ensure that regeneration trajectories remain favourable and are not diverted by invasive species or renewed pressures. When these conditions are met, passive riparian restoration often represents the most sustainable and ecologically robust pathway for river and stream rehabilitation.

Application scenarios

This measure is recommended when:

- Riparian zones still retain remnant vegetation, seed banks, or nearby source populations;
- Channel morphology and floodplain connectivity are largely intact;
- Pressures such as mowing, grazing, trampling, or soil compaction can be removed;
- The objective is long-term ecological recovery rather than short-term visual improvement.

The typical contexts include: recently abandoned or under-managed riparian strips, urban streams where mowing or landscaping is the main disturbance, agricultural or peri-urban areas after livestock exclusion.

Advantages / Solutions

- Promotes self-sustaining vegetation adapted to local hydrological variability;

- Maintains natural successional trajectories;
- Low implementation cost;
- Minimal soil disturbance;
- High ecological integrity and genetic diversity;
- Reduced risk of maladaptation or planting failure.

Limitations

Careful considerations because:

- Regeneration may be slow, especially in highly compacted or polluted soils;
- Success depends on the presence of seed sources and suitable hydrological conditions;
- Invasive species may colonise early successional stages if not monitored;
- Public perception may be challenging in urban areas where "untidy" vegetation is misunderstood;
- Requires long-term protection from renewed disturbance (e.g., re-mowing or any unnecessary action of "vegetation cleaning").

Case study section 5.1.3 (upstream)

4.1.2 Active riparian vegetation restoration: re-establishment riparian forest.

In many degraded or urbanised systems, however, the riparian zone has been so heavily altered, through channelisation, mowing, bank hardening, or complete vegetation removal, that natural regeneration alone is insufficient. In these cases, re-establishing riparian vegetation becomes a priority measure, requiring thoughtful planning and the deliberate replanting of species that are not merely native, but locally adapted. Using plant material sourced from nearby populations ensures that the genetic pool is suited to the specific climatic, hydrological, and geomorphological conditions of the site, increasing the long-term survival and functional performance of restored vegetation.

Active riparian restoration is required when degradation has exceeded the system's capacity for natural regeneration, e.g., where riparian vegetation has been removed, soils are compacted or contaminated, hydrological connectivity has been altered, or invasive species dominance prevents recovery. Active restoration is **not simply "planting trees along a river"**; it is the **deliberate re-establishment of a self-organising riparian plant community that can persist under the local disturbance regime** (flooding, sediment deposition, drought) and re-initiate key ecological functions (**González et al., 2015; Mohan et al., 2022**).

A major ecological risk in active riparian restoration lies in species selection and sourcing. Riparian corridors are naturally dynamic and highly connected (longitudinally and laterally), which makes them especially prone to biological invasions and to the rapid spread of propagules along the network. Consequently, poorly planned plant introductions can unintentionally simplify communities, alter successional pathways, create maladaptation under local hydrology, or even facilitate invasive re-colonisation.

For these reasons, an ecologically conservative approach to active restoration should be strictly process-informed: i) diagnose and, where possible, remove the drivers of degradation; ii) restore the physical and hydrological conditions that allow riparian vegetation to establish; to then iii) introduce

locally appropriate plant material to accelerate recovery or to overcome dispersal limitations. Active planting must follow river processes, not replace them. So, the first (essential) line of intervention is very connected to the structural second line of intervention, which should be planed together. Engineering-led revegetation that ignores channel-riparian interactions is often ineffective in achieving long-term ecological recovery (**Mohan et al., 2022**).

Active riparian vegetation restoration is most successful when it is framed as the re-establishment of ecological autonomy rather than the installation of a planted landscape. This requires prioritising river processes and spatial integrity, selecting regionally adapted species consistent with reference conditions, and designing planting schemes that support natural succession and resist invasion. When implemented conservatively, **yet ambitiously in its process goals**, active riparian restoration can rebuild the ecological backbone of river networks, enabling long-term resilience, biodiversity recovery, and improved ecosystem services in urban and peri-urban catchments (**Matono et al., 2019; Parkyn et al., 2010**).

Riparian vegetation forms the living interface between terrestrial and aquatic systems. Through protection, regulation, exchange, and connectivity, it allows rivers to function as integrated ecosystems. When this interface is degraded or absent, ecological processes are disrupted, and restoration actions applied within the channel alone become insufficient **Figure 4**.

Figure 4. Riparian vegetation, the living interface between terrestrial and aquatic systems.

For this, there are some ecological design rules and careful considerations to be followed:

I) **Start with hydro-geomorphic compatibility (the "non-negotiable"):** Riparian plant survival and the eventual community structure are strongly constrained by hydrology, groundwater dynamics, flood timing/magnitude, and sediment regimes. Where feasible, priority should be given to restoring flow/sediment conditions that create recruitment opportunities, rather than relying solely on planting into hostile conditions.

II) **Species selection must reflect the site's geomorphological template (rivers change spatially):** Species should be chosen to match the stream's morphology, position in the catchment, and disturbance gradients (e.g., frequently inundated edges vs higher terraces). Practical ecological zoning is recommended: fine-rooted, erosion-tolerant species closer to bank edges; larger woody species further inland where shear stress is lower.

III) **Use native and regionally adapted plant material (local genetic pool):** A conservative approach is to source propagules from nearby reference reaches or local populations to preserve regional genetic integrity and local adaptations. This reduces the risks of maladaptation and unintended genetic effects (e.g., "genetic swamping" or outbreeding issues) and supports resilient, functional vegetation development over time. (This principle aligns with the process- and site-specific selection emphasised in riparian restoration planning (**Figure 5**).

IV) **Avoid "one-species solutions" and ornamental/landscaping biases:** Active introductions frequently rely on a small set of fast-growing pioneers (e.g., willows/poplar in many regions) under the assumption they facilitate later succession. While this can be valid, excessive reliance on a narrow palette can lock the system into simplified states. Where propagule limitation exists, later successional species may need to be introduced deliberately, but always consistent with reference vegetation and local conditions.

V) **Treat invasive species risk as a design constraint, not an afterthought:** Riparian ecosystems are particularly prone to invasion, and a large proportion of restoration projects explicitly address exotic species control. Ecologically, the goal should be to restore conditions that favour native community assembly and resist reinvasion, using targeted control combined with the strategic establishment of native competitors (e.g., shading out invaders).

VI) **Plan for monitoring and adaptive management from day 0 (riparian revegetation takes time):** Riparian restoration is commonly framed in phases: pre-assessment, restoration implementation, and post-monitoring/maintenance, with monitoring being essential to steer adaptive decisions (e.g., replanting failures, adjusting protection, targeted invasive control).

VII) The ecological effectiveness of riparian vegetation is strongly constrained by corridor width. Continuous riparian forests typically require wider corridors (>30 m per bank) to support floodplain processes, diverse habitats, and long-term ecological resilience. Riparian vegetation width should therefore be maximised wherever possible and conceived as incremental over time (**González et al., 2015; Muhar et al., 2016; Qin, 2020**).

Application scenario(s)

Active targeted re-establishment is recommended when riparian vegetation is absent or severely fragmented and natural seed sources are too distant, when riverbanks and floodplain surfaces are compacted, disturbed or lack suitable microhabitats for plant recruitment, when hydrological and geomorphological conditions have been significantly altered (e.g. due to regulation, channel incision or sediment starvation) making spontaneous recovery unlikely, and when the dominance of invasive species prevents natural regeneration, particularly in situations where early intervention is required to avoid long-term, entrenched infestations.

Advantages / Solutions

- accelerates the return of core riparian functions (bank stabilisation, shading, filtration, habitat structure).

- helps overcome propagule limitation and “recruitment bottlenecks” where natural dispersal is insufficient.
- can be combined with ecological competition strategies to reduce reinvasion risk (native competitors, canopy shading).
- supports an explicitly process-oriented approach when aligned with hydrology and sediment dynamics rather than purely structural bank works.

Limitations

- **Maladaptation and ecological mismatch:** planting the wrong species (or wrong provenance) can lead to failure, poor functional performance, or long-term ecological shifts away from reference conditions.
- **Invasion and reinvasion:** disturbed riparian zones are invasion-prone; delay or inappropriate sequencing can make invaders harder to remove once established.
- **Ignoring drivers of degradation:** active planting can fail or even worsen degradation if underlying hydrological/sediment constraints remain (restoration “cosmetics”).
- **High early maintenance demand:** browsing pressure, drought, flood damage, vandalism and invasive recolonisation often require early protection, replanting, and adaptive management.

Case study sections 5.1.2, 5.1.3, 5.1.4

Figure 5. Restored riparian corridor (right: wider view of the restored area, left: closer view highlighting finer-scale features) along the Olo River (Alvão Natural Park, northern Portugal). Restoration and reinforcement of riparian vegetation were implemented to safeguard habitats protected under the EU Habitats Directive. The intervention focused on restoring and densifying the riparian buffer along the Olo River, a tributary of the Tâmega River (and part of the Douro River basin), aiming to improve the conservation status of degraded natural habitats and enhance ecological connectivity in an area subject to significant environmental pressures. Left: general view of the restored riparian corridor. Right: detail of the restored riparian vegetation.

4.1.3 Constrained riparian vegetation corridors ("buffers")

In some urban and peri-urban contexts, the full re-establishment of a continuous riparian forest is not feasible within the scope or timeframe of a restoration project due to persistent spatial, legal, or socio-economic constraints (e.g., critical infrastructure, consolidated urban or industrial areas, flood-control works, or rigid land-ownership patterns). In such cases, after opportunities for land recovery, acquisition, or reallocation have been carefully explored, restoration efforts may be limited to narrow riparian strips or linear vegetated corridors along the watercourse (streams or rivers).

Constrained riparian vegetation buffers should therefore be understood as **interim or compromise solutions**, implemented only where more ambitious riparian restoration is currently unachievable. They do not aim to recreate fully functional riparian ecosystems, but rather to maintain or reintroduce a minimum (or maximum possible, given constraints) functional interface between terrestrial surfaces and the stream, preserving essential ecological processes that would otherwise be lost. Where conditions allow, **these buffers should remain open to future widening or upgrading towards more complete riparian systems**.

Despite their reduced width and structural simplicity, constrained riparian buffers can still provide important functions when properly designed and managed. These include interception and partial filtration of runoff, moderation of microclimatic conditions (e.g., shading and temperature regulation), reinforcement of bank stability, and provision of linear habitat and movement pathways for some terrestrial and semi-aquatic species. In heavily modified environments, they often act as the **last line of defence** between urban surfaces and the stream, reducing direct inputs of sediments, nutrients, hydrocarbons, and other pollutants (**dos Reis Oliveira et al., 2020; Muhar et al., 2016; Qin, 2020**).

The effectiveness of constrained riparian buffers is strongly influenced by their width. Narrow buffers (approximately 5–10 m per bank) can deliver limited but valuable benefits, such as partial shading, interception of coarse sediments, and local bank stabilisation, particularly in highly constrained urban settings. Wider buffers (approximately 10–30 m per bank) provide substantially greater ecological benefits, including improved nutrient retention, temperature regulation, and habitat continuity. Nevertheless, even at these widths, constrained buffers cannot fully replicate the functions of continuous riparian forests, which generally require corridors wider than 30 m per bank to support floodplain processes, habitat diversity, and long-term resilience. Buffer width should therefore be maximised wherever possible and viewed as **scalable over time**, as opportunities for land recovery arise (**González et al., 2015; Muhar et al., 2016; Qin, 2020**).

Application scenario(s)

This measure is applicable when, despite active efforts to recover riparian space, the re-establishment of a continuous riparian forest is not feasible within the scope or timeframe of a given project. It is particularly relevant in urbanised settings where permanent infrastructure, land ownership patterns, or competing land uses currently restrict riparian widening, but where some linear space along the watercourse can still be secured and protected. Riparian buffers approximately 10 m wide (per bank) or more can provide basic protective functions; however, wider corridors exhibit higher ecological resilience and are capable of sustaining a broader range of ecosystem services.

Typical situations include highly urbanised settings where permanent infrastructure severely limits the space available for riparian restoration, contexts in which the riparian corridor is highly fragmented or

absent, but some linear space remains along stream margins, and restoration projects targeting the reduction of diffuse pollution and physical disturbance in heavily modified environments. These situations often involve combining riparian buffers with complementary measures (e.g., bank stabilisation, flow deflectors or constructed wetlands) and rely on planning instruments such as zoning regulations, easements or land acquisition mechanisms to ensure the long-term protection of narrow riparian strips.

Advantages / Solutions

When appropriately implemented, constrained riparian vegetation buffers and corridors can:

- Act as a last line of defence between urban surfaces and the watercourse, intercepting sediments, nutrients, hydrocarbons, and other pollutants before they reach the channel;
- Improve bank stability through root reinforcement, reducing local erosion and sediment inputs;
- Provide shading, contributing to lower water temperatures and improved dissolved oxygen conditions;
- Enhance habitat availability and connectivity for a subset of aquatic, semi-aquatic, and terrestrial organisms;
- Improve landscape aesthetics and public perception of streams in urban areas;
- Contribute to climate adaptation, including local cooling, runoff attenuation, and carbon sequestration;
- Support One Health principles by integrating water quality improvement, biodiversity support, and human well-being.

Limitations

Constrained riparian vegetation buffers and corridors present several ecological and management limitations:

- **Reduced ecological function** compared to continuous riparian forests, particularly regarding habitat diversity, floodplain processes, and long-term resilience;
- **Strong edge effects**, increasing vulnerability to invasive species, pollution, trampling, and disturbance;
- **Limited capacity** to buffer extreme hydrological events or high pollutant loads;
- Dependence on **frequent maintenance**, including watering during droughts, selective cutting, replanting, and invasive species control;
- Potential **accumulation of pollutants in soils and sediments**, requiring periodic management or removal;
- **Conflicts between ecological objectives and recreational or infrastructural uses**, if access and activities are not carefully regulated;
- **Risk of being perceived as a complete restoration solution**, potentially delaying or discouraging more ambitious riparian recovery where it could still be achievable in the future.

Case study section 5.1.1

4.1.4 Vegetated corridors promoting connectedness

While constrained riparian buffers (**section 4.1.2**) focus on maintaining a minimum ecological interface directly along the stream margins, vegetated corridors (also called green-blue corridors) promoting connectedness operate at a broader spatial and functional scale. These corridors integrate urban rivers with parks, wetlands, and other vegetated spaces into continuous networks that support ecological flows, climate regulation, and human well-being across the urban landscape.

In addition to their ecological and climatic functions, these corridors play a social and aesthetic role in urban environments, shaping how citizens perceive, access, and value river systems.

Application scenario(s)

This measure is applicable in urban contexts where rivers and streams have become physically, visually, and socially disconnected from surrounding neighbourhoods, often resulting in neglect, degradation or chronic anthropogenic pressure. It is particularly relevant where ecological restoration alone is insufficient to secure the long-term protection of river corridors without social recognition and legitimacy, and where re-establishing visibility, access and spatial continuity along rivers and streams is necessary to prevent further encroachment, misuse, or surface sealing. Typical circumstances include rivers that were previously buried, channelised or marginalised within cities, as well as urban renewal areas where waterways can be reintroduced as structuring ecological elements rather than residual spaces, supported by strategic planning instruments that integrate river corridors into the urban fabric while maintaining ecological priorities.

Advantages / Solutions

When designed with ecological primacy, green–blue corridors can:

- Reinforce **long-term protection of river systems** by restoring their presence in collective awareness and urban structure;
- Reduce pressures associated with abandonment (e.g., dumping, informal occupation, excessive channel modification);
- Facilitate **social stewardship**, where informed and engaged communities act as indirect guardians of river corridors;
- Secure **continuous space** along watercourses, preventing future fragmentation and enabling progressive ecological recovery;
- Support **ecological connectivity** at the landscape scale, particularly for generalist and dispersal-capable species;
- Enhance microclimatic regulation and hydrological buffering as secondary outcomes of spatial continuity.

In this context, social reconnection is not an objective *per se*, but a necessary condition for the long-term safeguarding of urban river corridors.

Limitations

- **Social visibility does not guarantee ecological quality** and may increase pressure if access is not carefully regulated;
- Corridors risk being reduced to **circulation or leisure infrastructures** if ecological design principles are subordinated;

- **Increased human presence may cause disturbance to sensitive species**;
- Long-term effectiveness depends on **clear governance frameworks**, maintenance responsibilities, and enforcement;
- **Without explicit ecological goals, social integration alone may fail to halt incremental degradation.**

CRITICAL NOTE! There is a clear risk that these vegetated corridors are **pursued as end-point solutions** in urban river management, precisely because they are relatively **easy** to implement, politically **attractive**, and highly **visible**. Their capacity to **rapidly transform the visual appearance of degraded river corridors** can create a perception of ecological recovery, even when fundamental processes, such as riparian functioning, hydromorphological dynamics, or water quality improvement, remain largely unaddressed.

When **prioritised in isolation**, these interventions may inadvertently **mask ongoing ecological degradation**, diverting attention and resources away from more demanding but necessary restoration actions, such as riparian space recovery or process-based rehabilitation. In such cases, the emphasis shifts from ecological function to **symbolic improvement**, resulting in interventions that are socially acceptable and aesthetically convincing, yet **ecologically shallow** (**Murphy et al., 2022**).

For this reason, vegetated corridors **should not be implemented without clearly defined ecological objectives, performance indicators, and an explicit connection to broader river restoration strategies**. Without these safeguards, they risk becoming instruments of **greenwashing** rather than genuine contributors to long-term river recovery.

Case study sections 5.1.1, 5.1.6

4.2 Essential chemical and water quality measures: first line measures

Urban streams are characterized by mixed and persistent chemical pressures originating from stormwater runoff, wastewater discharges, and diffuse urban pollution. Large proportions of impervious surfaces (roads, roofs, parking lots) generate fast and contaminated runoff during rain events. Pollutants such as hydrocarbons, nutrients, metals, and fine sediments are rapidly transported to streams through storm drains, producing “first-flush” episodes of severe degradation. Frequent small rainfall events maintain streams in a state of continuous chemical stress (**Qin, 2020; Walsh et al., 2005**). These stressors interact with altered hydrology and morphology, reducing self-purification and leading to chronic degradation of water quality.

The following measures focus on the most frequent problems of contamination of freshwaters in urban environment, and on rehabilitation techniques or complementary solutions that can contribute to their mitigation. **However, sewage waters should always be directed to a waste-water treatment plant and not directly to a stream or river.**

4.2.1 In-stream self-purification enhancement

Urban streams often suffer from reduced self-purification capacity due to channelization, loss of habitat heterogeneity, and disconnection from the hyporheic and riparian zones. Straightened and concrete-lined channels accelerate water flow, shorten residence time, and prevent natural contact between water, sediments, microorganisms, and vegetation. All of which are essential for biogeochemical processes that remove nutrients, degrade organic pollutants, and increase oxygenation (**Lewandowski et al., 2019; Muhar et al., 2016; Wynants et al., 2025**).

The simplification of flow and substrates reduces aeration, sediment retention, and microbial colonization surfaces, impairing processes such as nitrification, denitrification, and organic matter decomposition. Consequently, pollutants remain in the system, while the ecosystem's resilience to contamination and flow variability declines.

Even in well-vegetated and morphologically restored urban streams, episodic runoff peaks will persist due to impervious surfaces and rapid drainage pathways. The goal of rehabilitation is therefore not to eliminate high flows but to moderate their frequency and intensity while enhancing the stream's natural capacity to recover. By restoring structural complexity and riparian vegetation, self-purification processes can re-establish after each disturbance, ensuring long-term water quality and resilience.

Enhancing self-purification focuses on restoring physical complexity and ecological processes within the stream channel, enabling it to recover its natural cleaning and regulating functions.

Application scenario(s)

This measure applies mainly to urban or peri-urban stream reaches that still maintain permanent or seasonal baseflow and offer at least limited space for in-stream morphological enhancement. It is especially relevant in sections where the channel remains partly naturalized but suffers from hydrological alteration, moderate nutrient or organic pollution, or overly uniform flow and habitat conditions caused by past channelization.

In such contexts, the goal is to reactivate natural self-cleaning processes by restoring physical and biological complexity within the stream. This can be achieved through targeted interventions that slow down water flow, increase oxygenation, and create microhabitats for aquatic organisms.

Typical techniques include the use of boulder clusters, rock sills and coarse woody debris to increase hydraulic turbulence, enhance mixing and improve oxygen exchange; riffle-pool restoration to extend water residence time and create diverse hydraulic conditions; macrophyte planting to promote nutrient uptake, biofilm activity and sediment stabilisation; and substrate diversification through the introduction of varied particle sizes that support microbial colonisation and benthic biodiversity. These techniques may be implemented individually or combined within broader channel rehabilitation or urban park projects, contributing simultaneously to water quality improvement, ecological recovery, and recreational value in urban landscapes.

Advantages / Solutions

- Increases oxygenation and aeration, improving conditions for aquatic life.
- Enhances nutrient cycling (nitrification–denitrification) and organic matter breakdown.
- Improves pollutant retention and microbial degradation, reducing nutrient and chemical concentrations downstream.

- Creates hydraulic diversity and natural flow variation, benefiting biodiversity.
- Visibly restores ecological vitality, often improving aesthetics and public perception of the stream.

Limitations

- Requires minimum baseflow to ensure processes are active.
- Limited effectiveness in intermittent or ephemeral streams.
- Space constraints in fully urbanized channels can restrict physical interventions.
- Sediment clogging or excessive algal growth may reduce performance if nutrient inputs remain high.
- Maintenance needed to manage debris accumulation and vegetation.
- Limited pollutant removal efficiency for high or toxic loads, must be combined with upstream source control measures.

Case study sections 5.1.1, 5.1.2, 5.1.3, 5.1.5, 5.1.6

4.2.2 Sewer system and point-source improvements

In many urban areas, aging sewer networks, leaking pipes, and combined sewer overflows (CSOs) are major contributors to water quality degradation. During heavy rainfall, combined systems (carrying both wastewater and stormwater) frequently exceed their capacity, leading to untreated discharges of sewage and pollutants into urban streams. In separate systems, leakages, illegal connections, and infiltration of groundwater can still compromise performance. In addition, industrial effluents or untreated domestic discharges entering the drainage network constitute significant point sources of nutrients, organic matter, pharmaceuticals, and toxic compounds. These factors result in elevated concentrations of nutrients, suspended solids, and pathogens, creating sanitary risks and reducing the ecological quality of urban water bodies (**Muhar et al., 2016; Wynants et al., 2025; Zerega et al., 2021**).

Upgrading and optimizing sewer systems and point-source management are therefore fundamental to ensure the long-term success of ecological rehabilitation and the effectiveness of other chemical or hydrological measures.

In addition, the management of artificial drainage networks (e.g., roadside ditches, legacy drainage channels and auxiliary collectors) plays a key role in urban hydrology, as excessive drainage accelerates runoff, reduces water availability in soils and floodplains, and limits the buffering capacity of restored stream systems.

Application scenario(s)

This measure applies to urban and peri-urban catchments affected by sewage leaks, frequent CSOs, or direct untreated discharges into streams. It is particularly important in:

- Older city centres with combined sewer networks that often overflow during rainfall;
- Areas with industrial or commercial discharges, where monitoring and treatment are critical;
- Rapidly expanding urban areas, where sewer systems have not kept pace with development.

Interventions can be implemented as part of infrastructure renewal programs, green infrastructure integration, or regulatory upgrades (e.g., water utility modernization, stricter discharge permits). Typical actions include:

- Rehabilitation or separation of combined sewer systems to reduce overflow frequency;
- Installation of retention tanks or smart storage basins to buffer stormwater and delay discharges;
- Repair and lining of aging pipes to prevent leakage and groundwater infiltration;
- Decentralized treatment units (e.g., constructed wetlands, biofilters) for small or diffuse outfalls;
- Improved monitoring and control of industrial and domestic discharges.
- Selective blocking or reconfiguration of artificial drainage ditches and secondary collectors to slow drainage, enhance local water retention and support groundwater recharge and baseflow conditions.

Advantages / Solutions

- Reduces untreated discharges of sewage and pollutants during rainfall events.
- Improves water retention and hydrological resilience, increasing water availability during dry periods and reducing rapid runoff during storm events.
- Improves chemical and microbial water quality, reducing pathogen and nutrient loads.
- Prevents contamination of groundwater and soils by repairing leaking infrastructure.
- Supports the effectiveness of downstream ecological restoration and self-purification measures.
- Enhances public health and safety, aligning with the One Health framework.
- Enables compliance with water quality standards and WFD objectives.

Limitations

- Coordination challenges between utilities, municipalities, and environmental agencies.
- Residual pollution risk if illicit connections or diffuse discharges are not addressed.
- High financial and logistical costs associated with infrastructure renewal.
- Long implementation timelines due to technical complexity and urban constraints.
- Maintenance demands for new facilities (storage basins, decentralized units).

Case study sections 5.1.1, 5.1.2, 5.1.3, 5.1.5, 5.1.6

4.2.3 Litter, plastic, and hydrocarbon control

Urban streams are frequently contaminated by solid waste, plastics, and hydrocarbons originating from roads, public areas, storm drains, and mismanaged waste disposal. These pollutants are not only unsightly but also cause chemical and ecological degradation: plastics break down into microplastics that accumulate in sediments and aquatic organisms, while hydrocarbons from vehicle traffic and parking areas form toxic films that reduce oxygen exchange and damage aquatic biota.

High population density, inadequate waste collection, and combined sewer overflows aggravate the situation. These pollutants have both chemical impacts (toxic and chronic contamination) and social impacts, as they affect the perceived safety, aesthetics, and public acceptance of urban streams.

Because litter, plastics, and hydrocarbons derive from multiple diffuse and point sources, their mitigation requires an integrated combination of technical, maintenance, and behavioural measures (dos Reis Oliveira et al., 2020; Macedo et al., 2022; Santaoja et al., 2025; Wynants et al., 2025).

Structural and technical Measures

Structural interventions aim to intercept pollutants before they reach the stream channel or to remove them efficiently once they are deposited. Stormwater pre-treatment devices such as sediment traps, sump pits, vortex separators, oil-water separators, and gross pollutant traps help retain plastics, sediment-bound contaminants, and hydrocarbons before they enter the stream, although they require regular inspection and cleaning to remain effective.

In addition, floating or in-stream capture systems (such as booms, floating barriers, and litter traps placed at strategic points like culvert outlets, confluences, or detention basins) collect floating litter and microplastic-rich debris, either passively or with low-energy mechanical skimming.

Replacing impermeable pavements with permeable surfaces further reduces runoff velocity and the transport of hydrocarbons, while rain gardens, bioswales, vegetated strips, and constructed wetlands function as biofilters that trap plastics, absorb hydrocarbons, and facilitate natural degradation processes.

Finally, improving waste management infrastructure by providing adequate bins, closed containers, recycling points, and more frequent collection in hotspots such as bus stops, parks, schools, and riverwalks helps reduce wind-dispersed litter and lowers the pressure from illegal dumping.

Operational and maintenance measures

Even with technical solutions in place, consistent maintenance is essential for long-term effectiveness. Stormwater infrastructure such as catch basins, oil-water separators, and gross pollutant traps must be inspected and cleaned at regular intervals, particularly before wet seasons or periods of intense rainfall.

In parallel, riverbank and channel cleaning programmes are necessary to remove accumulated macroplastics (which may be mixed with other organic debris such as leaves, branches, wood, that is naturally present in the stream being important for biodiversity), and oily residues from margins, debris jams, and sediment bars, thereby preventing further fragmentation into microplastics and reducing downstream transport.

Additionally, emergency response protocols are crucial for accidental hydrocarbon spills, whether originating from leaking vehicles, industrial discharges, or combined sewer overflows, and should include the rapid deployment of absorbent barriers, temporary containment measures, and swift extraction of contaminants to minimise ecological damage.

Behavioural and community-based measures for trash, plastic, and hydrocarbon control

Diffuse pollution often requires behavioural change and active public engagement to reduce inputs at the source. Awareness campaigns and clear signage, supported by locally relevant examples, help communicate the impacts of inorganic trash and hydrocarbons and strengthen public responsibility; simple messages placed near storm drains have proven effective in discouraging dumping.

Community-based initiatives, including citizen science programmes and river clean-up events, further increase local stewardship, generate valuable data on pollution hotspots, and foster a cultural shift towards prevention, with schools and resident groups often playing a key role.

Complementing these efforts, policy and enforcement mechanisms such as fines for illegal dumping, stricter controls on waste disposal from commercial areas, and regulations to reduce parking-lot runoff, including the mandatory use of oil-grit separators, help address chronic contamination sources and reinforce long-term behavioural change.

Application scenario(s)

This set of measures applies to highly urbanized catchments where runoff transports visible and chemical pollutants from streets, parking lots, and industrial areas into nearby watercourses.

They are especially relevant:

- Downstream of stormwater outfalls, road crossings, or combined sewer overflows;
- In densely built areas with poor solid waste management or frequent street littering;
- In industrial and commercial zones where hydrocarbons and oils are common;
- In public parks or community zones, where aesthetic and recreational quality are key to social acceptance of restoration projects.

These interventions should be planned at multiple scales: localized devices (grates, traps, separators) complemented by regular street cleaning, community involvement, and educational campaigns.

Advantages / Solutions

- Reduces solid and chemical pollutant loads entering streams from roads and storm drains.
- Prevents microplastic formation and accumulation in sediments and food webs.
- Improves aesthetic and recreational value, fostering public engagement and stewardship.
- Reduces hydrocarbon contamination and oxygen depletion in water.
- Increases overall effectiveness of other restoration measures by decreasing secondary stressors.
- Enhances One Health benefits through cleaner, safer, and more pleasant environments.

Limitations

- Requires regular maintenance of traps, separators, and drainage infrastructure to remain effective.
- High implementation and operational costs for urban drainage retrofitting (especially in large cities).
- Behavioural dependency – long-term success depends on public awareness, enforcement, and waste management practices.
- Hydrocarbon separators need proper disposal of oily residues; mismanagement can shift contamination to another location.
- Microplastics remain difficult to capture completely due to their microscopic size and persistence.
- Inefficiency during extreme rainfall events that bypass filtration systems.

Case study sections 5.1.1, 5.1.6

CRITICAL NOTE! Evidence of general water-quality improvement and stormwater/wastewater management exists (e.g., sewer-system transformation, WWTP upgrades, wetland treatment). However, explicit, documented measures targeting litter/plastic and hydrocarbon interception are inconsistently reported across cases. In the sources consulted, clear, case-specific documentation of floatables/gross pollutant control was found for Bièvre daylighting (anti-floating screens / removal of floatables) and Kallang River rehabilitation in Singapore (gross pollutant traps), while hydrocarbon-specific interception was not clearly documented in the publicly available descriptions reviewed.

4.3 Structural measures: second line measures

To restore a river to its natural state and recover its natural channel form while ensuring the self-sustaining stabilization of its banks, the artificial structures (e.g., weirs, culverts, or artificial bank protection) should be removed and river restoration techniques applied.

4.3.1 Removing barriers

Barriers in streams fragment and degrade habitats, hamper the movement of fish and other aquatic species, alter sediment and nutrient flows and degrade water quality, leading to negative impacts on riverine ecosystems and biodiversity (**Addy, 2016**). As they modify natural sedimentation and water flow regimes, they amplify the erosive power of water downstream, modify the water level and impact the recharge of the aquifer. Low-head barriers (e.g., weirs) also pose a threat to human lives and are thus known as drowning machines, while barriers that have outlived their useful lives and now remain obsolete are at risk of structural failure. Also, during drought periods, low-head barriers may retain stagnant water, providing favourable conditions for mosquito breeding and thereby posing a potential public health risk (**Darre et al., 2025**).

Removing impoundments can restore the natural upstream and downstream connectivity of water, sediment, organic material, and aquatic organisms, thereby regenerating a naturally diverse and dynamic river habitat (see **Figure 6**). Such removal also helps re-establish the natural variability of flow depths and velocities. The significance of river connectivity is a central topic of the EU Nature Restoration Law approved in 2024, which includes an obligation to remove man-made barriers to contribute to restore the free-flowing condition of at least 25000 km of rivers in Europe by 2030.

Removing river barriers follows a systematic, multi-stage methodology. The process begins with prioritising barriers by collecting geospatial, ecological, and technical data and mapping opportunities for biodiversity gains, improved connectivity, costs, and overall feasibility. This prioritisation typically uses optimisation models and the “low-hanging fruit” approach to identify structures that offer high ecological benefit at relatively low cost. Next, detailed site assessments are carried out for the selected barriers, taking into account legal requirements, ownership, hydrological and ecological conditions, and potential risks. Stakeholder involvement – including landowners, local communities, and conservation groups – is essential from the outset to build support and ensure transparent planning.

A removal plan is then developed, usually targeting obsolete or redundant structures such as old dams, weirs, and culverts that impede fish migration, restrict sediment transport, or alter natural flows. This is followed by the implementation phase, where physical removal is undertaken with careful environmental safeguards to restore longitudinal and lateral river connectivity. Finally, post-removal monitoring is conducted to evaluate ecological recovery, sediment dynamics, hydrological responses, and socio-economic outcomes. Continuous monitoring enables adaptive management and ensures that restoration objectives are met over time.

Detailed guidance can be found in: **Buchholz and Younos (2007); Directorate-General for Environment (European Commission) (2022); Garcia de Leaniz and O’Hanley (2022)**.

Application scenario(s)

- Obsolete dams, weirs or barriers that pose a risk to human or environmental safety.

Advantages / Solutions

- Re-establishes continuous river systems, allowing for the natural movement of species, sediment, nutrients, and water.
- Allows fish to migrate to upstream habitats for spawning and escape extreme heat or drought conditions.
- Restores natural flow, which can improve the natural transport of nutrients and reduce pollution.
- A connected river system is more resilient to challenges like floods and droughts.
- Removing barriers can lead to new riverbanks and floodplains, creating new habitats and opportunities for recreation.
- Improves the fitness of native populations and allows the recolonization of downstream species.
- Improving water quality and longitudinal connectivity, enhances biodiversity and reduces the availability of breeding sites for mosquitoes and water-borne diseases.

Limitations

- The heritage, social and economic value of barriers, as well as public perception, can difficult the removal of barriers.
- Bad environmental outcomes, such as the spread of invasive species.
- Big load of sediment release, which may harm downstream habitats.
- Lower water quantity where the reservoir used to be before the removal.

Case study sections 5.1.1, 5.1.3, 5.1.4

Figure 6. From **a.** to **d.** the delicate process of removing an obsolete barrier, a dam in the Alviela River, Tagus Basin Portugal (**GEOTA RiosLivres Programme, 2023a**). Another example can be found in **Mouchlianitis (2024)**.

4.3.2 Passing barriers

When complete weir removal is not feasible due to societal or infrastructural constraints, several alternative measures can help mitigate its impacts. Rock-ramps, nature-like bypasses and step-pool fishways are sustainable alternatives. However, these measures provide limited broader ecosystem benefits because, unlike full barrier removal, they do not fully restore the natural transport of water, sediment, organic matter, and biota or re-establish characteristic river habitat dynamics (**Addy, 2016**). In many cases, complete weir removal remains the most cost-effective and ecologically beneficial solution (see **Figure 7**).

Rock-Ramp

Rock-ramp is a gently sloping, channel-spanning structure built within the main river channel through a barrier. It consists of a series of boulders placed in the stream channels and arranged either as a boulder garden or in regular rows – to create a sequence of step-pools that facilitate fish passage as the primary function. A key design element contributing to the hydraulic heterogeneity of rock ramp fishways is the presence of emergent rocks, which generate wake zones and create continuous low-velocity pathways for fish ascent, with resting pools incorporated to allow fish to recover as they move upstream over low weirs (**Stuart et al., 2024**). However, they should have a V shape profile to reduce debris collection. Often, the boulders are transported from other places, but they should, as much as possible, be composed of local rocks, in terms of mineral composition.

Figure 7. Rock ramp structure designed to restore channel continuity, stabilize the riverbed, and facilitate fish passage while mimicking natural riffle morphology. Step-pool design (left) and boulder garden design (right). Based on **Landing Road Rock Ramp Fishway Repair; NSW (2025**)

Application scenario(s)

- Fish ramps are used when longitudinal connectivity brings ecological benefits, such as the spawning of migratory fish, but barriers cannot be removed due to urban constraints, such as the retention of water for aesthetic or functional purposes.

Advantages / Solutions

- It can enable the partial restoration of natural water, sediment, and biotic fluxes, as well as improve habitat connectivity.
- They also improve aquatic habitat conditions by enhancing flow diversity and oxygenation.

- Maintain migratory pathways and enable fish to access separate habitats.
- Their aesthetics and lower material costs are often preferred over conventional technical (i.e., concrete or equivalent) fishways.
- They work under low baseflows

Limitations

- Limited ecosystem benefits.
- More engineered when compared to other natural fish passages.
- Plant debris can collect across the rocks and block fish passages.
- Scouring of the creek bed at the downstream entrance limits fish movement into the fishway.
- Natural rock is variable in its shape and size, making it difficult to achieve consistent water velocities and turbulence throughout the fishway.

Case study section 5.1.3

Nature-like bypasses

Nature-like by-passes are fishways designed to mimic natural streams and provide a passage for fish to avoid man-made barriers (**Figure 8**). These bypasses not only allow for migration but also create habitats that support various stages of a fish's life cycle, increasing biodiversity in rivers by providing areas for spawning, nurseries, feeding, and refuge **(Michael et al., 2025)**. They are built with materials like boulders to simulate natural stream conditions, increasing water depth and reducing flow velocity to aid fish movement. Unlike technical fishways, nature-like bypasses use natural features such as varied bed roughness and meanders to resemble a natural stream more closely (**Figure 9**).

Application scenario(s)

- Fish nature-like bypasses are used when longitudinal connectivity brings ecological benefits, such as the spawning of migratory fish, but barriers cannot be removed due to urban constraints, such as the retention of water for aesthetic or functional purposes.

Advantages / Solutions

- It can enable the partial restoration of natural water, sediment, and biotic fluxes, as well as improve habitat connectivity.
- Maintain migratory pathways and enable fish to access separate habitats.
- Supports a wider range of species than traditional fishways.
- Migratory fishes were observed spawning within nature-like fishways, suggesting that this type of fishway may also provide suitable environments for fish to spawn and for juveniles to grow (**Landsman et al., 2020**).
- They provide resting areas and places for fish to feed.
- Their aesthetics are often preferred over conventional technical (i.e., concrete or equivalent) fishways.
- Less engineered when compared to other fish passages.

Limitations

- They need moderate to high water discharges to work properly.

- They struggle with highly variable flows, because large fluctuations in headwater can drown-out a nature-like channel providing limited passage for flow-cued species.

Case study section 5.1.3

Figure 8. Nature-like bypass channel, mimicking a natural stream morphology, providing ecological continuity, and enhancing aquatic habitat diversity in a restored river reach.

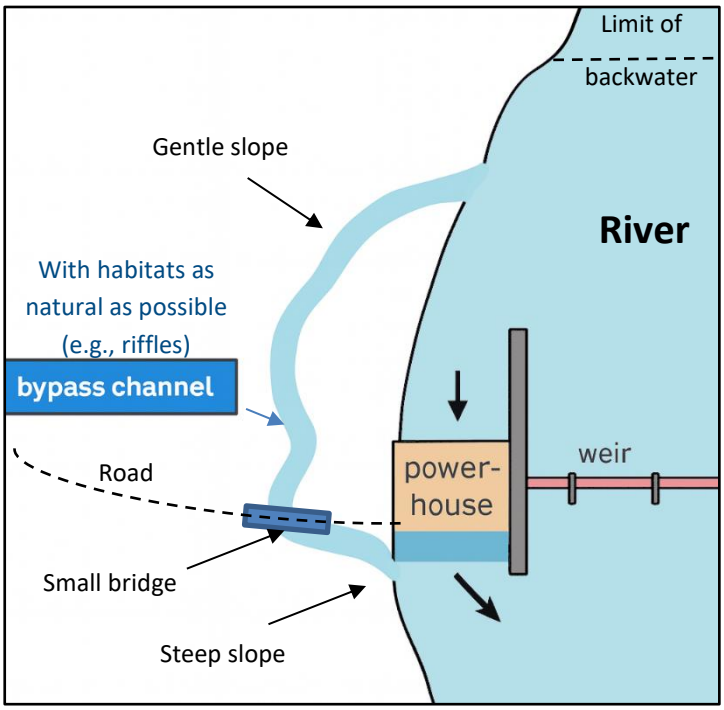


Figure 9. Schematic representation of nature-like bypass channel.

4.3.3 Stream re-meandering

Stream re-meandering is the process of restoring a straightened or channelized stream by reintroducing natural curvature and sinuosity (**Figure 10**). This can be achieved by allowing the stream to laterally migrate and form meanders naturally, or by artificially constructing new bends and reconnecting historical meander cut-offs. It can slow down the river's flow, increase habitat diversity, and improve flood mitigation and water quality, reversing the negative ecological consequences of past river straightening (**Radspinner et al., 2010**).

Application scenario(s)

- Re-meandering should only be conducted on a meander alluvial system (past or present).
- In streams that have been straightened or channelized before.

Advantages / Solutions

- It reduces flood risk downstream by increasing the channel's sinuosity and reducing its gradient.
- By expanding the functional river area and increasing the channel length, re-meandering slows down runoff on the banks and increases storage capacity (**Costaz-Puyou et al., 2025**).
- Meanders support infiltration and ground water recharge.
- It helps to reverse the loss of habitat diversity that occurs when rivers are straightened.
- By increasing the length and complexity of the channel, re-meandering creates a variety of habitats with different flow conditions, which benefits fish and invertebrates (**Costaz-Puyou et al., 2025**).
- It has a positive impact on sedimentation processes. By modifying the river profile and decreasing water velocity, re-meandering decreases erosion and increases sedimentation.

Limitations

- It is not suitable for rivers in braids, in alternating patches or anastomoses.
- On a river that never had meanders, this kind of modification may increase the risk of flood events.
- It requires free space in the margins of rivers

Case study sections 5.1.1, 5.1.2, 5.1.6

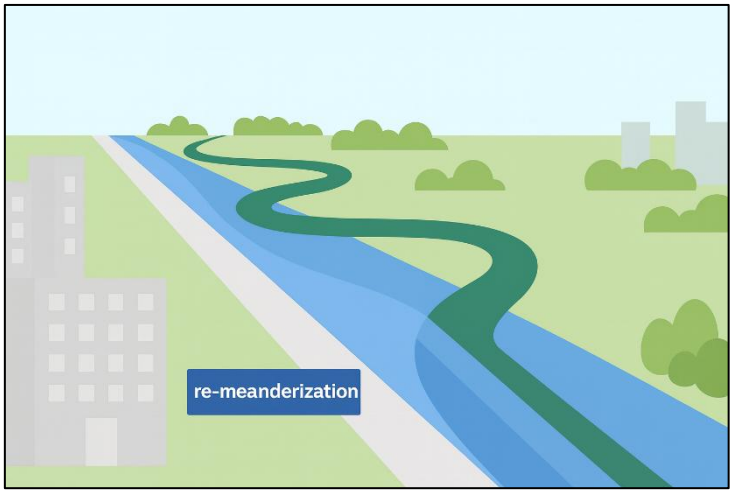


Figure 10. Conceptual visualization of stream/ river re-meandering alongside a channelized urban river.

4.3.4 Stream bed re-naturalization

In the past, riverbeds were artificially reconstructed with concrete or big stones, aiming at flood prevention, and therefore modifying flows and decreasing fauna habitat and vegetation diversity. This has led to uniform flows in the streams and often an effect of reducing travel time along the river. Streambed re-naturalisation consists of removing concrete or inert constructions in the riverbed, then replacing them with locally sourced natural substrate and vegetation structures, to recreate natural channel forms, hydrological processes, and in-stream habitats (**NWRM, 2024**). It is usually applied before other techniques such as re-meandering, constructed rifle-pool formations, flood plain reconnection or bank softening.

The re-naturalisation of riverbeds could have a high impact on the erosion process. The goal is to convert degraded, uniform, or channelized streambeds into ecologically functional habitats that support diverse aquatic communities and improve hydrological and geomorphic resilience.

Application scenario(s)

Stream bed re-naturalisation is suited for:

- Channels that have been artificially lined or straightened (e.g., concrete channels, culverted reaches, trapezoidal engineered beds);
- Flood risk mitigation projects.

Advantages / Solutions

- Restores natural flow variability, promoting sediment transport and channel self-formation.
- Improves energy dissipation through roughness elements (logs, boulders).
- Re-establishes riffle–pool dynamics, increasing habitat diversity.
- Promotes natural colonization of native fauna and flora.
- Enhanced nutrient uptake and microbial processing through restored substrate heterogeneity.
- Greater retention of fine particles and organic matter.
- Reduced downstream erosion by balancing sediment supply and transport.
- Creates more natural, aesthetically pleasing watercourses.

Limitations

- Effective re-naturalisation often requires channel widening or lateral space, which may be limited in dense urban areas.
- Earthworks, sediment import, and removal of hard infrastructure can be costly upfront.
- Full development of natural habitats and stable bedforms may take several years.
- Bridges, utilities, culverts, stormwater outlets, and property boundaries may constrain design options.
- Some early-phase maintenance is needed (e.g., managing invasive species, stabilizing introduced materials).

Case study sections 5.1.1, 5.1.2, 5.1.3, 5.1.6

4.3.5 Constructed riffles

Constructed riffles involve the placement of stones and boulders that are size-sorted and placed with a gentle dip toward the channel centre, often reinforced with transplanted aquatic vegetation or macrophytes (**Figure 11**). These structures are designed to dissipate flow energy by increasing channel bed undulation and roughness, while also promoting the spread of high flows into the floodplain (**Medina and Long, 2004**).

Application scenario(s)

- River and stream systems where natural bedload is insufficient to replace riffle materials lost to streambed erosion.
- They can be used to replace concrete bed revetment.

Advantages / Solutions

- Re-establish vertical stability within the existing channel pattern.
- Hydraulic and grade control.
- Constructed riffles promote a more natural flow environment that increases macroinvertebrate biodiversity and fish spawning, rest and feeding habitats.
- The use of naturally occurring materials and its lack of reliance on heavy equipment for installation.
- Mosquito reduction.

Limitations

- Run off events can scour or destroy riffles and low flows can reduce their effectiveness.
- Not suitable everywhere, since riffles need the right channel slope, discharge regime, substrate, and sediment supply.
- Constructed riffles often lack the full structural complexity of natural riffles (microhabitats, organic inputs, heterogeneity), so ecological benefits may be limited or short-lived.

Case study sections 5.1.3, 5.1.6

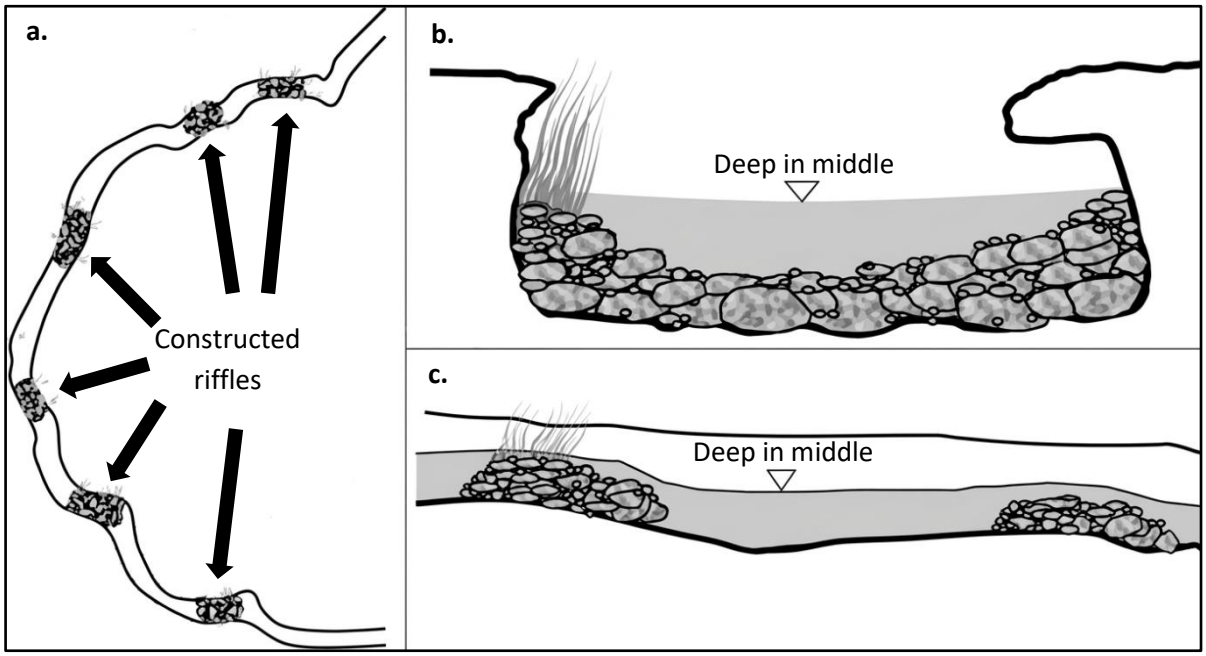


Figure 11. Conceptual visualization of constructed riffles in a stream diagram: **a.** plan view; **b.** cross-section view; **c.** and profile view. Illustrating a typical restoration design with constructed riffle formations, using grass-like wetland transplants. Based on **Medina and Long (2004)**.

4.3.6 Boulder clusters

Placing boulders in stream channels promotes riffles and pools formation and provide habitat and spawning areas for aquatic life **(Figure 12a** and **b)**. When properly implemented, boulder placements can create small scour pools and eddies that serve as rearing habitats for fish species, thus reducing erosion, preventing sedimentation, and maintaining a stable channel form (**Massachusetts Department of Environmental Protection, 2016**). In addition, they are often used to restore meanders, and pool features in channelized reaches, and to protect eroding streambanks by deflecting flow away from vulnerable areas. **The boulders used should consider the local geology and preferably be of local provenance.**

Application scenario(s)

- Stream restoration projects where stream stability and fish habitat improvements are objectives.
- Can be used in most stream habitat types, but are most effective in wide, shallow streams with gravel or rubble beds. In deep streams, they can provide cover and improve substrate.
- Streams typically with coarse substrate but are currently degraded or artificialized.
- Should be done in low flow periods to ensure proper location within the stream channel and to facilitate the movement of heavy equipment.

Advantages / Solutions

- Minimal operation and maintenance activities
- It creates habitat and shelter for aquatic species, increasing stream biodiversity.

- It creates hydraulically diverse regions of low and high flow velocity and deepness and increase river-bed substrate heterogeneity.

Limitations

Not recommended for use in the following conditions:

- Sand-bed streams, as boulders tend to become buried.
- Low-velocity streams (mean velocity < 0.6 m/s), where sufficient scour pools cannot form.
- Newly developing meanders, since boulder clusters may disrupt natural curvature and cause localized erosion or scour.
- Overwide channels or streams with large bedload transport, where flow energy is insufficient for proper structure function.
- Channels with highly erodible embankment soils, where stability cannot be maintained.

Case study section 5.1.6

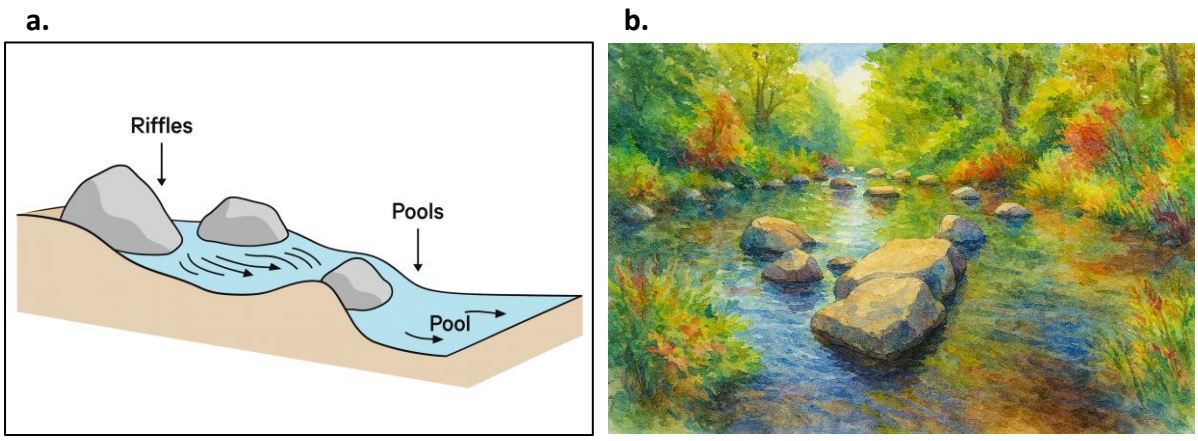


Figure 12. Rock Boulder Clusters placed in-stream. **a.** Enhancing habitats available. **b.** In-stream rock boulder clusters arranged in an upstream-oriented 'V' configuration; the recommended arrangement concentrates flow toward the channel centre, enhances riffle-pool formation, increases oxygenation, and protects streambanks by deflecting high-velocity currents away from the margin recommended.

4.3.7 Flow deflectors

Flow deflectors are used to protect eroding banks and support habitat development, and can be constructed in various designs and from a range of materials. They involve placing an obstruction within the channel – either along one bank, both banks, or the channel centre – and are intended to modify water surface gradients, longitudinal and cross-channel flow velocities, and sediment transport patterns (**Radspinner et al., 2010; Thompson, 2002a**).

Their primary function is to redirect shear stress away from the outer bank toward the main conveyance and mid-channel zones during bankfull flow conditions. Structures placed along the banks of a channel include Submerged vane (**Figure 13**), J-hook vein (**Figure 14a**), Rock vein (**Figure 14b** and **Figure 15**), Log veins (**Figure 16**), Log-frame deflector (**Figure 17**), Bendway weir (**Figure 18**), and cross vanes (**Figure 19**).

Although these structures may look similar, they are not interchangeable. Their geometry (single-arm vs. channel-spanning), crest shape, angle to the flow, and tip configuration control how velocity and shear stress are redistributed across the channel, thereby determining whether the primary effect is bank protection, grade control, thalweg repositioning, or the creation of scour pools and depositional benches.

CRITICAL NOTE! Although flow deflectors are often presented as river restoration measures, their **degree of naturalness and ecological compatibility** lies along a continuum between **nature-based solutions** and **hard engineering**, depending primarily on the **materials used, design, and construction approach**. Many deflector types are built as relatively "hard" interventions using imported quarry rock, concrete elements, gabions, sheet piling, or treated timber, which can introduce long-lived artificial structures with limited ecological integration and, if inadequately designed or placed, may shift erosion, scour, or hydraulic stress to adjacent or downstream reaches. **Contemporary restoration guidance** therefore emphasises the importance of selecting materials and configurations that **match local reference conditions and naturally occurring roughness elements**, prioritising **site-sourced stone consistent with native lithology** and, where appropriate for the river type, **untreated native large wood** (e.g., logs, rootwads, or engineered log-jam structures). Wood-based deflectors can better emulate natural channel processes, enhance habitat complexity, and reduce visual and ecological artificiality, particularly in systems where wood recruitment forms part of the natural disturbance regime. However, their application requires a high level of ecological and geomorphological understanding, robust anchoring, allowance for decay and structural mobility, and compatibility with the river's hydrological and sediment dynamics—conditions that may be difficult to meet in highly constrained urban settings. Regardless of material choice, deflectors must be conservatively sized and carefully aligned to avoid unintended effects such as excessive local scour, downstream bank attack, or back-cutting, reinforcing the need for site-specific design, adaptive management, and post-construction monitoring (**Hickman and Thompson, 2010; Palmer et al., 2010; Radspinner, 2009; Thompson, 2002b; Wohl et al., 2016; Yochum, 2018**). All the techniques provided below should have this in consideration.

Submerged vane

Submerged vanes are slender, angled foils placed within the flow and remain submerged even during low-flow conditions. They generate secondary currents within the flow, which help to stabilise the stream and prevent it from moving laterally (**Figure 13**). Typically, submerged vanes are installed in groups to counteract the erosive secondary flows that develop around meanders and are generally positioned away from the riverbank.

Most submerged vanes are made of galvanized steel or reinforced concrete, but timber is historically used in river training structures and showed good performance in small low-energy rivers (**Mosselman, 2020**). Prior to installation, topographic and bathymetric surveys must be carried out and the submerged vanes fully designed. Key design criteria include the vane orientation angle, dimensions, number of vanes per array, spacing between vanes and arrays, and the setback distance from the riverbank. Installation of timber vanes begins with preparing a stable foundation by excavating a shallow trench for the base (typically 0.3–0.6 m deep in small rivers). Vertical planks are then installed and secured using driven stakes or piles, supplemented with cross-bracing; robust anchoring is essential to ensure the structure withstands high-flow conditions. After placement, the trench is

backfilled with gravel or compacted native material. To reduce early toe scour, cobbles, coir rolls, or woody debris should be installed downstream (see sections **4.3.9**, **4.3.19**, **4.3.14**). Long-term performance requires post-installation monitoring, particularly during the first high-flow events, to verify stability and detect any necessary adjustments. Detailed guidance can be found in: **Odgaard (2009); Rodríguez-Amaya et al. (2020)**.

Application scenario(s)

- Submerged vanes are useful in a variety of applications ranging from the prevention of bank erosion and lateral migration to the protection of bridge piers, abutments, and intake structures.

Advantages / Solutions

- Protect vulnerable banks by redirecting high flows away from eroding areas.
- Encourages deposition in desired zones, maintaining channel shape.
- Submerged design minimally affects aesthetics or navigation.
- Creates pools, riffles, and varied flow velocities beneficial for fish and invertebrates.
- Typically, cheaper, and quicker to install than large-scale structural bank protection.
- It can be adapted to varying river widths, slopes, and flow conditions.

Limitations

- Limited lifespan under high flows.
- Sediment accumulation or scour around the vanes may need periodic maintenance.
- Protects specific reaches but does not address upstream/downstream erosion.
- Benefits some aquatic species while altering habitats for others, requiring careful ecological assessment.
- Requires hydraulic modelling to optimize angle, spacing, and dimensions for effectiveness.
- Are artificial structures foreign to the ecosystem.

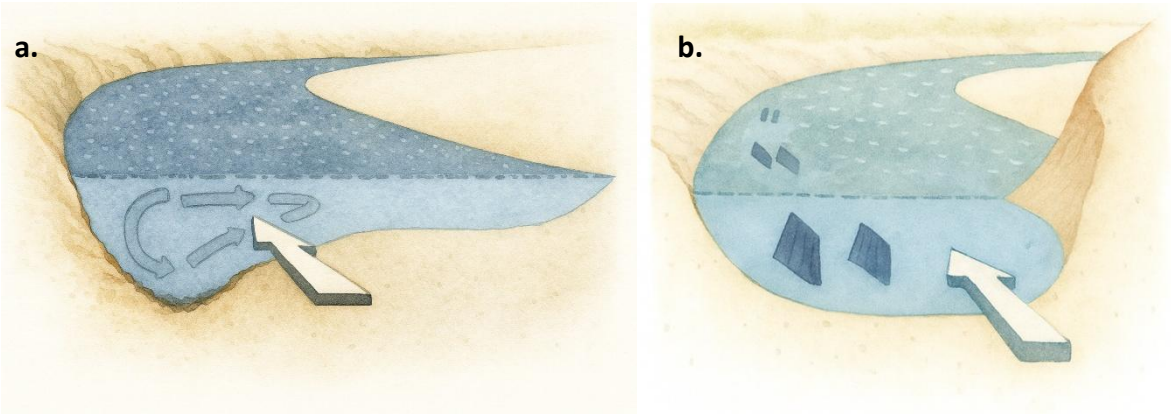


Figure 13. Submerged vanes mitigate streambank erosion by generating secondary currents that counteract natural bend-induced circulations, thereby stabilizing the riverbank. Based on **Odgaard (2015)**.

Log, rock and J-hook Vein

Veins are single-arm rock or log structures that extend from the bank into the flow (Figure 14 to Figure 16

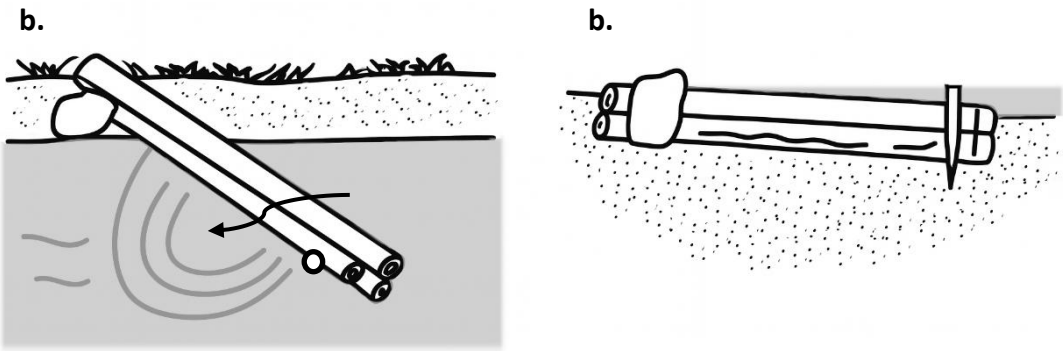


Figure 16). They essentially mimic the effect of a tree partially falling into the stream and minimize erosive flow patterns near the bank by diverting high-flow velocity away from the bank. Veins are constructed with a gentle downward slope from the bank toward the stream bed, so that the tip of the vein remains submerged even at low flow periods (**Figure 15**).

These structures are angled upstream into the flow to reduce erosive forces by redirecting high-velocity currents away from the bank and toward the centre of the channel, thereby creating calmer conditions and enhancing sediment deposition near the bank.

Rock vanes and other in-stream rock structures can reduce or eliminate the need for traditional bank armouring to stabilize eroding banks. They can also enhance the effectiveness of complementary erosion control measures such as riparian vegetation restoration.

In addition, vanes enhance aquatic habitat by increasing hydraulic diversity and promoting the formation of scour pools. Veins can also be paired and positioned in a channel reach to initiate meander development or migration on alluvial channels (**Khosronejad et al., 2018; Massachusetts Department of Environmental Protection, 2016**).

Although both J-hook vanes and straight rock vanes are single-arm flow-deflection structures, they differ in their hydraulic function and primary application. Straight rock vanes primarily redirect high-velocity flow away from the bank toward the channel centre, reducing near-bank shear stress and promoting sediment deposition along the margin.

In contrast, J-hook vanes incorporate a curved hook at the distal end, which generates localized flow recirculation and a stable scour pool downstream of the structure. This hook enhances energy dissipation, provides fish cover, and improves habitat complexity, while still maintaining effective bank protection. Consequently, straight rock vanes are mainly used for bank stabilization and thalweg repositioning, whereas J-hook vanes are preferentially applied where habitat enhancement and pool formation are key objectives in addition to erosion control.

Wherever feasible, stream restoration interventions should prioritise the use of autochthonous (locally sourced) materials, as these are inherently adapted to local hydrological, geomorphological, and ecological conditions. Native woody material and vegetation provide habitat complexity, food resources, and bank stability, while supporting natural flow dynamics, floodplain connectivity, and groundwater interactions. Such approaches enhance biodiversity, increase ecological resilience, and

typically result in lower long-term maintenance requirements, contributing to more sustainable and cost-effective restoration outcomes (**Palmer et al., 2014; Wohl et al., 2015**).

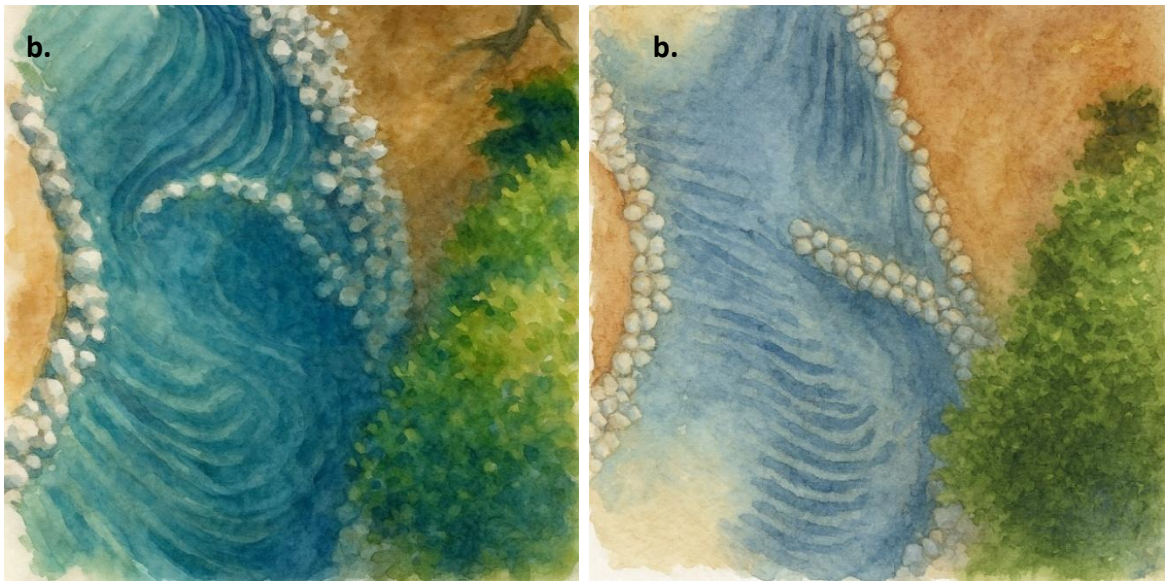


Figure 14. J-hook vane (left) and rock vane (right). Both structures function as habitat enhancement features that create downstream scour pools, narrow and deepen baseflow channels, and improve riffle habitat along the upstream side.

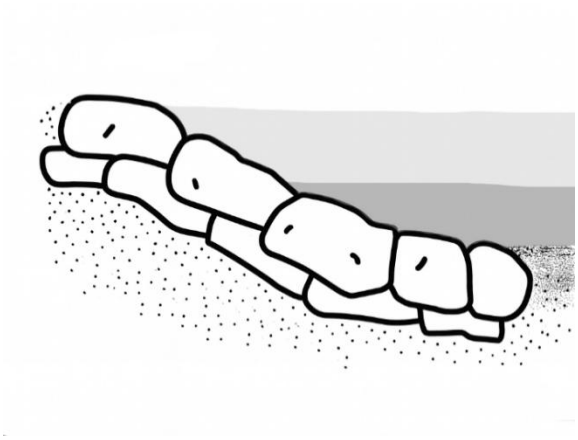


Figure 15. Rock vane section view. Based on (**Maryland Department of the Environment**).

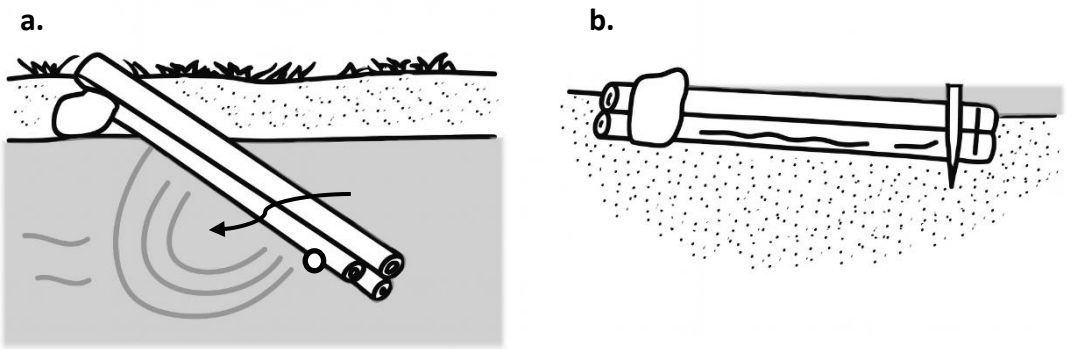


Figure 16. Log vane placement **a.** Plan view. **b.** Section view. Based on (**Maryland Department of the Environment**).

Application scenario(s)

- Stream's channel with a linear shape, low bed heterogeneity, low water retention and fast and/or flashy flows.
- Streams with unstable banks.

Advantages / Solutions

- Fading of the linear channel and development of a meandering river.
- Create hydraulically diverse regions of low and high flow velocity and deepness, induce scour pools and increase river-bed substrate heterogeneity.
- Low maintenance requirements.
- Enhance biodiversity, especially fish diversity.

Limitations

- Vanes cannot be installed in stream reaches with slopes exceeding 3%.
- Vanes are not suitable for channels that carry large sediment or debris loads, as accumulation can impair performance, and for bedrock channels since minimal bed scouring occurs.
- Subjected to failure by lateral circumvention, winnowing, local scour, aggradation, and displacement.
- At very high flow, most deflectors fail to create backwater conditions important in natural pool formation and increases erosion close to the riverbank.
- They look like unnatural structures in the stream or river.

Log-frame deflectors

Log-frame deflectors consist of triangular log frames filled with rocks (**Figure 17**). When constructed individually or in series within low-gradient, meandering streams, they redirect base flows toward the centre of the channel. Under appropriate hydraulic conditions, these structures alter flow depth and velocity, promoting the formation of scour pools and enhancing fish habitat quality (**Sahameddin Mahmoudi Kurdistani, 2018**).

Application scenario(s)

- Stream's channel with a linear shape, low bed heterogeneity, low water retention and fast and/or flashy flows.
- Streams with unstable banks.

Advantages / Solutions

- Create hydraulically diverse regions of low and high flow velocity and deepness, induce scour pools and increase river-bed substrate heterogeneity.
- Low maintenance requirements.
- Enhance biodiversity, especially fish diversity.
- Log-frame deflectors instead of log deflectors prevent scouring close to the riverbank and consequently, provide better riverbank protection.

Limitations

- Log-frame deflectors cannot be installed in stream reaches with slopes exceeding 3%.

- Log-frame deflectors are not suitable for channels that carry large sediment or debris loads, as accumulation can impair performance, and for bedrock channels since minimal bed scouring occurs.

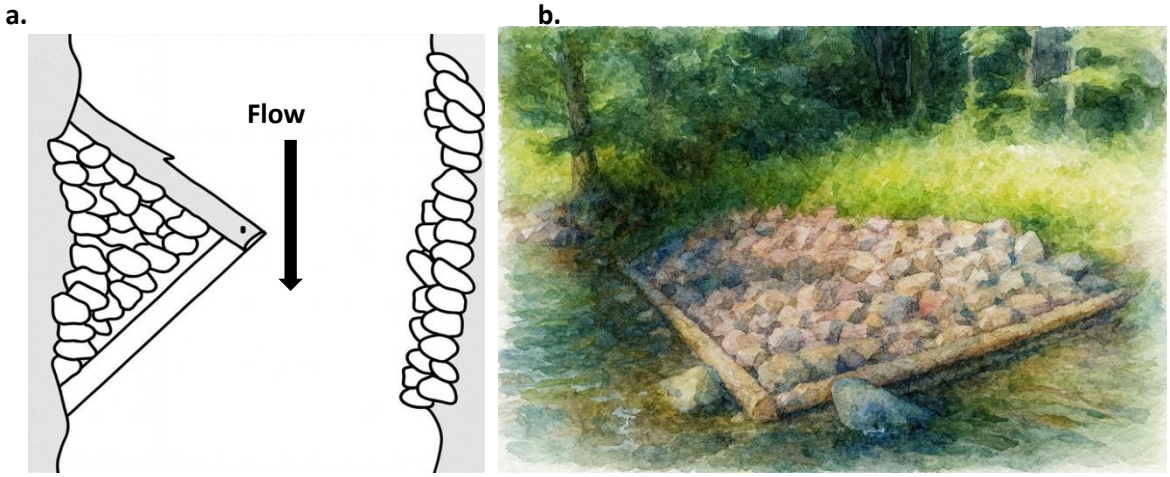


Figure 17. Log-frame deflector. **a.** diagram of typical log deflector used in channel-restoration. **b.** Visualization of how it can be applied in the field. Based on **Thompson (2002a)** and **ISAA**.

Bendway weirs

Bendway weirs are low, hard linear structures that extend outward and slightly upstream from the outer bank of a channel bend. They are typically installed in series or as part of an integrated system, positioned just above the base-flow water surface and angled upstream (**Figure 18**). This configuration redirects erosive flow energy away from the outer bank and can reduce velocities within the weir field by approximately 50%, even when overtopped by several centimetres of flow (**Abad et al., 2008**). The structures disrupt the formation of erosive helical (secondary) currents that develop as water moves through a bend. Overall, bendway weirs are designed to: deflect high-velocity near-bed flow away from the outer bank; increase flow resistance at the bank toe; and suppress helical flow and the associated redistribution of momentum near the outer bank (**Battelle Memorial Institute & The Nature Conservancy, 2014**).

Application scenario(s)

- Applied to reduce bank erosion along meandering rivers.
- These structures can also be employed to make a contraction, establish normal channel width, promote scour and sediment deposition, and trap the bedload to build new banks.

Advantages / Solutions

- Bendway weirs reduces flow velocity creates a resting area (within channel refugia) and increases diversity and complexity of depth, velocity, and substrate for fish.
- These structures are more effective than spur dikes in reducing flow velocity at vulnerable weir zones near outer banks.
- The reduction in stream forces immediately adjacent to the bank, combined with sediment deposited on the outer bank (seeds, nutrients), can benefit volunteer or planted vegetation.
- Bendway Weirs combine well with many other bank protection methods.

Limitations

- Although weirs generally protect the bank toe, they may lead to high shear stresses on the face of the outer bank (**Hemmati and Daraby, 2019**).
- Suitable for large rivers to medium-sized streams. In narrow streams (base-flow water width is less than 6 meters), Single Stone Bendway Weirs might be applicable.
- Very few Bendway Weir projects have been built in high velocity, supercritical flow, or steep-sloped stream systems.
- In cobble- or gravel-bed streams, the re-directive influence of Bendway Weirs is limited in the downstream direction because the coarse bed materials resist movement, preventing the channel thalweg from being realigned by the flow energy redirected by the weirs (**Hemmati and Daraby, 2019**).
- Optimal design guidelines for Bendway Weirs have not been successfully developed, namely the geometric parameters (e.g., length, height, space, crest slope, permeability and impermeability, and orientation angle).
- They appear as an artificial structure in the rivers.

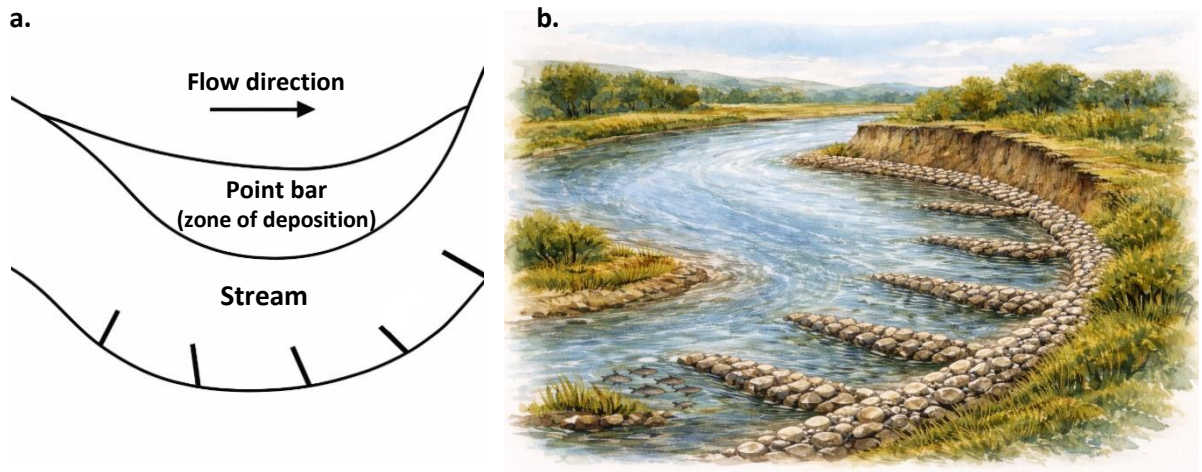


Figure 18. Bendway weirs. **a.** Bendway weir design and operating principles. **b.** Visualization of how it can be applied in the field.

Cross Vanes (Rock or Log)

Culverts, channel straightening, and the removal of riparian vegetation can lead to undesirable alterations in stream channel slope. These pressures often result in channel incision or aggradation, loss of natural pool–riffle sequences, channel widening and shallowing, and the accumulation of fine sediments on the streambed.

Cross vanes are low-profile, transverse in-stream structures designed to provide grade control, stabilise the riverbed, and restore hydraulic and morphological diversity. Functionally similar to riffles, cross vanes span the channel width and can enhance in-stream transient storage and hyporheic exchange, thereby supporting nutrient processing and contaminant attenuation along the stream reach.

Cross vanes are primarily used to enhance aquatic habitat and provide grade control in incising streams. They are typically constructed in a shallow “U” or “W” shape, with the apex oriented upstream to direct higher-velocity flows toward the centre of the channel (**Figure 19a-c**). This configuration reduces erosive forces along the banks, improves channel stability, and promotes the formation of scour pools immediately downstream of the structure, increasing habitat complexity.

Where feasible, cross vanes can be constructed using either rock or large woody material (log vanes). Log vanes, in particular, offer a more naturalised appearance and can be especially suitable where locally sourced wood is available, enhancing ecological integration and reducing construction impacts (**Figure 19c**; **Harman et al., 2012; Palmer et al., 2014**).

Application scenario(s)

- Streams lacking well-developed pool–riffle sequences and exhibiting high flow gradients.
- Urban streams characterised by flashy hydrological regimes, where grade control and energy dissipation are required.

Advantages / Solutions

- Promote increased bed heterogeneity and improved channel form.
- Create and maintain scour pools that provide critical aquatic habitats.
- Allow fish passage at low flows, as the crest elevation at the vane apex is set close to the streambed.
- Reduce reliance on continuous bank armouring when combined with riparian vegetation restoration.

Limitations

- Susceptible to local scour if improperly designed or constructed.
- May induce bank instability or unintended lateral channel migration if not well integrated with bank protection measures.
- When implemented using rigid, highly engineered materials, cross vanes may appear artificial and show reduced adaptability; these effects can be mitigated by using locally sourced (autochthonous) rock or wood and by applying a more naturalised design approach (e.g., using logs; **Figure 19c**).

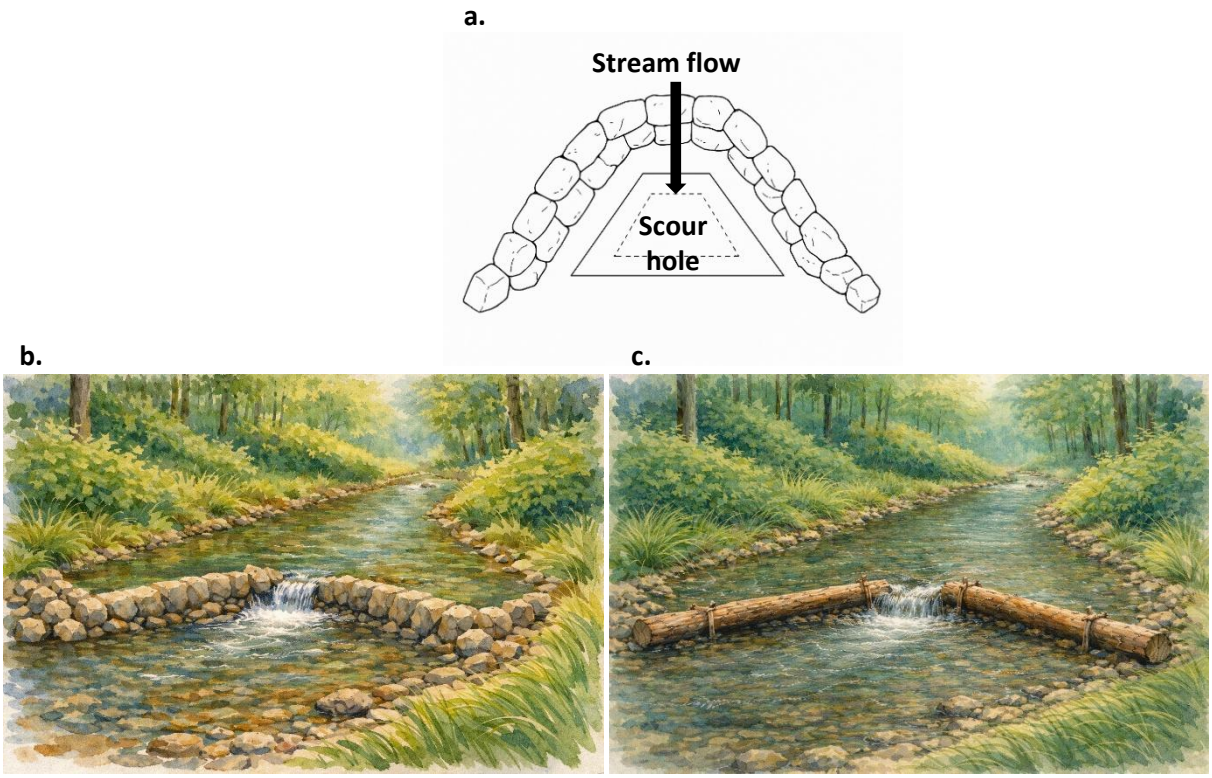


Figure 19. Cross vanes structures. **a.** plan view of a cross vane design and simple operating principles. How it could look like when applied in the field made with **b.** stones or **c.** logs (from the surrounding area).

4.3.8 Elimination of riverbank protection

A riverbank protection is an inert or living construction providing bank fixation but also an obstacle for the lateral connection of the river. Eliminating it consists in removing some parts of the bank protection, especially the inert one, to enhance lateral connections of the river, diversify flows (depth, substrate, and speed) and habitats, but also cap floods in the mainstream (**Figure 20**). Once hard armouring is removed, banks are re-naturalised through techniques such as re-meandering, regrading to gentler slopes, revegetation with native riparian species, and reconnection of the river with its floodplain.

This "de-armouring" approach restores dynamic geomorphological processes (erosion, deposition, meandering), enhances hydrological connectivity, and promotes the re-establishment of riparian habitats and self-sustaining river ecosystems (**NWRM, 2024**).

Application scenario(s)

- Riverbanks that are armoured and artificialized.
- It is commonly applied in urban and peri-urban streams where hard protection has reduced ecological value, increased flow velocities, and led to channel incision.

Advantages / Solutions

- Restores natural habitats (riparian plants, macroinvertebrates, fish nurseries).
- Improves water quality through filtration, shading, and organic matter retention.

- Reduces flow velocity, allowing more diverse flow patterns.
- Allows re-establishment of meanders and natural channel geometry.
- Increases adaptive capacity to extreme rainfall events and reduce flood risk.
- Increase groundwater recharge and storage.

Limitations

- Increased short-term erosion risk until vegetation establishes.
- Needs careful hydrological modelling to avoid risks to infrastructure.
- Public concerns may arise about allowing "erosion," requiring communication and co-design.

Case study sections 5.1.1, 5.1.2, 5.1.3, 5.1.6

Figure 20. Destruction works of an artificial riverbank (left) and what it can potential be afterwards (right). For examples see **EchoGéo (2013)**.

4.3.9Toe protection

This technique involves placing a row of stones, logs or root wads along the toe of an eroding bank, parallel to the stream channel (**Figure 21a**). The toe revetment protects the lower portion of the bank, where shear stress is maximum, providing structural support and promoting long-term bank stabilization. Typically, the height of the toe protection should be one-third to two-thirds of the total bank height. Installation below the baseflow water level or high above the high-water mark is not recommended, as this reduces the likelihood of success. Over time, sediment deposition behind the revetment allows the upper bank to gradually slump and regrade toward a more stable slope above the protected toe.

The design of the toe protection is often influenced by various site constraints. A viable design begins with an evaluation of existing and proposed channel dimensions, as well as soil conditions, hydrology, hydraulics, and environmental factors. During installation, if adequate coarse stone or valuable root mass is already present at the intended location of the toe protection, complete excavation and replacement (as illustrated in **Figure 21b**) may not be needed. Where natural materials are insufficient, excavation should proceed and be replaced with appropriate stones, logs, or roots (from the nearest donor habitat) to ensure proper structural integrity. When space and site conditions permit, steep

banks should be graded back to a more stable slope (see **section 4.3.10**), improving both bank stability and vegetation establishment.

Detailed guidance can be found at: **Billingsley (2021); Okanagan Lakeshore Living (2002); Rexine and Kalmon (2010)**.

Application scenario(s)

This technique is particularly effective where the upper bank is undercut near its base along gentle to moderately severe channel bends. It is most suitable for small to medium-sized streams and can be readily combined with other low-cost streambank protection measures, such as live staking, vanes, or wing deflectors (see **section 4.3.7** and **4.3.12**4.3.7).

Advantages / Solutions

- This kind of structure presents high flexibility, easy construction, easy maintenance and low cost.
- Hardened protection of banks in high stress areas or steep slope areas.
- Protection of utilities and infrastructures.

Limitations

- Erosion may be transferred upstream or downstream of the stabilised reach, as hydraulic energy is redistributed rather than eliminated.
- Toe protection alone does not address instability of the upper bank and may not prevent mass wasting or bank slumping.
- Rigid toe protection can reflect flow energy toward the channel centre, potentially increasing bed incision or inducing erosion on the opposite bank.
- Continuous toe protection may reduce lateral connectivity between the channel and floodplain and limit shallow marginal habitats if not combined with bank regrading and riparian vegetation restoration.
- Performance may decline over time due to undercutting or displacement during high-flow events, requiring regular inspection and maintenance.
- If poorly integrated or over-engineered, toe protection may appear artificial and reduce social and aesthetic acceptance, particularly in urban settings.

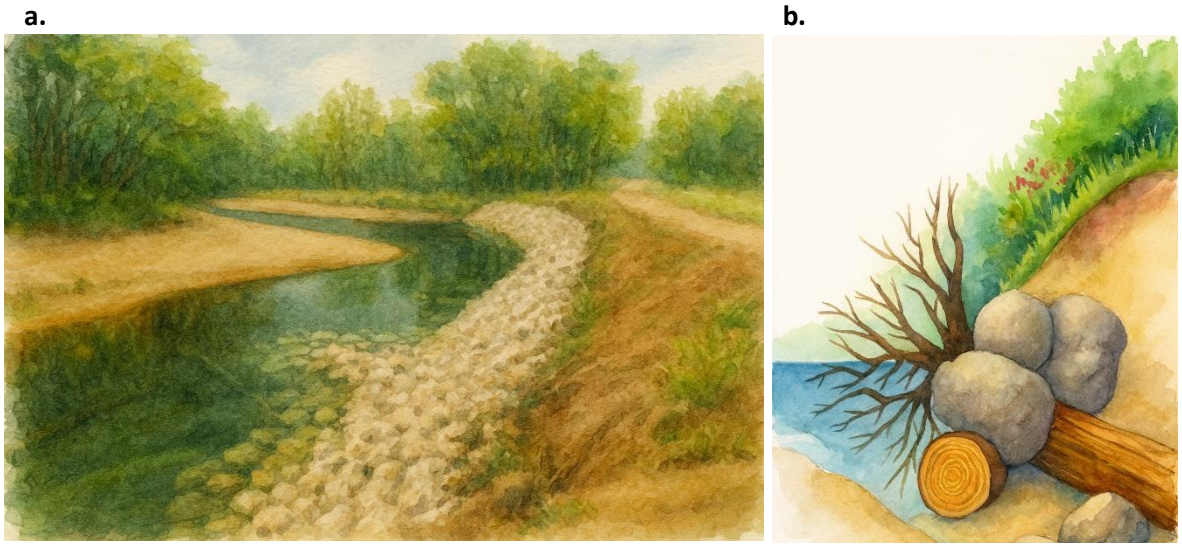


Figure 21 Toe protection, installed along the channel margin to prevent bank erosion and stabilize the toe during high-flow events: **a.** made of stone **b.** using stone and a tree-log. For other examples see **Maryland Department of the Environment**.

4.3.10 Riverbank regrading

Regrading involves reshaping steep, unstable, or eroding riverbanks into gentler, more stable slopes (**Figure 22**). This reduces erosion, allows vegetation to establish naturally, and restores the connection between the channel and its floodplain. Flow velocities, soil cohesion, and flood frequency should be assessed before design, and this measure should be integrated within wider river restoration efforts such as floodplain reconnection or in-channel habitat enhancement.

Riverbank regrading begins with site surveys and assessments to understand bank conditions, hydrology, and sediment dynamics. A target slope is then selected and detailed grading plans are prepared. During construction, the bank is excavated to the design angle, with sediment controls in place to prevent downstream impacts. Once re-graded, erosion-control measures such as fiber blanket, live stakes, brush layers, or toe protection are installed (see **sections 4.3.9, 4.3.12, 4.3.14** and **4.3.19**). Finally, the bank is replanted with native riparian vegetation (see **section 4.1.2**), and the site is monitored over time to verify stability, vegetation establishment, and overall performance. Detailed guidance can be found at (**the River Restoration Centre, 2021**).

Application

- Stabilizing actively eroding riverbanks.
- Restoring channel–floodplain connectivity.
- Facilitating riparian vegetation establishment.
- Improving access and safety in urban river restoration.

Preparing banks for additional bioengineering measures (coir rolls, live staking, brush layers).

Advantages / Solutions

- Reduces erosion risk by decreasing slope angle and shear stress.
- Promotes natural vegetation recovery, enhancing bank stability over time.

- Improves habitat diversity, creating low-energy shallow zones for aquatic species.
- Supports flood resilience by allowing overbank flow and sediment deposition.
- Lower long-term maintenance compared to hard-engineered structures.
- Enhances aesthetics and integrates well with urban green-blue infrastructure.

Limitations

- Requires space – not feasible where banks are constrained by infrastructure.
- Initial disturbance can temporarily increase sediment input.
- Vegetation must establish to achieve full stability, requiring time and maintenance.
- May need complementary stabilization in high-energy rivers (e.g., live staking, root wads).
- Earthworks cost can be significant depending on bank height and soil type.

Case study section 5.1.3

Figure 22. Regrading riverbanks to gentle slopes stabilizes eroding riverbanks, reduces sediment loss, and promotes the establishment of native vegetation, enhancing both ecological habitat and long-term bank resilience. These images illustrate the before and after.

4.3.11 Tree/ bushes direct planting (Live transplanting)

Live planting is a bioengineering technique used for establishing woody vegetation (such as shrubs, trees, and other deep-rooted plants) along slopes and streambanks (**Figure 23**). The primary objectives are to reduce soil erosion and reinforce the soil structure through root development. **It is important to assure that the trees and bushes planted are autochthonous to that region and would be present in that river or stream if the riparian vegetation was in good condition.**

During installation, pits are excavated along the slope to accommodate the plants, which are then backfilled with soil. The backfill material is often amended with mulch, compost, or fertilizer to enhance early growth and rooting. The effectiveness of live planting for soil reinforcement depends largely on the depth of placement of the plants or cuttings and the depth to which their roots can penetrate the soil mass. To maximize erosion control, plantings should be arranged in horizontal rows or contour lines along the slope face. This configuration helps intercept runoff, slow overland flow, and promote uniform vegetation coverage for long-term slope stability.

Application scenario(s)

- To establish woody vegetation in difficult locations or over a short period of time.
- In eroded and/or unstable banks.

Advantages / Solutions

- Live planting is highly effective on degraded sites, as mature plants skip germination and establish more quickly and reliably than seeds.
- Suitable for high steepness slopes.
- Faster vegetation establishment.
- Provide habitat and seed source to help re-establish native plants.
- Improves flood control.

Limitations

- Not suitable for rocky slopes.
- Local erosion can occur along the trunks and branches during high water flows.
- Trees can become heavy and cause instabilities along the slope.

Case study sections 5.1.1, 5.1.2, 5.1.3, 5.1.4, 5.1.5, 5.1.6

Figure 23. Live planting for riparian corridor streambank restoration, all these images were captured in several phases of rehabilitation of Alviela river at Vaqueiros site, Tagus basin in Portugal (**GEOTA RiosLivres Programme, 2023a**). See also other projects **Friends of the Rappahannock** and **Hargreaves (2021)**.

4.3.12 Live stakes planting

Live staking is a bioengineering technique that involves interweaving living, flexible branches from species with strong vegetative propagation and rapid rooting ability (such as willow or cottonwood) (**Figure 24**; **Pfeifer, 2024**). These branches are arranged in overlapping layers around wooden stakes driven into the ground. **It is important to assure that the species propagated are autochthonous to that region and would be present in that river or stream if the riparian vegetation was in good condition.** Ideally, they should be obtained from nearby existing vegetation, in the other margin, or up- or downstream.

The cuttings establish quickly, forming a protective, living layer that helps prevent soil erosion and provides multiple ecological benefits. This vegetative layer develops into a dense root mat that stabilizes the soil by reinforcing and binding particles together while extracting excess moisture. The woven structure is filled with soil and inert material to ensure slope and bank containment and to maintain adequate moisture for plant growth. Live staking is a low-cost, highly effective, and easily implemented technique suitable for a wide variety of sites.

Application scenario(s)

- This practice is applicable on all sizes of streams and for a wide range of bank characteristics.
- It is most appropriate where erosion is light, and washouts are unlikely.
- Live staking is a preventative measure and should be employed before severe erosion problems occur.
- Because live plant cuttings are more resistant to erosion than traditional seeding techniques, it is beneficial to use them on the lower portions of the bank to moderate flow velocities.

Advantages / Solutions

- Can enhance the performance of surface erosion control materials.
- Create favourable conditions for natural colonization of vegetation from the surrounding plant community.
- Stabilize intervening areas between other soil bioengineering techniques.
- Produce streamside habitat.
- Minimizes soil loss.
- Effective filtering action.
- Pleasant aesthetic effect.

Limitations

- Specialized labour required.
- Need for large quantities of live branches from the same watershed.
- Requirement of inert soil.

Case study section 5.1.6

Figure 24. Young willow live stakes just starting to leaf out along the edge of the margin stream, growing rapidly in a dense willow hedge to armour the margin slop to avoid erosion.

4.3.13 Live fascines

Live fascines are long, tubular bundles made from cuttings of living woody plant material, typically willow or other species capable of vegetative propagation (**Figure 25**). These bundles are placed in shallow trenches along the contour or across the slope of a bank and secured with wooden stakes. Once installed, the cuttings are expected to sprout and develop both root systems for subsurface soil reinforcement and shoots for surface protection. **It is important to assure that the fascines are from autochthonous species to that region and would be present in that river or stream if the riparian vegetation was in good condition.**

Live fascines serve as a natural measure to protect streambanks from washout and seepage, particularly in areas with moderate fluctuations in water levels (**LARIMIT**). Over time, the rooted vegetation acts as a living barrier, trapping sediment and dissipating the erosive energy of flowing water or small waves. The linear arrangement of vegetation, positioned parallel to the bank and perpendicular to flow or wave energy, helps reduce the erosive forces acting on the slope. In some applications, inert fascines are used to provide mechanical stabilization and sediment control where vegetative growth is not desired or feasible.

Application scenario(s)

- They are applied along the face of an eroded streambank, acting principally to protect the bank toe and bank face.
- They are also useful over the crown to improve erosion control, infiltration, and other riparian zone functions.

Advantages / Solutions

- Live fascines can improve erosion control, infiltration, and other riparian zone functions.
- Additionally, fascines can assist in drainage of wet or saturated zones, as the rooting and woody material can absorb and redirect excess moisture that might otherwise destabilize the slope.

- They can also be configured to act as current deflectors and pole drains that collect and transport water.
- As they provide food and cover, they can improve fisheries habitats.
- Also, they can provide a living filter to intercept and absorb excess nutrients and pollutants before they reach the water.
- Fast and simple construction.
- Useful for wet slopes.
- Short implementation time.

Limitations

- Intensive labour (construction of fascine bundles).
- Flexible branches necessary.
- Susceptible to rockfall.
- Scarce reinforcement of deeper soil layer.

Case study section 5.1.1

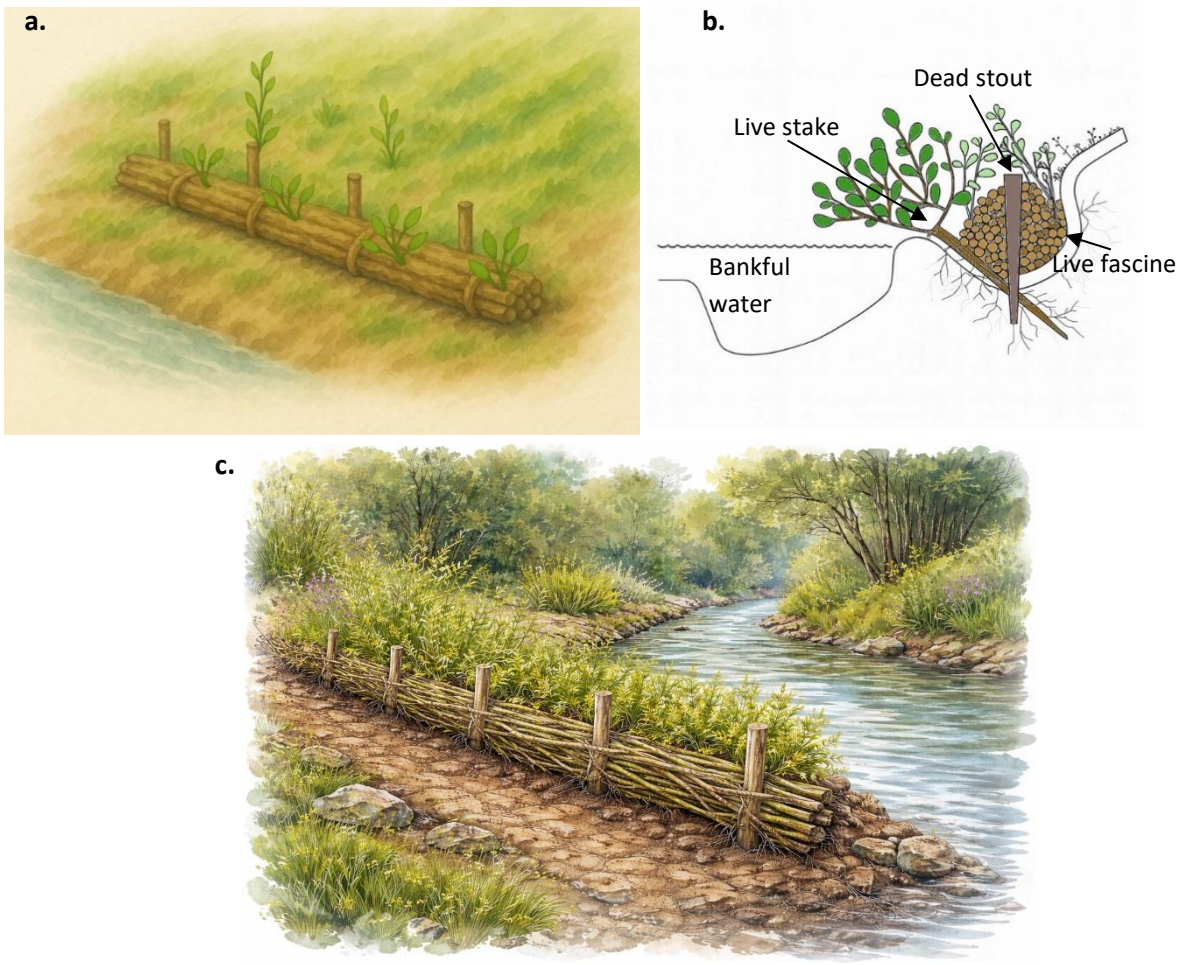


Figure 25. Live fascines constructed as bundles of live branch cuttings placed in trenches along the contour of a slope to control erosion and reinforce the soil through rooting. Live fascine in **a.** longitudinal view; **b.** cross-view. **c.** illustration in the field.

4.3.14 Live fences (wood weaving)

Live fences are constructed by intertwining of living, flexible branches from species capable of vegetative propagation (such as willow), placed in an overlapping pattern around wooden posts driven into the streambank to form a fence-like structure **Figure 26**). The space behind the fence is then backfilled with soil and inert materials, allowing for the containment of slopes and banks, providing the moisture necessary for the vegetative development of the cuttings. The outside of the structure has a rough surface which slows the river flow near the bank allowing the slow-moving water to deposit the silt at the base. In time the silt deposits and spreading roots stabilize the bank and create a habitat for wildlife. In 6 months, the root systems start stabilizing the bank, in 2-3 years full vegetation cover is typically reached and in 5 years the structure functions like a natural riparian zone (**Billingsley, 2021**) **It is important to assure that the plants used are autochthonous species to that region and would be present in that river or stream if the riparian vegetation was in good condition.**

Detailed guidelines can be found on: **Abbe and Brooks (2011); Ciotti et al. (2021); Evette et al. (2009); Moore and Rutherfurd (2017)**.

Application scenario(s)

- Live fences are used to protect slopes and enable plant growth where a steep gradient is preventing plant establishment.
- Live fences can provide protection and support to eroding riverbanks within a wide range of soil types and flows.
- This method is suitable for steep or high banks.
- Willow fences can also be constructed out into the channel, to deflect flow away from the bank and promote deposition near the bank to alter the course of the stream.

Advantages / Solutions

- It does not require heavy equipment, so it causes minimal disturbance to the river environment.
- The emergence of shoots and root systems will establish a long-lasting vegetation cover on the bank.
- Enhances biodiversity of the site and creates new habitats.
- Immediate protection after implementation.
- Minimises soil loss.
- Effective filtering action.

Limitations

- Specialised labour.
- Requirement for large quantities of live branches from the same river basin.
- Requirement for inert soil.
- Initial artificial look.

Live fascines (**Figure 25**) and live fences or wood weaving (**Figure 27**) are related, but they are not the same. Live fascines are horizontal bundles installed along slope contours primarily for erosion control, whereas live fences (wood weaving) are vertical, woven structures that provide greater mechanical stability and bank reinforcement, particularly near the channel edge (to understand the difference see **Table 3**).

Table 3. Comparing features of live fascines with live fences (wood weaving).

Feature	Live Fascines	Live Fences / Wood Weaving
Orientation	Horizontal	Vertical + woven
Shape	Cylindrical bundles	Fence-like wall
Primary role	Erosion control	Structural stabilization
Hydraulic resistance	Low–moderate	Moderate–high
Typical zone	Mid / upper bank	Lower bank / toe
Mechanical strength	Limited	Higher

Case study section 5.1.4

Figure 26. Live willow (native) weaving installed along the stream margin to stabilise the bank and reduce (**GEOTA RiosLivres Programme, 2023a**).

Figure 27. Illustration of the live fences in the field.

4.3.15 Brush layering

Brush layering is a bioengineering technique used for deeper soil stabilization, often as an alternative or complement to live fascines. It involves placing layers of live cut branches and rooted plants within excavated terraces or benches, which are then backfilled and compacted with soil (**Figure 28**). Because brush layers are linear structures, they are typically supplemented with surface planting or seeding to achieve full vegetative cover. In this method, the tips of the cuttings emerge from the slope face, where they can intercept rainfall, reduce surface runoff, and trap eroding soil particles. Meanwhile, the stems and buried portions of the cuttings extend into the slope, acting as tensile reinforcements that strengthen the soil mass through root growth and mechanical interlock. **It is important to assure that the plants used are autochthonous species to that region and would be present in that river or stream if the riparian vegetation was in good condition.**

For very steep slopes or areas prone to falling rocks and debris, a modified brush layering approach can be used. In this variation, each brush layer is supported by a small log, board, or beam that forms a minor terrace. These structures help intercept and retain small rocks or debris, preventing them from rolling downslope and damaging the vegetation, while also enhancing slope stability and moisture retention.

Application scenario(s)

- They are applied along the face of an eroded streambank, acting principally to protect the bank toe and bank face.
- They are also useful over the crown to improve erosion control, infiltration, and other riparian zone functions.
- Comparing with the technique from **section 4.3.13**, brush layering is more suitable for steep slopes.

Advantages / Solutions

- Brush layering is effective in slowing runoff, increasing infiltration and reducing surface erosion.

- Additionally, they can assist in drainage of wet or saturated zones, as the rooting and woody material can absorb and redirect excess moisture that might otherwise destabilize the slope.
- As they provide food and cover, they can improve fisheries habitats.
- Also, they can provide a living filter to intercept and absorb excess nutrients and pollutants before they reach the water.
- Suitable for very steep slopes.
- The deeper the root growth, the higher the stabilizing effect.

Limitations

- High demand on material.
- Not applicable for slopes with limited equipment access.
- Not suitable for rocky slopes or with low water content.

Case study section 5.1.6

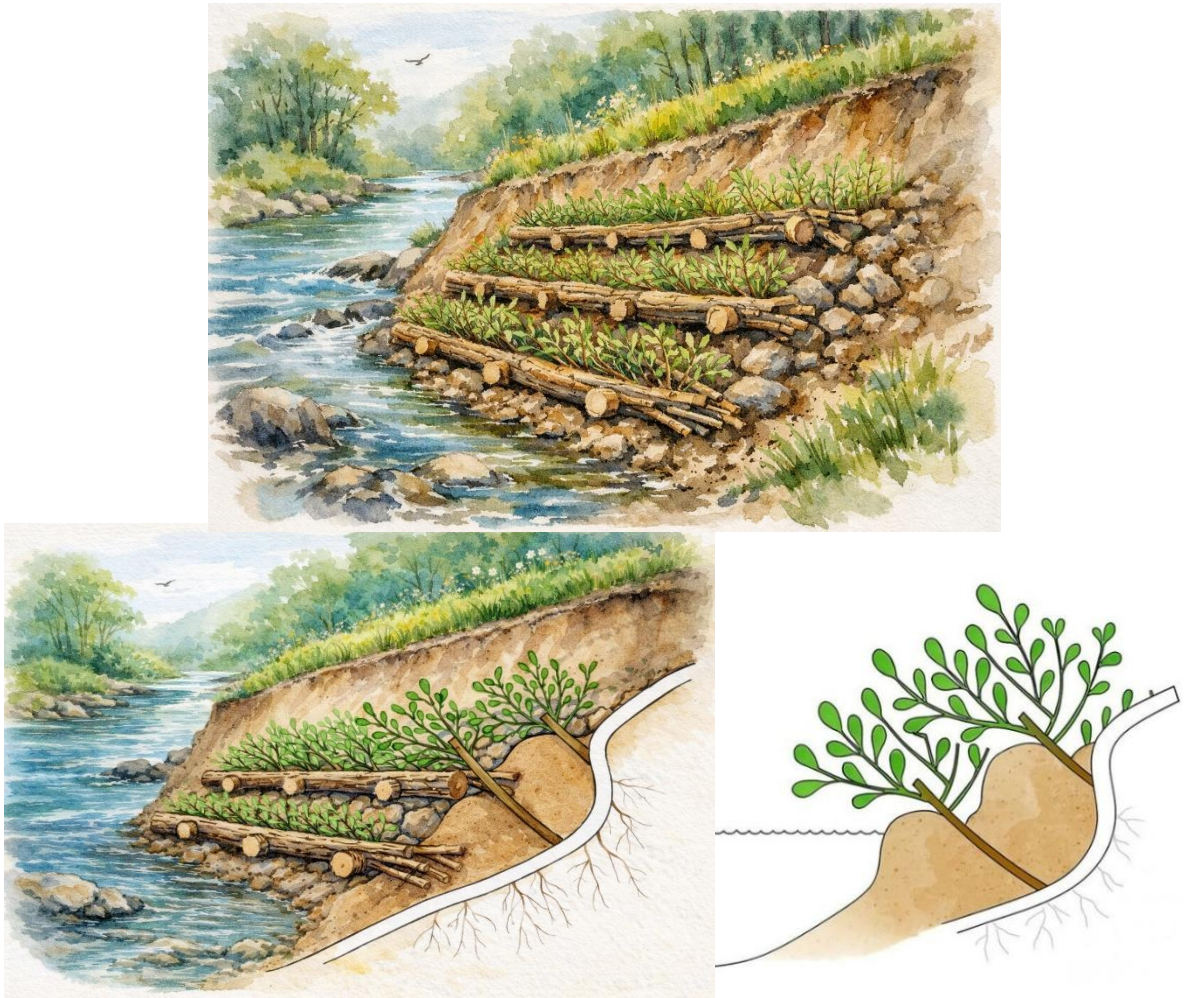


Figure 28. Illustration of a Brush layering installation (top), schematic representation of a Brush layering installation (bottom: cross-view). Examples found in **(ICEM)**.

4.3.16 Live smiles

Live smiles are willow fences shaped into a gentle catenary curve (or "smile") designed to hold slumping soil on slopes (**Figure 29**). Their curved configuration distributes the load from downslope soil movement into tensile forces along the live cuttings, which are naturally strong under tension. As a result, live smiles are generally more stable and effective than modified brush layers, which can collapse when overloaded with saturated soil or mud (**LARIMIT**).

Beyond their structural form, live smiles provide biological reinforcement as the willow cuttings root and grow, further stabilizing the slope. They are particularly valuable for arresting small slumps and gully formation before these become severe erosion problems. **It is important to assure that the willows used are autochthonous species to that region and would be present in that river or stream if the riparian vegetation was in good condition.**

Because of their high load-bearing capacity, live smiles are best suited to waterlogged or saturated slopes where shallow mudflows or surface slumps frequently occur, inhibiting natural vegetation establishment (**Goldsmith et al., 2014**). Although only a few centimetres of surface material may be mobile, such flows can extend over large areas, making this technique especially effective for large, shallow slumping zones. When properly anchored, the catenary structure can span significant distances along the slope, providing continuous stabilization and erosion control.

Application scenario(s)

- Live smiles are applied along the face of an eroded and unstable streambank, especially when vegetation cannot grow.
- Due to their capacity to hold a big amount of material, they are mostly used to treat sites with saturated surfaces where flowing mud is expected to frequently affect the slope.

Advantages / Solutions

- Willow cuttings are very strong in tension and therefore the structure would take advantage of this attribute.
- Superior stability under saturated conditions when compared to other techniques.
- Particularly valuable for stabilizing small slumps and gullies before they expand into severe and persistent erosion features.
- They can cover great distances along the slope surface.
- The catenary ("smile") shape efficiently holds large amounts of slumping soil or mud.
- The catenary curve can be adjusted to different slope geometries and can cover long sections of a slope when the ends are well anchored.
- Once established, live smiles integrate into the landscape and continue to provide ecological and structural benefits with minimal maintenance.
- As these materials dry, they can develop significant strength and thus can stand at much steeper slopes.

Limitations

- High demand of material.
- More technically demanding to install than other techniques, as it requires precise shaping, tying and anchoring of the catenary structure.

- Ineffective in dry, stony, or highly compacted soils where rooting and moisture retention are limited.
- Initial vulnerability, before rooting occurs.
- Best suited for shallow slumps and surface mudflows rather than deep-seated landslides or major slope failures.

Figure 29. Live smile, many can be done side by side, stabilizing stream banks by combining structural elements with living vegetation, reducing erosion, enhancing habitat complexity, and promoting long-term natural bank resilience. For real examples see **Polster (2002)**.

4.3.17 Brush mattresses

A brush mattress is a bioengineering (living) technique that uses layers of live cuttings or branches (willow, poplar, or other species capable of vegetative propagation) laid directly on the streambank surface and secured with stakes, to form an interwoven, protective layer that immediately covers and stabilizes streambanks (**Figure 30**). The primary goal of a brush mattress is to establish structural streambank protection that transitions into long-term vegetative stabilization. As the cuttings root and grow, they develop into a living, self-reinforcing system that stabilizes the soil through root binding and surface protection (**FISRWG, 1998**). **The site for material donations should be located within the same watershed and at a close distance, where the native vegetation has similar characteristics**. This technique is often used in combination with complementary measures such as live staking, stone toe protection, or fibber coir rolls to enhance stability and hydraulic resilience (see **sections 4.3.9, 4.3.10** and **4.3.11**).

Application scenario(s)

- Brush mattresses are applied to recover riparian vegetation and habitat and enhance conditions for colonization of native plants.
- They are also applied to reduce soil erosion and intercept sediment flowing down the streambank.
- They can also be useful on steep, fast-flowing streams.

Advantages / Solutions

- Promotes riverbank stabilization and riparian restoration.
- Provides instant soil cover, reducing surface erosion and sediment loss right after installation.
- It is a long-term technique and becomes self-sustainable with time.
- Development of dense root system and thicket.
- Flexibility in preparation and protection.
- Material easily available as structures also serve as nursery for new plants.
- After vegetation reaches a height of a few meters, it can improve fish habitat by shading the stream, lowering water temperatures and offering protection from predators.

Limitations

- High demand on material.
- Intensive labour.
- Request for occasional clearing of scrubland.

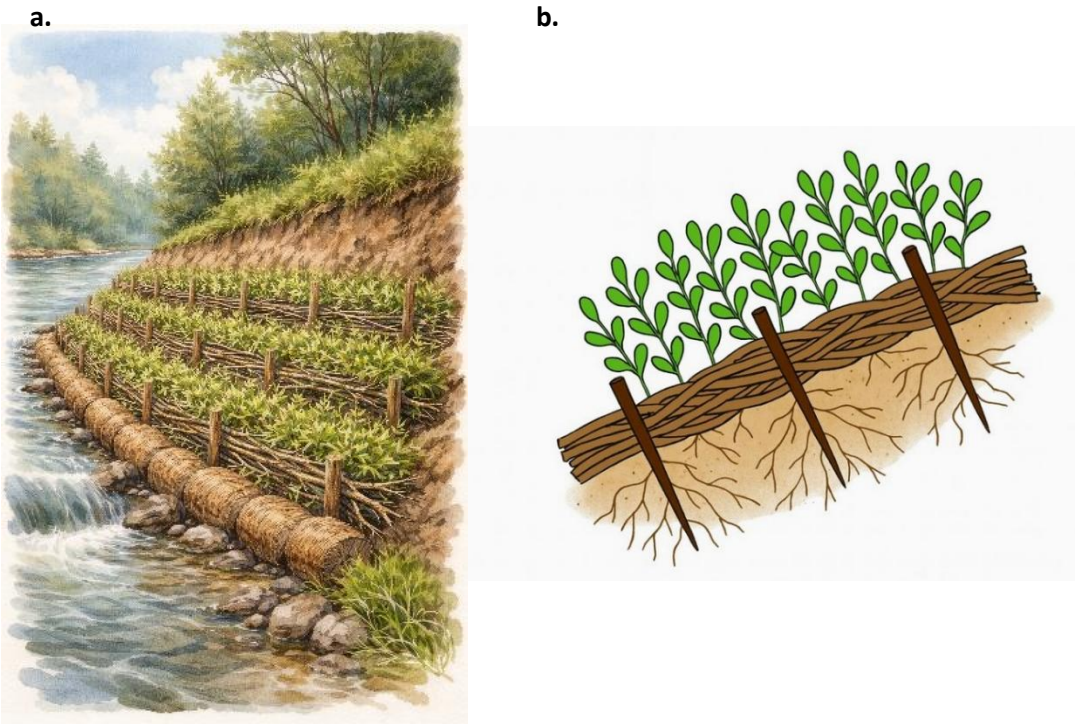


Figure 30. Illustration of brush mattresses. **a.** Stabilizing stream banks by layering live branches (horizontal and/or vertical) across the slope, creating immediate surface protection while promoting rapid root growth and long-term vegetative reinforcement. **b.** Schematic cross-view of these brush mattresses.

4.3.18 Live crib walls

Live crib walls are a specific type of gravity retaining structure constructed from locally available fill material, timber elements, and layers of live branch cuttings secured with wooden or iron pegs (**Figure 31).** Their primary purpose is to provide linear or spatial slope stabilization, particularly on steep banks or areas susceptible to undercutting.

These structures function by combining mechanical stability from the timber framework with biological reinforcement from the live cuttings. The timber forms a crib framework that is progressively filled with soil as it is built, while live cuttings or branches are inserted between the layers (like the brush layering technique). Over time, the cuttings root and grow through the structure, enhancing long-term stability as their root systems bind the soil and integrate with the framework.

Live crib walls are considered a flexible solution for stabilizing the toe of slopes subject to minor movements or settlements, offering both structural support and ecological benefits (**LARIMIT**). **It is recommended that native species well adapted to local site conditions be used for the live cuttings placed within the wall to ensure successful establishment and compatibility with the surrounding ecosystem.**

Application scenario(s)

- Steeply sloping banks, with substrate that is not exclusively rocky, in medium-high flow streams and beds originating from rocky substrate.
- Suitable for stabilising loose materials at the base of slopes or for stabilising the base of slopes that have suffered landslides.
- Most suited to rotational or pseudo-rotational slides.
- It could be useful to reduce toppling hazard in certain conditions.

Advantages / Solutions

- Robust and immediate stabilisation and consolidation.
- Suitable to stabilize loose materials at the toe or the base of the slopes.
- Easy to implement in locations with rocky substrate.
- If robust timber species are used, it can be used to stabilize the long profile of stream beds and to avoid regressive erosion along riverbank.
- When filled with earth it covers and protects underlying exposed bedrock from slaking and breaking.
- Suitable also for very steep slopes (up to 1:1) without the need for slope flattening.
- High durability (decades) and low maintenance.
- Allows vegetation to grow and log-term stabilization.
- Provides drainage and water retention.
- Aesthetic pleasing.

Limitations

- Timber species with durable structures cannot be available on site.
- Not designed for or intended to resist large, lateral earth stresses.
- Not adapted when big soil volumes need to be stabilized.
- Good soil foundation is essential for supporting from the bottom.
- Demanding labour and high labour demanding for the installation of the structure along the slope.
- May require the use of heavy machinery.
- Need for soil and aggregates to fill the wall.

Figure 31. Illustration of a live crib wall combining timber framework and live branch cuttings to provide structural and vegetative stabilization of a steep streambank.

4.3.19 Fiber rolls, blankets and pallets

Fiber rolls are cylindrical erosion-control devices usually wrapped with coconut fibber (burlap or jute can also be used) and filled with materials such as straw, flax, rice straw, coconut fibber, or compost (**Figure 32**). Whenever feasible, stream rehabilitation and bank‑stabilisation measures should prioritise the use of autochthonous (locally sourced) materials (e.g., native woody debris, locally available rock, and local plant material). Using materials that occur naturally within the catchment or comparable reference reaches typically improves structural compatibility with local hydraulics and geomorphic processes (e.g., sediment regime, bankfull hydraulics, and channel adjustment), reduces the risk of introducing non-native propagules or contaminants, and results in interventions that look and function more "natural" while supporting habitat complexity and ecological resilience. In addition, local sourcing often reduces transport-related impacts, costs, and can lower long-term maintenance needs when designs mimic locally stable configurations rather than imposing uniform, non-contextual materials (**Palmer et al., 2014**).

Between the filling options, coconut fibber is the best option, since it has a long lifespan (3–7 years), high tensile strength, low risk of environmental contamination and it is biodegradable (**Ishak et al., 2021**). Some of the other options are suitable for specific contexts and have disadvantages such as floating potential, short lifespan, weed seeds or low structural strength.

Designed to provide both temporary stabilization and long-term ecological restoration, fibber rolls are commonly installed along the toe of slopes, streambanks, or shorelines to protect against erosion, promote vegetation growth, and improve habitat quality. The fibber material has a strong ability to absorb and retain moisture, gradually releasing it to vegetation during dry periods. It also helps insulate the soil, maintain microclimatic stability, and support root establishment. Over time, as the planted or

naturally colonizing vegetation develops a dense root system, the coir matrix biodegrades, leaving behind a stable, self-sustaining vegetative framework.

In addition to fibber rolls, fibber blankets (see also **section 4.3.19**) and fibber pallets are widely used in riparian and wetland restoration. Fiber blankets provide surface protection and encourage revegetation of disturbed soils by preventing erosion and allowing plants to grow through the fibber. Fiber pallets, being thicker and more robust, offer a stable rooting medium in marginal or erodible conditions, helping plant colonies establish and expand.

For comprehensive instructions on how to use these techniques, please refer to the following: **Baird et al. (2015); Beckenham (2022); Rexine and Kalmon (2010)**.

Application scenario(s)

- These techniques are best suited for areas experiencing low shear stress, being suitable along the toe, top, face, and at-grade breaks of exposed and erodible slopes to shorten slope length and spread runoff as sheet flow.
- Coir rolls are generally used at the bank toe to protect the toe from wave action and erosion from the stream shear forces.
- Coir mats are suitable for the stabilization of stream and riverbanks, road embankments and wetland construction.
- Coir pallets are a useful way to quickly establish marginal vegetation around the edges of streams and riverbanks.

Advantages / Solutions

- They can slow down, filter, and disperse surface runoff, thereby reducing erosion and minimizing rill and gully formation.
- They also help to lower sediment loads entering downstream waters by trapping and retaining sediments within the roll matrix.
- Coir rolls are designed to dissipate wave energy, protect against water scour and retain the bank while plants develop.
- Coir mats are designed to protect banks against erosion and facilitate the establishment of vegetation on disturbed ground. They are used where the bank has a high potential for erosion due to heavy rainfall or on riverbanks and where re-vegetation requires added protection to establish.
- Coir pallets help to establish native marginal vegetation around lake edges, streams, riverbanks, and ponds, and are beneficial on projects where no suitable soil medium exists. The coir fibres retain water, helping to keep plant roots moist, even in dry weather conditions.
- They are more adaptable to slope applications and contour installations than other BMPs.
- Unlike other BMPs that could cause water to back up and flow around the edges, fibre structures allow water to flow through while capturing runoff sediments.
- They are readily moulded to fit the bank line.
- They blend in with the landscape and do not obstruct hydraulic mulch and seed applications.
- They can be removed or left in place after vegetation is established.

Limitations

- They should not be used in channels that are actively incising, or in reaches with high debris loads or a significant potential for ice accumulation, or unstable slopes prone to creep, slumping, or landslides, as these conditions can compromise their stability and effectiveness.
- They are also not suitable for very sandy soil or at sites subject to high-velocity flows or wave action since soil can be lost through the holes.
- Fiber rolls are ineffective unless they are properly trenched into the soil.
- Saturated fibre rolls can be heavy and difficult to reposition once installed.
- For slopes steeper than 5:1, fibre rolls placed at the toe must be at least 20 inches in diameter. Alternatively, stacked smaller-diameter rolls may be used to achieve comparable protection.
- If not securely staked and entrenched, fibre rolls may be dislodged by high flows.
- Fiber rolls have a limited sediment capture capacity and should be used in combination with other erosion control measures.

Case study section 5.1.6

Figure 32. Illustration examples of fibre rolls, mats, and pallets made from fibre (e.g., coconut) used for erosion control, soil stabilization, and vegetation establishment along slopes and streambanks.

4.3.20 Erosion control blanket

An Erosion Control Blanket (or EBC) is a biodegradable organic mat made of plant fibber (e.g., coconut fibber, jute, straw, biodegradable mesh, or geotextile) placed on soil to protect against surface erosion from rainfall or overland flow (**Figure 33**). These are secured with metal staples (or wooden stakes). Before laying the mats, the ground must be cleared of any objects that could damage them (stones, debris). This technique can be combined with other like planting/staking (see **sections 4.1.2** and **4.3.12**). **It should be assured that the materials used will not lead to the presence of non-native species (plants but also animals) in the ecosystem.**

Application scenario(s)

- Usually used for short-term erosion control, mainly to provide surface protection.
- Often used to assist vegetation establishment but does not provide rooting itself.

Advantages / Solutions

- Provide immediate physical protection from erosion.
- Hold soil and seeds in place until vegetation establishes.
- Prevents soil particle detachment and transport into streams, improving downstream water quality.
- Easy to apply with minimal equipment, suitable for small to medium-scale projects and steep slopes.
- Natural-fibre ECBs (like coir or jute) decompose over time, leaving no synthetic residue in the environment.

Limitations

- It is a short-term solution, since the ECB degrades with time.
- It has moderate ecological value.
- Unlike bioengineering methods (e.g., brush mattresses), ECBs don't root or strengthen the soil themselves.
- Can be displaced or damaged by strong water currents or concentrated runoff.
- Needs a smooth, compacted, and well-seeded soil surface.
- Low success rate, if the slope is actively eroding or unstable.
- Is unesthetic while it does not degrade or when used alone.

Figure 33. Installation of erosion control blankets, Odelouca River (Tributary of the Arade River, Algarve, southern Portugal), providing temporary surface protection on exposed soils, reducing runoff and sediment loss, and supporting vegetation establishment for long-term slope stabilization. The Odelouca River was characterised by dense and locally riparian vegetation dominated by Narrow-leaved ash (*Fraxinus angustifolia*), willows (*Salix* spp.), poplars (*Populus* spp.) and alder (*Alnus* spp.), with Tamarix and oleander (Nerium oleander) occurring in the lower reaches. Large portions of the riparian corridor were lost following the construction of the Odelouca Dam. To compensate for habitat loss, restoration actions were implemented along approximately 180 ha of the left bank, aiming to enhance riparian habitats and support conservation efforts for flagship species such as the endangered Iberian lynx and Bonelli's eagle, including the establishment of the Iberian Lynx National Captive Breeding Centre. **©Rui Cortes**

4.3.21 Floodplain reconnection and storage basins

In urban areas, stormwater is usually conveyed through pipes and sealed drains, which solves the problem of water in the pavements but prevents infiltration and increases flood risk. Disconnection of

impervious areas and infiltration trenches reduce the direct hydraulic link between sealed surfaces and sewers, promoting on-site infiltration and slowing runoff delivery. These techniques are core elements of pathway control within sustainable drainage systems (**Qin, 2020**). By intercepting runoff along its route rather than at its source or outlet, they help restore intermediate hydrological processes that support baseflow, water quality, and temperature regulation in urban streams.

Re-establishes the link between the river channel and its adjacent floodplain or former side channels, to enhance temporary water storage and attenuate flood peaks. Floodplain reconnection, including is a recognized restoration measure to re-establish lateral connectivity and attenuate floods in urban and peri-urban rivers (**dos Reis Oliveira et al., 2020; Hordones et al., 2025; Muhar et al., 2016**) **(Figure 34**). It can include lowering artificial levees, creating secondary channels or offline retention ponds that fill during floods, and **re-naturalizing former floodplain areas, which would be the ideal solution**. It is important to favour **solutions that re-establish the previous/natural hydrological connections, instead of creating new types of water bodies that are uncommon in natural systems of the regions (e.g., a pond in a region where there are no ponds).**

Application scenario(s)

Applied where space allows or where land can be reclaimed. Often integrated into green infrastructure or park design to combine flood protection, biodiversity, and recreation.

Advantages / Solutions

- Reduces flood risk by increasing temporary water storage.
- Recharges groundwater and supports riparian vegetation.
- Enhances habitat diversity and provides ecological connectivity (this is mentioned in more detailed below).
- May temporarily store and manage large volumes of water.

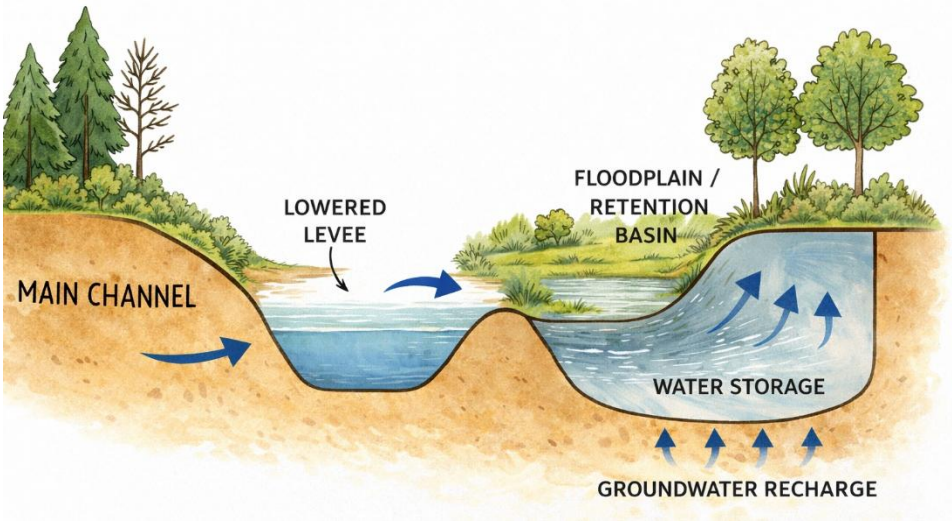
Limitations

- Requires available land and careful hydraulic design.
- May conflict with existing infrastructure or property.
- Maintenance needed to control sedimentation and invasive vegetation.
- May become prohibitively expensive in dense or built-up areas, where space is scarce and land values are high - high implementation costs in dense urban areas.
- This measure is more feasible in peri-urban or redeveloped areas where land-use flexibility exists.

The floodplain disconnection, reflecting the loss of the catchment's ability to retain and infiltrate water. While floodplain reconnection focuses on the river corridor, the following measures act at the urban catchment scale.

Case study sections 5.1.1, 5.1.2, 5.1.3, 5.1.5, 5.1.6

a.



b.

Figure 34. Floodplain reconnection. **a.** Simples schematic view of how a natural floodplain my attenuate flood peaks. **b.** Illustration of functional floodplain reconnection.

4.4 Social and community-based measures: third line measures

In many cities, people do not even see the streams around them, they are often hidden, degraded, or perceived as unsafe. Re-establishing the social and emotional connection with these ecosystems is therefore a key step in achieving real, lasting rehabilitation.

Therefore, the success of urban stream rehabilitation depends not only on physical and chemical improvements but also on social awareness, participation, and behavioural change. When citizens recognize urban streams as part of their daily landscape, they are more likely to support their restoration, protect them from pollution, and ensure their long-term maintenance.

Green and blue areas create spaces for recreation, learning, and social interaction, improving public health, wellbeing, and community cohesion, while generating green jobs related to monitoring, maintenance, and environmental education (**Hordones et al., 2025**).

4.4.1 Enabling governance, land stewardship and long-term management

This measure refers to the enabling social and institutional conditions that make urban stream restoration feasible and durable at scale (space and time). It focuses on: i) securing land access (e.g., easements/servitudes, land purchase, negotiated agreements with riparian landowners); ii) building a strong multi-actor coalition (public agencies, utilities, municipalities, NGOs, research bodies, user groups and private owners), and iii) establishing long-term management arrangements (roles, funding, maintenance duties, monitoring, and accountability); so that restoration outcomes persist beyond the construction phase.

In Europe, these enabling conditions are increasingly aligned with integrated river-basin and flood-risk planning (e.g., coordination of flood risk management and river basin management, including public participation), and with emerging large-scale restoration obligations under the EU Nature Restoration Regulation (entered into force in 2024), which requires Member States to plan and finance restoration actions over time (**European Commission, 2025**).

WHY IT MATTERS! Many restoration actions fail when long-term responsibilities and maintenance arrangements are unclear, underfunded, or not effectively monitored; voluntary agreements can work, but typically need clear benefits, monitoring, and credible enforcement/oversight to secure long-term delivery (**Moore and Rutherfurd, 2017**).

Application scenario(s)

- **Projects requiring "space for the river":** channel widening, floodplain reconnection, re-meandering, riparian corridor enlargement, wetland creation—especially where land is privately owned or land use is contested and needs negotiation or acquisition.
- **Large, multi-partner programmes** (city + water agency/utility + conservation bodies) where works span multiple jurisdictions and require coordinated permitting, budgets, and maintenance responsibilities.
- **Sites with long recovery trajectories** (vegetation establishment, geomorphic adjustment), where post-construction stewardship and adaptive management are essential.
- **Catchment-linked interventions where upstream–downstream coordination** is needed (e.g., diffuse pollution control, sediment management, flow regime measures).

- **Restoration tied to legal planning cycles** (river basin management / flood risk planning), where participation and coordination are built into the process.

Advantages / Solutions

- **Makes nature-based measures feasible at scale:** land access and multi-actor coordination unlock measures that otherwise cannot be implemented (e.g., floodplain reconnection, corridor widening).
- **Improves durability and performance:** clear long-term roles, adequate funding, transparency and accountability increase the likelihood that interventions are maintained long enough to achieve ecological recovery.
- **Reduces project failure risk from social conflict:** structured engagement with landowners and user groups can prevent removal or undermining of measures after floods or controversy (e.g., perceptions around instream wood) and supports compliance with on-site practices.
- **Enables adaptive management:** coalition-based governance supports learning-by-doing and iterative adjustments (monitoring → feedback → refinement), which is often necessary in dynamic urban corridors.
- **Aligns funding and responsibilities with multiple co-benefits:** integrates flood safety, biodiversity conservation, recreation, climate adaptation and human well-being within a single long-term management framework, consistent with a One Health perspective and EU-level restoration planning needs.

Limitations

- **High transaction effort:** negotiating access, compensation, or acquisition can be time-consuming and politically sensitive, particularly in dense urban settings.
- **Complex coordination:** multi-actor governance requires facilitation capacity and sustained institutional commitment; responsibility gaps can undermine long-term maintenance if not explicitly addressed.
- **Voluntary instruments may be fragile without oversight:** agreements can fail over years/decades if monitoring and enforcement are weak or benefits are unclear; independent oversight is repeatedly highlighted as critical for effectiveness.
- **Long-term funding dependencies:** where measures require ongoing maintenance (especially engineered components), durable funding streams and clear mandates are needed to avoid decline over time.

This enabling measure underpins the remaining social measures (citizen science, participatory planning, and pollution-prevention behaviour change). Without secured land access, clear roles, and long-term maintenance arrangements, even well-designed nature-based interventions may not persist long enough to deliver ecological recovery.

Case study sections 5.1.1, 5.1.2, 5.1.3

4.4.2 Citizen Science and educational partnerships

Citizen science and educational partnerships invite people of all ages to become part of the living system they observe and protect. By involving citizens directly in data collection, ecological monitoring,

and stewardship, these initiatives transform scientific observation into a shared cultural practice. Residents, students, and local associations learn to measure water quality, biodiversity, and hydrological indicators, interpreting what these reveals about the health and resilience of their local urban stream ecosystems.

Partnerships with schools, universities, and research institutions foster intergenerational learning, transmitting ecological knowledge, curiosity, and care from one generation to the next. These activities strengthen the bond between humans and urban streams/rivers, cultivating a sense of belonging and collective responsibility, while creating communities capable of supporting restoration efforts long after projects officially end.

Application scenario(s)

Most effective in urban and peri-urban catchments where restoration projects are active or planned, and where there is proximity to schools, universities, science centres, or community hubs that can host workshops and monitoring activities. Ideal for building continuity between scientific programs, educational curricula, and local rehabilitation/restoration long-term goals.

Advantages / Solutions

- Builds local stewardship and long-term guardianship of restored areas.
- Strengthens ecological literacy and awareness among children and young adults.
- Enhances data availability and supports adaptive management.
- Encourages trust and cooperation between citizens, scientists, and municipalities.
- Creates low-cost, high-impact engagement with strong educational and emotional value.

Limitations

- Requires continuous coordination, mentoring, and technical support.
- Data quality may vary and often needs expert validation.
- Sustaining participation can be challenging without institutional backing.
- Needs accessible, user-friendly monitoring tools and clear feedback loops.

Case study sections 5.1.2, 5.1.7

4.4.3 Participatory planning, educational trails and active cultural-recreational use of near-natural urban stream landscape

This measure combines participatory planning processes with eco-literacy initiatives to strengthen long-term community engagement and shared responsibility for restored urban stream corridors. Through participatory workshops, citizens, planners, designers and ecologists co-create restoration solutions, ensuring that interventions respond not only to ecological objectives but also to socially inclusive and context-specific needs. Such approaches recognise that restoration outcomes **extend beyond a single generation**, shaping landscapes, ecosystems and cultural values inherited by future communities.

Educational trails, equipped with interpretive signage, observation points and interactive elements, function as open-air classrooms where people of all ages can explore urban stream dynamics, biodiversity and ecosystem services. These spaces support continuous learning and dialogue between

humans and nature, fostering ecological awareness, empathy and a stronger sense of place within urban environments.

In addition, non-invasive cultural and sports events (e.g. temporary art installations, small-scale festivals, guided walks, cycling or running events, and nature-based recreational activities) are increasingly used as engagement tools in restored river corridors. Such activities should be typically designed to **minimise noise, artificial lighting and physical disturbance, and are often subject to spatial zoning and seasonal restrictions to protect these sensitive habitats**.

When carefully planned and managed, these activities strengthen emotional connections to rivers, promote regular use and visibility, and help embed restored streams into everyday urban life, while respecting ecological sensitivity and safety requirements.

Application scenario(s)

Best suited for restored or semi-natural stream corridors located near residential, educational, or recreational areas. Can be combined with citizen science initiatives, school partnerships, and eco-tourism activities, integrating immediate learning goals with **long-term ecological stewardship**.

Advantages / Solutions

- Builds **community pride** and a shared sense of **responsibility for local environments and future generations**.
- Enhances environmental education and eco-literacy, fostering informed stewardship.
- Provides opportunities for interdisciplinary learning (science, art, design, social studies).
- Strengthens the cultural, recreational, and aesthetic value of restored urban streams.
- Encourages intergenerational interaction and long-term vision in restoration planning.

Limitations

- Requires continuous engagement, institutional support, and well-trained facilitators.
- Vandalism or neglect may occur if there is no follow-up or community ownership.
- Needs initial investment for infrastructure and educational materials, and ongoing funding for maintenance and program renewal.
- Effectiveness depends on active communication between planners, educators, and citizens.

Case study sections 5.1.1, 5.1.2, 5.1.3, 5.1.5

4.4.4 Regulatory and behavioural measures for pollution reduction

This measure addresses the social roots of pollution by fostering cooperation between institutions and citizens to reduce both chemical and diffuse stressors in urban streams.

It connects municipal and utility governance with individual behaviour, linking the accountability of public systems with the everyday actions of households, schools, and businesses (**Hordones et al., 2025; Santaoja et al., 2025**).

Behavioural change initiatives encourage responsible use of household chemicals, proper disposal of oils, litter, and pharmaceuticals, and support for environmental regulations and incentives.

Strong governance frameworks, transparency, and community participation ensure that restoration outcomes are not temporary but **socially sustained across generations**.

In this sense, good governance acts as a "***collective immune system***", one that maintains the ecological health of urban waters by promoting shared responsibility, mutual trust, and continuity between people and nature.

Application scenario(s)

Most relevant in urban areas with persistent water quality problems, especially where industrial, commercial, or household pollutants still enter the drainage network. Applicable where municipalities and water utilities can influence waste management, environmental education, and incentive programs, fostering both structural and behavioural adaptation.

Advantages / Solutions

- Reduces illegal or accidental discharges, point-source inflows, and diffuse pollution.
- Strengthens institutional coordination, accountability, and policy coherence.
- Promotes inclusive and adaptive management, responsive to community needs.
- Ensures that technical improvements are maintained through social continuity.
- Encourages a culture of environmental responsibility that transcends projects.

Limitations

- Requires robust governance frameworks and consistent policy enforcement.
- Behavioural change tends to be gradual and uneven across social groups.
- Success depends on long-term political commitment and transparent communication.
- Needs integration across sectors (education, health, infrastructure) for lasting impact.

4.5 Complementary measures: fourth line measures

4.5.1 Control / Removal of invasive species

In many contexts, invasive species are more appropriately viewed as indicators of underlying habitat degradation rather than as isolated drivers of change. Consequently, management strategies that focus solely on invasive species removal risk overlooking the systemic stressors shaping ecosystem dynamics, often leading to rapid recolonisation if those pressures remain unaddressed.

Invasive species can quickly establish themselves in habitats ranging from freshwater wetlands and riparian corridors to stormwater basins, disrupting ecological balance and biodiversity, altering hydrology, and displacing native species (**Aronson et al., 2017; Tickner et al., 2001**). Left unmanaged, aggressive invasives such as Giant Reed (*Arundo donax)* or Tree of Heaven (*Ailanthus altissima*) can severely impact the stability of critical environmental systems (**Figure 35**). Both species are non-native and invasive in Europe, particularly associated with disturbed riparian and urban environments, where they outcompete native vegetation and hinder ecological restoration processes.

The removal of invasive species involves eliminating non-native organisms that outcompete or disrupt native communities. When effectively implemented, control strategies can support the recovery of ecosystem structure, function, and resilience, preserve biodiversity, and safeguard the provision of ecosystem services to humans and wildlife. Depending on the severity and extent of invasion, invasive species removal may function either as a first-line intervention (together with the riparian vegetation restoration) or as a complementary measure alongside broader restoration actions (**Lapin et al., 2016**).

Before implementing management actions, it is essential to establish realistic objectives, assess available resources (time, labour, and funding), and prioritize invasive species accordingly (**Cockel et al., 2014**; **Department of Environmental Conservation**). Depending on site conditions, desired outcomes, and the species present, management goals may include:

- **Eradication:** complete elimination of invasive species and, where feasible, their seed bank.
- **Containment:** applied when eradication is unlikely, aiming to prevent further spread into uninvaded areas.
- **Suppression:** long-term management focused on reducing invasive populations to levels that allow native species or ecosystem functions to persist.

Once management goals are defined, invasive species must be prioritized. A common approach is to target low- density infestations first, gradually working back toward core infestation areas over time (**Department of Environmental Conservation**). This strategy maximizes the likelihood of success and prevents small, manageable invasions from becoming larger and more costly in the future. Prioritization may also consider factors such as public access, risks to human health and safety, invasive potential, proximity to watercourses, and proximity to sensitive or critical wildlife habitats.

Management methods depend on the extent of infestation and site characteristics. In practice, most invasive species management is ongoing and long-term, and full eradication is rarely achieved. Early detection and rapid response are therefore critical in determining both the level of effort required and the likelihood of success. Where infestations are limited (e.g., <15% cover), physical control methods such as hand pulling, digging, or trapping may be sufficient. In contrast, large infestations (≥50% cover) may require more intensive interventions, including mechanical treatments (e.g., cutting, chipping, ploughing) or, where appropriate and legally permitted, the use of aquatic-approved herbicides due to proximity to water bodies (**ECRR, 2025**).

Preventing reinvasion through site management and cleaning of maintenance equipment is an essential ongoing task, as seeds and propagules may remain viable in riparian soils and streambeds for several years. While initial treatment is typically the most labour- and time-intensive phase, subsequent maintenance usually involves targeted removal or spot treatments to prevent re-establishment (**Moore and Rutherfurd, 2017**).

Sites affected by prolonged erosion, pollution, or invasive species dominance often exhibit low plant diversity, which in turn limits faunal diversity. Under such degraded conditions, even native species may display invasive-like behaviour and form monospecific stands. To avoid this outcome, low-diversity states should be actively addressed through complementary restoration measures that promote structural and compositional diversity.

Figure 35. Non-native invasive species in Europe, particularly associated with disturbed riparian and urban environments: **a.** Giant Reed (*Arundo donax*)**; b.** Tree of Heaven (*Ailanthus altissima*). **©Marcos Dias**

Application scenario(s)

In Stream where removing invasive plants is needed to restore native vegetation, bank stability, natural food webs and natural hydrological and ecological processes.

Advantages

- **Restores natural ecosystem functions** by reducing competition, predation, or habitat alteration caused by invasive species.
- **Enhances native biodiversity**, improving ecological integrity and community structure.
- **Improves ecosystem services**, including bank stability, nutrient cycling, and water quality.
- **It can increase resilience** to climate change by reinstating self-sustaining native communities.
- **Often low-tech and nature-led**, using manual, mechanical, or biological control methods.
- Public health improvements through removal of potentially toxic species.
- Improve **pest** and **disease regulation**.
- Reduce **flood risk**.

Disadvantages / Limitations

- **It can be labour-intensive and costly**, especially for well-established invasions.
- **Risk of reinvasion** if follow-up monitoring and maintenance are not maintained.
- **Potential non-target impacts** if removal is poorly planned (e.g., soil disturbance, by-catch, chemical herbicide risks).
- **Requires long-term management**, not a one-off intervention.
- **May not achieve desired outcomes** unless paired with habitat restoration or native species re-establishment.

CRITICAL NOTE! Effective management of biological invasions in riparian ecosystems requires coordinated action among local stakeholders and authorities responsible for upstream catchment management (**Pabst et al., 2022**).

4.6 Compensatory measures: hydrological

4.6.1 Rain gardens

Rain gardens are shallow, vegetated depressions designed to collect, filter, and infiltrate stormwater runoff from nearby impervious surfaces such as roofs, sidewalks, and parking lots. They consist of a permeable soil mix (sand and compost), mulch, and native plants adapted to alternating wet and dry conditions. Water infiltrates through the soil, where pollutants are removed by filtration, sorption, and microbial degradation before percolating into the ground or being released to drains via an overflow (**Figure 36**). This is considered an On-Site Biofiltration and Bioretention technique.

They should not be viewed as a measure to recover the freshwater ecosystem but could be an additional solution in the urban planning of cities. During periods of intense precipitation, they help preventing the flash floods in urban streams that are included in the drainage systems of pluvial waters.

Application scenario(s)

- Installed near the runoff source, typically next to buildings, parking areas, or along streets in residential or institutional areas.
- Most effective in sites with permeable soils and available open space.
- Can be integrated into landscaping, parks, or courtyards as part of low-impact urban design.
- Not suitable for compacted clay soils unless equipped with underdrains or pre-treatment units.

Advantages / Solutions

- Reduces runoff volumes and delays storm peaks.
- Removes sediments and reduces erosion.
- Removes nutrients, and hydrocarbons through filtration and biological uptake.
- Promotes infiltration and groundwater recharge.
- Enhances urban microclimate.
- Cost-effective, decentralized, and adaptable to various scales.
- Increases biodiversity of native plants within the city (flora, pollinators, small fauna).
- Enhances urban aesthetics.

Limitations

- Ineffective on sites with impermeable soils unless engineered with underdrains.
- Requires periodic maintenance (sediment removal, plant renewal).
- Limited capacity for large catchments (>0.5 ha).
- If poorly drained, can create temporary stagnant water pockets that support mosquito larvae and other disease vectors; this risk increases in warmer climates and requires complementary solutions (well-draining substrate, no standing water >48 hours) and regular maintenance.

In alternative some hydrological measures may also help the filtration a retention of runoff wate, for example, see sections below **sections 4.6.3** and **4.6.4**.

Figure 36. Rain gardens that are designed to capture and absorb stormwater runoff.

4.6.2 Rainwater harvesting systems

Rainwater harvesting systems collect and store precipitation from rooftops using gutters and storage tanks (cisterns) for later non-potable use. They can be above- or below-ground and include pre-filtration devices to remove debris, so besides helping regulate rapid runoff after rainy periods may also be associated with some kind of water quality treatment (**Figure 37**). So, these systems capture and store rainfall directly at the origin before it can contribute to surface runoff or enter the sewer system. **They should not be viewed as a measure to recover the freshwater ecosystem but could be an additional solution in the urban planning of cities. During periods of intense precipitation, they help preventing the flash floods in urban streams that are included in the drainage systems of pluvial waters.**

Application scenario(s)

Installed at the building scale for homes, schools, or industrial facilities with large roof surfaces. Most effective in regions with regular rainfall and moderate water scarcity. Stored water is typically reused for irrigation, toilet flushing, or cleaning, with overflow directed to infiltration areas or storm drains.

Advantages / Solutions

- Reduces runoff volume and pollutant load entering sewer networks and freshwater ecosystems.
- Provides an alternative water source, lowering potable water demand.
- Relatively easy to install and visible to the public as a sustainability measure.

Limitations

- Limited storage capacity relative to storm size; less effective for large events.
- Requires routine maintenance of filters, gutters, and tanks to prevent contamination (including the development of larvae that may favour mosquito larvae of public health interest or nuisance insects (particularly in warmer climates).
- Water quality can deteriorate if storage is prolonged or if roofs are made of materials that leach metals (e.g., zinc, lead).

- High initial cost for large or underground systems.

Case study sections 5.1.1, 5.1.2, 5.1.5, 5.1.6

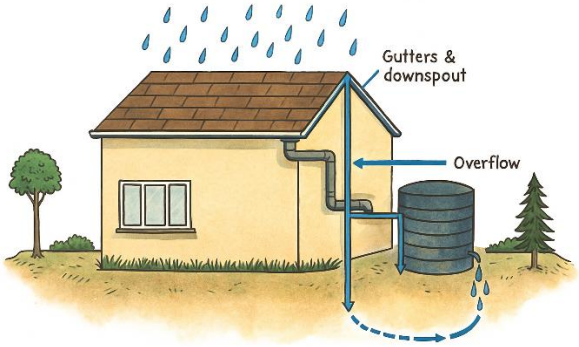


Figure 37. Schematic view of how rainwater harvesting systems may be established.

4.6.3 Permeable pavements

Permeable pavements are surface materials that allow rainwater to infiltrate through pores, joints, or voids into an underlying gravel sub-base where it is stored temporarily and gradually infiltrated or drained. They include porous asphalt, pervious concrete, and modular block pavers with open joints, or ideally even of earth or other local soil materials. These systems can retain small rainfall events and filter sediments and pollutants trapped in the sub-base (but see **Figure 38**). **They should not be viewed as a measure to recover the freshwater ecosystem but could be an additional solution in the urban planning of cities. During periods of intense precipitation, they help preventing the flash floods in urban streams that are included in the drainage systems of pluvial waters.**

Application scenario(s)

Installed on streets, sidewalks, parking areas, and pedestrian zones with light to moderate traffic. Most effective where subsoil has moderate permeability (sandy to loamy soils). Often used in new developments or redeveloped areas as part of sustainable urban drainage systems. Can be combined with underdrain pipes where infiltration to subsoil is limited. **Should not be used in the riparian zone.**

Advantages / Solutions

- Reduces surface runoff volume and peak discharge.
- Promotes infiltration and groundwater recharge where conditions allow.
- Improves water quality by filtering sediments and hydrocarbons.
- Contributes to urban cooling and reduces the heat-island effect.
- Integrates easily into urban landscapes and existing paved areas.

Limitations

- Clogging risk due to accumulation of fine sediments or oils; requires periodic vacuum cleaning.
- Not suitable for heavy-traffic roads or areas with high pollutant loads.
- Ineffective in clayey or compacted soils with very low infiltration capacity.
- Higher installation cost compared to conventional pavements.

- Reduced efficiency during prolonged or intense rainfall events.

Case study section 5.1.2

Figure 38. Illustration of permeable pavement systems and their functionality.

4.6.4 Infiltration trenches

Linear gravel-filled excavations designed to collect, temporarily store, and infiltrate runoff from adjacent impervious surfaces such as roads, roofs, or parking areas. Water enters the trench via curb cuts or shallow swales, fills the gravel voids, and slowly infiltrates into the subsoil. Optional underdrain pipes may convey excess water when infiltration is limited (**Figure 39**). **They should not be viewed as a measure to recover the freshwater ecosystem but could be an additional solution in the urban planning of cities. During periods of intense precipitation, they help preventing the flash floods in urban streams that are included in the drainage systems of pluvial waters.**

Application scenario(s)

Typically constructed along roadsides, parking lots, or property boundaries where space is available, and soils are moderately permeable. Ideal for retrofit projects or compact urban settings where large detention basins cannot be implemented. Can complement other measures such as permeable pavements (for pre-treatment) or rain gardens (for enhanced storage).

Advantages / Solutions

- Reduces runoff volume and peak flows, contributing to flood mitigation.
- Enhances groundwater recharge and stabilizes low flows in streams.
- Filters sediments, nutrients, and hydrocarbons, improving water quality.
- Compact, linear design fits into street corridors or parking areas.

Limitations

- Susceptible to clogging if inflow is not pre-treated or regularly maintained.
- Ineffective in low-permeability or contaminated soils.

- Requires inspection and sediment removal to maintain function.
- Limited capacity for extreme rainfall events; mainly effective for frequent, moderate storms.
- Potential risk of groundwater contamination if near polluted soils or industrial areas.

Permeable pavements and infiltration trenches are complementary techniques along the same hydrological pathway. While permeable pavements manage rainfall where it falls (source control), infiltration trenches intercept and infiltrate runoff along its path. Their combined application enhances both local infiltration and overall catchment-scale retention.

Case study section 5.1.2

Figure 39. Illustration of infiltration trenches and their function within urban stormwater pathways.

4.6.5 Disconnection of impervious areas

This measure redirects runoff from impervious surfaces such as roofs, sidewalks, and driveways away from stormwater drains and toward vegetated or permeable zones where infiltration and evapotranspiration can occur. It can involve rerouting downspouts, installing shallow swales or vegetated strips, or using infiltration beds to absorb water close to its origin. **They should not be viewed as a measure to recover the freshwater ecosystem but could be an additional solution in the urban planning of cities.**

Application scenario(s)

Applied at the property or neighbourhood scale, particularly in older districts with combined sewer systems where small retrofits can significantly reduce overflow events. Suitable for residential, school, or commercial sites. Often implemented incrementally as a low-cost solution in combination with other nature-based measures such as rain gardens or infiltration trenches (see **section 4.6.1** and **4.6.4**).

Advantages / Solutions

- Simple and low-cost retrofit; reduces the volume and frequency of stormwater entering sewer systems.
- Promotes infiltration and evaporation, mitigating flash floods and **reducing pollutant loads**.

- Reduces combined sewer overflows (CSOs) events and helps stabilize baseflow.
- Can be easily implemented by property owners, municipalities, or community groups (or municipalities).

Limitations

- Requires available permeable area and gentle slopes to ensure infiltration and prevent local flooding.
- Ineffective in compacted or clayey soils without infiltration capacity.
- Must be carefully designed to avoid water accumulation near building foundations.
- Effectiveness depends on public participation and maintenance commitment.

Case study section 5.1.2

4.6.6 Vegetated swales

Vegetated swales are wide, shallow, open channels with flat or gently sloping bottoms, typically constructed along roadsides, paths, or parking areas (**Figure 40**). They are designed to convey stormwater runoff while also providing primary treatment through filtration, sedimentation, and infiltration. Swales are often vegetated with native or local grasses, sedges, or turf species that promote uniform flow and enhance pollutant removal.

The vegetation plays a crucial role in slowing flow velocity, allowing sediment deposition and the capture of litter and organic matter, while also enhancing infiltration and nutrient uptake. The height, density, and roughness of the planted vegetation directly influence both hydraulic conveyance and treatment efficiency, and therefore species selection must balance these two functions.

Swales are often used where distributed inflows of runoff need to be collected and conveyed on the surface, such as along roads, car parks, or access corridors, while maintaining a natural and accessible landscape. They can have uniform or non-uniform profiles, and their design and planting strategy can be adapted to site-specific conditions and performance objectives. To manage heavy rainfall or high flow conditions, vegetated swales may incorporate underdrains or infiltration sumps, which increase their storage and drainage capacity while maintaining water quality benefits. Dense native grasses and herbaceous vegetation should be used, enhancing soil permeability, nutrient uptake, and habitat provision, while maintaining an aesthetically pleasant and accessible landscape.

These swales however should not be viewed as a measure to recover the freshwater ecosystem but could be an additional solution in the urban planning of cities. During periods of intense precipitation, they help preventing the flash floods in urban streams that are included in the drainage systems of pluvial waters.

Application scenario(s)

- Bioswales are commonly used in urban and suburban environments to manage stormwater runoff, improve water quality, and reduce localized flooding.
- They are especially effective along roadsides, parking lots, and within new residential or commercial developments where large impervious surfaces generate significant runoff.

Advantages / Solutions

- Disturbance regulation.
- Reduce runoff volume and promotes infiltration, groundwater recharge, and peak flow reduction.
- Reduce pollutant loads, especially nutrients, hydrocarbons, and heavy metals through vegetation, soil and microbial processes.
- Erosion control and sediment retention.
- Can be easily implemented as they are linear structures.
- Less expensive to construct and maintain than subsurface drainage systems.
- Swales provide habitat for small fauna and beneficial insects, improve the visual quality of infrastructure corridors, and integrate well into green infrastructure networks.
- Aesthetic pleasant.

Limitations

- Swales are less effective in conveying large storm volumes or flash floods; underdrains or bypasses are often needed for overflow management.
- They require additional land in comparison to piped drainage systems.
- Performance may vary seasonally, with reduced infiltration during frozen or saturated conditions.
- Poorly designed or unmaintained swales may retain stagnant water, leading to mosquito breeding or odour problems.
- Not suitable for steep slopes.

Case section study 5.1.1

Figure 40 Vegetated swales under contrasting conditions. Vegetated swales illustrated during a rainfall event (left) and under non-rain conditions (right). During rainfall, runoff from adjacent impervious surfaces is conveyed at low velocity, promoting infiltration and pollutant retention. Under non-rain conditions, the swale functions as a vegetated green infrastructure element, providing ecological and aesthetic benefits while remaining integrated into the urban landscape.

4.6.7 Retention ponds and floodable parks

Retention ponds and floodable parks are multifunctional water management systems designed to store, treat, and attenuate stormwater runoff while delivering ecological and social benefits (**Figure**

41). Both techniques reduce flooding risks by temporarily retaining excess surface water and releasing it in a controlled manner once rainfall subsides.

Retention ponds are permanent water bodies with additional storage capacity designed to attenuate runoff peaks during storm events. They typically consist of a permanent pond area surrounded by landscaped banks and vegetated margins, created through excavation, embankment construction, or adaptation of natural depressions. The permanent water body allows sediment deposition and pollutant removal, improving the quality of urban runoff through physical, chemical, and biological processes. In addition to stormwater attenuation, retention ponds enhance biodiversity, aesthetic value, and microclimatic regulation within urban and peri-urban landscapes.

Floodable parks extend this concept by combining stormwater storage capacity with public and ecological functions. These areas are designed to temporarily store and later release floodwater during heavy rainfall or overflow events, but also to function as leisure and recreation spaces for better human health and wellbeing. Floodable parks help mitigate flash floods and surface runoff from roads, urban catchments, and small or medium-sized streams. **Yet, floodable parks and retention ponds should not be interpreted as measures to recover freshwater ecosystems. The ponds are also not recommended in regions where they would not exist naturally, to avoid changing the local biodiversity and trophic chains, and attract disease vectors.**

Application scenario(s)

- Suitable for a wide range of urban and peri-urban catchments where surface runoff control, flood risk reduction, and water quality improvement are key management objectives.
- Sites downstream of large impermeable catchments such as roads, parking lots, or residential developments.

Advantages / Solutions

- Provides flood control, especially downstream areas.
- Reduces pressure on sewerage systems by retaining excess runoff.
- Creates habitat diversity and supports urban biodiversity.
- Promotes sedimentation, pollutant trapping, and biological uptake, enhancing the quality of stormwater before discharge.
- Increase climate resilience, by controlling intense rainfall and mitigating heat island effects through open water and vegetation.
- Provides recreational and educational opportunities while enhancing landscape amenities.

Limitations

- Poorly designed or unmaintained ponds may retain stagnant water, leading to mosquito breeding or odour problems.
- Needs large surface areas, which can limit feasibility in densely built environments.
- Earthworks, embankments, and landscaping increase initial investment.
- Requires periodic maintenance, mainly removal of sediments, vegetation management, and monitoring of water quality.
- They have a varying performance, depending on local soil infiltration, rainfall patterns, and hydraulic design.
- Less effective in areas with steep topography, or high groundwater levels.

Case study sections 5.1.1, 5.1.2, 5.1.4, 5.1.5

Figure 41. Example of a multifunctional stormwater management system combining a retention pond with adjacent floodable park areas. The system attenuates runoff peaks, enhances stormwater quality through sedimentation and biological processes, and provides recreational space during non-flood conditions.

4.7 Compensatory measures: chemical

4.7.1 Natural wastewater treatment plants

Natural technologies of wastewater treatment use modified natural self-treatment processes, such as phyto-purification (wetland plant filters) and soil filtration (substrate-based filters) (**Figure 42**). These systems mimic the biogeochemical processes of natural wetlands to treat and recycle wastewater efficiently and sustainably. **They are not part of the rehabilitation of the river and stream ecosystems but additional (optional) measures to be installed in wetlands or retention basins, that will contribute to prevent the contamination of urban freshwater ecosystems**.

Constructed wetlands are engineered ecosystems that reproduce the natural mechanisms of contaminant removal found in wetland environments. They consist of a substrate layer, which supports aquatic vegetation and microbial communities, and emergent macrophytes, which play key roles in treatment performance. The plants provide surface area for microbial biofilms, facilitate oxygen transfer to the substrate, filter and adsorb pollutants, remove nutrients, and limit algal growth by reducing light penetration.

While centralized natural wastewater treatment plants can effectively purify water, they also have notable limitations, including the large surface area required, potential clogging of infiltration zones, and odour emissions. To overcome these issues, decentralized and community-based wastewater treatment systems have emerged as more adaptable and efficient alternatives. These localized systems demonstrate higher removal rates of organic compounds compared to traditional phyto-purification technologies (**Rozkošný et al., 2014**). They typically use iron-rich substrates (such as

laterite soils) and macrophyte species with high bioaccumulation capacity (e.g., *Typha* sp., *Phragmites* sp. or *Stipa* sp.), enabling effective nutrient uptake and contaminant retention. There are different types of natural wastewater treatment plants divided by the kind of vegetation (emergent, woody emergent, submerged, floating leaved or free-floating vegetation), by the water flow direction (vertical or horizontal flow) and water flow trajectory (surface or sub-surface flow) (but see **Abou-Elela et al., 2013; Vymazal, 2005**)

Application scenario(s)

- Suitable for wastewater treatment from decentralized houses, small settlements, dwelling, hotels, recreational facilities, restaurants and summer camps, smaller municipalities or their parts, usually up to 2000 population equivalent.
- Depending on the composition of wastewater, these methods are also applicable for treatment of industrial wastewater.

Advantages / Solutions

Water purification trough key wetland functions:

- Biological digestion and removal of organic compounds.
- Degradation of suspended solids.
- Precipitation of metals.
- Pathogen removal.
- Nutrient removal (Nitrogen and Phosphorus).
- Degradation of toxic compounds.
- Degradation of some pharmaceuticals.

Beyond water purification, natural treatment systems offer multiple co-benefits, including:

- Decentralised wastewater treatment.
- Treatment of organically low-loaded wastewater that cannot be treated by conventional methods.
- Rapid incorporation of the treatment process and achievement of the performance efficiency quality target in a short period of time.
- Habitat creation and enhancement of local biodiversity.
- The fertilizer value of wastewater and improvement of soil fertility.
- Relatively simple technological implementation.
- Reduction of energy and maintenance costs compared to mechanical treatment systems.
- Integration into landscape and green infrastructure networks, improving aesthetic and ecological value.

Limitations

- Natural wastewater treatment technologies are unsuitable without prior pretreatment for wastewater with extreme or toxic characteristics. This includes:
    - High organic loads and elevated concentrations of fats, oils, or hydrocarbons.
    - Extremely acidic or alkaline waters, such as mine drainage.
    - Highly polluted runoff from roads, car parks, and industrial sites containing toxic compounds beyond safe limits.
    - Wastewater with excessive surfactants, pesticides, or radioactive substances.

    - Effluents from hospitals, veterinary facilities, and rendering plants that may contain pathogens, pharmaceuticals, or other hazardous materials.
- Relatively high area required.
- Low efficiency in removing ammonia nitrogen.

Case study section 5.1.6

Figure 42. Natural wastewater treatment plants illustration of a horizontal flow constructed wetland layout with different filter material and vegetation of each treatment beds.

4.7.2 Floating treatment wetlands

Active Island Reactors are floating, modular treatment systems designed for in situ bioremediation of contaminated surface waters and sediments (**Figure 43**). **They are not part of the rehabilitation of the river and stream ecosystems but additional (optional) measures to be installed in wetlands or retention basins, that will contribute to prevent the contamination of urban freshwater ecosystems**.

They integrate the ecological functions of floating treatment wetlands with engineered bioreactor technology, creating a hybrid system capable of enhancing natural purification processes within the waterbody itself, without the need for water extraction or off-site treatment. Each floating island unit supports a combination of substrate media, microbial biofilms, and vegetation that work synergistically to degrade or transform pollutants. The system promotes aerobic and anaerobic microbial processes, enabling the breakdown of organic matter, nutrients, and certain toxic compounds such as hydrocarbons, heavy metals, and agricultural runoff contaminants.

Active Island Reactors typically consist of a buoyant frame filled with porous bioactive media that provides surface area for microbial colonization. The upper layer supports emergent macrophytes, whose roots extend into the water column, while aeration or circulation systems may be integrated to enhance oxygen transfer and hydraulic mixing. The bioreactor operates in situ, harnessing natural biological processes to treat the surrounding water. The plant roots and microbial communities

facilitate nutrient uptake and contaminant degradation. Some designs include embedded sensors or dosing systems to optimize conditions for microbial activity and monitor treatment performance.

Application scenario(s)

- Polluted rivers, lakes, and reservoirs, particularly where direct intervention is challenging.
- Stormwater treatment
- Combined sewage outflows.
- Agricultural and industrial applications.
- Complementary treatment of existing natural or engineered water management systems.

Advantages / Solutions

- Enables on-site treatment without excavation or pumping.
- Less capital and operational cost when compared with conventional wastewater treatment plants.
- Portable island structure.
- Variable operation, adjustable to seasonal requirements.
- Requires low energy and maintenance compared to conventional systems.
- Promotes biodiversity and habitat creation.
- Adaptable to different contamination levels and waterbody sizes.
- Enhances aesthetic and ecological value of degraded sites.

Limitations

- Treatment efficiency may vary with pollutant type, temperature, and flow conditions.
- Requires regular monitoring of biological activity and hydraulic performance.
- Limited capacity for highly toxic or concentrated industrial pollutants.
- Biofouling and sediment accumulation may reduce efficiency over time.

Figure 43. Active Island Reactors for in situ bioremediation. The islands support pollutant degradation, nutrient removal, and habitat creation while improving the ecological and aesthetic quality of degraded aquatic environments.

4.7.3 Microbial electrochemical biofilter

Microbial electrochemical biofilters are an emerging NbS that combines biofilm-based treatment with microbial electrochemical processes to remove pollutants from wastewater using the natural metabolic activity of electroactive microorganisms. Positioned at the intersection of ecological treatment and low-energy electrochemical stimulation, these systems enable simultaneous biodegradation and bioelectricity-mediated redox processes within a compact treatment unit (**Peñacoba-Antona et al., 2022**).

The biofilters consist of a porous, electroconductive substrate (e.g., activated carbon, granular graphite, biochar, or conductive ceramics) that supports dense biofilms of electroactive bacteria. These microorganisms transfer the electrons generated during their metabolism to the conductive matrix, creating an interconnected electroactive community. This electron-sharing network allows the system to optimise metabolic pathways, enhancing the degradation of a wide range of contaminants, including those that are typically persistent or difficult to treat using conventional biological processes.

The electroconductive bed functions like an internal electrical grid, distributing electrons efficiently throughout the filter. This unique mechanism accelerates redox reactions, improves treatment performance, and increases the removal rate of pollutants. As a result, microbial electrochemical biofilters offer a promising approach for advancing decentralised, low-energy wastewater treatment, particularly where persistent contaminants or space constraints limit the effectiveness of traditional NbS.

Application scenario(s)

Microbial electrochemical biofilters are suited for:

- Decentralised wastewater treatment.
- Greywater recycling.
- Stormwater cleaning.
- Pre-treatment for constructed wetlands.
- Incorporate into hybrid nature-based systems (e.g., constructed wetlands, vegetated filters, or floating wetlands).
- Improving treatment efficiency in cold climates or low-carbon systems.
- Industrial wastewater streams with high organic loads.

Advantages / Solutions

- Use natural microbial communities and their inherent metabolic and electron-transfer capabilities.
- High treatment efficiency in a small footprint.
- Low energy requirements and potential energy recovery.
- Enhanced nutrient and micropollutant removal.
- Compatible with vegetated systems.
- Reduced sludge production.
- Resilient to hydraulic and organic loading fluctuations.
- Their compactness and modularity make them adaptable for both urban retrofits and community-scale installations.
- It prevents the production of biomass (sludge) as a by-product.

Limitations

- Still emerging and not fully standardised.
- Site-specific design, monitoring and adaptive operation are required, with some parameters (e.g., hydraulic loading, temperature, and influent composition) strongly affecting performance.
- Performance depends on maintaining healthy electroactive biofilms.
- Conductive materials can be expensive.
- Power generation is typically low (not yet a primary energy source).

5 Practice, challenges, and limitations

5.1 Case studies

5.1.1 Daylighting and restoration of Bièvre River (Paris, France)

The Bièvre is a small tributary of the Seine that historically flowed through Paris and its southern suburbs. During the 19th and early 20th centuries, rapid urbanisation and industrialisation led to severe pollution of the river. Consequently, large sections of the Bièvre were progressively culverted, buried, or built over.

In recent years, local authorities have initiated efforts to reopen and restore parts of the river, particularly in the Val-de-Marne area, between Arcueil and Gentilly. In 2022, a 600-metre stretch of the Bièvre was successfully **daylighted** and restored to open air. The project combined ecological, hydraulic, and landscape interventions, resulting in a **re-meandered** stream and improved river dynamics (**Communauté d'agglomération du val de Bièvre, 2010**).

The elimination of wastewater connections to the river constituted the first and most critical phase of the restoration. The project subsequently included the **planting** of 213 trees and 220 shrubs, the construction of approximately 200 m² of **pedestrian footbridges**, and the creation of a **retention area for flood management**. This retention zone, developed along the reopened section, helps buffer high flows and reduce flood risk during extreme events.

By **removing impoundments (longitudinal connectivity)**, the project also facilitated the re-establishment of **lateral wetlands (lateral connectivity)**, **improved ecological connectivity**, and enhanced overall **ecosystem resilience**. **Riparian vegetation** and **vegetated swales** were restored, contributing to the creation of a **continuous green ecological** corridor that supports biodiversity and strengthens links between urban green areas.

The daylighting initiative forms part of the broader "Bièvre, Eau, Climat et Trame Verte et Bleue" strategy (2020–2024). The City of Paris is planning further river reopening projects, and a feasibility study is currently underway for an additional section in Parc Kellermann (13ᵉ arrondissement), where preliminary design work has already been completed.

The benefits of the Bièvre restoration have been clearly demonstrated through post-project monitoring activities. Notable outcomes include the **return of a diverse range of species**, including birds, fish, amphibians, and several aquatic insect taxa; the successful development of aquatic vegetation and the establishment of stable aquatic biocenoses; and increased habitat heterogeneity, supporting the re-diversification of riverine habitats.

Importantly, these outcomes were achieved within a **highly urbanised and historically degraded context**, demonstrating that **meaningful ecological recovery** is possible even under severe spatial and infrastructural constraints (**Figure 44**). The reopening of the 600-metre stretch of the Bièvre, which required an investment of approximately €10 million, represents a significant **long-term commitment to urban ecological restoration, flood risk management, and climate adaptation**.

Restoring buried rivers in dense urban fabrics inevitably involves complex interactions with existing infrastructure, including underground utilities, roads, and buildings. In this context, the selective daylighting of priority segments reflects a pragmatic and phased approach, allowing ecological, social,

and hydraulic benefits to be delivered where feasibility is highest, while keeping open opportunities for future extensions.

Although the restored section represents a limited proportion of the historic river course, it already functions as a strategic ecological nucleus within the urban landscape. By improving longitudinal and lateral connectivity, and by integrating riparian vegetation and flood retention areas, the project enhances ecosystem resilience and provides a demonstrator for similar interventions elsewhere.

The involvement of multiple stakeholders, including local authorities, water agencies, and urban planners, adds complexity to governance and decision-making processes, but is also a fundamental strength of the project. This collaborative approach is essential for delivering integrated, large-scale urban river restoration in densely populated environments (**Figure 45)**.

Figure 44. Photographs showing the Bièvre River in Arcueil and Gentilly (Paris, France), illustrating the scale of hydromorphological interventions required to restore the river to open air. **©Eric Legrand-CD94**

Figure 45. Photographs of the rehabilitated Bièvre River in Arcueil and Gentilly (Paris, France), where sustained efforts under constrained conditions resulted in an inclusive, interactive stream embedded within the city. **©Eric Legrand-CD94**

5.1.2 The Emscher river restoration, Dortmund, Germany

The Emschergenossenschaft (EGLV) implemented the Emscher Generation Project, one of the **largest river restoration programmes in Europe**. The Emscher catchment, a sub-basin of the River Rhine located in North Rhine-Westphalia, Germany, covers approximately 865 km² and hosts around 2.2 million inhabitants in one of the most densely populated regions of the country.

During the last century, intensive coal mining and rapid industrialisation profoundly altered the Emscher River system. Large areas of the valley were drained to support industrial expansion and population growth, and the river network was transformed into an open wastewater channel, characterised by straightened courses, concrete beds and dikes. This solution was adopted at the time due to severe ground subsidence caused by underground mining. As a result, hydrological regimes were altered, groundwater levels declined, riparian wetlands disappeared, flood peaks increased and ecological conditions deteriorated (e.g., **MIP4Adapt, 2024**).

Initiated in 1992, the Emscher Generation Project spanned more than 30 years and focused on eliminating wastewater discharges through the construction of a new underground sewage infrastructure, followed by large-scale ecological restoration measures. These included river re-meandering, floodplain reconnection, wetland rewetting, retention basin creation, rainwater management and urban greening solutions, aiming to achieve more natural and climate-resilient watercourses (e.g., **Climate Adapt, 2024**).

Key interventions comprised the removal of concrete riverbeds and banks and their replacement with near-natural channels, the creation of side channels and shallow backwaters, the blocking of drainage ditches to restore groundwater levels, soil remediation in former industrial areas, and the integration of sustainable urban drainage measures such as rainwater supply to water bodies, green roofs, façade greening and rainwater harvesting.

The project significantly improved water quality, hydromorphology and biodiversity, while enhancing flood retention capacity and urban liveability. Outcomes include the restoration of 170 km of rivers (out of a planned 326 km), the creation of 322 ha of near-natural flood retention areas, an increase in invertebrate and bird species richness, the decoupling of paved surfaces from the combined sewer system, and the development of extensive recreational infrastructure along the restored waterways.

A further success factor was the broad-based participation process promoted by EGLV, combining statutory planning procedures with voluntary stakeholder engagement, cultural initiatives (e.g., *Emscher Kunst*), sports events and environmental education programmes (“blue classrooms”).

As a long-term commitment, the restoration of the Emscher River confluence into the River Rhine in Dinslaken/Voerde illustrates a dynamic process towards ecological sustainability in Germany, as documented in 2025 (**Figure 46**) and 2025 (**Figure 47**).

Figure 46. Confluence of the Emscher River into the River Rhine in Dinslaken/Voerde (Germany) in 2015. **©Hans Blossey/EGLV**

Figure 47. Confluence of the Emscher River into the River Rhine in Dinslaken/Voerde (Germany) in 2025, showing a more natural and ecologically functional river-floodplain landscape, reflecting the legacy of long-term channelisation and infrastructural modification **©Rupert Oberhäuse/EGLV**

5.1.3 Isar river water management plan and restoration, Munich, Germany

The Isar River through Munich is an alpine gravel-bed river that historically featured a wide, dynamic channel **with braided sections**, gravel bars and islands. Over the 19th–20th centuries, the river corridor was progressively constrained for flood protection, hydropower and urban development, with hard embankments, fixed banks, and training structures that simplified morphology, reduced lateral connectivity and habitat diversity, and limited public access. From the 1980s onward, flood risk concerns increased, and the ecological condition of the urban Isar became a major public issue (**Naturvation project: Enabling Urban Nature-Based Solutions, 2017**).

Isar-Plan ("Neues Leben für die Isar") is a large-scale, integrated river corridor project implemented over an ~8 km reach in Munich (commonly reported between Großhesseloher Brücke and the Deutsches Museum area), with construction running ~2000–2011 and high total costs (cost-sharing between Bavarian state institutions and the City of Munich). The project explicitly combined flood protection with ecological restoration and recreation/amenity upgrades, aiming to recover key geomorphic processes (within an urban constraint envelope) while improving safety for high flows. Isar Plan was a large-scale project to remove hard bank protections, widen the channel, and restore the river's natural processes, to improve flood control, biodiversity, and recreational quality (**Climate Adapt, 2020**).

Main restoration and water-management interventions:

- **Channel widening and natural bank shaping** along most of the 8 km reach: **hard concrete banks were removed** and replaced by gently sloping natural-looking riverbanks, **regrading banks** into more natural slopes allowing lateral erosion, giving the river more space to flow and adjust naturally (and passive revegetation);
- **Re-establishment of riparian vegetation:** native riparian vegetation (such as willows, shrubs, reeds) was planted or allowed to recolonise naturally, stabilising banks and improving ecological quality;
- **Restoration of riverbed structure and sediment dynamics:** gravel, cobbles and wood were reintroduced to recreate a more natural riverbed, allowing the formation of riffles, shallow areas and gravel bars typical of alpine rivers;
- **Improved longitudinal continuity and fish passage:** old weirs and barriers were removed or transformed into gently sloping rock ramps, allowing fish and sediment to move more freely along the river;
- **Creation of side channels and shallow habitats:** side channels (bypass) and shallow shoreline areas were created to increase habitat diversity and provide suitable conditions for fish, invertebrates and other wildlife.
- **More nature-based flood protection:** flood protection was improved by setting defences further back from the river (reconnecting floodplains, restoring upstream lateral connectivity) and redesigning them in a more natural way, while still ensuring safety during high flows;
- **Improved public access and recreational use:** new paths, access points and open spaces were created along the river, making the restored river corridor attractive and accessible for recreation and daily use.

The design intentionally allowed the river to move, erode, and deposit sediment, restoring geomorphic dynamics in the urban corridor. The Isar-Plan combined water retention and renaturalisation measures

for the Isar River in Munich. It significantly improved flood protection, water quality, biodiversity habitat, and recreational opportunities in the area (**ECRR, 2011**).

The Isar-Plan's nature-based approach depended on a **broad stakeholder alliance**. Key public actors (Bavarian water management authorities and the City of Munich) worked alongside nature conservation agencies, river engineers, ecologists and landscape planners to design measures that enhanced river dynamics and natural resilience while ensuring flood safety. Because the corridor is intensively used, engagement with residents, NGOs and user groups (e.g., recreation and sports communities) was essential to manage trade-offs such as bank stability versus habitat quality, access versus sensitive areas, and safety versus allowing controlled morphodynamic change (**Figure 48**).

Figure 48. Conceptual illustration of the Isar River restoration in Munich, showing a widened gravel-bed channel with braided sections, gravel bars, riparian vegetation and public access integrated within the urban corridor.

5.1.4GEOTA and RiosLivres

The GEOTA – Grupo de Estudos de Ordenamento do Território e Ambiente – is a Portuguese Non-Governmental Environmental Organization, existing since 1981 but formally since 1986, with a long-standing commitment to biodiversity conservation, ecological restoration, and sustainable land and water management.

Over the last years, GEOTA has played a particularly relevant role in the restoration of river ecosystems, with a strong focus on river connectivity, ecological processes, and community engagement. GEOTA is an active member of the Dam Removal Europe network, a coalition of organizations working across Europe to restore river continuity by removing obsolete barriers that no longer serve a clear social or economic function. Through this collaboration, GEOTA has contributed to several river restoration initiatives in Portugal, including the removal of small weirs and other transversal obstacles that disrupted sediment transport, aquatic organism movement, and natural flow regimes.

Importantly, GEOTA's approach to river restoration goes well beyond the physical removal of obsolete barriers. Through its Rios Livres (meaning *Free Rivers*) programme, GEOTA promotes an integrated and ecosystem-based vision of river restoration, combining structural interventions with Nature-based Solutions (NbS) and long-term ecological recovery measures.

These actions include:

- Replanting and reinforcement of riparian vegetation using native species, aiming to restore shading, bank stability, and ecological corridors;
- Bioengineering techniques, such as live fascines, live staking and vegetated brushwood structures, to stabilise eroding banks while maintaining natural river morphology;
- Selective and ecologically sensitive interventions that respect natural channel dynamics instead of rigid engineering solutions;
- Community involvement and awareness-raising, ensuring that local populations understand and support river restoration efforts.

Overall, GEOTA's work demonstrates how barrier removal, when embedded within a broader Nature-based and ecosystem-centred strategy, can act as a catalyst for river restoration. By combining technical expertise, ecological knowledge, and social engagement, GEOTA provides a strong example of how non-governmental organizations can contribute effectively to the restoration of free-flowing, resilient river systems in Europe.

Some representative examples of Rios Livres program, includes actions like the identification of obsolete barriers in Alviela River like the Vaqueiros weir (**GEOTA RiosLivres Programme, 2023a**) and Sourinho dam (**GEOTA RiosLivres Programme, 2023b**) briefly present below.

Removal of Vaqueiros weir in Alviela River sub-basin.

The River Alviela, located in central-eastern Portugal, is a tributary of the Tagus River with a length of approximately 51 km and a drainage basin of about 333 km², spanning several municipalities, including Alcanena and Santarém.

The basin has high ecological value and includes three important protected areas: the Serras de Aires e Candeeiros Natura 2000 site and Natural Park, and the Paúl do Boquilobo Natural Reserve and Special Protection Area for Avifauna. Thus, the Alviela sub-basin hosts rare and vulnerable aquatic plant species, notably *Butomus umbellatus* and *Hydrocharis morsus-ranae*, the latter occurring exclusively within this sub-basin in Portugal.

Historically, the river was remembered by local communities as a clean, transparent and biologically rich system, supporting abundant fish populations such as barbels, other cyprinids and European eel, and even allowing small-boat navigation in certain stretches.

Over recent decades, however, the river has been subjected to multiple anthropogenic pressures, including water quality degradation from agricultural, livestock and industrial activities (particularly from the leather-processing sector), as well as hydrogeomorphological alterations that disrupted river connectivity. As a result, populations of several native fish species, including the European eel (*Anguilla anguilla*), the Portuguese boga (*Iberochondrostoma lusitanicum*) and the southern Iberian chub (*Squalius pyrenaicus*), have declined, alongside reductions in native riparian vegetation such as ash,

willow and alder. River fragmentation is a major issue in the basin, where 33 artificial barriers have been identified, including weirs, road crossings and levees.

One of these structures was the Vaqueiros Weir, a 1.1-m-high and 14-m-long barrier originally built to support leather-industry infrastructure that ceased operating in the 1980s. Despite being obsolete, the weir continued to be used informally by the local population for leisure and crossing, contributing to resistance to its removal (**Figure 49**).

Figure 49. The Vaqueiros weir (at different stages of the project) in Alviela River. For more information visit **GEOTA RiosLivres Programme (2023a)**.

The project leading to its demolition was initiated in 2022 by the GEOTA Rios Livres programme, following extensive dialogue with landowners, municipalities and other stakeholders. The intervention took place in April 2023, after completion of the licensing process overseen by the Portuguese Environment Agency (APA), within the general legal framework governing water resources in Portugal.

The removal of the Vaqueiros Weir aimed to restore longitudinal connectivity in the River Alviela and to contribute to the development of a national approach to barrier removal (**Figure 50**). The project was first developed under the Reconnecting Iberian Rivers programme, funded by the MAVA Foundation (MAVA), and later finalized within the ROLLIN' RIVERS project (RR), funded by DIMFE.

Figure 50. The removal of the Vaqueiros weir required the temporary use of heavy machinery within the channel, which was unavoidable in this case due to the river width. For more information, including video, visit **GEOTA RiosLivres Programme (2023a)**.

Beyond restoring fish migration, sediment transport and natural flow dynamics, the intervention included the replacement of invasive riparian species with native vegetation (**Figure 51**), as well as bank stabilization using Nature-based and bioengineering techniques (**Figure 52**).

Figure 51. Several stages of the programme required the removal and control of invasive riparian species, as well as the maintenance and planting of native vegetation (**GEOTA RiosLivres Programme, 2023a**).

Figure 52. Bank stabilization using live willow (native) fences with woven branches (wood weaving technique) (**GEOTA RiosLivres Programme, 2023a**).

One of the main challenges was communicating the rationale and benefits of barrier removal to the local community, where such interventions remain uncommon and barriers are often perceived as assets, particularly in a context of water scarcity.

Through repeated field visits and engagement activities, the project gradually shifted perceptions, demonstrating that obsolete infrastructures that unnecessarily artificialize river systems can and should be removed. The project ultimately achieved strong local and political acceptance and became a symbol of consensus-based river restoration.

Its impact extended beyond the local scale, contributing to the announcement of a National Programme for the Removal of Obsolete Dams in Portugal and receiving international recognition through the **Dam Removal Europe Award 2023**, highlighting the role of ENGOs such as GEOTA in catalysing ecological restoration while supporting European environmental goals.

Sourinho stream restoration – Let Alviela run

A further concrete illustration of GEOTA's integrated river restoration approach is provided by the Sourinho intervention, where barrier removal is being implemented alongside a broader set of rehabilitation measures. In addition to eliminating an obsolete barrier with negative ecological impacts, the ongoing actions include bank stabilisation and requalification, control of invasive species (**Figure 53**), promotion of native riparian vegetation, and monitoring of fish communities and sediment dynamics. Initiated in 2023 under the Rios Livres GEOTA programme, funded by DIMFE the intervention also involved the mapping, characterisation and prioritisation of barriers in the Alviela basin. Additonally it is also funded by Calouste Gulbenkian Foundation (Climate Action and Public Participation Programme) and the Project "Let Alviela Run – Sourinho's Dam Removal in Portugal", allowing the active engagement with local communities.

The Sourinho barrier removal (**Figure 54**) and subsequent rehabilitation works have been developed in close coordination with APA, the Municipality of Alcanena, and adjacent landowners. Following the removal of the structure, restoration works are being carried out along approximately 300 m on both

riverbanks, using Nature-based solutions wherever possible, the planting of native species (such as ash, alder and quince) also some bioengineering techniques.

The rehabilitation process is being scientifically monitored by researchers from the Instituto Superior Técnico (Lisbon), who are assessing sediment dynamics and ecological quality to support adaptive management and long-term recovery.

Figure 53. Dominance of the invasive species *Arundo donax*, which suppresses the establishment of native riparian trees (**GEOTA RiosLivres Programme, 2023b**).

Figure 54. Before (top), after (bottom) the removal of an obsolete barrier and invasive species (*Arundo donax*) (**GEOTA RiosLivres Programme, 2023b**).

5.1.5 La Marjal floodable park, Alicante, Spain

La Marjal Floodable Park (Alicante, Spain), inaugurated in 2015, is a multifunctional flood-adaptation project that combines stormwater retention with urban greening and wetland habitat creation. Designed to reduce pluvial flash-flood risk in surrounding residential areas, it provides temporary storage (up to ~45,000 m³) during intense rainfall events, particularly Mediterranean storms in autumn. Stored water is subsequently conveyed to the Monte Orgegia treatment plant, where it is treated and reused for non-potable purposes such as irrigation, street cleaning and recreational uses, contributing to circular urban water management.

Beyond its hydraulic function, La Marjal incorporates wetland habitats that support both resident and migratory bird species, integrating biodiversity enhancement with urban recreation. Its design, inspired by natural hydrological systems, combines landscape quality, ecological value and technical efficiency within a dense urban setting. Since its inauguration, the park has proven highly effective in stormwater management and **has been recognised as a model of sustainable, nature-based urban design; by November 2020**, it had collected approximately 52,200 m³ of rainwater.

To engage and educate the local population, the City Council of Alicante and Aguas de Alicante have developed an environmental itinerary, free guided tours and a range of educational activities, promoting awareness of urban water management and the conservation of local biodiversity (**Aguas de Alicante; Spanish Climate Change Adaptation Platform**).

Main objectives included:

- **Native vegetation mosaics (wetland + Mediterranean landscapes):** carefully selected vegetation forms distinct "ecosystem-like" zones (wetland/riparian-type vegetation and other local Mediterranean vegetation types), improving habitat structure, shading and microclimate regulation, and reinforcing the park's long-term ecological value and resilience;
- **Floodable park (multi-functional land use)**: the park converts urban land into a designed floodplain that can safely inundate during storms, reducing peak flows and protecting nearby areas while remaining a usable green space in normal conditions;
- **Constructed wetland basins and shallow-water habitats:** shallow basins/ponds and wetland-like zones were created to provide habitat diversity and support urban biodiversity, especially birds **("Itinerario ambiental Parque Inundable La Marjal," 2020)**, while contributing to water storage and sediment settling during events;
- **Biodiversity enhancement and monitoring/activities:** the site functions as an urban refuge for wildlife (notably birds) and is supported by outreach and recurring activities that strengthen stewardship and long-term social sustainability.
- **Environmental education and public engagement ("environmental itinerary"):** an environmental trail, guided tours and educational initiatives help residents understand flood risk, water reuse and local biodiversity, supporting long-term acceptance and care of the system;
- **Stormwater diversion, inlet/outlet control and regulated detention:** during heavy rainfall, runoff is routed into the park and temporarily detained, with controlled filling and emptying to reduce flood impacts, ensuring reliability under extreme events;

- **Pumping/conveyance to treatment and reuse (circular water management):** stored water is transferred to the Monte Orgegia treatment plant and then reused for non-potable purposes (e.g., irrigation), linking flood management to circular water efficiency.

Overall, La Marjal demonstrates how multifunctional urban water spaces can contribute to climate adaptation by reducing flood risk while delivering ecological, social, and educational benefits. The creation of floodable green areas and wetland habitats supports urban biodiversity, improves microclimatic conditions, and enhances the liveability of surrounding neighbourhoods. At the same time, the project strengthens urban resilience by integrating stormwater management with water reuse strategies. Achieving these outcomes required sustained collaboration between key public authorities, the local water utility, technical experts and planners, as well as active engagement with citizens, highlighting the importance of strong governance and stakeholder commitment in implementing nature-based solutions in dense urban environments (**Figure 55**).

Figure 55. Schematic representation of how a floodable park such as La Marjal operates within an urban environment.

5.1.6 Kallang river rehabilitation, Singapore

The Kallang River, the longest river in Singapore (approximately 10 km), flows through some of the most densely urbanised districts of the city-state, including Bishan–Ang Mo Kio Park. In the 1970s, the river was transformed into a straight, trapezoidal concrete drainage canal designed to rapidly convey stormwater and reduce flood risk. While hydraulically efficient, this channelised system generated high flow velocities, poor ecological quality, limited habitat diversity, and a strong physical and social disconnection between the river and surrounding communities (**Chandrashekhara, 2012**).

In 2009, Singapore's national water agency (PUB) and the National Parks Board (NParks) launched a landmark rehabilitation project to transform a 2.7 km reach of the former concrete canal into a naturalised river integrated within a 35-hectare urban park. This intervention, one of the largest urban river restoration projects in Asia, aimed to reconcile flood protection with ecological recovery, urban cooling and public use, representing a major shift in urban water management philosophy under Singapore's ABC Waters Programme (**Sini, 2020**).

The measures applied included:

- **Removal of concrete canal and naturalised river reconstruction:** the concrete-lined channel was dismantled and replaced by a reconstructed riverbed composed of gravel, cobbles, sand and boulders, constructing riffles, enabling more natural hydraulic behaviour and habitat diversity;
- **Re-meandering of the river channel:** the previously straight canal was reshaped into a sinuous, meandering planform, increasing channel length by approximately 1.7 times. This reduced flow velocities, enhanced hydraulic heterogeneity and created a wider range of aquatic habitats;
- **Bio-engineered riverbanks and riparian edges:** riverbanks were stabilised using nature-based bioengineering techniques, including vegetated geogrids, live staking, brush layering, coir rolls, erosion control blankets, river terraces and wet meadow zones. These measures provided both structural stability and ecological function;
- **Floodplain reconnection within a multifunctional park:** the river was reconnected to a wide floodplain integrated into the surrounding park landscape. During dry conditions, flow remains within a defined low-flow channel; during intense rainfall, water safely spills into the park, which functions as temporary flood storage;
- **In-channel and riparian habitat features:** Natural habitat elements such as woody debris, shallow wetlands and vegetated margins were incorporated to support fish, macroinvertebrates, amphibians and riparian biodiversity;
- **Flood-risk design and hydraulic modelling:** the restored river and floodplain were carefully designed to meet Singapore's strict flood-safety standards, ensuring that increased naturalness did not compromise urban flood protection;
- **Integrated Park infrastructure:** paths, bridges and recreational facilities were designed to coexist with dynamic river processes, allowing public access while maintaining safety during high-flow events.

The rehabilitation of the Kallang River delivered multiple co-benefits within a highly constrained urban context. Monitoring showed a rapid **increase in biodiversity (approximately 30% within two years)**, including the return of native birds, freshwater fish, amphibians and aquatic invertebrates. Riparian vegetation and wet meadow habitats became established, contributing to shading, flow moderation and urban cooling.

From a hydraulic perspective, the park now safely stores significantly more floodwater than the former concrete canal, reducing flood peaks while lowering long-term maintenance needs and contributing to a more self-sustaining system. The park can safely detain up to 40% more floodwater than the previous canal. Socially, the project transformed a previously inaccessible drainage corridor into a vibrant public space, strengthening everyday interactions between people and enhancing their connection with urban stream ecosystems, water and nature.

As with **many large-scale urban river restorations**, the project required substantial space for floodplain integration and involved high upfront planning and design costs. Vegetation establishment demanded careful phasing and early maintenance, and public safety during flood events required clear communication and education. These aspects were addressed through adaptive management and ongoing monitoring.

What sets the Kallang River rehabilitation apart is the scale and depth of transformation achieved within a dense tropical city, moving beyond a narrow riparian buffer (if any) to create a landscape-scale riparian corridor. The project successfully integrates flood management, ecological restoration, climate adaptation, urban cooling and recreation within a single system (**Figure 56**).

Crucially, this transformation was made possible through strong inter-agency collaboration, led by PUB and NParks, supported by engineers, ecologists, landscape architects and urban planners. Their coordinated effort demonstrates how institutional alignment and **long-term vision** are essential to deliver ambitious nature-based solutions in highly urbanised environments.

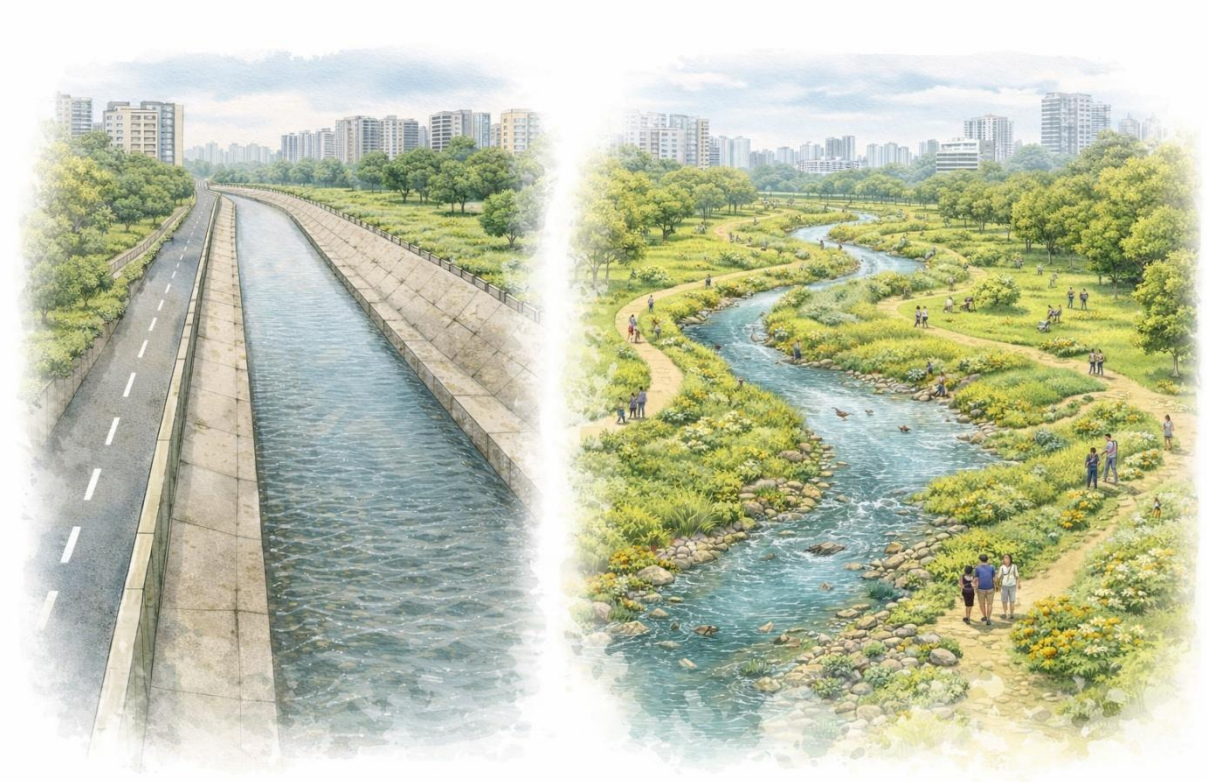


Figure 56. Conceptual schematic of the rehabilitation of the Kallang River, showing the transition from a concrete drainage canal (right) to a meandering river integrated within a multifunctional urban floodplain (left).

5.1.7 CresceRio project

CresceRio (meaning GrowRiver) project (**CresceRio**) is an environmental education project developed by MARE/ARNET at the University of Coimbra, in collaboration with Marionet (a theatre company based in Coimbra), researchers from the University of Aveiro, and local primary schools in Coimbra, with growing interest from the wider school community.

Created in 2018 and still ongoing the project was designed to reconnect children, families and local communities with urban streams and their ecological value, combining scientific research, experiential learning and artistic expression to foster long-term ecological awareness and stewardship (**Figure 57**).

Figure 57. Several examples of activities developed within the CresceRio project. **a.** Visit to a more preserved natural stream. **b.** Visit to an urban stream. **c.** Posters and other communication materials created for the whole community. **d.** Children being encouraged to listen attentively to the water, and the birds in a stream. **©CresceRio**

Children take part in a sequence of activities that includes field visits to a well-preserved reference stream outside Coimbra and to urban streams within the city (often close to their schools), allowing them to directly observe contrasts in hydromorphology, riparian vegetation, water quality and biodiversity which included macroinvertebrates, biofilm (where diatoms microalgae can be found), amphibians, fish and birds, using scientific sampling methods adapted to these activities.

These outdoor experiences are complemented by classroom-based sessions, where children examine benthic macroinvertebrates and diatoms under microscopes, identify riparian plant species from leaves, birds fish and amphibians by photographs, and learn how biological quality indices are used to assess ecological status in Portugal (**Figure 58**).

Building on the initial school-based work, CresceRio has progressively created additional outdoor activities involving caregivers (parents and other family members) and the wider school community, and it has also connected with other initiatives, including OAH project.

Rather than relying on a single intervention, CresceRio emphasizes **continuity over time**, with **repeated activities** that help children gradually build understanding, reduce initial fears associated

with streams, and recognize both key stressors (e.g., litter, invasive species, artificial barriers) and the ecosystem services provided by healthy rivers; this sustained engagement proved essential for meaningful learning and behavioural change, as documented in a peer-reviewed scientific publication **(Feio et al., 2022)**.

Figure 58. Outdoor and laboratory activities in which children experienced sampling methods, and simple protocols for evaluating the ecological status, and laboratory classes. **a.** Kick-sampling macroinvertebrates**. b.** Example of simple protocols (for ecological status using macroinvertebrates). **c.**Brushing stones to collect diatoms. **d.** Sampling of amphibians. **e.** Observation of live fish captured during the electrofishing surveys. **f.** Observation and census of birds conducted using mist nets along the streams**. g.** and **h.** Laboratory sessions for the identification of several specimens of diatoms, invertebrates, riparian tress leaves. **©CresceRio**

A distinctive component of the project is its creative and performative dimension developed with Marionet: drawing on their scientific observations and emotional experiences with rivers, children co-create a theatre play, contributing to the story and script, taking part in rehearsals, and performing the characters themselves, transforming ecological knowledge into storytelling and collective expression that can be shared with families and the broader community in an accessible, emotionally engaging way (**Figure 59**).

Figure 59. Community engagement activities. **a.** Presentation of the project activities to other school classes, allowing them to learn about the work developed by the participating class. **b.** Theatre performance developed in collaboration with Marionet. **©CresceRio & ©Marionet**

5.2 Key Learnings

- **Urban river renaturalisation is feasible**, even when costly and technically demanding, particularly in densely built environments. When designed at the scale of the riparian corridor and supported by resilient wide riparian communities, both ecological and human, renaturalisation processes can evolve towards **self-sustaining systems** that strengthen **long-term ecological**, **social**, and **climate resilience**.
- The **re-acquisition and reallocation of land to establish wider riparian corridors is both possible and desirable**. Although it may require initial investment and negotiation, restoring room for rivers leads to more self-sustaining systems, reduces long-term maintenance costs, and enhances ecological connectivity, resilience, and multifunctionality over time.
- Nature-based Solutions (NbS), including the **renaturalisation of water bodies, riparian vegetation, and reconnected floodplains** and the creation of near-natural retention areas, play a significant role in climate change mitigation and adaptation, notably through carbon sequestration, flood regulation, and temperature moderation. The **integration of stream landscape within the city** also generates added value for living, working, and overall quality of life in urban areas.
- **Space is a critical enabling factor**. Even in highly urbanized contexts, allocating sufficient space for rivers and floodplains maximizes ecological, hydrological, and social benefits.
- **Water management is a key driver of ecological and social transformation**. Sustainable outcomes require a good planning together with long-term thinking and action, moving beyond short-term engineering solutions towards approaches that support **ecological resilience**, **social well-being**, and **climate change adaptation**.
- Public water management based on adaptive, cooperative and **non-profit-oriented governance models**, involving municipalities, citizens, policymakers, and NGOs, enhances project success, social acceptance, and the long-term effectiveness of adaptation measures.

5.3 Main challenges and limitations

Even when well-designed interventions are implemented, many urban stream rehabilitation projects **fail to meet legally binding environmental targets**, particularly those defined under the **EU Water Framework Directive** (WFD; **European Parliament and Council, 2000**). These targets include the achievement of **good ecological status**, assessed through standardized biological quality elements such as macroinvertebrates, fish, and diatoms, and good chemical status, evaluated against environmental quality standards for nutrients and priority substances. In urban environments, persistent diffuse pollution, altered hydrological regimes, and legacy contamination often prevent these objectives from being achieved.

In numerous cases, rehabilitation actions successfully improve **local physical habitat structure and hydromorphological** diversity, for example through channel reconfiguration, riparian planting, or bank stabilization. However, such reach-scale improvements do not necessarily translate into **measurable biological recovery** of aquatic communities, nor into substantial reductions in nutrient concentrations, sediment loads, or chemical contaminants, particularly when catchment-scale pressures remain unaddressed.

These limitations reflect the **multifactorial nature of urban stream degradation**, where chemical, hydrological, morphological, and social stressors interact across spatial and temporal scales. Urban streams are typically embedded in highly constrained environments characterized by impervious surfaces, modified flow regimes, fragmented riparian corridors, and complex governance structures, which limit ecological responses to isolated restoration measures.

Beyond the WFD, the recently adopted **EU Nature Restoration Regulation** (Regulation (EU) 2024/1991; **EU Nature Restoration Law, 2024**) introduces additional, binding restoration objectives for freshwater ecosystems, including the restoration of ecological functions, habitat connectivity, and the ambition to re-establish at least 25,000 km of free-flowing rivers by 2030. While this regulation strengthens the policy mandate for restoration, it also highlights key limitations in urban contexts, notably the **lack of available space for widening riparian corridors**, the need for land reallocation or re-acquisition, and the challenge of reconciling restoration goals with existing urban infrastructure and land uses.

Moreover, **ecological and social benefits** often manifest only after long timeframes, as ecosystems and communities gradually reorganize. This temporal delay complicates the demonstration of short-term success within typical political and funding cycles, making it difficult to sustain long-term commitment. Nevertheless, urban stream rehabilitation should be understood as a long-term investment, yielding cumulative benefits for biodiversity, climate adaptation, and human well-being.

Another recurrent challenge lies in the **underestimation of long-term maintenance, coordination, and governance requirements** (**Moore and Rutherfurd, 2017**). Continuous monitoring, upkeep of rehabilitated habitats, and effective coordination among municipalities, water authorities, private landowners, and civil society actors require sustained funding, institutional alignment, and shared responsibility. Without these conditions, even technically successful interventions may deteriorate or lose functionality over time.

In complex urban catchments exposed to multiple pressures, such as dense populations, diffuse pollution, fragmented land ownership, and the accelerating impacts of climate change, **single-sector**

or single-stressor approaches rarely produce lasting outcomes. Meaningful recovery requires systemic and integrated strategies that link water management, land-use planning (often involving profound structural changes around streams), community engagement, and innovative governance models.

Urban stream rehabilitation is therefore **highly context dependent**. Each project must adapt to local geomorphology, climate, ecological potential, and surrounding land uses. No single measure fits all conditions; success depends on selecting locally appropriate combinations of interventions and maintaining flexibility as environmental and social conditions evolve.

Finally, the **social dimension** remains both a major challenge and an opportunity. Public engagement, behavioural change, and participatory governance are essential but demanding processes that require time, trust, and a shared long-term vision. Bridging the gap between ecologically sound restoration design and social acceptance and stewardship is one of the defining challenges of contemporary urban stream rehabilitation.

Overall, urban stream rehabilitation must be understood as an **adaptive, long-term process rather than a one-off intervention**. Its success depends on sustained collaboration, ecological patience, and an intergenerational ethic, recognizing that restoring the vitality of urban waters is not only a regulatory obligation but also a cultural and moral commitment to future generations.

6 Linking measures to ecosystem services and health

Urban stream rehabilitation measures restore the physical, chemical, and biological processes that support ecosystem functioning. When these functions recover, they provide ecosystem services – such as water purification, temperature regulation, flood mitigation, and recreation – which directly and indirectly enhance human well-being. In the OneAquaHealth context, these relationships form a cyclical system where indicators reveal stressors, which guide rehabilitation measures, leading to improved ecosystem functions, services, and ultimately human health outcomes (**Figure 60**).

Rehabilitation urban streams enhance environmental quality and reduce health risks linked to pollution and habitat degradation. Improved biodiversity and water quality contribute to safer and healthier urban environments. For instance, a study conducted in Glasgow, Scotland (with 137,032 inhabitants) found that residents living within 700 meters of a regenerated urban stream had a significantly reduced risk of developing chronic diseases. The results showed a 15% lower risk of cardiovascular disease, hypertension, and stroke, a 12% lower risk of diabetes, a 10% lower risk of incident obesity, and a 3% reduction in overall mortality rate (**Tieges et al., 2022**). At the same time, access to restored blue-green areas promotes physical activity, relaxation, and psychological well-being. In this sense, the catalogue of measures contributes to the broader One Health approach, linking ecosystem integrity to human health benefits.

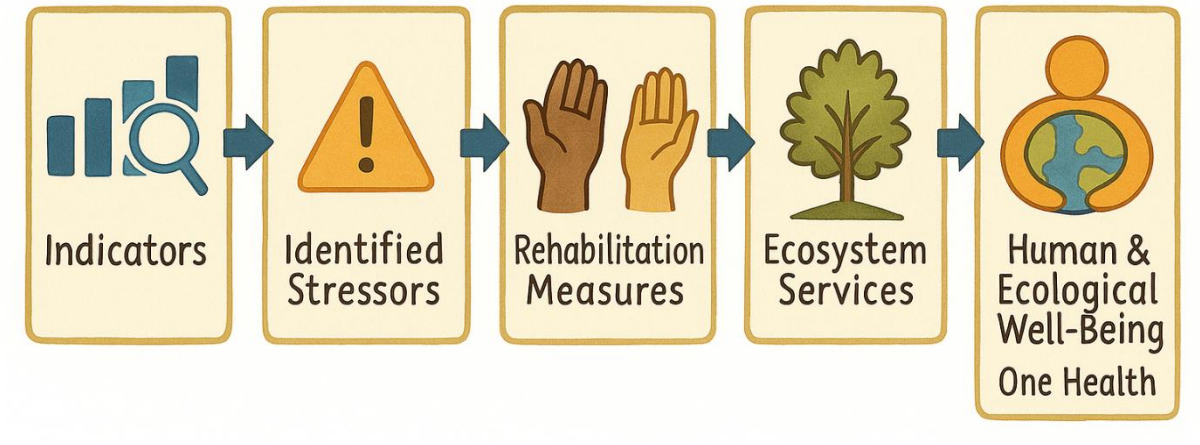


Figure 60. Conceptual framework of the OneAquaHealth project, illustrating the link between indicators, identified stressors, rehabilitation measures, ecosystem functions and services, and human & ecological well-being (One Health).

7 Conclusions

Urban stream rehabilitation represents one of the most complex yet promising fields in contemporary ecological restoration. The measures compiled in this catalogue show that, although urban rivers can **rarely be returned to pristine conditions**, they can be **re-designed to recover essential ecological functions and social value**. By addressing morphological, hydrological, chemical, biological, and social dimensions together, these interventions contribute to the resilience and sustainability of urban stream ecosystems.

A key lesson emerging from the review is that success depends on a **hierarchical and systemic approach**: first reducing pollution and stabilizing riparian and hydrological conditions, then restoring channel structure and ecological processes, and finally strengthening community engagement and long-term stewardship. Rehabilitation measures are most effective when supported by adaptive governance, continuous monitoring, and participatory planning that integrates technical, ecological, and social knowledge.

The benefits of these measures extend beyond the biophysical recovery of streams. They **reinforce ecosystem services** such as flood regulation, water purification, temperature moderation, and habitat provision, while also enhancing human health, wellbeing, and social cohesion. This alignment between ecological and human dimensions is at the heart of the One Health framework, which recognizes that healthy ecosystems underpin healthy societies.

Ultimately, the rehabilitation of urban streams is not merely an environmental task but a collective social project. It requires **cooperation** between municipalities, citizens, scientists, and planners to reconnect people with water and to **cultivate a shared responsibility for future generations**. Through integrated design, evidence-based management, and sustained commitment, rehabilitated urban streams can become **living laboratories of coexistence between nature and city**, were ecological integrity and human wellbeing flow together.

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References

Abad, J.D., Rhoads, B.L., Güneralp, İ., García, M.H., 2008. Flow Structure at Different Stages in a Meander-Bend with Bendway Weirs. J. Hydraul. Eng. 134, 1052–1063. https://doi.org/10.1061/(ASCE)0733-9429(2008)134:8(1052)

Abbe, T., Brooks, A., 2011. Geomorphic, Engineering, and Ecological Considerations when Using Wood in River Restoration, in: Stream Restoration in Dynamic Fluvial Systems. American Geophysical Union (AGU), pp. 419–451. https://doi.org/10.1029/2010GM001004

Abou-Elela, S.I., Golinielli, G., Abou-Taleb, E.M., Hellal, M.S., 2013. Municipal wastewater treatment in horizontal and vertical flows constructed wetlands. Ecol. Eng. 61, 460–468. https://doi.org/10.1016/j.ecoleng.2013.10.010

Addy, S., 2016. River restoration and biodiversity: nature-based solutions for restoring the rivers of the UK and Republic of Ireland. The James Hutton Institute, Aberdeen, Scotland, UK.

Aguas Alicante. Parque Urbano Inundable "La Marjal". Available: https://www.aguasdealicante.es/parque-la-marjal Last accessed: 21/12/2025

Aronson, M.F.J., Patel, M.V., O'Neill, K.M., Ehrenfeld, J.G., 2017. Urban riparian systems function as corridors for both native and invasive plant species. Biol. Invasions 19, 3645–3657. https://doi.org/10.1007/s10530-017-1583-1

Arsénio, P., Rodríguez‐González, P.M., Bernez, I., S. Dias, F., Bugalho, M.N., Dufour, S., 2020. Riparian vegetation restoration: Does social perception reflect ecological value? River Res. Appl. 36, 907‐920. https://doi.org/10.1002/rra.3514

Baird, D.C., Fotherby, L., Klumpp, C.C., Sculock, S.M., 2015. Bank Stabilization Design Guidelines. US Dep. Inter. Bur. Reclam. Manag. Water West Tech. Serv. Cent. SRH-2015-25.

Battelle Memorial Institute & The Nature Conservancy, 2014. Blackstone River fact sheet. Available: https://maumeeaoc.org/wp-content/uploads/2024/06/3.BW-FACT-SHEET-FINAL-12-22-2014-KP.pdf Last accessed: 21/12/2025

Beckenham, P., 2022. Coir Roll Drain Enhancements: Installation, Management and Maintenance Plan. Available: https://www.ada.org.uk/wp-content/uploads/2022/03/Coir_Roll_Management_Maintenance_Guide_FINAL.pdf Last accessed: 21/12/2025

Billingsley, Z., 2021. Bank Stabilization with Fabric Encapsulated Soil Lifts (FESL). Available: https://www.engr.colostate.edu/faculty/pnelson/wp-content/uploads/sites/23/2024/03/Billingsley_MS_all.pdf Last accessed: 21/12/2025

Buchholz, T., Younos, T., 2007. Urban Stream Daylighting Case Study Evaluations (Special Report), SR35-2007. Virginia Water Resources Research Center, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA.

Chandrashekhara, 2012. Restoring an urban river bed to its natural Eco-system; A Singapore experiment. Sand Prints. Available: https://chandrashekharasandprints.wordpress.com/2012/05/11/restoring-an-urban-river-bed-to-its-natural-eco-system-a-singapore-experiment/ Last accessed: 21/12/2025

Church, M., Ferguson, R.I., 2015. Morphodynamics: Rivers beyond steady state. Water Resour. Res. 51, 1883–1897. https://doi.org/10.1002/2014WR016862

Ciotti, D.C., Mckee, J., Pope, K.L., Kondolf, G.M., Pollock, M.M., 2021. Design Criteria for Process-Based Restoration of Fluvial Systems. BioScience 71, 831–845. https://doi.org/10.1093/biosci/biab065

Climate Adapt, 2020. Isar-Plan – Water management plan and restoration of the Isar river, Munich (Germany) [WWW Document]. Shar. Adapt. Knowl. Clim.-Resilient Eur. Available: https://climate-adapt.eea.europa.eu/en/metadata/case-studies/isar-plan-2013-water-management-plan-and-restoration-of-the-isar-river-munich-germany Last accessed: 21/12/2025

Climate Adapt, 2024. The Emscher Restoration: A Contribution to Climate Adaptation. Clim. Adapt - Shar. Adapt. Knowl. Clim.-Resilient Eur. Available: https://climate-adapt.eea.europa.eu/en/mission/solutions/mission-stories/the-emscher-restoration-story19 Last accessed: 21/12/2025

Cockel, C.P., Gurnell, A.M., Gurnell, J., 2014. Consequences of the Physical Management of an Invasive Alien Plant for Riparian Plant Species Richness and Diversity. River Res. Appl. 30, 217–229. https://doi.org/10.1002/rra.2633

Communauté d'agglomération du val de Bièvre, 2010. Reopening of a section of the River Bièvre in an urban environment. Available: https://professionnels.ofb.fr/sites/default/files/en/doc/documentation/REX_Hydromorphology_2010_Bievre.pdf Last accessed: 21/12/2025

Cortes, R., Ferreira, T., Hughes, S.J., 2019. Conservação e restauro fluvial, in: Rios de Portugal: comunidades, processos e alterações. Imprensa da Universidade de Coimbra, Coimbra.

Costaz-Puyou, I., Williams, R., Black, A., Spray, C., MacDonell, C., 2025. Re-meandering attenuates frequent high-flows and diversifies physical habitat in a gravel-bed river. J. Environ. Manage. 388, 125672. https://doi.org/10.1016/j.jenvman.2025.125672

Darre, M.E., Domisch, S., Hermoso, V., Ørsted, M., Arsanjani, J.J., 2025. Optimizing river restoration: A multi-scenario approach to barrier removal prioritization. J. Environ. Manage. 389, 126176. https://doi.org/10.1016/j.jenvman.2025.126176

Department of Environmental Conservation, Managing Invasive Plants in Riparian Areas. New York State of Opportunity. Available: https://extapps.dec.ny.gov/docs/lands_forests_pdf/tftismg17.pdf Last accessed: 21/12/2025

Directorate-General for Environment (European Commission), 2022. Biodiversity strategy for 2030: barrier removal for river restoration, Environment — Ecology. Publications Office of the European Union.

dos Reis Oliveira, P.C., van der Geest, H.G., Kraak, M.H.S., Westveer, J.J., Verdonschot, R.C.M., Verdonschot, P.F.M., 2020. Over forty years of lowland stream restoration: Lessons learned? J. Environ. Manage. 264, 110417. https://doi.org/10.1016/j.jenvman.2020.110417

EchoGéo, 2013. Document sans titre. EchoGéo 26. https://doi.org/10.4000/echogeo.13596

ECRR, 2011. Isar River, Munich (Case study). Available: https://www.ecrr.org/Portals/27/Isar%20River%20Munich.pdf Last accessed: 21/12/2025

ECRR, 2025. Manage invasive species [WWW Document]. Netw. Best Pract. River Restor. Gt. Eur. Available: https://www.ecrr.org/River-Restoration/Flood-risk-management/Healthy-Catchments-managing-for-flood-risk-WFD/Environmental-improvements-case-studies/Manage-invasive-species Last accessed: 21/12/2025

Elias, C.L., Calapez, A.R., Almeida, S.F.P., Feio, M.J., 2015. Determining useful benchmarks for the bioassessment of highly disturbed areas based on diatoms. Limnologica 51, 83–93. https://doi.org/10.1016/j.limno.2014.12.008

England, J., Angelopoulos, N., Cooksley, S., Dodd, J., Gill, A., Gilvear, D., Johnson, M., Naura, M., O'Hare, M., Tree, A., Wheeldon, J., Wilkes, M.A., 2021. Best Practices for Monitoring and Assessing the Ecological Response to River Restoration. Water 13, 3352. https://doi.org/10.3390/w13233352

EU Nature Restoration Law, 2024. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1991&qid=1722240349976 and https://environment.ec.europa.eu/topics/nature-and-biodiversity/nature-restoration-regulation_en and https://environment.ec.europa.eu/topics/nature-and-biodiversity/nature-restoration-regulation_en#documents Last accessed: 21/12/2025

European Commission, 2025. COMfinal (2025) - European Water Resilience Strategy. Available: https://environment.ec.europa.eu/topics/water/floods_en Last accessed: 21/12/2025

European Commission, 2025. Floods - Environment - European Commission. Energy Clim. Change Environ. Available: https://environment.ec.europa.eu/topics/water/floods_en Last accessed: 21/12/2025

European Parliament and Council, 2000. Water Framework Directive. OJL 327 Article 175, 1–73. Available: https://www.eea.europa.eu/policy-documents/water-framework-directive-wfd-2000 or https://environment.ec.europa.eu/topics/water/water-framework-directive_en Last accessed: 21/12/2025

Evette, A., Labonne, S., Rey, F., Liebault, F., Jancke, O., Girel, J., 2009. History of Bioengineering Techniques for Erosion Control in Rivers in Western Europe. Environ. Manage. 43, 972–984. https://doi.org/10.1007/s00267-009-9275-y

Falasco, E., Ector, L., Wetzel, C.E., Badino, G., Bona, F., 2021. Looking back, looking forward: a review of the new literature on diatom teratological forms (2010–2020). Hydrobiologia 848, 1675–1753. https://doi.org/10.1007/s10750-021-04540-x

Feio, M.J. (ed), Ferreira, V. (ed), 2019. Rios de Portugal: comunidades, processos e alterações. Imprensa da Universidade de Coimbra. https://doi.org/10.14195/978-989-26-1624-7

Feio, M.J., Hughes, R.M., Serra, S.R.Q., Nichols, S.J., Kefford, B.J., Lintermans, M., Robinson, W., Odume, O.N., Callisto, M., Macedo, D.R., Harding, J.S., Yates, A.G., Monk, W., Nakamura, K., Mori, T., Sueyoshi, M., Mercado-Silva, N., Chen, K., Baek, M.J., Bae, Y.J., Tachamo-Shah, R.D., Shah, D.N., Campbell, I., Moya, N., Arimoro, F.O., Keke, U.N., Martins, R.T., Alves, C.B.M., Pompeu, P.S., Sharma, S., 2023. Fish and macroinvertebrate assemblages reveal extensive degradation of the world's rivers. Glob. Change Biol. 29, 355–374. https://doi.org/10.1111/gcb.16439

Feio, M.J., Mantas, A.I., Serra, S.R.Q., Calapez, A.R., Almeida, S.F.P., Sales, M.C., Montenegro, M., Moreira, F., 2022. Effect of environmental education on the knowledge of aquatic ecosystems and reconnection with nature in early childhood. PLOS ONE 17, e0266776. https://doi.org/10.1371/journal.pone.0266776

FISRWG, 1998. Stream Corridor Restoration: Principles, Processes, and Practices. Available: https://directives.nrcs.usda.gov/sites/default/files2/1712931021/20691.pdf Last accessed: 21/12/2025

Friends of the Rappahannock, n.d. Friends of the Rappahannock | The voice and active force for a healthy and scenic Rappahannock River. Available: https://riverfriends.org/ Last accessed: 21/12/2025

Gaertner, M., Fisher, J., Sharma, G., Esler, K., 2012. Insights into invasion and restoration ecology: Time to collaborate towards a holistic approach to tackle biological invasions. NeoBiota 12, 57–76. https://doi.org/10.3897/neobiota.12.2123

Garcia de Leaniz, C., O'Hanley, J.R., 2022. Operational methods for prioritizing the removal of river barriers: Synthesis and guidance. Sci. Total Environ. 848, 157471. https://doi.org/10.1016/j.scitotenv.2022.157471

GEOTA RiosLivres Programme, 2023a. Vaqueiros Weir Removal Portugal: Restoring Alviela's Ecosystem. Dam Remov. Eur. Available: https://damremoval.eu/portfolio/vaqueiros-weir-removal-portugal/ Last accessed: 21/12/2025

GEOTA RiosLivres Programme, 2023b. Sourinho | Rios Livres GEOTA Let Alviela Run. Available: https://rioslivres.geota.pt/sourinho/ Last accessed: 21/12/2025

Gilvear, D.J., Spray, C.J., Casas-Mulet, R., 2013. River rehabilitation for the delivery of multiple ecosystem services at the river network scale. J. Environ. Manage. 126, 30–43. https://doi.org/10.1016/j.jenvman.2013.03.026

Goldsmith, W., Gray, D., McCullah, J., 2014. Bioengineering Case Studies: Sustainable Stream Bank and Slope Stabilization. Springer New York, New York, NY. https://doi.org/10.1007/978-1-4614-7996-3

González Del Tánago, M., García De Jalón, D., 2006. Attributes for assessing the environmental quality of riparian zones. Limnetica 25, 389–402. https://doi.org/10.23818/limn.25.27

González, E., Sher, A.A., Tabacchi, E., Masip, A., Poulin, M., 2015. Restoration of riparian vegetation: A global review of implementation and evaluation approaches in the international, peer-reviewed literature. J. Environ. Manage. 158, 85–94. https://doi.org/10.1016/j.jenvman.2015.04.033

Gurnell, A.M., Scott, S.J., England, J., Gurnell, D., Jeffries, R., Shuker, L., Wharton, G., 2020. Assessing river condition: A multiscale approach designed for operational application in the context of biodiversity net gain. River Res. Appl. 36, 1559–1578. https://doi.org/10.1002/rra.3673

Hargreaves, J., 2021. Volunteers plant 200 native trees as river restoration project is completed on local nature reserve. Sheff. Rotherham Wildl. Trust. Available: https://www.wildsheffield.com/volunteers-plant-200-native-trees-as-river-restoration-project-is-completed-on-local-nature-reserve/ Last accessed: 21/12/2025

Harman, W., Starr, R., Carter, M., Tweedy, K., Clemmons, M., Suggs, K., Miller, C., 2012. A Function-Based Framework for Stream Assessment & Restoration Projects. Available: https://www.epa.gov/sites/default/files/2015-08/documents/a_function_based_framework_for_stream_assessment_3.pdf Last accessed: 21/12/2025

Haubrock, P.J., Ahmed, D.A., Cuthbert, R.N., Stubbington, R., Domisch, S., Marquez, J.R.G., Beidas, A., Amatulli, G., Kiesel, J., Shen, L.Q., Soto, I., Angeler, D.G., Bonada, N., Cañedo‐Argüelles, M., Csabai, Z., Datry, T., Eyto, E., Dohet, A., Drohan, E., England, J., Feio, M.J., Forio, M.A.E., Goethals, P., Graf, W., Heino, J., Hudgins, E.J., Jähnig, S.C., Johnson, R.K., Larrañaga, A., Leitner, P., L'Hoste, L., Lizee, M., Maire, A., Rasmussen, J.J., Schäfer, R.B., Schmidt‐Kloiber, A., Vannevel, R., Várbíró, G., Wiberg‐Larsen, P., Haase, P., 2022. Invasion impacts and dynamics

of a European‐wide introduced species. Glob. Change Biol. https://doi.org/10.1111/gcb.16207

Hemmati, M., Daraby, P., 2019. Erosion and sedimentation patterns associated with restoration structures of bendway weirs. J. Hydro-Environ. Res. 22, 19–28. https://doi.org/10.1016/j.jher.2018.11.001

Hickman, E.L., Thompson, T.M., 2010. Stream Restoration Series: J-Hook Vane (Fact Sheet Number 3). Available: https://cbtrust.org/wp-content/uploads/J-Hook-Vane-Fact-Sheet.pdf Last accessed: 21/12/2025

Hordones, R.H., Boëchat, I.G., Cunha, D.G.F., Brauns, M., Gücker, B., 2025. Toward effective river restoration in Brazil: a systematic review of current practices, regional disparities, and success metrics. Restor. Ecol. 33, e70041. https://doi.org/10.1111/rec.70041

ICEM. Adaptation Measures – LISA. Available: https://lisa.icem.com.au/nbs Last accessed: 21/12/2025

ISAA. What is a digger log? Available: https://www.riversandfish.ca/faq Last accessed: 21/12/2025

Ishak, M.I.S., Al Manasir, Y., Nor Ashikin, N.S.S., Md Yusuff, M.S., Zuknik, M., Abdul Khalil, H.P.S., 2021. Application of cellulosic fiber in soil erosion mitigation: Prospect and challenges. BioResources 16, 4474–4522. Available: https://bioresources.cnr.ncsu.edu/resources/application-of-cellulosic-fiber-in-soil-erosion-mitigation-prospect-and-challenges/ Last accessed: 21/12/2025

Itinerario ambiental Parque Inundable La Marjal, 2020. Ayunt. Alicante. Available: https://www.alicante.es/es/documentos/itinerario-ambiental-parque-inundable-marjal Last accessed: 21/12/2025

Khosronejad, A., Kozarek, J.L., Diplas, P., Hill, C., Jha, R., Chatanantavet, P., Heydari, N., Sotiropoulos, F., 2018. Simulation-based optimization of in-stream structures design: rock vanes. Environ. Fluid Mech. 18, 695–738. https://doi.org/10.1007/s10652-018-9579-7

Landing Road Rock Ramp Fishway Repair. Catchment Solut. available https://www.catchmentsolutions.com.au/projects/landing-road-rock-ramp-fishway-repair/ Last accessed: 21/12/2025

Landsman, S.J., McLellan, N.R., Platts, J., Van Den Heuvel, M.R., 2020. Fishway Effectiveness and Upstream Residency of Three Fish Species at Four Fishways in Prince Edward Island, Canada. Northeast. Nat. 27, 48. https://doi.org/10.1656/045.027.0105

Lapin, K., Bernhardt, K.-G., Mayer, E., Roithmayr, S., Neureiter, J., Horvath, C., 2016. Monitoring River Restoration Efforts: Do Invasive Alien Plants Endanger the Success? A Case Study of the Traisen River. J. Environ. Prot. 07, 831–843. https://doi.org/10.4236/jep.2016.76076

LARIMIT. Mitigation measures. Available: https://www.larimit.com/mitigation_measures/ Last accessed: 21/12/2025

Lewandowski, J., Arnon, S., Banks, E., Batelaan, O., Betterle, A., Broecker, T., Coll, C., Drummond, J.D., Gaona Garcia, J., Galloway, J., Gomez-Velez, J., Grabowski, R.C., Herzog, S.P., Hinkelmann, R., Höhne, A., Hollender, J., Horn, M.A., Jaeger, A., Krause, S., Löchner Prats, A., Magliozzi, C., Meinikmann, K., Mojarrad, B.B., Mueller, B.M., Peralta-Maraver, I., Popp, A.L., Posselt, M., Putschew, A., Radke, M., Raza, M., Riml, J., Robertson, A., Rutere, C., Schaper, J.L., Schirmer, M., Schulz, H., Shanafield, M., Singh, T., Ward, A.S., Wolke, P., Wörman, A., Wu, L., 2019. Is the Hyporheic Zone Relevant beyond the Scientific Community? Water 11, 2230. https://doi.org/10.3390/w11112230

Lim, S., Do, Y., 2023. Macroinvertebrate conservation in river ecosystems: Challenges, restoration strategies, and integrated management approaches. Entomol. Res. 53, 271–290. https://doi.org/10.1111/1748-5967.12665

Loo, S.E., Mac Nally, R., O'Dowd, D.J., Lake, P.S., 2009. Secondary Invasions: Implications of Riparian Restoration for In-Stream Invasion by an Aquatic Grass. Restor. Ecol. 17, 378–385. https://doi.org/10.1111/j.1526-100X.2008.00378.x

Macedo, D.R., Callisto, M., Linares, M.S., Hughes, R.M., Romano, B.M., Rothe-Neves, M., Silveira, J.S., 2022. Urban stream rehabilitation in a densely populated Brazilian metropolis. Front. Environ. Sci. 10. https://doi.org/10.3389/fenvs.2022.921934

Magdaleno, F., Martínez, R., 2014. Evaluating the quality of riparian forest vegetation: the Riparian Forest Evaluation (RFV) index. For. Syst. 23, 259–272. https://doi.org/10.5424/fs/2014232-04488

Maryland Department of the Environment. Maryland's Guidelines for Waterway Construction. Md. Dep. Environ. Available: https://mde.maryland.gov/programs/water/WetlandsandWaterways/DocumentsandInformation/Pages/default.aspx Last accessed: 21/12/2025

Masouras, A., Karaouzas, I., Dimitriou, E., Tsirtsis, G., Smeti, E., 2021. Benthic Diatoms in River Biomonitoring—Present and Future Perspectives within the Water Framework Directive. Water 13, 478. https://doi.org/10.3390/w13040478

Massachusetts Department of Environmental Protection, 2016. The Clean Water Toolkit. Available: https://megamanual.geosyntec.com/npsmanual/default.aspx Last accessed: 21/12/2025

Matono, P., Silva, J., Bernardo, J., Costa, A., Fragoso, S., Roque, L., Pinheiro, P., Almeida, J., Ilhéu, M., 2019. Conservação do saramugo e de rios temporários, Universidade de Évora. ed.

Medina, A.L., Long, J.W., 2004. Placing Riffle Formations to Restore Stream Functions in a Wet Meadow. Ecol. Restor. 22, 120–125. https://doi.org/10.3368/er.22.2.120

Methratta, E.T., 2020. Monitoring fisheries resources at offshore wind farms: BACI vs. BAG designs. ICES J. Mar. Sci. 77, 890–900. https://doi.org/10.1093/icesjms/fsaa026

Michael, S., Horst, Z., Regina, P., Reckendorfer, W., 2025. The Role of a Near‐Natural Fish Bypass in Facilitating Downstream Movements and Providing Habitat for a Potamodromous Fish. River Res. Appl. rra.70060. https://doi.org/10.1002/rra.70060

MIP4Adapt, 2024. The Emscher Restoration: A Contribution to Climate Adaptation. Clim. Adapt - Shar. Adapt. Knowl. Clim.-Resilient Eur. Available: https://climate-adapt.eea.europa.eu/en/mission/solutions/mission-stories/the-emscher-restoration-story19 Last accessed: 21/12/2025

Mohan, M., Chacko, A., Rameshan, M., Gopikrishna, V.G., Kannan, V.M., Vishnu, N.G., Sasi, S.A., Baiju, K.R., 2022. Restoring Riparian Ecosystems During the UN-Decade on Ecosystem Restoration: A Global Perspective. Anthr. Sci. 1, 42–61. https://doi.org/10.1007/s44177-022-00009-1

Moore, H.E., Rutherfurd, I.D., 2017. Lack of maintenance is a major challenge for stream restoration projects. River Res. Appl. 33, 1387–1399. https://doi.org/10.1002/rra.3188

Mosselman, E., 2020. Studies on River Training. Water 12, 3100. https://doi.org/10.3390/w12113100

Mouchlianitis, F.A., 2024. Dam Removal Progress 2023. World Fish Migration Foundation. Available: https://www.ecrr.org/Publications/id/1196 and https://www.ecrr.org/Portals/27/Publications/Web-version_DRE-Report-2023.pdf Last accessed: 21/12/2025

Muhar, S., Januschke, K., Kail, J., Poppe, M., Schmutz, S., Hering, D., Buijse, A.D., 2016. Evaluating good-practice cases for river restoration across Europe: context, methodological framework, selected results and recommendations. Hydrobiologia 769, 3–19. https://doi.org/10.1007/s10750-016-2652-7

Murphy, B.M., Russell, K.L., Stillwell, C.C., Hawley, R., Scoggins, M., Hopkins, K.G., Burns, M.J., Taniguchi-Quan, K.T., Macneale, K.H., Smith, R.F., 2022. Closing the gap on wicked urban stream restoration problems: A framework to integrate science and community values. Freshw. Sci. 41, 521–531. https://doi.org/10.1086/721134

Naturvation project: Enabling Urban Nature-Based Solutions, 2017. Snapshot - Munich: The restoration of the Isar River. European Union's Horizon 2020, UK (coordination University of Durham). Available: https://naturvation.eu/sites/default/files/munich_snapshot.pdf Last accessed: 21/12/2025

NSW. DPI Website. Available: https://www.dpi.nsw.gov.au/dpi/fishing/fish-passage-nsw/improving-fish-passage/fishways/precast-rock-ramp Last accessed: 21/12/2025

NWRM, 2024. Catalogue of NWRM | Natural Water Retention Measures. Available: https://www.nwrm.eu/measures-catalogue Last accessed: 21/12/2025

O'Hare, M.T., Gunn, I.D.M., Critchlow-Watton, N., Guthrie, R., Taylor, C., Chapman, D.S., 2020. Fewer sites but better data? Optimising the representativeness and statistical power of a national monitoring network. Ecol. Indic. 114, 106321. https://doi.org/10.1016/j.ecolind.2020.106321

Odgaard, A.J., 2009. Review of "River Training and Sediment Management with Submerged Vanes". ASCE. Journal of Hydraulic Engineering. 136(1). https://doi.org/10.1061/(ASCE)HY.1943-7900.0000159

Odgaard, A.J., 2015. River Channel Stabilization with Submerged Vanes, in: Yang, C.T., Wang, L.K. (Eds.), Advances in Water Resources Engineering. Springer International Publishing, Cham, pp. 107–136. https://doi.org/10.1007/978-3-319-11023-3_3

Okanagan Lakeshore Living, 2002. Streambank and shoreline protection manual. Lake County Stormwater Management Commission, Lake County Planning, Building and Development Department - Engineering and Environmental Services, U.S.D.A. Natural Resources Conservation Service/Lake County Soil and Water Conservation District, U.S. Army Corps of Engineers - Chicago District. Available: https://lakeshore-living.okcp.ca/wp-content/uploads/2024/06/Streambank-Shoreline-Protection-Manual.pdf Last accessed: 21/12/2025

Pabst, R., Dias, F.S., Borda-de-Água, L., Rodríguez-González, P.M., Capinha, C., 2022. Assessing and Predicting the Distribution of Riparian Invasive Plants in Continental Portugal. Front. Ecol. Evol. 10. https://doi.org/10.3389/fevo.2022.875578

Palmer, M.A., Bernhardt, E.S., Allan, J.D., Lake, P.S., Alexander, G., Brooks, S., Carr, J., Clayton, S., Dahm, C.N., Follstad Shah, J., Galat, D.L., Loss, S.G., Goodwin, P., Hart, D.D., Hassett, B., Jenkinson, R., Kondolf, G.M., Lave, R., Meyer, J.L., O'Donnell, T.K., Pagano, L., Sudduth, E., 2005. Standards for ecologically successful river restoration. J. Appl. Ecol. 42, 208–217. https://doi.org/10.1111/j.1365-2664.2005.01004.x

Palmer, M.A., Hondula, K.L., Koch, B.J., 2014. Ecological Restoration of Streams and Rivers: Shifting Strategies and Shifting Goals. Annu. Rev. Ecol. Evol. Syst. 45, 247–269. https://doi.org/10.1146/annurev-ecolsys-120213-091935

Palmer, M.A., Menninger, H.L., Bernhardt, E., 2010. River restoration, habitat heterogeneity and biodiversity: A failure of theory or practice? Freshw. Biol. 55, 205–222. https://doi.org/10.1111/j.1365-2427.2009.02372.x

Parkyn, S., Collier, K., Clapcott, K., David, B., Davies-Colley, R., Matheson, F., Quinn, J., Shaw, W., Storey, R., 2010. The restoration indicator toolkit: Indicators for monitoring the ecological success of stream restoration. National Institute of Water & Atmospheric Research Ltd, Hamilton, New Zealand.

Peñacoba-Antona, L., Ramirez-Vargas, C.A., Wardman, C., Carmona-Martinez, A.A., Esteve-Núñez, A., Paredes, D., Brix, H., Arias, C.A., 2022. Microbial Electrochemically Assisted Treatment Wetlands: Current Flow Density as a Performance Indicator in Real-Scale Systems in Mediterranean and Northern European Locations. Front. Microbiol. 13, 843135. https://doi.org/10.3389/fmicb.2022.843135

Pfeifer, C., 2024. All About Live Staking - Sovereign Homestead Design. Available: https://thesovereignhomestead.com/all-about-live-staking/ Last accessed: 21/12/2025

Pinto, R., Mortágua, A., Almeida, S.F.P., Serra, S., Feio, M.J., 2020. Diatom size plasticity at regional and global scales. Limnetica 39, 387–403. https://doi.org/10.23818/limn.39.25

Polster, D.F, (2002). Soil Bioengineering Techniques for Riparian Restoration. Proc. 26 Annu. Br. Columbia Mine Reclam. Symp. Dawson Creek. Available: https://chapter.ser.org/westerncanada/files/2015/01/2002-polster.pdf Last accessed: 21/12/2025

Qin, Y., 2020. Urban Flooding Mitigation Techniques: A Systematic Review and Future Studies. Water 12, 3579. https://doi.org/10.3390/w12123579

Radspinner, R.R., 2009. Development of design guidelines for in-stream flow control structures (Master of Science in Civil Engineering). Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA. Available: https://vtechworks.lib.vt.edu/server/api/core/bitstreams/6dc3ecf2-ed9b-44ee-9ea1-85afa6762c6b/content Last accessed: 21/12/2025

Radspinner, R.R., Diplas, P., Lightbody, A.F., Sotiropoulos, F., 2010. River Training and Ecological Enhancement Potential Using In-Stream Structures. J. Hydraul. Eng. 136, 967–980. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000260

Rexine, T., Kalmon, D., 2010. A Guide to Bank Restoration Options for Large River Systems: Part II Bioengineering Installation Manual. Available: https://www.mwmo.org/wp-content/uploads/2017/11/Part-II_Installation_Manual_20171117.pdf Last accessed: 21/12/2025

Reynoldson, T.B., Norris, R.H., Resh, V.H., Day, K.E., Rosenberg, D.M., 1997. The Reference Condition: A Comparison of Multimetric and Multivariate Approaches to Assess Water-Quality Impairment Using Benthic Macroinvertebrates. J. North Am. Benthol. Soc. 16, 833–852. https://doi.org/10.2307/1468175

Rodríguez-Amaya, C., Durán-Ariza, A., Duarte-Méndez, S., 2020. Submerged Vane Technology in Colombia: Five Representative Projects. Water 12, 984. https://doi.org/10.3390/w12040984

Rozkošný, Miloš., Kriška, M., Šálek, J., Bodík, I., Istenič, D., Griessler Bulc, Tjaša., Arias, C.A., 2014. Natural technologies of wastewater treatment. GWP CEE, Bratislava. Available: https://www.gwp.org/globalassets/global/gwp-cee_files/regional/natural-treatment.pdf Last accessed: 21/12/2025

Sahameddin Mahmoudi Kurdistani, 2018. Scour Morphology Downstream of Log-Frame Deflectors in Series. https://doi.org/10.15142/T3835R

Santaoja, M., Squires, T., Klimkowska, A., Mc Guinness, S., Granath, G., Törmänen, T., Biedroń, I., Terrisse, A., 2025. Best practices in European wetland restoration: a review of manuals and guidelines. Wetl. Ecol. Manag. 33, 54. https://doi.org/10.1007/s11273-025-10061-4

Sini, R., 2020. Singapore's Green Infrastructure and Biophilic Urbanism, in: Singapore's Park System Master Planning, Advances in 21st Century Human Settlements. Springer Singapore, Singapore, pp. 211–251. https://doi.org/10.1007/978-981-13-6746-5_8

Spanish Climate Change Adaptation Platform. Plataforma sobre Adaptación al Cambio Climático en España, Urban flood park "La Marjal" Available: https://adaptecca.es/en/casos-practicos/urban-flood-park-la-marjal-0 Last accessed: 21/12/2025

Stuart, I.G., Marsden, T.J., Jones, M.J., Moore, M.T., Baumgartner, L.J., 2024. Rock fishways: Natural designs for an engineered world. Ecol. Eng. 206, 107317. https://doi.org/10.1016/j.ecoleng.2024.107317

the River Restoration Centre, 2021. Manual of River Restoration Techniques. Man. River Restor. Tech. Available: https://www.therrc.co.uk/manual-river-restoration-techniques Last accessed: 21/12/2025

Thompson, D.M., 2002a. Channel-Bed Scour with High versus Low Deflectors. J. Hydraul. Eng. 128, 640–643. https://doi.org/10.1061/(ASCE)0733-9429(2002)128:6(640)

Thompson, D.M., 2002b. Long-Term Effect of Instream Habitat-Improvement Structures on Channel Morphology Along the Blackledge and Salmon Rivers, Connecticut, USA. Environ. Manage. 29, 250–265. https://doi.org/10.1007/s00267-001-0069-0

Tickner, D.P., Angold, P.G., Gurnell, A.M., Mountford, J.O., 2001. Riparian plant invasions: hydrogeomorphological control and ecological impacts. Prog. Phys. Geogr. Earth Environ. 25, 22–52. https://doi.org/10.1177/030913330102500102

Tieges, Z., Georgiou, M., Smith, N., Morison, G., Chastin, S., 2022. Investigating the association between regeneration of urban blue spaces and risk of incident chronic health conditions stratified by neighbourhood deprivation: A population-based retrospective study, 2000–2018. Int. J. Hyg. Environ. Health 240, 113923. https://doi.org/10.1016/j.ijheh.2022.113923

Underwood, A.J., 1994. On Beyond BACI: Sampling Designs that Might Reliably Detect Environmental Disturbances. Ecol. Appl. 4, 3–15. https://doi.org/10.2307/1942110

USEPA, 2017. Learn About Stressors. Available: https://www.epa.gov/caddis/learn-about-stressors Last accessed: 21/12/2025

Van Andel, J., Aronson, J. (Eds.), 2012. Restoration Ecology: The New Frontier, 1st ed. Wiley. https://doi.org/10.1002/9781118223130

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. The River Continuum Concept. Can. J. Fish. Aquat. Sci. 37, 130–137. https://doi.org/10.1139/f80-017

Verdonschot, P.F.M., Verdonschot, R.C.M., 2023. The role of stream restoration in enhancing ecosystem services. Hydrobiologia 850, 2537–2562. https://doi.org/10.1007/s10750-022-04918-5

Vymazal, J., 2005. Horizontal sub-surface flow and hybrid constructed wetlands systems for wastewater treatment. Ecol. Eng., Constructed wetlands for wastewater treatment 25, 478–490. https://doi.org/10.1016/j.ecoleng.2005.07.010

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., Morgan, R.P., 2005. The urban stream syndrome: current knowledge and the search for a cure. J. North Am. Benthol. Soc. 24, 706–723. https://doi.org/10.1899/04-028.1

Wohl, E., Bledsoe, B.P., Fausch, K.D., Kramer, N., Bestgen, K.R., Gooseff, M.N., 2016. Management of Large Wood in Streams: An Overview and Proposed Framework for Hazard Evaluation. JAWRA J. Am. Water Resour. Assoc. 52, 315–335. https://doi.org/10.1111/1752-1688.12388

Wohl, E., Lane, S.N., Wilcox, A.C., 2015. The science and practice of river restoration. Water Resour. Res. 51, 5974–5997. https://doi.org/10.1002/2014WR016874

Wynants, M., Hallberg, L., Prischl, L.-A., Livsey, J., Bieroza, M., 2025. Trends and purposes of European river monitoring and restoration. Environ. Sci. Policy 170, 104130. https://doi.org/10.1016/j.envsci.2025.104130

Yochum, S., 2018. Guidance for Stream Restoration (No. Technical Note TN-102.4). U.S. Department of Agriculture, Forest Service, National Stream & Aquatic Ecology Center, Fort Collins, Colorado, US. Available: https://www.fs.usda.gov/biology/nsaec/assets/yochumusfs-nsaec-tn102-4guidancestreamrestoration.pdf Last accessed: 21/12/2025

Zerega, A., Simões, N.E., Feio, M.J., 2021. How to improve the biological quality of urban streams? Reviewing the effect of hydromorphological alterations and rehabilitation measures on benthic invertebrates. Water Switz. 13. https://doi.org/10.3390/w13152087

Additional useful websites

Climate-ADAPT (case studies): https://climate-adapt.eea.europa.eu/en/observatory/solutions/case-studies Last accessed: 21/12/2025

CresceRio: https://www.facebook.com/cresceriocoimbra/ Last accessed: 21/12/2025

ECRR. European Centre for River Restoration: https://www.ecrr.org/ Last accessed: 21/12/2025

Global Water Partnership: https://gwpo-gwp.org/ Last accessed: 21/12/2025

LARIMIT: https://www.larimit.com/mitigation_measures/ Last accessed: 21/12/2025

Marionet: https://marioneteatro.com/ Last accessed: 21/12/2025

Nordic Guidance for Nature-based solutions: https://nbsguide.org/ Last accessed: 21/12/2025

NSW government: https://www.lls.nsw.gov.au/ Last accessed: 21/12/2025

NWRM, Natural Water Retention Measures: https://www.nwrm.eu/measures-catalogue Last accessed: 21/12/2025

RESTORE Wiki: https://www.restorerivers.eu/wiki/index.php?title=RESTORE_Wiki_Main_Page Last accessed: 21/12/2025

STROUD, Water Research Center: https://stroudcenter.org/ Last accessed: 21/12/2025

Water Action Hub: https://wateractionhub.org/ Last accessed: 21/12/2025