Inventory of NBS methodologies for slow hydrology

12th June 2024

A. Scrieciu, A. Toma, D. Florea

Deliverable Name	Inventory of NBS methodologies for slow hydrology (surface water retention, groundwater recharge)
Deliverable Number	D2.1
Work Package	WP2
Associated Task	T2.1
Deliverable Lead Partner	GeoEcoMar
Contributors	Amalie Laursen (REGIONH), Emilie Rønde Nielsen (REGIONH), Helene Lykke Strøbech (REGIONH), Helene Müller (BOKU), Johann Peter Rauch (BOKU), Magdalena von der Thannen (BOKU), Miguel Potes (UEVORA), Peter van der Keur (GEUS), Rikke Munck Petersen (UCPH)

Change Control | Document History				
Version	**Date**	**Change History**	**Authors**	**Organization**
1.1	28.11.2024	First draft	Albert Scrieciu Andrei Toma Daniela Florea	GeoEcoMar
1.2	14.01.2025	Second draft	Albert Scrieciu Andrei Toma Daniela Florea	GeoEcoMar
1.3	28.03.2025	Final deliverable	Albert Scrieciu Andrei Toma Daniela Florea	GeoEcoMar

Disclaimer

The content of this deliverable does not reflect the official opinion of the European Union. Responsibility for the information and views expressed herein lies entirely with the author(s).

Content

List of Abbreviations

EC .... European Commission

EEA .... European Environment Agency

EU .... European Union

FAO .... Food and Agriculture Organization

IUCN .... International Union for Conservation of Nature

IFI .... Infiltration Feasibility Index

LL .... Living Lab

NBS .... Nature-Based Solutions

SH .... Slow Hydrology

SWBE .... Soil and Water Bioengineering

WP .... Work Package

Executive Summary

The **INTERLAYER Project Deliverable D2.4** presents a detailed catalogue of **Nature-Based Solutions (NBS)** for **Slow Hydrology (SH)**, targeting improved water retention, groundwater recharge, flood/drought resilience, and ecosystem services. Structured into eight key NBS methodologies, the document details technical implementation, benefits, costs, challenges, and monitoring frameworks:

1. **Half-Moon Water Harvesting**: Semi-circular bunds used in arid regions (e.g., Sahel) to capture rainwater, enhance soil moisture, and stabilize degraded landscapes.

2. **Terrace Farming (Beitang System)**: Ancient Chinese slope management combining irrigation and drainage for soil conservation, adapted to modern agricultural challenges.

3. **Continuous Contour Trenches/Keylines**: Contour-aligned trenches (India) and landscape-scale water management (Australia/Germany/US) to slow runoff, recharge groundwater, and prevent erosion.

4. **Ridge and Furrow Systems**: Medieval European agricultural practice to optimize drainage and moisture retention on heavy soils, still visible in preserved landscapes.

5. **Artificial Recharge Systems**: Techniques like infiltration basins and riverbed gravel systems (e.g., Gabardine Project, Portugal) to enhance groundwater replenishment in semi-arid regions.

6. **Wetland Restoration & Floodplain Reconnection**: Danube Delta case study demonstrating habitat restoration, flood risk reduction, and socio-economic benefits through reconnecting rivers to floodplains.

7. **Soil and Water Bioengineering (SWBE)**: Vegetation-based erosion control (e.g., vegetated crib walls) to stabilize slopes, improve water retention, and restore degraded ecosystems.

8. **Blue-Green Urban Infrastructure**: Copenhagen's St. Kjelds Quarter model integrating green spaces and stormwater management for urban flood resilience and biodiversity.

Cross-Cutting Themes:

- **Co-Benefits**: Biodiversity enhancement, carbon sequestration, community engagement, and economic opportunities (e.g., eco-tourism).
- **Challenges**: Labor-intensive implementation, site-specific adaptability, maintenance requirements, and initial funding barriers.
- **Monitoring**: Emphasis on hydrological metrics (infiltration rates, groundwater levels), ecological recovery (vegetation growth, habitat diversity), and stakeholder feedback.

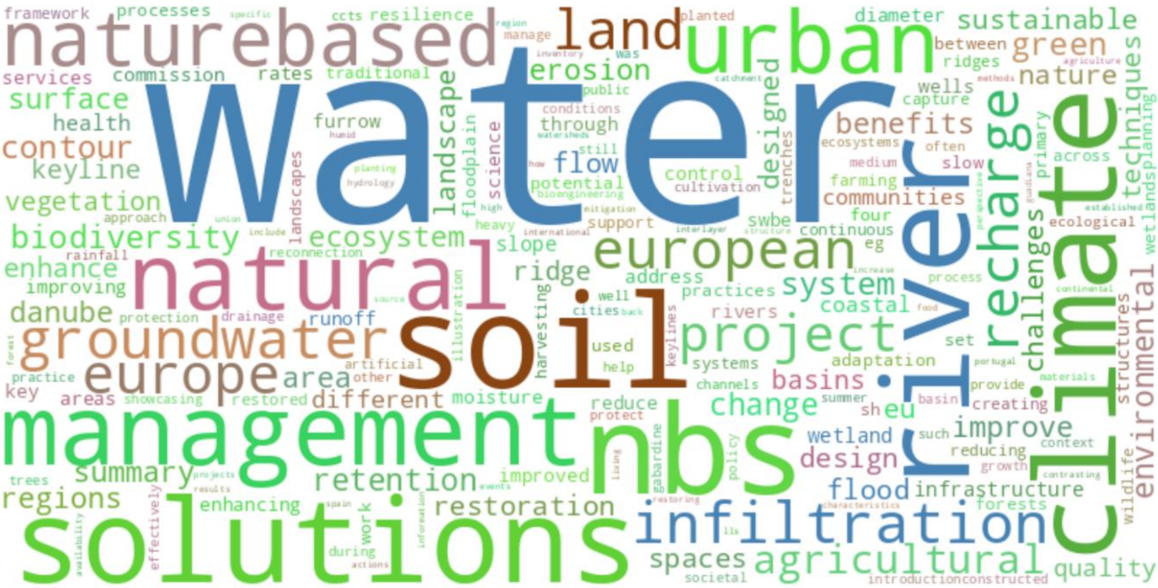

Figure 1. Word cloud illustrating key concepts from the NBS catalogue, highlighting themes such as water management, river systems, soil stabilization, and sustainable hydrology solutions.

1. Introduction

1.1 Project Introduction

INTERLAYER focuses on how water retention technologies can contribute to improve resilience, adaptation and mitigation to hydroclimatic extreme events while increasing water availability and quality by balancing groundwater and surface water management practices. INTERLAYER will study groundwater and surface water availability and relate it to land use (including specific agricultural practices) and water quality from a synergetic perspective so that available Slow Hydrology (SH) techniques are used in future River Basin Management Plans. To do so, we set up four Living Labs (LL) in four contrasting European watersheds to include and compare different European edaphoclimatic regions with different geologic characteristics, see Figure 2

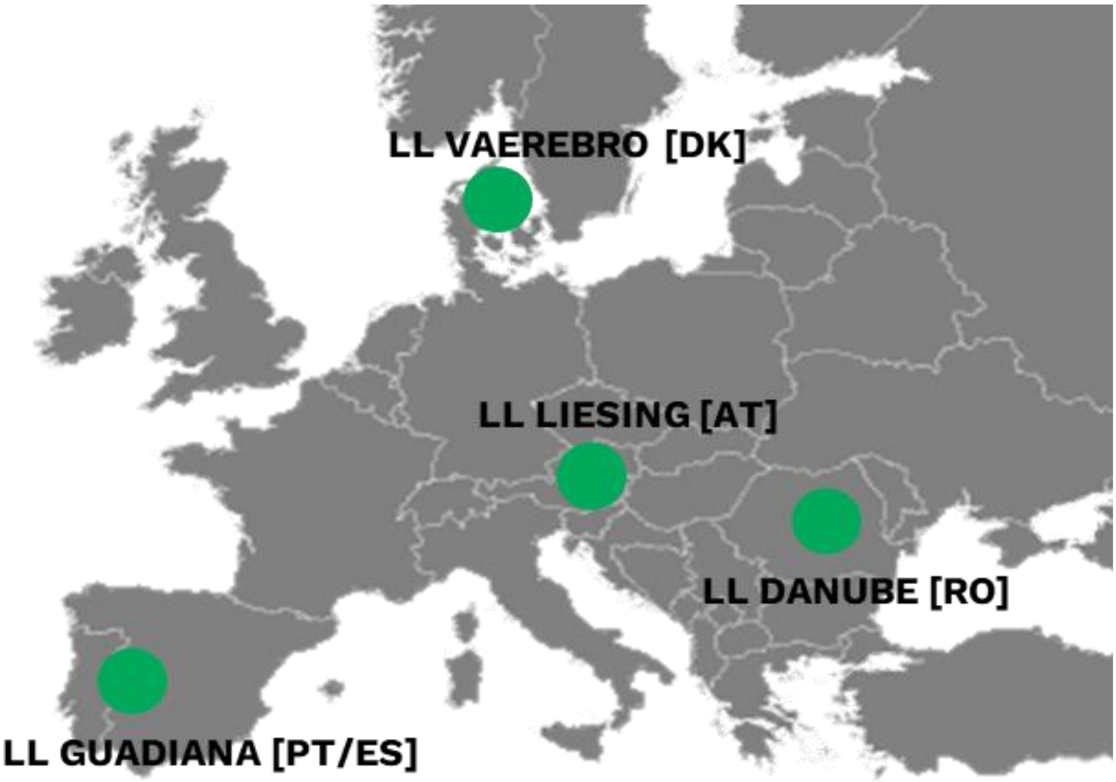

Figure 2. INTERLAYERs four LLs, located in contrasting watersheds in different regions of Europe.

Portugal, Guadiana River - This living lab covering 136 km^2 in the Toutalga sub-basin is dominated by intermittent rivers and ephemeral streams (IRES), characterized by flash flood and dry-phase periods. The basin has a hot summer Mediterranean climate.

Denmark, Vaerebro River - The catchment of the Vaerebro river is 153 km^2 and the river itself is 35 km long, having its source in a biodiversity-rich bog area. This living lab has a mixed land use with small and medium-sized villages, many spare-time farmers, and some agriculture, before discharging to Roskilde Fjord. It allows for a source-to-sea approach in a region with a continental humid and warm summer climate.

Austria, Liesing River - The Liesing river with a catchment of 112 km^2, the Liesing is often affected by strongly fluctuating water flows. During dry periods, the Liesing carries very little water. However, during heavy or prolonged rainfall, the Liesing can quickly turn into a river with high water levels. The catchment can be divided in a forest-dominated area followed by an urban river section. in a region with a continental humid and warm summer climate.

Romania, Danube River - Spanning 77 km^2 along the Danube River floodplain between Salcia and Maglavit, this site features agricultural lands, wetlands, and peri-urban areas, with an elevation under 100 meters. It experiences a continental humid climate with hot summers. Protected under the Natura 2000 site, it also lies near other important conservation zones. The key challenges include drainage, water abstraction, urban development, deforestation, and rising temperatures, disrupting the hydrological balance and increasing drought risk.

As the LLs are located in different and contrasting European regions, they show different processes and settings in the landscape as well as various microclimatic, hydrological and geological characteristics. It is a great chance to observe four different watersheds Nevertheless, it is also a challenging process to find common characteristics and methodologies fitting to all four LLs in order to generate comparable results.

1.2 Graphical summery of the work packages

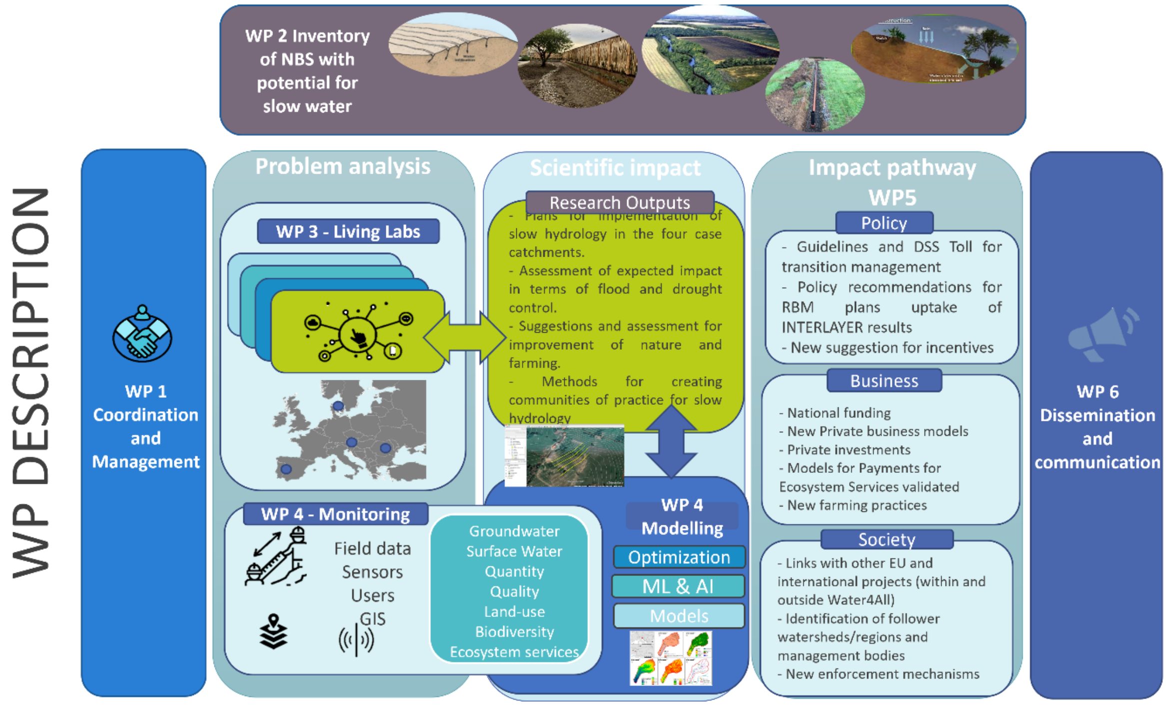

Figure 3. INTERLAYER project structure: Six work packages for Nature-Based Solutions in slow water management, addressing flood/drought control, ecosystem services, AI/ML modeling, and cross-sector collaboration (policy, business, communities).

1.3 WP 2 Short Summary

Inventory of NBS for slow hydrology

The overall objective of WP2 is to develop an inventory of nature-based solutions that combine additive results in surface water retention promoting slow hydrology for groundwater recharge, flood resilience and enhance ecosystem services at catchment level.

1.4 Introduction to Nature-Based Solutions

What Are Nature-Based Solutions?

NBS are actions that use natural processes to address challenges like flooding, pollution, or food insecurity. They include:

- Restoring ecosystems: Bringing back forests, wetlands, or rivers to their natural state.
- Creating green spaces: Building parks, green roofs, or community gardens in cities.

- Sustainable farming: Using methods like planting trees alongside crops (agroforestry) to improve soil health (FAO, 2022).

The International Union for Conservation of Nature (IUCN) defines NBS as “actions that protect, manage, and restore ecosystems to solve societal problems while supporting biodiversity” (Cohen-Shacham et al., 2016). Unlike traditional engineering solutions, NBS focus on long-term benefits. For instance, mangrove forests in coastal areas not only protect shorelines from storms but also provide habitats for fish, which supports local fishing communities (Spalding et al., 2014; Barbier et al., 2011).

Figure 4. NBS framework connecting ecosystem management and protection to human well-being and biodiversity benefits. Source: (IUCN, 2016).

Nature-based solutions are gaining momentum across Europe as practical, sustainable ways to tackle environmental issues like climate change, biodiversity loss, and extreme weather. Instead of relying only on human-made infrastructure (like concrete dams or drainage systems), NBS work *with* nature to solve problems. For example, restoring forests to prevent landslides, creating urban parks to cool cities during heatwaves, or rebuilding wetlands to absorb floodwaters. These solutions are not just good for the environment—they also help communities thrive economically and socially (**IPBES, 2019**).

The European Union has recognized the value of NBS, calling them “actions inspired by nature that are cost-effective, provide benefits for people and the planet, and help societies adapt to climate change” (**European Commission, 2021**). This aligns with major EU policies like the **European Green Deal** and the **Biodiversity Strategy for 2030**, which aim to protect ecosystems, cut greenhouse gas emissions, and make Europe resilient to climate impacts (**European Commission, 2020**).

While NBS continue to evolve as a restoration methodology, their development remains an ongoing process that has not yet reached full maturity. Despite this, the core principles and foundational strategies of NBS are firmly established, and no significant revisions to its fundamental framework are anticipated moving forward.

Why Are NBS Important for Europe?

Europe faces urgent challenges: rising temperatures, disappearing wildlife, and more frequent floods and droughts (EEA, 2021). NBS offer a way to address these issues while creating jobs, improving public health, and reducing costs. For example:

- Climate action: Peatlands and forests absorb carbon dioxide, helping fight climate change (Leifeld & Menichetti, 2018; Griscom et al., 2017).
- Disaster prevention: Restored wetlands in the Danube River basin reduced flood risks for thousands of people (WWF, 2020; Acreman et al., 2021).
- Health benefits: Access to green spaces in cities lowers stress and improves mental health (WHO, 2016; Bratman et al., 2019).

The EU supports NBS because they often cost less than “grey” infrastructure (like dams or seawalls) and provide multiple benefits at once. A single project—like planting trees in a city—can cool the air, reduce noise pollution, and create recreational spaces for residents (EC, 2022; Kabisch et al., 2017).

Key Principles of NBS

For NBS to work, they must follow core principles:

1. Work with nature, not against it: Use natural processes, like letting rivers flow freely instead of building concrete channels (Opperman et al., 2009).
2. Deliver multiple benefits: A restored forest should capture carbon, protect wildlife, and offer hiking trails (Eggermont et al., 2015).

3. Include local communities: Projects succeed when residents help design and maintain them (Nesshöver et al., 2017; Raymond et al., 2017).
4. Adapt to change: Solutions must evolve as climate conditions shift (Colls et al., 2009).

Challenges and the Path Forward

Despite their potential, NBS face hurdles. Many policymakers and businesses still prefer traditional infrastructure (Nesshöver et al., 2017). Funding is limited, and there's a lack of data on long-term impacts (Faivre et al., 2017). To scale up NBS, the EU needs:

- Stronger partnerships: Governments, scientists, and communities must collaborate (Albert et al., 2019).
- Better funding: EU programs like Horizon Europe and LIFE can support pilot projects (EC, 2021).
- Education: Teaching people about NBS benefits builds public support (Wamsler et al., 2020).

2. NBS Catalogue for SH

A nature-based solutions catalogue is a structured repository or database that compiles standardized information about green interventions, their applications, benefits, and implementation guidelines. It serves as a practical tool for policymakers, planners, and communities to identify, compare, and select appropriate NBS for specific environmental or societal challenges (European Commission, 2020). Unlike generic environmental databases, an NBS catalogue focuses on solutions that:

- Integrate natural processes (e.g., wetland restoration for flood control),
- Deliver co-benefits (e.g., biodiversity conservation, carbon sequestration),
- Align with sustainability goals (e.g., EU Green Deal, SDGs)

2.1 Data Collection Framework

The data collection process for this catalogue utilized a standardized survey framework designed to capture extensive information on NBS implemented for SH. The survey forms included detailed sections on project descriptions, objectives, costs, stakeholder involvement, and observed outcomes. Key parameters recorded encompassed the type of intervention, location, implementing cost, hydrological impacts (e.g., runoff reduction, groundwater recharge), and ecosystem co-benefits (e.g., biodiversity conservation, cultural and economic benefits). The survey was circulated among project partners, who provided detailed responses to ensure a thorough and reliable dataset.

2.1.1 Half-moons

Half-moons, also known as semi-circular bunds, are an indigenous water harvesting technique widely used in the Sahel regions of West Africa, particularly in Mali, Niger, and Burkina Faso (Lahmar et al. 2012). These structures are designed to capture and retain water and nutrients for agricultural purposes, especially for the cultivation of sorghum, millet, and other crops. Half-moons are typically 1–3 meters in diameter and are constructed with their tips along the contour of the slope, pointing uphill to intercept rainwater flowing downhill (Sawadogo 2011). This technique is essential for regenerating rangelands, improving crop yields, and stabilizing the soil in degraded and arid regions (Slingerland and Stork 2000). The half-moon structures are sometimes placed in a pattern across the landscape to maximize water capture and are considered more efficient than trapezoidal bunds in terms of the ratio between the bund volume and the ponded area.

Figure 5. Half-moon structures for water harvesting in arid landscapes.

Water4All
Water security for the planet

INTERLAYER
Safeguarding water in hydroclimatic extremes

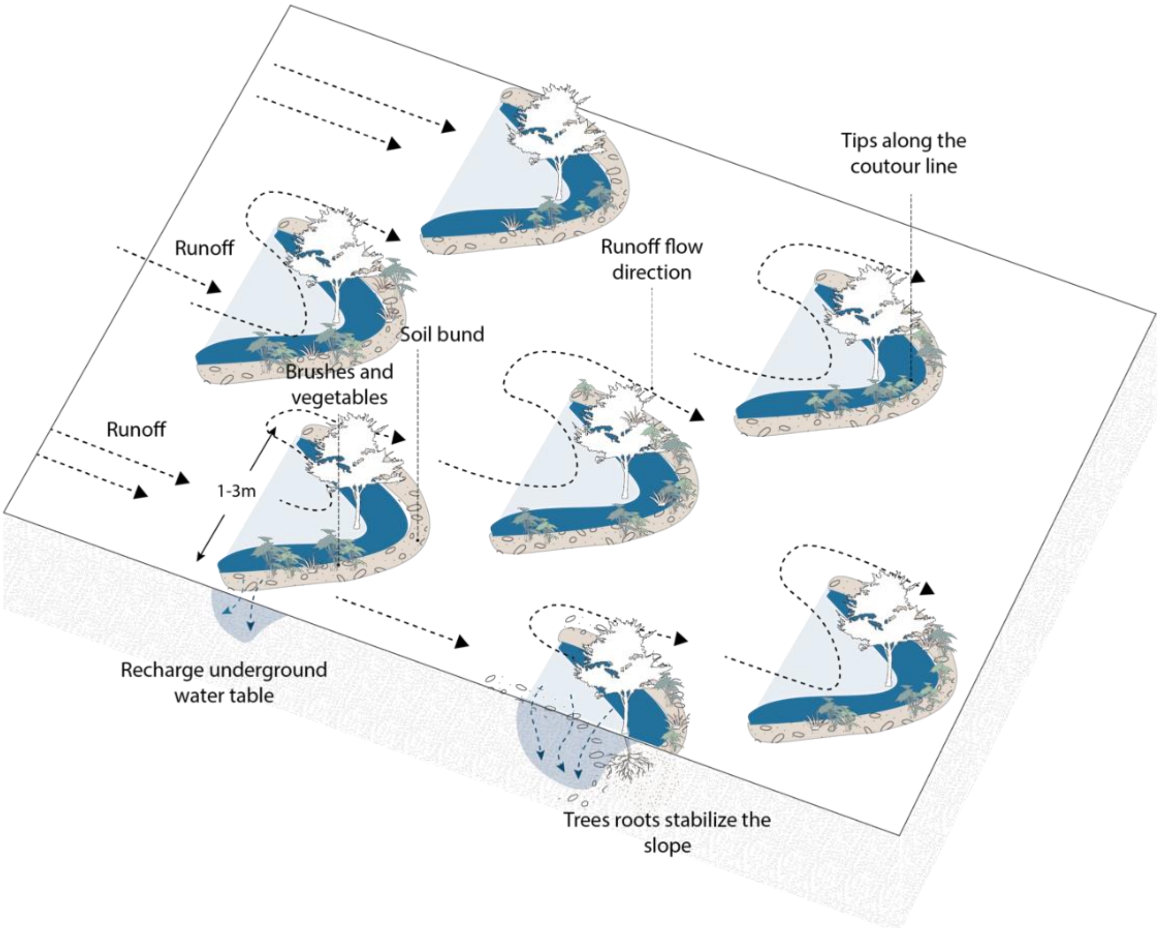

Figure 6. Illustration of half-moon structures designed for water harvesting, showing optimal placement on sloped terrain to enhance soil moisture retention, support vegetation growth, and stabilize the landscape.

Summary

General Description

Half-moon structures have been used for decades in the Sahel regions of West Africa, particularly in countries like Mali, Niger, and Burkina Faso, as a rainwater harvesting technique to sustain agriculture in arid environments.

Monitoring and Evaluation

Monitoring of half-moon structures focuses on measuring soil moisture, vegetation growth, and crop yields to assess water retention and agricultural benefits. Erosion control is tracked by observing sediment accumulation, while community feedback helps evaluate socio-economic impacts.

Primary Benefits

- Enhanced Soil Moisture Retention
- Groundwater Recharge
- Increased Crop Yields
- Soil Fertility Improvement
- Desertification Prevention
- Erosion Control

Co-Benefits

- Biodiversity Enhancement
- Carbon Sequestration
- Improved Microclimate
- Cultural Value

Costs of Implementation

The cost of implementing half-moon structures varies based on factors such as labor, materials, and site conditions. While specific cost data for half-moon structures is limited, similar soil and water conservation methods provide some context. For instance, the implementation of contour stone bunds in the Sahel region has been estimated at approximately US$200 per hectare, requiring between 100 to 150 person-days of labor per hectare.

Challenges

The construction process is labor-intensive and time-consuming, often requiring significant manual effort, which can slow large-scale deployment. In regions with rocky or compacted soils, excavation becomes more difficult, demanding additional effort or specialized tools.

Proper placement is crucial, as technical precision is needed to align half-moons correctly on slopes for effective water capture. Once constructed, they require regular maintenance to manage sediment buildup and ensure long-term functionality.

2.1.2 Terrace Farming

The Beitang system is an ancient Chinese water management practice designed to enable farming despite steep topography. It is composed of two primary elements: Bei for water transport (ditches) and Tang for water storage (dam). The dam is placed above the cropping area it is serving, while the ditches serve as both irrigation and drainage channels and therefore have a rather complicated layout. Control of water flow in and out of the cropping area is based on small connecting canals, referred to as Qu, which can be closed and opened with a pile of soil. In addition to advanced water harvesting, distribution and drainage technology, the Beitang system represents indigenous knowledge on agro-forestry synergies and nutrient recycling, offering a cropping system with little environmental impact. The Beitang system is still in operation in China, but under pressure due to urban development and competition from modern farming practices.

Figure 7. Aerial view of terraced farmland showcasing strategic land management practices that optimize water retention, reduce soil erosion, and enhance agricultural productivity in hilly landscapes.

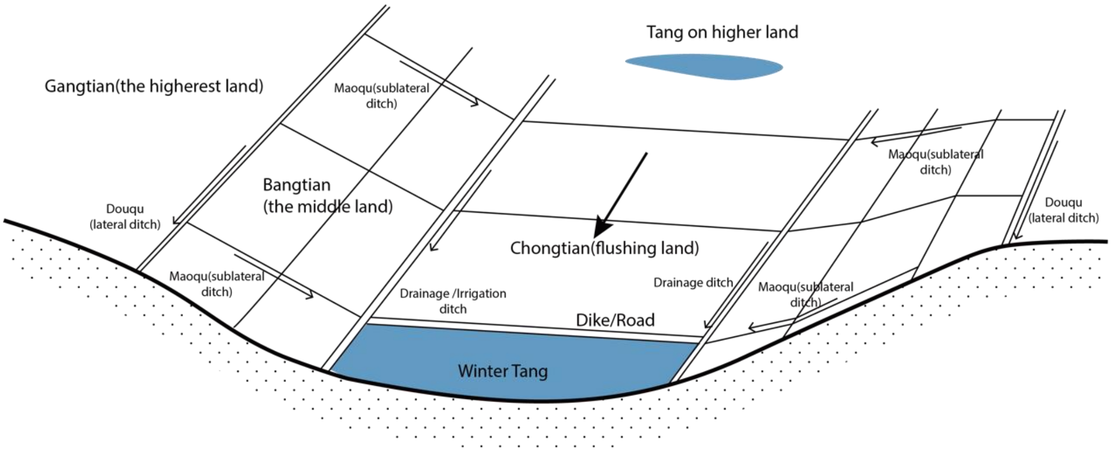

Figure 8. Diagram illustrating the structure of terrace farming with distinct land zones: higher land (Gangtian), middle land (Bangtian), and lower land (Chongtian) for efficient water management, soil retention, and improved agricultural productivity.

Summary

General Description

Terrace farming has been practiced for centuries in Asia, Mediterranean, parts of Africa and in Andes in South America. Here is a presentation from China, where the method is known as Beitang.

Monitoring and Evaluation

Monitoring and evaluation of the Beitang system can be effectively conducted through a combination of field assessments and modern tools. Water flow can be monitored by installing flow meters in the ditches (Bei) and Tang (dams) to track movement. Soil moisture levels should be measured using soil moisture sensors or manual probes to evaluate infiltration rates and prevent over-saturation. Visual inspections are essential for identifying signs of erosion or sediment buildup.

Primary Benefits

- Efficient water distribution and storage
- Enhanced soil moisture retention
- Improved crop resilience in steep and arid terrains

Co-Benefits

- Promotion of agro-forestry systems that enhance biodiversity
- Improved microclimate due to increased vegetation cover
- Enhanced groundwater recharge through controlled water infiltration

- Effective erosion control, minimizing soil loss on sloped landscapes
- Preservation of indigenous farming techniques and cultural heritage
- Strengthened community cooperation through shared irrigation practices

Costs of Implementation

The cost of implementing the Beitang system can vary depending on factors such as terrain complexity, labor availability, and material requirements. Construction typically involves expenses related to digging ditches (Bei), building dams (Tang), and installing small connecting canals (Qu) for water flow control. Since the system relies heavily on manual labor and traditional techniques, labor costs can be significant, particularly in steep or challenging landscapes. Materials are generally minimal as the system primarily utilizes locally available soil, stones, and natural barriers.

Challenges

The Beitang system's reliance on manual soil barriers for water regulation requires continuous monitoring and frequent adjustments, increasing labor demands. Sediment buildup in the ditches is a recurring issue, necessitating regular maintenance to prevent blockages. Furthermore, the system's design, which depends on natural slope contours, limits its suitability for flatter landscapes, reducing its adaptability in varied terrains.

2.1.3 Continuous Contour Trenches/Keylines

General Description of the Continuous Contour Trenches (CCTs) (India)

The Continuous Contour Trenches (CCTs) are structures for upland water harvesting, designed to enhance soil moisture and reduce surface runoff. Implemented and popularized in the last decade of the 20^{th} century, CCTs are dug along contour lines at right angles to the slope. These trenches, which can be 10 m long, with a width and depth ranging from 30 to 60 cm, are primarily constructed in low rainfall areas to conserve moisture. The soil excavated from the trench is used to form a berm on the downhill edge, which is planted with permanent vegetation such as native grasses and legumes. This stabilizes the soil, and the roots and foliage help trap sediment during heavy rainfall events. The primary purpose of CCTs is to reduce surface water flow velocity, promote infiltration, and prevent pollutants like suspended sediments, nitrogen, and phosphorous from draining into water bodies.

Figure 9. Early-stage construction of continuous contour trenches and plantations.

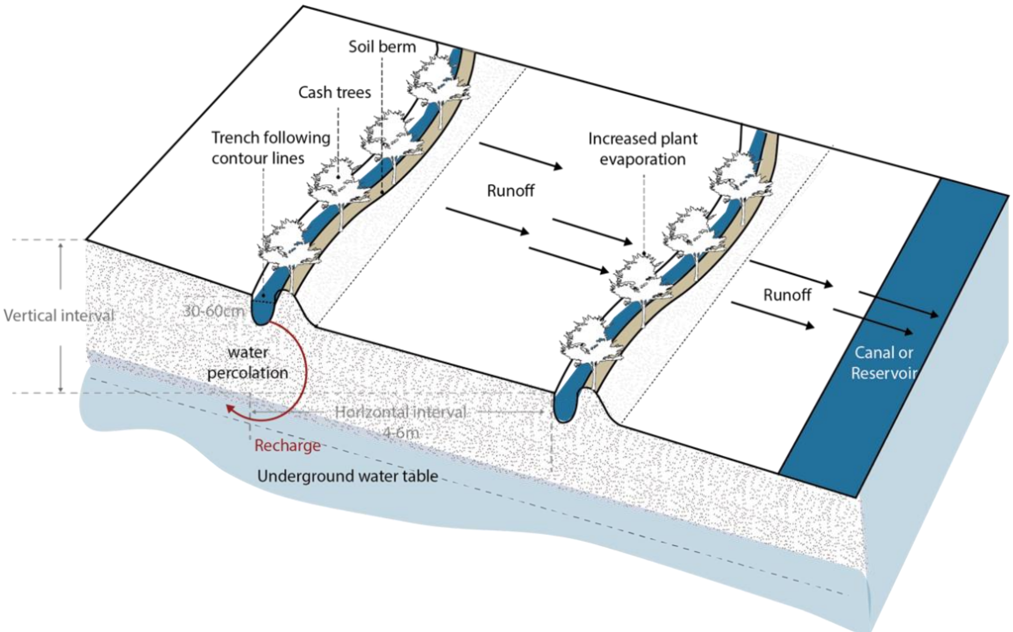

Figure 10. Illustration of continuous contour trenches designed for water percolation and groundwater recharge, showing trees planted along berms to stabilize soil and promote water infiltration, with excess runoff directed to a canal or reservoir.

Keylines in the US

Keyline design was originally developed by P.A. Yeomans in the 1950s to address dwindling water supplies and soil erosion on Australian rangeland. He worked out a system of 'amplified contour ripping' that maximizes productive use of rainfall and facilitates the uniform irrigation of land. Keyline is a comprehensive whole farm water management plan that uses natural landscape contours and cultivation techniques to harvest rainwater and build soil fertility. The central idea behind keyline design from a water perspective is to capture water at the highest possible elevation and comb it outward toward the ridges using gravitational forces, reversing the natural concentration of water in valleys. Maximizing the flow of water to the drier ridges using precise plow lines falling slightly off-contour slows the movement of water and spreads it more uniformly, infiltrating it across the broadest possible area.

Keyline design involves a landscape-scale understanding of the relationship of topography and water movement. A key point is the point on a slope cross-section where the slope transitions from convex to concave, where the convex ridge characterized by high erosion gives way to the depositional concave slope. Key points are often characterized by the beginning of a discernable channel, where subsurface flow from higher in the slope surfaces, in effect like the end of a pipe, and can be effectively captured and redistributed. A keyline is the contour line that intersects with the key point. As opposed to contour lines which often vary in distance along their length, keylines fall off contour at the same elevation along the length of the line such that keylines are always parallel to each other, making the creation of keyline cuts particularly amenable to mechanical management using a tractor and plow.

Keylines in Germany

Keyline design is a planning approach that aims to contribute to sustainable agriculture by enhancing soil fertility based on landscape morphology and water inventory. Its primary goals are to improve soil structure and soil fertility as well as to increase actual depth of fertile soil. Originated from water management techniques in the mining industry of 13th century, modern Keyline design is gaining attention as a tool for water management in sustainable agricultural production systems.

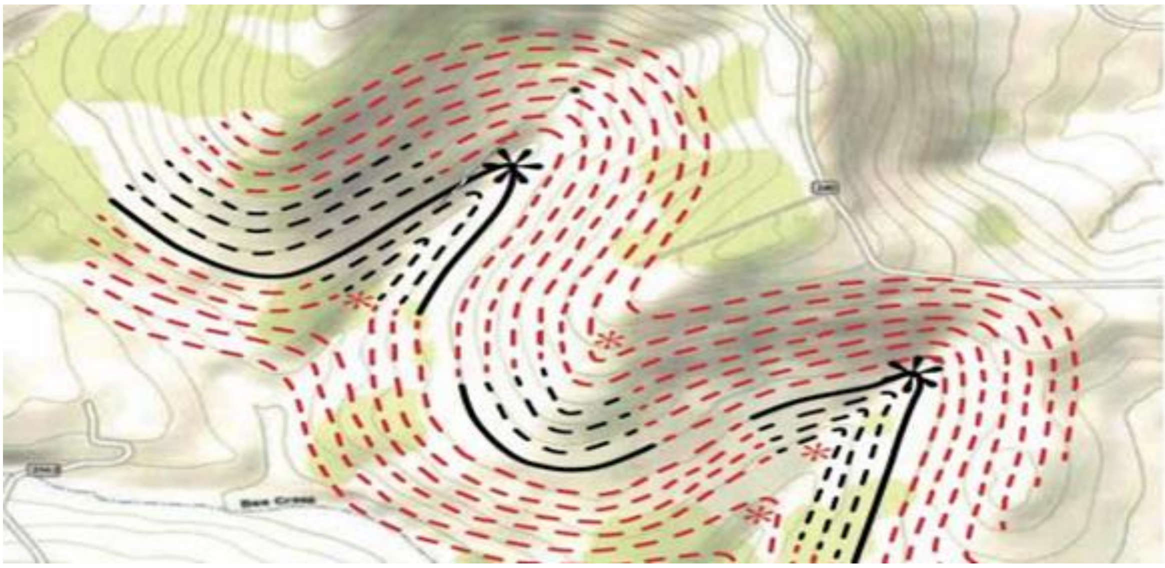

Figure 11. Combined primary valley and primary ridge cultivation pattern. The result is a cultivation pattern that considers the special geographical features and guides water from the valley to the ridges.

Summary

General Description

Continuous Contour Trenches is a structure for upland water harvesting that was implemented and popularized in the last decade of the 20th century in India. A similar approach is known from Western countries, including Germany, Australia and the US under the name Keylines.

Monitoring and Evaluation

Monitoring and evaluation of Continuous Contour Trenches focus on assessing soil moisture retention, runoff reduction, and erosion control. Soil moisture sensors and manual probes measure infiltration efficiency, while visual inspections and flow meters track runoff patterns. Sediment buildup in trenches and vegetation growth on berms are monitored to ensure stability. Water quality tests in nearby water bodies help assess pollutant reduction. Regular maintenance checks are crucial for long-term effectiveness.

Primary Benefits

- Efficient water conservation by enhancing soil moisture retention
- Significant reduction in surface runoff, protecting topsoil from erosion

Co-Benefits

- Promotion of native vegetation growth, fostering local biodiversity
- Contribution to climate resilience through improved ecosystem stability

- Improved groundwater recharge, supporting long-term water availability
- Enhanced soil stability on slopes, reducing risks of land degradation
- Increased agricultural productivity in drought-prone areas
- Mitigation of downstream flooding by slowing water flow across landscapes
- Support for sustainable farming practices with reduced reliance on irrigation
- Improved soil structure, enhancing fertility and long-term productivity

Costs of Implementation

Implementing Continuous Contour Trenches costs approximately $645 per hectare, mainly for labor. Maintenance involves periodic inspections and sediment removal. Keyline design costs about $700 per hectare, with additional expenses for specialized equipment like the Yeomans plow. Costs vary based on terrain, labor, and project scale.

Challenges

Accurate contour mapping is important to ensure proper water flow control, and mistakes can reduce their effectiveness. The construction process is labor-heavy, requiring time and effort, especially in rough or uneven terrain. Trenches are prone to sediment buildup, which requires regular cleaning to keep them functional.

2.1.4 Ridge and furrow – Medieval system

Ridge and furrow systems are an ancient agricultural practice that emerged in Europe during the Middle Ages, particularly associated with the open field system (Langewitz et al. 2020). It is characterized by a series of parallel ridges (elevated areas) and furrows (depressions) that resulted from repeated plowing of the same strips of land over time. Most medieval ridge and furrow had a standard width of ca 10 m, and most strips had a standard length of ca 200 m, standing up to 61 centimeters in height. This method was commonly used on heavy, non-permeable soils to manage water distribution and improve drainage. The practice dates back to the post-Roman period and was widely used until the 17th and 18th centuries. Ridge and furrow landscapes are still visible today in parts of Great Britain, Ireland, and other regions in Europe, as well as in places as far away as Australia. The system was not only practical for agricultural production but also served as a means of land ownership demarcation and communal management that also established of clear field borders, thus minimizing loss of topsoil to neighboring fields (Alcántara 2017).

Figure 12. An aerial view of preserved ridge and furrow patterns, showcasing the distinctive medieval ploughing technique still visible in modern grasslands, commonly found in parts of the UK.

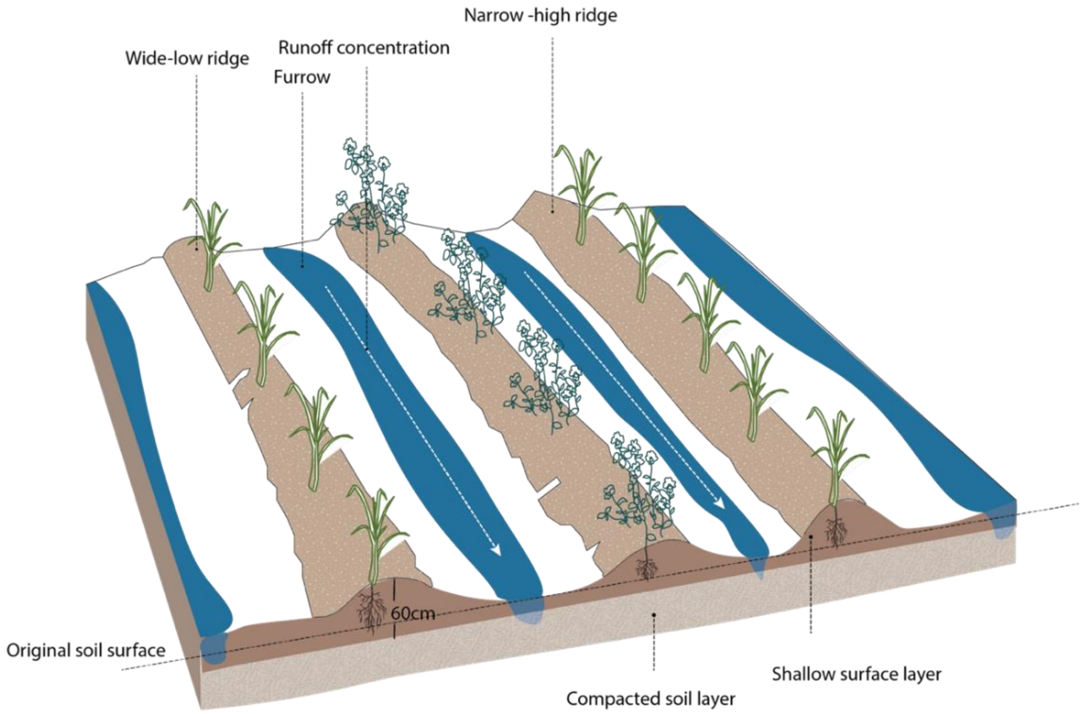

Figure 13. Illustration of a ridge and furrow system designed for water management, showing alternating ridges for planting crops and furrows for directing water flow, improving soil moisture retention and reducing runoff.

Summary

General Description

Ridge and furrow systems have been used across Europe since the Middle Ages, particularly in countries like Great Britain and Ireland, to improve cropping conditions, especially on heavy, non-permeable soils.

Monitoring and Evaluation

Monitoring and evaluating ridge and furrow systems focus on key aspects such as soil moisture, water infiltration, and crop performance. Studies (Gan et al., 2013; Zhang et al., 2020) have demonstrated that ridge-furrow configurations significantly improve soil water availability, enhance crop water use efficiency, and increase grain yields in dryland agroecosystems.

Primary Benefits

- Improved soil moisture retention through enhanced water infiltration
- Increased crop yields by optimizing water distribution
- Effective runoff control, reducing soil erosion on sloped terrains
- Enhanced root development due to better soil aeration in ridge zones
- Efficient drainage in areas prone to waterlogging

Co-Benefits

- Improved drought resilience by maximizing water use efficiency
- Enhanced soil fertility through controlled nutrient distribution
- Reduced reliance on irrigation in water-scarce regions
- Creation of microhabitats that support biodiversity
- Contribution to climate resilience through improved soil structure and stability

Costs of Implementation

Specific cost data for implementing ridge and furrow systems is limited in the available literature. Costs can vary significantly depending on labor, equipment, and site conditions. While some studies (Li et al., 2007) explore enhancements like plastic film mulching to improve water retention and crop yields, detailed cost analyses are generally not provided. Consequently, estimating implementation costs requires a site-

Challenges

Setting up ridge and furrow systems comes with several challenges. Getting the contours right is important for proper water flow, and mistakes can reduce their effectiveness. The process can be labor-heavy, especially without mechanized tools. In areas with heavy rainfall, erosion can damage ridges if they aren't properly maintained.

specific assessment based on local factors.

2.1.5 Artificial Recharge Using Infiltration Basins, Medium and Large Diameter Wells, and River Bed Infiltration Basins

Artificial recharge techniques are designed to enhance groundwater replenishment by facilitating controlled infiltration of surface water into aquifers. The Gabardine Project in the Algarve (Portugal) explored several methods to improve groundwater quality and availability in semi-arid regions. These included infiltration basins, large diameter wells, medium diameter wells, and river bed infiltration basins, each tailored to specific conditions. Infiltration basins were constructed in sandy soils to assess infiltration rates and pollutant filtration. Maintaining a constant water column helped determine infiltration capacities, confirming their effectiveness in reducing nitrogen and phosphorus contamination. Large diameter wells, such as the Algarve's traditional "noras", were tested to assess their recharge potential. Results showed infiltration rates reaching 24.5 m/day, influenced by the water column height. Medium diameter wells offered a smaller-scale alternative, with infiltration rates recorded at 11.5 m/day in the Gabardine tests. River bed infiltration basins, filled with gravel, were tested in the Rio Seco riverbed. These basins successfully improved groundwater recharge rates while filtering sediments and pollutants.

The Gabardine Project demonstrated that combining these recharge methods can effectively enhance groundwater storage and improve water quality, offering strategies for regions facing water scarcity.

Figure 14. Artificial recharge infrastructure in the Rio Seco riverbed, constructed as part of the Gabardine Project to enhance groundwater infiltration using gravel-filled basins and monitoring wells for assessing recharge rates and water quality improvements.

Summary

General Description

Artificial recharge system in a riverbed designed to enhance groundwater infiltration, featuring gravel-filled basins and monitoring wells for tracking water flow and quality.

Monitoring and Evaluation

Hydrological monitoring involved multiparametric water sensors, flow meters, and tracer tests at Rio Seco. Infiltration rates were measured by maintaining a 90 cm water column in the basin for three days, with groundwater levels monitored at LNEC4 well. Geophysical methods like Ground Penetration Radar, Electrical Resistivity, and Electromagnetic techniques (EM31 and EM34) were used alongside mathematical models such as FEFLOW and Visual MODFLOW. The BALSEQ model estimated recharge rates, and an

Infiltration Feasibility Index (IFI) identified optimal recharge areas.

Primary Benefits	Co-Benefits
➢ Enhanced groundwater recharge improving water availability ➢ Improved infiltration rates, reducing surface runoff ➢ Increased aquifer storage capacity for drought resilience ➢ Stabilized water levels in wells and aquifers ➢ Utilization of existing infrastructure like wells, minimizing additional costs	➢ Improved water quality through natural filtration processes ➢ Reduced soil erosion by slowing surface water flow ➢ Reduced risk of saltwater intrusion in coastal areas ➢ Enhanced ecosystem health by supporting vegetation growth ➢ Increased resilience to climate change impacts

Costs of Implementation	Challenges
The total project funding for the Gabardine Project was €3,286,579, financed under the Sustainable Development, Global Change, and Ecosystems thematic priority 6 within the Focusing and Integrating Community Research Programme (2002-2006). This funding supported research, infrastructure development, and implementation of artificial recharge methods to improve groundwater quality and availability in the Algarve region.	Clogging of infiltration basins and wells due to sediment buildup can reduce infiltration rates and require frequent maintenance. Ensuring water quality is another concern, as introducing untreated or contaminated water risks polluting the aquifer. Variability in soil permeability may affect infiltration efficiency, making site selection and monitoring crucial. Additionally, high initial costs for construction, equipment, and monitoring infrastructure can pose financial challenges.

2.1.6 Wetland Restoration and Floodplain Reconnection

Wetland restoration involves re-establishing natural wetland conditions to improve water retention, promote vegetation growth, and support wildlife. Floodplain reconnection restores the natural link between rivers and their surrounding landscapes, allowing excess water to spread across the land during periods of heavy rainfall. This process reduces flood risks, enhances groundwater recharge, and improves soil moisture.

The ecological restoration project in the Carasuhat agricultural enclosure successfully integrated wetland restoration and floodplain reconnection to address habitat degradation and improve water management in the Danube Delta. By reintegrating previously embanked agricultural lands into the natural floodplain system, the project improved water retention and soil moisture, helping to restore natural water flow while reducing flood risks and enhancing groundwater recharge. Restored wetlands created essential habitats for aquatic species, promoted biodiversity, and improved water quality through natural sediment deposition and nutrient cycling. Additionally, the introduction of native plant species stabilized soil, reduced erosion, and provided food and shelter for wildlife. The project also enhanced habitat connectivity by creating ecological corridors that allowed species to move freely and ensured genetic diversity.

Figure 15. Aerial view of the Carasuhat Agricultural Enclosure showcasing restored wetlands and reconnected floodplains in the Danube Delta.

Summary

General Description	Monitoring and Evaluation
The Carasuhat Agricultural Enclosure project in the Danube Delta successfully combined wetland restoration and floodplain reconnection to restore natural hydrological processes and enhance biodiversity. By reintegrating embanked agricultural lands into the floodplain, the project improved water retention, soil	Tracking water levels, soil moisture, and flow rates helps assess improvements in water retention and groundwater recharge. Observing vegetation growth and habitat conditions ensures plant establishment and soil stabilization, while wildlife surveys measure biodiversity recovery. Water quality testing confirms pollutant reduction,

moisture, and groundwater recharge while creating vital habitats for wildlife. Active involvement of local stakeholders, including the Mahmudia Local Council and local communities, ensured the project aligned with sustainable land use, balancing ecological restoration with community benefits.

and engaging local stakeholders supports long-term stewardship and adaptive management. Assessing socio-economic impacts further highlights the project's broader environmental and community benefits.

Primary Benefits

- Improved water retention and groundwater recharge enhancing drought resilience.
- Reduced flood risks through improved water flow management.
- Reduced travel distance by 50 km to reach the heart of the Danube Delta.
- Creation of nearby space for tourist excursions and eco-tourism activities.
- Development of new tourism businesses, supporting local economic growth.

Co-Benefits

- Following restoration efforts, 70 bird species were identified in the Carasuhat area.
- The restored area now serves as a nesting, feeding, and resting habitat for these bird species, contributing to enhanced biodiversity.
- Strengthened community engagement through stakeholder involvement.

Costs of Implementation

The Carasuhat Agricultural Enclosure restoration project was implemented at a total cost of €7.5 million. This investment supported wetland restoration, floodplain reconnection, biodiversity enhancement, and the integration of sustainable land-use practices to benefit both the environment and local communitie

Challenges

The project faced technical challenges during construction, which were successfully addressed through continuous communication with the contractor and other involved technical specialists. This proactive approach ensured that issues were promptly resolved, maintaining project progress and effectiveness.

2.1.7 Soil and Water Bioengineering Techniques (SWBE)

Soil and Water Bioengineering Techniques involve the use of plants for technical purposes, providing valuable ecosystem services (ES). In the context of SH, SWBE can be applied to design and implement interventions using living plants and locally sourced natural materials. These techniques are effective for managing both floods and droughts, improving water quality, and enhancing habitat creation and structural diversity. By promoting vegetation growth, SWBE strengthens soil stability and supports long-term ecological balance.

One key SWBE method for erosion control is the protection of gully and rill erosion using vegetated crib walls that function as consolidated check dams. These structures, built with dead materials such as logs and stones, effectively slow down erosion processes, creating conditions that encourage vegetation growth. Gullies and rills are then planted with cuttings, trees, or revegetated with grass and herbs. As vegetation develops, plants gradually take over the stabilization role, improving soil stability and reducing water flow velocity.

Revegetated gullies and rills increase surface roughness, further slowing runoff and enhancing water retention. This improved vegetation cover positively influences the local water balance, contributing to flood prevention and drought resilience.

By combining natural materials and vegetation, SWBE offers a sustainable, cost-effective solution for improving water management, controlling erosion, and restoring degraded landscapes.

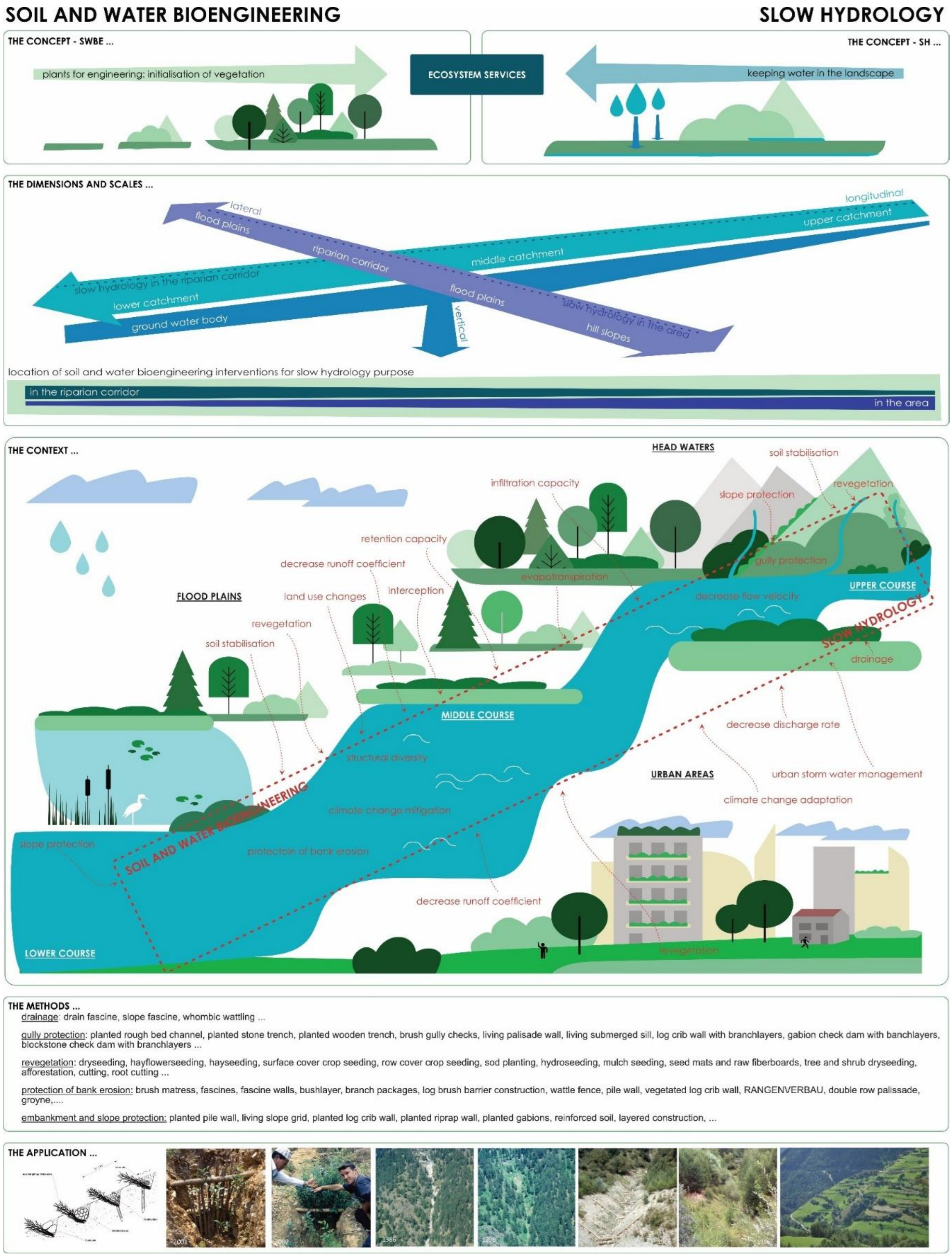

Figure 16. Illustration of SWBE concepts applied in the context of SH. The figure highlights the use of vegetation-based techniques to provide ecosystem services, stabilize soil, reduce runoff, and manage water retention across different landscape scales.

Figure 17. Example of a bioengineering measure for gully and rill erosion control, showcasing the transformation from an eroded slope stabilized with vegetated crib walls and natural materials to a fully revegetated and stabilized landscape.

Figure 18. Example of a bioengineering measure for river engineering, demonstrating the transformation from a heavily channelized, concrete-lined river to a restored, vegetated watercourse with improved ecological function.

Summary

General Description

SWBE uses plants and natural materials to stabilize soil, manage water flow, and provide ecosystem services. In the context of SH, SWBE helps regulate floods and droughts, improve water quality, and enhance biodiversity. Techniques such as vegetated crib walls combine logs, stones, and plants to control erosion and create conditions for vegetation growth. As plants establish, they further stabilize the soil, slow runoff, and improve water retention. SWBE offers a sustainable, cost-effective approach to landscape restoration and water management.

Monitoring and Evaluation

Monitoring of SWBE focuses on tracking plant growth, ecosystem services, and hydrological impacts. Vegetation monitoring assesses plant development, root strength, and canopy expansion, which improve infiltration, evapotranspiration, and resilience to floods and droughts. Ecosystem services monitoring evaluates water quality, habitat diversity, and shading effects. Hydrological monitoring tracks runoff reduction and infiltration rates to measure improved water balance.

Primary Benefits

- Erosion Protection
- Water Retention
- Enhanced Evapotranspiration

Co-Benefits

- Social Benefits
- Economic Benefits
- Climate Resilience

Costs of Implementation

SWBE is generally cost-effective compared to traditional methods. In Brazil, such interventions can cost approximately 50% less than conventional approaches. Similarly, bioengineering treatments are often less expensive than traditional streambank erosion control methods like riprap revetment and bulkheads. Costs can vary based on factors such as material availability, labor rates, and site-specific conditions. Despite potential variability, SWBE offers a sustainable and economically viable alternative for erosion control and landscape restoration.

Challenges

Establishing vegetation can be time-consuming, as plant growth depends on seasonal conditions and may require ongoing care to ensure successful establishment. Climatic factors, such as drought or extreme rainfall, can hinder vegetation growth and reduce system effectiveness. Soil conditions may also limit SWBE success, especially in highly compacted or nutrient-poor soils, requiring additional soil preparation.

2.1.8 Blue-Green Urban Infrastructure

The St. Kjelds Quarter in Copenhagen exemplifies Blue-Green Urban Infrastructure, an innovative approach that combines natural and engineered solutions to improve climate resilience. This method integrates green spaces with sustainable water management systems, enhancing flood control, biodiversity, and public spaces while preparing urban areas for climate challenges. The project introduces bicycle paths that act as storm water channels, water towers, green roofs, urban gardens, green houses and canals that carry water from the neighbourhood to the harbour. By making use of future heavy rain, St. Kjelds Quarter holistically integrates solutions, art and aesthetics which combined give rise to Copenhagen's greenest neighbourhood.

Figure 19. Blue-Green Urban Infrastructure in Copenhagen featuring green spaces, rainwater channels, and sustainable design elements that effectively manage stormwater while enhancing public spaces and urban aesthetics.

Summary

General Description	Monitoring and Evaluation
Mitigating the effects of cloudburst events in urban areas can partly be done by establishing green areas, in combination with drainage channels to flush excess	Monitoring and evaluation of Blue-Green Urban Infrastructure focus on tracking water flow, infiltration rates, and runoff reduction using sensors and flow meters.

water is in general a good method and has a number of co-benefits, including a more attractive green environment which benefits biodiversity, public health, also by decreasing traffic density, and increased property values. This is replicable to other urban areas. In dense urban areas, especially in historic centers, establishing green areas can be costly and associated with hinder during the building phase. Including stakeholders from the beginning is key.

Regular assessments of vegetation health and biodiversity ensure green areas remain functional and ecologically beneficial. Routine maintenance checks help prevent clogged channels or damaged vegetation.

Primary Benefits

- Flood Mitigation
- Improved Drainage
- Climate Resilience
- Replicability

Co-Benefits

- Enhanced Biodiversity
- Improved Public Health
- Aesthetic Improvements
- Reduced Traffic Density
- Increased Property Values

Costs of Implementation

DKK 48.450.000 (app. 6.5 M€)

Challenges

Local residents, businesses and traffic experienced hinder during the construction phase which was anticipated during the hearing phase in meetings and workshops so residents and businesses felt included in the process which helped facing the challenges.

3. Conclusions

The NBS Catalogue for Slow Hydrology presented in this document serves as a resource detailing a diverse range of NBS designed to improve water management, ecosystem restoration, and climate resilience. The catalogue consolidates practical solutions, implementation guidelines, and performance insights to support stakeholders, planners, and policymakers in addressing water-related environmental challenges.

Key Takeaways from the Catalogue:

1. Versatility and Adaptability

- The catalogue features NBS approaches that can be adapted to various environmental conditions, including arid regions, temperate zones, and urban settings.
- Solutions such as **Half-Moons**, **Terrace Farming**, and **Ridge and Furrow Systems** showcase how traditional techniques can be modernized to meet contemporary challenges.
- Innovative urban-focused measures like **Blue-Green Infrastructure** demonstrate the flexibility of NBS in densely populated environments.

2. Multi-Functionality and Co-Benefits

- Many NBS deliver multiple benefits beyond their primary objectives. For example:
  - **Wetland Restoration** provides flood control, biodiversity enhancement, and improved water quality.
  - **Soil and Water Bioengineering** offers erosion control while enhancing vegetation growth and carbon sequestration.
  - **Blue-Green Urban Infrastructure** combines climate resilience, public health benefits, and improved aesthetics in urban environments.

3. Cost-Effectiveness and Sustainability

- Several NBS measures offer cost-effective alternatives to traditional infrastructure by utilizing natural processes for water management and soil stability.

- Techniques such as **Continuous Contour Trenches** and **Artificial Recharge Systems** provide low-cost yet highly effective water retention strategies in rural and semi-arid landscapes.

4. Environmental and Social Benefits

- The catalogue emphasizes solutions that integrate environmental improvement with socio-economic gains.
- Measures like **Floodplain Reconnection** not only enhance ecological health but also promote eco-tourism and recreation opportunities.
- Community engagement is a common theme across multiple NBS approaches, ensuring solutions are socially inclusive and sustainable.

Implementation Considerations

The NBS catalogue emphasizes several critical factors for successful deployment:

- **Site-Specific Design:** Each solution requires careful customization to local hydrological, geological, and climatic conditions.
- **Stakeholder Involvement:** Engaging local communities, authorities, and environmental groups during planning and execution is essential for securing long-term success.
- **Monitoring and Maintenance:** Continuous monitoring frameworks are vital to track performance metrics such as soil moisture retention, water infiltration rates, and ecosystem recovery. Regular maintenance ensures these solutions remain effective over time.

Challenges and Opportunities

While NBS solutions offer effective tools for environmental management, certain challenges must be addressed to maximize their impact:

- **Knowledge Gaps:** Wider dissemination of technical knowledge and capacity-building is needed to support local actors in implementing NBS measures effectively.
- **Resource Availability:** Labor-intensive methods like **Terrace Farming** or **Half-Moons** may require additional resources for scaling and maintenance.

- **Policy Integration:** Stronger alignment between NBS implementation and regional/national policy frameworks can promote long-term adoption.

References

1. Acreman, M., et al. (2021). Evidence for the effectiveness of nature-based solutions to water issues in Africa. 10.1088/1748-9326/ac0210
2. Alcántara, V., Don, A., Well, R., & Nieder, R. (2017). Legacy of medieval ridge and furrow cultivation on soil organic carbon distribution and stocks in forests. CATENA, 154, 85-94. https://doi.org/10.1016/j.catena.2017.02.013
3. Albert, C., et al. (2019). Addressing societal challenges through nature-based solutions: How can planning support governance? Environmental Science & Policy, 98, 20–29. https://doi.org/10.1016/j.envsci.2019.04.014
4. Barbier, E. B., et al. (2011). The value of estuarine and coastal ecosystem services. Ecological Monographs, 81(2), 169–193. https://doi.org/10.1890/10-1510.1
5. Bowler, D. E., et al. (2010). Urban greening to cool towns and cities: A systematic review. Landscape and Urban Planning, 97(3), 147–155. https://doi.org/10.1016/j.landurbplan.2010.05.006
6. Bratman, G. N., et al. (2019). Nature and mental health: An ecosystem service perspective. Science Advances, 5(7), eaax0903. https://doi.org/10.1126/sciadv.aax0903
7. Cohen-Shacham, E., et al. (2016). Nature-based Solutions to address global societal challenges. IUCN. https://portals.iucn.org/library/node/46191
8. Colls, A., et al. (2009). Ecosystem-based adaptation: A natural response to climate change. IUCN. https://portals.iucn.org/library/node/9691
9. de Schipper, M. A., et al. (2016). Initial spreading of a feeder berm to enhance the sand nourishments at Delfland coast. Coastal Engineering, 111, 23–38. https://doi.org/10.1016/j.coastaleng.2015.10.008
10. Eggermont, H., et al. (2015). Nature-based Solutions: New influence for environmental management and research in Europe. GAIA, 24(4), 243–248. https://doi.org/10.14512/gaia.24.4.9
11. European Commission. (2020). EU Biodiversity Strategy for 2030: Bringing nature back into our lives. https://ec.europa.eu/environment/strategy/biodiversity-strategy-2030_en
12. European Commission. (2021). Forging a climate-resilient Europe: The new EU Strategy on Adaptation to Climate Change. https://ec.europa.eu/clima/policies/adaptation/what_en
13. European Environment Agency (EEA). (2021). Climate change adaptation in Europe. https://www.eea.europa.eu/publications/adaptation-in-europe
14. FAO. (2022). The State of the World's Forests 2022. Food and Agriculture Organization. https://doi.org/10.4060/cb9360en
15. Faivre, N., et al. (2017). Nature-based Solutions in the EU: Innovating with nature to address social, economic, and environmental challenges. Environmental Research, 159, 509–518. https://doi.org/10.1016/j.envres.2017.08.032
16. Fernández, S., et al. (2016). Traditional irrigation systems in Spain: A review of the "acequias" in Andalusia. Water History, 8(3), 259–278. https://doi.org/10.1007/s12685-016-0169-7
17. Gan, Y., Siddique, K. H. M., Turner, N. C., Li, X.-G., Niu, J.-Y., Yang, C., Liu, L., & Chai, Q. (2013). Ridge-furrow mulching systems—An innovative technique for boosting crop productivity in semiarid rain-fed environments. In D. L. Sparks (Ed.),

Advances in Agronomy (Vol. 121, pp. 429-476). Academic Press. https://doi.org/10.1016/B978-0-12-405942-9.00007-4
18. Gómez-Baggethun, E., et al. (2019). Traditional agricultural practices in Spain: Linking cultural heritage and sustainability. Sustainability, 11(12), 3352. https://doi.org/10.3390/su11123352
19. Griscom, B. W., et al. (2017). Natural climate solutions. Proceedings of the National Academy of Sciences, 114(44), 11645–11650. https://doi.org/10.1073/pnas.1710465114
20. IPBES. (2019). Global assessment report on biodiversity and ecosystem services. https://ipbes.net/global-assessment
21. IUCN. (2016). Nature-based solutions to address global societal challenges. IUCN. https://doi.org/10.2305/IUCN.CH.2016.13.en
22. Kabisch, N., et al. (2017). Nature-based Solutions to climate change mitigation and adaptation in urban areas. AMBIO, 46(1), 15–26. https://doi.org/10.1007/s13280-016-0820-7
23. Lahmar, R., Bationo, B.A., Lamso, N.D., Guéro, Y., & Tittonell, P. (2012). Tailoring conservation agriculture technologies to West Africa semi-arid zones: Building on traditional local practices for soil restoration. Field Crops Research, 132, 158-167. https://doi.org/10.1016/j.fcr.2011.09.013
24. Langewitz, T., Fülling, A., Klamm, M., & Wiedner, K. (2020). Historical classification of ridge and furrow cultivation at selected locations in Northern and central Germany using a multi-dating approach and historical sources. Journal of Archaeological Science, 123, 105248. https://doi.org/10.1016/j.jas.2020.105248
25. Leifeld, J., & Menichetti, L. (2018). The underappreciated potential of peatlands in global climate change mitigation strategies. Nature Communications, 9, 1071. https://doi.org/10.1038/s41467-018-03406-6
26. Li, X., Su, D., & Yuan, Q. (2007). Ridge-furrow planting of alfalfa (Medicago sativa L.) for improved rainwater harvest in rainfed semiarid areas in Northwest China. Soil and Tillage Research, 93(1), 117-125. https://doi.org/10.1016/j.still.2006.03.022
27. Masse, D., Venn, J., & Zougmoré, R. (2011). Developing climate-smart agriculture to face climate variability in West Africa: Challenges and lessons learnt. Journal of Cleaner Production, 83, 124-132. https://doi.org/10.1016/j.jclepro.2011.03.014
28. Nesshöver, C., et al. (2017). The science, policy, and practice of Nature-based Solutions. Science of the Total Environment, 579, 1215–1227. https://doi.org/10.1016/j.scitotenv.2016.11.106
29. Opperman, J. J., et al. (2009). Sustainable floodplains through large-scale reconnection to rivers. Science, 326(5959), 1487–1488. https://doi.org/10.1126/science.1178256
30. Raymond, C. M., et al. (2017). A framework for assessing and implementing the co-benefits of Nature-based Solutions in urban areas. Environmental Science & Policy, 77, 15–24. https://doi.org/10.1016/j.envsci.2017.07.008
31. Sawadogo, H. (2011). Using soil and water conservation techniques to rehabilitate degraded lands in northwestern Burkina Faso. International Journal of Agricultural Sustainability, 9(1), 120-128. https://doi.org/10.3763/ijas.2010.0552
32. Slingerland, M.A., & Stork, V. (2000). Determinants of the Practice of Zaï and Mulching in North Burkina Faso. Journal of Sustainable Agriculture, 16, 53-76. https://doi.org/10.1300/J064v16n02_06