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Innovative Catchment and In-Lake Restoration Solutions:
Operational Pilots

Deliverable D1.2

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Summary

The FutureLakes project aims to demonstrate and evaluate innovative solutions for lake restoration. Through ten operational-scale innovation pilots across Europe, this report evaluates nature-based solutions (NbS), circular blue economy solution (CBS) and biodiversity focused solutions (BfS), that are designed to address key pressures affecting European lakes, including eutrophication, biodiversity loss, habitat degradation and climate related challenges.

The innovation pilots included in-lake solutions (algal harvesting, phosphorous recovery through sediment removal and island creation), catchment focused solutions (flexible water levels management, multi-structured wetland and raingardens) and combined approaches, which integrated multiple restoration measures addressing both internal and external nutrient sources in lakes.

The pilots demonstrated that restoration innovations can create different types of value. Phosphorus recovery through sediment removal showed strong potential for nutrient recycling and circular economy applications, by recovering a scarce resource while reducing the internal nutrient loading. Algal harvesting demonstrated potential for biomass valorisation and may provide particular value in in regions where cyanobacterial blooms threaten drinking-water supplies. The value of these innovations therefore extends beyond improvement of ecological status.

Several innovations generated substantial biodiversity benefits. Marker Wadden island creation created valuable habitats for birds, fish and aquatic vegetation. Constructed wetlands and raingardens also enhanced biodiversity while providing additional ecosystem services.

The pilots also highlighted that restoration measures differ in the timing and magnitude of their ecological effects. Individual measures such as phosphorus recovery, algal harvesting, and biodiversity-focused habitat creation can provide important benefits, but do not necessarily result in rapid improvements in overall lake ecological status. In contrast, the strongest ecological outcomes were observed in projects that combined multiple restoration measures. Lakes Kralingse Plas, Groote Melanen, and Bleiswijkse Zoom all showed substantial reductions in phosphorus concentrations, improved water clarity, recovery of aquatic vegetation and reduced cyanobacterial blooms. These projects demonstrated that long-term restoration of eutrophic lakes requires integrated management of both external nutrient inputs and internal nutrient loading.

The catchment-focused innovations further highlighted the value of preventative approaches. The multi-structure constructed wetland successfully reduced nutrient and sediment loads while increasing flood resilience. Raingardens enhanced urban biodiversity and pollinator abundance but required implementation at a much larger scale to achieve measurable catchment-level water-quality benefits. The flexible water-level management pilot demonstrated how adaptive hydrological control can improve climate resilience and freshwater availability under changing climatic conditions.

Across all pilots, several common lessons emerged. First, restoration success depends on a thorough understanding of lake-catchment processes and local pressures. Second, ecological recovery often occurs over timeframes longer than typical project durations, highlighting the importance of continued monitoring. Third, while innovative technologies can complement conventional restoration methods, integrated approaches addressing multiple pressures simultaneously provide the greatest likelihood of achieving long-term ecological recovery.

Overall, the FutureLakes pilots demonstrate that innovative restoration solutions can play an important role in addressing persistent challenges facing European lakes. The knowledge generated through these operational-scale demonstrations provides a strong foundation for future upscaling, policy implementation, and the development of more effective and resilient lake restoration strategies across Europe.

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Abbreviations

APC – Allophycocyanin

C – Carbon

Chl – Chlorophyll

COD_{Mn} – Chemical oxygen demand

CW – Constructed wetland

DW – Dry weight

EGD – European Green Deal

EU – European Union

HAB – Harmful Algal Bloom

LMB – Lanthanum modified bentonite

LWD – Large woody debris

MC – Microcystin

N – Nitrogen

NH_4 – Ammonium nitrogen

NIVA – Norwegian Institute for Water Research

NO_{2+3} – Sum of nitrate and nitrite nitrogen

NRC – Nature Research Centre

P – Phosphorus

PAC –Poly-Aluminium Chloride

PC – C-Phycocyanin

PO_4 – Phosphate phosphorus

SS – Suspended sediment

SuDS – Sustainable drainage systems

Syke – Finnish Environment Institute

TN – Total nitrogen

TOC – Total organic carbon

TP – Total phosphorus

TPC – Total phenolic content

TRL – Technology Readiness Level

UKCEH – UK Centre for Ecology & Hydrology

UWM – University of Warmia and Mazury in Olsztyn

WFD – Water Framework Directive

WUR – Wageningen University

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1 Introduction

Lake ecosystems are highly valued for their ecological, economic and societal functions (WWAQ, 2024). They provide a wide range of ecosystem services including drinking water, nutrient retention and cycling, biodiversity support, recreational opportunities, fisheries, climate regulation and in some cases energy production. Across Europe, lakes and their services are under increasing pressure due to multiple stressors, particularly nutrient enrichment, hydro-morphological alternations, land-use changes and climate change impacts.

Despite decades of restoration efforts in numerous lakes, many lake ecosystems remain in a degraded ecological state or show limited recovery (EEA 2024). Eutrophication and the persistence of legacy nutrient in lake sediments continue to constrain the effectiveness of conventional management and restorations measures. This highlights the need for more integrated, innovative and scalable restoration approaches that address both external and internal nutrient sources, while also enhancing ecological resilience and ecosystem functioning.

European policy frameworks, including the Water Framework Directive (WFD) and supporting directives such as the Urban Wastewater Treatment Directive (UWWTD), Nitrate Directive, Bathing and Drinking Water Directives, set clear objectives for achieving good ecological status. In addition, the Habitats Directive (HD) supports the protection of aquatic biodiversity. However, implementation gaps remain, particularly in relation to nutrient reductions, restoration of ecological integrity and long-term recovery in degraded lake ecosystems. This underlines the importance of demonstrating and validating new and innovative restoration approaches under real-world conditions to support their wider uptake in lake restoration practice.

In this context, innovative solutions based on Nature-based Solutions (NbS), Circular Blue economy Solutions (CBS) and Biodiversity focused Solutions (BfS) are increasingly being modified and developed to complement traditional restoration measures (Härkönen et al. 2025, Härkönen et al. 2026a). These innovative approaches aim to improve water quality, enhance ecosystem function and recover resources. This deliverable presents the implementation and evaluation of innovation pilots carried out under Task 1.2 of the FutureLakes project.

1.1 Objectives

FutureLakes is a Horizon Europe Framework project funded under the call of *European natural lakes* (HORIZON-MISS-2023-OCEAN-01-04). The project contributes to the EU Mission “Restore our Ocean and Waters” by accelerating the implementation of innovative lake restoration solutions. A key Specific Objective (SO1) of the project is to pilot and demonstrate innovative NbS, CBS and BfS solutions in an operational environment.

Within Task 1.2, 10 innovation sites are used to pilot and evaluate these innovative solutions in a real lake and catchment context. The pilot sites address key pressures affecting lake ecosystems, including nutrient inputs from catchments, internal nutrient loading from sediments and habitat degradation, while also supporting nutrient recovery. Many of the pilots build on ongoing restoration activities supported by external funding, enabling assessment under realistic management conditions.

The performance of the piloted solutions is evaluated using indicators that focus on water quality, ecological status and biodiversity improvements, as well as indicators of circular economy, green growth and the energy-efficiency and cost-effectiveness of measures. This evaluation builds on the framework developed by Carvalho et al. (2024) and its adaption to the lake-context in T4.1 (Kramer et al. 2026). The results presented in this deliverable provide evidence on the effectiveness and feasibility of the tested solutions and will contribute to WP5 upscaling efforts. The outcomes also contribute to the development of the FutureLakes Blueprint (D4.4) and European Lakes Digital Innovation Hub (ELDIH) (D6.2).

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2 Overview of Innovation Pilots

2.1 Types of innovations for lake restoration

The FutureLakes innovation pilots represent a range of restoration interventions implemented at operational scale to address key pressures affecting European lake ecosystems. The pilots include both **preventive external solutions at catchment scale**, which aim to reduce external nutrient and pollutant input and **restorative in-lake solutions**, which target existing ecological degradation by reducing symptoms of eutrophication and addressing legacy nutrients stored in lake sediments. Several pilots **combine multiple restoration measures** across internal and external scales in order to improve ecosystem functioning at system scale. The innovative solutions can further be grouped into three types based on their primary restoration approach and intended impact:

- **Nature-based Solutions (NbS):** Actions to protect, sustainably manage and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits
- **Circular Blue economy Solutions (CBS):** Innovative solutions that include efficient recovery of resources by integrating circular economy principles into the bioeconomy.
- **Biodiversity-focused Solutions (BfS):** Solutions focused primarily on improving ecological structure and biodiversity conditions. They may include established restoration measures applied in an innovative way and scale.

• Definitions adapted from Härkönen et al. (2025)

The innovation pilots include three NbS pilots, three CBS pilots, and four BfS pilots covering catchment-scale, in-lake, and combined restoration approaches, forming the basis for the comparative evaluation presented in Section 4 (Table 1). The innovation pilots are ranging from early-stage technologies and concepts (Technology Readiness Level, (TRL), 2-3) to pilot-scale demonstrations (TRL 6-7).

Several pilots focus on internal phosphorus recovery from sediments to address legacy nutrient loading, while others aim to enhance water storage capacity and improve catchment resilience to drought and flooding. In addition, biodiversity-focused pilots test combinations of structural and ecological restoration measures designed to improve habitat conditions and ecological status. Together, the innovation pilots provide an opportunity to evaluate how different restoration solutions perform under operational conditions with respect to their environmental effectiveness, technical feasibility and potential for wider replication.

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Table 1. Overview of the 10 innovation pilots, which are grouped in three restoration approaches i.e. In-lake focused solutions, catchment focused solutions and combined solutions. The innovation pilots also cover different types of restoration methods, such as nature-based Solutions (NbS), Circular Blue Economy Solutions (CBS) and Biodiversity-focused Solutions (BfS) implemented across the FutureLakes Innovation pilot sites. Benefit abbreviations: Biodiversity (BD), Water Quality (WQ), Ecotourism (ET), Flood Safety (FS), Water Storage (WS), Nutrient & Carbon Capture (NCC), Product Value (PV), Greenhouse Gas emissions (GHG).

Category	**In-lake focused**				**Catchment focused**			**Combined**		
Innovation Pilot	Algal harvesting	P-recovery from lake sediments	P-recovery from lake sediments	Island creation	Flexible water levels	Multi-structure wetland	Raingardens	Multiple measures*	Multiple measures **	Multiple measures ***
Country	FI	PL	DK	NL	NL	FI	UK	NL	NL	NL
Lake	Lake Enäjärvi	Kartuzy lakes	Lake Ormstrup	Ijssel	Ijssel	Lake Vesijärvi	Loch Leven	Kralingse Plas	Groote Melanen	Bleiswijkse Zoom
Type	CBS	CBS	CBS	BfS	NbS	NbS	NbS	BfS	BfS	BfS
TRL start	3-7	1-2	4	2	2	5	1-3	5	5	5
TRL end	6-8	9	7	7	7	7	4-6	7	7	7
Assumed benefits	BD, WQ, NCC, PV	BD, WQ, NCC, PV, GH,ET	BD, WQ, NCC, PV, GHG,ET	BD, ET	BD, WS	WQ,BD, WS	FS, WQ, BD	BD, WQ, ET, NCC	BD, WQ, ET, NCC	BD,WQ, ET, NCC

* Fish removal, sediment dredging and sand capping, bank reconstruction, inlet-water diversion, LMB application, leaf litter and bird-dropping removal. ** Fish removal, inlet-stream diversion, sediment dredging, sand capping, PAC and LMB, bank reconstruction, vegetation planting. *** Bypass construction, water-level management, fish removal, sediment dredging, LMB application, interception zone, reed and shoreline vegetation management.

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3 Evaluation approach

The approach for assessing the success of the 10 Innovation Pilots includes an evaluation that combines policy-relevant indicators, technical performance metrics, and cost-effectiveness criteria to ensure a comprehensive understanding of each pilot's impacts and practical viability. Together, these elements will support evidence-based recommendations for wider adoption and development needs of the innovative solutions for lake restoration.

3.1 Policy-relevant indicators

The policy-relevant indicators used align with those defined in FutureLakes Task 4.1 (Kramer et. al. 2025) and are adapted from the evaluation framework developed in the MERLIN project (Carvalho et al. 2022) to assess the contribution of nature-based solutions on the broad objectives of the European Green Deal (EGD). The adapted framework covers five themes: environmental policy (WFD, biodiversity and zero pollution), climate policy (net zero ambitions and climate resilience) and a range of societal, economic and sector criteria (Table 2). These criteria support evaluation of both positive and negative impacts on key sectors, helping to ensure that restoration measures are sustainable.

Table 2. Criteria for evaluating policy-relevant indicators in FutureLakes Innovation pilots.

#	Criterion Type	Criterion
1	Environmental	WFD
2		Biodiversity net gain
3		Zero pollution
4	Climate	Climate regulation
5		Climate resilience
6	Societal	Health & Well-being
7		Inclusivity
8		Recreation
9	Economic	Circular economy
10		Blue economy
11	Economic Sectors	Sustainable Agriculture
12		Sustainable transport
13		Sustainable energy
14		Sustainable Tourism
15		Water supply & sanitation

3.2 Technical performance metrics

In addition to the policy-relevant indicators, the technical performance of each Innovation pilot was assessed to determine whether it can deliver its intended environmental benefits reliably and at scale under operational conditions. An overview of possible technical performance metrics is shown in Table 3.

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Table 3. Overview of possible technical performance metrics

Technical performance metrics	Examples of what could be evaluated
Achievement of design targets	% of nutrient removal, % sediment removal and recovery, or % habitat area restored
Operational stability over different seasons and conditions	Seasonal variability in nutrient removal efficiency, sensitivity to temperature, ice cover, and extreme weather, passive or nature-based performance stability vs. energy-dependent systems
Level of maintenance and operational intervention required	Frequency and type of maintenance interventions, need for specialized equipment, degree of automation or self-maintenance, use of locally available materials or organisms, maintenance adaptability as the ecosystem recovers
Identification of any unexpected technical challenges or limitations	Core metrics Incidence of system failure, emergence of unintended ecological effects (e.g., invasive species), regulatory or permitting challenges for novel approaches
Replicability and scalability in other lake catchments and regions	Potential for implementation in multiple lake types

3.3 Cost-effectiveness assessment

Cost-effectiveness is an important factor influencing adoption, replication and upscaling of lake restoration measures. The assessment considers both the financial requirements of implementing the measures and the environmental outcomes achieved. Because the FutureLakes pilots differ substantially in scale, objectives, technological readiness and data availability, a fully standardised economic comparison was not possible. Instead, pilot-specific assessments were undertaken using the best available cost data.

For each pilot, cost data were structured into investment costs and operational costs to reflect the different phases of implementation. Investment costs include expenses related to planning, design and implementation of the measure. These may cover activities such as research and development, permitting, construction works and the purchase of equipment and materials. These costs are typically incurred early and represent the initial investment required to establish the restoration measure. Operational costs include expenses associated with the ongoing functioning of restoration measure after implementation. These include operation and maintenance activities, personnel requirements, consumables and monitoring of environmental effects. Where information on the lifetime of the measure was available, total project costs were converted to annualised costs to facilitate comparison between interventions with different operational lifespans.

Environmental effects were linked to the primary objective of each innovation. Depending on data availability, these included nutrient removal (€/kg N or P removed), habitat creation or restoration (€/ha).

Many restoration benefits develop over years or decades, while implementation costs occur immediately. Moreover, potential revenues associated with recreation, tourism, resource recovery or other ecosystem services were generally not included. Consequently, the reported cost-effectiveness values represent conservative estimates of the economic performance of the innovation pilots.

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3.4 Radar charts

The ten innovation pilots differ in type, scale and maturity and data availability, which makes direct comparison difficult. Radar charts provide a way to translate this complexity into clear visual profiles that show how each pilot performs across a set of shared dimensions. By scoring all pilots on the same four-level scale (*i.e.* 3=High, 2=Moderate, 1=Low, 0=not assessed/no data), the radar charts make it possible to compare very different solutions and identify where they are strong, weak or uncertain.

The shape of each radar offers an immediate interpretation (Figure 1). A wide and balanced shape indicates that the piloted solution performs well across most dimensions. A narrow shape suggests limited performance or high uncertainty. A spiky shape shows that the pilot is strong in some areas but weaker in others, indicating important trade-offs such as high costs and strong environmental benefits, but limited scalability and highly dependent on local conditions. Because radar charts are intuitive and easy to read, they are useful for communicating results to policymakers and practitioners. The selected dimensions and scoring criteria are shown in Table 4 and they form the basis for comparing the ten innovation pilots.

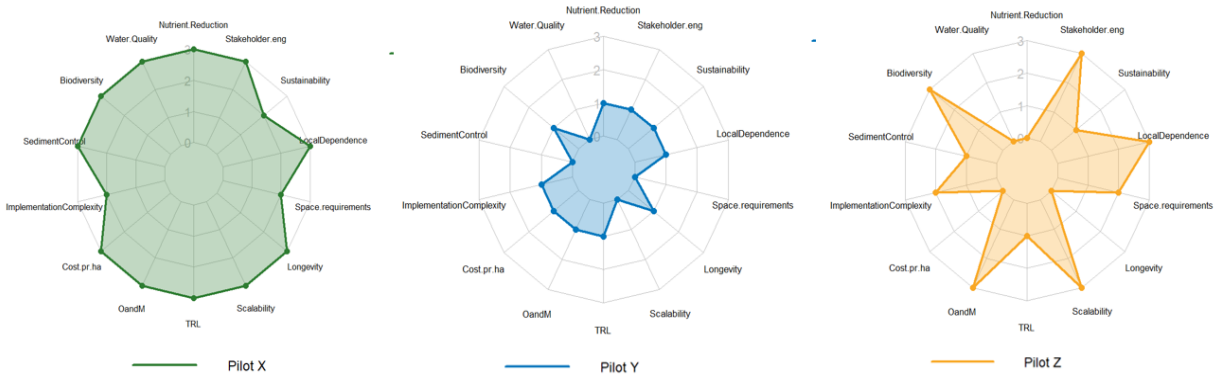


Figure 1. Examples of different shapes of radar charts. The left chart illustrates a wide and balanced shape, that indicates the solution performs well across dimensions. The middle chart shows a narrow shape, that indicates limited performance and high uncertainty. The right chart shows a spiky radar shape, characterised by large variation between dimensions, where a pilot performs well in some areas but weakly in others.

Table 4. Overview of the scoring framework and criteria used to assess each pilot across fourteen dimensions (High = 3, Moderate = 2, Low =1 and NA = 0).

Dimension	Criteria
Nutrient reduction (N/P)	**High:** Clear N/P reduction. **Moderate:** Some reductions. **Low:** Weak/unclear. **NA:** No data.
Water quality improvement	**High:** Clear improvement. **Moderate:** Some improvement. **Low:** None/unclear. **NA:** No data.
Biodiversity & habitat	**High:** Strong BD gains. **Moderate:** Some gains. **Low:** Minimal/none. **NA:** No data.
Sediment & internal load control	**High:** Strong effect. **Moderate:** Some effect. **Low:** Weak/none. **NA:** No data.
Implementation complexity	**High:** Complex installation. **Moderate:** Some complexity. **Low:** Easy to implement. Complex installation. **NA:** Not described.

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Total cost pr. ha	**High:** Low €/ha. €/ha is low compared to similar solutions. Suitable for large-scale or catchment-wide application. **Moderate:** euro/ha is acceptable but not optimal, some cost drivers exist (equipment, materials). **Low (poor):** High cost per hectare €/ha is high relative to the benefits or area treated. Suitable only for small areas or high-value sites. Often includes expensive technology, machinery, or repeated interventions.NA= Not assessed
Operational & maintenance needs	**High:** High/frequent maintenance**, Moderate:** Manageable. **Low:** Low maintenance. **NA:** Not described.
Innovation maturity (TRL)	**High:** TRL 7-9 (operational to commercialized). **Moderate:** TRL 4–6 (pilot). **Low:** TRL 1–3 (experimental). **NA:** Not stated.
Sustainability (multi-benefit)	**High:** Multiple long-term benefits (BD, WQ, ET, NCC, PV, GHG). **Moderate:** One–two benefits. **Low:** Few/none. **NA:** Not assessed.
Scalability & transferability	**High:** Easily transferable to other lakes /catchments. **Moderate:** transferable with some adjustments needed. **Low:** highly Site-specific. **NA:** Not assessed.
Longevity of intervention	**High:** The intervention is long-lasting, requires rare or one-time action, and maintains effect over many years. **Moderate:** The intervention needs occasional renewal or maintenance (e.g., yearly or multi-year cycles). **Low**: The intervention requires frequent or continuous actions to maintain effect. **NA:** Unknown or not assessed.
Space / area requirements	**High:** Small area. **Moderate:** Medium area. **Low:** Large area. **NA:** Not described.
Independence on local conditions	**High:** Works broadly across different lake types, hydrology, soils, and climates. **Moderate**: Some sensitivity to local conditions; performance varies but remains acceptable. **Low:** Highly dependent on specific local conditions; limited transferability. **NA:** No information available.
Stakeholder engagement	**High:** Strong, proactive engagement with key stakeholders (municipalities, water boards, NGOs, landowners, citizens). Co-creation, regular communication, and broad acceptance. **Moderate:** Some engagement with relevant stakeholders; communication occurs but is not continuous. Acceptance is mixed but manageable. **Low:** Limited engagement; few stakeholders involved; low acceptance or resistance. **NA:** No information or engagement not relevant for this pilot.

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4 Evaluation of Innovations

In-lake-focused solutions

4.1 Algal Harvesting

4.1.1 Restoration innovation

Algal harvesting is an in-lake technique potentially mitigating harmful algal blooms (HABs) (Macario et al. 2021). Harvested cyanobacterial biomass can provide high-value compounds (Prabha et al. 2022), and is a potential source of food, feed, antibiotics and medicines, biofuel, fertilizers and wastewater treatment, although some applications require toxin removal (Vijayakumar and Menakha 2015; Singh and Patidar 2018; Khalifa et al. 2021, Chen et al. 2021).

Algal harvesting has been applied mainly in closed industrial systems for wastewater or drinking water treatment (Pandhal et al. 2017) but some case studies also exist from eutrophic lakes and reservoirs (Miao et al. 2014; Koreivienė et al. 2019). The method relies on suitable harvesting technologies and has been suggested to reduce algal biomass, toxins and other contaminants (Chen et al. 2017). It may also improve bathing water quality and reduce internal loading (Napiórkowska-Krzebietke & Łuczyński 2022). However, because the harvesting devices do not distinguish cyanobacteria from other planktonic organisms, the method may negatively affect non-target species.

4.1.2 Pilot specific objectives

A small-scale mesocosm experiment was conducted in Lake Enäjärvi (13-18 August 2025) to assess the feasibility of algal harvesting and its effects on water quality and plankton communities. The pilot was done in collaboration with Syke, Nature Research Centre (NRC; Lithuania) and Peel Tech (UK). All the three tested algal harvesting configurations (Figure 2) consist of two main components: a floating collector and a concentrator standing on the shore.

- **AlgaeTech** has been invented and developed by Peel Tech (https://www.peeltech.co.uk/). The device has not been commercialised for harvesting algae (TRL 3) but is in commercial use in the food sector for filtering vegetable waste from effluent. The device is equipped with a 56-µm mesh plankton net and has a filtration area of 0.1 m². Tap water is used to rinse the system, biomass concentrates on the net and is scraped off with a spatula.
- **AS-LAND** is a nationally patented (Lithuanian Patent No. 7081, 12.08.2024) device, developed and commercialised by NRC and UAB Baltic UAV Services (TRL 7). Biomass is collected in a concentrator with successive compartments along a 57-µm plankton net to filter and concentrate material over an effective area of 3.94 m².
- **VIBRO**, developed by NRC for the FutureLakes project (TRL 3) and not commercialised or patented, harvests algae in a concentrator with a 57-µm plankton net and fractionating biomass through stacked vibrating compartments of progressively denser meshes. These retain cyanobacterial cells while preventing clogging and concentrating material over a 0.062 m² filtration segment. (Koreivienė 2025).

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Figure 2. Algal harvesting pilot was performed collecting cyanobacteria with three different devices. AS-LAND (on the left), VIBRO (on the upper right) and Algae Tech (on the lower right). © Kristiina Vuorio

4.1.3 Pilot site description

Lake Enäjärvi is a 492-ha shallow lake (mean depth 3.2, maximum depth of 9.1 m) in Southern Finland. It belongs to a naturally eutrophic lake type but has further eutrophicated due to extensive external loading (Pellikka et al. 2020). The ecological status is poor, and the lake suffers annually from HABs (e.g. Horppila et al. 2019).

Altogether, 12 mesocosms (diameter 1,5 m, depth 1.7–1.8 m, total volume ca. 3000 L) were established (Figure 3) to run each harvesting configuration and control treatment in triplicate. The harvesting trial was conducted on 13–14 August 2025 by pumping 1000 L of water from the surface (top 0–10 cm) of each mesocosm and filtering through the harvesting configurations. Pumping rates were adjusted according to the harvester-dependent capacities, with pumping rates for AlgaeTech, AS-LAND, and VIBRO exceeding 39, 119, and 13 L/min, respectively.

The water table within the mesocosms remained unchanged during harvesting, because their open bottoms allowed replacement water to seep in. No collapsing of the plastic walls was observed.



Figure 3. Algal harvesting trial at Lake Enäjärvi, southern Finland was performed as a mesocosm experiment. © Laura Härkönen

4.1.4 Monitoring and indicators used

The algal harvesting pilot focused on environmental (WFD) and societal (Health & Well-being) indicators. Additionally, economic indicators (Circular economies) were evaluated in terms of potential added-value products that could be obtained from the harvested biomass (Table 5). These criteria

were selected to address the knowledge gaps related to environmental impacts of algal harvesting (Härkönen et al. 2026a) and earlier discussions on potential circular economic applications (Vijayakumar and Menakha 2015; Singh and Patidar 2018; Khalifa et al. 2021).

A detailed description of sampling and analytical methods is provided in Annex a. Samples for all the indicators were collected from each mesocosm and from the lake one day before harvesting, immediately after harvesting and five days after the trial.

Table 5. Policy area, policy criterion and indicators used in the assessment of the algae harvesting pilot

Policy area	Policy criterion	Indicator name	Data sources
Environmental	Biodiversity net gain WFD	TP, TN, PO_4, TOC Chlorophyll *a* Phytoplankton Zooplankton	Mesocosm experiment (FutureLakes)
	Zero Pollution	TP, TN, PO_4, TOC	Mesocosm experiment (FutureLakes)
Societal	Health & Well-being	Cyanotoxins (microcystins, anatoxins and saxitoxins)	Mesocosm experiment (FutureLakes)
Economic	Circular economy	Proximate composition (ash, moisture, lipid, carbohydrate, and protein content of the biomass, potential toxic components)	Mesocosm experiment (FutureLakes)

4.1.5 Results and evaluation

WFD and Zero pollution

Water quality

Overall, the three algal harvesting configurations did not produce measurable improvements in key water quality indicators (Figure 4). Chlorophyll-*a*, PO_4 and TOC concentrations remained broadly similar before and after harvesting and differences between devices were small. TP and TN concentrations, in turn, showed a short-term rise immediately after harvesting followed by a decline to slightly below starting levels. This pattern occurred in both harvested and control mesocosms, suggesting it was part of normal variation rather than a response to the harvesting itself (Figure 4).

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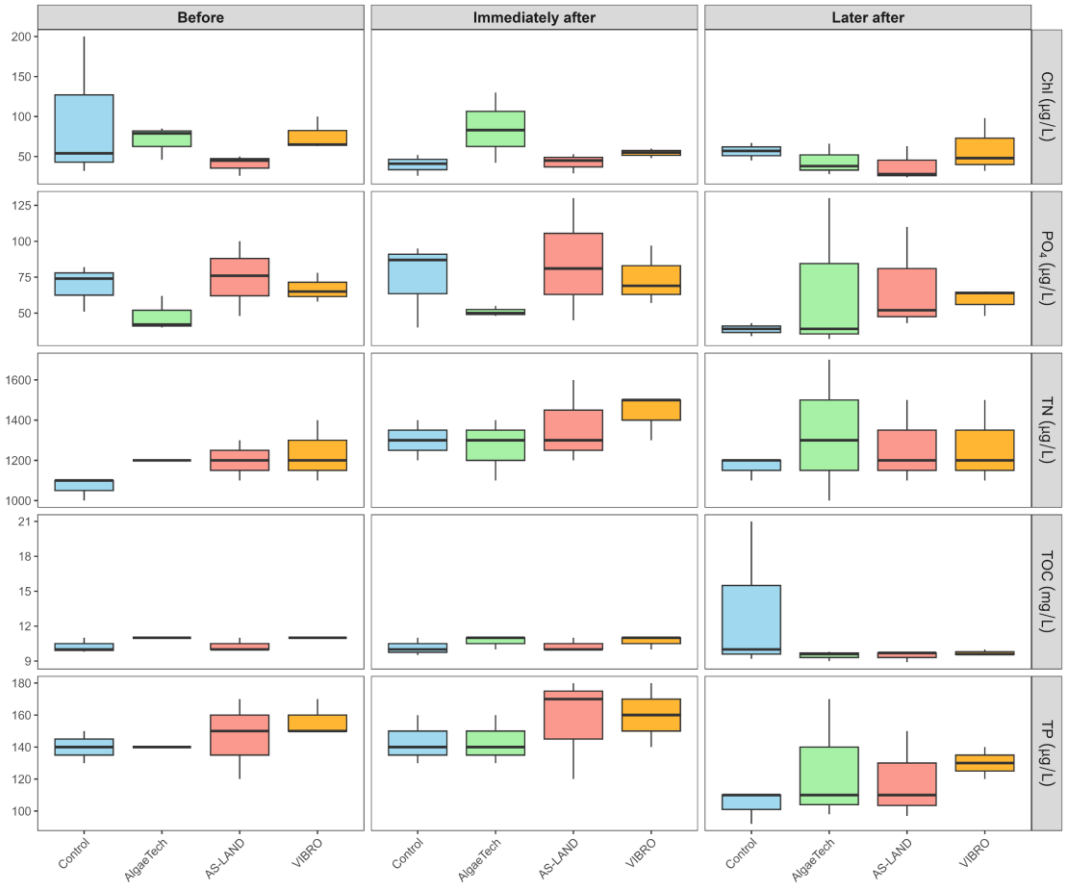


Figure 4. Box plots presenting the minimum, lower quartile, median, upper quartile and maximum values of Chlorophyll a (Chl), phosphate phosphorus (PO_4), total nitrogen (TN), total organic carbon (TOC) and total phosphorus (TP) in the mesocosms under different treatments before, immediately after and later after (5 d) the harvesting.

Phytoplankton

Phytoplankton communities in the mesocosms

Phytoplankton biomass in Lake Enäjärvi was around 6813 µg L^{-1} prior to harvesting, during harvesting 15325 µg L^{-1} and later after harvesting 8630 µg L^{-1}. The phytoplankton biomass in the mesocosms was overall higher, ranging from 11472 to 52930 µg L^{-1} (Figure 5), reflecting the enclosed conditions.

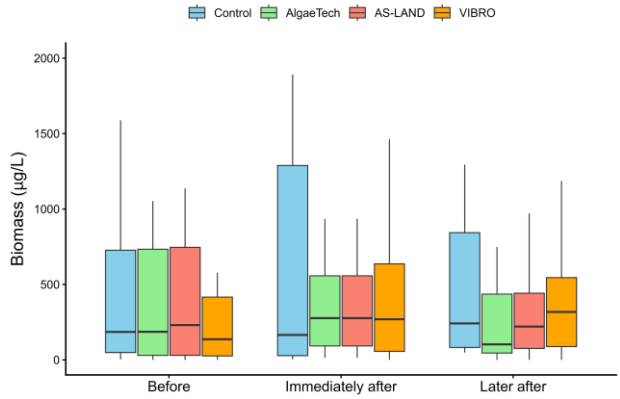


Figure 5. Box plots presenting the minimum, lower quartile, median, upper quartile and maximum values of phytoplankton fresh weight biomass in the mesocosms before, immediately after and later after (5 d) the harvesting.

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Phytoplankton communities in Lake Enäjärvi and the mesocosms were dominated by coiled *Dolichospermum* species. Bloom-forming cyanobacteria comprised ~80% of the lake community and 77% of the mesocosm community before harvesting, declining to 49% immediately after harvesting and recovering to 71% within five days.

All mesocosms showed a short-term reduction in cyanobacteria after harvesting, but the bloom rapidly recovered, indicating unchanged growth conditions. Diatoms increased later across all treatments, while cryptophytes declined in the AS-LAND and Algae Tech treatments.

Phytoplankton communities in harvested scum

Harvesting efficiency varied markedly among devices. VIBRO collected the most biomass, followed by AS-LAND and Algae Tech (Figure 6). Area-adjusted efficiency further highlighted VIBRO as the most effective system, while AS-LAND's lower performance was largely due to its large filtration area, designed for higher water volumes than those used in this pilot (Koreivienė 2025).

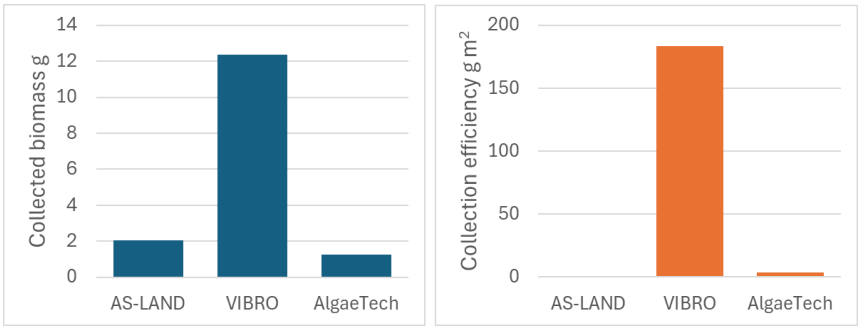


Figure 6. Mean fresh weight biomass (g) of collected scum and collection efficiency (g m^2) of the harvesting devices AS-LAND, VIBRO and AlgaeTech.

All devices effectively harvested large Microcystis colonies despite their low abundance (1-5% of cyanobacterial biomass). Harvested *Dolichospermum* filaments were fragmented, likely allowing some biomass to pass through the sieves. All devices also collected larger phytoplankton, including dinoflagellates, diatoms, green algae, and desmids. Cyanobacteria dominated the biomass collected by Algae Tech and VIBRO, whereas dinoflagellates dominated AS-LAND samples (Figure 7).

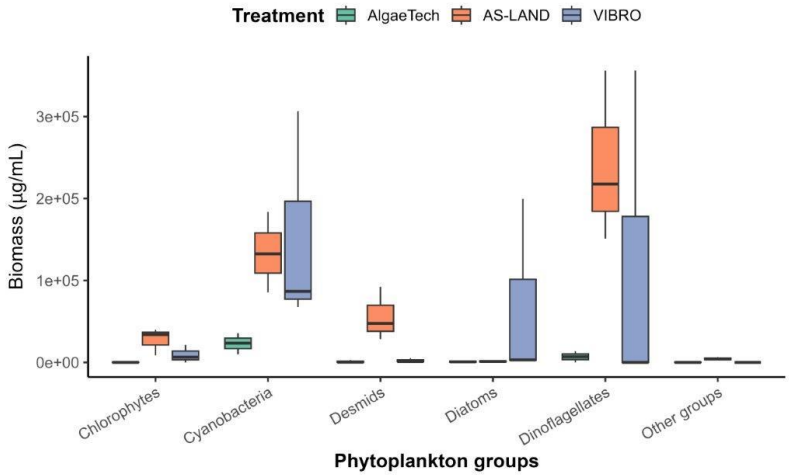


Figure 7. Box plots presenting the minimum, lower quartile, median, upper quartile and maximum values of fresh weight biomass of different phytoplankton groups harvested by the devices AS-LAND, VIBRO and Algae Tech.

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Zooplankton

Zooplankton communities in the mesocosms

Zooplankton communities in the mesocosms were represented by three main groups: Cladocera, Copepoda and Rotifera. Harvesting did not cause notable differences between devices and zooplankton density responded in a similar way across all mesocosms (Figure 8). Throughout the experiment, the zooplankton density increased in both the harvested mesocosms and the controls, indicating that the changes were driven by natural dynamics. The strongest increase was observed in Cladocera, which became more abundant immediately and later after harvesting.

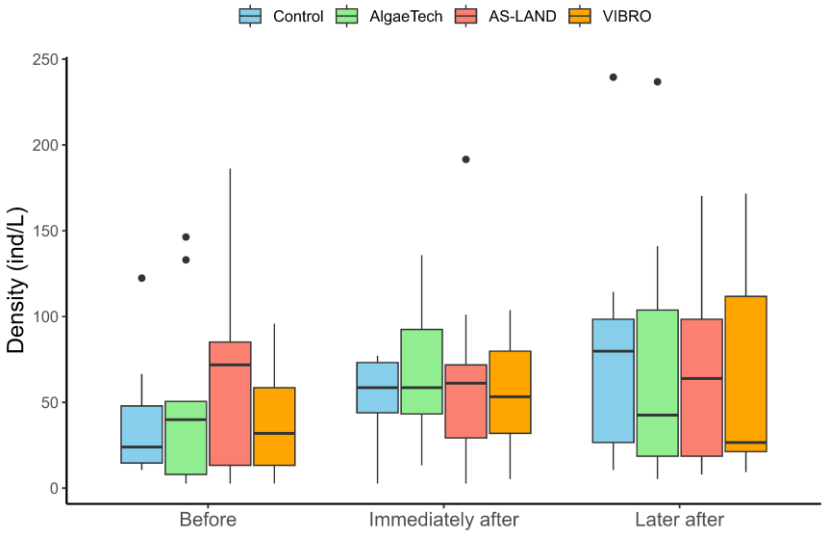


Figure 8. Box plots presenting the minimum, lower quartile, median, upper quartile and maximum values of zooplankton densities in the mesocosms before, immediately after and later after (5 d) the harvesting.

Zooplankton communities in harvested scum

While harvesting showed no effect in the mesocosms, all three harvesting devices equipped with 56-57-µm plankton nets expectedly collected substantial amounts of zooplankton. Rotifers and copepods were the most abundant groups within the scum with cladocerans also common (Figure 9). The collected Copepod biomass mainly consisted of Cyclopidae and Diaptomidae, while the collected cladoceran biomass mainly consisted of Chydoridae, Daphnidae and Sididae. No differences in harvested zooplankton were observed between harvesting devices.

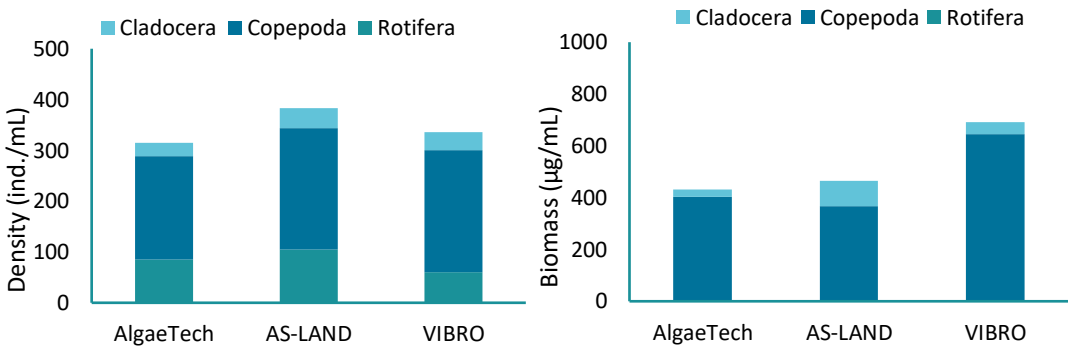


Figure 9. Total densities and biomasses of Cladocerans, Copepods and Rotifers in scum collected by the three algal harvesting devices.

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Health and Well-being

Microcystins

The mean microcystin (MC) concentrations were highest before the harvesting trial (Figure 10), ranging from 1.6 µg L^{-1} to 9.8 µg L^{-1} and being above the guideline value for drinking water of 1 µg L^{-1} (WHO 2020). After harvesting, the MC concentration decreased across all the mesocosms, including control.

Possible MC producers included the cyanobacterial genera *Microcystis* and *Dolichospermum*, both present in the lake and in the mesocosms. Toxic and non-toxic strains often coexist and shifts in their relative abundance may partly explain the observed decline in MC concentrations, which also occurred in the control and lake samples.

MC concentration in freeze-dried scum averaged 776 µg g^{-1} dry weight in samples collected from the lake near mesocosms.

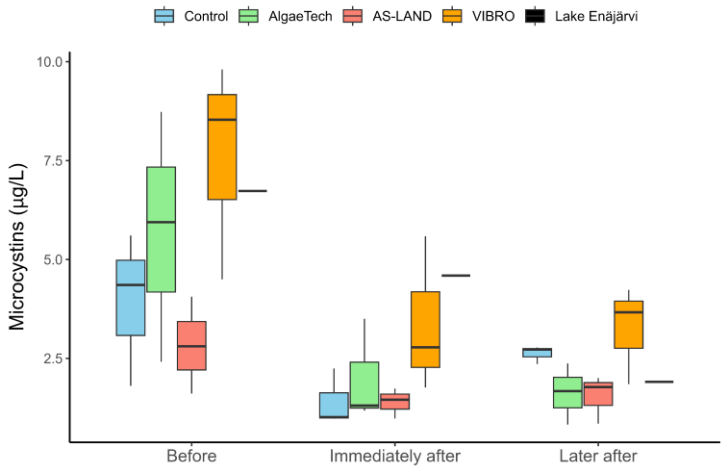


Figure 10. Microcystin concentrations in Lake Enäjärvi and mesocosms before and after harvesting of phytoplankton biomass. Detection limit = 0.1 µg L^{-1}.

Anatoxins and saxitoxins

Anatoxin concentrations were detected at low levels (≤208 ng L^{-1}) before harvesting, mostly near the detection limit (100 ng L^{-1}) and within the range of possible false positives. After harvesting, concentrations were at or below the detection limit in all samples. Potential anatoxin producers include *Dolichospermum* spp, the dominant cyanobacteria in the mesocosms and lake.

All saxitoxin concentrations measured in Lake Enäjärvi and mesocosms before and after harvesting were below the detection limit of 15 ng L^{-1}.

Circular economies

Four scum samples using AS-LAND and VIBRO were collected from Lake Enäjärvi near the mesocosms to assess the circular economy potential of the harvested biomass.

Proximate composition and nutrient recovery potential

The harvested biomass contained on average 0.6% phosphorus, 7.4% nitrogen, 33.4% carbon, and 85.0% organic matter (Koreivienė 2025). Protein was the dominant macrocomponent (Figure 11), indicating substantial nitrogen capture and highlighting potential for use as a protein-rich feed or fertiliser within circular nutrient system. Carbohydrates were the second most abundant fraction, representing a recoverable carbon fraction. Lipid content suggested moderate potential for lipid-based valorisation, whereas ash and moisture content were low.

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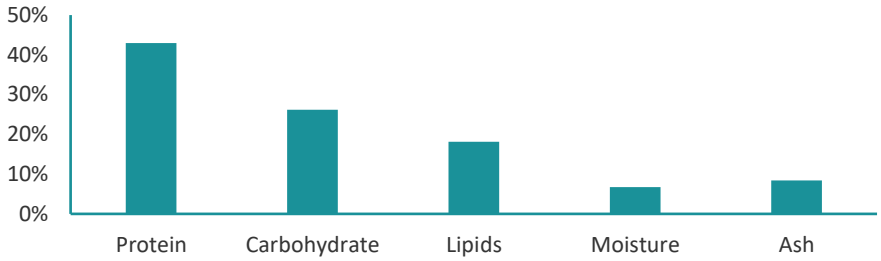


Figure 11. Proximate composition (% dry weight) of freeze-dried cyanobacterial scum collected from Lake Enäjärvi, Finland.

Photosynthetic pigments as high-value co-products

Mean pigment concentrations in harvested scum were 12 µg L^{-1} total carotenoids, 54 µg L^{-1} chlorophyll *a*, and 5 µg L^{-1} chlorophyll *b*, indicating potential for recovery as natural colorants and functional ingredients. Although extraction technologies are established for cultivated cyanobacterial biomass, their application to mixed-species bloom biomass requires further development.

C-Phycocyanin and Allophycocyanin: Cyanobacteria-specific high-value pigments

C-Phycocyanin (PC) and allophycocyanin (APC), pigments unique to cyanobacteria, are high-value compounds used in food colouring, cosmetics, and diagnostics. Mean PC and APC contents were 2.2% and 0.5%, respectively, indicating potential for pigment recovery as an additional revenue stream to support harvesting and processing costs.

Bioactive compounds and antioxidant capacity

Total phenolic content was modest, but antioxidant activity (mean DPPH 4.9 and ABTS 4.7 mg mL^{-1}) indicates potential for producing functional ingredients from harvested cyanobacterial biomass. Together with its proteins, carbohydrates, pigments, and phycobiliproteins, the biomass represents a promising multi-product biorefinery feedstock. Although recovery technologies exist, valorisation of mixed-species bloom biomass and safe use of residual biomass require further development and cyanotoxin management.

4.1.6 Technical performance

This small-scale algal harvesting pilot assessed how well the three different harvesting configurations (AS-LAND, VIBRO and Algae Tech) performed under experimental conditions and whether they succeeded in delivering the intended environmental benefits. Since the harvesting had to be carried out by pumping water from mesocosms rather than collecting surface scums, the trial represents a low-efficiency scenario compared with real lake conditions.

Achievement of design targets

All configurations collected cyanobacterial biomass, but only in small quantities, as they are designed for surface scums rather than water-column material. Non-target plankton were also captured highlighting the need for more selective harvesting technologies if bloom removal is to be a sustainable management approach. Although algal harvesting has been proposed to remove cyanotoxins and nutrients and potentially enhance carbon capture (Koreivienė 2025), this study detected no measurable improvements in key water-quality variables or cyanotoxin concentrations following harvesting. Additionally, effects of algal harvesting on greenhouse gas emissions remain unknown and require further study.

Cyanobacterial declines in the mesocosms were influenced by weather-driven mixing, as similar reductions occurred in controls. Nevertheless, AS-LAND and VIBRO demonstrated potential for efficient cyanobacterial biomass collection, provided their operation is tailored to bloom density and species composition (Koreivienė 2025).

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Maintenance and operational requirements

Despite low pumping and scum-concentration energy requirements (Koreivienė 2025), all harvesting methods tested were labour-intensive and required 2-3 people for continuous operation, scum collection, and net maintenance. Consequently, algal harvesting appears better suited to targeted interventions than continuous use.

Although all devices operated reliably, mesocosm conditions reduced efficiency through filament fragmentation and net clogging. Performance for biomass collection would likely improve under natural bloom conditions, where intact surface scums can be harvested directly.

Technical challenges and limitations

Algal harvesting faces several challenges. Non-target capture of zooplankton and other phytoplankton may affect lake ecology, while cyanobacterial fragmentation can reduce capture efficiency and promote dispersal. In addition, microcystin concentrations in harvested scum exceeded thresholds for food, feed, and most industrial uses, requiring effective detoxification and regulatory compliance before valorisation.

Replicability and scalability

AS-LAND demonstrated moderate potential for replication across eutrophic lakes with recurrent surface scums, as the technology is robust, relatively simple (yet labourious) to operate, and adaptable to different cyanobacterial communities through mesh-size selection (Koreivienė 2025). However, the scalability is strongly dependent on bloom density, duration, and labour availability. The method is suited for targeted removal of nearshore scums, rather than large-scale lake restoration. Its greatest potential may lie in local biomass recovery, while whole-lake impacts with such limited spatial and temporal scales are highly unlikely.

4.1.7 Cost-effectiveness

Cost-effectiveness was assessed only for AS-LAND, the only commercialized device tested. Assuming 30 harvesting days per year, 8 h d^{-1} operation, three operators, a 5-year equipment lifetime, and average Finnish electricity and labour costs, annual harvesting costs were estimated at approximately €29,000. Under these assumptions, about 3,400 kg DW biomass could be harvested per season, corresponding to the removal of approximately 19 kg P, 252 kg N, and 1,138 kg C. This equates to a harvesting cost of roughly €21 kg^{-1} nutrients and carbon removed.

4.1.8 Knowledge gaps

Although the pilot provided valuable insights into the short-term performance of the harvesting configurations, important knowledge gaps remain. The long-term ecological impact of repeated harvesting, including impacts from non-target organism removal, nutrient and carbon capture, are unknown.

In addition, the economic feasibility of algal harvesting under real lake conditions remains uncertain, as cost-effectiveness could only be assessed for the commercial AS-LAND system, limiting comparison among technologies.

4.1.9 Overall evaluation and recommendation

Algal harvesting may serve as a short-term, small-scale mitigation tool for acute cyanobacterial blooms while creating opportunities for biomass valorisation (Table 6). Similar changes in water quality and plankton communities were observed in both harvested and control mesocosms, suggesting normal or weather-driven fluctuations rather than a response to the harvesting itself. However, the harvested cyanobacterial biomass showed promising biorefinery potential, containing recoverable protein, lipids, pigments, and bioactive compounds. However, high microcystin concentrations and the capture of non-target organisms currently limit practical applications. Moreover, the pilot found no measurable

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improvements in water quality. Based on this small-scale experiment, algal harvesting cannot be recommended as a stand-alone restoration or long-term eutrophication management measure.

Future development should focus on improving harvesting selectivity and minimizing impacts on non-target organisms, while recognizing that greater selectivity may alter biomass composition and valorisation options.

Table 6. Innovation performance summary for the mesocosm-scale algal harvesting trial.

Evaluation component	Results	Explanation
Intended function achieved	Partly	Biomass successfully harvested. However, non-selective method for cyanobacteria.
Ecological improvement observed	No	No impact on water quality or phytoplankton communities.
Replication potential	Medium	Replicable but only moderately scalable, best suited for targeted nearshore bloom removal.
Unexpected effects	Negative	Negative implications for non-target plankton.
Knowledge gaps	Significant	Long-term ecological effects, nutrient and carbon removal benefits, economic feasibility under real lake conditions.

4.2 Sediment P-recovery by semi-automated dredging

4.2.1 Restoration innovation

Lakes retain nutrients, such as phosphorus, in their sediment due to the constant sedimentation from either particles entering from the catchment or from organic matter produced in the lake from primary producers. This stored phosphorus can fuel internal loading, prolong eutrophication and delay ecological recovery even after external nutrient inputs have been reduced. The innovation tested in this pilot aims to remove phosphorus-rich sediment gently and with minimal disturbance, and to reuse the recovered material as agricultural fertiliser. In doing so, the method seeks to reduce the internal P-loading, improve water quality and simultaneously provide an alternative source of phosphorus for agriculture.

To test this concept, a newly developed semi-automated dredger was deployed in a full-scale restoration project in eutrophic Lake Ormstrup (11 ha) between 2020 and 2025 (Figure 12). The dredger was pulled along two wires established across the lake. After completion on an area of the lake the wires were removed for another section and area of the lake. The operation of the dredger could be controlled from land/online. The dredged sediment was placed in large Geotubes and left drying for 3-4 months before it was tested for its potential to serve as fertiliser for farming products. Prior to dredging, the lake underwent biomanipulation through removal of roach (*Rutilus rutilus*) in 2021 and 2022 to support overall restoration outcomes.

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Figure 12. Sediment dredging from Lake Ormstrup, dewatering sediment and recycling of P by spreading dried sediment on agricultural areas. The upper figure shows the dredger and how the dredger is positioned between two wires established across the lake. The three middle figures show 1) the pipe leading the dredged sediment from the dredger to land, 2) the Geotubes where the dreaded sediment were placed and used to dewater the sediment and 3) the removal of the dried sediment from the Geotubes to be spread on agricultural areas. The lower figure shows in the dredged areas of the lake.

4.2.2 Pilot specific objectives

The main objective of this pilot was to evaluate how effectively a newly developed sediment dredger performs under a full-scale condition, how the removed sediment can be processed and reused and what effects the dredging had on lake water characteristics.

Measurable targets included dredger performance and its ability to remove sediment and further handling of the sediment (drying, storage, spreading on agricultural areas) and the expenses associated with the dredging. Measurable targets also included current lake functioning and the ability of the dredging to create changes in the lake (based on water quality, nutrients, turbidity, greenhouse gas emission, biological structure).

4.2.3 Site description

Lake Ormstrup is an 11-ha lake located in central Jutland, Denmark (*Figure 13*). The lake has a mean depth of 3.2 m and a maximum depth of 5.5 m. The hydraulic (and external nutrient) loading is low, and inflows and outflow are often low or missing during summer periods. Consequently, nutrient concentrations dynamics are primarily controlled by internal processes, particularly phosphorus from

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the sediments. The lake is highly eutrophic and has experienced persistent cyanobacteria blooms, high chlorophyll-a concentrations, low water transparency and elevated phosphorus concentrations (around 0.5 mg/l) for several decades. The substantial phosphorus pool accumulated largely during a period when the lake was used for intensive stocking and feeding of up to 3,000 mallard ducks annually. Palaeoecological analyses indicate that the lake historically used to be mesotrophic or even oligotrophic, demonstrating a substantial long-term decline in ecological quality.



Figure 13. Lake Ormstrup with lake characteristics, depth map and position of Lake Ormstrup in Jutland, Denmark.

4.2.4 Monitoring and indicators used

Monitoring for the sediment P-recovery pilot focused on documenting how lake conditions changed before and after the biomanipulation and dredging. A set of policy-relevant indicators was monitored throughout the project (Table 11). Indicators were selected to capture key ecological processes affected by sediment removal, including water quality, biological structure and green-house gas dynamics, as well as the technical performance and circular-economy potential of the recovered sediment. Another target of the study was to evaluate the performance of the dredger during the dredging and sediment handling. Time and expenditures were evaluated to estimate the cost of restoring lakes by this technique.

The monitoring programme covered the period 2020-2025, including pre-biomanipulation year (2020), fish removal (2021-2022), post-biomanipulation year (2022-2025), sediment dredging (2024) and post dredging effects (2025). The work was carried out within the Lake Stewardship I-III and REPAIR projects, funded by the Poul Due Jensen Foundation.

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Table 11. Policy area, policy criterion and indicators used in the assessment of the sediment P-recovery by semi-automated dredging in Lake Ormstrup

Policy area	Policy criterion	Indicator name	Data sources
Environmental	WFD	Chlorophyll *a*, zooplankton, Secchi depth	Lake Stewardship I-III
	Zero Pollution	Total phosphorus	Lake Stewardship I-III
Climate		CO2 and CH4 fluxes	REPAIR project (https://repairprojektet.dk/ Søndergaard et al., 2023)
Economic	Circular economy	Value of fertilizer	

4.2.5 Results and evaluation

WFD

Overall, only limited changes in lake water quality were observed following the implementation of the restoration measures. Fish removal resulted in short-term ecological responses during 2022-2023, including reductions in chlorophyll-a concentrations and changes in zooplankton densities (Figure 14 and Figure 15). The improved grazing pressure and temporary increase in water transparency allowed submerged macrophytes (*Elodea nuttallli*) to establish in the shallower areas of the lake. The colonized area reached a maximum in 2024, but macrophyte abundance decreased again in 2025 due to reduced light conditions. Phytoplankton and invertebrate data are not fully analysed yet, but preliminary data also suggest few or no changes after the dredging. Overall, the ecological quality did not change significantly in Lake Ormstrup as a result of the restoration measures.

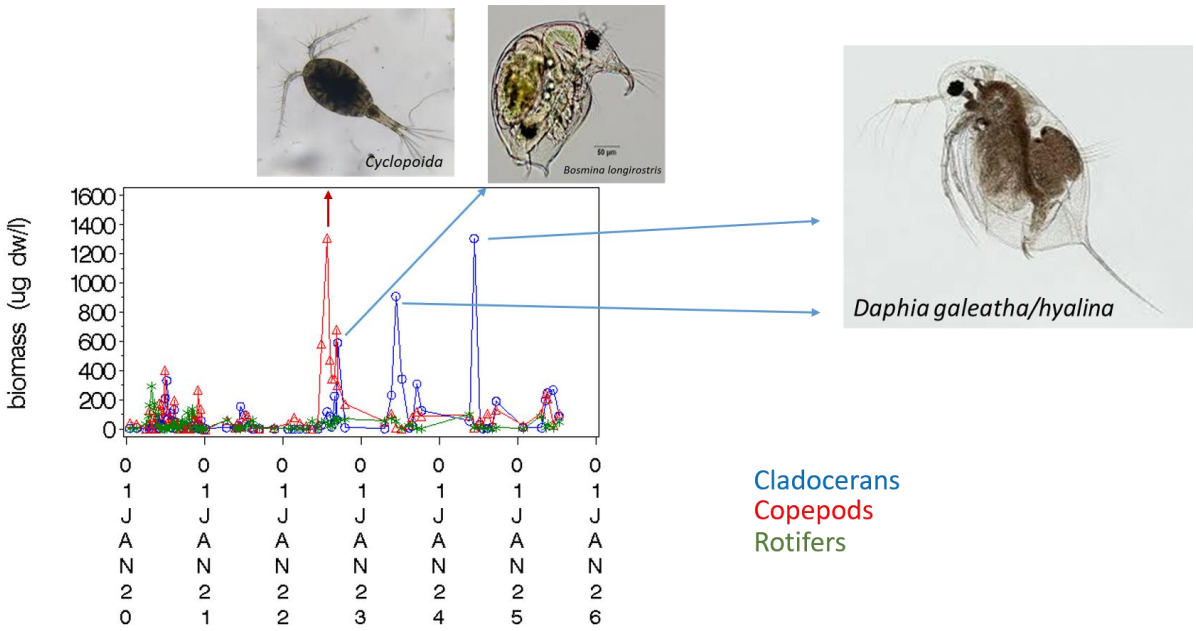


Figure 14. Zooplankton biomass from the pelagic area in Lake Ormstrup in 2020-2025.

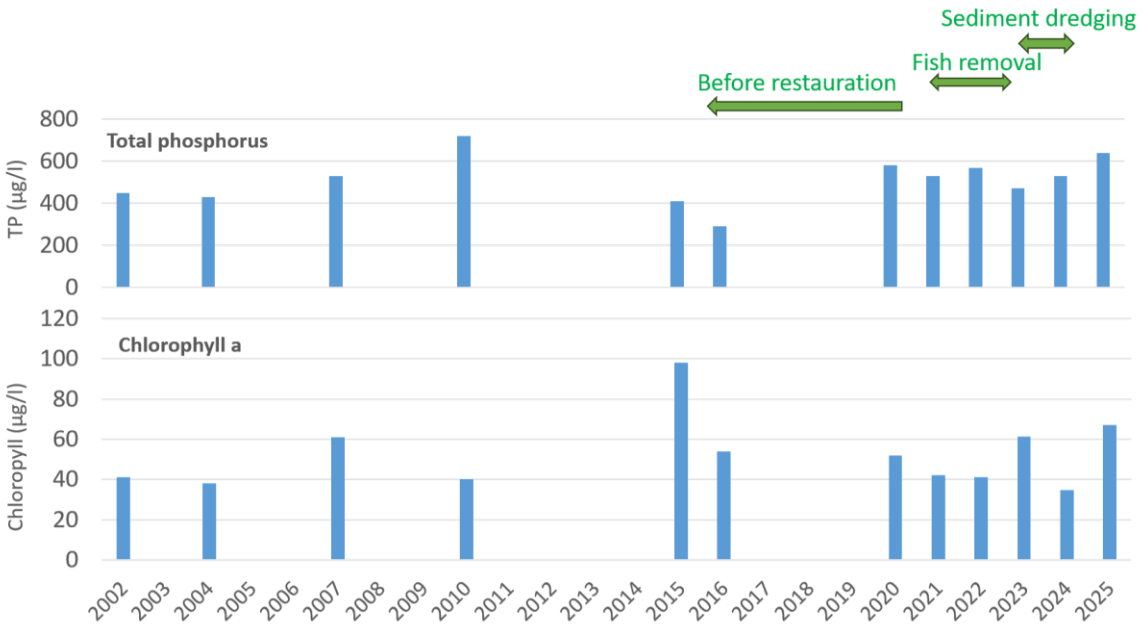


Figure 15. Total phosphorus and chlorophyll a before, during and after restoration. Mean summer values are shown.

Zero pollution

No significant reductions in total phosphorus concentrations were observed following the dredging (Figure 18). The limited extent of sediment removal meant that internal loading remained high and continued to drive eutrophic conditions. As a result, Lake Ormstrup continues to function as a source of phosphorus to downstream areas. However, this does not change the fact that the internal phosphorus pool in the top 20 cm of sediment was removed from the lake.

Climate regulation

Methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions were monitored throughout the project period at several locations. Consistent with the limited changes in water quality and nutrient dynamics, preliminary data suggest that no significant changes in greenhouse gas emissions were observed (Figure 16). However, the monitoring programme provided valuable process-based understanding of greenhouse gas dynamics in shallow eutrophic lakes. The results indicate that methane is strongly linked to lake stratification and mixing with elevated emissions occurring during periods of thermal instability (Søndergaard et al. 2023). The results further suggest that successful reduction in nutrient concentrations and in internal loading could contribute to long-term reductions in greenhouse gas emissions.

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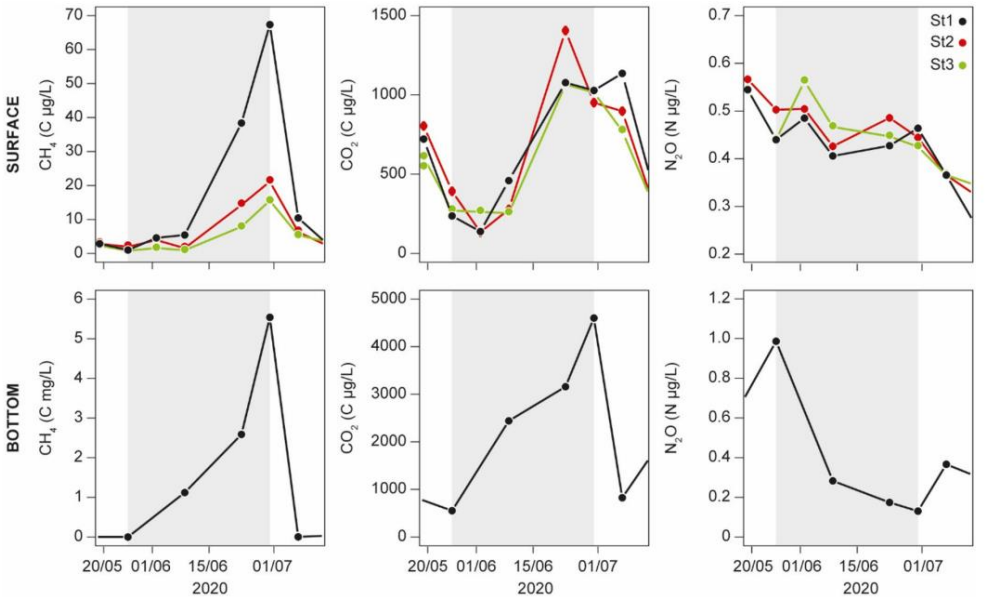


Figure 16. GHG concentrations in surface (1 m) and bottom (4 m) waters measured from 19 May to 7 July 2020 at three locations in Lake Ormstrup. Note the different scale and units. Complete water column mixing occurred on 30 June. From: Søndergaard et al., 2023.

Circular economy

The direct circular economic benefits achieved in Lake Ormstrup were relative limited because of the limited volume of sediment removed. Nevertheless, the pilot successfully demonstrated the complete phosphorus recovery chain, from sediment removal and dewatering to agricultural use and the potential for widespread use.

4.2.6 Technical performance

Achievement of design target

The sediment dredging pilot achieved mixed results. From a technical perspective, the newly developed dredger performed reliably under the full-scale operational conditions in Lake Ormstrup. The sediment dredger successfully removed phosphorus-rich sediments, transported sediment from the upper 20 cm into Geotubes on land for dewatering. After dewatering for 4 months, the recovered sediment was reused on agricultural land, thereby demonstrating the complete recovery chain from sediment removal to fertilizer.

However, the ecological restoration target wasn't achieved because the extent of sediment removal was insufficient. Post-dredging, it was estimated that approximately 60% of the target dredging area was visited by the dredger and that the sediment removed within these areas was incomplete. Overall, it is estimated that 30-40% of the total lake area was effectively dredged, which is far from the goal of at least 80-90% of the sediment required to achieve a significant reduction in internal phosphorus loading. Therefore, no changes in either phosphorus concentrations or chlorophyll a concentration were detected after the dredging (Figure 14).

Maintenance and operational requirements

The dredger developed for Lake Ormstrup functions as a semi-automated system and requires only limited person-involvement during operation. Power can be supplied either through an onboard generator or from a shore-based electricity supply, where the latter has shown to perform best. During

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the dredging process, addition of polymers and placement of sediment in Geotubes on land are needed for dewatering.

Replicability and scalability

The developed semi-automated dredger has a strong potential for replication in lakes where internal phosphorus loading is the dominant driver of eutrophication. The approach is particularly suitable for shallow lakes and medium sized lakes with high sediment phosphorus pools. In addition, this method also requires good accessibility and space for implementing the Geotubes. Given the large number of eutrophic lakes affected by legacy nutrients, the potential application area extends to thousands of lakes in Europe and globally.

Technical challenges and limitations

Overall technical performance of the dredger was positive. The semi-automated dredger generated minimal sediment resuspension during operation and demonstrated a gentle sediment removal approach.

Key limitations identified during the pilot included:

- Insufficient positioning accuracy under windy conditions
- Limited ability to operate in very shallow area (<1.4 m)
- The need for space for the dewatering infrastructure (Geotubes)
- Potential restrictions on sediment reuse if contaminants occur, e.g., heavy metals
- Logistical challenges associated with transporting the current version of the dredger (requires heavy transport).

The challenges are currently being addressed through follow-up research and technology development projects. Future developments will focus on improving the positioning systems and increasing the modularity of the dredger to simplify the transport between restoration sites and to reduce the logistical requirements and challenges.

4.2.7 Cost effectiveness

Preliminary budget estimates suggest that this method is comparable to the cost needed for other types of restorations (phosphorus fixation by aluminium or Phoslock). The estimated price for removing the upper 20 cm of the sediment and placing the sediment in Geotubes is estimated to be 10,000 Euro per hectare lake.

4.2.8 Knowledge gaps

The semi-automated dredging in the Lake Ormstrup pilot highlighted several uncertainties that need to be addressed before sediment phosphorus recovery can be implemented more widely as a restoration measure. These include the long-term impacts of sediment removal on ecosystem structure, nutrient cycling and greenhouse gas emissions. Furthermore, the suitability of dredged sediments for agricultural reuse requires further investigation, in particular sediment from lakes that may contain elevated concentrations of heavy metals or other contaminants.

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4.2.9 Overall evaluation and recommendations

The Lake Ormstrup pilot successfully demonstrated the technical feasibility of low-disturbance sediment dredging (Table 12). However, the ecological restoration objective was not achieved because the extent of sediment removal was insufficient to significantly reduce the internal nutrient loading. The pilot nevertheless provides a strong foundation for further development of sediment-based phosphorous recovery as a circular-blue economy solution. Future development should focus on improving the dredging precision and spatial coverage, extending operation to shallow lake areas, addressing the sediment contamination issues and documenting the ecological and climate benefits across a wider range of lake types. The experience gained from the pilot has already formed the basis for two new research and innovation projects aimed at further developing and scaling up the semi-automated dredging technology.

Table 12. Innovation performance summary for P-recovery

Evaluation component	Results	Explanation
Intended function achieved	Partly	Partly, the dredging overall worked fine, but the amount and lake area from where sediment was dredged was not enough. Consequently, impact on lake water quality was not observed.
Ecological improvement observed	No	No
Replication potential	High	High. Replication in more lakes have already been planned.
Unexpected effects	Neutral	Neutral. Overall, positive experience of the dredging technique, but improvements are scheduled to be tested in other lakes. Many lake sediments are polluted by heavy metals which need to be handled before the sediment can be used on agricultural areas. The approval of lake restorations by local authorities (municipalities) can take a long time (up to one year) and needs to be considered more in the planning process.
Knowledge gaps	Significant	How to remove heavy metals and other hazardous matters from sediments. How to control the dredging more precisely. How to make a dredger which can perform also in very shallow waters. How to make a more modular dredger which can more easily be removed from one lake to another.

4.3 P-recovery from lake sediments through integrated dredging and resource recovery

4.3.1 Restoration innovation

Sediment dredging is a well-established lake restoration method used to reduce internal phosphorus loading from lake sediments. In addition to improving water quality, recovered sediments may provide opportunities for reuse of sediment components for various goals e.g. sand and gravel reuse in the building industry and recovery of nutrients bound in sediment for agricultural purposes, especially phosphorus. However, conventional dredging operation are often associated with high logistic costs

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and environmental risk related to sediment handling, dewatering, storage and disposal (Grochowska et al. 2021, Yan and Li 2025). A particular challenge is the management of nutrient-rich pore water released during sediment handling. If dredged material is temporarily stored close to the lake shore, leakage may result in a secondary pollution of the ground water and lake itself, which could impair the positive effects of restoration.

The innovation tested in Lake Karczemne aimed to address these challenges by integrating the sediment removal by dredging with a dedicated treatment and resource recovery system located at the Kartuzy wastewater treatment plant (WWTP) (Figure 17). Instead of storing the dredged material near the lake, the dredged material (mixture of sediment and water) was directly transported to the WWTP through a 4.5 km pipeline (diameter 225 mm, efficiency ca. 230 m^3/h, daily amount of sediment entering was up to 2300 m^3 per day), reducing the risk of nutrient leakage and creating the basis for large-scale sediment processing and recovery of phosphorus. The sediment transport via the pipes was made under pressure created by pump stations.

A full-scale treatment line was established at the WWTP, including sedimentation tanks (where gravel, sand and small stones were separated from sediment), a sieve and sand trap for mineral separation (efficiency 40 L/s), centrifuges for dewatering (two centrifuges with efficiency 2 x 60 m^3/h) and storage facilities for the final products (area 2500 m^2, with ability to store 4500 tonnes of treated sediment).

Sediment dredging was carried out between 2020 and 2023. During this period, approximately 1.2 millions m^3 sediment-water mixture, corresponding to around 240,000 m^3 of dry sediment. The final product was ca 70% and it was rich in nutrients, soil-like consistence, ready for agricultural purpose.

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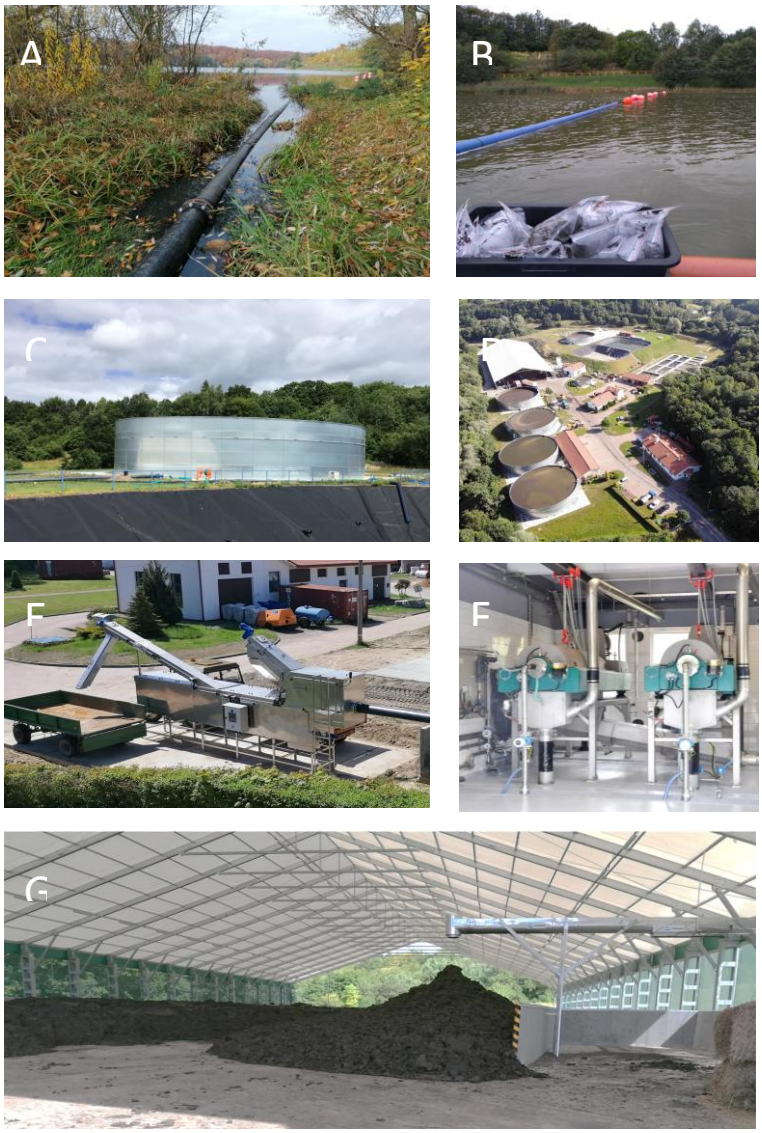


Figure 17 A-B). Pipeline transporting sediment from Lake Karczmene to the Kartuzy WWTP; C) First sedimentation tank; D) Aerial view of the sediment treatment facility; E) Sieve and sand trap; F) Sediment dewatering station and G) Storage facility with the final treated sediment product (photo: Kartuzy WWTP, J. Grochowska).

4.3.2 Pilot specific objectives

Without the Karczemne Lake restoration, the renovation effects of downstream Klasztorne Małe and Klasztorne Duże Lakes could be threatened. Therefore, the goals of sediment dredging on Karczemne Lake in Kartuzy were: a) reduction of P concentrations in the top layer of the bottom sediment via removal of the most polluted, P-rich sediments, and thus reduction of internal nutrient loading; b) increasing the safety of the sediment dredging method via minimizing the risk of pore water re-contaminating the lake by avoiding sediment storage on the lake shore; c) improving water quality in Karczemne Lake; d) limiting the impact of water outflow from Karczemne Lake on the state of the two Klasztorne Lakes, located lower in the cascade of Klasztorna Struga River and e) creating the possibility of use of the recovered P from Karczemne Lake sediment for agricultural purposes outside the catchment.

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4.3.3 Site description

The Kartuzy Lakes comprise a chain of four lakes, located within Kartuzy city, northern Poland. The system consists of Mielenko Lake (area 7.9 ha, max depth 1.9 m), Karczemne Lake (area 40.4 ha, max depth 3.2 m), Klasztorne Małe Lake (area 13.7 ha, max depth 20 m) and Klasztorne Duże Lake (area 58.5 ha, max depth 8.5 m). The lakes are connected via Klasztorna Struga River (Figure 18).

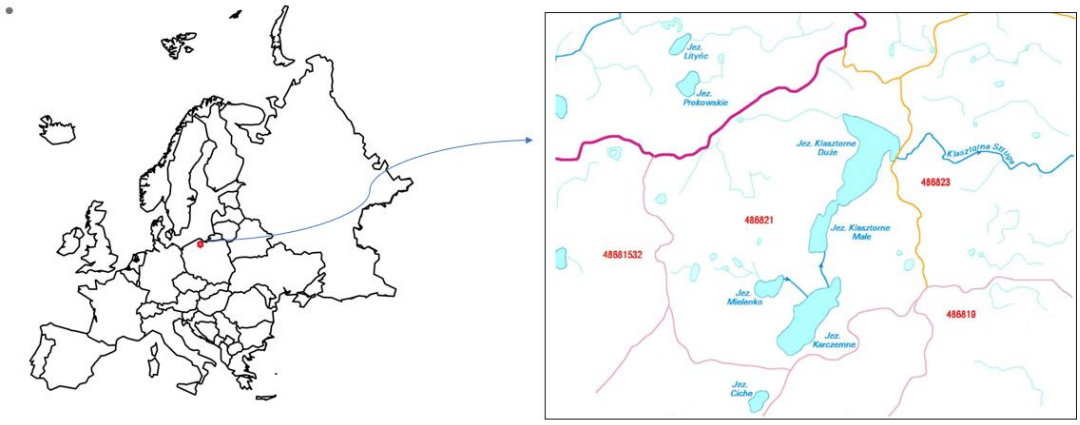


Figure 18. Location of Kartuzy Lakes (source: connected parts of sheets N-34-49-C i N-34-61-A (MPHP))

Karczemne Lake, second lake in the cascade, was selected as the pilot site due to its severe eutrophication and high internal nutrient loading (Figure 19). For several decades, the lake received untreated domestic and industrial sewage through multiple outlets, resulting in the accumulation of large quantities of nutrients and organic matter in the sediments. Although external wastewater inputs have been eliminated, the historical legacy pollution continues to influence the lake water quality.

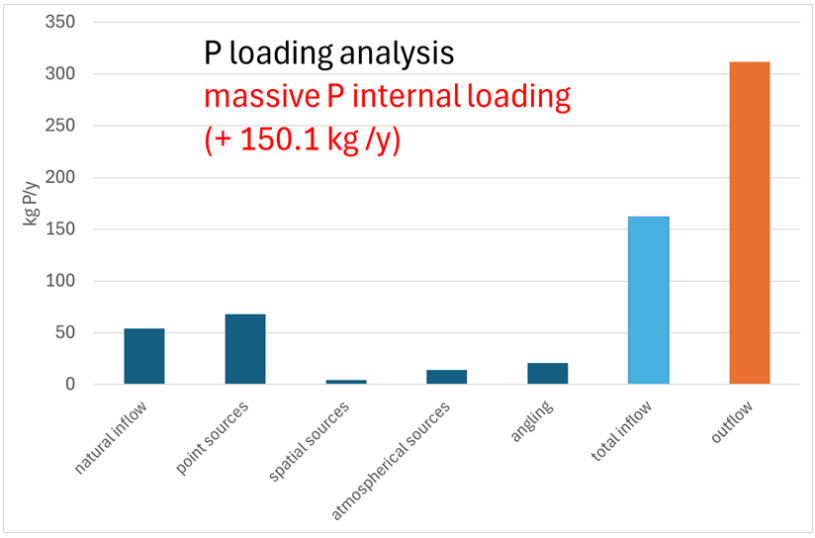


Figure 19. Phosphorus mass balance in Karczemne Lake before restoration together with assessed internal loading (basing on Department of Water Protection Engineering and Environmental Microbiology data)

Nutrient concentrations in the lake water before restoration were very high, and exceeded 1.2 mg TP/L and 3.3 mg TN/L. This condition favoured phytoplankton proliferation – and chlorophyll a concentration was higher than 100 µg/L, and Secchi Depth amounted to 0.2 m (Grochowska et al. 2019).

Sediment of Karczemne Lake was very rich in nutrients (up to 3% N in d.w. and up to 7% P_2O_5 in d.w.)(Figure 20), especially in phosphorus, and it was able to sustain high primary production. P in the

sediment was stored mainly in the hard mobile fraction HCl-P (above 40% TP on average) and medium mobile fraction NaOH-P (up to 40% TP). The most mobile P fractions (NH_4Cl-P and BD-P) occupied several % TP. But taking into consideration the extremely high phosphorus level in the Karczemne Lake sediment (up to 30 mg P/g d.w.), even several % of TP had a high potential for P internal loading.

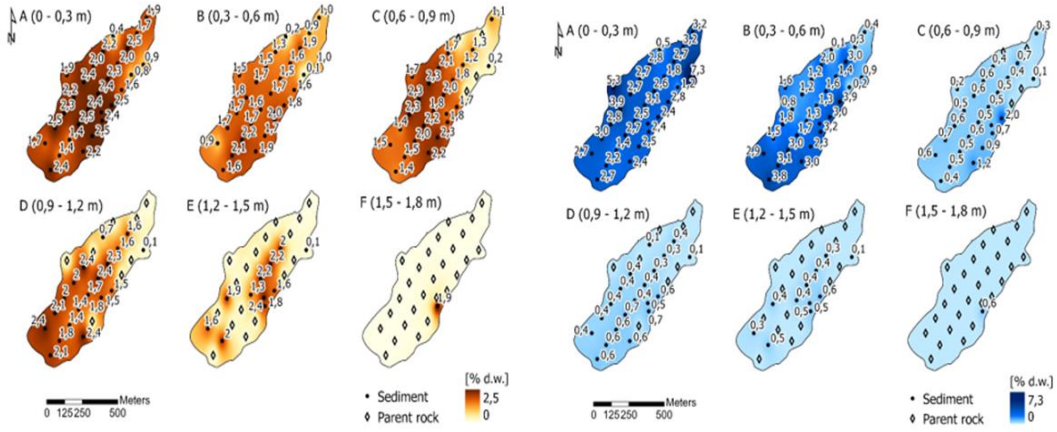


Figure 20. Nitrogen (orange) and phosphorus (blue) amounts in Karczemne Lake sediment layers before restoration (Grochowska et al. 2021).

4.3.4 Monitoring and indicators used

During the Kartuzy Lakes restoration project (2019-2023), water quality monitoring (physico-chemical properties) was performed monthly. Biological elements (phytoplankton, zooplankton, macrozoobenthos, macrophytes and ichthyofauna) were monitored during the vegetation season. The dredging started in the second half of 2020, and it ended in 2023 (Grochowska et al. 2023, Grochowska 2024, Kramer et al. 2026).

Table 13. Policy area, policy criterion and indicators used in the assessment of sediment P-recovery and reuse in Kartuzy lakes.

Policy area	Policy criterion	Indicator name	Data sources
Environmental	WFD	Chlorophyll *a*, zooplankton, Secchi depth	Described in Kramer et al. 2026, Augustyniak-Tunowska et al. 2026 (Annex b in Kramer 2026)
	Zero Pollution	Total nitrogen Ortho phosphate	Kramer et al. 2026, Augustyniak-Tunowska et al. 2026 (Annex b in Kramer 2026)
Climate		GHG emission assessment	Described in Kramer et al. 2026, Augustyniak-Tunowska et al. 2026 (Annex b in Kramer 2026)
Economic	Circular economy	Fertilizer	Information from Kartuzy Municipality

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4.3.5 Results and evaluation

WFD

The restoration programme in Karczemne lake resulted in a measurable improvement in water quality indicators, where a decrease in chlorophyll-a concentrations was measured, indicating a reduction in phytoplankton biomass. In addition, Secchi depth increased compared with pre-restoration conditions, reflecting improved water transparency. Prior to restoration, water transparency in Karczemne Lake was extremely low, averaging approximately 0.2 m (Figure 21).

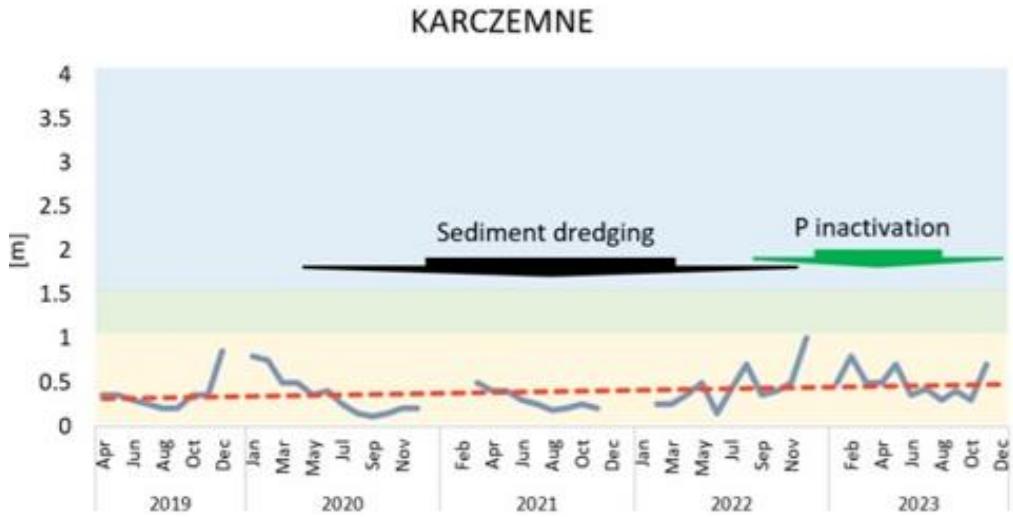


Figure 21 Secchi depth changes in Karczemne Lake (Augustyniak-Tunowska and Grochowska 2026 (Annex b)

The phytoplankton assessment index (PMPL) improved after restoration and the normalized ecological quality ratio (nEQR) showed positive trends. However, the lake has not yet achieved Good ecological status because the biological recovery process is still ongoing and cyanobacterial blooms can occasionally occur following major stormwater inflow events (Kramer et al. 2026, Augustyniak-Tunowska and Grochowska 2026 (Annex b)).

Zooplankton communities also responded positively to reduced eutrophication pressure. Increased grazing pressure by large-bodied zooplankton was supported through fish manipulation reducing the dominance of planktivorous cyprinids and increasing the proportion of predatory fish. Further biological improvement in Karczemne Lake is expected in the future, after sequential P inactivation. Using P inactivating agent after dredging seems to be proper practice, as it improves sediment P sorption abilities, which is lower in the older sediment layers uncovered after dredging.

Zero pollution

Sediment removal directly targeted the largest nutrient pool in Karczemne Lake. Approximately 240,000 m^3 of nutrient-rich sediment were removed between 2020 and 2023. The intervention significantly reduced sediment phosphorus concentrations and lowered the potential for internal phosphorus loading.

The largest reduction was observed for total phosphorous. Before restoration, sediment phosphorus concentrations reached more than 30 mg P g^{-1} dry weight and consisted largely of potentially mobile HCl-P and NaOH-P fractions (Figure 22). Dredging removed the most contaminated upper sediment layer and reduced the phosphorus storage available for release to the water column.

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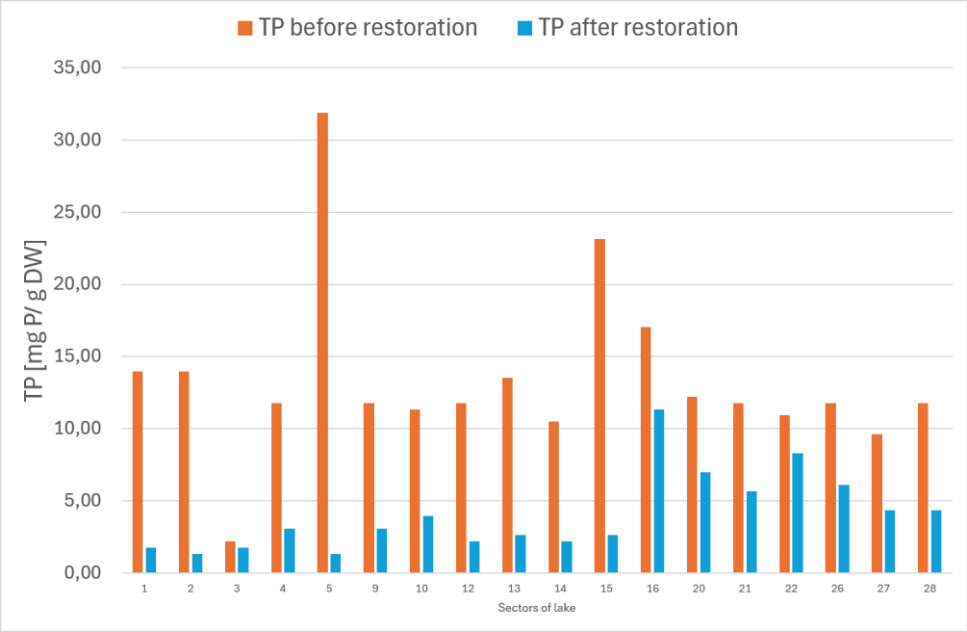


Figure 22. Changes in sediment TP amounts in the upper 30 cm lake sediment, before and after sediment dredging in the particular lake sectors.

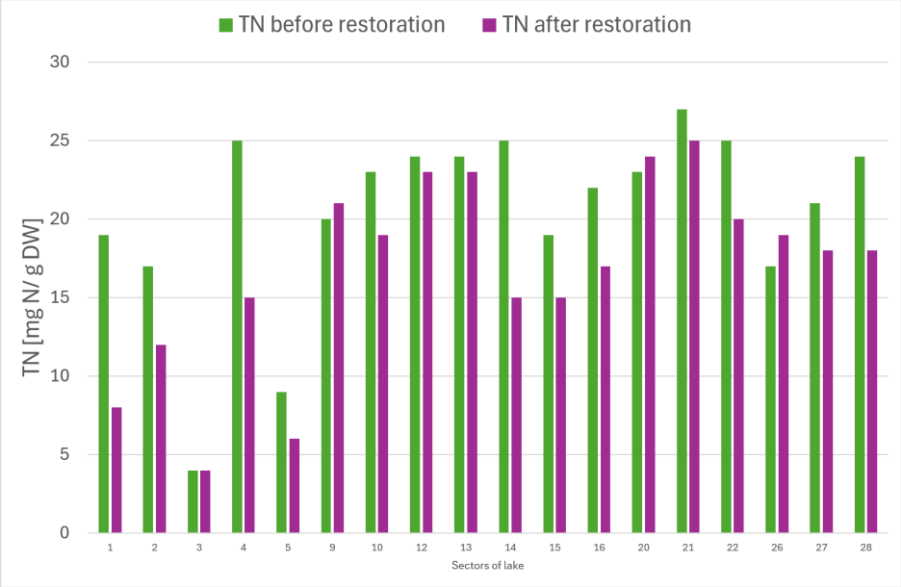


Figure 23. Changes in sediment TN amounts in the upper 30 cm lake sediment, before and after sediment dredging in lake sectors.

Climate regulation

The FutureLakes climate assessment indicates that improved water quality resulting from restoration is associated with reduced methane emissions (Kramer et al. 2026). For the Kartuzy Lakes, methane emissions estimated using a Bayesian model declined from approximately 0.063 Gg CH_4-C yr^{-1} before restoration (2019) to 0.034 Gg CH_4-C yr^{-1} after restoration (2023-2025), corresponding to a reduction of approximately 46%. Although direct measurements are not yet available, these results suggest that sediment dredging combined with phosphorus management may deliver an additional climate-regulation benefit through reduced eutrophication and lower methane emissions.

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Circular economy

An important innovation outcome was the conversion of dredged sediment into an agricultural product that satisfied Polish regulations for agricultural use of sludge-derived materials (Ordinance of the Ministry of the Environment, Dz U. 2023, position. 23 (6.02.2015)). Analysis demonstrated that heavy metal concentrations remained well below legal thresholds and pathogen indicators fulfilled sanitary requirements. The values in the treated sediment is given in Table 14 below. The product could therefore be used for fertilization of non-food crops outside the lake catchment, preventing phosphorus recirculation to the Kartuzy Lakes system.

Table 14. Average properties of lake sediment from Karczemne Lake after treatment

	Threshold from Ordinance for agricultural use	Value in treated sediment	Unit
Chromium	500	31	mg/kg DW
Zinc	2500	158	mg/kg DW
Phosphorus	-	0.30	% DW
Cadmium	20	0.966	mg/kg DW
Magnesium	-	0.40	% DW
Copper	1000	33.9	mg/kg DW
Nickel	300	18.1	mg/kg DW
Lead	750	36.4	mg/kg DW
Calcium	-	1.58	% DW
N-NH_4	-	<0.05	% DW
TKN	-	2.04	% DW
pH	-	6.9	
Organic matter	-	37.4	% DW
Dry mass	-	25.7	%
Presence of Salmonella spp.	Non present in 100 g	Non present in 100 g	
Live eggs of parasites (Ascaris sp. Toxocara sp. Trichuris sp.)	0	0	Ind./kg DW

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4.3.6 Technical performance

Achievement of design target

The sediment dredging and treatment system successfully achieved its primary objective. Around 240,000 m^3 highly nutrient rich sediment were removed from Karczemne lake during 2020-2023 and transported directly into the Kartuzy WWTP through a 4.5 km long pipe system. This eliminated the temporary storage of sediment on the shoreline and substantially reduced the risk of nutrient rich pore-water to re-enter the lake. Sediment dredging, performed in full technical scale on Karczemne Lake, caused substantial changes in the lake sediments composition and water quality improvement.

Maintenance and operational requirements

There is no major maintenance required once the dredging operation is completed. However, operation of the treatment line requires regular technical servicing of pumps, pipelines, centrifuges and sediment handling equipment during active dredging periods.

Replicability and scalability

The Kartuzy solution demonstrates high technical feasibility for application in other shallow eutrophic lakes suffering from severe internal phosphorus loading. Its greatest advantage is the integration of lake restoration with existing wastewater treatment infrastructure. The method is particularly suited where:

- where the lake is shallow and eutrophic
- nutrient rich sediment is the main source of phosphorous loading
- a WWTP exists within a reasonable distance and it has the capacity to treat large sediment volumes
- recovered sediment can be reused outside the lake catchment

- Where it is possible to store and treat a large volume of removed sediment

Technical challenges and limitations

Several challenges were identified during the sediment dredging. Firstly, accurate determination of dredging depth is critical to ensure removal of the most polluted sediment layer. In addition, it may also require site-specific dredging strategies, as sediment can be heterogenous. Secondly, lake sediment is very rich in nutrients (it contains more than 90% of P and N of the whole lake ecosystem) and mistakes in storage, transport and treatment could result in the secondary pollution of restored lake and ecological disaster, as was observed eg. in the case of Mogileńskie Lake in Poland, where pore water leakage from sediment stored on the lake shore came back to lake and caused dense cyanobacterial blooms (Goszczyński 2000). A third challenge is to have a WWTP that has the capacity to treat the very large volumes of sediment. In the case of Karczemne Lake restoration, it was possible to expand present area of WWTP for technological line construction for sediment treatment.

4.3.7 Cost effectiveness

Because of its complexity level, lake sediment removal and treatment is costly. In the whole Kartuzy Lakes restoration project, sediment removal and treatment was the most expensive part. It consumed almost half of funds directed to all project (more than 6.5 milion €). The treated sediment fulfilled criteria for sewage sediment used for agricultural purposes, which opened the possibility to use it for cultivation of non-edible plants. This shows the method's potential for nutrient recycling.

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4.3.8 Knowledge gaps

Karczemne Lake restoration was the first full-scale sediment removal project. Sediment was removed almost from the whole lake. Post-intervention data is still gathered for research on effectiveness and durability of positive changes in the Karczemne Lake ecosystem. In the scientific literature, few publications describe the long-term effects of sediment dredging, and comprehensive analysis of restoration using several methods (dredging, P inactivation, biomanipulation of the fish structure) is absent in the literature. Therefore, long-term observations of Karczemne Lake restoration effects will fill this knowledge gap.

4.3.9 Overall evaluation and recommendations

The sediment removal and treatment were a part in the Kartuzy Lakes restoration project (Table 15). This was an innovative solution, tailored to local conditions and lake state. It is a good solution for heavily degraded shallow lakes, with a small water area. The longer term post-intervention observation will bring more information about effectiveness of the sequence of lake restoration methods. Until now, the method has resulted in several positive results in the overall ecosystem functioning evaluation: decreased water and sediment nutrient levels, improvement in phytoplankton and macrophyte indices, and improvement of the fish structure. However, the macrozoobenthos index decreased because of the intervention, and it will take time to recover. Removed sediment was successfully treated and transformed into a suitable agricultural product, which opened the possibility for nutrient recycling and qualifying the procedure as a CBS solution.

Table 15. Innovation performance summary for P-recovery

Evaluation component	Results	Explanation
Intended function achieved	Partly	The most polluted sediment layer was removed from the lake. The lower influence of outflow from Karczemne Lake on Klasztorne Małe Lake.
Ecological improvement observed	Partly	Water quality improved through reduced nutrient concentrations, improved phytoplankton composition, and the reappearance of submerged macrophytes. Nevertheless, cyanobacterial blooms still occurred after major stormwater inflows, indicating that recovery is ongoing.
Replication potential	Medium	The approach can be transferred to other eutrophic lakes, particularly where suitable wastewater treatment infrastructure is available nearby. Site-specific conditions, treatment capacity, and economic considerations will influence feasibility.
Unexpected effects	Neutral	The approach can be transferred to other eutrophic lakes, particularly where suitable wastewater treatment infrastructure is available nearby. Site-specific conditions, treatment capacity, and economic considerations will influence feasibility
Knowledge gap	Significant	As the first full-scale lake sediment recovery project in Poland, several uncertainties remain. Key questions relate to the long-term effectiveness of pollutant removal, agricultural reuse of recovered sediments, and management of contaminated sediments containing heavy metals or PAHs. Additional research on biological

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		remediation and long-term ecosystem recovery is needed.

4.4 Island creation

4.4.1 Restoration innovation

Marker Wadden are a group of constructed islands built in Lake Marken, The Netherlands (Figure 24). These islands were sculpted from sand, clay and silt from Lake Marken itself. To build the islands, a structure of ring dikes was used to contain the sediment and combined with nearby gullies and trenches to further trap and stabilize lake sediments (Hüsken et al, 2025). After consolidation of the sediment, new material was added until the islands reached their desired height (de Rijk et al., 2022). The islands provide the natural transition zones between water and land that were lacking in the lake and thereby stimulate the biodiversity and productivity of the lake food web and its surrounding area.



Figure 24. Left: Location of Marker Wadden within Lake Marken. Right: Impression of the islands after construction in 2020 (Photo: Mennobart van Eerden).

Marker Wadden is an innovative approach to building with nature because the material it was built with (i.e., the fine sediments from the lake floor) is not the primary material to use to create islands with. However, engineers were able to transform part of the problem (the fine silt causing issues with transparency in the lake) into part of the solution by using the fine sediments as building material. Moreover, the islands were designed from the start as a combination of nature and recreation. On top of that, the intention was to not only improve the area immediately surround the newly constructed islands, but also to improve the whole lake: by improving the water transparency and stimulating food chains throughout the ecosystem (although this element is still under research). Lastly, the island construction and subsequent ecological development were seen as a living lab, rather than just a measure – and learning has explicitly been made a part of the process. A research station on the visitor's island facilitates scientific learning and research, and provides a home for students at the University of Amsterdam during a yearly recurring course on ecology. Marker Wadden is the largest natural ecosystem that has been built in the Netherlands.

Between 2016 and 2021, a cluster of 5 islands was built, of which one island was intended to combine recreation with nature, while the other islands were all reserved for nature only. By now there are 7

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islands, and further expansion is under discussion. The innovation covers roughly 1300 ha of areas located above and below the water surface level.

4.4.2 Pilot specific objectives

The environmental objectives of this site were: to improve the transparency of the lake by collecting suspended sediment in deep underwater pits, to improve the biodiversity of the site by attracting birds and other wildlife, and to improve the productivity of the lake via a boost in primary production.

The social objectives of this site were to create a new recreation opportunity, to learn how to best monitor impacts and to learn about innovations (e.g., working together in new constructs).

The economic objective of this site was mainly to attract new members for the non-governmental organization Natuurmonumenten, a Dutch foundation for nature protection.

4.4.3 Site description

The Lake IJssel complex (Figure 25) is a large, human-made freshwater system created after the closure of Zuiderzee in 1932 (with the Afsluitdijk), the creation of an additional dam (Houtribdijk), and land-reclamation works. The Lake IJssel complex is the largest lake complex in the Netherlands, consisting of two large lakes (IJssel and Marken) and a series of smaller "border lakes" that are situated around some of the reclamated areas (Figure 25; see Table 16 for lake characteristics). Please note that these border lakes are not studied within the FutureLakes project. Lake IJssel receives most of its inflow from the river IJssel (up to 70%), a branch of the river Rhine. The other 30% of water comes from rainfall and water of smaller rivers, sluices and pumps. The main export route from Lake IJssel is towards the Wadden Sea via sluices in the Afsluitdijk and can be up to 100 million m^3 per day (Rijkswaterstaat, 2026). Water from Lake Marken flows via sluices in the Houtribdijk to Lake IJssel and via Lake IJssel to the Wadden Sea. Both lakes are WFD water bodies, albeit heavily modified, and designated N2000 areas and important national and international areas for birds. Almost all shoreline of the lakes has been converted into dikes, and the lakes experience reversed seasonal water levels fluctuation patterns in comparison to natural conditions (low in winter, high in summer).



Figure 25. Map of the Lake IJssel complex and its surrounding area. Markermeer = Lake Marken, IJsselmeer = Lake IJssel, Waddenzee = Wadden Sea. Darker blue colors indicate a greater depth. Source: Noordhuis et al. (2014).

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Table 16. Lake characteristics.

Type of characteristics	Characteristics	Unit	Value Lake IJssel	Value Lake Marken
Geographical characteristics	Latitude	-	5.32683	5.24578
	Longitude	-	52.81796	52.55366
Lake characteristics	Area	km^2	1130.7	675.20
	Maximum depth	m	20.61[1]	30.91[2]
	Mean depth	m	4.58	3.91
	Water volume	bn. m^3	~ 4.7 (in winter)	~2.4 (in winter)
	Water residence time (τ)	years	0.3	~1
	Mixing type		polymictic	polymictic

Although the main reason for constructing the Afsluitdijk, and thereby the creation of the Lake IJssel complex, was water safety, the complex has become a crucial part of water management in the Netherlands. The lakes supply drinking water, water for irrigation, and are used to flush salt or highly eutrophic water out of canals and drainage ditches in other parts of the Netherlands. As such, it has been nicknamed "the rainbarrel of the Netherlands". On top of that, the lakes provide a habitat for a plethora of birds, fish species and water plants, are used to mine sand, are used for transport and recreation. As such, the water level and water quality of the Lake IJssel complex is carefully managed by Rijkswaterstaat, a governmental body that is part of the Ministry of Infrastructure and Water Management and that is dedicated to enhancing safety, mobility and quality of life in the Netherlands.

The main pressures on the ecosystem include intensive water-level regulation, (the after-effects of) eutrophication, and the lack of natural shallow land-water transitions and their impacts on the ecosystem (e.g., less biodiversity and/or biomass).

4.4.4 Monitoring and indicators used

In addition to the regular monitoring by the government (Rijkswaterstaat) of Lake Marken, a separate monitoring program was set up to monitor the development of Marker Wadden. As Marker Wadden has been the largest effort the create natural islands in the Netherlands, it has been well studied, in particular regarding its ecological development and innovative way of building.

The Marker Wadden study has been done within the Kennis- en Innovatieprogramma Marker Wadden (KIMA; Knowledge and Innovation program Marker Wadden). KIMA ran from 2016 – 2021 and was followed by KIMA 2.0 (of which unfortunately no synthesis report has been published yet). KIMA has resulted in 3 PhD theses, 10 scientific articles and a multitude of reports. In KIMA many different elements have been monitored: ranging from different species (birds, fish, plants, insects), to water quality parameters, to the material of which the islands were made. Additionally, the funding process and the governance of the measure were studied as well.

The species and water quality were monitored to follow and learn how the islands would ecologically develop. The sediment and its settling were studied because this use of this material was novel, and the funding process and subsequent governance were relatively novel as well and thus worthy of study

too. The whole effort was seen as a living lab. An overview of indicators used can be found in Table 17.

Table 17. Policy area, policy criteria and indicators used for assessment of the island creation pilot

Policy area	Policy criterion	Indicator name	Data sources
Environmental	Biodiversity net gain	Bird species condition Fish species condition Habitat condition	De Rijk et al. (2022)
	WFD	Other: water clarity	De Rijk et al. (2022)
Societal	Recreation	Number involved in general recreation Length of active travel routes (walking) Features supporting nature-friendly recreation	Website Natuurmonumenten (www.natuurmonumenten.nl)
Economic	Circular economy	Sediment reuse	De Rijk et al. (2022)
	Blue economy	Jobs created attributable to restoration outcomes	Website Natuurmonumenten (www.natuurmonumenten.nl) De Rijk et al. (2022)
Economic sectors	Sustainable tourism	Total visitor numbers Number of overnight stays in an area on an annual basis Infrastructure supporting nature-friendly tourism	Website Natuurmonumenten (www.natuurmonumenten.nl)

4.4.5 Results and evaluation

The following sections are largely based on the first KIMA synthesis report and subsequently moulded to fit with different elements of the T1.2 evaluation framework (e.g. Biodiversity Net Gain, WFD, Recreation). For an overview of these elements see Table 18.

Biodiversity Net Gain

Primary productivity of the area has improved, particularly in the shallow waters between the islands. Here, the ratio between inorganic material and chlorophyll has shifted, making phytoplankton more readily available in the food web, benefiting species such as water fleas and mussels. This is also reflected in the observed improvement of freshwater mussel populations in the island surroundings.

Fish species increasingly use the shallow zones as breeding grounds. In the early stages, mainly common species have colonised the area, but as submerged vegetation continues to develop, it is expected that a greater diversity of species will follow.

Bird populations have also established strongly on the islands. In 2021, 47 breeding bird species were recorded. The first colonisers were species that prefer bare sand and low pioneer vegetation, such as

terns (e.g. Common Tern and Little Tern). These were followed by species associated with marsh vegetation, including ducks, reed songbirds and rails. In addition to nesting birds, the islands serve as an important location for foraging and resting. Between July 2020 and July 2021, more than 60,000 migrating birds used Marker Wadden.

In terms of Natura 2000 (N2000) goals, Marker Wadden has not benefitted all non-breeding bird species of the open water so far. Some species on the other hand, showed a strong positive response, like the breeding population of Common Terns did. Other bird species of pioneer habitats and marshes do not have N2000 targets for Lake Marken, because they were absent at the time the local targets were set. Nevertheless, their settlement on the islands has contributed to improvements of national conservation status for these species.

The deeper areas surrounding the islands, such as the harbour and former sand mining pits that have been created during the construction of the islands, also have an impact on the area, both negatively and positively. For example: they provide important refuge habitats for both small and larger fish, collect organic material and nutrients within their depths, and make it harder for mussel-eating birds to forage there.

WFD

Although other parameters have been monitored as well, water clarity was one of the main reasons for the development of the islands. Lake Marken has had continuous issues with fine sediment causing a high turbidity of the waters. After the islands were built, the water clarity was indeed improved in close vicinity to the islands, due to the silt getting captured in the deeper pits surrounding the island and in the shallows of the island. Although it remains uncertain how far the impact of Marker Wadden reaches beyond the immediate vicinity of the islands, the fine silt concentration at the monitoring station in the centre of Lake Marken has decreased by 1/3 since 2018.

Recreation

There is a small visitor centre on the main island - the only island accessible for recreation - and there are several kilometres of walking paths that guide visitors around the island. Along these paths are multiple features that supporting nature-friendly recreation, amongst which are three watchtowers mainly intended for bird watching. In addition to the small harbour, with 30 spots for boats, there is a ferry taking a maximum of 100 people to and from the island twice a day.

The impact of the public on the ecosystem of the visitors island is carefully monitored by Natuurmonumenten. Natuurmonumenten tries to keep people on the walking routes and has established the maximum amount of people allowed on the island per day to minimize the stress on the bird populations on the visitors island.

Blue economy and Sustainable tourism

There are four lodges on the island, that can be rented for an overnight stay by a maximum of 5 people. Additionally, there are several forest rangers active on site to maintain the island and aid visitors and there is a ferry that travels twice a day between the mainland and the main island. In total roughly 30 000 to 50 000 people visit Marker Wadden each year. Unfortunately, exact figures on the amount of money used to provide these services are not available.

Circular economy

Marker Wadden was built using the fine sediments of the lake itself. Using this fine sediment instead of the more commonly used sandy material was an innovative approach to building with nature. The approach was successful, although the material did consolidate substantially during the settling period (e.g., the 4.4 m layer of material at the start consolidated to 2.7 m within two years, with the main consolidation period being the first 3 months after the material was applied). The topmost layer of the islands formed a crust that could be used by geese after several weeks after the initial application. The reed vegetation that established itself aided in keeping the sediment in place and preventing erosion.

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4.4.6 Technical performance

Achievement of design targets

As a whole, the islands function well, they host a range of species and are starting to support the ecological system of the lake through improving the primary production in the area. It is also well-visited by researchers and citizens alike, thus providing its function as a living lab.

Maintenance and operational requirements

The islands need to be maintained ecologically and structurally. Ecologically, the main threats appear to be the encroachment of willow trees in several areas and heavy grazing by geese. Without continuous intervention the islands could turn into a willow forest, while a wetland area would be more beneficial to the birds that were intended to populate the islands. The heavy grazing by geese is a threat to the reed beds that offer valuable habitat to desired bird species. However, both elements are difficult to manage. The island also has to be supplemented with sediments over time to keep the sediment surface level at its desired height, as there is less natural 'heightening' than expected, and to keep the sandy shores functioning, as during storm events part of the sandy foreshores can get swept away. Furthermore, the pathways and facilities made for visitors need to be maintained and the ferry that transports people to and from the island needs to be operated.

Technical challenges and limitations

Working with fine sediments rather than with sand does require careful monitoring of the amount of subsidence taking place. Due to this process, it should be expected that suppletions will be required to obtain and maintain the desired surface level height of the islands. The process of subsidence will be influenced amongst others by the water level, the potential evaporation, the exact composition of the sediments.

The ecosystem that develops on the islands will be dependent on how fast certain species will reach the island and will also be influenced by (external) factors such as predators or invasive species. It can be an option to aid the process of colonization by removing unwanted variables and by planting specific plants, although the size and accessibility of the islands might limit the feasibility of such endeavours.

Replicability and scalability

Building with fine sediments does have its challenges, but has been shown to be a viable option. This innovation could be replicated at other sites where ways to improve the shoreline are limited and the open water surface area is sufficient. Building nature islands within a (shallow) lake should always take into consideration that it does take away open water surface area as well. The size and amount of islands can be adjusted according to desired scale of the application.

4.4.7 Cost-effectiveness

The inflation-adjusted capital investment costs amount to approximately €112 million (2025 prices). In addition, operational and maintenance costs over the assessed period amount to approximately €25.8 million (2025 prices). Together, these result in total estimated costs of approximately €137.8 million over the project assessment period. For details on the conversion to 2025 prices please refer to Annex a Island creation.

Project construction took place approximately between 2016 and 2020, after which the asset entered its operational phase in 2021. The intervention is assumed to have an economic lifetime of 10 years, corresponding to the duration of the Design-Build-Maintain (DBM) contract. While the physical islands are expected to remain in place well beyond 2030, potentially until around 2050 or later, substantial maintenance interventions are anticipated after the expiry of the DBM contract. Consequently, only the initial 10-year operational period, i.e., 2021-2030, is included in the cost-effectiveness assessment.

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Within the assumed economic lifetime of the intervention (2021-2030), three monitoring programmes are considered:

1. Monitoring Programme 1: 2018-2022
2. Monitoring Programme 2: 2023-2026
3. Monitoring Programme 3: 2028-2031

The first monitoring programme partly overlaps with the construction phase and the early operational phase, while the second and third programmes are undertaken during the operational period. Detailed cost information was available only for the first monitoring programme. Due to the absence of programme-specific budget information for subsequent monitoring activities, it is assumed that the total costs of Monitoring Programme 2 and Monitoring Programme 3 are equal to those of Monitoring Programme 1. Because the economic lifetime considered in this assessment ends in 2030, only the share of Monitoring Programme 3 that falls within the assessment period has been included. Monitoring Programme 3 covers the period 2028-2031, of which three of the four programme years (2028, 2029 and 2030) fall within the economic lifetime of the intervention. Accordingly, it is assumed that 75% of the total costs of Monitoring Programme 3 are incurred within the assessment period and are therefore included in the analysis.

Based on the assumed costs and lifetime, the intervention has an estimated annual cost of approximately €37 million per year. When relating costs to the achieved environmental outcome, the resulting cost-effectiveness ratio equals approximately €0.028 million per hectare (or approximately €28,500 per hectare) of habitat created.

4.4.8 Knowledge gaps

The use of a 10-year lifetime has introduced a conservative bias into the cost-effectiveness calculation. Benefits that continue after 2030 are not fully captured, whereas a significant share of construction costs is allocated to the initial assessment period. At the same time, substantial future maintenance activities are expected after the expiry of the DBM contract, and these costs are not included in the current analysis. Future assessments could therefore consider a longer evaluation horizon that explicitly accounts for both long-term benefits and long-term maintenance requirements.

Although the immediate surroundings of the islands have been clearly impacted by the islands themselves, it remains hitherto unknown how far the impact of the islands reaches (e.g., does it influence the ecosystem of the whole lake or just a certain radius?).

Lastly, although there is a list of potential benefits of the islands, the benefits of this innovation in terms of economics and human well-being remain largely unknown.

4.4.9 Overall evaluation and recommendations

It proved challenging to connect the builders of the site with the researchers. This was partly due to the different pace at which these processes operate—research typically progresses more slowly than construction—but also due to a lack of familiarity between the people working in these two domains.

At the same time, the project demonstrates that co-financing can successfully support large-scale nature restoration. In this case, a combination of governmental and private funding made it possible to bring the project to life.

Table 18. Innovation performance summary for island creation.

Evaluation component	Results	Explanation
Intended function achieved	Partly	The islands serve as a prime spot for breeding birds, and fish and plants have arrived and thrive as well. However, the idea was also to improve the ecosystem status of the whole lake and this impact might be not as great as expected / is still under research.
Ecological improvement observed	Yes	Locally, the measure caused a vast improvement of the shoreline available to the lake ecosystem (NB this measure does come with a loss of open water habitat).
Replication potential	High	This innovation could be replicated elsewhere.
Unexpected effects	Negative	An overabundance of geese and willows threaten the desired habitat type of the islands.
Knowledge gaps	Economic benefits	The impact of the islands in terms of economic benefits remain largely unknown.

Catchment-focused innovations

4.5 Flexible Water levels

4.5.1 Restoration innovation

The flexible water-level regime in the Lake IJssel complex is a water-management innovation that replaces the former fixed water-level strategy with a more adaptive, climate-responsive approach. The measure was implemented in 2019, following the Ministry of Infrastructure and Water management's decision in June 2018. The innovation introduces a seasonal bandwidth of acceptable water levels: in summer, levels may fluctuate between -0.10 cm NAP – -0.30 cm NAP, while in winter a target level of –0.40 cm NAP should be aimed for (Figure 26). NAP stands for Normaal Amsterdams Peil and translates to "regular Amsterdam water level". NAP is roughly equal to the mean sea level of the North Sea. Under the flexible regime, water managers can adjust lake levels strategically throughout the year. Five operational scenarios guide the use of this flexibility for water management: delaying the set-up of the usual high water level in mid-March, keeping a high water level throughout April, recreating a higher water level in May, using the buffer in June and July, and delaying the onset of lower water levels in mid-August. The flexible water level system enables the creation of a summer water buffer of approximately 400 million m^3 (RWS, 2018). This volume is sufficient to supply at least 30% of the Netherlands with freshwater during periods of extreme drought until at least 2050 under projected climate change scenarios. Water levels in the Lake IJssel complex are regulated through a carefully managed system of sluices and pumps, examples of which are the sluices in the Afsluitdijk (the largest dam in the Netherlands that separates Lake IJssel from the Wadden Sea) and the pumps in the province of Friesland. The water levels of the Lake IJssel complex are monitored daily at 4 measuring stations per lake.

Before the implementation of the flexible water level, the Lake IJssel complex was managed according to fixed water levels. The fixed water levels entailed a water level target of –0.20 cm NAP in summer and a water level target of –0.40 cm NAP in winter. This management practise was in place since 1992. NB: Although the water level of the lake is fixed, the large surface area of the lakes (~1130

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km² for Lake IJssel and ~675 km² for lake Marken, also see Table 16) allows wind to create water level differences of up to one meter between different sides of the lake.

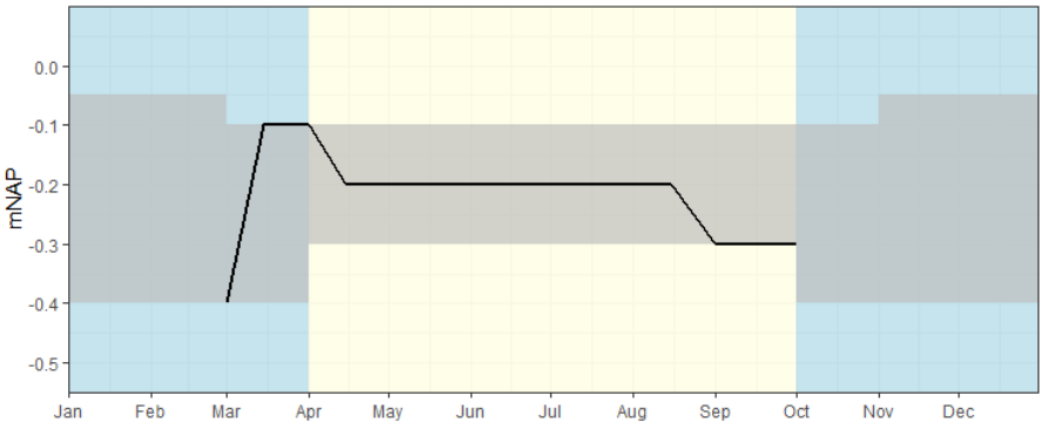


Figure 26. Flexible water levels for Lake IJssel complex during the year in mNAP. Blue areas = winter season, yellow areas = summer season, grey band = allowed water levels, black line = usual water level during this time in Lake IJssel (usual water levels for Lake Marken are slightly different in spring). Figure based on Figure 1 from WSP (2025).

4.5.2 Pilot specific objectives

The flexible water level regime in the Lake IJssel complex aims to increase the system's resilience to climate change, particularly in response to more frequent heavy rainfall events and prolonged periods with droughts, in combination with water user needs, while ensuring no additional risks for water safety (flooding) and minimizing impact for the other functions that the Lake IJssel complex fulfils. Ecological considerations are considered where possible, although these are not the main purpose of the water level decision.

By introducing a summer water-level range, the water management authority that is regulating the water levels of the Lake IJssel complex (i.e., Rijkswaterstaat) can better respond anticipate weather conditions and the corresponding increase in the demand for freshwater (WSP, 2025). For example, in periods of expected water shortage, higher water-levels can be retained to create a buffer. Additionally, the possibility of a higher water level in spring and lower water levels at the end of summer allow for a more natural water level gradient over time.

Measurable targets for this innovation relate primarily to water-level fluctuations, but also to flooding events in the direct catchment, (hindrance of) shipping, changes in swimming water quality, water temperature, and/or the surface area of reed beds.

4.5.3 Site description

Please refer to section 4.5.3 for the site description (environmental context and main pressures) of Lake Marken. Lake Marken, in which Marker Wadden was created, was low in transparency, suffered from decreasing fish populations, too little breeding grounds for birds, and too little area with gradual land-water transitions. The latter caused by the fact that almost all shorelines of the Lake IJssel complex consist of dikes.

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4.5.4 Monitoring and indicators used

The implementation of the flexible water levels has been monitored yearly from 2019 – 2024. The flexible water level innovation was evaluated on 15 themes, which have been reported as factsheets. These factsheets have been collected in a comprehensive report written by WSP (2025b). In Table 19 we have transposed the 11 themes that were related to direct impacts from the flexible water level innovation into their policy relevant indicator counterparts. The selected themes explore the impact of the innovation on the environment, climate, society and specific water related sectors.

2018 was used as a reference to evaluate the impact of this innovation. For some elements data from regular monitoring efforts could be used (e.g., water quality monitoring network of Rijkswaterstaat or bird data from the Sovon Dutch Centre for Field Ornithology), for other elements specific reference measurements were taken (e.g., reed bed monitoring by Neelen & Schuurmans and Scirpus Ecologisch Advies). In hindsight, the drawback to using 2018 as a reference year is that it was a relatively dry year in comparison to Dutch average climatological conditions. Thus, in some cases, comparing the monitoring data from 2019 – 2024 to 2018 may have caused an overestimation of the impact of the innovation.

Table 19. Policy area, policy criterion and indictor used for assessment of the flexible water level pilot.

Policy area	Policy criterion	Indicator name	Data sources
Environmental	Biodiversity Net Gain	Habitat trend	Reed beds. Factsheet 2 from WSP (2025b)
		Bird trend	Breeding birds. Factsheet 5 from WSP (2025b)
Climate	Drought resilience	Increased volume of lake	Water supply. Factsheet 1 from WSP (2025b)
	Flood resilience	Other (water safety)	Water safety and nuisance. Factsheet 3 and 4 from WSP (2025b)
Societal	Health & Well-being	Bathing water quality: cyanobacteria	Bathing water quality. Factsheet 9 from WSP (2025b)
	Recreation	Other (recreational shipping)	Recreational shipping. Factsheet 10 from WSP (2025b)
Sectors	Sustainable transport	Other (commercial shipping impacts)	Commercial shipping. Factsheet 7 from WSP (2025b)
	Sustainable energy	Energy consumption changes as a result of lake or catchment measures	Energy use of pumps. Factsheet 6 from WSP (2025b)
		Other (energy production changes as a result of lake or catchment measures)	Water temperature and power plants. Factsheet 11 from WSP (2025b)

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	Sustainable agriculture	Outputs: farm productivity	Inundation of agricultural areas outside of the dike. Factsheet 8 from WSP (2025b)

4.5.5 Results and evaluation

The impacts of this innovation were reported in two main evaluation reports from WSP (2025a and 2025b) written for Rijkswaterstaat. As these reports were written in Dutch, we have summarized and translated their conclusions into English in the following section. The results have been grouped together per policy criterion (Table 19).

Biodiversity net gain

No impact was shown on the coverage and quality of reed beds. The coverage and quality of reed beds is defined in large parts by birds grazing on the reed and the occurrence of extreme water levels (which are not due to the flexible water level innovation) (Coops et al. 2025).

The available data on breeding birds does not show negative effects that can be directly related to the innovation. For example, fluctuations in breeding birds from SOVON on the Bittern (*Botaurus stellaris*) are more likely related to periods of harsh conditions in winter or unfavourable nesting conditions due to rainfall in spring. However, local terrain managers and nature organizations have indicated that there might be negative impacts that have not been shown by the data. One possible negative impact of the water level fluctuation innovation is, for example, that birds that breed on open ground near the shoreline may experience an increased risk of their nests washing away (although the aim from high water levels in early spring is to prevent this from happening). Furthermore, in the rather dry year of 2023, water level was kept at the high end of the targeted range (-10 cm NAP) until early August. Researchers indicate that as a result, breeding Avocets on the islands of Marker Wadden were not able to raise any fledgelings, because too much water remained on the mudflats for the small chicks to forage on.

Flood and drought resilience

The Flexible water level innovation was successful in providing a larger buffer of water during the (drier) summer months. However, this buffer was used multiple times since the implementation of the innovation. Additionally, according to the estimations of water levels use in the driest years of the evaluation period, surrounding regions may use up to 3 times the amount of available freshwater – meaning that the water buffer by itself will not be sufficient to supply all the freshwater these regions require and that these regions are thus still heavily dependent on rainfall and supply from rivers in very dry years. This result is different than the originally estimated use of the water buffer once every 20 years. The causes for the underestimations of the required water buffer are: 2023 climate scenarios showing even bigger weather extremes than the earlier 2018 climate scenarios, a new water demand to prevent salt-intrusion and to maintain the moisture content of peat-areas, the process of autonomous soil-erosion of the river IJssel lessening the water supply to Lake IJssel.

The innovation did not have any impact on regional water flooding events or on water safety. The fluctuations caused by the flexible water levels are minimal in comparison to the effects of wind and natural water supply. Furthermore, current protocols are already well equipped to handle the impacts of extreme weather conditions.

Health and wellbeing

No impact was shown on swimming water quality. The swimming water quality turned out to be more substantially influenced by local impacts (e.g., rainfall, presence of animals). Additionally, the water temperature is not linearly related to water level, but more influenced by air temperature and irradiance.

Recreation

Recreational shipping did not experience negative effects from the lower water levels in (late) summer.

Sustainable transport

Commercial shipping did not experience negative effects from the lower water levels in (late) summer. However, although the lower water levels in (late) summer do not cause a hindrance to shipping, the higher water levels over summer *do* cause a more frequent closure of the "Ramspolkering" (a storm surge barrier intended to protect the hinterland at the most eastern point of the Lake IJssel complex from flooding) and therefore can hinder shipping (detours that have to be made due to the closure of the storm surge). Notably, more frequent closures of the Ramspolkering also heighten its maintenance costs.

Sustainable energy

No impact was shown on water temperature. Water temperature is not linearly related to the water level, but more influenced by air temperature and irradiance. This also means that the intake of cooling water is not influenced substantially by the water level fluctuation innovation.

The larger water level difference between the Lake IJssel complex and the surrounding waters did also cause a higher energy use of pumps, although data is lacking for a precise estimation of the increased costs for the use of these pumps.

Sustainable agriculture

A larger agricultural area may now become inundated due to the flexible water levels; however, the calculation of this inundated area was largely theoretical and the largest factor influencing the inundated areas is likely climatological change.

4.5.6 Technical performance

Achievement of design target

The Flexible Water Level innovation achieved its intended physical goal – the ability to create a larger buffer of water in summer to supply surrounding regions with freshwater during dry periods. Furthermore, there was either no impact on the observed ecological elements (water temperature, coverage of reedbeds) or the results were inconclusive (possible negative effects on birds).

Maintenance and operational requirements

The implementation of the flexible water-level innovation requires the ability to monitor and influence the water levels continuously. In case of Lake IJssel Complex the monitoring network (weather forecasts, water level monitoring, discharge monitoring) and water management system (sluices, storm surges etc.) are all in place. The water system of Lake IJssel Complex is large (lake surface area > 1800 km^2) and vital to the Netherlands, and thus managed by a national water management authority (Rijkswaterstaat). We did not find the exact number of people working on the water level of Lake IJssel Complex, however, we expect these to be in the range of 10 – 100's. Rijkswaterstaat itself has over 10 000 employees.

The amount of maintenance and the operational requirements will vary with the size of the water body the innovation is applied to. For small water bodies the amount of people working would be substantially reduced, similar to the amount of pumps, sluices, etc. required to observe and maintain the desired water levels.

Replicability and scalability

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This method can be applied elsewhere. However, the ease by which this measure can be applied is heavily dependent on the amount of influence management already has on water levels. In the case of the Lake IJssel Complex the water level has been heavily monitored and managed since decades. Thus, the implementation of the flexible water level innovation only required careful research into the impacts of the changing water levels on several aspects (described in the sections above) and barely required adjustments for managing the water levels themselves (pumps and sluices were already in place). The scale at which this pilot has been executed has been substantial and thus this innovation has proven itself to be effective at large scales already.

Technical challenges and limitations

Although initial scenarios had shown that the designed water buffer would be sufficient to supply 30% of the Netherlands with freshwater in dry summers (its use estimated to occur roughly every 20 years), the buffer was already used multiple times during the evaluation period. Moreover, during these extremely dry summer periods, the buffer turned out to be not sufficient to supply the region with freshwater – showing a remaining dependence on rainfall and rivers. This result indicates that the Netherlands will need to take further steps to ensure sufficient amounts of drinking water in the near future, including heightening dikes and possibly discussing a further increase in the allowable range of water levels.

The underestimation of the likelihood that water shortages would occur likely happened due to a combination of factors, amongst which are evolving insights for climate scenarios (2018 vs 2023) showing even more extreme weather patterns.

In addition to the above, the lake also loses substantial amount of water due to its large size and the process of evaporation during hot and dry periods. This is something that cannot be prevented and that needs to be taken into account while estimating the amount of available water during summer time. Also, during high water level periods the water level of the Lake IJssel Complex is largely controlled through discharges from Lake IJssel to the Wadden Sea via sluices in the Afsluitdijk. However, when the sea level on the outside of the Afsluitdijk is too high this process cannot take place. Pumps are being added to the Afsluitdijk to counter this problem.

4.5.7 Cost effectiveness

Flexible water level management (or control) in the Lake IJssel complex is primarily a change in how the water system is operated, rather than a major change in the physical water infrastructure. In terms of the investments required, the associated costs can broadly be categorized into two components: 1) the costs associated to the pre-investment phase and 2) the costs associated to the investment (implementation) phase.

Pre-investment phase costs comprise all costs incurred in securing the legal and administrative approval for changing the water level regime of the Lake IJssel complex, including environmental impact assessments, technical studies, and the preparation of the necessary (legal) governmental and policy documentation. These costs fall outside the scope of this study.

Investment (implementation) phase costs comprise the expenditures required to operationalise the revised water level regime. These costs fall within the scope of this study (Figure 27). However, data availability constraints meant that only part of these costs could be identified and quantified. Consequently, the estimated implementation costs should be interpreted as a lower-bound estimate of the total costs associated with the transition to flexible water level management. The implementation costs rest on three pillars, namely 1) Infrastructure costs 2) Research and monitoring costs 3) and operational costs.

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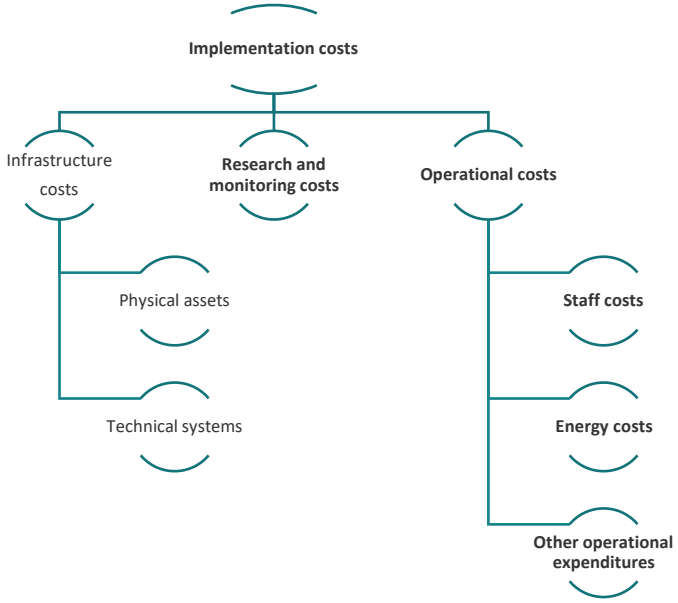


Figure 27. Overview of main components of investment costs. **Bold** *items are those that have been (partly) surfaced in this study.*

1) Infrastructure costs

Infrastructure costs comprise investments in physical assets and technical systems that support the implementation and operation of flexible water level management and as such are made to increase operational flexibility, water conveyance capacity, and discharge capacity where required. These include upgrades to hydraulic infrastructure such as sluices, pumping stations, gates. It is important to note that many of these infrastructure investments are not directly attributable to the introduction of flexible water level management itself. Rather, they constitute adjacent or parallel investments that strengthen the effectiveness and long-term robustness of the water management system while addressing broader challenges such as climate adaptation, water security, flood risk management, and sea level rise. A key example is the expansion of pumping capacity at the Afsluitdijk, which increases the ability to control water levels and maintain freshwater storage under changing climatic conditions.

In addition, the introduction of lower operational water levels has required, or will require, modifications to specific water management structures. Examples include the Stenen Beer inlet structure and the Hoogland pumping station, which need to be adapted to continue functioning effectively under lower water levels. However, no cost information for these adjustments could be retrieved and they are therefore not included in the cost assessment.

Identifying and quantifying these investments is challenging, as the associated costs are often fragmented across multiple programmes, projects, organisations, and funding streams, making it difficult to distinguish expenditures undertaken specifically in support of flexible water level management from broader water management and climate adaptation investments.

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2) **Research and Monitoring costs**

Research and monitoring costs comprise the expenditures associated with generating the knowledge base required to implement, monitor and evaluate flexible water level management. The research and monitoring costs associated with the implementation of the Flexible Water Level are estimated at €1.9 million over the period 2016-2025 (expressed in 2025 prices based on inflatiecalculator.nl version 2.1.3). This data was derived based on an interview with Anjo van Stralen-Wagner (Rijkswaterstaat) on the 14th of July, 2026.

3) **Operational costs**

Operational costs include personnel, energy, maintenance, and other expenditures associated with implementing and managing the Flexible Water Level Innovation. Compared to research and monitoring costs, information on operational expenditures is incomplete and often dispersed across multiple organisations and budgets. Consequently, only part of the operational costs could be identified and quantified, which are detailed below.

Personnel (Staff): The implementation of the innovation was led by Rijkswaterstaat and was largely accommodated within existing organisational capacity. No additional staffing was required, with the exception of one junior assistant who worked full-time on the project for a period of two years (pers. comm. Anjo van Stralen-Wager). The personnel costs associated with this position are estimated at €140,000 (expressed in 2025 prices).

Energy Costs: The water level in the catchment is generally lower than the water level of the lake system itself. As a result, water is pumped into the lake system whenever regional water managers need to discharge excess water. The increase in spring water levels resulting from flexible water level management therefore leads to additional pumping energy requirements. The additional energy expenditure associated with the higher spring water levels was estimated at approximately €60,600 (2025 prices) over the period 2019-2024[1] .

Other operational expenditures: Higher spring water levels have increased the number of closures of the Ramspol storm surge barrier (Ramspolkering). Between 2019 and 2024, the barrier was required to close an additional three days as a result of the revised water level regime. These additional closures are associated with increased personnel deployment and potentially higher maintenance expenditures. They may also impose costs on the shipping sector due to detours and delays, although such impacts fall outside the scope of operational expenditures considered in this study. No reliable cost estimates for these effects were identified.

Lower water levels in late summer and autumn can reduce the accessibility of harbours in the lakes. To mitigate this risk, a €7 million reserve was established for dredging activities near harbours and navigation channels. By 2025, approximately €600,000 had been spent

[1] The additional energy expenditure was estimated based on a cumulative increase in electricity consumption of 597.84 MWh between 2019 and 2024 (WSP, 2025). Using an average electricity price of €95/MWh (E-Bridge, 2024), the additional energy costs amount to €56,794.80. Expressed in 2025 price levels using inflatiecalculator.nl (version 2.1.3), this corresponds to €60,605.32. As annual electricity consumption and price data were unavailable, this estimate should be regarded as an approximation.

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from this reserve. Although these expenditures are related to managing the consequences of the revised water level regime, it is not always possible to determine the extent to which they are directly attributable to flexible water level management. As such, these costs are not considered as part of the cost-effectiveness analysis in this study.

4.5.8 Knowledge gaps

From the research on the reed beds, it has become clear that it would be desirable to gain more knowledge on habitat types in the Lake IJssel complex to better understand the development of reedbeds and the suitability of the area for birds living in these habitats. Additionally, the current data have gaps regarding the operational costs of this innovation (e.g. the higher energy use of the pumps, the impact of the closure of the storm surge dam and the adjustment of two water management structures). Finally, a larger agricultural area could now become inundated due to the flexible water levels; however, the calculation of this inundated area was largely theoretical and the largest factor influencing the inundated areas is likely climatological change. Nonetheless, it remains unclear how changes in these areas will impact the owners of these areas. It might be advisable to ensure the robustness of these areas against flooding events.

4.5.9 Overall evaluation and recommendations

In conclusion, the flexible water level options (see section "Restoration Innovation") were used frequently during the monitoring period of 2019 – 2024 to ensure the right water level for water supply and to prevent flooding. To keep the pace with climate change it will likely become necessary to further increase the water buffer in the future. However, thus far the innovation has been deemed successful with manageable or minimal impacts on the environment (meaning that negative ecological effects have been deemed of minor importance) and the innovation will remain in place.

Table 20. Innovation performance summary.

Evaluation component	Results	Explanation
Intended function achieved	Yes	The flexible water levels function as predicted, with little negative influence on the ecosystem.
Ecological improvement observed	No	There was either no impact on the observed ecological elements (water temperature, coverage of reedbeds) or the results were inconclusive (possible negative effects on birds)
Replication potential	Medium	Depending on the amount of already present water level regulation measures, this measure might be replicated elsewhere.
Unexpected effects	Negative	More frequent closure of the storm surge barrier Ramspolkering. Larger requirement of freshwater buffer than expected based on initial estimates.
Knowledge gaps	Multiple	Costs associated with higher energy use of the pumps, habitat use by wetland birds and in particular birds that live in reed zones, inundation of agricultural zones located outside of the dikes

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4.6 Multi-structure constructed wetland combined with a sand filter

4.6.1 Restoration innovation

The multi-structure wetland is a constructed wetland (CW) that is supported by further smaller-scale structures for enhanced control of the external loading both during the construction of residential areas in the upper catchment and beyond (Figure 28; Hakala et al. 2025). The system has been established by the municipality of Hollola in 2023-2024, i.e. well prior to the beginning of the residential construction in 2025 that is anticipated to last several years.

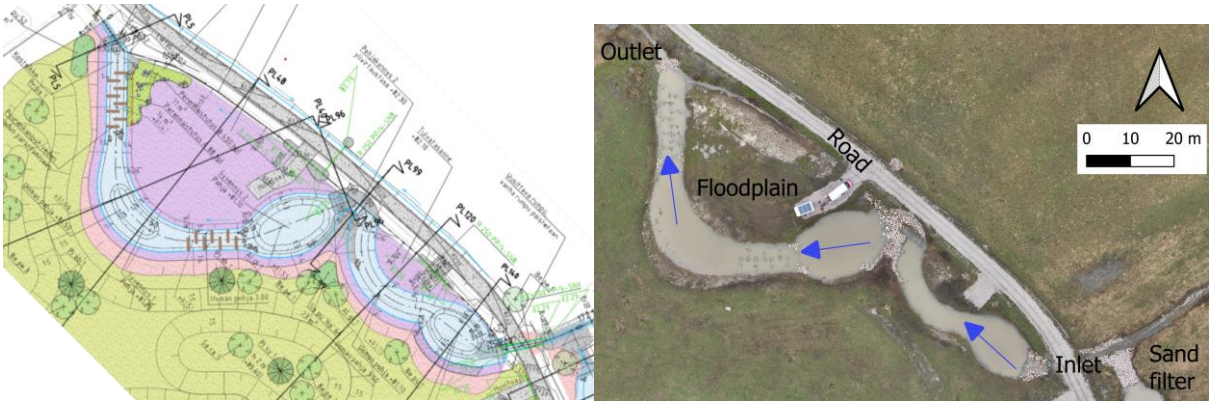


Figure 28. The planform design plan (left) and orthoimage (right) of the multi-structure CW with combined sand-filter located in the catchment area of L. Vesijärvi, Finland. In the plan, permanent water areas are shown in light blue, floodplains in purple, elevated ground in light green, and planted woody vegetation as green circles. The brown bars and grey areas within the wetland indicate the woody structures and rocky sills, respectively. Direction of the flow shown with blue arrows in the orthoimage.

The innovative part of this multi-structure wetland compared to conventional CWs is the inclusion of additional sand filter, rocky sills (Figure 29) and large woody debris (LWD), creating structural diversity and expected to boost its performance. A further innovative aspect is the proactive implementation of measures ahead of planned residential development and its expected increase in external loading. Construction activities can generate substantial sediment and nutrient loads, while increased impervious surfaces can increase runoff (Sillanpää & Koivusalo, 2015). Mitigation is often implemented reactively, despite requiring several years for planning, construction, and ecological maturation. In contrast, the present system is expected to be sufficiently mature to provide effective load control before construction-related pressures and increased runoff intensify.

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Figure 29. Part of the wetland with a rocky sill during spring 2025 (left), and aerial image of the newly constructed roads and pedestrian lanes in the catchment. © Kaisa Västilä, Erkki Heikkilä Oy

This multi-structure CW is located ~200 m upstream from the outlet of ditch Vähäselänoja draining to Lake Vesijärvi. The long-term mean discharge in the ditch is 10 l/s, the maximum discharge 171 l/s and the minimum discharge less than 1 l/s based on modelled values in 2008-2025 derived from operational hydrological model (e.g. Huttunen et al. 2016).

The wetland has a maximum inundated area of 2900 m^2 (0.2% of its catchment area of ~127 ha) and was excavated adjacent to the existing ditch on former clayey fields during winter 2023-2024 (Hakala et al. 2025). It consists of a permanently wet low-flow channel having three wider and deeper pond areas for settling of sediment. Additionally, there are wider floodplain areas to allow for reducing flood peaks. There are also two rocky sills with rapid-like designs to maintain the level of water and to support aeration. Additionally, there are woody structures in the wetland channels to support biofilm development and associated nutrient uptake. The ground south of the wetland was elevated with the excavated soil masses, covered with the excavated surface layers containing a seed bank of local meadow vegetation, and planted sparsely with trees. Seeds of meadow vegetation including flowering species were planted on the floodplains during construction and most of the floodplain areas were covered with vegetation already in the summer-autumn 2024 after construction.

Complementary measures were constructed in the catchment during 2023 including excavation of a new drainage ditch equipped with the sand-filter before discharging to the wetland. The sand-filter contains natural sand with a grain size of 0-16 mm, and the sand layer is 0.5 m thick, 4 m long and 6.8 m wide between the tops of the ditch banks and covered by natural rocks. The sand filter receives inflow only during extremely high runoff events and it is not possible to monitor its load retention performance as its outflow cannot be reliably sampled. Additionally, short sections with floodplains and detention ponds were constructed on some existing ditches to prevent fooding of the surrounding areas and trap suspended sediment. Detention systems are required on residential plots.

4.6.2 Pilot specific objectives

The primary aim of the innovation is to reduce suspended sediment (SS), phosphorus (P) and nitrogen (N) loads to downstream water bodies. The measure is intended to function both during residential construction, when erosion and runoff are expected to increase, and after the catchment development is complete. An additional aim is to improve the efficacy of nutrient processing compared to typical constructed wetlands through the multi-structure design. The wetland is also aimed at mitigating floods by regulating the flow and temporarily storing runoff, complementing other stormwater

management measures. Although no quantitative performance targets were defined during design by an external consultant, load reductions are expected to be moderate because the wetland area is relatively small compared to the upstream catchment area.

4.6.3 Site description

Lake Vesijärvi (107 km^2) with a mean depth of 6.8 m is located in Southern Finland and is surrounded by the City of Lahti, and the municipalities of Asikkala and Hollola. The lake flows through the River Vääksynjoki into L. Päijänne in the north. L. Vesijärvi is divided into four main basins: Enonselkä, Kajaanselkä, Komonselkä and Laitialanselkä, of which Kajaanselkä is the only basin that has reached a good ecological status, and the rest remain in moderate. Additionally, there are two bays, Paimelanlahti-Vähäselkä and Kirkkolahti that are especially vulnerable to external loading that originates from land use and are currently among the most eutrophied areas of the lake.

New residential areas are under construction by the municipality of Hollola on the catchment of the Ditch Vähäselänoja that drains into the shallow bay Vähäselkä. The planned developments have been estimated to increase the residential land use from the current by 30%, which is expected to pose increasing external loading to the lake. The construction of the new roads, pedestrian lanes and water supply pipeline in the first new area took place from late 2024 to mid-2025 (Figure 29). The construction of the first residential buildings started in spring-summer 2026. Infrastructure and residential buildings will also be constructed at another part of the catchment in the future.

4.6.4 Monitoring and indicators used

The wetland's monitoring activity in FutureLakes focuses on the Environmental (Zero pollution; water quality) and Climatic indicators (Climate resilience; water storage) (Table 21). These indicators were selected to evaluate the wetland's effectiveness in reducing pollutants loads, enhancing climate resilience and supporting ecological recovery during the early years of implementation. A detailed description of sampling and analytical methods is provided in Annex a. Samples and measurements were collected at the wetland inlet and outlet unless otherwise stated.

Table 21. Policy area, policy criterion and indicators used for assessment of multi-structure wetland pilot.

Policy area	Policy criterion	Indicator name	Data sources
Environmental	Biodiversity net gain	Vegetation cover	Drone surveys (FutureLakes)
	Zero pollution	TP, PO_4, TN, NO_{2+3}, NH_4, COD_{Mn}, TOC, turbidity	Water samples and sensors (FutureLakes project & Vesijärvi Foundation)
Climate	Flood resilience	Water storage capacity	Design drawings (Municipality of Hollola)

4.6.5 Results and evaluation

Zero pollution

Based on the combined water sample and discharge-based load estimates, the innovative multi-structured wetland reduced loads of NO_3+NO_2-N, SS, TOC and COD_{Mn} loads during the first two years after construction, with annual retention efficiencies averaging 6-13% (Table 22). The highest retention efficiency was observed for PO_4-P (33%). TN showed a small net retention (1.6%). In contrast, negative retention efficiencies, indicating net release of substances from the wetland, were observed for NH_4-

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N and TP as averaged over the first 2 years. For both NO_3+NO_2-N and TN, performance improved from the first into the second year, changing from net release to net retention.

The loads estimates are associated with some uncertainty because of the monitoring constrains due to the relatively few samples and most samples represent flows below the modelled long-term average discharges. Thus, some individual samples collected at high flows and having larger differences between the upstream and downstream concentrations have a substantial impact on the total loads. To provide a more robust assessment, changes in concentrations between the upstream and downstream ends of the wetland were also evaluated (Table 23).

Load-based and concentration-based assessments did not always produce consistent results. The largest discrepancies were observed for COD_{Mn}, SS and TOC. These indicators show 12-59% increases in average concentrations (Table 23) but 6-13% decreases in total loads (Table 22) moving from upstream to downstream. The most consistent changes between loads and concentrations were found for PO_4-P, which was retained by the wetland, and for TP, which was released from the wetland, according to the water samples. The weak performance of this innovative multi-structure wetland for TN and TP loads compared to conventional constructed surface-flow wetlands is likely explained by its low wetland-to-catchment ratio (Nan et al. 2023) and the monitoring period covering only the first two years after its establishment when the biota was not yet fully recovered (Anderson et al. 2024).

Table 22. Changes in annual loads of zero pollution indicators caused by the multi-structure wetland during the 1st and 2nd year after its establishment and the 2-y period, as well as the 2-y retention efficiencies. Negative changes and positive retention efficiencies indicate net retention in the wetland.

Water-sample based annual load estimates				
Parameter (unit)	Load change, 1st year after	Load change, second year after	Total load change during first 2 years	Retention efficiency during first 2 years (%)
COD_{Mn} (kg/a)	-47	-112	-159	6.3
NH_4-N (g/a)	565	645	1210	-10.3
NO_3+NO_2-N (kg/a)	12.6	-79.7	-67.1	9.4
TN (kg/a)	38.6	-53.8	-15.2	1.6
PO_4-P (kg/a)	-0.06	-1.79	-1.85	33.2
TP (kg/a)	-3.4	8.0	4.6	-10.5
SS (t/a)	-2.2	-1.7	-3.9	13.4
TOC (kg/a)	NA	-223	NA	6.4
Average retention efficiency (%)				**6.2**
Annual mean discharge (l/s)	5.6	7.5	6.5	NA

Table 23. Changes in average concentrations of zero pollution indicators during the 1st and 2nd year after the establishment and over the 2-y period, as well as the relative change in concentration. Negative and positive changes indicate concentration decreases and increases, respectively, as water passes the wetland.

Water-sample based average concentration estimates				
	Average concentration change, 1st year	Average concentration change, 2nd year	Average concentration changes during first 2 years	Relative concentration changes during first 2 years (%)
COD_{Mn} (mg/L)	0.4	0.9	0.6	12.3

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Conductivity (mS/m)	-0.9	-0.9	-0.9	-1.2
NH_4-N (µg/L)	14.4	5.5	10.9	76.9
NO_3+NO_2-N (µg/L)	3.1	-754.1	-299.8	25.4
TN (µg/L)	80.0	-640.0	-208.0	-0.4
pH	-0.5	0.0	-0.3	-4.0
PO_4-P (µg/L)	0.2	-2.4	-0.8	-4.9
TP (µg/L)	13.4	12.9	13.2	23.3
SS (mg/L)	14.7	1.7	9.5	58.6
TOC (mg/L)		1.1	1.1	14.8
Turbidity (FNU)		-2.1	-2.1	42.5
Average relative concentration change (%)				**20.1**

Performance was strongly dependent on both discharge and season. Water sample analyses showed increasing retention with increasing discharge for most parameters, with the exception of TN and PO_4 (Figure 30). Similarly, sensor-based observations indicated enhanced retention of SS and NO3-N with increasing discharge, whereas the SAC254 data indicated a slight increase in TOC at higher flows (Figure 31).

Seasonal patterns were also evident. Concentration increases during low flows may be partly explained by biotically generated turbidity and organic matter during the summer, when the lowest flows occur. In contrast, the high-resolution sensor-based estimates indicated a marked improvement in SAC254-based TOC and SS as the growing season progressed (Figure 31), which coincided with increasing abundance of vegetation (Section vegetation, Figure 32). Overall, for SS and turbidity, the wetland changed from a net source to a net sink as flow magnitude and vegetation coverage increased (Figure 30–Figure 31).

The results should be interpreted cautiously because only a few sampling instances coincided with flows higher than the annual average (10 l/s). Concentrations measurements during very low flows show rather large variability, partly reflecting uncertainties associated with water sampling at low flows. At summer low flows the retention time in the wetland is long and evaporation occurs, which likely partly explain the large scatter at low flows. On the other hand, at high flows the incoming concentration peak is high and quick, so that sampling occurs at different times. There is uncertainty in the magnitudes of the highest discharges (Figure 33) since the rating curve had to be extrapolated to over 100% of the highest manually measured discharge.

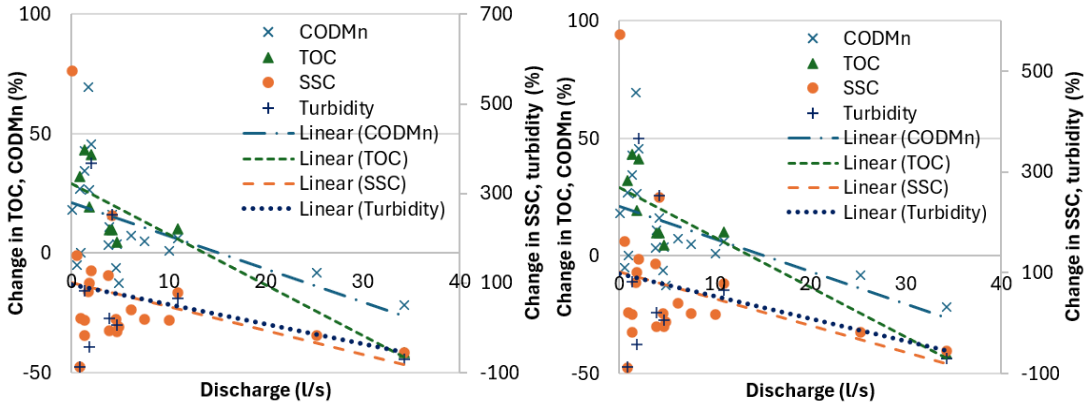
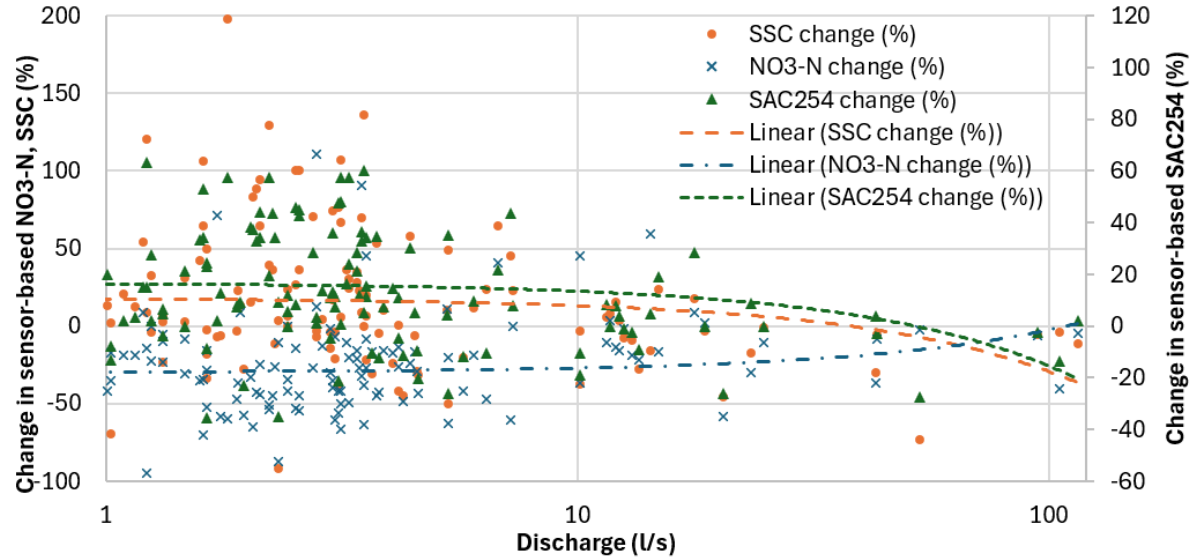


Figure 30. Changes in instantaneous water sample-based concentrations of TN, TP, NO_{2+3} and PO_4 (left) and of COD_{Mn} TOC and SSC (right) between upstream and downstream as a function of discharge. A negative change indicates concentration decreases as flow passes the wetland.



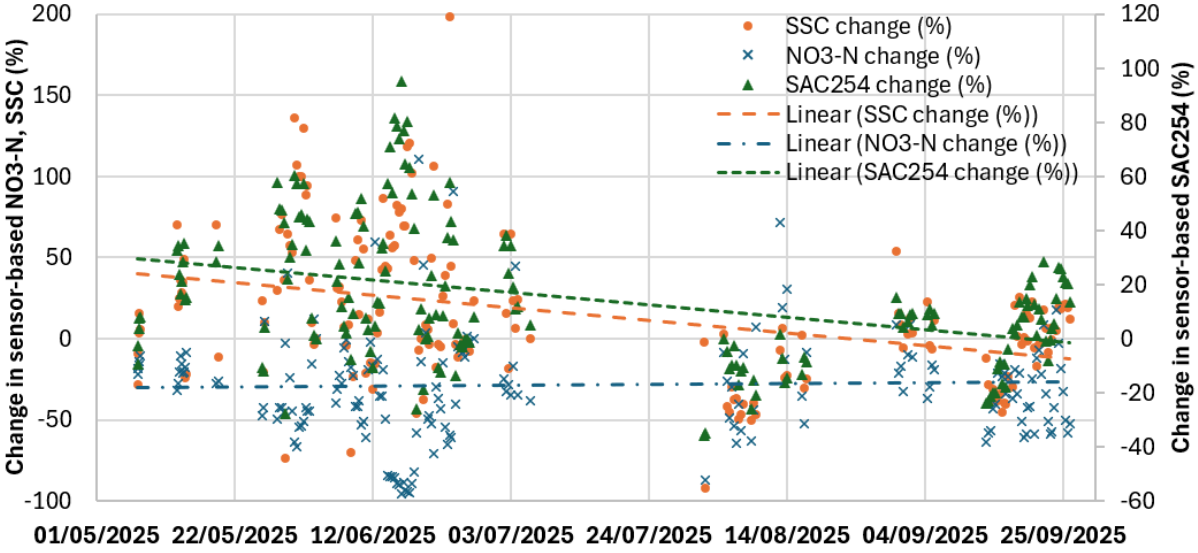


Figure 31. Changes in instantaneous sensor-based concentrations of SSC, NO_3 and TOC (as indicated by SAC254) between upstream and downstream during the growing season of the second year after implementation, as a function of discharge (top) and progress of the growing season (bottom). A negative change indicates concentration decreases as flow passes the wetland. Monitoring was malfunctional from early July to early August.

Climate resilience

Flood resilience

The multi-structure wetland provides a maximum storage volume of ~2300 m^3. Considering the whole upstream catchment area, the maximum storage volume corresponds to a runoff resulting from 1.8 mm of water depth spread equally over the entire catchment. Thus, for the design situation involving a low-density residential area with some more natural areas and an estimated runoff coefficient of 0.4, the rainfall corresponding to maximum storage is 5 mm. These observations suggest that the wetland can notably decrease the peak flows at design storms with durations of less than 1 hour with return

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periods of up to ~10 years. There is additional storage capacity in the open ditches and smaller detention ponds upstream of the wetland (Hakala et al. 2025), which enhances flood resilience at longer duration storms. Overall, the real runoff coefficient is likely lower than standard reference values as stormwater detention systems are required on individual residential plots.

Biodiversity net gain

Development and diversity of vegetation

The photographic survey revealed that both the deeper, permanently wet areas of the wetland and the floodplain areas were largely bare of vegetation in the spring and early summer of the 1st year (Figure 32, top left). The floodplain areas and drier banks above the summer water level obtained vegetation cover by the end of the 1st summer. By contrast, there was very limited development of vegetation in the permanently wet areas of the wetland during the entire 1st summer. The vegetation coverage in the permanently wet areas was substantially higher in the 2nd summer (Figure 32, middle right). Outside of the growing season, there remained low vegetation cover on the riparian areas in the form of wilted grasses whereas the vegetation cover of the wet areas notably decreased over the winter.



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Figure 32 Development of vegetation in the permanently wet parts of the wetland (areas with turbid water in the images) and on the floodplain area visible as dry land left of the water area: from a few months after construction (June 2024, top left) to late summer of the 1st year (August 2024, top right), spring of the 2nd year (early May 2025, middle left), late summer of the 2nd year (August 2025, middle right), after the end of the growing season of the 2nd year (November 2025, bottom left), and spring of third year (March 2026, bottom right). © Anna Hakala, Mirva Ketola, Kaisa Västilä

4.6.6 Technical performance

Achievement of design target

The design targets of the multi-structure wetland were partially achieved based on the 2-year monitoring data after the construction. The wetland together with the complementary measures in the catchment enhances flood resilience. It also decreased the loads of suspended sediment, TOC and total and dissolved nutrients except for NH_4-N and TP. As NH_4-N forms a negligible part of the total nitrogen flux, it can be considered insignificant for the overall technical performance evaluation. By contrast, the increase in TP concentrations and loads by the wetland disagrees with the design target and most literature observations (e.g., Kill et al. 2022; Härkönen et al. 2026a) and is unexpected in relation to the observed decrease in SS loads. This discrepancy is likely partly explained by the fact that the vegetation and other biota were not yet fully developed during the first 2 years, while retention efficiency in wetlands typically improves with increasing vegetation coverage (Kill et al. 2022). The retention of TOC loads by the wetland was also unexpected as water protection structures are typically not capable of retaining dissolved organic carbon which is commonly the dominant fraction of TOC (cf. Härkönen et al. 2023).

The wetland demonstrated a satisfactory operational stability. It appeared to perform well under growing-season storm events with high flows and loads, although only few such events were covered by the monitoring. For most parameters, the performance notably increased from the first to the

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second year, indicating a quick start of the biogeochemical processing after implementation. This finding is in agreement with the rather quick development of both the aquatic and riparian vegetation, which can be used as a proxy of the recovery of the biogeochemical processing after excavation works (e.g., Västilä & Jilbert 2025). We anticipate further improvement in the retention efficiencies in the next years as the ecosystem becomes fully established.

Maintenance and operational requirements

There are no operational requirements of the measure as it is a passive, nature-based treatment system that requires energy inputs mainly during the construction phase. Maintenance requirements of the measure are expected to be low and consist of occasional removal of the deposited sediment, with rather well-established procedures available. Widely available standard excavators can be used in small wetlands, whereas larger wetlands require more expensive long-reach excavators or floating machines. Wetlands with similar areal shares are emptied of deposited sediment approximately every 7th year in the region (Härkönen et al. 2026b), which is also expected a-priori for the multi-structure wetland, noting however that the interval is highly dependent on site-specific conditions. The maintenance needs can be more objectively determined based on monitoring the change in bed elevation or nutrient retention with time. Additionally, approximately annual visual monitoring of the stability of the woody and stony structures and sand filter is required at least until the system has matured. The maintenance frequency can be adapted after the first maintenance cycle. Postponement of the maintenance does not cause immediate failure of the system but likely decreases its performance for flood retention and for at least part of the zero pollution variables.

Replicability and scalability

The measure is well replicable and scalable. The flood resilience performance is expected to be similar in comparable fine soils and climate conditions whereas nutrient retention efficiency is likely dependent on more detailed soil biogeochemistry. The replication is supported by available knowledge and established design guidelines and processes on standard CWs, whereas the design guidance of the additional within-wetland structures is less established. The up-scaling is supported by targeting such wetlands on flood-prone depressions with less valuable and profitable land, which decreases the alternative costs.

Technical challenges and limitations

Limitations include the sensitivity of biological nutrient processing to temperature, and thus particularly NO_3-N removal is not efficient at temperatures close to 0 °C, i.e., during Boreal winter and early spring, as also shown by the data from February to April in the 1st year. The retention of particulate substances is also expected to be lower in winter and spring before vegetation re-establishment than in the growing season when above-ground vegetation is more abundant.

4.6.7 Cost-effectiveness

Cost-efficiency was evaluated in relation to the main targets of reducing TP, TN and SS loading to Lake Vesijärvi. Within the first two years of monitoring, the multi-structured CW has managed to reduce the TN load by 1.6%, and SS load by 13.4% (Table 22). The TP load, in turn, has increased by 10.5%. However, the sum of decreased TN, TP and SS load within the first two years has been 14.5 kg a^{-1}. The estimated total capital costs for the planning and construction of the 0.29-ha multi-structure wetland were c. M€0.23, i.e. M€0.79 ha^{-1} (value of 2025). The annual operational costs including maintenance were not obtained. Using the sum of TP, TN and SS change over the first two monitoring periods and the capital and operational costs of the structure, the load reduction cost-effectiveness is estimated to be on a level of M€0.009 kg^{-1} ha^{-1}.

The wetland is intended to function for at least 50 yr, assuming that it is regularly maintained by e.g., removing the settled material. The efficiency of CWs generally improves at least during the first 3-8

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years (Kill et al. 2022) and the sand-filter module is expected to reduce the loads during and after the construction of the second residential area, potentially improving the cost-efficiency further.

4.6.8 Knowledge gaps

The results of zero pollution indicators (Table 22. –Table 23) must be interpreted with caution as the performance of the wetland appeared to be discharge-dependent (Figure 31) and very limited monitoring data was available from events of higher-than-average discharge. These events are known to typically generate most annual loads in corresponding geographical conditions (e.g. Kämäri et al. 2019) but are poorly captured by most studies on CWs (Anderson et al. 2024). The discharge- and season-dependent results produce particular uncertainty on annual fine sediment retention efficiency (Figure 32–Figure 33), which is likely further reflected particularly on TP as over 80% of TP is particle-bound at the site.

While meta-analyses of conventional CWs show generally removal of TN and NO_3-N (Nan et al. 2023), very varied performance has been reported regarding phosphorus removal with substantial knowledge gaps existing (Anderson et al. 2024). To address these gaps, the monitoring should continue or be repeated after a few years to capture the performance when the biota has fully recovered from the construction works. This would also enable covering more high flow events and winter-time events with substantial flow. Knowledge gaps also remain on the performance and significance of the single structures inside the complex and on the cumulative impact of the multi-structure wetland and complementary measures on droughts.

4.6.9 Overall evaluation and recommendations

The multi-structure constructed wetland appears to provide a rather stable and operationally easy solution for mitigating floods. Further benefits included slight (6%) load reductions already during the first 2 years after construction, as averaged over all nutrient and sediment parameters, likely supported by the rocky sills and additional features expected to improve the performance compared to conventional CWs. Retention efficiency enhanced with time but also with increasing flow, which is encouraging although the latter is somewhat unexpected. With the innovation claiming an area corresponding to 0.2% of its catchment area, annual removal efficiencies of nutrients are likely at best moderate in Boreal–Northern Temperate conditions as substantial flow occurs outside the growing season with limited biological activity. The performance is expected to improve if replicated at further sites with higher area ratios. Overall, the multi-structure wetland appears a climate- and nature-friendly solution for the management of stormwaters from low-density residential catchments or of agricultural waters. We recommend further research on the knowledge gaps on such innovative boosted CWs to decrease the uncertainties.

Table 24. Innovation performance summary for multi-structure wetland

Evaluation component	Results	Explanation
Intended function achieved	Partly	Partly positive, partly negative changes in zero pollution indicators.
Ecological improvement observed	Partly	Created wetland area likely supports local biodiversity.
Replication potential	High	Costs lowest when established on flood-prone depressions.
Unexpected effects	Neutral	Increased TP load despite decreased SS load. Decreased TOC load. Enhanced performance with increasing discharge.

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Knowledge gaps	Significant	Performance outside growing season, during mean to high flows, and after biota fully developed. Performance of single structures inside the complex.

4.7 Raingardens

4.7.1 Restoration innovation

Raingardens are nature-based sustainable drainage systems (SuDS) designed to capture, store and infiltrate stormwater runoff from impervious surfaces such as roofs, roads and pathways. Rather than allowing rainwater to flow directly into storm drains, a raingarden temporarily stores runoff and enables it to infiltrate naturally into the ground. Most raingardens are designed to drain within 12-48 hours after a rainfall event.

Raingardens can take many forms, including infiltration basins, bog gardens, filter strips, green roofs and walls, ponds and wetlands, swales and in-ground raingardens (Raingardens Glossary - www.10kraingardens.scot). Although designs vary according to local conditions, effective raingardens typically combine three components; a site adaptation that directs stormwater to the raingarden via swales, pipes, or appropriate landscape grading, a specially designed soil profile that supports the removal of nutrients and heavy metals,, and selective planting of vegetation, ideally, native plants with deep root systems that can tolerate fluctuations in moisture (floods and droughts) and absorb excess water and nutrients, thereby improving water quality while stabilising the soil.

Unlike traditional drainage systems, which were designed primarily to remove water as quickly as possible, raingardens are designed to manage water as a resource. Raingardens provide a sustainable, nature-based solution to flood mitigation by mimicking natural rainwater retention and infiltration processes within a constructed bioretention system. By incorporating selected plant species that can withstand very wet and very dry conditions, rain gardens also can enhance habitat for biodiversity.

When compared to drainage infrastructure, raingardens are a low-cost intervention to reduce storm water run-off. The costs of implementing raingardens have been estimated as 450 Euros to 600 Euros per m^2, although this is likely to vary widely depending on the type of raingarden chosen and the level of engineering required to install it (Siwiec et al., 2018). In addition to investment costs, operation and maintenance costs also need to be considered. The time it takes to implement a raingarden depends on scale, context, and approval requirements. The physical construction itself usually takes 1-3 days. Most of the time is spent on planning, approvals, and coordination. Annual maintenance of the raingarden is required.

In Scotland, SuDs have been mandatory in new developments since 2003 (Water Environment and Water Services (Scotland) Act 2003 (WEWS Act) and Water Environment (Controlled Activities) (Scotland) Amendment Regulations 2021 (CAR)) with strong involvement and guidance from the Scottish Environment Protection Agency (SEPA) (Regulatory Method WAT-RM-08) and CIRIA (The SuDS Manual C753). In addition, the Scottish Government (2021) framework supports transition to water resilient places via Blue-Green infrastructure. The Scottish Green Infrastructure Forum has set an objective to implement 10,000 raingardens in Scotland (Figure 33) (About the campaign - www.10kraingardens.scot).

The Loch Leven catchment has experienced long-standing challenges associated with urban run-off, surface water flooding and combined sewer overflows. In response, the Kinross Raingardens Challenge promoted the installation of raingardens throughout the catchment as a community-led approach to managing stormwater while delivering wider environmental and social benefits. By 2021, 39 raingardens had been established within the catchment (D'Arcy et al., 2021). This case study focused on one basin and three in-ground rain gardens in Kinross within the Loch Leven catchment.

The objectives of the case study were to evaluate the effectiveness of rain gardens as a nature-based solution for enhancing biodiversity, supporting pollinators, reducing surface-water runoff and contributing to wider catchment management objectives. The assessment combined field surveys of vegetation and pollinator communities with hydrological modelling to evaluate both local ecological benefits and potential contributions to flood-risk mitigation. Vegetation surveys were used to compare plant species richness, diversity and composition between rain gardens and surrounding habitats, while pollinator surveys assessed the value of rain gardens as foraging resources for insects. In parallel, catchment-scale modelling was undertaken to explore the potential contribution of rain gardens and other nature-based interventions to runoff reduction and flood management within the Loch Leven catchment. Together, these approaches enabled assessment of both site-scale ecological outcomes and the extent to which rain gardens could contribute to broader environmental improvements across the catchment.

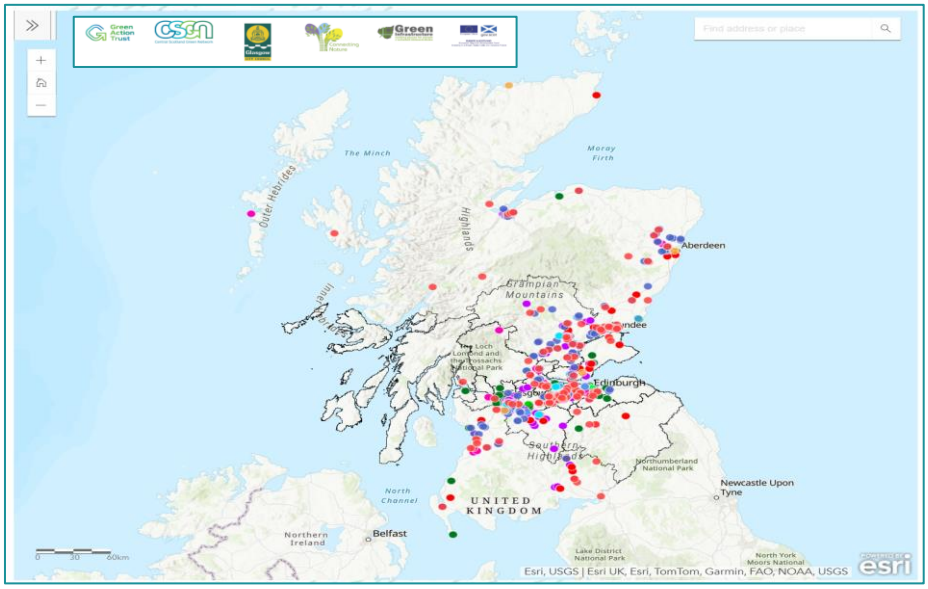


Figure 33. Location of 989 raingardens in Scotland. Accessed 09/07/2026 [Where are the raingardens? - www.10kraingardens.scot]

4.7.2 Pilot specific objectives

The original aim of the Kinross Raingardens Challenge was to achieve 20 new or existing raingardens in Kinross-shire by 2020. Raingardens were defined as “any green infrastructure designed to accept rainfall runoff” and the focus area was described as a “small towns and villages in the catchment of Loch Leven National Nature Reserve” (D’Arcy et al., 2021). The area of interest comprises a landscape of sandy soils and gravels and the water table is high in some areas. Most of the small towns in the area are served by combined sewerage systems and there is a history of pollution problems associated with discharges from combined sewer overflows and industrial/commercial premises.

4.7.3 Site descriptions

Four existing raingardens within the town of Kinross were selected for vegetation and biodiversity assessment based on their type, location and accessibility. These were: Kinross Park and Ride, Kirkgate Park, Kinross Link Road and Loch Leven Harbour Car Park. The locations of these sites within the Kinross area are shown in *Figure* 34.

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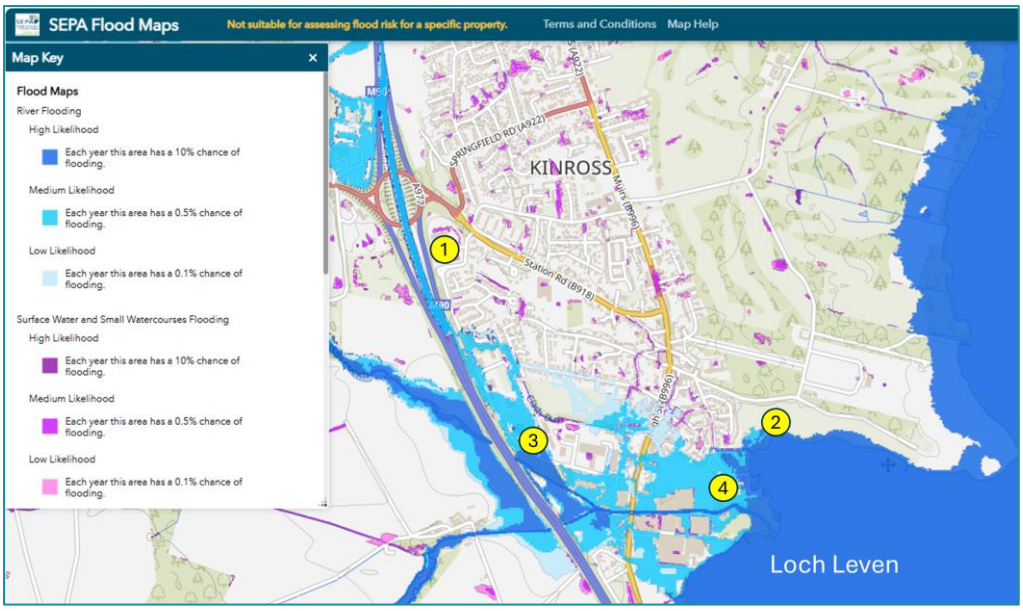


Figure 34*. SEPA flood risk map highlighting current risk of river flooding (shades of blue) and surface water flooding (shades of purple) and locations of raingardens assessed. Information on this flood map, including copyright information, can be found at* SEPA Flood Maps (accessed 10/07/26)

Site 1: Kinross Park and Ride

The Kinross Park and Ride rain gardens (Figure 35) were constructed in March 2022 following the failure of two soakaways within the public car park. The scheme comprises three central rain garden areas. The smallest area, which consists largely of coarse rock, was excluded from vegetation sampling. The two larger areas were designed as infiltration swales and mostly sown with wildflower seed mixes ('Urban Wildflower Meadow and 'Get nectar quick' mixes from Scotia seeds; Kinross Newsletter March 2022, p 32). At the time of the survey, vegetation was approximately 60 cm tall and formed a dense herbaceous cover. The survey was conducted on 6 July 2026 in calm, overcast and dry weather.

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Figure 35. Kinross Park and Ride showing section covered with large rocks and little vegetation (left) and seeded raingarden section (right).

Site 2: Kirkgate Park

The Kirkgate Park rain garden consists of three planted areas of varying sizes and shapes, embedded within a park landscape of regularly mown grassland and pedestrian paths *(Figure 36*). Unlike the Park and Ride rain gardens, these areas were not seeded and supported naturally colonised vegetation. Plant growth was relatively dense, reaching approximately 1 m in height. The survey for this site was conducted on 7 July 2026 in calm, overcast and dry weather.



Figure 36. Kirkgate Park rain garden (left) and the surrounding mown grass area (right).

Site 3: Kinross Link Road

The Kinross Link Road site comprises a roadside SuDS network including four narrow grass swales and a larger settling pond (Figure 37). The swales receive runoff directly from the road via gully-free drainage and are managed through annual cutting. The settling pond, which receives drainage from the surrounding road network and adjacent commercial premises, supports deeper soils and a more structurally diverse plant community than the roadside swales. The pond landscape was enhanced as part of recent improvement works completed in 2023. Together, these sites represent a range of SuDS designs, management regimes and vegetation structures. Their comparison provides an opportunity to assess how different SuDS features contribute to plant biodiversity and pollinator habitat within an

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urban environment. The survey for this site was conducted on 8 July 2026 in calm, sunny and dry weather.



Figure 37. Settling pond (left) and roadside SuDS (right) along the Kinross link road.

Site 4: Loch Leven Harbour car park

The Loch Leven Harbour Car Park site (Figure 38) was redeveloped to incorporate a series of shallow vegetated depressions and permeable paving. Large gaps between paving blocks were designed to allow grasses and herbaceous species to colonise the surface, while surrounding planted areas were sown with a range of species to enhance biodiversity. The site therefore represents a highly engineered SuDS feature that combines drainage and habitat creation within a busy public car park. The survey for this site was conducted on 9 July 2026 in calm, sunny and dry weather.



Figure 38. Raingardens in Loch Leven Harbour car park showing permeable parking areas (left) and surrounding seeded areas (right).

4.7.4 Monitoring and indicators used

Raingarden monitoring within the FutureLakes project focused on their impacts on biodiversity and the potential contribution of raingardens to flood-risk mitigation (Table 25). As the raingardens were

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already installed in 2021 baseline monitoring data were not available and before and after comparisons could not be undertaken. Instead, raingardens were compared to those from unimpacted areas of ground nearby. It was not possible to retrofit water flow and water quality monitoring into raingardens that were already established. However, their likely impacts on water flow were assessed using a modelling approach based on the UKCEH City Explorer Toolkit Detailed survey methodologies are provided in Annex a.

Table 25. Policy area, policy criterion and indicators used in the assessment of raingardens

Policy area	Policy criterion	Indicator name	Data sources
Environmental	Biodiversity net gain	Vegetation cover; pollinators	Vegetation surveys; pollinator surveys
Climate	Flood resilience	Water storage capacity	Model output

4.7.5 Results and evaluation

Biodiversity net gain

The raingardens supported more diverse vegetation communities than the surrounding habitats (Table 26). Across the four study sites, species richness and Shannon diversity were generally higher within the raingardens than in adjacent mown grass areas or sparsely vegetated urban areas (Figure 39; Figure 40). The strongest differences were observed at the Park and Ride and Link Road sites, where purpose-designed planting created more structurally diverse vegetation communities than the surrounding habitats. The Harbour Car Park site exhibited the highest overall diversity and species richness, demonstrating the biodiversity benefits that can be achieved through species-rich planting and reduced management intensity.

The quadrat level-data also showed substantial variation within individual raingardens, reflecting differences in vegetation establishment, management history and site conditions. Despite this variability, rain garden habitats consistently supported more complex plant communities than the surrounding comparison areas.

While diversity metrics at Kirkgate were similar between the rain garden and adjacent grassland habitats, the rain garden supported a greater abundance of flowering herbaceous species and a more heterogeneous vegetation structure. These characteristics are not fully captured by species richness and Shannon diversity alone but are likely to provide additional ecological value through increased habitat complexity and resource availability for invertebrates and other wildlife.

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Table 26. Summary of quadrat-evel Shannon diversity (H') and species richness (mean ± SE) for rain garden and background habitats (controls) across the four Kinross rain garden sites surveyed in July 2026.

Site	Management	Number of quadrats	Mean H'	SE H'	Mean Species Richness	SE Species Richness
Park and Ride	Background	10	1.14	0.17	5.5	0.67
Park and Ride	Rain garden	10	1.74	0.07	11.5	0.73
Kirkgate	Background	20	1.54	0.06	6.75	0.35
Kirkgate	Rain garden	20	1.45	0.07	6.9	0.39
Link Road	Background	10	1.25	0.13	6.6	0.64
Link Road	Rain garden	30	1.57	0.05	8.57	0.41
Harbour Car Park	Rain garden	35	1.93	0.05	10.74	0.39

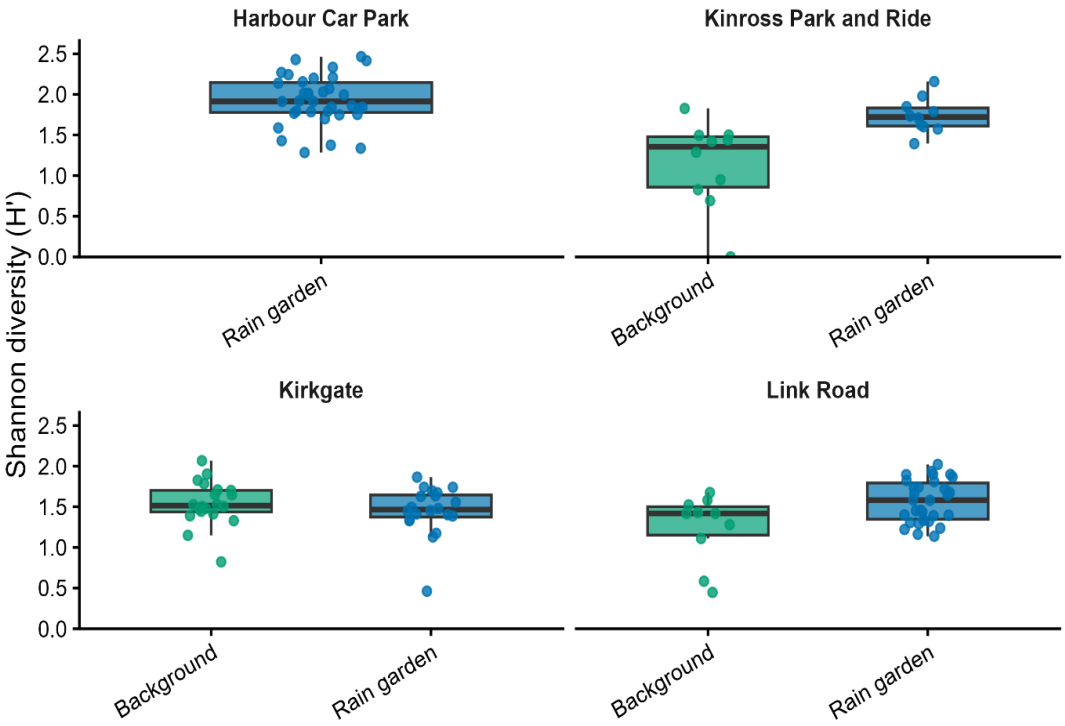


Figure 39. Quadrat-level Shannon diversity (H') in rain garden and comparison habitats (except Harbour Car Park) across the four Kinross rain garden sites. Each point represents an individual quadrat, with boxplots showing the median, interquartile range and range of values. Shannon diversity was calculated from normalised percentage cover values.

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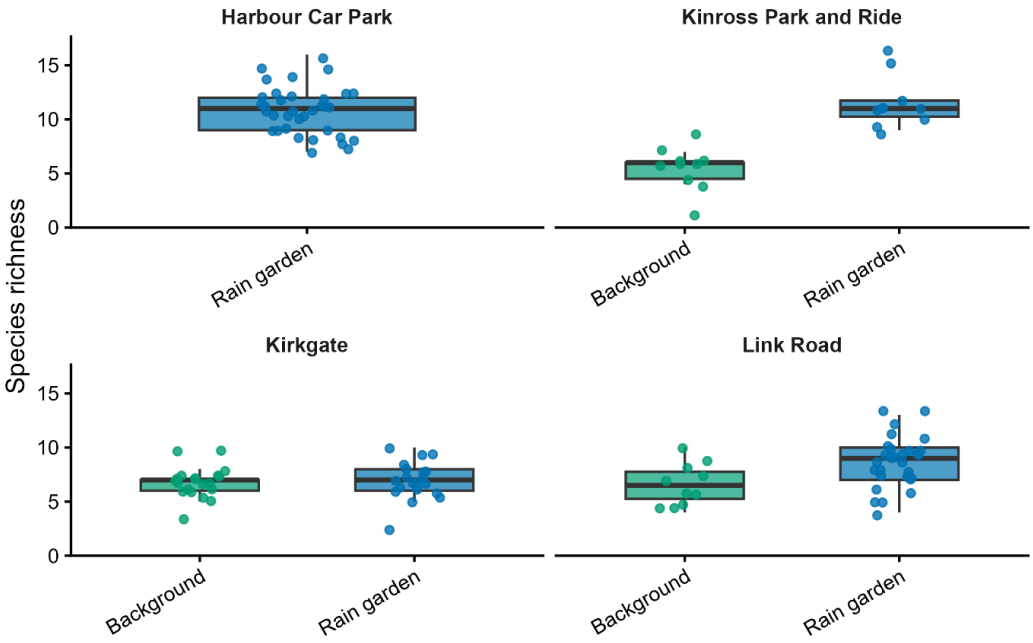


Figure 40. Quadrat-level species richness in rain garden and comparison habitats (except Harbour car park) across the four Kinross rain garden sites. Each point represents an individual quadrat, with boxplots showing the median, interquartile range and range of values. Species richness was calculated as the number of species recorded within each quadrat.

The raingardens also provided substantial benefits, where the average number of pollinators recorded across the raingardens surveyed compared to nearby areas of bare earth or mown grass is show in Figure 41. No pollinators were recorded on the bare earth or mown grass plots whereas, in contrast, an average of 92 pollinators m^{-2} were recorded in the raingarden plots, although some (e.g. bumblebees and honeybees) were found in higher densities than hoverflies, other flies and wasps. Overall, raingardens increased the number of pollinators in any given area from zero to almost 100 individuals m^{-2}. Overall, the biodiversity objective of the pilot was achieved. The raingardens successfully increased plant diversity, flowering vegetation and pollinator abundance at the local scale, demonstrating their value as urban biodiversity enhancement measures.

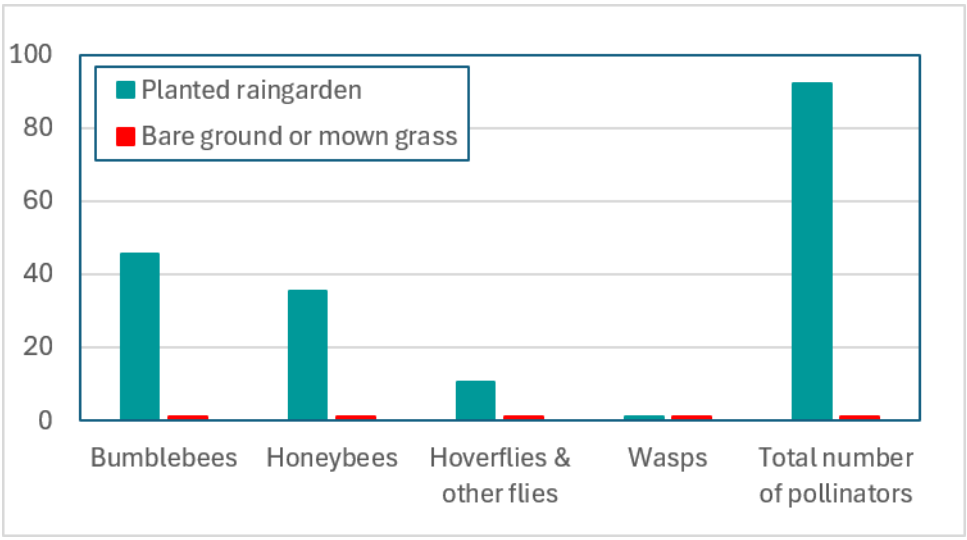


Figure 41. The average number of different insect pollinators across all raingardens compared to all bare ground or mown grass surveyed nearby (individuals m^{-2})

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Climate regulation

Hydrological modelling was undertaken to assess water storage capacity and scalability using the UKCEH City Explorer Tool, adapted for raingardens (see detailed methods in Annex a). The purpose of this approach was two fold; firstly to provide some context to the hydrological capacity of the installed systems and secondly to develop a planning approach to inform future initiatives. The following potential change scenarios were investigated to determine their impacts on water flow and its accumulation in relation to the following questions:

- Where are the best places to install rain gardens?
- What coverage of rain gardens gives meaningful reduction in surface flows?
- Can the same benefit be achieved by multiple smaller areas, or fewer larger areas?

The modelled changes in land-use are summarised in *Table 27,* showing that a total of 5384 m^2 of new NbS were installed in the "change" scenario compared to the "current" scenario. As illustrated in Figure *42*, the largest flow reductions occurred where impermeable surfaces were converted to raingardens, with local flow reductions up to 96.6%, assuming that NbS have runoff coefficients equal to grassland on Hydrological Soil Group B. Despite installing NbS in the locations chosen for the "change" scenario has no effect on runoff in the Clash Burn catchment because no new NbS were installed there (*Figure 42*). The effects in the Ury Burn catchment were also negligible because only 48 of the 1,450,000 m^2 were converted to NbS. Similarly, while the 5384 m^2 of total new SuDS all lie within the South Queich catchment, they comprise a negligible fraction of the 159,520,000 m^2 total area and, therefore, have a negligible effect at catchment scale.

Table 27. Areas of different land-use classes changed between "current" and "change" scenarios.

"current" land use	"change" land use	Area affected (m^2)	% change
Arable & horticulture	NbS	976	18
Improved grassland	NbS	972	18
Buildings	NbS	4	4
Roads	NbS	988	18
Suburban grass	NbS	2444	44
TOTAL		**5384**	

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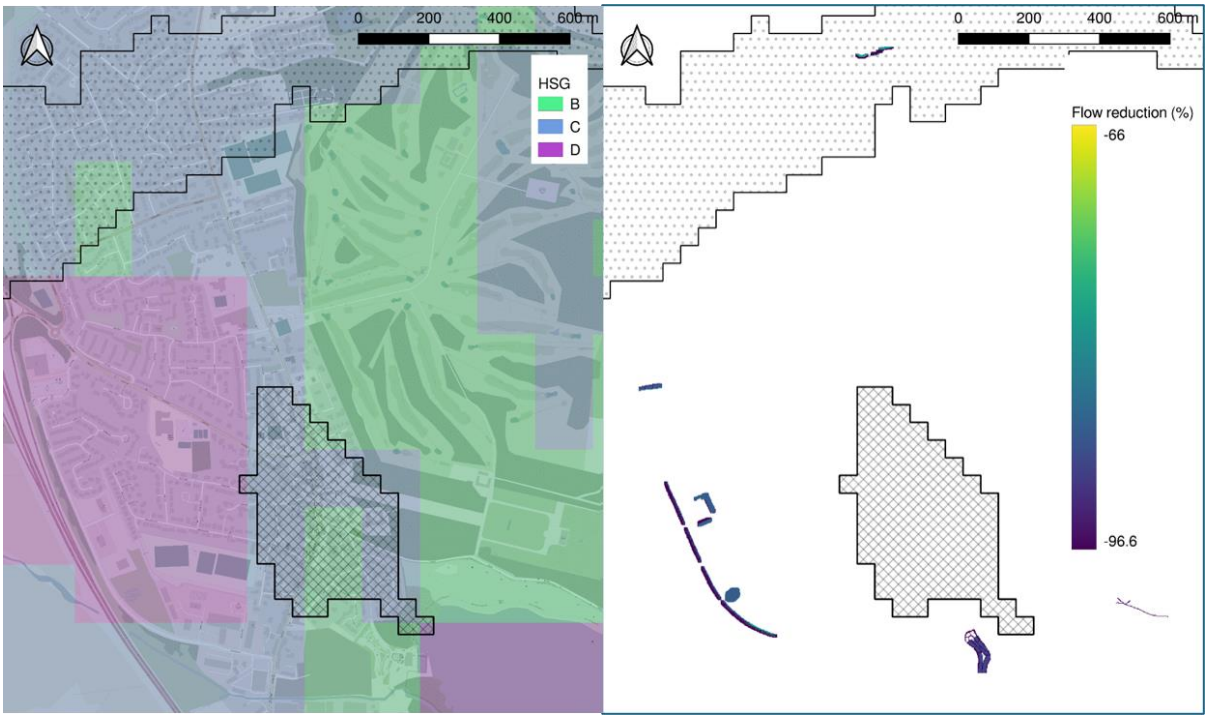


Figure 42. Left: Map of Kinross showing Hydrologic Soil Groups (HSGs) in green-blue-purple, the Clash Burn catchment (hatched), part of the Ury Burn catchment (dotted), and potential sites of new NbS (dark magenta). Right: Level of flow reduction (%) between "current" and "change" scenarios tested. Background map data from OpenStreetMap. © OpenStreetMap contributors.

4.7.6 Technical performance

Achievement of design target

The Kinross Raingarden Programme was established to address local stormwater management challenges and reduce the impacts of combined sewer overflows while enhancing urban biodiversity and community engagement. Evidence collected during the FutureLakes project indicates that biodiversity objectives were successfully achieved at the site scale. Rain gardens consistently supported higher plant species richness, a greater abundance of flowering plants and substantially higher pollinator numbers than adjacent mown grassland and other comparison habitats. However, the extent to which hydrological objectives have been achieved is less certain. Modelling suggests that rain gardens and associated nature-based solutions can contribute to reductions in surface runoff and local flood risk, but direct measurements of runoff attenuation, sewer overflow reduction and water-quality improvement were not undertaken during implementation. Consequently, it remains unclear whether the scale of intervention achieved within the catchment has delivered measurable hydrological or ecological benefits at the scale of Loch Leven.

Maintenance and operational requirements

Rain gardens are generally low-maintenance interventions once established, although periodic management is required to maintain both vegetation quality and hydraulic performance. Experience from the Kinross scheme indicates that vegetation management, occasional reseeding, litter removal and management of sediment accumulation are necessary to sustain biodiversity value, infiltration capacity and visual amenity. A notable feature of the project has been the involvement of volunteers and community groups in establishment and maintenance activities. This has reduced management costs while generating wider social and educational benefits. However, long-term reliance on volunteer participation may create challenges if community engagement declines, highlighting the importance of continued support from local authorities and community organisations.

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Replicability and scalability

Raingardens are a highly replicable nature-based solution that can be incorporated into a wide range of urban and peri-urban environments. The approach requires relatively modest infrastructure and can be adapted to local site conditions. The biodiversity benefits observed are likely to be transferable to other locations, particularly where species-poor amenity grassland is replaced by more diverse planting schemes. However, modelling indicates that wider environmental benefits are highly dependent on scale and placement. While individual rain gardens can provide localised runoff reduction and biodiversity gains, meaningful improvements in downstream water quality, flood regulation and the ecological condition of Loch Leven are likely to require a strategically located network of interventions across the catchment. Given the scale of investment indicated below, raingardens should therefore be viewed as components of an integrated nature-based solution strategy rather than as standalone measures.

Technical challenges and limitations

Several factors constrained evaluation of rain garden performance within the project. Most notably, baseline monitoring was not undertaken prior to installation and monitoring of the rain gardens within the Loch Leven catchment could not easily be retrofitted. As a result, direct assessment of runoff reduction, sewer overflow mitigation, pollutant retention and water-quality improvement was not possible, despite these benefits forming part of the rationale for implementation. In addition, the relatively small number of rain gardens included in the assessment limited the ability to detect downstream ecological effects. These limitations emphasise the importance of incorporating baseline surveys and long-term monitoring into future rain garden programmes from the outset.

4.7.7 Cost effectiveness

Using the figures cited above from our literature review (i.e., €450-600 m^{-2} installation cost) and the FutureLakes 'change scenario' area from the hydrological modelling exercise (i.e., 5,384 m^2 of additional NbS) we derive indicative implementation costs, excluding land acquisition, monitoring and long-term maintenance costs of:

- Lower estimate: 5,384 m^2 × €450 m^{-2} = €2.42 million
- Upper estimate: 5,384 m^2 × €600 m^{-2} = €3.23 million

Assuming annual maintenance costs of roughly 2%-5% of capital costs, which is typical for planted SuDS infrastructure, annual maintenance expenditure could be expected to fall in the range of approximately €50,000 - €160,000 per year, depending on management requirements and volunteer contributions. While volunteer-led management can substantially reduce operational costs, experience from the Kinross Raingardens Challenge suggests that reliance on community stewardship may become increasingly uncertain as public interest declines over time. Consequently, long-term maintenance budgets should assume a gradual transition from volunteer-led management towards greater institutional support.

FutureLakes modelling demonstrated that the environmental return on this investment depends strongly on spatial planning. Rain gardens located within critical runoff pathways and pollutant source areas are likely to generate substantially greater benefits for flood-risk mitigation and nutrient retention than equivalent investments elsewhere. A robust cost-benefit assessment would therefore combine hydrological modelling with ecosystem service valuation and maintenance-cost projections to identify the number and placement of rain gardens that maximise environmental benefits per unit cost.

This study draws similar conclusions to (Vesuviano et al., 2025), namely that small-scale NbS installations can have impact at street- or property-level, but are less likely to have noticeable effects at town-level. At this scale, there needs to be a greater area of NbS that actively collect runoff from a wider area (compare the sizes of the areas of interest in *Figure 44* with the sizes of the areas converted

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to NbS). Implementing modified flow paths in the model would require more time, potentially site surveys, and the incorporation of different modelling tools, such as RHESSys (Tague & Band, 2004) or i-Tree Hydro (Wang et al., 2008), all of which have their own limitations.

4.7.8 Knowledge gaps

Although the results demonstrate local benefits (particularly for biodiversity), important uncertainties remain regarding the long-term effectiveness of rain gardens and their contribution to catchment-scale impacts. While rain gardens are widely promoted as providing multiple ecosystem services in Scotland, including biodiversity enhancement, nutrient retention, flood-risk management, climate regulation and amenity benefits, the relative magnitude of these benefits within the Loch Leven catchment remains questionable at the scale of implementation.

A key knowledge gap relates to nutrient retention and water-quality improvement. Rain gardens are designed to intercept, infiltrate and treat urban runoff before it enters receiving waters, and have been promoted as a means of reducing sediment, phosphorus and other pollutants reaching Loch Leven. However, no direct monitoring of inflow and outflow water quality, nutrient retention or pollutant removal was undertaken during this implementation of the facilities considered here. In addition, we know of no such monitoring across any of the raingardens implemented in this catchment. For biodiversity effects, long-term monitoring is required to understand ecological succession, the persistence of pollinator populations, the potential encroachment of undesirable species and the extent to which active management is required to maintain biodiversity gains over time.

Uncertainty also surrounds the effectiveness of rain gardens for flood-risk management and hydrological regulation. Modelling undertaken within FutureLakes suggests that rain gardens can contribute to reduced runoff generation and provide local flood-mitigation benefits. However, direct measurements of infiltration rates, runoff attenuation, peak flow reduction or reductions in combined sewer overflows were not available. As a result, hydrological benefits remain largely inferred rather than empirically demonstrated. Further monitoring is required to validate model predictions and improve understanding of rain garden performance under different rainfall conditions and over longer timescales. The modelling demonstrated that while individual rain gardens can provide valuable local benefits, meaningful improvements in downstream water quality, flood regulation and ecosystem condition within Loch Leven are only likely to be achieved through the coordinated implementation of large numbers of interventions at strategically targeted locations throughout the catchment.

Vegetation establishment and enhanced soil organic matter may contribute to carbon sequestration, while reductions in stormwater conveyance and treatment requirements may reduce emissions associated with conventional drainage infrastructure. However, these potential benefits were not quantified during the project. Likewise, the embodied carbon cost of construction, maintenance activities and biogeochemical processes within rain garden soils remain uncertain. Quantification of net greenhouse gas balances would improve understanding of the wider climate benefits of rain garden implementation.

Finally, the long-term social and governance requirements for sustaining rain garden performance remain uncertain. Community engagement and volunteer participation have been important factors underpinning the success of the Kinross rain garden programme, delivering both practical maintenance support and wider educational benefits. However, the durability of these arrangements over time, and the implications of declining community participation for site condition and ecosystem service delivery, are not yet fully understood.

4.7.9 Overall evaluation and recommendations

A key driver for the raingardens project was the significant storm sewage overflow problems in Kinross and Milnathort, which increase phosphorus inputs to Loch Leven. Initially, 20 rain gardens were planned by 2020. However, there were 39 gardens in the area by 2021 and these had been turned into a local attraction and recreational activity by creating a rain garden trail (*Figure 43*). The

local community received an achievement award from Susdrain in recognition of this. This inspired them to continue their engagement with the project and attracted small amounts of funding to enable the raingardens project to continue. This helped to erect signage and encouraged local businesses to install new or retrofit systems on their properties. It also helped fund annual re-seeding of raingarden plots in spring, which produced attractive raingarden features with multiple benefits.

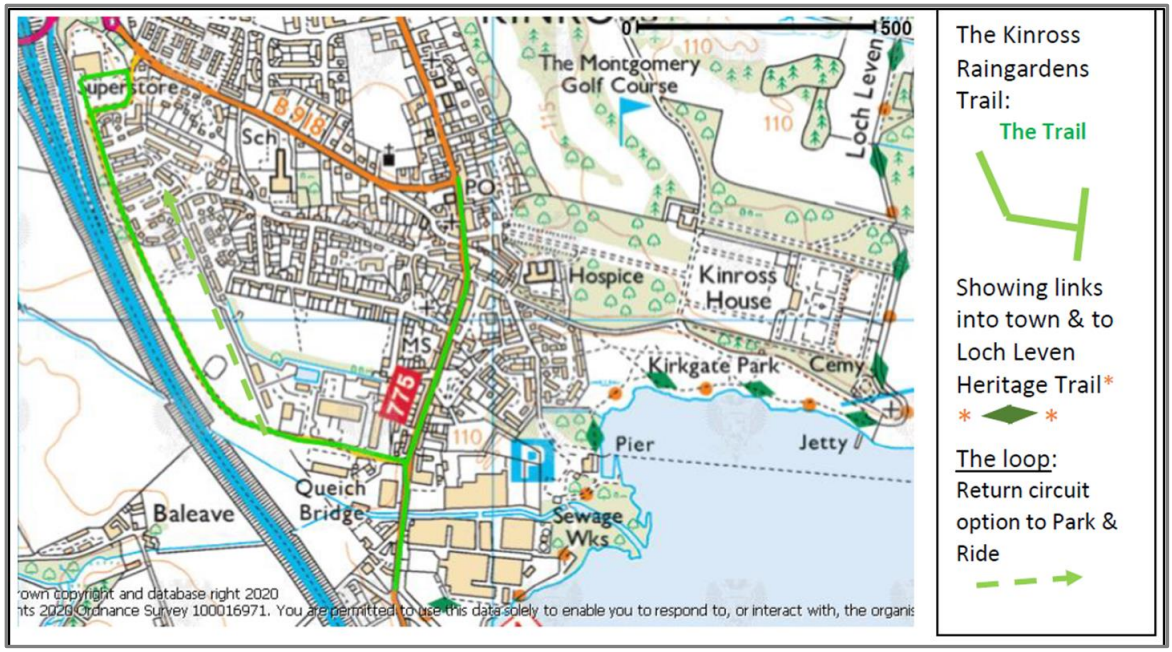


Figure 43. Map of the Loch Leven Heritage trail (after D'Arcy et al., 2021)

Some members of the public did not respond as expected. Instead, they viewed the wildflowers as weeds that had flourished because of the local council had reduced the grass mowing budget. It was also found that creating a realistic enhancement in habitat was a long-term task in established areas of mown grass. Over time, interest in and enthusiasm for the raingardens project waned, as is indicated in *Figure 44* which shows the number of mentions in the Kinross Newsletter, a monthly magazine for the local community, between 2021 and 2025.

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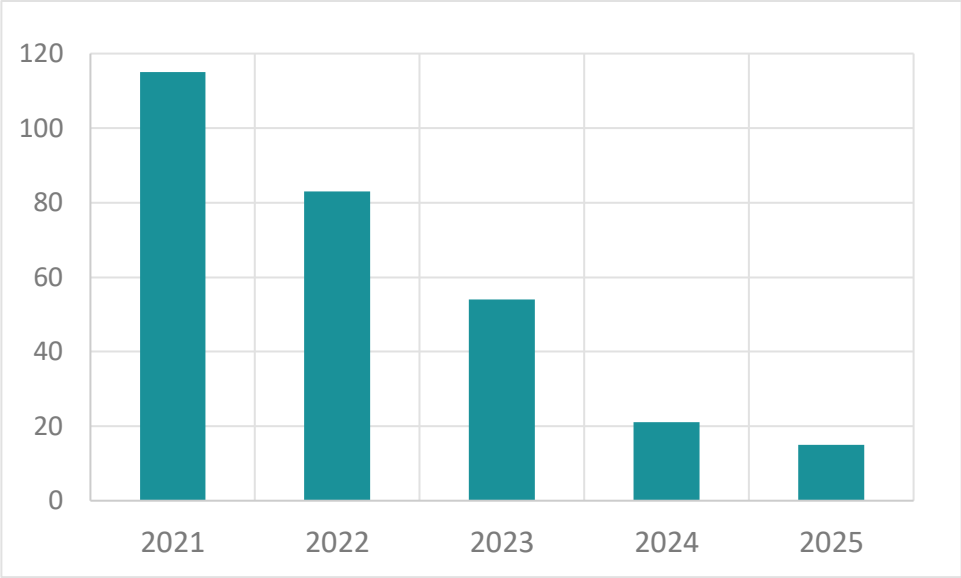


Figure 44. Total number of mentions of 'raingarden(s)' in the Kinross Newsletter, by year, between 2021 and 2025.

Overall, the results indicate that rain gardens can provide multiple ecological benefits beyond their primary drainage function, including enhanced plant diversity, increased floral resources for pollinators and improved habitat structure. These findings suggest that well-designed and appropriately managed rain gardens can contribute meaningfully to local biodiversity enhancement while supporting sustainable urban drainage objectives that reduce pollution inputs to the loch. Future pollinator surveys will help determine whether the observed increases in flowering plant diversity translate into measurable benefits for insect communities in the longer term.

The results of the hydrological modelling have suggested that rain gardens may be able to provide property or street-level mitigation, but there are not currently enough, in terms of number or total area converted, to mitigate runoff at whole catchment or town scale. These results are similar to those reported from elsewhere by Vesuviani et al. (2025).

Key recommendations from this work are as follows:

- Implement long-term monitoring programmes to quantify runoff attenuation, nutrient retention, water-quality improvement and biodiversity outcomes, including baseline surveys prior to future installations.
- Use spatial modelling tools such as the UKCEH City Planner Toolkit to identify locations where rain gardens will intercept the greatest runoff and pollutant loads and maximise environmental benefits.
- Develop a catchment-scale rain garden strategy that moves beyond isolated installations and focuses on coordinated deployment of multiple interventions in priority source areas.
- Undertake a full cost-benefit analysis that incorporates capital costs, maintenance requirements, volunteer contributions, ecosystem service benefits and the long-term costs associated with declining community participation.
- Establish sustainable governance and maintenance arrangements that combine community stewardship with long-term institutional support to ensure continued performance and resilience of the rain garden network.

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Table 28. Innovation performance summary for raingardens at Loch Leven

Evaluation component	Results	Explanation
Intended function achieved	Partly	The intended function was to reduce rainwater flow into the combined sewage system that overwhelms sewage works capacity and increases spills into the loch's inflows. Although this is a likely outcome, no evidence has been collected.
Ecological improvement observed	Yes	Local biodiversity improvements were observed, with rain gardens supporting greater plant diversity and pollinator abundance than surrounding habitats. However, their contribution to ecological improvement in Loch Leven is likely to be limited unless implemented at much greater scale as part of wider catchment management interventions.
Replication potential	Medium	Although rain gardens can be replicated, in principle, in practice their functioning depends on their local context. So, it is often difficult to predict, or replicate, their effects in different locations.
Unexpected effects	Neutral	No unexpected effects have been reported.
Knowledge gaps		More monitoring data needed before multiple benefits of raingardens can be assessed. Raingardens need to be re-seeded and maintained every spring; this is undertaken by volunteers; unclear how to maintain this volunteer community in the longer term.

Combined solutions

4.8 Multiple external and internal measures - Kralingse Plas (NL)

4.8.1 Restoration innovation

After a thorough system analysis, a combined restoration package (Figure 45) was implemented in Lake Kralingse Plas, Rotterdam, the Netherlands. Measures targeting external nutrient inputs included reconstruction of the sluice gate, removal of leaf litter and bird droppings, diversion of an inlet, and the planned renovation of the inlet water dephosphatisation system. Measures addressing internal nutrient loading included the application of 1,064 tonnes of lanthanum-modified bentonite (LMB; commercial name Phoslock®) to reduce P release from the sediment during periods of photosynthesis-driven high pH.

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Figure 45. The overview of planned restoration measures in Lake Kralingse Plas in 2019. ©Rotterdam municipality.

P in sediment is mainly adsorbed by clays, metals (Fe, Mn and Al) oxides and hydroxides (Wetzel, 2001). At various physical, chemical and biological conditions, mobile P may be regenerated, contributing to internal P loading (Rydin, 2000). Under anoxic conditions, sediment ferric (Fe^{3+}) iron is reduced to ferrous (Fe^{2+}) iron, and the redox-related release of P leads to its diffusion into the overlying water. Similarly, under alkaline conditions, hydroxide ions (OH^-) compete with phosphate ions for binding sites on metal hydroxides, resulting in P release into the overlying water. In shallow lakes, such as Kralingse Plas, strong photosynthesis from macrophytes in spring and early summer may cause a high pH. This is a consequence of bicarbonate uptake (HCO_3^-), which is converted into carbonic acid (H_2CO_3) by using a proton (H^+) that is split from water, leaving an OH^- ion that is excreted to the water to balance the uptake of bicarbonate (Kirk, 1994), and that may led to pH > 10 (Wetzel, 2001). Summertime values of pH 10 have been recorded in Lake Kralingse Plas, which boosted P release from the sediment under aerobic conditions from 0.6 mg P m^{-2} d^{-1} at pH 7.3 to 15 mg P m^{-2} d^{-1} at pH 10, but not when this sediment was treated with LMB (Poelen and Smolders, 2021). The initial option of sand-capping was replaced by use of LMB as solid phase phosphate binder, because much less material is needed (Figure 47) and the capacity of LMB in keeping phosphate bound under elevated pH conditions (*Figure 46*). Hence, LMB was considered fit for purpose and applied to the lake in November 2021.

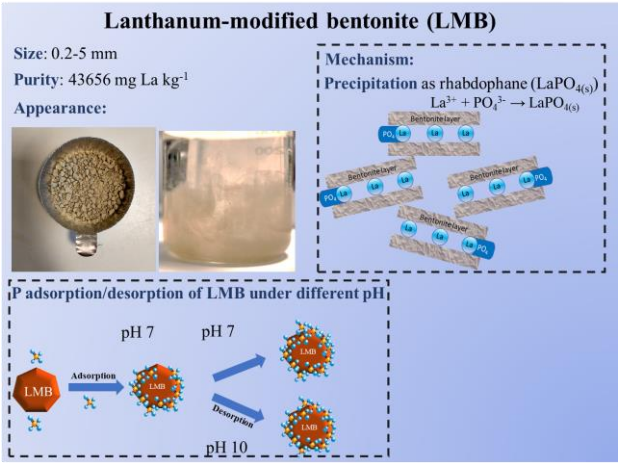


Figure 46. Characteristics and P immobilisation mechanism of Lanthanum-modified bentonite (LMB)

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The lake was sectioned into 42 zones, with 10 intact sediment core samples in each zone, in March 2021. The first 10 cm of the sediment was used to analyse the bioavailable P (considered here as the sum of redox-sensitive P, organic P, and Al-P) through a sequential P extraction (Psenner, 1988). This revealed 10.56 tonnes of bioavailable P in the top sediment layers. The 1,064 tonnes of LMB applied was based on the bioavailable P in the sediment and the TP mass in the water column (0.078 tonnes of P) using a 1:1 molar ratio of La:P (100:1 (w/w) of LMB and P) (Yasseri and Mucci, 2021). Due to variations in sediment across Kralingse Plas, LMB was applied proportionally to the mobile P to be bound in each of the 42 sections (*Figure 47*). LMB was mixed with lake water and sprayed onto the lake surface from a barge. Two GPS-guided barges were running simultaneously to ensure correct dosing in each of the 42 segments (*Figure 50*).

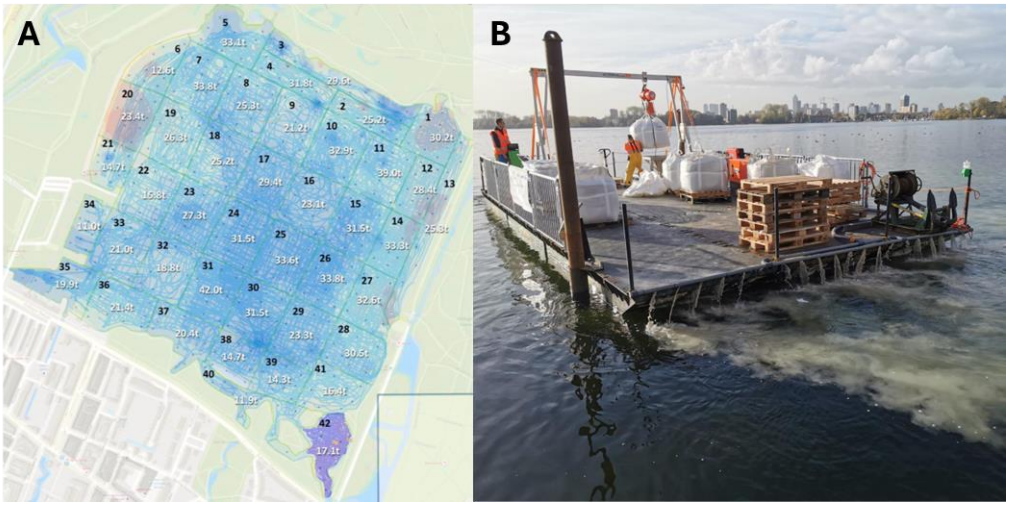


Figure 47. LMB application in Lake Kralingse Plas. A: LMB dosages in 42 sections; B: two GPS-guided barges © Miquel Lurling.

The restoration was finally conducted after around 7 years of system analysis by the municipality, Water Authority Schieland and Krimpenerwaard (HHSK) and various research institutes. The overview of the proposed 11 different restoration measures in 2019 can be found in Figure 47. External nutrient controls were conducted before 2021. From 8th to 29th November in 2021, LMB was applied in whole lake with 42 sections.

4.8.2 Pilot specific objectives

This innovation is trying to achieve three linked goals. First, it aims to improve the ecological status and reach to “good” status of Kralingse Plas in line with the EU Water Framework Directive (WFD), by reducing nutrient loading, cyanobacterial blooms and internal phosphorus release. Second, it aims to support biodiversity by creating better conditions for aquatic organisms and their habitats. Third, because Kralingse Plas is an important urban recreational lake, the pilot also aims to improve bathing water quality, reduce the number of swimming ban days, and support recreation and local ecotourism.

The measurable targets are reductions in TP, filterable P, chlorophyll-a and sediment P release, together with continued monitoring of water quality and ecological response.

4.8.3 Site description

Lake Kralingse Plas is located in the city of Rotterdam, the Netherlands. It is a moderately large (114 ha), shallow lake (mean depth is 2.3 m) that originated from peat excavation in the 17th century and currently fulfils an important recreational function, attracting more than 3.5 million visitors annually.

Due to anthropogenic activities, approximately one-third of the lake's sediment in the southern part was contaminated with lead. According to information from HHSK, the first recordings of

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cyanobacteria date back to 1971. From 1992 to 1996, the lake was dominated by the cyanobacterium *Planktothrix*, whereas *Microcystis* blooms developed in the early 2000s. In 2000, a massive fish kill occurred, and the overall WFD classification was "bad". HHSK, together with the municipality of Rotterdam, initiated a restoration program between 2009 and 2012 that included diverting a nutrient-rich seepage ditch, dephosphatizing inlet water, dredging polluted sediment (approximately 30,000 m^3), sand capping of newly exposed peat, and reconstructing the banks to make them less steep. However, during the execution of this intervention, nutrient-rich water entered the lake, and the sediment used to reconstruct the banks appeared too nutrient-rich, exacerbating eutrophication again. In 2012, for instance, a massive bloom of *Gloeotrichia* developed during summer, which was succeeded by a mixed bloom of *Dolichospermum* and *Microcystis*. In subsequent years, canopy-forming submerged macrophytes developed, along with the regular summer cyanobacterial blooms, which severely hampered several aquatic ecosystem services. The water balance and external P load were determined by Witteveen+Bos, and varied between 0.6 and 1.0 mg P m^{-2} d^{-1} over the period 2012-2018 (Mandemakers, 2020) (*Figure* 48).

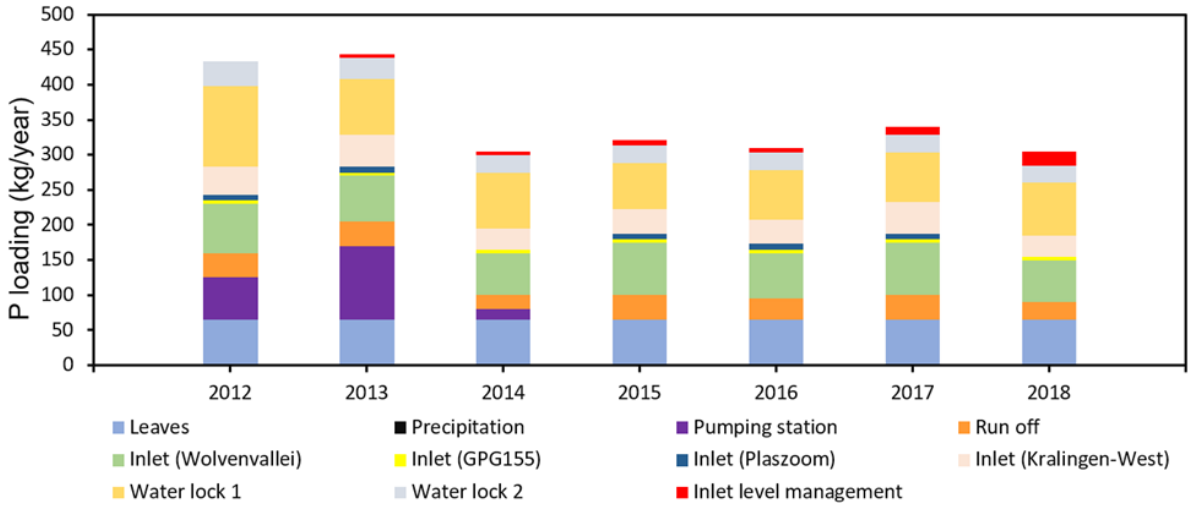


Figure 48*. External nutrients loading from 2012-2018 in lake Kralingse Plas.*

4.8.4 Monitoring and indicators used

The indicators were selected to cover both policy outcomes and the technical performance of the Kralingse Plas pilot within FutureLakes (*Table 29*). Long-term water quality monitoring data are available from 2015-2025, covering the period before and after the 2021 intervention. This allows comparison of pre-intervention conditions with post-intervention water quality trends. Sediment monitoring was carried out just before the LMB application and again 3, 15 and 36 months after application, to evaluate changes in sediment P release, P fractions and lanthanum fate over time. Biological EQR indicators, including fish, phytoplankton, macrophytes and macrofauna since 2010, can be used alongside these data to assess longer-term ecological response.

Table 29. Policy area, policy criterion and indicators used in the assessment of pilot lake Kralingse Plas

Policy area	Policy criterion	Indicator name	Data sources
Environmental	WFD	Ecological Quality Ratio based on fish, phytoplankton, macrophytes, macrofauna	HHSK water quality monitoring (https://www.schielandendekrimpenerwaard.nl/actueel/actuele-metingen-waterstanden-en-waterkwaliteit); Kralingse Plas research paper (Kang, et al, 2026)
	Zero Pollution	Total P, filterable P, total N, ammonium, nitrate/nitrite, Chlorophyll-a and cyanobacterial blooms	
	Biodiversity net gain	Ecological Quality Ratio based on fish, phytoplankton, macrophytes, macrofauna	
Technical performance	Internal P control	Sediment P release, mobile P, HCl-P/La-bound P, La distribution, P release under high pH conditions	Kralingse Plas research paper (Kang, et al, 2026)
Economic	Ecotourism	Swimming-ban days, recreational water use	Municipality records

4.8.5 Results and evaluation

Environmental & policy relevant indicators

Water quality

The main environmental improvement was the reduction of P availability after the 2021 restoration package. Total P and filterable P deceased and remained low during the monitoring period, while chlorophyll-a also stayed low (*Figure* 49). These results indicate reduced pressure and lower risk of cyanobacterial bloom, supporting the WFD-related objective of improving ecological water quality and also contribute to Zero Pollution goals.

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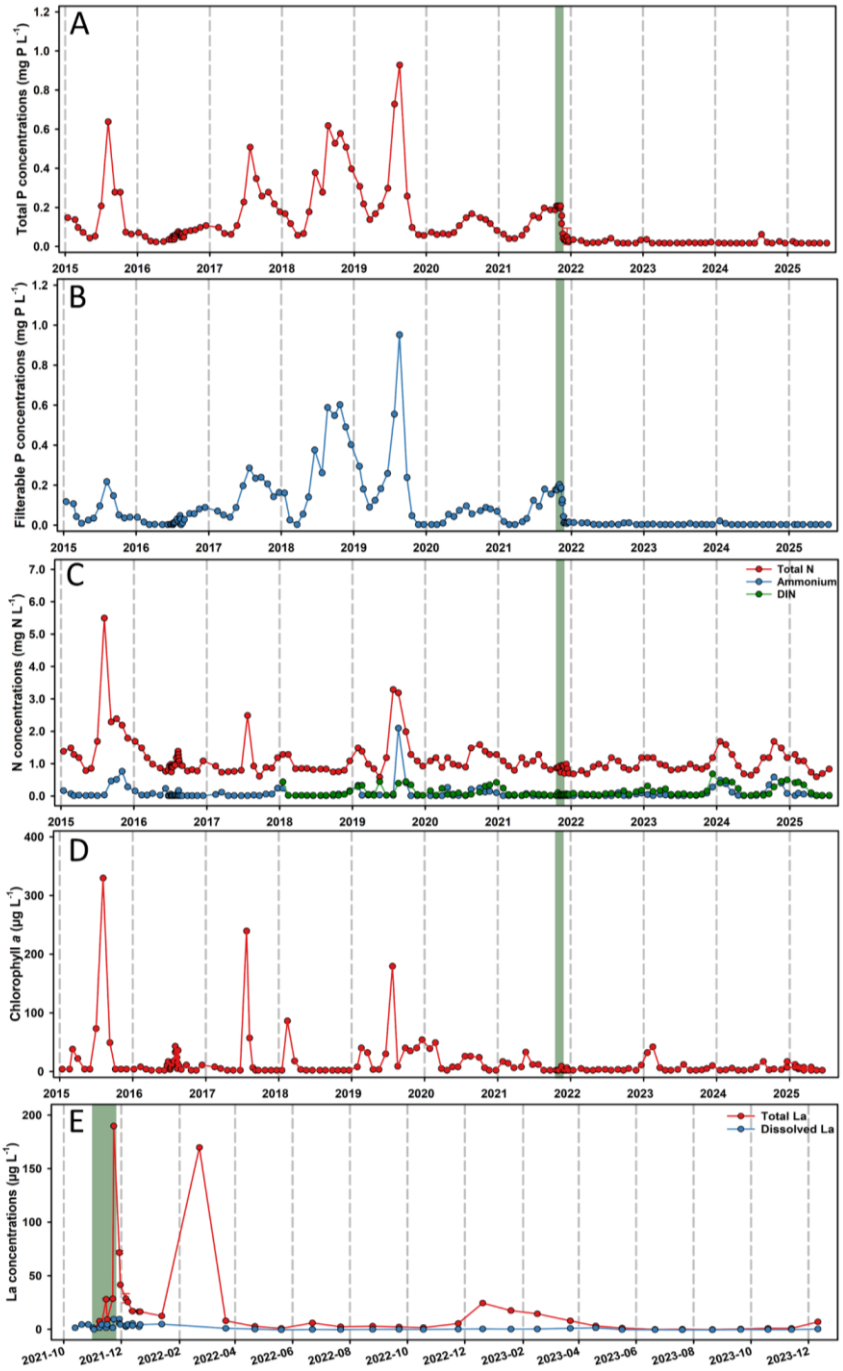


Figure 49. *Temporal trends in total P (panel A), FP (panel B), total N, AN and NN (panel C), Chl a (panel D) from 2015 to 2025 and total La and dissolved La (panel E) from 2021 to 2023 in Lake Kralingse Plas. The green vertical bar indicates the duration of LMB application.*

Ecological quality ratio

The WFD-related ecological response was assessed using EQR indicators for fish, phytoplankton, macrophytes and macrofauna. Fish-based EQR improved from *bad* before restoration to *moderate* and remained stable hereafter. Phytoplankton EQR fluctuated strongly, but after the intervention it reached "good" status. The macrophyte EQR showed the clearest recovery, improving from "poor" in 2010 to "good" in 2022. Macrofauna showed less change and remained around "moderate" status across the observed years (*Figure* 50). Overall, the ecological indicators suggest substantial improvement in ecosystem conditions particularity for phytoplankton and macrophytes.

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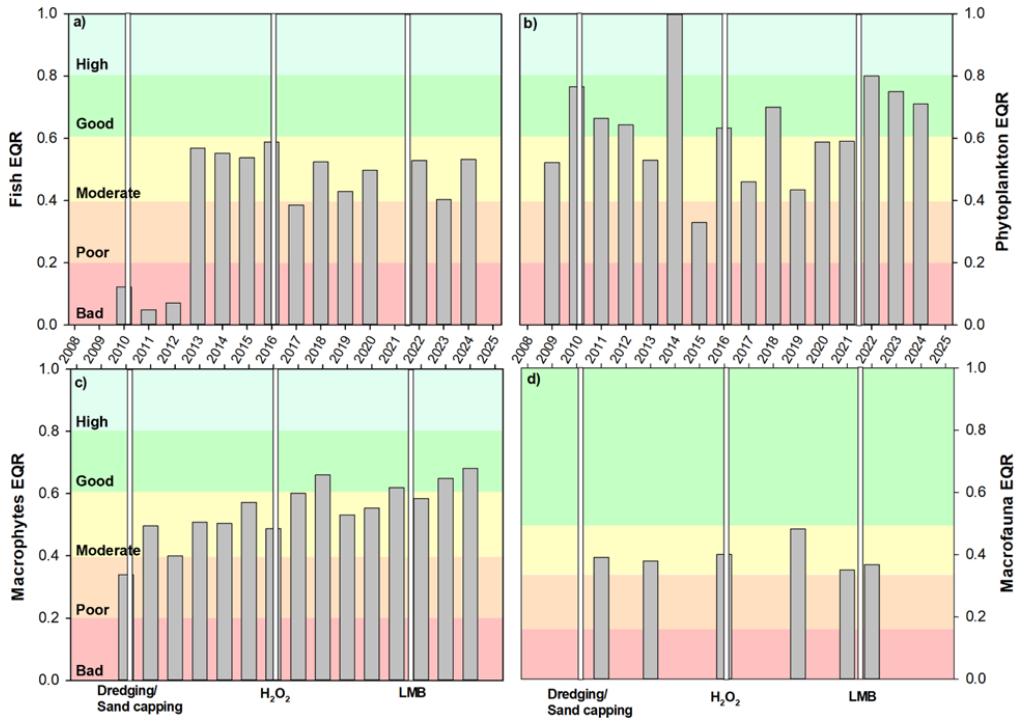


Figure 50*. The ecological quality ratio (EQR) for fish (a), phytoplankton (b), macrophytes (c), and macrofauna (d)* in lake Kralingse Plas. Kang et al., 2026, manuscript submitted.

Economics/Ecotourism

Kralingse Plas is an important urban recreational lake and improvements in water quality have generated clear societal benefits. Better water quality and lower bloom risk can support safer swimming, fewer negative swimming advice days, and improved recreational and ecotourism value. Swimming advice improved after the 2021 intervention, with no swimming bans shown afterwards (*Figure 51*). Before the intervention, warnings, negative swimming advice and a swimming ban occurred mainly in summer. After 2021, only warnings were recorded, suggesting improved recreational water quality, although continued summer monitoring is still needed.

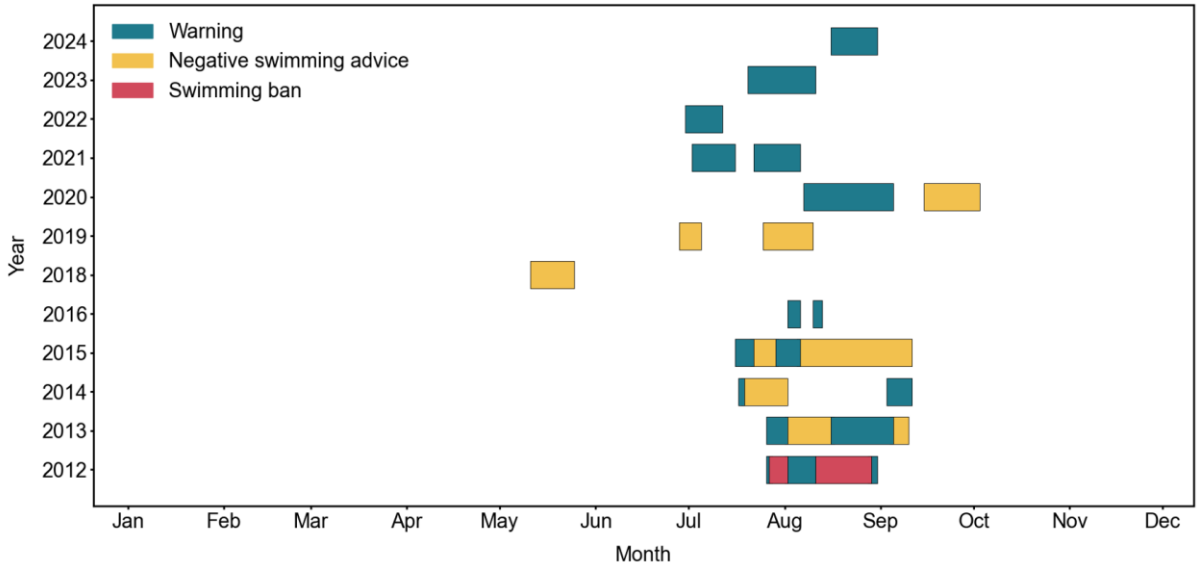


Figure 51. Annual swimming advice during the Dutch swimming season (May 1-October 1 every year) in lake Kralingse Plas *including warning, negative swimming advice and swimming ban.*

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A key trade-off is that the lake still depends on external nutrient control. A local nearshore algal accumulation occurred in 2024 (*Figure 52*), likely linked to insufficient control of external nutrient inflow. This means the main objective was largely met in terms of water quality and internal P control, but continued catchment and maintenance measures are still needed (Kang et al, 2026).



Figure 52. Nearshore small surface algal accumulation in Lake Kralingse Plas in November 2024. © Jéssica Papera

4.8.6 Technical performance

Achievement of design targets

From a technical perspective, the main achievement was the control of internal phosphorus loading. Before application, the top sediment contained a mobile P pool of about 21.5% of total P, while after 36 months this decreased to about 5.2%. At the same time, the more stable HCl-P/La-bound P fraction increased from 53.7% before application to 66.7% after 36 months, showing that mobile phosphorus was shifted into less bioavailable P fractions (*Figure 53*). Sediment P release was also strongly reduced under anoxic conditions, average filterable P flux decreased from 6.27 mg P m^{-2} day^{-1} before application to 0.29 mg P m^{-2} day^{-1} after 3 months, -4.65 mg P m^{-2} day^{-1} after 15 months, and 0.27 mg P m^{-2} day^{-1} after 36 months (*Figure 54* and *Figure 54*). This indicates that the LMB part of the combined solution worked as intended. A further technical strength is that P binding remained stable under high pH conditions. This is important because Kralingse Plas can reach around pH 10 during periods of strong photosynthesis, which normally increases the risk of sediment P release. The pilot showed that P in water column did not increase under pH 10 in LMB-treated sediment cores, meaning that the internal P control was stable under alkaline conditions.

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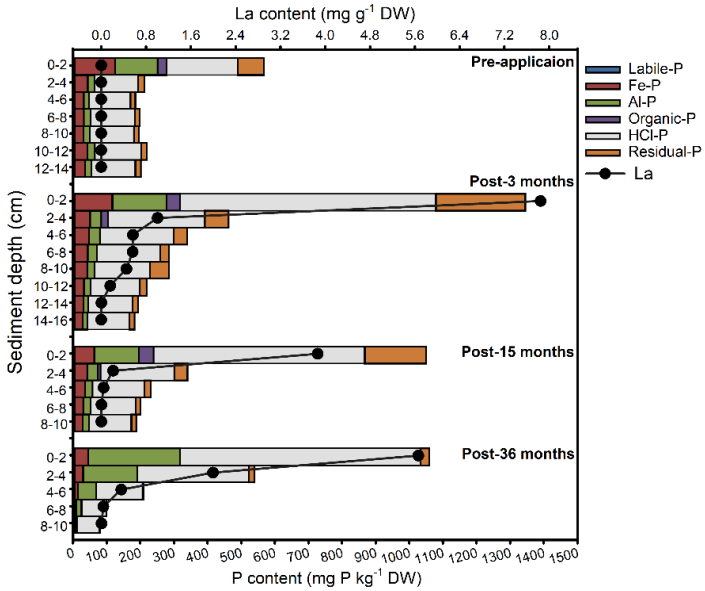


Figure 53. All P fractions (stacked bars) and La content (black lines) in sediment depth profiles at pre-, post-3 months, post-15 months and post-36 months of LMB application in Lake Kralingse Plas.

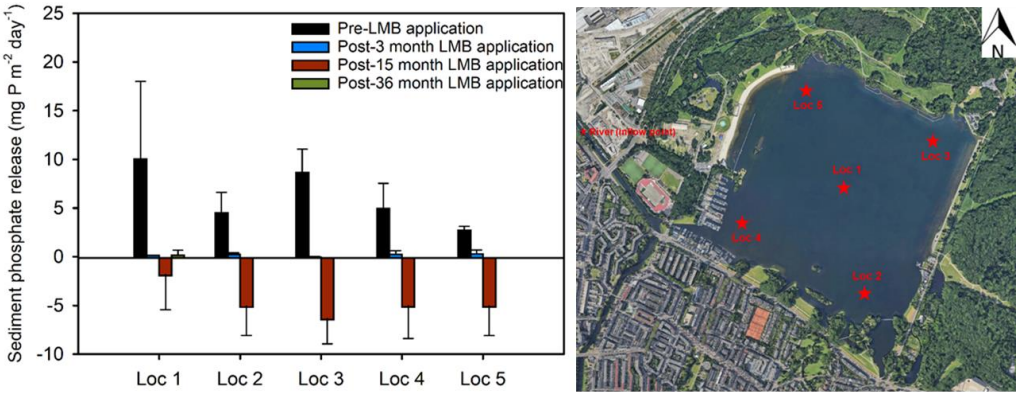


Figure 54. Spatial-temporal of phosphate fluxes in sediment cores taken from five locations (Loc 1 is the middle of the lake) in the Kralingse Plas that had been incubated under anoxic conditions.

Maintenance and operational requirements

Continued operation and maintenance were needed to support the long-term effect of the combined solution. These actions included reducing external nutrient inputs, reconstructing the sluice gate, disconnecting nutrient-rich inflows, removing bird droppings and leaf litter, mowing macrophytes, controlling geese reproduction, and reducing nutrient inputs from recreational boating.

Monitoring was also an important part of the operational requirements. Water quality, sediment P fractions, sediment P release and P-binding stability under high pH conditions were followed after the intervention. This monitoring was needed to check whether the LMB layer continued to function and whether additional management actions were needed.

Technical challenges and limitations

The intervention required a detailed system analysis, technical preparation, stakeholder consultation, regulatory approval, safety assessment and coordination between different actors. This makes the approach more demanding than simple short-term measures.

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Stakeholder acceptance was also a challenge. Previous restoration actions in Kralingse Plas had not achieved the expected results, and cyanobacterial blooms continued to occur after earlier interventions. Because of this, the choice of LMB had to be carefully explained and supported by additional testing and ecotoxicological assessment.

The cost of the whole intervention was € 5.8 million (external and internal nutrients controls), in which LMB application cost € 2 million. Such an investment will not be feasible in all regions of the EU, but it reflects the cost required to clean up nutrient pollution that has accumulated over decades. Budgeting for adequate monitoring and repeated maintenance actions may be needed. The case of Kralingse Plas presented here demonstrates that, based on a proper systems analysis, restoration is possible, but at a price, which is always more expensive than preventing eutrophication in non-impacted ecosystems. Therefore, priority should be given to preventative measures that avoid or strongly delay the degradation of healthy aquatic ecosystems.

Replicability and scalability

The Kralingse Plas case shows that this type of combined restoration approach can be replicated in other eutrophic shallow lakes, but only after a proper lake system analysis. The approach is most relevant for lakes where internal P loading remains important after external nutrient inputs have been reduced or controlled. LMB can be a possibility of wider restoration package to reduce internal P loading.

4.8.7 Cost-effectiveness

The interventions are not simple single technologies. They are combined restoration packages with moderate costs but potentially long lifetimes and multiple benefits. The total intervention cost was €5.8 million, including €2 million for the LMB application. Kralingse Plas treated the largest area, 114 ha, with a capital investment cost of €4.8 million, operational costs of €1 million, an observed lifetime of 4.5 years, and potential lifecycle of 10 years. This gives an annualized cost of about €2.07 million per year, equal to 0.018 M€/ha/year. Although the total cost is a bit high, the cost per hectare is relatively low because the lake area is large and has important recreational and bathing water functions.

4.8.8 Knowledge gaps

Some knowledge gaps remain. First, the long-term durability of the intervention beyond the current monitoring period still needs to be confirmed. The results after 36 months were positive, but continued monitoring is needed to see whether the reduction in internal P loading remains stable over a longer period.

Second, more information is needed on how often maintenance actions are required to keep the system in a good condition. External nutrient inputs, bird droppings, leaf litter, macrophyte growth and recreational use may all influence the long-term outcome.

Finally, the transferability of this approach to lakes with different sediment chemistry, hydrology or social conditions still needs further evaluation. The technical principle is transferable, but the design and cost-effectiveness will differ between lakes.

4.8.9 Overall evaluation and recommendations

A thorough system analysis and deep understanding of the specific characteristics of the lake, here photosynthesis-driven high pH in late spring and summer, together with the extensive interaction with multiple stakeholders, sharing ideas, aligning expectations, resulted in a widely supported action plan, tightly coordinated implementation of measures, and strong cooperation between actors. Budgeting for adequate monitoring and repeated maintenance actions may be needed.

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Any lake restoration project should begin with a system analysis, encompassing both the lake's characteristics and its socio-ecological context, including public/social acceptance, regulatory approval, cost-benefit analysis, safety (ecotoxicity), and importantly, the effectiveness of the suggested measures (Douglas et al., 2016; Tammeorg et al., 2024). To this end, the Dutch authorities conducted a thorough system analysis that included water and sediment nutrient balance, stakeholder engagement, and evaluation of measures in terms of existing scientific underpinnings, safety, and cost. The total package of measures consisted of those reducing the external P load, such as reconstructing the sluice gate to be filled with lake water instead of nutrient-rich river water, disconnecting the inlet Kralingerhout (Golf course) and Plaszoom (drainage water from the forest), annual removal of bird droppings, mowing macrophytes, birth control of the geese by removing eggs in breading season, leaf litter, recreational boating sewage, and the main measure of adding LMB to counteract the periodically high internal P release.

During the pre-intervention period, several stakeholder meetings were held to inform, discuss, and exchange ideas. On a regular basis, meetings were organised with stakeholders who had expressed main concerns to inform, explain, and align their understanding of a healthy ecosystem. Their skepticism was partly fed by previous interventions that had not led to the desired outcome for several reasons. A restoration project executed in 2009-2012, which included dredging lead-polluted sediment, sand capping whole lake sediment, and shoreline reconstruction, was followed by a massive outbreak of the cyanobacterium *Gloeotrichia echinulata* in the subsequent summer, leading to a prolonged swimming ban. Cyanobacterial blooms reoccurred regularly in the years that followed, and subsequent fish biomass estimates, following hydrogen peroxide interventions in 2016, revealed a significantly reduced fish community. The city council of Rotterdam put a 25-year ban on the use of peroxide in Lake Kralingse Plas. Under these conditions, the choice for LMB as the best option to counteract the sediment P release had to be explained. The choice for LMB was supported by additional tests performed by an independent research institute (Poelen and Smolders, 2021), as well as a thorough ecotoxicity report that included not only peer-reviewed but also grey literature data from other LMB lake restoration projects (Finsterle et al., 2020).

Table 30. Innovation performance summary for Kralingse Plas

Evaluation component	Results	Explanation
Intended function achieved	Yes	The main intended function was achieved. The combined package reduced internal P loading and improved water quality
Ecological improvement observed	Partly	Water quality improved, and EQR results showed improvement for fish, phytoplankton and macrophytes
Replication potential	Medium	The approach can be transferred to other shallow eutrophic lakes, but only after lake-specific system analysis
Unexpected effects	Neutral	No major technical failure was found. However, a local nearshore algal accumulation was observed in 2024, showing that external nutrient inflow still needs to be controlled
Knowledge gaps	Some	Long-term ecological response and external nutrient control. More monitoring is needed after 2025 to assess whether TP remains controlled,

		whether external nutrient inputs are sufficiently reduced, and whether biodiversity indicators such as fish, macrophytes and macrofauna continue to improve.

4.9 Multiple external and internal measures - Lake Groote Melanen (NL)

4.9.1 Restoration innovation

A full-scale system analysis was conducted that revealed external nutrient load, internal nutrient load and ecosystem restructuring had to be implemented. The innovation lies in the tailored combination of measures, the dredging and reuse of materials, and the construction of a sand cap with an active phosphate binder LMB, incorporated into it.

Fish was removed and placed to a nearby lake. The sediment was dredged by Kurstjens B.V. (https://kurstjens.nl/en) using as Cutter Suction Dredger. The dredged material was pumped through a pipe (max 2 km) to the shore where it was treated in mobile units: First large items were sieved out using a sorting drum (8 mm) that was followed by separating sand from sludge using a hydrocyclone (63 µm). The sand was used in reconstruction of walk/bike paths around the lake. Subsequently, the sludge was dewatered using two centrifuges and the addition of polyacrylamide (C-491, Kemira) as flocculant. Process water returned to the lake, whereas half of the dewatered sludge was used in agriculture, and the other half was used in Lake Dassenplas for shallowing (3.6 km northeast of Groote Melanen) as this former sand excavation was draining the surrounding.

Dredging exposed a fresh peat layer. To minimize breakdown and nutrient release the peat layer was capped with clean sand in which LMB (14 tonnes) was added to the lower 5 cm of the new sand layer. After this, the lake water was also treated with poly-aluminium chloride (PAC), calcium hydroxide and LMB to settle suspended particles and bind the remaining phosphorus in the water.

The restoration design was based on a lake system analysis, which showed that both external and internal nutrients loading had to be reduced. The total P load was estimated at about 5.7 mg P m^{-2} day^{-1}, including around 3.8 mg P m^{-2} day^{-1} from external sources and 1.9 mg P m^{-2} day^{-1} from internal loading. The estimated critical P loads were 1.04 mg P m^{-2} day^{-1} for the transition from turbid water to clear water, and 3.48 mg P m^{-2} day^{-1} for the transition from clear to turbid water (*Figure 55*). Therefore, the design (*Figure 56*) combined fish removal, external load reduction, internal load restriction and macrophytes planting.

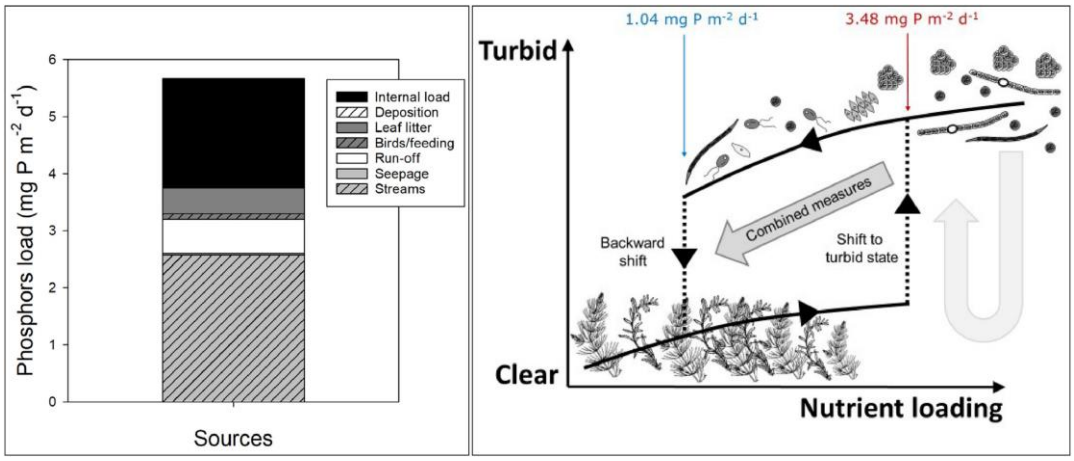


Figure 55. Estimated P load (mg P m^{-2} d^{-1}) to the lake from different sources (left panel) and estimated critical P loads for the transition from clear to turbid water (red) and for the transition from turbid water to clear water (blue) based on PCLake (right panel) in Lake Groote Melanen.

Fish removal

Prior to implementing measures, fish was removed from the lake by a certified company (*Figure 56*). On February 26th and 27th 2015, the lake was first divided in two compartments using a turning net, then two trawls were performed with a 325 m seine net (mesh 40 mm decreasing to 24 mm) covering approximately 1.5 ha each, and four trawls with a 225 m seine net (mesh 40 mm decreasing to 22 mm) covering approximately 0.65 ha each (Kalkman, 2015). About 90 % of the lake surface could be covered with this method. Finally, the entire shoreline was covered using 5 kW electrofishing equipment. All caught and measured fish were immediately identified, weight and length were measured, after which they were released in nearby Lake Binnenschelde, as demanded by law. Inasmusch as Lake Binnenschelde is much larger (180 ha), the addition of all fish from Groote Melanen implied only 1.7 kg fish ha-1 added to Binnenschelde, a low density that is not expected to cause any impact

External load reduction

To reduce the external P load the two inflowing waters, a small stream (Jankebergloopje) and a drainage ditch, were disconnected and diverted to the lake outflow receiving stream. Water level in the lake was monitored continuously and registered in hourly intervals from January 15th 2013 until June 6th 2023. Leaf litter was reduced by pruning the bushes and removing overhanging vegetation, run-off was reduced by construction of more vegetated banks. These actions took place in October and November 2015. Meanwhile, at several stakeholder meetings the citizens were informed to reduce feeding of birds and fish, also information signs were made and placed around the lake to remind citizen to remove dog faeces and limit feeding of waterfowl and fish.

Internal load reduction

The sediment layer was removed by cutter suction dredging until the original sand or peat layer, in total 29,000 m^3 of sediment was removed by a specialised dredging company, Kurstjens B.V. (Hedel, the Netherlands; https://kurstjens.nl/baggeren-en-bezanden-kleine-en-groote-melanen). The dredged material was pumped through a pipe (max 2 km) to the shore where large items were sieved out using a sorting drum (8 mm), and sand was separated from sludge using a hydrocyclone (63 µm) that yielded ~150 m3 of sand. This sand was used in reconstruction of walk/bike paths around the lake. The remaining sludge was dewatered using two centrifuges and the addition of polyacrylamide (C-491, Kemira) as flocculant, which achieved a volume reduction from 29,000 m3 to 8,000 m3. The water returned to the lake. Of the dewatered sludge half (~4,000 m3) was used in agriculture, and the other half was used in Lake Dassenplas for shallowing (3.6 km north east of Groote Melanen) as this former sand excavation drains its surroundings. Dredging was performed from April 9th until July 25th 2015. As dredging alone would not reduce the internal P loading sufficiently, additional measures were taken. From 19 November 2015 until 7 January 2016, a capping layer (average thickness of 27.8 cm) of nutrient poor sand was applied (13,000 m^3) in which LMB (14 tonnes) was added to the lower 5 cm of the new sand layer. The sand was selected after analysis of eight different batches on potential P release. The sand used had lowest potential releasable P (2 mg P kg^{-1} dry sand) and originated from location MVO Moerdijk (former Shell area Moerdijk, the Netherlands). The main reason for this capping was to prevent mineralisation, and therewith nutrient release from the newly exposed peat layer. The LMB dose was based on pore water analysis of the sand/peat layer, the potential releasable P in the sand, and the estimated seepage flux for a period of five years.

From April 18th to 20th 2016, PAC (3200 L), buffer (25 kg calcium hydroxide) and LMB (13.65 tonnes) were added to the water to settle resuspended material and to bind P that remained in the water after dredging and sand capping.

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Increased resilience

The resilience of the lake to switch from the clear to turbid state was increased by removing the hard banks and transforming them into soft banks with gentle slope. Designated sites were constructed to aid angling. In addition, on May 27th 2016, macrophytes were planted at three spots in the lake and helophytes were planted at five spots with the help of school kids. Macrophytes were commercially obtained and delivered in perforated crates (50 cm length, 30 cm width, 10 cm height) in which multiple specimens of the native macrophyte species were growing. Crates were placed at 75 cm depth. Per location two crates with *Potamogeton lucens*, two with *Potamogeton crispus*, two with *Potamogeton natans*, two with *Hottonia palustris*, and one crate with *Chara* sp. were planted.

The helophytes were delivered in perforated pots that were planted just below the water line. At four locations, five specimens of the native species, *Iris pseudacorus, Lythrum, salicaria, Sparganium emersum, Lycopus europaeus*, and *Filipendula ulmaria* were planted, while at one other location an additional five specimens of *Typha angustifolia* were planted.



Figure 56. Combined restoration packages in Lake Groote Melanen. ©Miquel Lurling

The main restoration works were carried out between February 2015 and May 2016. Fish removal was done first, on 26-27 February 2015, before the other restoration works started. Suction dredging was then carried out from 9 April to 25 July 2015, removing the nutrient-rich sediment layer.

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External load reduction measures followed in October and November 2015. Sand capping was carried out from 19 November 2015 to 7 January 2016, with LMB incorporated into the lower part of the new sand layer. The lake water was then treated from 18-20 April 2016 (*Figure 57*and *Figure 56*). Finally, macrophytes and helophytes were planted on 27 May 2016 (*Figure 57*). Water quality monitoring continued after the intervention to compare pre- and post-restoration conditions. The resilience of Lake Groote Melanen to switch from the clear to turbid state was increased (*Figure 57*).



Figure 57. Lake Groote Melanen before (early 2000's-2015) and after (2016-present) the intervention.

4.9.2 Pilot specific objectives

This innovation is trying to achieve three goals. First, it aims to improve the ecological condition of Lake Groote Melanen by controlling eutrophication, cyanobacterial blooms and fish kill risk. Second, it aims to shift the lake from a turbid, phytoplankton-dominated state towards a clearer and more resilient aquatic ecosystem, with better conditions for submerged macrophytes, aquatic habitats and biodiversity. Third, in line with European water quality and WFD objectives, it aims to support long-term ecological recovery and improve the recreational. The pilot was evaluated by comparing eight years of pre-intervention water quality data with 10 years of post-intervention data.

4.9.3 Site description

Lake Groote Melanen is located in the Southwestern part of the Netherlands (*Figure 58*). The lake originated in 1721 after peat excavation in a swamp area and was part of a military defence line – the West-Brabantse Waterlinie – between 1628 and 1830. The lake size is 4.8 ha (47.884 m^2), and prior to restoration it had a mean depth of 1.2 m. There was a 0.65 m thick layer of sediment laying on peat in the southern part of the lake, while in the northern part the sediment was laying on sand (Waltjé et al., 2009). The water was turbid, the lake had no macrophytes and suffered annually from cyanobacterial blooms (*Figure 61*). The main activity was angling, and the vast majority of the fish stock was comprised of carp. There were winter fish kills in 2009 and 2010 most likely due to anoxic conditions under the ice.

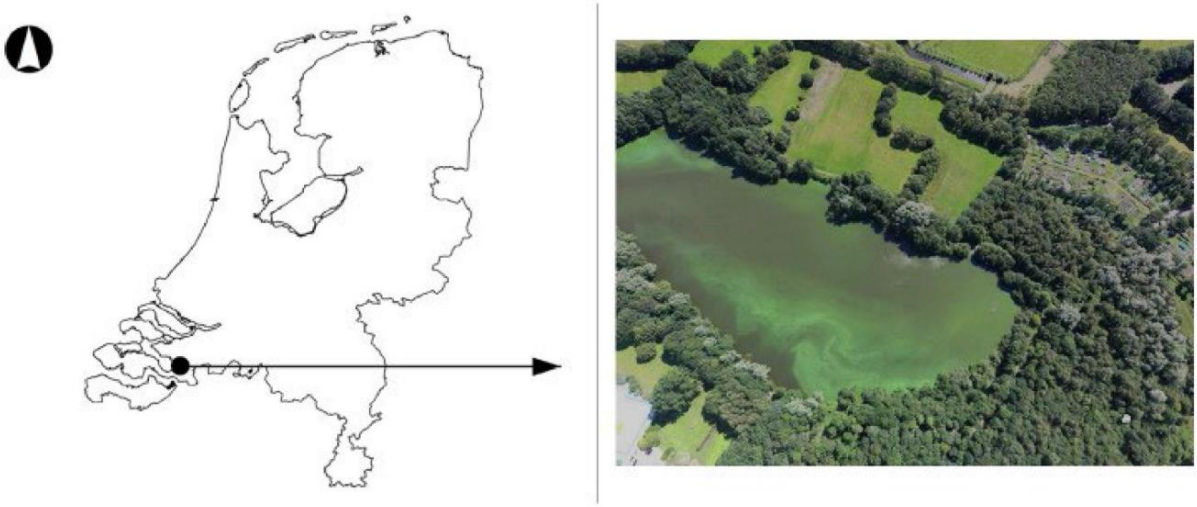


Figure 58. Location of Lake Groote Melanen in the Southwest of the Netherlands (left panel) and a photograph of the re-occurring cyanobacteria bloom in summer (right panel) © Municipality Bergen op Zoom.

4.9.4 Monitoring and indicators used

The indicators were selected to cover both policy-relevant indicators and the technical performance of the Lake Groote Melanen pilot within FutureLakes (*Table 31*). Long-term water quality monitoring data are available for Lake Groote Melanen from January 2008 to December 2025, covering approximately eight years before and ten years after the main intervention period. The intervention period itself ran from February 2015 to May 2016 and was excluded from the before-after comparison. Water quality was sampled monthly at the centre of the lake, while monitoring was intensified during the PAC and LMB application period. Fish stock was assessed in 2015, 2016, 2017 and 2019, and vegetation surveys were carried out before the intervention and annually during the post-intervention period from 2016 to 2021. This monitoring design allows the pilot to be evaluated across water quality, ecological recovery and technical performance.

Table 31. Policy area, policy criterion and indicators used in the assessment of pilot Lake Groote Melanen

Policy area	Policy criterion	Indicator name	Data sources
Environmental	WFD	Water quality, submerged macrophyte cover, fish stock, fish community composition	Municipality records; Lake Groote Melanen research paper (Lurling, et al, 2024)
	Zero Pollution	TP, phosphate, TN, DIN, total chlorophyll-a, cyanobacteria chlorophyll-a, suspended solids, turbidity	
	Biodiversity net gain	Submerged macrophytes, emergent/floating vegetation, fish stock and fish community composition	

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Economic	Ecotourism	Cyanobacterial nuisance, recreational water use, amenity value	Municipality records

4.9.5 Results and evaluation

Environmental & policy relevant indicators

Water quality

The restoration resulted in a substantial improvement in water quality (*Figure 59*). Before the intervention, TP was high and showed strong seasonal peaks, with an average concentration of 0.47 mg P L^{-1}. After the intervention, TP dropped to 0.03 mg P L^{-1}, and the large seasonal peaks were no longer visible. Phosphate showed the same pattern, decreasing from 0.3 mg P L^{-1} before the intervention to 0.008 mg P L^{-1} afterwards. The boxplots also show that both TP and phosphate were much lower after restoration.

Nitrogen concentrations also decreased after the measures. TN declined from 3.73 mg N L^{-1} before the intervention to 1.25 mg N L^{-1} after the intervention. DIN also dropped from 1.27 mg N L^{-1} to 0.21 mg N L^{-1}. In the post-intervention period, nitrogen concentrations were lower and more stable, with fewer high peaks compared with the period before restoration.

The reduction in nutrients availability was accompanied by a decrease in algal biomass. Before restoration, total chlorophyll-a showed repeated peaks, but after the intervention these peaks became much smaller and less frequent. Average total chlorophyll-a decreased from 68 µg L^{-1} to 17 µg L^{-1}. Cyanobacteria chlorophyll-a showed an even stronger improvement, decreasing from 31.9 µg L^{-1} before the intervention to 3.9 µg L^{-1} afterwards. The high cyanobacteria peaks seen before restoration largely disappeared after the intervention, suggesting a clear reduction in bloom risk.

Overall, the combined restoration measures strongly reduced nutrients and algal biomass. The main water quality objective was therefore largely met, with lower P, N, total chlorophyll-a and cyanobacteria chlorophyll-a after the intervention.

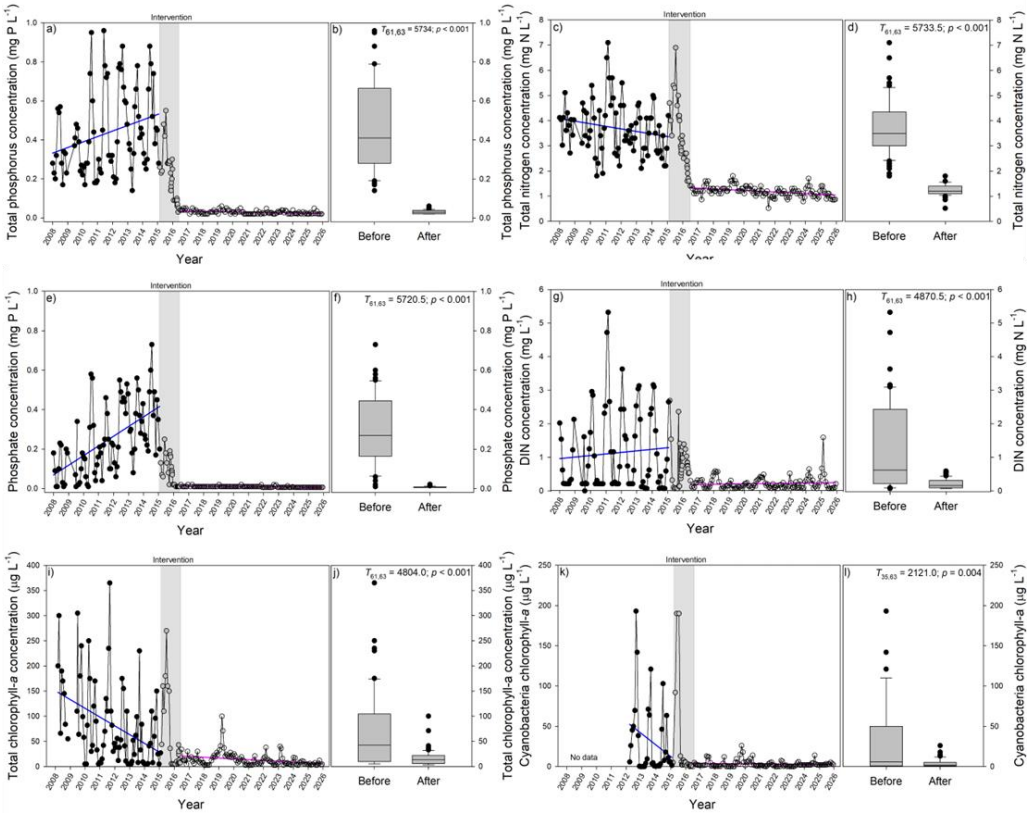


Figure 59. Course of total phosphorus concentrations (TP, panel a), box plot of TP before and after the intervention (panel b), total nitrogen (TN, panel c), box plot of TN before and after the intervention (panel d), phosphate (PO_4-P; panel e), box plot of phosphate concentrations before and after the intervention (panel f), dissolved inorganic nitrogen (DIN, panel g), box plot of DIN before and after the intervention (panel h), total chlorophyll-a concentrations (panel i), box plot of chlorophyll-a concentrations before and after the intervention (panel j), cyanobacteria chlorophyll-a concentrations (panel k), box plot of cyanobacteria chlorophyll-a concentrations before and after the intervention (panel l), during 2008 – 2025. The grey area indicates the period of intervention (Feb 2015 – May 2016). The blue line indicates the trend line before the interventions, the pink line after intervention. The box represents the 25th to 75th percentile range, where the boundary of the box closest to zero indicates the 25th percentile, the line within the box marks the median, and the whiskers (error bars) above and below the box indicate the 90th and 10th percentiles. The dots indicate outlying points.

Vegetation and fish

Before restoration, submerged macrophytes were absent, only a low coverage of floating plants was observed, which comprised floating macrophyte i.e. *Lemna minor* (lesser duckweed) and *Spirodela polyrhiza* (greater duckweed). In 2016, some spots with *Chara globularis* and *C. vulgaris* were found on other locations than where Chara was planted. In general, plant coverage increased over the years (*Figure 62*). In 2019, 2020 and 2021, the macrophyte-based WFD classification yielded scores for a good ecological condition, 0.62, 0.64 and 0.63, respectively.

In 2015, the total fish stock was estimated at 268 kg ha^{-1}, of which 89 % was comprised of sediment resuspending species such as bream and carp (*Figure 60*). All fish caught were relocated to a lake nearby. In 2016, total fish stock was estimated at 472 kg ha^{-1}, of which 90 % was comprised of sediment resuspending species (bream, carp). All bream and carp caught were again relocated to a lake nearby. In 2017, the fish stock was estimated to be 177 kg ha^{-1}, of which 90 % was comprised of bream, and particularly carp. All bream and carp caught were relocated to a lake nearby. The efficacy of the relocating effort in 2017 was tested by subsequent fishing that yielded an estimated fish stock of 57.5 kg ha^{-1}, of which 68 % was comprised of bream and carp (*Figure 60*). In 2019, the estimated fish stock was 157 kg ha^{-1}, of which 49 % was comprised of bream, and particularly carp. All bream and carp caught were relocated to a lake nearby. Subsequent fishing revealed a remaining estimated fish stock of 91.4 kg ha^{-1}, of which 12 % was comprised of bream and carp (*Figure 60*).

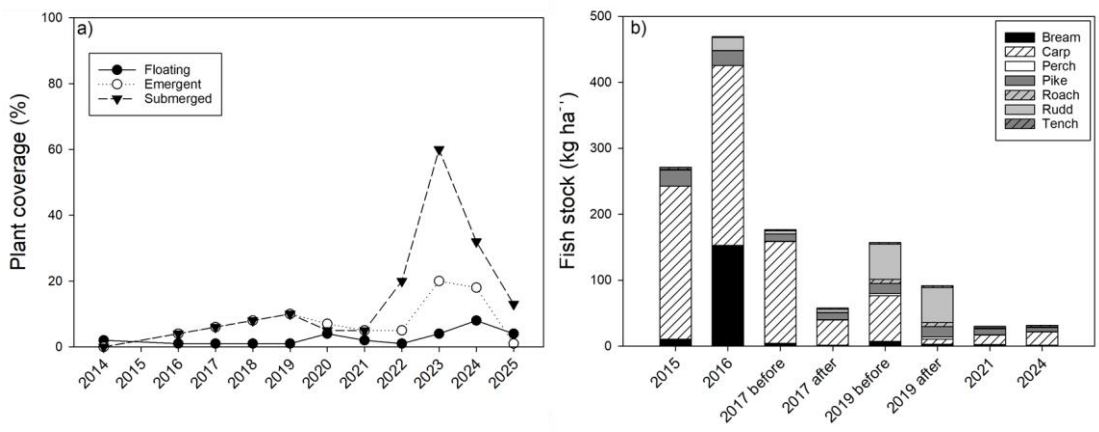


Figure 60. Coverage (%) of floating, emergent and submerged aquatic plants in Lake Groote Melanen (panel a) and fish stock in Lake Groote Melanen. In 2015 all fish that had been caught were removed, in 2016, 2017 and 2019 only bream and carp were removed. The 2017 and 2019 'before' indicates the initial catch and fish stock, while 'after' indicates the fish stock determined by fishing after bream and carp had been removed.

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4.9.6 Technical performance

Achievement of design targets

The technical aim was not only to reduce P, but also to move the lake away from a high phosphorus, high algal biomass state. The dark symbols before the intervention are mostly located in the red or orange WFD classes, indicating poor water quality. After the intervention, the light grey symbols shift towards the lower-left part of the plot, with much lower summer mean TP and chlorophyll-a. This shows that the combined measures were technically effective in reducing nutrient availability and algal biomass (*Figure 61*).

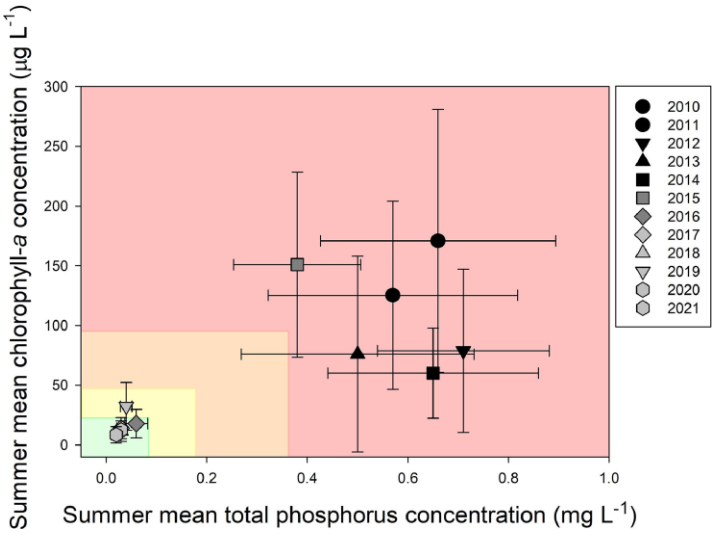


Figure 61. Mean summer chlorophyll-a concentrations (± 1 SD) versus mean summer TP concentrations in Lake Groote Melanen. The dark symbols indicate the years before the restoration intervention, the light grey symbols the years after, while dark grey symbols were in years when activities took place (restoration February 2015-May 2016). The coloured planes represent the Water Framework Directive classification for lake type M11 (smaller, area <50 ha; shallow, water depth < 3 m; buffered lakes): Green = good, yellow = moderate, orange = insufficient, red = bad water quality

Maintenance and operational requirements

After implementation, Groote Melanen required continued water quality monitoring and ecological follow-up. Regular maintenance is also needed to keep external nutrient inputs low. This includes maintaining the diverted streams, banks and surrounding areas, and preventing new nutrient-rich inflows. Aquatic vegetation should be monitored and, if needed, managed to support clear-water conditions. Fish-stock monitoring is also important, because a return of bottom-disturbing fish could reduce water clarity again.

Technical challenges and limitations

The lake needed a full combined package, including fish removal, dredging, sand capping, LMB application, PAC treatment and planting of aquatic vegetation. This made the project technically complex and required careful planning and timing.

Another limitation is that the success depends on keeping both external and internal nutrient loading low. If external nutrient inputs increase again, or if the sediment cap is disturbed, the lake may become more nutrient-rich again. The handling and reuse of dredged material also required space and practical organisation. Therefore, the method is effective, but it needs good preparation, sufficient budget and long-term management.

Replicability and scalability

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The Groote Melanen approach can be replicated in other shallow eutrophic lakes, especially where poor water quality is caused by internal P release, nutrient-rich sediment, fish disturbance and poor light conditions. The case shows that a combined restoration package can shift a lake towards clearer water and better ecological conditions. However, replication should always start with a system analysis.

4.9.7 Cost-effectiveness

Groote Melanen covered a much smaller area of 4.8 ha, with an investment cost of €1.5 million, operational costs of €1 million, and a lifetime of 10 years. The annualized cost is €1.15 million per year, resulting in 0.240 M€/ha/year.

4.9.8 Knowledge gaps

The main knowledge gap is the long-term stability of the combined measures. Further monitoring is needed to assess whether the sand cap and LMB layer remain effective over time, especially under sediment disturbance, fish activity and vegetation development. More information is also needed on long-term ecological recovery, lanthanum distribution in the sediment and the maintenance costs required to keep the lake in a clear-water state.

4.9.9 Overall evaluation and recommendation

The main lesson from Lake Groote Melanen is that eutrophic shallow lakes often need a combined restoration package rather than a single measure. External nutrient reduction alone may not be enough, because internal phosphorus stored in the sediment can continue to delay recovery. At the same time, internal P control alone is also not sufficient if the lake remains turbid due to fish disturbance and lack of submerged plants. In Groote Melanen, the combination of inlet diversion, fish removal, dredging, sand and LMB capping, bank reconstruction and macrophyte planting worked together to reduce nutrient pressure and help shift the lake towards a clearer-water state.

The case also shows that implementation can cause short-term side effects. Dredging and sand capping temporarily increased turbidity and suspended solids, while LMB application caused temporary increases in lanthanum. However, these effects declined after the works were completed. A further lesson is that successful restoration requires upfront investment in diagnosis and project management.

Table 32. Innovation performance summary for Lake Groote Melanen

Evaluation component	Results	Explanation
Intended function achieved	Yes	The combined package achieved its main function
Ecological improvement observed	Yes	Ecological improvement was observed through the recovery of submerged macrophytes. Repeated fish removal also reduced fish stock.
Replication potential	Medium	The approach can guide other shallow eutrophic lakes, but it needs lake-specific system analysis.
Unexpected effects	Neutral	Some short-term negative effects occurred during implementation, including temporary increases in turbidity. These were implementation-related effects and

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		did not prevent long-term water-quality improvement.
Knowledge gaps	Upfront investment in diagnosis; project management	

4.10 Multiple external and internal measures - Lake Bleiswijkse Zoom (NL)

4.10.1 Restoration innovation

Lake Bleiswijkse Zoom pilot demonstrates an integrated restoration approach that simultaneously addresses both external and internal nutrient loading, hydrological management and ecological resilience. The restoration strategy was based on a system analysis using the Dutch Ecological Key Factors (ESF). This framework helps to identify the main problems in a lake and to select suitable restoration measures. In Lake Bleiswijkse Zoom, it indicated that no single measure would be sufficient to restore the lake from a turbid, algae-dominated state to a clear-water state.

The innovation lies in the systematic combination of multiple restoration measures targeting different pressures at the same time. Rather than relying on a single conventional intervention, such as dredging or P inactivation, this innovation pilot combined hydrological restoration measures (stream diversion, flexible water level management), nutrient-load reduction (dredging and P-binding by LMB application), fish removal and habitat restoration (nature-friendly banks and shoreline vegetation) within a coordinated restoration program.

Bleiswijkse Zoom was designed as a whole-lake restoration project, and restoration measures were implemented between 2019-2023 (Figure 62). The design aimed to reduce the external P load from almost 7 mg P m^{-2} d^{-1} to a level closer to the critical thresholds, while also forcing the system from a turbid to a clear-water state. A key design measure was the construction of a bypass to stop the direct inflow of nutrient-rich water from the nutrient-rich River Rotte. Before the intervention, the lake received about 2,000 m^3/day of water during the summer, equal to a water layer of around 13 mm/day across the whole lake. After the bypass, this water no longer passes through the lake but flows underneath the lake instead. Flexible water-level management was also introduced. The water-level range was first increased to 25 cm and later to 55 cm between -5.45 and -6.00 m NAP. With the larger water-level range, the water balance indicates that no additional River Rotte water should be needed under normal summer conditions.

The sediment design included dredging of the nutrient-rich layer (approximately 25 cm) down to the underlying clay and sand by a specialised dredging company (JP Schilder B.V.; https://www.jpschilder.nl/project/baggerwerkzaamheden-bleiswijkse-zoom/). The spill and remaining lake bed after dredging were checked for P relase reduced the calculated P release from 81 cores collected after dredging and subjected to a sequential P fractionation. This yielded that dredging had lowered P release from the sediment by about 60%, from 3.5 to 1.5 mg P m^{-2} d^{-1}. Because P was still present in the deeper sediment layer, 90 tonnes of LMB were applied after dredging to bind P and reduce future release into the water column. The dredged material was temporarily stored in raised deposition sites and reused for building a park landscape. This reduced waste and supported local reuse of material. Overall, the innovation lies in the integrated package: reducing external load, improving light conditions, reducing sediment P release and increasing ecological resilience at the same time.

The shoreline was also constructed (*Figure 63*). Bleiswijkse Zoom has about 6 km of shoreline, of which around 3 km is suitable for reed growth. Along 300 m, the bank slope was made gentler, with a width

of 1 to 2.5 m. After the measures, about 0.45 ha became available for shoreline vegetation, equal to around 3% of the lake surface. These areas help trap suspended solids, support denitrification and provide habitat for macrofauna and fish.

Fish stock management was included because the lake had a high fish biomass of about 423 kg/ha, dominated by carp and bream. These fish worsened the light climate by resuspending sediment. The fish stock was therefore reduced before dredging, with target levels of maximum 15 kg/ha planktivorous fish and 30 kg/ha benthivorous fish. Some large carp were kept for angling, while surplus fish were relocated.

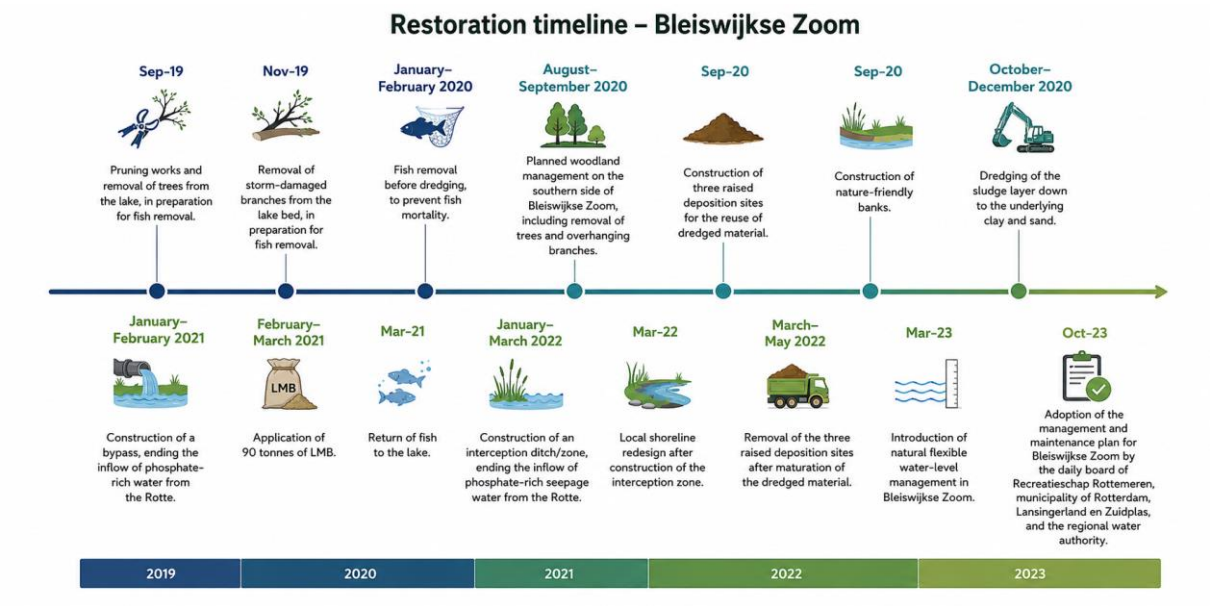


Figure 62. Restoration timeline of pilot Lake Bleiswijkse Zoom. Figure is generated with ChatGPT.



Figure 63. Shoreline reconstruction of Lake Bleiswijkse Zoom.

4.10.2 Pilot specific objectives

The main objective was to improve water quality, achieve the WFD objectives and support better bathing water quality. The desired ecological state was a clear water system with submerged aquatic plants, with a target of 50% submerged vegetation cover. The measurable targets were linked to P loading, sediment release, fish stock and vegetation recovery.

Ecological targets included better water transparency, lower algal growth, recovery of submerged aquatic plants and better fish stock. Fish stock management aimed to reduce the pressure from fish, with target levels of maximum 15 kg/ha planktivorous fish and 30 kg/ha benthivorous fish. Shoreline

restoration and flexible water-level management were also expected to support reed development and the recovery of aquatic habitats.

Overall, the pilot aimed to create a clearer, more stable and more resilient lake system. Success can be assessed through reduced P loading, lower sediment P release, improved light conditions, reduced fish disturbance, expansion of aquatic vegetation and better bathing water quality.

4.10.3 Site description

Lake Bleiswijkse Zoom (*Figure 64*) is a 14-ha shallow recreational lake located north of the City of Rotterdam, the Netherlands. The elongated lake is approximately 2.5 km in length and 5-140 m wide, with water depth ranging from 1 m at the northern bathing area to 1.5-2 m in the southern basin. The lake was excavated in 1970/1971 and constructed with hard revetments. It was subjected to a biomanipulation experiment from 1987 until 1991 that included a division of the lake in a control part and a treatment part with fish removal (1987, 1988, 1989) and 0+ pike stocking (1987-1991) (Meijer, 2000).

Prior to restoration, the lake was subject to multiple pressures associated with eutrophication. The water level in the adjacent area was maintained by the inflow of nutrient-rich water from the River Rotte, which flowed through Lake Bleiswijkse Zoom. Moreover, the River Rotte water was used to maintain a fixed water level in the lake. Over the decades, a thick sediment layer developed, macrophytes disappeared, and the lake became turbid, infested by cyanobacteria with few macrofauna and mostly sediment-resuspending fish (carp, bream). The lake suffered from massive cyanobacteria blooms annually. The poor water quality led to 100 days of warnings for cyanobacteria blooms in 2017, 102 days in 2018 and 54 days in 2019 (HHSK, 2025).

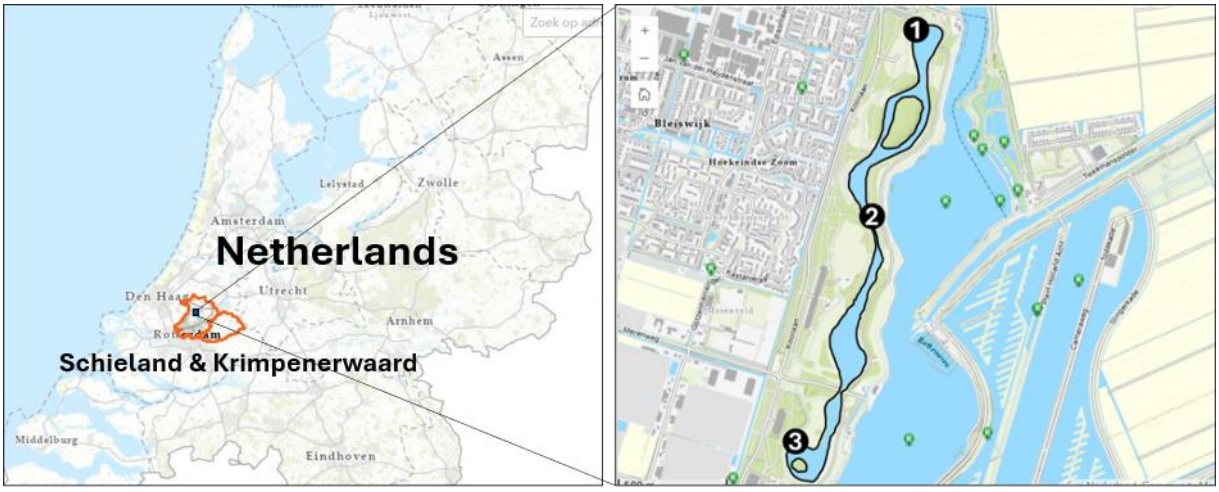


Figure 64. Location of Lake Bleiswijkse Zoom in the jurisdiction of HHSK (area within red lines in left panel) with three sampling stations (location 1 Badzone; location 2 Voetbrugand; location 3 Zuidpunt in right panel)

4.10.4 Monitoring and indicators used

The indicators were selected to assess whether the Bleiswijkse Zoom pilot supports WFD objectives, improves bathing-water quality and helps the lake shift towards a clear-water state. The monitoring focuses on nutrient concentrations, aquatic vegetation, fish stock and swimming advices (*Table 33*). The monitoring period for water quality covers approximately 2014-2026, including a pre-intervention period, the main intervention period around 2020-2021, and continued post-intervention monitoring. The indicators were measured at three lake locations: Badzone (location 1 in *Figure 64*), Voetbrug (location 2 in *Figure 64*) and Zuidpunt (location 3 in *Figure 64*).

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Table 33. Policy area, policy criterion and indicators used in the assessment of pilot Bleiswijkse Zoom

Policy area	Policy criterion	Indicator name	Data sources
Environmental	WFD	Water quality, water clarity, submerged macrophyte cover, fish stock, fish community composition	HHSK records
	Zero Pollution	External P load, inlet water from the Rotte, sediment P release, TP, chlorophyll-a, suspended solids, turbidity	
	Biodiversity net gain	Submerged aquatic plants, reed zones, nature-friendly banks, macrofauna habitat, fish community composition	
Economic	Ecotourism	Bathing-water quality, cyanobacterial nuisance, recreational water use, amenity value	HHSK records

4.10.5 Results and evaluation

Environmental & policy relevant indicators

Water quality

The monitoring results (*Figure 65*) showed that the restoration measures led to clear improvements in the main water quality indicators before 2025. Before the intervention, TP concentrations were high and showed strong seasonal fluctuations. These fluctuations were mainly related to P release from sediment, especially during summer periods. After combined measures, the seasonal P peaks largely disappeared. Average TP decreased from about 0.34 mg P L^{-1} before the intervention to about 0.07 mg P L^{-1} after the intervention.

Between 2021 and 2024, TP concentrations remained low and relatively stable at the three monitoring locations. However, the monitoring also showed that TP started to increase again in 2025, with new peaks at some locations. This means that the restoration strongly reduced P pressure, but the system may still be vulnerable to internal P release.

Total nitrogen also decreased after the intervention. Average TN declined from about 1.89 mg N L^{-1} to about 1.47 mg N L^{-1}. Large nitrogen fluctuations became less frequent after the measures, however, TN started to increase in 2024.

Chlorophyll-a decreased from about 37 µg L^{-1} before the intervention to about 23 µg L^{-1} afterwards. Cyanobacteria biovolume showed a stronger reduction, from about 18.4 mm^3 L^{-1} to about 2.4 mm^3 L^{-1}. However, after 3 years of intervention, blue-green algae nuisance has returned.

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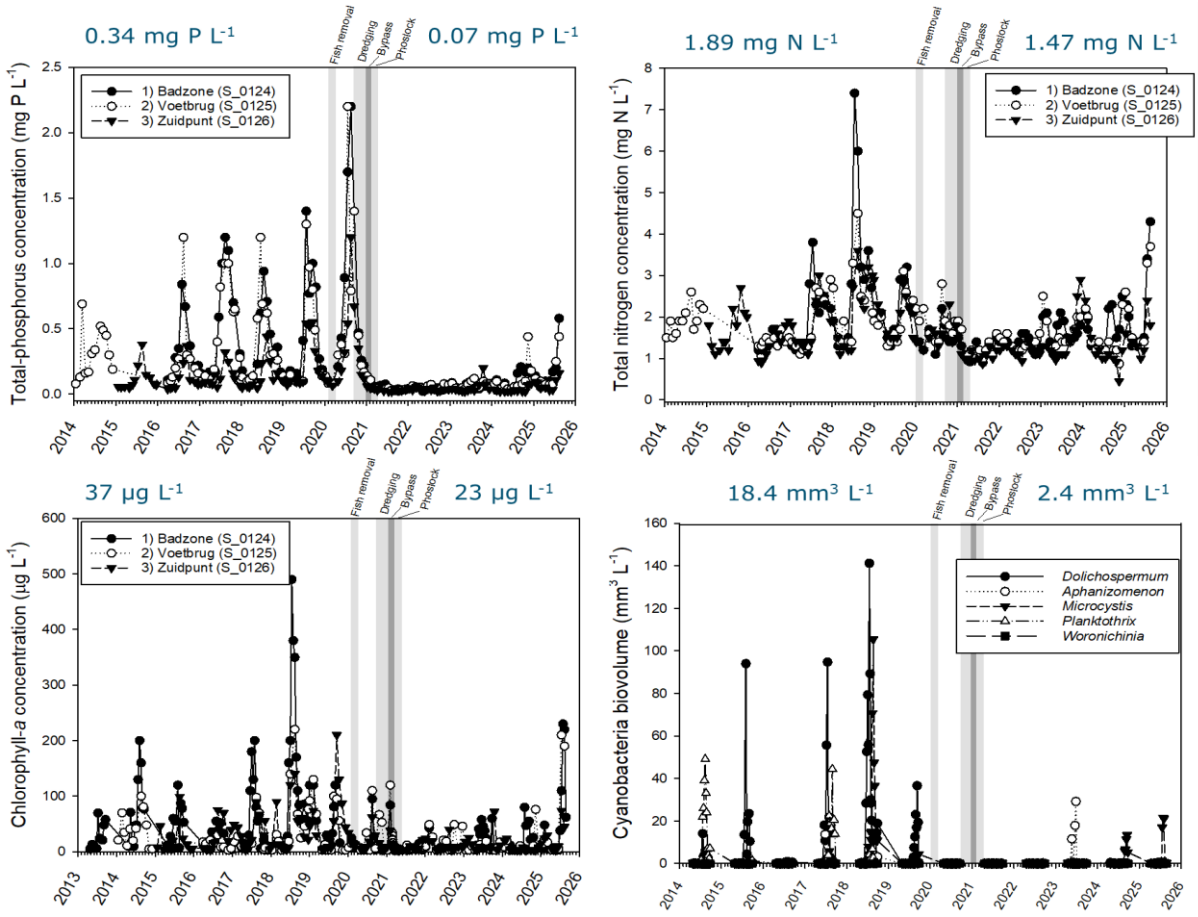


Figure 65. Course of total P concentrations (mg P L^{-1}) from 2014 until 2025 (upper left panel), total nitrogen concentrations (mg N L^{-1}) from 2014 until 2025 (upper right panel), the chlorophyll-a concentrations (µg L^{-1}) from 2013 until 2025 (lower left panel), and Cyanobacteria biovolume from 2014 until 2025 (lower right panel) in Lake Bleiswijkse Zoom at three different stations (location 1: Badzone, S_0124; location 2: Voetbrug, S_0125; location 3: Zuidpunt, S_0126) is plotted in the lower panel B, including various restoration measures. Grey area indicates the post-intervention period

Vegetation

The ecological response is also visible in the vegetation monitoring (*Figure 66*). Submerged vegetation increased strongly, from an average cover of 30% in 2018 to around 85% in 2022. This means that the original target of 50% submerged vegetation cover was exceeded. In 2022, *Elodea nuttallii* and Chara were the dominant species. This suggests that the lake moved towards the desired clear-water state with aquatic plants.

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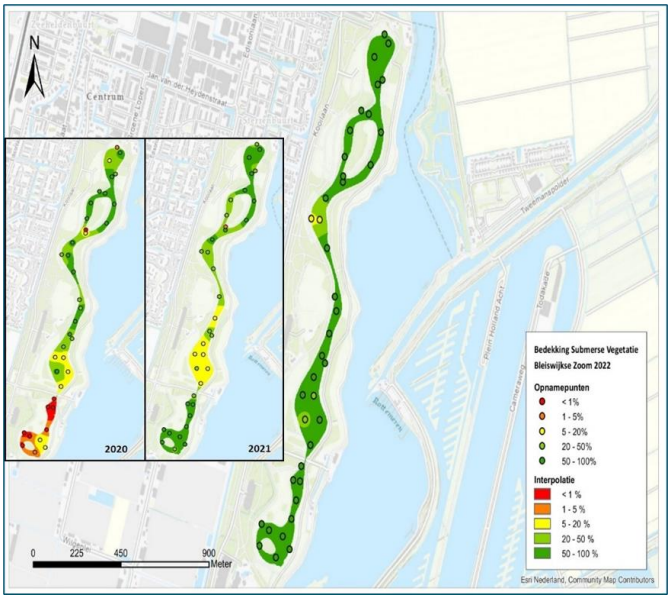


Figure 66. Submerged vegetation cover in Bleiswijkse Zoom in 2020, 2021 and 2022.

Ecotourism

Figure 67 showed the number of days with bathing water warnings and negative swimming advice in Bleiswijkse Zoom. The official swimming season in the Netherlands runs from May 1 to October 1. Before the restoration, several years had long periods with poor bathing water conditions. The highest values were around 100 days, and a large part of these periods consisted of negative swimming advice. After the restoration measures, the situation improved clearly. In 2020, 2021 and 2022, no negative swimming advice was issued for cyanobacteria. This suggests that the measures helped reduce bathing water problems and improved the recreational use of the lake. After 2023, warnings appeared again, with about 35 and 54 days.

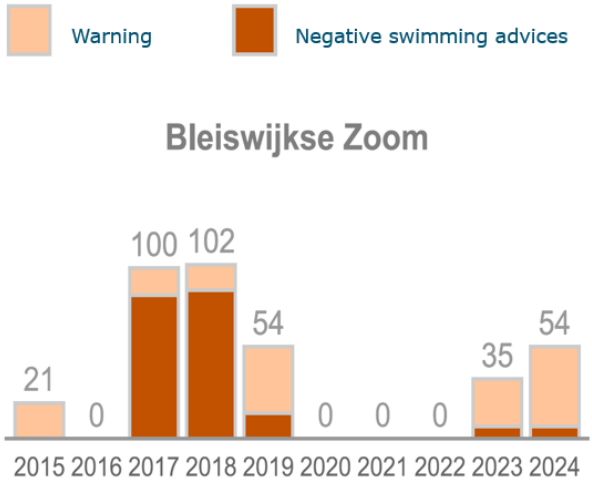


Figure 67. Swimming advice for Lake Bleiswijkse Zoom (The light orange bars represent warnings, while the dark orange bars represent negative swimming advice)

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4.10.6 Technical performance

Achievement of design targets

The restoration measures in Bleiswijkse Zoom largely achieved the main design targets in the first years after implementation. The pilot aimed to reduce P pressure, improve water clarity, reduce fish disturbance and support the recovery of submerged vegetation. After the measures, TP decreased from about 0.34 mg P L^{-1} to about 0.07 mg P L^{-1}, and the strong seasonal phosphorus peaks became much smaller. Submerged vegetation increased from about 30% in 2018 to about 85% in 2022, which was higher than the target of 50% cover. This shows that the lake shifted towards a clearer water state. However, TP increased again in 2024/2025, blue-green algae nuisance has returned, so the long-term stability of the system still needs to be focused.

Maintenance and operational requirements

The pilot requires continued monitoring and regular maintenance. Water quality, TP, chlorophyll-a, cyanobacteria, submerged vegetation and fish stock should be monitored to check whether the lake remains in a clear-water state. The bypass, interception zone and flexible water level management also need to be maintained, because they are important for reducing the inflow of nutrient-rich water. Shoreline vegetation and reed zones need regular management to avoid too much organic matter entering the lake. Fish stock may also need follow-up control if bottom-disturbing fish increase again.

Technical challenges and limitations

A main technical challenge is that the lake is not fully isolated from all P sources. Although the direct inflow of nutrient rich Rotte water was largely stopped, other sources such as groundwater seepage, runoff, leaching or internal phosphorus release may still contribute nutrients. This may explain the TP increase observed again in 2024/2025. Another limitation is that the restoration depended on several measures working together, including the bypass, dredging, LMB application, fish removal and shoreline restoration. This makes the project technically complex and requires good coordination, long-term monitoring and maintenance.

Replicability and scalability

The innovation worked well in the first year after implementation. The technical measures were implemented as planned. The bypass reduced the inflow of nutrient-rich water from the Rotte. Dredging reduced P release from the sediment, and 90 tonnes of LMB were applied to bind remaining P. Fish removal also helped reduce sediment disturbance and improve the light conditions. However, monitoring data in 2025 shows that continuous nutrients keep entering the system, probably seepage from the river Rotte and via groundwater.

4.10.7 Cost-effectiveness

Bleiswijkse Zoom covered 14 ha, with an investment cost of €1 million, operational costs of €0.5 million, and a lifetime of 4.5 years. The annualized cost is about €0.72 million per year, corresponding to 0.052 M€/ha/year.

4.10.8 Knowledge gaps

The main knowledge gap is the long-term stability of the restored clear-water state. The measures clearly improved water quality and aquatic vegetation in the first years after implementation. However, TP increased again in 2024/2025, showing that the system may have much P inputs. It is still unclear whether this increase was mainly caused by groundwater seepage, runoff and leaching, remaining external inputs, or internal P release from the sediment. More long-term monitoring is needed to identify the main P source and to assess whether additional management actions are needed.

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4.10.9 Overall evaluation and recommendations

The main lesson from Bleiswijkse Zoom is that a combined approach is needed when a lake has several pressures at the same time. Reducing external P alone would not have been enough, because the lake also had multiple nutrients sources (groundwater, runoff, internal P), poor light conditions and sediment-disturbing fish. The project shows that hydrological measures, dredging, LMB application, fish management and vegetation recovery can work well together. However, nutrients started to increase again from 2024/2025. As the direct inlet from the Rotte had been largely stopped, the increase may be linked to other remaining sources, such as groundwater seepage, runoff, leaching or internal P release from the sediment. Hence, restoration success needs long-term monitoring (*Table 34*).

Table 34. Innovation performance summary for Bleiswijkse Zoom

Evaluation component	Results	Explanation
Intended function achieved	Yes / Partly	Water quality improved strongly, but TP increased again in 2024/2025.
Ecological improvement observed	Yes	Submerged vegetation increased from 30% in 2018 to 85% in 2022.
Replication potential	Medium	Useful for similar shallow lakes, but site-specific analysis is needed.
Unexpected effects	Neutral / Negative	TP increased again after several stable years.
Knowledge gaps		More monitoring is needed

5 Comparison of innovations

The FutureLakes innovation portfolio includes a diverse set of solutions addressing different pressures and processes within lake-catchment systems. The innovations range from targeted in-lake interventions addressing nutrients and harmful algal blooms, to catchment-scale nature-based solutions and integrated restoration programmes combining multiple measures. As a result, the innovations differ substantially in their objectives, maturity, implementation requirements, expected outcomes and time horizons. The rationale for the selected criteria, scoring approach, and interpretation of the radar plot are described in Annex b.

To support comparison, the pilots were grouped into three categories: In-lake focused solutions, catchment focused solutions and combined solutions. Figures 68-70 represent radar chart summaries of the innovation pilots within each category based on environmental, technical and economic dimensions. The radar charts should not be interpreted as indicators of overall success or failure, but rather as visual representations of the different strengths, limitations and application context of the innovations. The following sections compare the innovation within each group and highlight the specific restoration challenges they were designed to address.

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5.1 In-lake focused solutions

The in-lake solutions focused on pressures already present within the lake ecosystem. Figure 68 shows that the in-lake solutions are characterized by relatively high scores for innovation maturity, scalability and limited space requirements, but generally lower scores for nutrient reduction, water-quality improvement and biodiversity enhancement. Overall, the radar-chart profiles indicate that these solutions are highly targeted interventions designed to address specific symptoms of eutrophication rather than the broader drivers affecting lake condition.

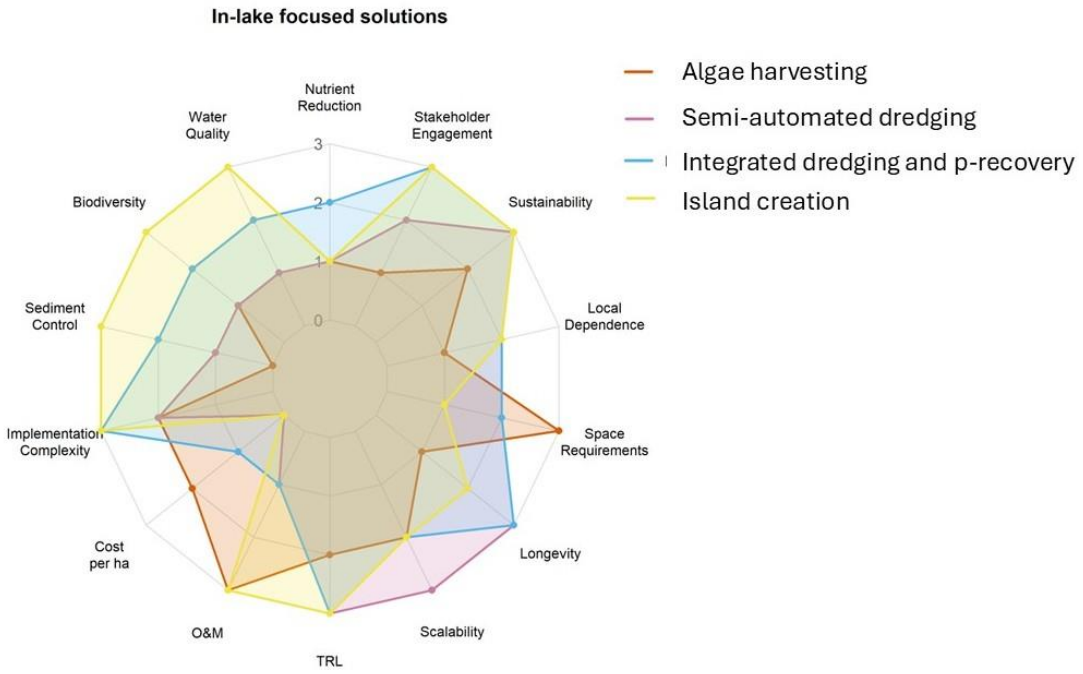


Figure 68 Radar chart for in-lake solutions. Scales: 3=High, 2=Moderate, 1=Low, 0=not assessed/no data. O&M refers to Operational & maintenance needs.

The experimental algal harvesting pilot evaluated three technologies as a potential response to HABs. Compared with phosphorus-recovery approaches, harvesting has potential for small-scale biomass recovery and valorisation, although the spatial and temporal scales of this pilot were limited. One of the tested systems (AS-LAND) is already commercialised, suggesting a relatively mature technology with moderate potential for replication in lakes with recurrent surface scums. However, this experimental harvesting did not produce measurable changes in water quality, nutrient concentrations, or cyanotoxin levels. The study also highlighted challenges related to the capture of non-target organisms, biomass toxicity, and operational requirements. Consequently, while algal harvesting suggests promise for targeted biomass recovery (e.g. Macario et al. 2021), this innovation appears suitable as a small-scale supplementary management measure rather than a stand-alone restoration solution. While the pilot provided valuable short-term insights, the long-term ecological effects, nutrient and carbon removal benefits, and economic feasibility of large-scale algal harvesting remain uncertain.

The two phosphorus-recovery pilots addressed eutrophication from a different perspective by targeting nutrients accumulated in the sediment. A particular strength of these approaches is their contribution to circular resource reuse. Phosphorus is a finite and strategically important nutrient and recovering phosphorus-rich sediments from eutrophic lakes may simultaneously contribute to nutrient recycling and lake restoration (Chowdhury et al., 2017). The use of P-fertilizers in agriculture is expensive and furthermore, P is an element which is becoming rare with limited numbers of mines

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available world-wide and with limited amounts of easily accessible phosphorus. We therefore potentially face a situation where the worlds food production will be threatened by limited P access within the next 50-150 years (Chowdhury et al., 2017). Internal P-loading is common in many lakes after the external loading has been reduced and may prevent or delay lake recovery and the fulfilment of ecological standards such as the WFD. The Kartuzy pilot demonstrated the highest level of technical development, including a full-scale sediment treatment and reuse, while the dredging with a semi-automated dredger in the Ormstrup pilot focused more on the development and optimisation of the dredging technology. Both pilots demonstrated that phosphorus recovery is technically feasible and both innovations have large replication potential. Despite their technical success, however, the ecological status outcomes remain relatively modest in terms of water quality improvement.

Island creation presents a third and different profile within the in-lake restoration approaches. By targeting habitat and ecosystem functioning, the innovation achieved some of the highest scores for biodiversity enhancement, sustainability and longevity. New habitats were created for birds, fish and aquatic vegetation while also providing recreational opportunities. However, the measure did not directly address nutrient inputs or internal nutrient loading, which is also reflected in the low score of the nutrient reduction. Island creation should therefore be viewed primarily as a habitat-restoration and biodiversity measure rather than a nutrient-management intervention.

The four innovations in the in-lake category also reveal several knowledge gaps and implementation challenges. For algal harvesting, uncertainties remain regarding the long-term ecological consequence of removing non-target organisms, i.e. zooplankton, and the scale of harvesting required to improve overall water quality. For the two phosphorus-recovery pilots, key challenges included sediment contamination, regulatory approval processes and the need for more precise dredging techniques. These findings suggest that the primary challenges for in-lake solutions are not technical feasibility itself but implementation that should be conducted at a large enough scale to secure improvement in ecological status and support long-term lake recovery. For island creation, long-term habitat development and ecological succession remain important uncertainties, particularly the establishment of species such as willows and geese that may alter the intended habitat characteristics over time.

5.2 Catchment-focused solutions

The catchment-focused solutions showed the most diverse profile among the three innovation categories (Figure 69). Unlike the in-lake focused solutions, the catchment-focused solutions occupy different niches within the restoration toolbox. Their radar-chart profiles show specific strength areas and generally score highly for sustainability, longevity, biodiversity enhancement and stakeholder engagement.

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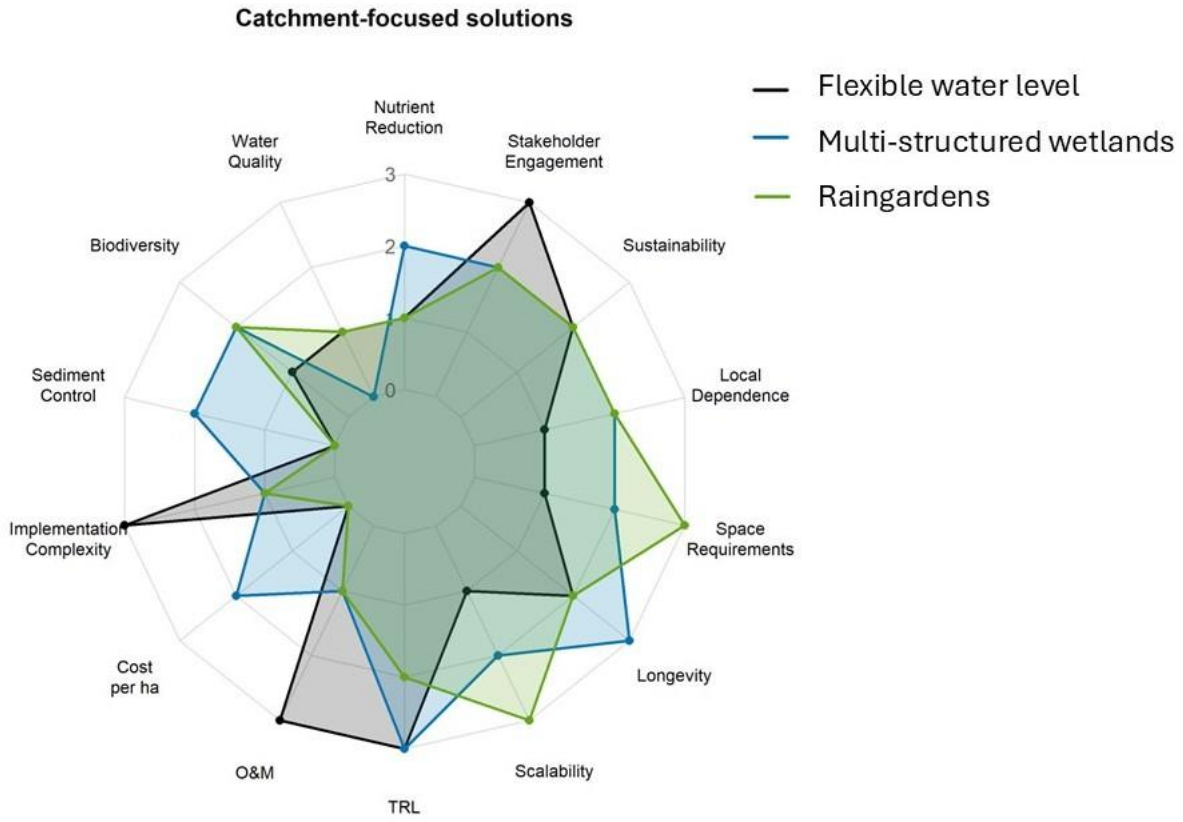


Figure 69. Radar charts on the catchment-focused solutions. Scales: 3=High, 2=Moderate, 1=Low, 0=not assessed/no data. O&M refers to Operational & maintenance needs.

The multi-structure CW has the most balanced profile in the group, performing moderately to well across most dimensions. It combines nutrient and sediment retention, biodiversity enhancement, and long-term sustainability, with particularly strong scores for longevity, transferability, and sustainability. While the effects of the studied CW on nutrient reduction and water quality are more moderate than those of combined restoration projects, the results indicate that CWs can simultaneously support lake restoration, habitat creation, and climate adaptation.

The Loch Leven raingardens show a very different profile. Compared with the wetland, they score lower for nutrient reductions and water quality improvements, but is strong for the biodiversity enhancement, sustainability and stakeholder engagement. Their strength lies in providing local benefits through stormwater management, pollinator habitat and urban greening rather than direct lake restoration. The radar chart therefore reflects that this nature-based solution delivers multiple societal and ecological co-benefits but whose influence on lake-scale ecological status is currently difficult to detect.

The water-storage pilot showed a third position within the catchment-focused restoration approaches. In contrast to both wetland and raingardens, its profile is centred on technical feasibility and longevity and less on the biodiversity, which is not surprising as the solutions mainly aims to reduce flooding and the impact of droughts. This highlights its role as a hydrological adaptation measure that strengthens resilience of the wider water-management system rather than directly improving lake ecological status.

Overall, Figure 69 illustrates that the catchment-focused innovations provide complementary approaches. The wetland is the strongest performer for nutrient retention and overall balance of benefits, the raingardens excel in biodiversity and local stormwater management, while the water-storage innovation contributes primarily to hydrological resilience and long-term climate adaptation.

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5.3 Combined solutions

The combined solutions differ from the other innovation pilots by integrating multiple restoration measures into coordinated restoration programs. As shown in Figure 70, the three solutions display remarkably similar radar-chart profiles, with high scores for nutrient reduction, water-quality improvement, biodiversity enhancement, sediment and internal-load control, sustainability and longevity. Their profiles are broader and more balanced than those of the other innovation groups, reflecting the comprehensive nature of the restoration approaches.

A common characteristic of all three innovation pilots was the simultaneously management of both external and internal drivers of eutrophication. Therefore, all three lakes achieved substantial ecological improvements that were reflected across multiple indicators rather than only one aspect of lake condition.

Compared with the other innovation categories, the combined solutions show the clearest link between intervention and measurable ecological recovery. Figure 70 illustrates that they are the only solutions that consistently score highly across nutrient reduction, water-quality improvement, biodiversity enhancement and control of internal nutrient loading simultaneously. This suggests that successful restoration of eutrophic lakes often requires management of multiple pressures rather than reliance on a single intervention. The strengths of the combined solutions are accompanied by greater implementation requirements. All three restoration programmes involved substantial financial investment, extensive planning, stakeholder engagement and detailed lake-specific analyses before implementation. Their relatively high complexity reflects the need to understand local nutrient dynamics, hydrology, sediment characteristics and ecological interactions before selecting an appropriate combination of measures. The radar chart profiles therefore show a clear trade-off between ecological effectiveness and implementation effort.

Several knowledge gaps and challenges remain despite the strong outcomes achieved. The most important uncertainty concerns the long-term stability of restoration gains and the extent to which continued management may be required. The increase in P concentrations observed in Bleiswijkse Zoom highlights the potential vulnerability of restored systems to ongoing external pressures. Continued monitoring is therefore needed to assess the durability of improvements in water quality, aquatic vegetation and ecological status. In addition, although the general restoration principles are transferable, the specific combinations of measures used in each project remain highly dependent on local conditions, limiting direct replication without detailed lake-system analysis.

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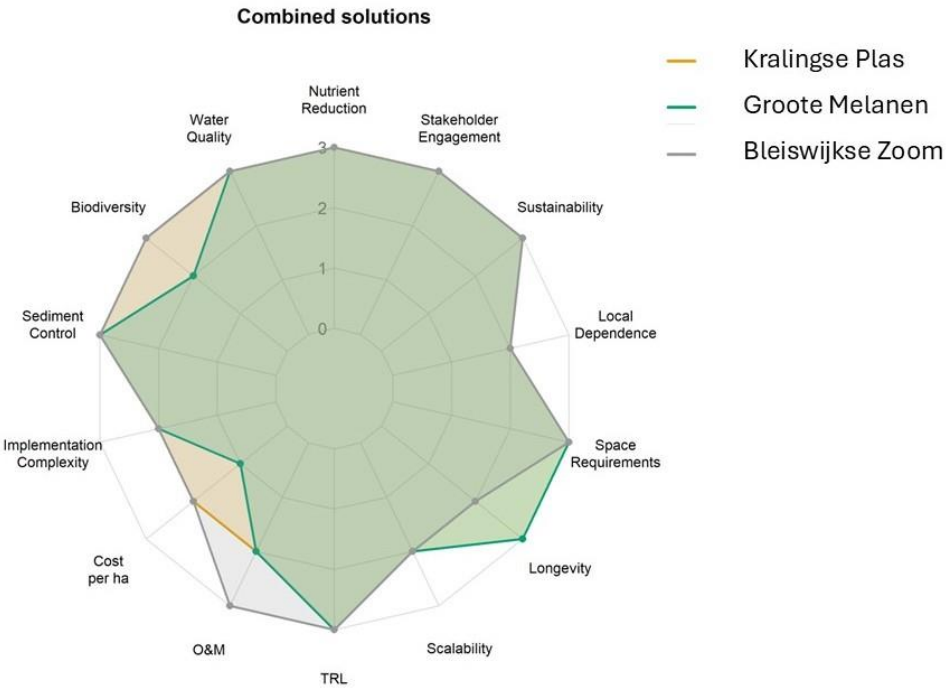


Figure 70. Radar-charts of the combined solutions. Scales: 3=High, 2=Moderate, 1=Low, 0=not assessed/no data. O&M refers to Operational & maintenance needs.

6 Overall lessons learned

The FutureLakes innovation pilots demonstrate both the opportunities and challenges associated with developing and implementing new restoration approaches. Together, the pilots address several of the key pressures identified for European lakes, including eutrophication, legacy nutrients in sediments, habitat degradation and climate related pressures by testing innovative NbS, CBS and BfS under operational conditions.

A recurring finding across the pilots was that technical feasibility was often demonstrated more clearly than ecological effectiveness. Several innovations reached high levels of technological readiness. However, measurable improvements in ecological status were often limited, difficult to detect, or occurred more slowly than expected. In many cases, this reflected the scale of implementation rather than the underlying effectiveness of the innovation, as was the case with the dredging in Lake Ormstrup and harvesting algae in Lake Enäjärvi. Several pilot interventions were applied to relatively small areas compared with the entire lake or catchment, making it challenging to detect lake-scale responses within the project period. Ecological recovery processes such as reductions in nutrient loading, changes in food-web structure, and recovery of aquatic vegetation often occur over timescales of several years (Søndergaard et al. 2003). As a result, some innovations may require longer monitoring periods before their full ecological benefits become apparent. These findings highlight both the complexity of lake ecosystems and the importance of considering spatial scale and recovery trajectories when evaluating restoration success.

The evaluation of pilots also highlighted challenges related to evaluating economic performance. Comprehensive cost-effectiveness analyses were difficult to make because ecological benefits often emerge gradually over many years while costs are incurred during implementation. Furthermore, baseline information before implementation was not always available at the level required for robust before-after comparisons. This limited the ability to quantify the full environmental and economic benefits achieved by some of the innovations. For those measures that were able to calculate the cost-effectiveness, the operational and maintenance costs included in the cost-effectiveness analyses represent the expenditures required to maintain the functionality of the implemented measure during

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the assessed project lifetime. However, these costs do not fully reflect the net financial implications of the intervention. In practice, part of the maintenance and operational expenditures may be offset by revenues generated through recreational activities. Examples include visitor-related income, harbour-related revenues, guided activities and other forms of recreational use enabled by the project infrastructure. These revenues fall outside the scope of the present analysis and have therefore not been deducted from the reported operational costs. Consequently, the reported cost-effectiveness values may be viewed as conservative from a financial perspective, as they do not account for potential revenue streams associated with recreational use.

More broadly, the cost-effectiveness analysis highlights the importance of systematic cost reporting for (large-scale) nature-based and infrastructure-related measures. Although ecological outcomes are increasingly monitored and evaluated, detailed information on project costs, maintenance expenditures and monitoring investments is often fragmented or unavailable. This limits the ability to compare interventions, evaluate efficiency and identify cost drivers across projects. Improved transparency and standardised reporting of capital, operational and monitoring costs would strengthen future evaluations and facilitate evidence-based decision-making regarding nature restoration and infrastructure investments. Particularly for innovative projects such as reported here, documenting costs is essential for understanding not only the financial resources required to implement the intervention, but also the costs associated with long-term management, monitoring and adaptive learning. Greater transparency regarding these expenditures would improve the comparability of future projects and contribute to a more robust evidence base for assessing the cost-effectiveness of large-scale ecosystem restoration and nature-based infrastructure measures.

The FutureLakes' pilots have demonstrated a wide range of innovations with considerable potential for future lake restoration projects. Several of the tested solutions progressed from concept development or pilot testing towards implementation under operational conditions. The phosphorus-recovery pilots have advanced knowledge on nutrient recycling and sediment management. Algal harvesting has demonstrated potential emergency measures for managing harmful blooms, the multi-structured wetland and raingarden pilots have strengthened the evidence base for nature-based solutions, and the water-storage pilot has highlighted innovative opportunities for climate adaptation. The three pilots show that system analysis is essential for lake restoration, both before implementation to choose the right measures and after implementation to understand whether further actions are needed. The innovation pilots therefore provide a strong foundation for future restoration efforts. While further monitoring and evaluation are required for many of the pilots, the results suggest that innovative restoration approaches can complement conventional measures and help address persistent challenges that have limited the effectiveness of traditional restoration programmes. Future restoration strategies are likely to benefit from combining different types of interventions according to local conditions, restoration objectives and dominant pressures within the lake-catchment system.

Overall, the FutureLakes innovations demonstrate the value of adopting a systems perspective in lake restoration. Successful restoration depends not only on selecting appropriate technologies, but also on understanding how different pressures interact within the lake-catchment system and how restoration measures can complement one another. The knowledge obtained through these pilots provides an important foundation for the future uptake, scaling and refinement of innovative restoration approaches across European lake ecosystems.

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Loch Leven raingardens: Perth & Kinross Council; NatureScot

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a. Annex: Method descriptions for pilots

1. Algal harvesting

WFD

Water quality

Water chemistry samples (TP, PO_4-P, TN, TOC, Chl *a*) were collected from 0.5 m depth using a 2.7 L water sampler (Limnos water sampler, Limnos Ltd., Poland). Water quality analyses were performed in a FINAS-accredited laboratory following standard methods described in Mitikka and Ekholm (2003). Additionally, the temperature profiles during each sampling occasion were measured from the mesocosms (EXO2, YSI Incorporated, Yellow Springs, Ohio, USA). The temperature from surface to bottom remained ~21 °C in each of the mesocosms.

Plankton

Composite phytoplankton samples were taken from 0–1 m depth from each mesocosm with the water sampler and fixed with acid Lugol's solution (0,5 mL per 100 mL) in 100 mL polyethylene plastic bottles. Phytoplankton was identified to species when possible and counted using an inverted light microscope (Leica DMi8) and phase contrast illumination with a modified Utermöhl technique (EN 15204:2006). Phytoplankton abundances were converted to fresh weight biomasses using appropriate geometric formulae (EN 16695:2015), assuming a density of 1 g cm^{-3}.

Composite zooplankton samples were taken by sieving the water column of each mesocosm from 0–1 m depth through a 50 µm plankton net and placing the sieved water in 250 mL polyethylene plastic bottles. The samples were fixed with acid Lugol's solution (1.0 mL per 100 mL of water). Using an inverted microscope (Leica DM IRB, Wetzlar, Germany), zooplankton were identified to species level, and the lengths of crustacean zooplankton were converted to carbon biomass using carbon to length regressions (Watkins et al. 2011 and references therein).

Samples (10-15 mL) were taken also from the dense scum collected by each of the harvesting devices. Both phytoplankton and zooplankton were analyzed from 0.1 mL subsamples to quantify organisms.

Health & Well-being

Cyanotoxins

The cyanotoxin samples were collected into 50 mL tubes (Falcon) from each mesocosm and from the lake water near the mesocosms from 0.5 m depth using a 2.7 L water sampler (Limnos Ltd., Poland) before, after and later after harvesting. In addition, toxicity (microcystins) of freeze-dried scum of four samples (VIBRO shore (FL1), AS-LAND shore (FL2), AS-LAND shore (FL3) and AS-LAND close to mesocosms (FL4) were analysed. The cyanotoxin analyses in the water samples comprised microcystins, anatoxins and saxitoxins using the Gold Standard diagnostics Microcystins/Nodularins (ADDA), Anatoxin (VFDF) ELISA kits and Saxitoxins (PSP) ELISA kits (Gold Standard diagnostics Horsham, PA, USA). The detection limit for MC-LR is 0.10 µg L^{-1}, for anatoxin a is 100 ng L^{-1} and for Saxitoxin is 15 ng L^{-1}.

Circular economies

Proximate Composition

Proximate composition analyses were performed to determine ash, moisture, lipid, carbohydrate, and protein content of the biomass. In addition, potential toxic components were evaluated, with particular focus on cyanobacterial bloom-associated metabolites (see 4.1.4.3).

Ash and moisture content were determined gravimetrically. Moisture was measured by drying samples at 105°C to constant weight, and ash content by combustion in a muffle furnace at 550°C for 5 hours. Total lipid content was extracted and quantified using a modified gravimetric method based on Bligh

and Dyer (1959). Protein content was determined using the colorimetric Lowry method (Lowry et al., 1951). Total carbohydrate content was quantified using the phenol-sulfuric acid colorimetric method (Dubois et al. 1956).

Photosynthetic Pigment Analysis

Chlorophyll *a*, and total carotenoids were extracted and quantified spectrophotometrically following Lichtenthaler (1987). Biomass was extracted in 96% ethanol and absorbance of the clarified supernatant measured at 470, 648.6, and 664.2 nm using a UV-Vis spectrophotometer.

Phycocyanin Extraction and Quantification

C-phycocyanin (C-PC) content was determined spectrophotometrically according to Bennett and Bogorad (1973). Biomass was suspended in phosphate buffer (pH 6.8) and subjected to repeated freeze-thaw cycles to disrupt cell walls, followed by centrifugation (10,000 × *g*, 15 min, 4°C) to obtain a cell-free extract. Absorbance was measured at 615 nm and 652 nm, and phycocyanin concentration calculated as: C-PC (mg mL^{-1}) = (A_{615} − 0.474 × A_{652}) / 5.34.

Bioactive Compound and Antioxidant Assessment

The bioactive compound profile and antioxidant capacity of lipophilic extracts were characterised. Biomass was extracted using a dichloromethane/methanol (DCM:MeOH, 1:1, v/v) solvent system followed by sonication. The resulting extract was evaporated to dryness under reduced pressure and reconstituted in methanol at a defined concentration prior to analysis. Total phenolic content (TPC) was determined using the Folin–Ciocalteu colorimetric method (Singleton & Rossi, 1965), DPPH radical scavenging activity was evaluated following Brand-Williams et al. (1995), and ABTS radical cation decolourisation was assessed following Re et al. (1999).

Statistical Analysis

Zooplankton and phytoplankton biomass and density, water quality parameters and microcystins in mesocosms were analysed using generalized linear mixed-effects models (GLMMs, e.g., Asar et al. 2020). Fixed effects included Treatment and Class/Group (taxonomic group), and when relevant Timing, as well as their interactions. Post hoc comparisons were conducted to assess differences among treatments, sampling times and within classes. When applicable, temporal responses were evaluated relative to a baseline condition (“Before”) using treatment-versus-control contrasts.

R Statistical Software (v4.4.1; R Core Team 2024) was used to perform calculations and analyses. R packages *glmmTMB* (McGillycuddy et al. 2025), *DHARMa* (Hartig 2024), *emmeans* (Wood 2011) and *ggplot2* (Wickham, 2016) were used for GLMM modeling, model diagnostics, post hoc comparisons and visualizations, respectively.

2. Island creation

Converting costs to 2025 prices

All costs have been converted to 2025 price levels to ensure comparability across investments, maintenance expenditures, and research and monitoring activities undertaken in different years.

For this purpose, the CBS input price index for the Dutch Ground, Road and Hydraulic Engineering sector (GWW) was applied, with an annual inflation rate of 1.4%. The GWW index was selected because the project concerns the development, operation and maintenance of infrastructure assets. The index reflects price developments relevant to civil engineering projects, including labour, materials, equipment, machinery and construction-related services.

The same index was also applied to the project's research and monitoring programme. Although these activities include scientific and monitoring components, a substantial part of the programme is directly related to infrastructure assets, field installations, monitoring equipment, sensors, inspection activities

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and associated technical services. Consequently, the cost development of these activities is considered to be more closely aligned with the civil engineering sector than with general consumer price inflation. Therefore, the GWW index was considered the most appropriate and consistent basis for price level adjustment across all project components.

For expenditures occurring after 2025, costs were converted to 2025 prices by discounting future values using an assumed annual GWW inflation rate of 1.4%, consistent with the long-term price development assumed for infrastructure-related costs.

3. Multi-structure wetland

Zero pollution

We calculated the changes in suspended sediment (SS) and nutrient concentrations (P, N) and loads between the upstream and downstream ends of the wetland and its structures reducing the flow velocity. As the planned residential area has not yet been constructed, the incoming discharge to the sand-filter is currently too low to allow for water quality monitoring and the impact of sand-filter on water quality remains to be evaluated once the construction has been initiated.

The innovative aspects in monitoring include the utilization of a field measurement platform "EnviStation", which is a trailer equipped with flow-through system and YSI PRO autosampler, EXO3 multiparameter sonde, Trios Opus spectrometer probe, and a weather station. Additionally, water level sensors were established at the upstream and downstream ends of the wetland

EnviStation operates with solar panels, batteries and automated generator allowing for a more reliable comparison between the upstream and downstream concentrations than based on separate sensors mounted on these positions. The parameters covered by EnviStation here were NO_3, TSS, and SAC254, which indicates TOC. A further benefit of the monitoring design is that half less sensors and calibration is needed compared to typical upstream vs downstream monitoring. EnviStation was used to monitor the upstream and downstream water quality variables at time intervals of ~8 hours from May to October in the second year after wetland construction. The simultaneous discharges were estimated based on a rating curve developed between sensor-based water level and manual discharge measurements.

In situ water samples were collected 8-12 times annually starting after the construction of the wetland, covering a period of 2 years, now complemented by sampling in the FutureLakes project. First the incoming flow was sampled at the upstream end of the wetland, followed by sampling of the outgoing flow at the downstream end, with a typical lag of approximately 15 minutes. At the same time, discharge was measured at both the upstream and downstream ends of the wetland. Water samples were analysed at Syke's accredited laboratory for basic quality parameters (TP, PO_4, TN, NO_{2+3}, NH_4, COD_{Mn}, TOC, turbidity).

Instantaneous loads were derived from the laboratory-analysed water samples by multiplying the instantaneous concentrations by the associated instantaneous discharge averaged between the upstream and downstream. Changes in annual loads between the upstream and downstream ends of the wetland were computed assuming the instantaneously sampled events are representative for the whole year.

Climate resilience

Flood and drought resilience was evaluated based on the water storage capacity of the wetland. We considered its maximum inundated area of 2900 m^2 and the corresponding estimated mean water depth of 80 cm based on the design plan.

Biodiversity net gain

The temporal development of the vegetation cover and abundance was monitored by repeat photography. Photographs were taken near the outlet of the wetland, allowing to characterize rough trends in the vegetation cover and abundance both in the deep, permanently wet areas and the occasionally inundated floodplain areas. Vegetation coverage was also captured by orthorectified images created with Structure from Motion technique (Westoby et al. 2012) from planform images collected with DJI Mavic 3-M drone.

4. Raingardens

Assessment methods

Vegetation surveys were conducted from the 6th to the 9th of July 2026 across four rain garden sites in Kinross: the Park and Ride, Loch Leven Car Park, Kirkgate Park, and the Link Road verge and settling pond. Sampling was designed to assess plant biodiversity within the rain gardens and compare it with that of adjacent surrounding habitats.

A total of 130 quadrats, each measuring 50 cm × 50 cm, were surveyed across the selected sites. Of these, 90 quadrats were randomly located within the rain garden areas to provide a representative assessment of vegetation composition and species diversity within the rain garden features. An additional 40 quadrats were surveyed in surrounding habitats adjacent to the rain gardens, enabling comparisons between rain garden and non-rain garden areas.

Quadrat locations within the rain gardens were selected randomly to minimise sampling bias and ensure coverage across the range of vegetation types present. Within each quadrat, plant species presence and percentage abundance were recorded for subsequent biodiversity analyses. The data collected were used to calculate the Shannon Diversity Index (H'), allowing quantitative comparison of plant diversity between rain garden habitats and adjacent areas. This index incorporates both species richness and species evenness, providing a measure of overall biodiversity across the surveyed sites.

1. Kinross Park and Ride

At the Kinross Park and Ride site, the rain garden habitat comprised three blocks located along the centre of the car park (*Figure 71*, Figure 72). The smallest, easternmost block was excluded from the survey because it was largely covered by coarse rocks containing almost no vegetation. The remaining two blocks were surveyed using a systematic random sampling approach.

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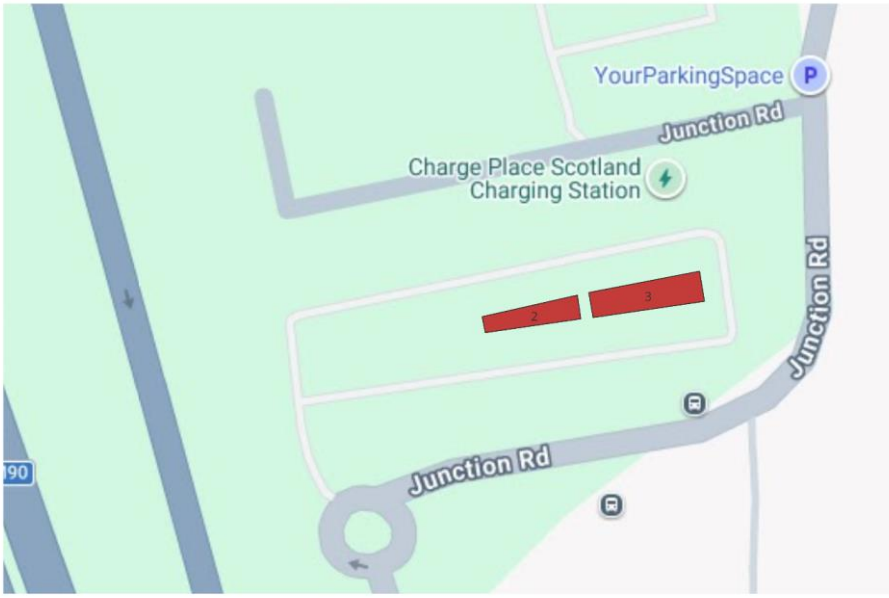


Figure 71 Location of the two rain gardens surveyed at the Kinross Park and Ride.



Figure 72 The area surrounding the rain gardens in Kinross Park and Ride; this area has not been seeded with wildflower mix and is edged by a raised kerb that impedes water ingress.

For each block, two transect tapes were laid parallel to the longest side of the rain garden, positioned centrally on either side of the dividing wooden beam. Quadrats (50 cm × 50 cm) were placed at 4 m intervals along each transect, with sampling commencing at the 4 m mark on the left hand side of the tape for both transects. Five quadrats were surveyed in each block section, giving a total of 10 quadrats within the rain gardens. To provide a comparison with surrounding habitats, an additional 10 quadrats were sampled in other vegetated areas of the car park. It should be noted that the surrounding areas were not mown grass areas, but sparsely vegetated strips of land.

2. Kirkgate Park

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The rain garden at Kirkgate Park consisted of three distinct planted areas of differing sizes and shapes (*Figure 73*). The smallest, triangular area located on the western side of the site was sampled using a randomly thrown 50 cm × 50 cm quadrat, with two quadrats surveyed. Three quadrats were sampled in the adjacent medium-sized area using the same method, while 15 quadrats were surveyed in the largest rain garden area. In total, 20 quadrats were sampled within the rain gardens. For comparison, a further 20 quadrats were randomly located within the surrounding mown grassland areas of the park (Figure 74).



Figure 73 Locations of the three rain gardens surveyed at Kirkgate Park.



Figure 74 The Kirkgate Park rain garden and surrounding area of mown grass (left) and a 50x 50cm quadrat deployed in the mown grass area (right).

3. Kinross Link Road Verge and Settling Pond

At the Link Road site, sampling was undertaken in the settling pond and selected rain garden roadside verges (Figure 75, Figure 76). Within the settling pond (Figure 75), 20 quadrats were randomly surveyed, excluding the permanently inundated central area containing standing water. The

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surrounding vegetation was unmanaged and supported many of the same species, as well as trees and shrubs, and was therefore not considered an appropriate comparison habitat.



Figure 75 Location of the settling pond and two rain garden verges surveyed on the Link Road.



Figure 76 Mown grass area adjacent to the Kinross Link Road settling pond (left) and used as a comparison habitat during the survey (left), and the adjacent rain garden along the roadside that was surveyed for comparison with a nearby area of mown grass (right).

In addition, two roadside rain garden verge sections (Figure 76) were surveyed and compared with two nearby areas of mown grassland. Five randomly located quadrats were sampled within each rain garden verge, giving a total of 10 rain garden quadrats. A further 10 quadrats were sampled within the adjacent mown grassland areas (five in each area) to facilitate biodiversity comparisons between the rain garden and conventional roadside verge habitats.

4. Loch Leven Harbour Car Park

The Loch Leven Harbour Car Park rain gardens comprised a series of small planted patches of varying sizes and shapes, including areas of permeable paving that supported the growth of grasses and other vegetation (*Figure 77*; Figure 78). Ten rain garden patches were surveyed using a randomly thrown 50

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cm × 50 cm quadrat. A total of 22 quadrats were sampled across the rain garden features. As the surrounding areas were not managed as mown grassland and had instead been sown with species-rich vegetation to enhance biodiversity, they were not considered suitable comparison habitats. Nevertheless, eight additional quadrats were sampled in these surrounding areas to provide a broader assessment of site biodiversity.

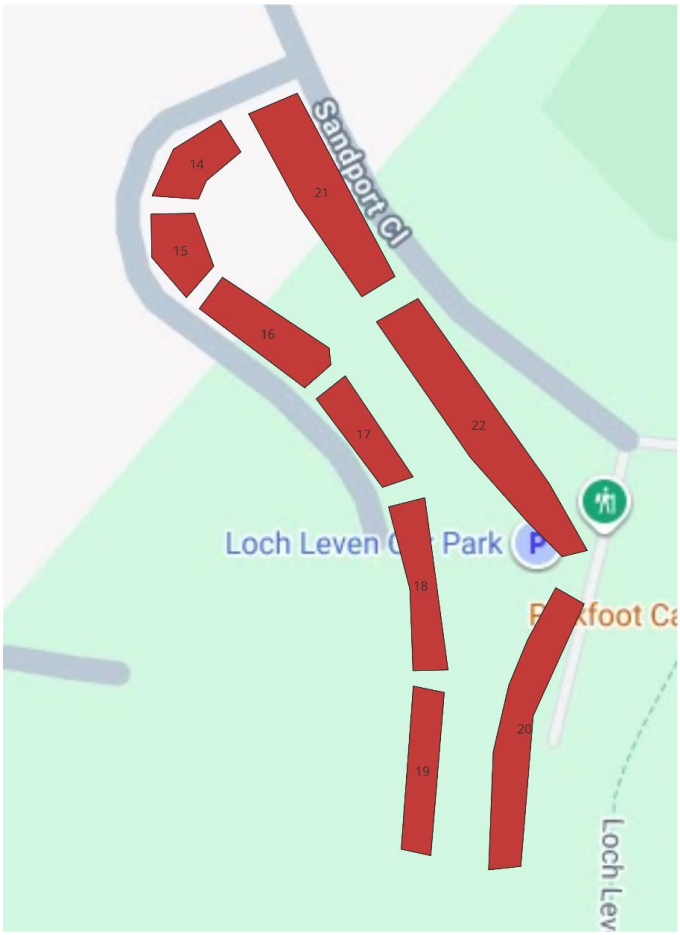


Figure 77 Location of the rain garden areas surveyed at Loch Leven Harbour car park.



Figure 78 Supplementary areas sampled in Loch Leven Harbour car park to give an overall picture of the biodiversity of the site. Areas around the rain garden are managed for biodiversity and pollinators.

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5. **Pollinator surveys (all sites)**



Figure 79 Locations of pollinator surveys: (1) & (2) = Kinross Park & Ride; (3) & (4) = Link road verges; (5) = Settling pond; (6) & (7) = Loch Leven Harbour car park; (8) = Kirkgate Park

To assess the potential benefits of rain gardens for pollinators, pollinator surveys were also undertaken within the rain gardens and in adjacent areas for comparison (Figure 79). Pollinator activity was recorded using the UK Pollinator Monitoring Scheme (PoMS) FIT Count app, which standardises observations of flower-visiting insects over a fixed area and time period. Counts were conducted on flowering vegetation within and outside of the rain gardens to estimate pollinator abundance and activity levels over timed 10 minute periods. The resulting data was used to compare pollinator use of rain garden habitats relative to surrounding areas and to evaluate the contribution of rain gardens to local pollinator populations.

Assessment methods for hydrological impacts

Hydrological modelling: The potential hydrological benefits of rain gardens and other nature-based solutions (NbS) were assessed using the UK Centre for Ecology & Hydrology (UKCEH) City Planner Toolkit. The City Planner Toolkit is a spatial decision-support tool that combines land-cover, topographic, soil and hydrological data to evaluate the potential effectiveness of nature-based interventions for managing surface-water runoff and reducing flood risk. Within the FutureLakes project, the tool was used to model the effects of existing and potential NbS interventions on runoff generation across the Loch Leven catchment.

Hydrological modelling was based on the Curve Number (CN) approach, which estimates runoff generation as a function of land cover, soil characteristics and rainfall. Spatial datasets describing land cover, soil type and digital terrain were incorporated within the modelling framework to identify areas

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where natural flood management interventions could most effectively intercept and attenuate surface-water flows. A series of scenarios were modelled to estimate the influence of rain gardens and other NbS measures on runoff volumes and flood-risk mitigation at both local and catchment scales. The modelling outputs were used to assess the likely cumulative benefits of NbS implementation rather than the performance of individual rain gardens.

This study assesses changes in runoff that result from changes to land cover, specifically the introduction of sustainable drainage systems (SuDS) into Kinross urban area. Runoff was modelled using ANaRM (Miller et al., 2023), as it is simple to set up and understand, and has been verified in several cities across Europe (Kjeldsen et al., 2025; Miller et al., 2023; Vesuviano et al., 2025).

As ANaRM is a modification/extension of the rational method (Kuichling, 1889), runoff coefficients are required for each land use within the study area. Here, runoff coefficients are calculated via the curve number method (Soil Conservation Service, 1986) using the following relation:

$$C_V = \frac{\left(P - 0.2\left(\frac{25400}{CN} - 254\right)\right)^2}{P\left(P + 0.8\left(\frac{25400}{CN} - 254\right)\right)}$$

Where C_V is the runoff coefficient for use in the rational method, CN is the curve number for the land cover from Table 2-2 in Soil Conservation Service (1986), and P is event precipitation depth in mm. Here, an event depth of 50 mm was used: a rainfall of 50 mm in 12 hours in Kinross has a return period of approximately 10 years.

In curve number methodology, each land use type has four curve numbers, corresponding to four hydrologic soil groups, HSG A-D, where A is most permeable and D is least permeable. These are conceptually similar to but numerically different from the five WRAP soil classes (NERC, 1975) or 29 HOST classes (Boorman et al., 1995) mapped in the UK. HSG can also be "dual class", of the form *x*/D, indicating group *x* soils that are regularly saturated and therefore behave as group D soils.

Runoff coefficients were therefore assigned based on a combination of land use and hydrologic soil group.

Datasets

Land cover data were derived from LCM2024 vector data (Rowland et al., 2025), resampled to a 2-metre raster, with urban and suburban areas in Kinross reclassified: into buildings, roads, and grass in the "current" scenario, and into buildings, roads, grass, and SuDS in the "change" scenario. A very high spatial resolution of 2 m was used to represent the NbS, some of which were linear features with a width of approximately 2 metres.

LCM2024 classes (*Table 31*) were mapped to the classes given in Table 2-2 of Soil Conservation Service (1986) using expert judgement informed by Thomas (2018) (Table 1). Following standard UK SuDS guidance, urban and road classes were assigned 100% conversion of rainfall to runoff in all circumstances. However, buildings were assigned an unusually small runoff ratio of just 10%, on the assumption that most roof runoff would be conveyed out of the study area. There is no SCS equivalent to bog or fen. However, Thomas (2018) used a fixed *CN* of 85 for bogs with all soil types. This study repeats that decision and applies it to fens.

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Table 31. LCM2024 land cover classes, Soil Conservation Service (1986) equivalent classes, and corresponding curve numbers for hydrologic soil groups (HSGs) B-D (the study area contains no HSG A soil).

Land cover (LCM class)	SCS equivalent	*CN* (HSG B)	*CN* (HSG C)	*CN* (HSG D)
Broadleaved woodland (1)	Woods, fair	60	73	79
Coniferous woodland (2)	Woods, fair	60	73	79
Arable & horticulture (3)	Fallow, CR, good	83	88	90
Improved grassland (4)	Open space, good	61	74	80
Neutral grassland (5)	Open space, good	61	74	80
Calcareous grassland (6)	Open space, good	61	74	80
Acid grassland (7)	Open space, good	61	74	80
Fen, marsh & swamp (8)	-	85	85	85
Heather (9)	Brush, good	48	65	73
Heather grassland (10)	Brush, fair	56	70	77
Bog (11)	-	85	85	85
Inland rock (12)	Impervious, paved	98	98	98
Saltwater (13)	-	100	100	100
Freshwater (14)	-	100	100	100
Littoral rock (17)	Impervious, paved	98	98	98
Urban (20)	-	100	100	100
Suburban (21)	Open space, good	61	74	80
Buildings	-	68.6*	68.6*	68.6*
NbS	Open space, good (HSG B)	61	61	61
Roads	-	100	100	100
Suburban grass	Open space, good	61	74	80

*C_V set to 10% and *CN* back calculated. This unusually low C_V assumes that roof runoff mostly drains out of subcatchment.

Hydrologic soil groups across the study area were derived from HYSOGs250m (Ross et al., 2018). While HYSOGs250m has fewer soil classes than either WRAP or HOST, it has a finer spatial resolution (7.5 arc-minutes vs 1 km) and the four classes that it does have are immediately compatible with curve number methodology. HYSOGs250m contains some cells with "dual classes" in the study area. In this study, these were always considered as group D soils. HYSOGs250m was resampled to the same 2-metre

resolution as LCM2024 was, so that each square of LCM2024 land cover had a corresponding underlying soil group.

ANaRM is intended to accumulate flows along topographical gradients, a process that requires a digital terrain model (DTM) of the study area. This must be at the same resolution as the land cover layers. A 2-metre DTM of the UK was recently produced from LIDAR data by the Carbon & Place project (Morgan, 2026), which was already aligned with this study's land cover and soil datasets. This was tested with ANaRM, but, due to the extreme flatness of the study area, topographically-based flow accumulation was not possible, and study-area subcatchments were instead derived from UKCEH's Integrated Hydrological Digital Terrain Model (IHDTM: CEH, 2011; Morris & Flavin, 1990). This has a relatively (for this study) coarse resolution of 50 metres, but clearly defines flow directions due to the greater elevation differences experienced over 50 metres cf. 2 metres. The IHDTM was not used in runoff modelling, but only to provide subcatchment outlines, which were overlaid on ANaRM spatial modelled runoff outputs, with total runoff being the sum of all gridded runoff values within the outline.



Figure 80 Current land use for Kinross based on 2024 data

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Figure 80 shows “current” land use for Kinross. *Figure 45* shows underlying HSGs, the Clash Burn and part of the Ury Burn catchments, and, in magenta, all areas converted to SuDS in the “change” scenario relative to the “current” scenario. It is noted that the area shown in these figures measures 1.7 km east-west and 2 km north-south, while the full area modelled by ANaRM measured 25 km east-west and 20 km north-south, encompassing the full area draining through Loch Leven, as topographical flow accumulation (which was ultimately not used) can only be performed on complete watersheds.

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b. Annex: Background for Radar plots

		In-lake focused solutions							
		Algae Harvesting		Semi-automated dredging		Integrated dredging and P-recovery		Island creation	
Dimension	How to Rate (High / Moderate / Low / NA)	Score	Short Justification	Score	Short Justification	Score	Short Justification	Score	Short Justification
Nutrient reduction (N/P)	**High:** Clear N/P reduction. **Moderate:** Some reduction. **Low:** Weak/unclear. **NA:** No data.	Low	Algal biomass itself contains P and N that can be removed from the lake along with the biomass. However, no evidence on water quality improvement in mesocosms.	Low	Not enough sediment removed	Moderate	Not enough sediment removed in one sector, too low coagulant doses for P inactivation stage after sediment removal	Low	no imppact on emissions
Water quality improvement	**High:** Clear improvement. **Moderate:** Some improvement. **Low:** None/unclear. **NA:** No data.	Low	No evidence on water quality improvement.	Low	Not enough sediment removed	Moderate	not enough sediment removed in one sector, too low coagulant doses for P inactivation stage after sediment removal	High	creates clear zones with clear (not turbid) waters where submerged vegetation has a chance to grow, especially in the emediate surroundings of the islands
Biodiversity & habitat	**High:** Strong BD gains. **Moderate:** Some gains. **Low:** Minimal/none. **NA:** No data.	Low	No evidence on biodiversity imrovement. Potential negative implications to non-target planktonic organisms.	Low	Not enough sediment removed	Moderate	new submerged and partly submerged macrophytes stands, less algal blooms, but less macrozoobenthos abundance	High	creates new habitats and thus at these specific new habitats the biodiversity will increase
Sediment & internal load control	**High:** Strong effect. **Moderate:** Some effect. **Low:** Weak/none. **NA:** No data.	NA		Low	Not enough sediment removed	Moderate	lower N and P in the interistial water and sediment	High	see row 11
Implementation complexity	**High:** Complex installation. **Moderate:** Some complexity. **Low:Easy to implement.** Complex installation. **NA:** Not described.	Moderate	Easy to implement with suitable equipment. However, requires labor and an electricity supply.	Moderate	Many legal issuses. Development of dredger	High	Many legal issues, space availability in WWTP for constructing and using sediment treatment line, necessity to have agricultural entities for sediment utilization	High	building islands with soft sediments requires specialist knowledge
Total cost pr. ha	**High:** Low €/ha.€/ha is low compared to similar solutions.Suitable for large-scale or catchment-wide application. **Moderate:** euro/ha is acceptable but not optimal, some cost drivers exists (equipment, materials).**Low (poor):** High cost per hectare €/ha is high relative to the benefits or area treated.Suitable only for small areas or high-value sites.Often includes expensive technology, machinery, or repeated interventions.NA= Not assessed	Moderate	Equipment itself not expensive but the harvesting requires labor and enegy. Suitable for relatively smll areas.	Not applicable	Research project, but estimated price is 10,000 Euro/ha	Low	Cost is high (270 800 Euro/ha), but environmental benefits can be substantial	NA	not compared to other solutions
Operational & maintenance needs	**High:High/frequent maintenance, Moderate:** Manageable. **Low: Low maintenance** . **NA:** Not described.	Moderate	Collection of biomass not automated, requires labor	low	depends, but if external loading reduced sufficiently and enough sediment removed only one restoration would be needed	Low	the whole complex restoration was one action	High	maintance of islands and shores need continuous attention because of subsidence and erosion
Innovation maturity (TRL)	**High:** TRL 7-9. **Moderate:** TRL 4–6 (pilot). **Low:** TRL 1–3 (experimental). **NA:** Not stated.	High	Harvester dependent. One of the technologies patented and in operational use.	High		High	the restoration was implemented in full technical scale	High	Has been applied at full scale
Sustainability (multi-benefit)	**High:** Multiple long-term benefits (BD, WQ, ET, NCC, PV, GHG). **Moderate:** One–two benefits. **Low:** Few/none. **NA:** Not assessed.	Moderate	Potential emergency intervention for HAB management with potential benefits to bathing water quality and circular economies.	High		High		High	benefits for recreation, health, education, research, and floodsafety (=protection of dike). prossibly GHG reduction
Scalability & transferability	**High:** Easily transferable to other lakes /catchments. **Moderate: transferable with** Some adjustments needed. **Low:** highly Site-specific. **NA:** Not assessed.	Moderate	Easily transferable to other lakes but mostly suited to small lakes with abundant cyanobacteria and surface scums	High		Moderate	every lake is individual case, solutions should be tailored	Moderate	I assume this is possible in other lakes, providing it is a shallow lake and sediment is available - the amount and the size of the islands can be adapted to suit the needs of the new location
Longevity of intervention	**High:** The intervention is long-lasting, requires rare or one-time action, and maintains effect over many years.**Moderate:** The intervention needs occasional renewal or maintenance (e.g., yearly or multi-year cycles).**Low**: The intervention requires frequent or continuous actions to maintain effect.**NA: Unknown or not assessed.**	Low	Repetition required, does not affect the cause behind eutrophication	High		High	after this intervention some soft NbS techniques could be implemented if necessary	Moderate	Islands are build for long term, but do need upkeep to prevent erosion/too much subsidence. Additionally, because specific types of habitats have been indicated as 'desired', the process of succession has to be slowed down/stopped if possible - this requires maintenance too.
Space / area requirements	**High:** Small footprint. **Moderate:** Medium area. **Low:** Large area. **NA:** Not described.	High	Limited area needed for the equipment.	Moderate		Moderate	the area in WWTP for sediment treatment technological line location	Low	Islands need space, however, their size can be adapted based on the requirements at a new site
Dependence on local conditions	**High:** Works broadly across different lake types, hydrology, soils, and climates.**Moderate**: Some sensitivity to local conditions; performance varies but remains acceptable.**Low:** Highly dependent on specific local conditions; limited transferability.**NA: No information available.**	Low	Dependent on the formation of surface scums of cyanobacteria. Limited ability to treat larger areas.	Moderate	Sediment reuse on agricultural areas demands "clean" sediment	Moderate	this method also should be tailored to local conditions	Moderate	Islands can be build in shallow lakes with available sediment
Stakeholder engangement	**High:** Strong, proactive engagement with key stakeholders (municipalities, water boards, NGOs, landowners, citizens). Co-creation, regular communication, and broad acceptance. **Moderate:** Some engagement with relevant stakeholders; communication occurs but is not continuous. Acceptance is mixed but manageable. **Low:** Limited engagement; few stakeholders involved; low acceptance or resistance. **NA:** No information or engagement not relevant for this pilot.	Low	Consent from water areas owners required but the resistance for harvesting algae supposedly low. Stakeholder engagement has potential for managing the work load required by the biomass collection.	Moderate		High	this method needs strong cooperation between stakeholders (science, local government, land owners, fishery users)	High	Because of the costs, size and spatial impact this intervention needs engagement of stakeholders

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		Catchment-focused solutions					
		Flexible water level		Multi-structured wetland		Raingardens	
Dimension	**How to Rate (High / Moderate / Low / NA)**	**Score**	**Short Justification**	**Score**	**Short Justification**	**Score**	**Short Justification**
Nutrient reduction (N/P)	**High:** Clear N/P reduction. **Moderate:** Some reduction. **Low:** Weak/unclear. **NA:** No data.	Low	low - no impact on nutrient input, change of residence time might influence nutrient cycling, however, the measure itself is not designed to impact nutrient inputs.	Moderate	Partly positive, partly negative changes in zero pollution indicators.	Low	Main reduction will be in pollution that enters the loch from CSO spills but these are small compared to the total load.
Water quality improvement	**High:** Clear improvement. **Moderate:** Some improvement. **Low:** None/unclear. **NA:** No data.	Low	no impact on water quality (see reasoning @ nutrient reduction)	NA		Low	No evidence of loch water quality improvement linked to raingarden installation.
Biodiversity & habitat	**High:** Strong BD gains. **Moderate:** Some gains. **Low:** Minimal/none. **NA:** No data.	Low	Habitat: No impact on coverage and quality of reed beds shown. Biodiversity: mixed impact on birds, early high water levels might prevent birds from building nests to close to the (future) shoreline, but high water levels later in year might also prevent fledglings from foraging on the mud flats. No conclusive evidence yet. Not taken into account: the availability of freshwater during periods of drought will likely positively impact nature in the catchment. No data on this available though.	Moderate	Created wetland area likely supports local biodiversity	Moderate	Large bidiversity gains in terms of tererstrial vegetation and pollinators. No evidence of biodiversity gains for freshwater species.
Sediment & internal load control	**High:** Strong effect. **Moderate:** Some effect. **Low:** Weak/none. **NA:** No data.	NA	not monitored.	Moderate	Slight retention of suspended sediment load	NA	
Implementation complexity	**High:** Complex installation. **Moderate:** Some complexity. **Low:Easy to implement.** Complex installation. **NA:** Not described.	High	number of technical conditions of the watersystem to manage the water levels and need of legal regulations to allow deviations from previous water level targets. This is also due to the fact that the Lake IJssel complex is a key water body for the Netherlands and thus many people are dependent on this water body.	Low	Implementation supported by available knowledge and established design processes on standard constructed wetlands	Low	Relatively easy to implement in many cases, but very dependent on the scale and situation. Some raingardens may require substantial engineering works - especially if replacing hard engineering such as roads and car parks.
Total cost pr. ha	**High:** Low €/ha.€/ha is low compared to similar solutions.Suitable for large-scale or catchment-wide application. **Moderate:** euro/ha is acceptable but not optimal, some cost drivers exists (equipment, materials).**Low (poor):** High cost per hectare €/ha is high relative to the benefits or area treated.Suitable only for small areas or high-value sites.Often includes expensive technology, machinery, or repeated interventions.NA= Not assessed	NA	Only partial costs available	Moderate	Costs generated by required land area, which is taken away from e.g. agriculture		Costs are generally quoted to be about 400 - 500 Euros per m^2, which equates to 4m to 5 m Euros per hectare. However most installations are relatively small in size so costs are low. The estimated costs for the raingardens included in this project (4497 m^2) is therefore 1,798,800 to 2,248,500 Euros.
Operational & maintenance needs	**High:High/frequent maintenance, Moderate:** Manageable. **Low: Low maintenance** . **NA:** Not described.	High	Especially for the Lake IJssel complex constant monitoring of water levels is required and the host of equipment to maintain the water levels for this 1800 km2 site needs to be maintained.	Low	Maintenance required on average once in 7 years, but interval site-specific	Low	Once estabished, annual maintenance is required - usually in spring. This usually compriese weeding and re-seeding which, at Loch Leven, is mainly carried out by volunteers.
Innovation maturity (TRL)	**High:** TRL 7-9. **Moderate:** TRL 4–6 (pilot). **Low:** TRL 1–3 (experimental). **NA:** Not stated.	High	Already operational at full scale	High	TRL 7. Knowledge gaps remain at high flows and outside growing season	Moderate	Raingardens are in general still at the pilot stage in the Loch Leven catchment.
Sustainability (multi-benefit)	**High:** Multiple long-term benefits (BD, WQ, ET, NCC, PV, GHG). **Moderate:** One–two benefits. **Low:** Few/none. **NA:** Not assessed.	moderate	Increased drought and flood resilience; possibly protection of nature areas (and thus biodiversity) in the catchment	Moderate	Main benefit is load reduction; potential additional benefits not evaluated	Moderate	Rain gardens provide bidiversity benefits and can reduce flooding; pollution mitigation/control benefits have not been quantified but likley to be low at the catchent scale although high locally.
Scalability & transferability	**High:** Easily transferable to other lakes /catchments. **Moderate: transferable with** Some adjustments needed. **Low:** highly Site-specific. **NA:** Not assessed.	low	can only be applied in lakes of which the water level can be monitored and regulated	Moderate	Costs lowest when established on flood-prone depressions, established design processes on standard CWs	High	Easily transferable to other sites; upsacling of individual raingardens could be difficult due to the local context but upsacling can be achieved by putting muliple small plots across larger areas.
Longevity of intervention	**High:** The intervention is long-lasting, requires rare or one-time action, and maintains effect over many years.**Moderate:** The intervention needs occasional renewal or maintenance (e.g., yearly or multi-year cycles).**Low**: The intervention requires frequent or continuous actions to maintain effect.**NA: Unknown or not assessed.**	moderate	the intervention can be maintained as is, but due to changes in the climate will require a re-evaluation. The evaluation of the current implementation already shows that a larger buffer of water will be required in the (near) future.	High	expected life cycle at least 50 yr, assuming regular straightforward maintenance	Moderate	Requires annual maintenance
Space / area requirements	**High:** Small footprint. **Moderate:** Medium area. **Low:** Large area. **NA:** Not described.	low	Changing the water level will influence the whole lake. Due to the large area dependent on the Lake IJssel complex in periods of drought, the water volume that needs to be stored is large too. The amount of water that needs to be stored could change according to the specifics of another site.	Moderate	requires >0.1% of the catchment area (typically flood-prone field area)	High	The space requirement of an individual raingarden is small.
Dependence on local conditions	**High:** Works broadly across different lake types, hydrology, soils, and climates.**Moderate**: Some sensitivity to local conditions; performance varies but remains acceptable.**Low:** Highly dependent on specific local conditions; limited transferability.**NA: No information available.**	low	see "Scalability and transferability"	Moderate	Expected to work rather broadly, but performance likely weaker and acclimatization period longer in cold climates	Moderate	Effectiveness depends on location, local soil type and local hydrology.
Stakeholder engangement	**High:** Strong, proactive engagement with key stakeholders (municipalities, water boards, NGOs, landowners, citizens). Co-creation, regular communication, and broad acceptance. **Moderate:** Some engagement with relevant stakeholders; communication occurs but is not continuous. Acceptance is mixed but manageable. **Low:** Limited engagement; few stakeholders involved; low acceptance or resistance. **NA:** No information or engagement not relevant for this pilot.	High	Strong proactive engagement with key stakeholders is a necessity as the water level is influencing the livelihoods of a large amount of people, additionally, the regulation is also a legal document esteblished by a ministry.	Moderate	Stakeholder engagement needed as typically implemented on private land. Annual CAP maintenance compensation to stakeholders	Moderate	There is some engagement with local stakeholders, but this is intermittent. Communication with local people is mainly through a local newsletter that is published monthly and/or local community groups. Communication with other stakeholders is via the Loch Leven Catchment Management Group.

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		Combined solutions					
		Kranlingse plas		Groote melanen		Bleiswijkse Zoom	
Dimension	How to Rate (High / Moderate / Low / NA)	Score	Short Justification	Score	Short Justification	Score	Short Justification
Nutrient reduction (N/P)	**High:** Clear N/P reduction. **Moderate:** Some reduction. **Low:** Weak/unclear. **NA:** No data.	High	The combined package reduced external and internal P loading; mean TP fell from 0.18 to 0.03 mgP/L, while N remained unchanged	High	TP was reduced by 93% and TN by 66% after the combined measures	High	The combined package reduced TP concentrations from 0.34 mg P/L to 0.07 mg P/L, and reduced TN concentrations from 1.89 mg N/L to 1.47 mg N/L
Water quality improvement	**High:** Clear improvement. **Moderate:** Some improvement. **Low:** None/unclear. **NA:** No data.	High	Chlorophyll-a remained low after the combined package application	High	Chlorophyll-a, and turbidity all decreased, and no cyanobacterial blooms were recorded from 2016-2021	High	The combined package reduced Chlorophyll-a and cyanobacteria biovolume
Biodiversity & habitat	**High:** Strong BD gains. **Moderate:** Some gains. **Low:** Minimal/none. **NA:** No data.	High	Ecological quality ratio of macrophytes and Phytoplankton reached "good" status	Moderate	Macrophyte planting improved habitat, with submerged plants increasing from absent to around 10-15% cover	High	Submerged vegetation improved after applictaion in 2021
Sediment & internal load control	**High:** Strong effect. **Moderate:** Some effect. **Low:** Weak/none. **NA:** No data.	High	Phoslock (LMB) within the package reduces mobile sediment P and strongly suppressed sediment P release	High	Dredging, sand capping and LMB active capping directly reduced internal nutrient loading	High	LMB usage aims to reduce internal P loading
Implementation complexity	**High:** Complex installation. **Moderate:** Some complexity. **Low:Easy to implement.** Complex installation. **NA:** Not described.	Moderate	Several external nutrients control measures, 42-zone dosing and GPS-guided barges required substantial coordination and technical expertise	Moderate	Combined fish removal, dredging, capping, stream diversion, bank works and planting	Moderate	Combined fish removal, dredging, bypass and LMB
Total cost pr. ha	**High:** Low €/ha.€/ha is low compared to similar solutions.Suitable for large-scale or catchment-wide application. **Moderate:** euro/ha is acceptable but not optimal, some cost drivers exists (equipment, materials).**Low (poor):** High cost per hectare €/ha is high relative to the benefits or area treated.Suitable only for small areas or high-value sites.Often includes expensive technology, machinery, or repeated interventions.NA= Not assessed	Moderate	The full package cost 5.8 million euros for 114 ha (about 50,900/ha), and LMB cost 2 million euros	Low	Cost around 2 million for a 4.8 ha lake (about 416,000/ha), so the cost per hectare was high	Moderate	The full package cost 1.5 million euros for 14 ha (about 107,142/ha)
Operational & maintenance needs	**High:High/frequent maintenance, Moderate:** Manageable. **Low: Low maintenance** . **NA:** Not described.	Moderate	LMB is mainly applied once using GPS guided barges, but monitoring and regular management of litter, birds, plants and inflows are still needed	Moderate	Fish removal was repeated and vegetation, banks and water quality still need monitoring	High	Requires high maintenance, as external nutrient inputs were not fully controlled and TP started to rise again after 2025
Innovation maturity (TRL)	**High:** TRL 7-9. **Moderate:** TRL 4–6 (pilot). **Low:** TRL 1–3 (experimental). **NA:** Not stated.	High	The measures were implemented at full lake scale using established technologies and were followed by multi-year operational monitoring.	High	The measures were implemented at full lake scale using established technologies	High	The measures were implemented at full lake scale using established technologies
Sustainability (multi-benefit)	**High:** Multiple long-term benefits (BD, WQ, ET, NCC, PV, GHG). **Moderate:** One–two benefits. **Low:** Few/none. **NA:** Not assessed.	High	The package supports WFD and bathing water goals, recreation, health and well-being	High	The project improved ecological status and also supported recreation	High	The project improved macrophtes status and also supported recreation.
Scalability & transferability	**High:** Easily transferable to other lakes /catchments. **Moderate: transferable with** Some adjustments needed. **Low:** highly Site-specific. **NA:** Not assessed.	Moderate	The integrated approach is transferable, but the exact measure, dosage and costs require site-specific system analysis and adaptation	Moderate	It can guide similar lake restorations, but the measure package needs lake-specific diagnosis	Moderate	It can guide similar lake restorations, but the measure package needs lake-specific diagnosis
Longevity of intervention	**High:** The intervention is long-lasting, requires rare or one-time action, and maintains effect over many years.**Moderate:** The intervention needs occasional renewal or maintenance (e.g., yearly or multi-year cycles).**Low**: The intervention requires frequent or continuous actions to maintain effect.**NA: Unknown or not assessed.**	High	Confirmed effective for more than 3 years; with continued external nutrient control	High	Water quality stayed improved during the 10-year post-intervention monitoring period	Moderate	Longevity of intervention only had 4.5 years
Space / area requirements	**High:** Small footprint. **Moderate:** Medium area. **Low:** Large area. **NA:** Not described.	High	The measures mainly use the existing lake and inlet infrastructure and require little additional land area	High	Most measures used the lake area itself, but bank reconstruction, stream diversion and planting needed some space	High	Most measures used the lake area itself and small land space
Dependence on local conditions	**High:** Works broadly across different lake types, hydrology, soils, and climates.**Moderate**: Some sensitivity to local conditions; performance varies but remains acceptable.**Low:** Highly dependent on specific local conditions; limited transferability.**NA: No information available.**	Moderate	Depends on lake conditions, inflows and stakeholder acceptance, but can be adapted to similar urban lakes	Moderate	Performance depends on nutrient loads, sediment type, fish stock and hydrology	Moderate	Performance depends on local condition
Stakeholder engangement	**High:** Strong, proactive engagement with key stakeholders (municipalities, water boards, NGOs, landowners, citizens). Co-creation, regular communication, and broad acceptance. **Moderate:** Some engagement with relevant stakeholders; communication occurs but is not continuous. Acceptance is mixed but manageable. **Low:** Limited engagement; few stakeholders involved; low acceptance or resistance. **NA:** No information or engagement not relevant for this pilot.	High	Authorities held repeated stakeholder meetings and coordinated municipal, water board, regulatory, safety and cost assessments	High	The project involved cooperation between authorities and stakeholders such as residents and anglers	High	The project involved cooperation between authorities and stakeholders

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