Map of existing solutions for remediation and protection of European Natural Lakes (ENL)

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List of Abbreviations and Acronyms

Acronym	Meaning
ENL	European Natural Lakes
NbS	Nature-based Solutions
KBWPS	Kis-Balaton Water Protection System
TP	Total Phosphorus
DS	Demonstration Sites
MS	Monitoring Sites

Executive Summary

European natural lakes (ENL) are essential to biodiversity, ecosystem services, and community well-being, yet they face significant threats, including nutrient pollution, habitat degradation, invasive species, and climate change. This document presents a comprehensive analysis of existing solutions for the remediation and protection of ENL, with a primary focus on Nature-Based Solutions (NbS). By synthesizing 12 case ENL spread across Europe, it provides actionable insights into successful strategies for safeguarding these vital ecosystems.

The deliverable aims to evaluate existing approaches to lake remediation and protection. This includes measures such as reducing nutrient loads, mitigating the impacts of invasive species, restoring riparian zones, and adapting to climate change. Another objective is to highlight case studies from twelve European lakes to identify strategies. By considering these approaches and lakes, the work identifies key trends and highlights best practices that can be applied to other lakes facing similar challenges. This information can be helpful also for the demonstration sites of the PROCLEANLAKES and next Deliverable 1.7.

Key findings include:

- NbS, such as constructed wetlands and hydrological restoration, have proven effective in improving water quality, enhancing biodiversity, and increasing resilience to climate impacts.
- Case studies, such as the Kis-Balaton Water Protection System for Lake Balaton, illustrate how NbS can address nutrient pollution while supporting broader ecosystem health.
- Role of integrated planning: Holistic, watershed-level approaches are critical for sustainable lake management. Collaborative frameworks, like

the EU Water Framework Directive, enable effective transboundary cooperation and stakeholder engagement.

- Diverse challenges and tailored solutions: Lakes across Europe face varied environmental pressures, necessitating context-specific interventions. For instance, invasive species control measures at Lake Banyoles have preserved native biodiversity, while flood-resilient green infrastructure at Lake Vänern addresses climate risks.
- Resilience measures, such as drought-tolerant vegetation and carbon sequestration initiatives, are essential to mitigate climate change impacts. Lakes in vulnerable regions, like the Ebro Delta, provide valuable models for adaptation.

Recommendations include to pprioritize investment in NbS to maximize ecological, social, and economic benefits; enhance monitoring systems and scientific research to inform adaptive management strategies; and strengthen stakeholder engagement and public awareness to foster community cooperation.

This work provides a valuable roadmap for stakeholders, policymakers, and conservationists, equipping them with the knowledge and tools necessary to protect and restore European natural lakes based in experience of twelve examples.

1 Introduction

Lakes are the fundamental elements of Europe's natural landscapes, offering invaluable resources for biodiversity, recreation, and local economies while playing a critical role in climate regulation and ecosystem health. Yet, these vital ecosystems face growing threats, including nutrient pollution, invasive species, and climate change, that jeopardize their sustainability and ecological balance (Schmieder, 2004; EEA, 2018). Addressing these challenges is not just an environmental priority but also a societal one, as the health of these water bodies profoundly influences human livelihoods and well-being (Assessment, 2005; Carr and Neary 2008, EEA, 2024).

This deliverable map existing solutions for the remediation and protection of European natural lakes (ENL), with a particular focus on Nature-Based Solutions (NbS). These innovative approaches use the power of natural systems to restore ecological health, strengthen resilience to climate impacts, and ensure sustainable management of these critical water bodies (Vymazal et al., 2021; Tranvik et al., 2009). By analysing successful interventions across Europe, such as the implementation of constructed wetlands (Land et al., 2016; Honti et al., 2020) and the restoration of riparian zones (Carpenter & Cottingham, 1997; Tammeorg et al 2024), this work provides a comprehensive framework for addressing the most pressing threats to lake ecosystems.

The objectives of this analysis are threefold. First, it offers a detailed review of existing remediation strategies, ranging from nutrient load reduction and invasive species control to climate resilience measures. Second, it presents case studies of twelve European lakes, each illustrating specific environmental challenges and the initiatives employed to address them. Finally, it synthesizes these insights to propose actionable recommendations for stakeholders seeking to preserve and restore ENL.

The following sections of Del 1.6 begin with an overview of key stressors and existing solutions employed across Europe. This is followed by case studies that explore targeted interventions for lake restoration, drawing on diverse geographic and climatic contexts. The concluding chapter consolidates these findings, offering strategic guidance for advancing sustainable lake management across Europe.

1.1 Task 1.4 and Del 1.6 description

This deliverable (Del 1.6) of PROCELANLAKES project is under Task 1.4 of the WP1 which is composed of four Tasks (Table 1-1).

Table 1-1 – Overview of WP1 and tasks of PROCLEANLAKES project.

WP 1	Tasks
Assessment of ecological status and design of the NbS for restoration and protection of ecosystem and biodiversity in ENL	T1.1. Identification and monitoring of chemical pollutants within the Monitoring Sites (MS) and Demonstration Sites (DS)
	T1.2. Evaluation of DS biodiversity status
	T1.3. Remote sensing framework for the evaluation of DS and MS ecosystem status
	T1.4. Design of NbS.

Task 1.4 focuses on designing NbS tailored to the specific needs of each demonstration lake by analysing data from previous tasks (T1.1, T1.2, T1.3) (Table 1-1). The design will consider historical and monitored water quality data, proposing strategies like vegetated buffer strips, constructed wetlands, and multi-layer biofilters to mitigate pollution. The approach emphasizes integrated NbS solutions to maximize effectiveness, adapted to local conditions and supported by collaborative efforts between partners.

Deliverable 1.6 is conceptualized as a literature review of existing initiatives and solutions implemented in twelve European lakes regarding their environmental challenges. Later in the project, Deliverable 1.7 will focus exclusively on designing the NbS for the demonstration and monitoring lakes of the PROCLEANLAKES project.

The methodology involved two main phases. In the first phase, research focused on identifying potential solutions to address the protection and restoration of lakes. The second phase entailed analysing twelve European lakes located in different geographical and climatic zones through an extensive literature review for each.

1.2 Objectives of the Work Reported in this Deliverable

The objectives of the work presented in this deliverable are as follows:

- To provide an overview of existing solutions aimed at protecting and restoring natural European lakes from pressing environmental stressors, including water quality deterioration (eutrophication), biodiversity loss, and lakeshore erosion and urbanization (Chapter 2).
- To present twelve European lakes as small case studies, summarizing their environmental challenges and the NbS initiatives implemented to address these challenges (Chapter 3).

1.3 Outline of the Deliverable

Deliverable 1.6 is structured to provide a comprehensive analysis of existing solutions for protecting and restoring natural European lakes. The introductory section (**Chapter 1**) outlines the objectives and sets the context for addressing key environmental stressors impacting lakes. This is followed by **Chapter 2**, an overview of key focus areas, including water quality, pollution, eutrophication, invasive species, climate change, and human intrusion. This chapter also examines respective actions and technical solutions, including NbS but not only. The deliverable then presents in **Chapter 3,** a detailed examination of 12 European lakes based in literature review. For each lake, the environmental challenges are identified, and the restoration and protection measures undertaken are summarized, creating small case studies that highlight both challenges and solutions. Finally, the document draws conclusions (**Chapter 4**) from the analysis and findings presented in the previous chapters.

2 Existing solutions for the remediation and protection of lakes

This chapter provides a summary review of current strategies, methodologies, and solutions utilized across Europe for the remediation and protection of natural lake ecosystems. The deliverable is then connected with Chapter 3 which focuses on 12 specific lakes across Europe, the challenges they face and the NbS implemented.

European natural lakes are vital to biodiversity, climate regulation, and community livelihoods, yet they face significant threats from pollution, eutrophication, invasive species, climate change, and human intrusion. This chapter and the next consolidates both well-established and innovative practices aimed at maintaining and restoring the ecological health and resilience of these water bodies, drawing from case studies, scientific research, and policy frameworks across Europe.

Table 2-1 shows a summary of the existing solutions implemented for the remediation and protection of European natural lakes for different focus areas, discussed in this chapter.

Table 2-1 – Summary table of the topics discussed in this chapter –existing solutions for remediation and protection of European natural lakes for each key focus area and action.

Key focus area	Actions	Example of techniques & solutions
Water quality management	Nutrient load reduction (before reaching the lake)	• Buffer zones • Constructed Wetlands • Wetland restoration
	Sediment control	• Sediment traps • Bank stabilization
	Pollution mitigation (before reaching the lake)	• Constructed Wetlands • Green belts
Eutrophication control and Algal bloom management	In-Lake treatment options	• Aeration systems • Chemical phosphorus binding • Biological treatment
	Watershed-based approach	• Integrated land-use planning • Pollution prevention • Conservation practices • Riparian buffer zones
Invasive species management	Invasive species	• Monitoring • Early detection • Rapid Response Protocols
		• Biological Control • Habitat restoration
Ecosystem restoration and habitat protection	Stabilizing lake shorelines (Riparian zone restoration	• Riparian vegetation • Restoration efforts by increasing native plants
	Reintroduction of native species	• Reintroduction of native **fauna** and **flora** species
	Hydrological restoration	• Re-establishing natural water flow patterns and reconnecting lakes with wetlands and rivers
Climate change adaptation and resilience	Resilience measures. Carbon sequestration	• Drought-resilient vegetation along shorelines • Salt-tolerant plants in deltas • Enhance sedimentation

Policy governance approaches	Collaborative water management.	• Multi-stakeholder approaches • Implementing European Framework (WFD)

2.1 Water quality management

Water quality in European lakes is frequently compromised by excess nutrient input, primarily from agricultural runoff, urban stormwater, and industrial waste. High concentrations of nitrogen and phosphorus lead to algal blooms, decreased water clarity, and oxygen depletion, all of which harm aquatic life (Weyhenmeyer et al., 2009; Bhateria and Jain 2016; EEA, 2018). Below possible solutions are considered.

2.1.1 Nutrient load reduction

Techniques such as buffer zones, constructed wetlands, and wetland restoration are used to filter out nutrients before they reach lake systems. For example, the Danube Basin has implemented buffer strips that reduce nitrogen, and phosphorus loads by approximately 30% (EEA, 2018). Other successful applications include wetland restoration efforts in Poland's Vistula River Basin, which have reduced nutrient outflow and enhanced biodiversity (Vymazal, 2018).

2.1.2 Sediment control

Sediment from erosion can carry attached pollutants into lakes, reducing water quality and harming habitats. Sediment control measures, including sediment traps and bank stabilization, have proven effective in lakes in the Alpine region. For instance, sediment traps installed in Lake Geneva have significantly reduced sedimentation rates, preserving water quality and aquatic habitats (Schulz and Huwe, 2021). These solutions are critical in agricultural regions where soil erosion rates are high, and similar methods are increasingly applied in other European lakes, such as Lake Balaton in Hungary.

2.1.3 Pollution mitigation

Pollution from urban and industrial sources poses severe risks to lake ecosystems. Constructed wetlands have been widely implemented across Europe to treat stormwater and wastewater before it reaches lakes. In the UK and France, constructed wetlands have reduced concentrations of nitrates, heavy metals, and other pollutants by up to 80%, significantly improving lake water quality (Vymazal, 2018; EEA, 2024). Additionally, stricter enforcement of waste management laws has helped reduce pollution in urban-adjacent lakes.

2.2 Eutrophication control and algal bloom management

Excess nutrients in lakes can trigger eutrophication, causing harmful algal blooms, which reduce oxygen levels and disrupt aquatic ecosystems. Algal blooms not only degrade water quality but also lead to fish die-offs and other ecological imbalances (Corell, 1998; Schindler, 2006; EEA, 2018).

2.2.1 In-lake treatment options

Aeration systems, chemical phosphorus binding, and biological treatments are commonly employed to manage nutrient levels in lakes directly, addressing challenges such as eutrophication and algal blooms. Aeration systems, for example, have been successfully used in Finnish lakes to improve oxygen levels in deeper zones, thereby reducing internal nutrient recycling and decreasing algal blooms (Klutas, 2016). Similarly, Danish lakes have benefited from aeration, with studies showing improvements in oxygen distribution and reductions in phosphorus release from sediments (Liboriussen et al., 2009). Chemical treatments, such as aluminum sulfate (alum) applications, are another used method to bind phosphorus and reduce its bioavailability. Alum effectively binds with free phosphorus in the water column, forming aluminum phosphate, which is insoluble and settles in sediments, thus curbing nutrient-driven algal blooms. However, this method must be applied with caution due to potential side effects. Overdosing or improper application of alum can lead to increased acidity in lake waters, negatively affecting aquatic organisms such as fish and invertebrates. Furthermore, the long-term accumulation of aluminum in sediments may pose risks to benthic organisms and disrupt sediment chemistry. Studies have indicated that alum application can cause temporary decreases in water pH and elevate aluminum concentrations to levels that may be toxic to aquatic life if not properly managed (Cooke et al., 2005). These findings underscore the importance of thorough monitoring and precise dosing during alum treatments to ensure that the benefits outweigh the potential ecological risks. Consequently, while aluminum sulfate is a valuable tool in phosphorus management, it is best utilized as part of an integrated nutrient control strategy that combines chemical, biological, and mechanical methods for sustainable lake management.

2.2.2 Watershed-based approaches

Eutrophication control requires addressing nutrient sources at the watershed level. Integrated land-use planning helps reduce nutrient inputs from agriculture, urban areas, and industrial sites. The implementation of the Water Framework Directive (WFD) in Lake Garda, Italy, has led to significant nutrient reductions, with phosphorus levels falling by over 20% in recent years (EEA, 2018). This holistic approach combines pollution prevention, conservation practices, and riparian buffer zones.

2.3 Invasive species management

Invasive species such as zebra mussels and invasive plants disrupt native ecosystems by competing for resources, altering habitats, and displacing native species. Invasive species management is crucial for maintaining the biodiversity and ecological balance of European lakes (Walsh et al., 2016). To tackle this issue, two strategies are usually suggested that have to do with monitoring and rapid response, and biological control and habitat restoration.

2.3.1 Monitoring and rapid response protocols

Early detection and rapid response are essential for managing invasive species (plant and animal species) effectively. Lake Constance in Germany has implemented comprehensive monitoring programs to identify and contain invasive zebra mussel (*Dreissena polymorpha*) populations early (Schmieder, 2004). These methods prevent extensive invasions and preserve native biodiversity (Gallardo & Aldridge, 2018). Vander et al., (2010) emphasizes the importance of early detection and rapid response as a cost-effective and ecologically sound strategy to manage invasive species. While focusing on the Laurentian Great Lakes, its principles can be applied to European lakes. Key points include:

- Proactive Monitoring: Regular sampling and surveillance to detect invasive species before they establish.
- Cost-Benefit Analysis: Investing in prevention and early removal is significantly less costly than long-term management.
- Stakeholder Collaboration: Involving government agencies, scientists, and communities ensures rapid and coordinated responses.

2.3.2 Biological Control and Habitat Restoration

Habitat restoration combined with biological control methods has been effective in managing invasive species. For instance, Spain's Lake Banyoles employs selective removal of invasive fish species and the re-establishment of native vegetation, which has improved habitat conditions and water quality (European Commission, 2019). Introducing native plants that outcompete invasives can also aid in restoration efforts.

2.4 Ecosystem restoration and habitat protection

Loss of riparian zones, habitat fragmentation, and shoreline erosion weaken lake ecosystems, reducing their ability to support diverse species and filter pollutants. Below we discuss strategies how to restore the ecosystem and protect its habitat.

2.4.1 Riparian zone restoration

Riparian vegetation plays a critical role in stabilizing lake shorelines, filtering out pollutants, and providing habitat for wildlife. Riparian zones occur as transitional areas between aquatic and upland terrestrial habitats. They generally can be described as long, linear strips of vegetation adjacent to streams, rivers, lakes, reservoirs, and other inland aquatic systems that affect or are affected by the presence of water. The restoration of riparian vegetative corridors is important for improving water quality, reducing erosion and conservation of wildlife (Fischer and Fischenich, 2000; Gonzalez et al., 2015).

Restoration efforts in several lakes across world have increased native plant cover and reduced erosion, enhancing the stability and ecological health of these lakes (Gulati et al., 2012; Haskell et al., 2017; Chen et al., 2019). Similar projects across the Baltics demonstrate the positive impact of riparian restoration on water quality and biodiversity (Schernewski et al., 2023).

2.4.2 Reintroduce of native species

Reintroduction programs help restore ecological functions in degraded lakes. In Lake Neusiedl, Austria, native fish restocking efforts have successfully restored food webs and improved water quality by re-establishing a balanced predator-prey dynamic (Lakes Restoration Project, 2020).

2.4.3 Hydrological restoration

Re-establishing natural water flow patterns and reconnecting lakes with their surrounding wetlands and rivers is essential for maintaining lake ecosystem functions. Markermeer Lake in the Netherlands underwent hydrological restoration, which improved water quality and strengthened biodiversity corridors (Rijkswaterstaat, 2017; Swinkels, 2020).

2.5 Climate change adaptation and resilience

Climate change is another pressing issue that intensifies challenges for lake ecosystems by altering water temperatures, disrupting seasonal water cycles, and increasing the frequency of droughts and extreme weather events (WWF, 2019). Implementing climate-resilient vegetation along shorelines and carbon sequestration initiatives may help to mitigate effects of climate change for European lakes.

2.5.1 Resilience measures

Implementing climate-resilient vegetation along lake shorelines helps mitigate the effects of warming and increased drought frequency. In the Ebro Delta, salt-tolerant plants have stabilized shorelines and reduced flood risks, providing a model for other Mediterranean lakes facing similar challenges (WWF, 2019).

2.5.2 Carbon sequestration initiatives

Carbon sequestration in lake sediments represents a promising solution to mitigate climate change impacts. Lake basins bury surprisingly high amount of atmospheric carbon (~70×10^6 t/a) which is about one fourth of the annual atmospheric carbon burial in the modern oceans. Therefore, the contribution of lakes and artificial reservoirs in counteracting man-made CO_2 emissions should not be neglected according to a study of Einsele et al., (2001). This is mainly accomplished by the rapid accumulation of lacustrine sediments. Tranvik et al., (2009) also discussed the role of lakes in carbon cycling, the mechanisms influencing carbon pools and transformations in lakes.

2.6 Policy and governance approaches

Effective lake management requires coordinated policy frameworks and collaborative governance to address cross-border challenges and promote long-term protection (European Commission, 2019).

2.6.1 Collaborative water management

Multi-stakeholder governance approaches involving local communities, NGOs, scientists, and policymakers can support more sustainable lake management. Slovenia's Lake Bled serves as an example, where a collaborative governance model has led to improved water quality and stakeholder engagement (EEA, 2018).

2.6.2 European Framework implementation

The Water Framework Directive (WFD) fosters transboundary cooperation and standardized water quality goals. Its implementation in the Danube and Baltic regions has successfully improved water quality, particularly in high-biodiversity lakes like Lake Peipsi (or Peipus), which is situated on the Estonia-Russia border or other transboundary lakes discussed in the next chapter (European Commission, 2019).

3 Environmental challenges and solutions for twelve European Lakes.

NbS offer effective strategies for addressing environmental challenges, particularly in water management and ecosystem restoration. This chapter bring as example various case studies in European lakes where NbS have been successfully applied. Table 3.1 presents the twelve natural lakes investigated their location and surface area varying from 1.14 to 5655 km2. The overview map of the lakes considered is also presented in Figure 3.1.

Table 3-1 European Lakes case studies considered for this deliverable

No.	Lakes	Latitude	Longitude	Area (km^2)
1.	Lake Balaton, Hungary	46.7500° N	17.7000° E	594
2.	Lake Constance, Germany/Austria/Switzerland	47.6500° N	9.2500° E	536
3.	Lake Neusiedl	47.7500° N	16.7500° E	315
4.	Lake Geneva	46.4500° N	6.5833° E	582
5.	Lake Ohrid	41.06286° N	20.72360° E	358
6.	Lake Trasimeno, Italy	43.10050° N	12.19862° E	128
7.	Lake Vänern, Sweden	58.54276° N	13.07175° E	5655
8.	Lake Albufera, Valencia	39.38280° N	0.36412° W	24
9.	Lake Chiemsee, Germany	47.8833° N	12.3667° E	80
10.	Lagoa das Sete Cidades, Portugal	37.8550° N	25.78639° W	4.35
11.	Lake Bañolas, Catalonia	42.122481° N	2.75077° E	1.14
12.	Lake Sanabria, Spain	42.120686° N	6.72532° W	3.14

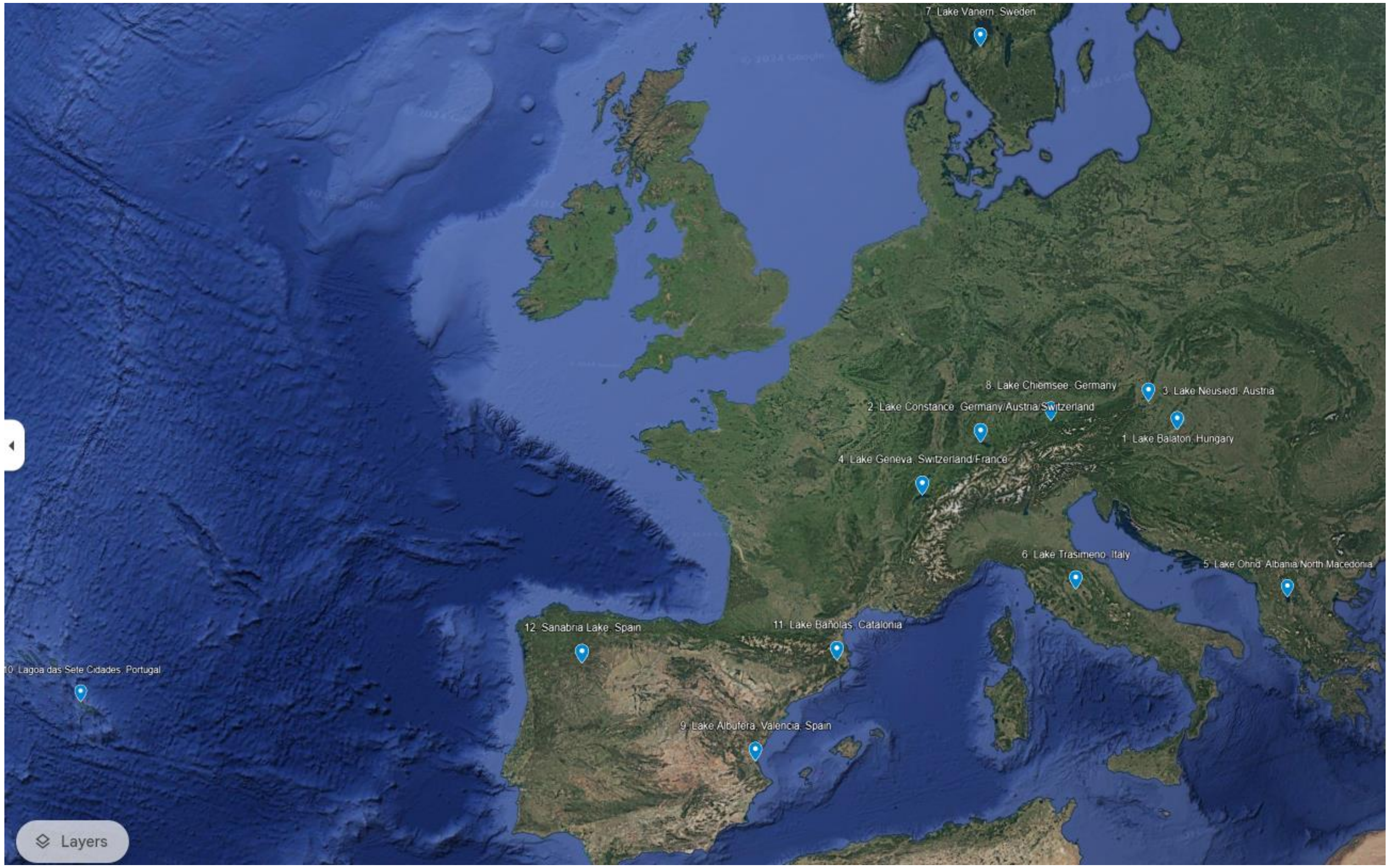

Figure 3-1. Map of the 12 lakes researched in this deliverable. Source: Google Earth application MyMap. (see Annex 1: for more configurations)

3.1 Lake Balaton, Hungary

Lake Balaton, often called the "Hungarian Sea," is the largest freshwater lake in Central Europe, covering around 594 km² with a mean depth of 3.3 m (Zlinszky et al., 2012). This shallow lake is a popular tourist spot for swimming, sailing, and fishing and serves as an essential habitat for diverse fish and bird species. However, agricultural runoff and urban development have led to significant nutrient pollution, especially eutrophication during the 1970s.

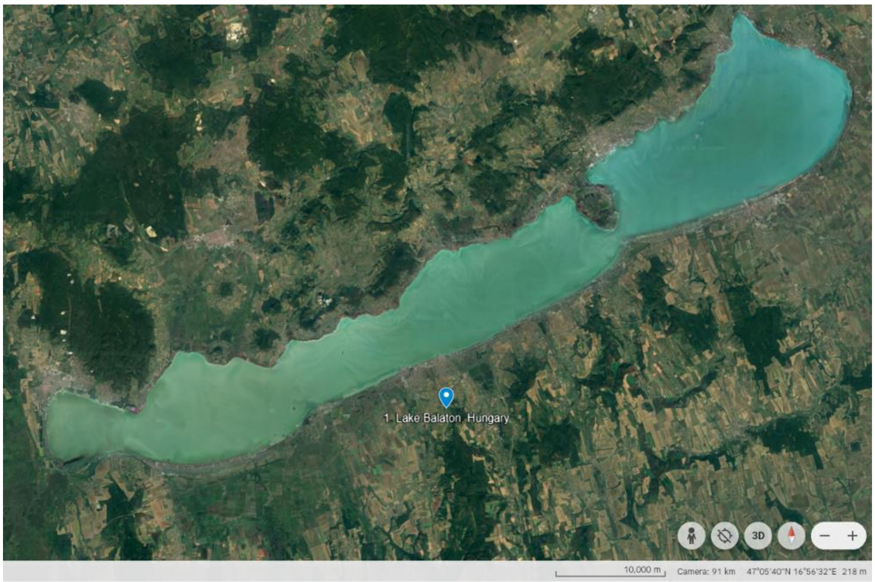

Figure 3-2 – Lake Balaton. Source: Google Earth, (04.10.2024)

Kutics (2019) outlined both negative and positive impacts of human interventions, with the following measures proving beneficial:

- **Restoration of the Kis-Balaton Wetlands**: The Kis-Balaton Water Protection System (KBWPS) was established to filter nutrient loads, particularly at Keszthely Bay, by constructing Hídvégi Pond, a hypertrophic pond (18 km², depth 1.1 m, with a retention time of 30 days) in 1985. Between 1986 and 1997, Hídvégi Pond retained 78,000 t of suspended solids, 290 t of total phosphorus (TP), and other pollutants, with nutrient loads declining due to reduced agricultural production and phosphorus precipitation at a Zalaegerszeg sewage plant (Tátrai et al., 2020).

- **Development of sewer systems**: Recognized as urgent in the 1970s, sewage infrastructure was implemented in the 1990s, reducing sewage phosphorus load from 32 tons/year in 1975-1979 to about 1 ton/year after 2000.
- **Phosphorus precipitation**: stricter effluent phosphorus standards were introduced at sewage treatment plants.
- **Effluent diversion**: Treated effluent was diverted to other watersheds to reduce lake pollution.
- **Ban on liquid manure**: liquid manure technology was banned at livestock farms in the watershed.
- **Dredging**: the heavily polluted Keszthely basin was dredged.
- **Fertilizer reduction**: use of fertilizers in the watershed was minimized.

These efforts have collectively improved Lake Balaton's water quality and ecological health.

Hatvani et al (2020) investigated the changes in Lake Balaton's trophic (nutrient) status over the past thirty years (1985-2017). The lake transitioned from a state of rapid eutrophication in the 1970s and 1980s—characterized by high nutrient levels and frequent algal blooms—to a more balanced trophic state in recent years. This improvement was mainly due to successful management interventions.

Key Eutrophication Drivers

High phosphorus input was the main eutrophication driver. Mitigative measures, such as reducing agricultural runoff and upgrading sewer systems, significantly decreased phosphorus loads and improved water quality.

Spatial Variation Across the Lake

The lake exhibited spatial differences in nutrient levels and trophic status, with the western end (Keszthely Bay) initially more affected by nutrient loads due to its proximity to agricultural runoff from the River Zala, the lake's main tributary.

The construction of the Kis-Balaton Water Protection System, particularly the Hídvégi Pond, as a nutrient filter zone has been instrumental in reducing the nutrient load to Keszthely Bay.

Impact of Wetland Restoration

The Kis-Balaton Water Protection System has significantly helped mitigate nutrient loads entering the lake. This system captured and processed nutrient runoff, particularly from the River Zala, which previously carried a high phosphorus load into Lake Balaton

In summary the study of Hatvani et al., (2020) highlighted the importance of integrated nutrient management, land-use regulation, and adaptive strategies in restoring and maintaining water quality in Lake Balaton. Restoration efforts such as the Kis-Balaton wetland and improved sewage treatment facilities have proven effective in reversing eutrophication. However, long-term ecological stability will depend on continued management in response to changing environmental conditions and climate impacts.

Other NbS approached were also explored for the protection and improvement of the water quality in Lake Balaton such as: **a) reforestation and afforestation initiatives** that aimed planting trees in the watershed areas helped reduce erosion, improve water retention, and enhance biodiversity; **b) establishing buffer zones** along the shores of Lake Balaton helped filter runoff from agricultural lands, reducing nutrient loads entering the lake (Kerekes et al., 2018); **c) promoting sustainable agricultural practices** such as organic farming and agro-ecological practices; **d) community involvement** in conservation efforts and awareness campaigns encouraged sustainable practices and fostered stewardship of the lake’s ecosystem.

3.2 Lake Constance, Germany/Austria/Switzerland

Lake Constance, situated at the borders of Germany, Austria, and Switzerland, is a significant ecological and economic resource, covering an area of about 530 km^2. It ranks among the largest lakes in Europe (glacial lake) and is one of the few alpine and pre-alpine lakes (Schmieder, 2004). The lake is recognized for its rich biodiversity, hosting over 40 species of fish and numerous bird species, making it a key area for conservation efforts.

Challenges

However, the increasing pressures from urbanization, agricultural practices, and tourism have led to pollution and habitat degradation, threatening the delicate balance of this ecosystem.

Like many other European lakes, Lake Constance underwent a rapid eutrophication in the 1960s – 1970s, mainly due to phosphorus concentrations. Since the 1980s, the phosphorus concentration has decreased constantly (Schmieder, 2004) but other factors like intense urbanization apply a high pressure on the shore of Lake Constance. In addition, also recreational use of the Lake is intensive, with 55000 boats which contribute to problems through structural damage and chemical pollution. Building of harbours and landing stages destroy habitats for several plant and animal species, the waves created by boats and ships also harm the natural environment. While the chemical pollution from hydrocarbons emitted from motorboats is also of concern (Nilsson, 2002).

Figure 3-3 – Lake Constance. Source: Google Earth, (accessed 04.10.2024)

Solutions to the pressing issues

The nutrient (phosphorus and nitrogen) concentrations in the lake were reduced by constructing channel systems and efficient sewage treatment plants throughout the basin, connecting 93% of inhabitants to the sewage system, and by banning phosphorus in detergents (Nilsson, 2002).

In response to challenges facing the lakeshore of Lake Constance, Schmieder (2004) advocated for sustainable development practices that balance ecological preservation with the demands of urbanization and tourism. Effective management includes nutrient control, invasive species management, and international cooperation, as Lake Constance is shared by three countries.

To address additional environmental challenges, a range of Nature-Based Solutions have been implemented, including wetland restoration and urban green infrastructure (green roofs, permeable pavements, rain gardens). These initiatives aim to filter pollutants, enhance habitat connectivity, and support local wildlife. For instance, green roofs in urban areas help absorb rainwater and reduce runoff, while restored wetlands act as natural filtration systems that improve water quality. These efforts point out the importance of integrating ecological considerations into urban planning and land management.

3.3 Lake Neusiedl, Austria/Hungary

Lake Neusiedl, a UNESCO World Heritage Site, is one of the largest steppe lakes in Europe, spanning around 315 km^2. Its unique ecosystem, characterized by a diverse range of habitats, is home to a wealth of migratory birds and numerous aquatic species. Despite its ecological significance, the lake faces considerable threats from invasive species, agricultural runoff, and habitat loss due to human activities.

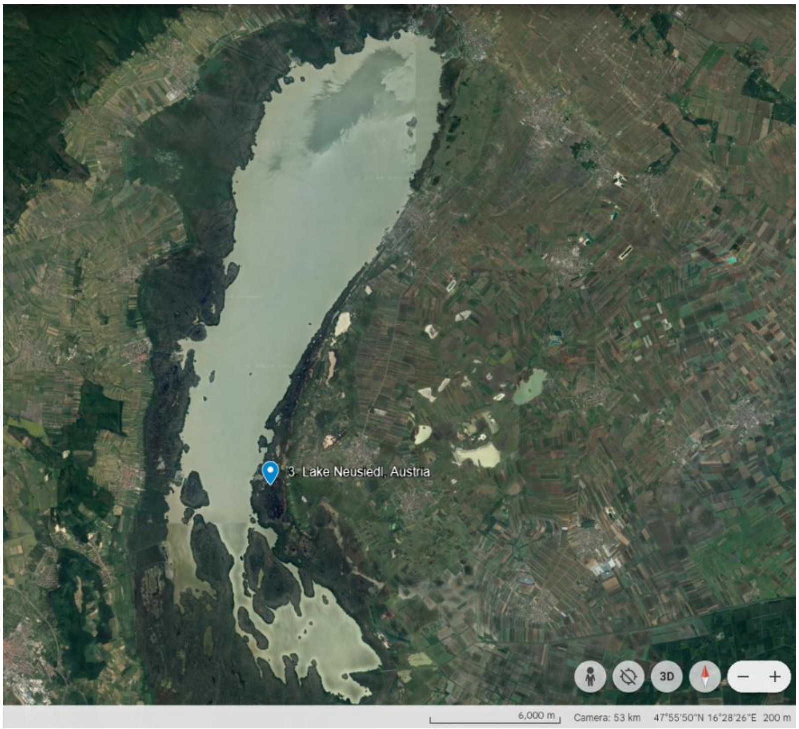

Figure 3-4 – Lake Neusiedler. Source: Google Earth, MyMap, (accessed 04.10.2024)

To address these pressing issues, restoration efforts have focused on wetland rehabilitation and the establishment of buffer zones to mitigate runoff. These NbS are designed to restore natural habitats, enhance biodiversity, and improve the lake's resilience to climate change. By creating protected areas and encouraging sustainable agricultural practices in the surrounding landscape, stakeholders aim to strike a balance between human use and ecological health. The positive outcomes of these initiatives include improved water quality and increased bird populations, which are critical indicators of the lake's ecological recovery. These efforts aimed not only to protect the unique biodiversity of Lake Neusiedl but also promote sustainable tourism and community engagement.

Ficker et al. (2017) explored the role of NbS in improving lake ecosystems, particularly in mitigating the effects of agricultural runoff and invasive species. Their study highlighted the importance of wetland rehabilitation around Lake Neusiedl, which functioned as a natural filtration system, trapping sediment and nutrients before they reached the lake. Buffer zones were equally essential, reducing nutrient loads and improving water quality. This study demonstrated that NbS approaches not only enhanced biodiversity but also strengthened the lake’s resilience to climate variability and human pressures.

Similarly, Oral et al. (2020) discussed comparable NbS methods for water quality improvement in European lakes, with Lake Neusiedl as a case study. Their research emphasized the impact of constructed wetlands and buffer zones in filtering pollutants and controlling runoff, leading to increased populations of native species and improved habitat connectivity. They emphasized that community engagement and sustainable agricultural practices were vital for long-term success, as these strategies helped balance ecological health with human use.

In another study, the potential for landscape services to aid ecological restoration was assessed (Hainz-Renetzeder et al., 2015). A GIS-based approach to map constructed vegetation types and their potential to deliver various landscape services, such as habitat, nutrient regulation, and biodiversity support was used. The study highlighted that most areas in the region could provide greater landscape service potential than what is currently being utilized, suggesting opportunities for further restoration efforts.

3.4 Lake Geneva, Switzerland/France

Lake Geneva, or Lac Léman is one of the largest alpine lakes in Europe (approx. 582 km^2) and is crucial for local ecosystems and drinking water supply. Settled between Switzerland and France, this lake is famous for its stunning scenery and cultural significance. It serves as a vital resource for local communities, offering recreational opportunities, fishing and supporting diverse ecosystems.

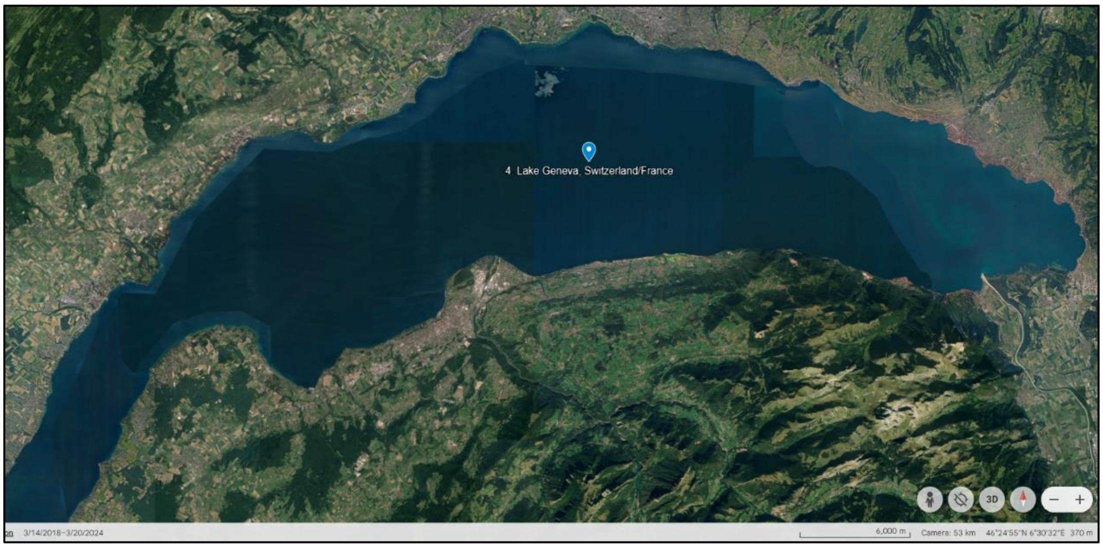

Figure 3-5 – Lake Geneva. Source: Google Earth, MyMap, (accessed 04.10.2024)

Nonetheless, the lake faces significant environmental challenges, including pollution from urbanization (Pardos et al., 2004), agricultural runoff, pharmaceuticals (Chèvre, 2014), microplastics (Boucher et al, 2019), pesticides (Copin et al., 2018), Germanium (Filella & Matoušek, 2022), and other chemicals (Gregorio & Chèvre, 2014), which threaten its water quality and aquatic habitats.

In response, local authorities have implemented a variety of Nature-Based Solutions aimed at improving the lake's ecological health. Key initiatives included:

- **Sustainable agricultural practices.** A key strategy implemented in the Lake Geneva basin has been the promotion of sustainable farming techniques, such as the use of cover crops, reduced fertilizer applications, and organic farming. This approach is designed to reduce agricultural runoff, which has been a significant contributor to water quality degradation. Studies have shown that these practices help mitigate nutrient loading and improve soil health, thereby reducing pollutants entering the lake (Miralles-Wilhelm, 2021).

- **Ecological restoration:** Wetland restoration around the lake has been a priority, as wetlands act as natural filtration systems. These ecosystems trap sediments and nutrients before they can reach the lake, helping to preserve water quality and increase biodiversity. The rehabilitation of wetlands also contributes to enhancing habitat connectivity and supports local wildlife populations, including migratory birds.
- **Green infrastructure**. The installation of green roofs and the development of sustainable stormwater management systems around urban areas near Lake Geneva also aimed to improve water quality. Green roofs absorb rainwater, reducing runoff that can carry pollutants into the water. Additionally, these systems help manage excess water during storms and provide a habitat for local wildlife (UNEP, 2018).

3.5 Lake Ohrid, Albania/North Macedonia

Lake Ohrid is one of the oldest and deepest lakes in Europe, with a maximum depth of 288 meters and a surface area of 358 km^2 shared among Albania and North Macedonia. Its rich biodiversity includes many endemic species, making it a critical area for conservation (Kostoski et al., 2010; Trajanovski et al, 2019). However, the lake faces threats from pollution (pesticides, heavy metals, nutrients, etc), habitat degradation, and the introduction of invasive species, which have negatively impacted its delicate ecosystem (Cullaj et al., 2005; Delipetrov & Doneva, 2006; Matzinger et al., 2006; Veljanoska-Sarafiloska et al., 2011; Trajanovska et al., 2014; Bani et al., 2021).

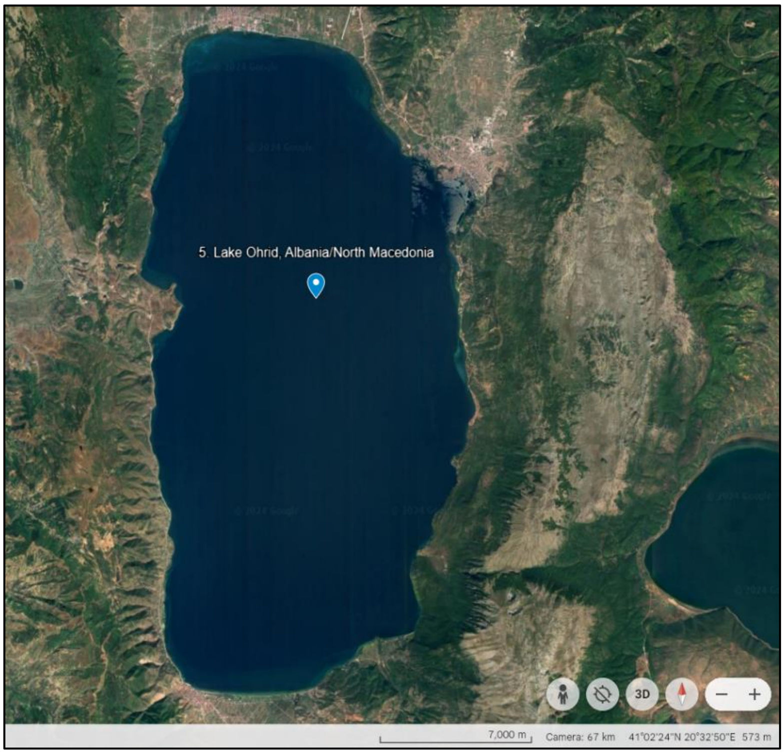

Figure 3-6 – Lake Ohrid. Source: Google Earth, MyMap, (accessed 04.10.2024)

In response to these threats, collaborative conservation efforts have been made to restore natural habitats and improve water quality through the implementation of NbS. These initiatives include reforestation efforts in the catchment area (Kousis et al., 2018; Vermaat et al., 2020) and the establishment of protected zones to preserve critical habitats (Miho et al., 2023). The restoration of riparian vegetation helps to stabilize the shoreline, reduce erosion, and filter pollutants before they reach the lake (Vermaat et al., 2020). These efforts not only aim to restore ecological balance but also enhance the lake's resilience to climate change.

3.6 Lake Trasimeno, Italy

Lake Trasimeno, located in the picturesque region of Umbria, is the largest lake in central Italy, spanning approximately 128 km^2. Trasimeno is also one of Europe's most important wetlands areas thanks to the many botanical species, fauna, and fish of great value that inhabit in and around it. The lake faces environmental pressures related to nutrient pollution, habitat loss (ARPA Umbria, 2012) and climate change (Frondini et al., 2019).

Figure 3-7 – Lake Trasimeno. Source: Google Earth, MyMap, (accessed 04.10.2024)

These challenges have prompted local authorities and conservation organizations to implement a series of actions in the area of Lake Trasimeno Park aimed at enhancing the reserve area and lake's ecological health described in Regione Umbria, (2015):

- the protection and reconstitution of the native flora to allow their development in specific habitats around the lake,
- the protection of the naturalistic elements by their direct enhancement (intervention by new planting) or indirect (natural evolution),
- the creation of a park with predominantly native species in the Castiglione airport area, as well as the adaptation of existing building structures without increasing their volumes,
- an expansion of the reserve area and reconversion of current agricultural activities towards eco-sustainable practices for the "Valle" natural oasis,

- the creation of green buffer strips between the infrastructures and the lake shores (wooded and shrubby), in the Passignano area (between the lake and the infrastructures). The construction of experimental units linked to lake vegetation and fauna, for recreational and education activities.

Fabbretto et al., (2024) in a recent study tracked the water quality and macrophyte changes in Lake Trasimeno using Spaceborne hyperspectral imagery, which outputs could support the water monitoring activities of authorities.

3.7 Lake Vänern, Sweden

Lake Vänern is Sweden's largest lake and the fourth largest glacial lakes in Europe, renowned for its biodiversity and ecological significance. Spanning approximately 5,650 km^2, it plays a crucial role in supporting local fisheries and providing recreational opportunities for residents and visitors. The region has a vast forest coverage of 70% and also agricultural landscapes (European Commission et al, 2024).

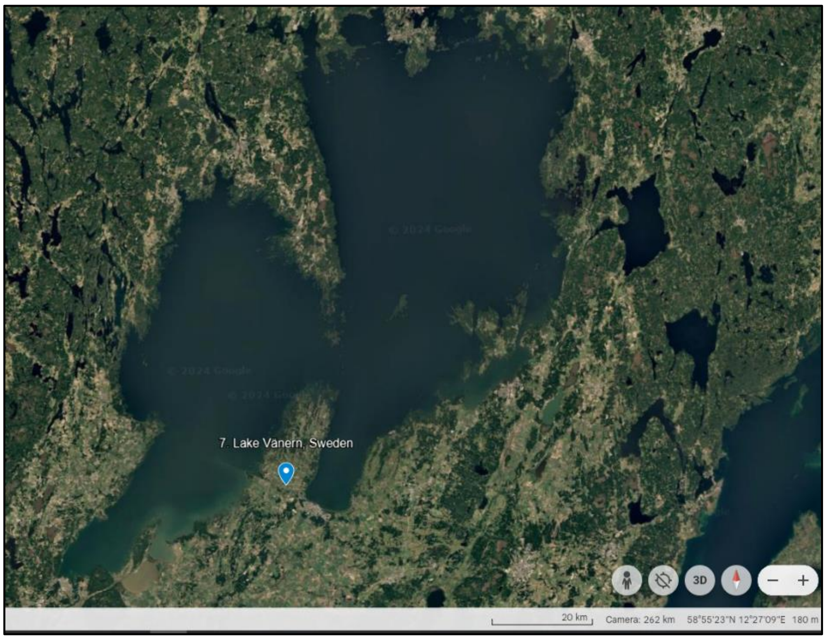

Figure 3-8 – Lake Vänern. Source: Google Earth, MyMap, (accessed 04.10.2024)

However, the lake faces challenges related to nutrient pollution and habitat degradation, primarily due to agricultural runoff and urban development. The area near the lake (Värmland region) is susceptible also to climate change risks such as floods, forest fires, landslides, and increase in temperatures. In a scenario of RCP4.5 emissions from Swedish Meteorolical and Hydrological Institute flood occurrence in Lake Vänern will increase by 8.7% until 2071-2100 (European Commission et al, 2024). Having green recreational areas in high-risk flood areas serves as a preventive measure, limiting also the urbanization in vulnerable zones and mitigating potential future damages. An example is the Mariebergsskögen recreational area in Karlstad, located in the delta of the river Klara and surrounded by lake Vänern, making it highly susceptible to floods. The park covers a significant area and offers a diverse range of attractions for locals and visitors (European Commission et al, 2024).

Restoration efforts around Lake Vänern in Sweden, particularly within the Lake Vänern Archipelago and Mount Kinnekulle Biosphere Reserve, have focused on revitalizing wetlands and creating buffer zones to support biodiversity and mitigate environmental pressures. These initiatives aimed to enhance water quality and protect the lake's ecosystems (SEPA, 2008).

- **Wetland restoration**: Efforts include rehabilitating wetland areas to act as natural filtration systems, capturing nutrients and sediments from agricultural and urban runoff before they enter the lake. These projects are part of broader strategies to maintain the ecological integrity of the biosphere reserve.
- **Buffer zones**: Establishing buffer zones between agricultural lands and the lake helps reduce nutrient loading, prevent erosion, and sustain biodiversity. These zones also support wildlife habitats and foster ecological connectivity.
- **Community engagement and sustainable practices**: The biosphere reserve has encouraged local communities to adopt sustainable

farming techniques, such as organic farming and reduced fertilizer use, which contribute to long-term ecological health. Education and training programs for stakeholders have been key to promoting these practices.

These projects have showcased the biosphere reserve as a model for sustainable development, integrating conservation with economic and social benefits. They also provide valuable lessons for balancing human activity and ecological preservation in similar regions globally (SEPA, 2008).

3.8 Lake Chiemsee, Germany

Lake Chiemsee, a pre-alpine lake situated in Bavaria between Rosenheim, Germany and Salzburg, Austria. It is often called the "Bavarian Sea," and is a vital freshwater resource covering an area of about 80 km^2. The region around the Chiemsee is called Chiemgau and is a famous recreation area. The lake supports diverse wildlife, including various fish species, birds, and other aquatic organisms. Chiemsee as a pre-alpine lake, is less polluted in comparison to the lakes in the North Germany. Its trophic status is mesotrophic (Alpine Convention, 2009).

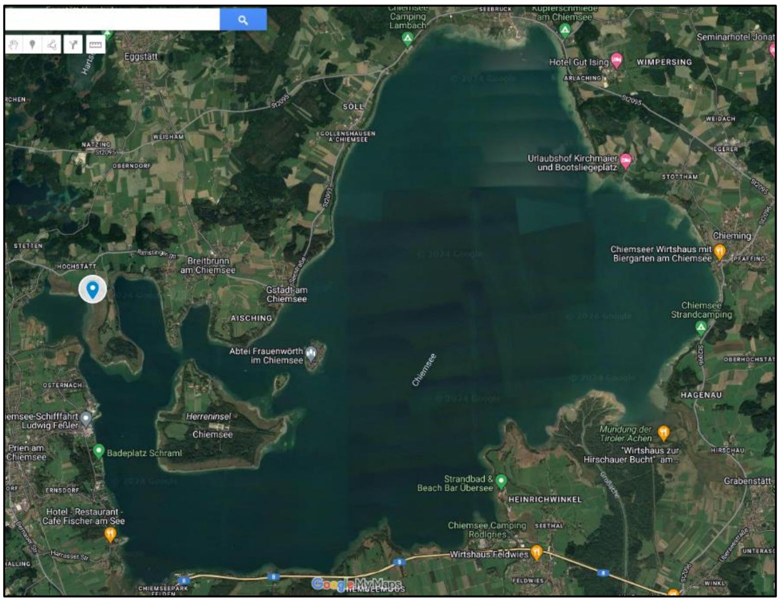

Figure 3-9 – Lake Chiemsee. Source: Google Earth MyMap, (accessed 04.10.2024)

Tourism-related activities can exert significant pressure on the environment, leading to habitat degradation. One area of concern is the presence of macroplastics and microplastics in aquatic ecosystems, which has been the focus of recent research. According to a pilot study conducted by the Bavarian Federal Office for the Environment in 2019 (*Blue Lake Project, 2021*), the microplastic concentration in lake water ranged between 4 and 42 particles/m^3, with particle sizes between 20 and 300 µm. These particles were particularly abundant in shore sediments; one bay recorded a concentration of 124,796 particles/m^3, predominantly composed of polypropylene and polyethylene. Interestingly, no macroplastics were detected in the analyzed water samples from the lake (*Blue Lake Project, 2021*).

3.9 Lake Albufera, Spain

Lake Albufera, located just south of Valencia, is one of the largest coastal lagoons in Spain, encompassing approximately 24,000 hectares when including the surrounding wetlands. This critical ecosystem is celebrated for its rich biodiversity, providing habitat for numerous bird species and aquatic life, and serving as an important resource for local fisheries. However, the lake faces significant challenges, particularly nutrient pollution (eutrophication) caused by agricultural runoff and urban development, as outlined in the 50-year eutrophication analysis by Martín et al. (2020).

D1.6 Map of existing solutions for remediation and protection of ENL

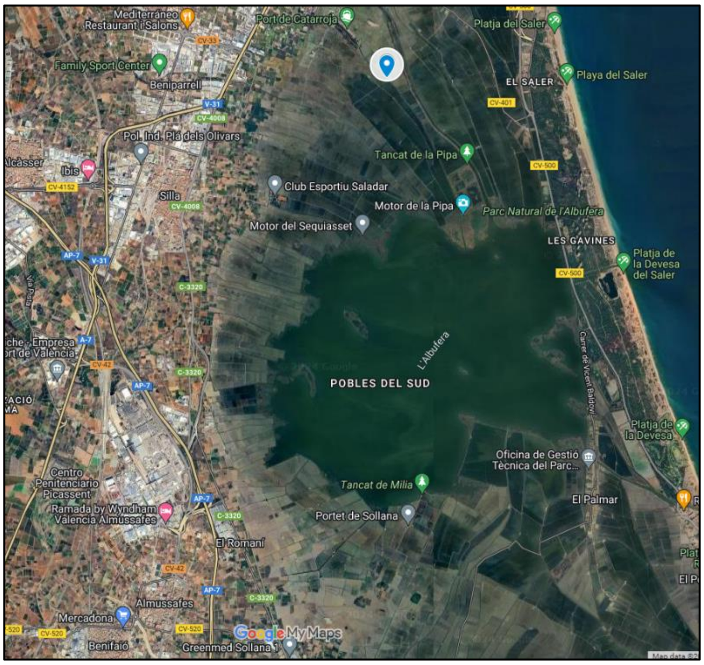

Figure 3-10 – Lake Albufera. Source: Google Map, (accessed 04.10.2024)

Restoration efforts have included a variety of initiatives (Veraart et al., 2004; Riddiford et al., 2014; Martín et al., 2020):

- Development of constructed wetlands to filter pollutants and improve water quality.
- Habitat restoration, including the replanting of native vegetation, to support biodiversity.
- Improved agricultural and urban management practices, such as reducing fertilizer use in surrounding farmlands and upgrading wastewater treatment systems to limit the influx of pollutants.
- Establishment of buffer zones around the lake to intercept surface runoff.
- Community and stakeholder engagement, including volunteer-driven conservation efforts like *The Albufera Initiative for Biodiversity*.

These actions highlight the importance of integrating ecological restoration, community involvement, and policy measures to safeguard the essential ecosystems of Lake Albufera.

3.10 Lake of Sete Cidades, Portugal

The Lake of Sete Cidades (Lagoa das Sete Cidades) is a twin lake (4.38 km²) located in a volcanic crater on São Miguel Island in the Azores, Portugal. It consists of two interconnected bodies of water, Lagoa Verde (Green Lake) and Lagoa Azul (Blue Lake), named for the distinct colors they exhibit due to light reflection and other natural factors.

Figure 3-11 – Lake of Sete Cidades. Source: Google Earth, MyMap, (accessed 04.10.2024)

The lake faces several environmental challenges, including eutrophication caused by nitrogen and phosphorus runoff, invasive species (Costa et al., and pollution and habitat disturbance driven by increased human activity and tourism pressure (Martins et al., 2008; Cruz et al., 2015).

Restoration efforts have focused on implementing nutrient management plans, establishing buffer zones, controlling invasive species, and encouraging community involvement. Additionally, the lake is protected under the Ramsar Convention (https://rsis.ramsar.org/ris/1802), recognizing its significance as a wetland of international importance, especially for migratory birds and endemic species.

3.11 Lake Banyoles (Bañolas), Spain

Lake Bañolas is a karstic lake covering approximately 1.14 square kilometers. It is the main lake of Catalonia, located in the northeast of Iberian Peninsula near the town of Girona. The lake is known for its natural attractiveness and ecological significance and is frequented by locals and tourists.

Figure 3-12 – Lake Bañolas, Catalonia, Spain. Source: Google Earth, MyMap, (accessed 04.10.2024)

Adverse factors within the site include recreational and tourist activities, illegal hunting and fishing, introduction of exotic species (fish, crustacean, reptile), and habitat fragmentation (roads)[1]. An example of introduction of invasive species in the lake is the coypu (*Myocastor coypus*), a semi-aquatic rodent native in South America (Latorre et al., 2020).

Various restoration and conservation efforts[2] have been implemented to address these challenges:

- Efforts to manage nutrient pollution in Lake Banyoles have included improving wastewater treatment in the surrounding areas and controlling agricultural runoff. These measures aim to reduce the influx of

[1] https://www.iberianature.com/regions/catalonia/lake-banyoles/, accessed on 15.11.2024
[2] https://econservation.jrc.ec.europa.eu/project/2002449, accessed on 15.11.2024

nitrogen and phosphorus, which are primary contributors to eutrophication.

- While there is limited documentation specific to erosion in Lake Banyoles, broader conservation practices have been implemented in similar Spanish freshwater ecosystems. These often involve the establishment of riparian vegetation to stabilize lake edges and reduce sedimentation.
- Native species conservation and reintroduction programs are indirectly supported by controlling invasive species like the coypu (Latorre et al., 2020) or other fish species (Pou-Rovira et al., 2012). Rapid response protocols to eliminate invasive populations have helped mitigate their impact on native flora and fauna, ensuring ecosystem stability and supporting species dependent on aquatic habitats.

3.12 Lake Sanabria, Spain

Lake Sanabria is the largest glacial lake in Spain but relatively small (3.14 km^2) compared to the other lakes investigated in this deliverable, typically oligotrophic to oligo-mesotrophic, placed within the attractive Sanabria Lake Natural Park. It is renowned for its landscape and unique biodiversity. A few environmental challenges, including water quality, and increased nutrient input from watershed during winter, have been noted (Jambrina-Enríquez et al., 2017; Catalan et al 2024). The lake has also been researched with regard to the climate change effects on it, plus water quantity and land use changes (Ramos-Fuertes et al 2020; Brugues et al., 2007).

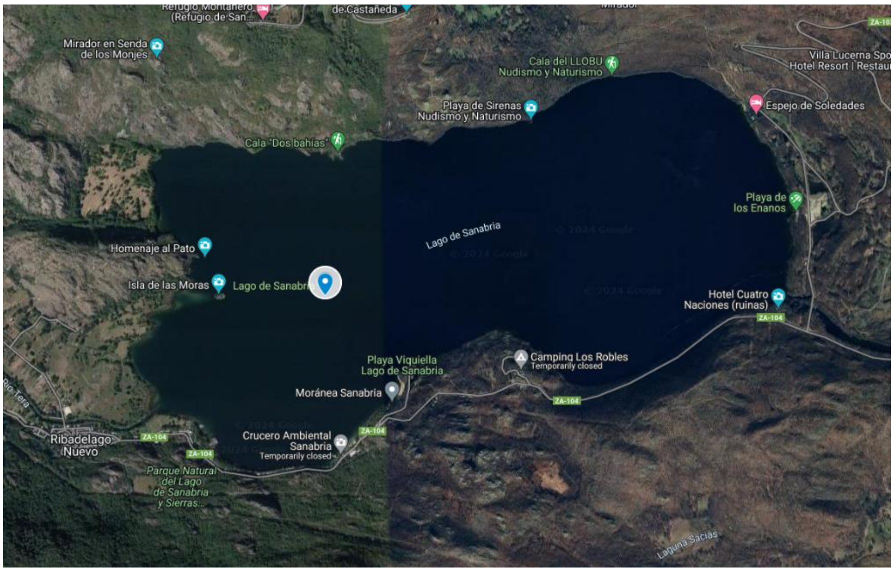

Figure 3-13 – Lake Sanabria, Spain. Source: Google Map, (accessed 04.10.2024)

Efforts to address these issues have focused on several key restoration strategies. Among them, eutrophication control, restoring native species, management of aquatic vegetation, control of nutrient inputs, erosion control measures, and the implementation of sustainable tourism practices have been prioritized. There have been also actions aimed at improving waste management and reducing pollution from surrounding agricultural activities.

3.13 Economic benefits following NbS applications to restore and protect lakes

Nature-based solutions (NbS) for lake restoration and protection offer a wide array of economic benefits, which complement their ecological and social advantages. By using natural processes to address challenges like nutrient pollution, habitat degradation, and climate impacts, these solutions provide cost-effective alternatives to traditional engineered systems. For instance, constructed wetlands and riparian buffer zones naturally filter excess nutrients, reducing the need for expensive water treatment facilities and saving municipalities significant operational costs over the long term. NbS also create opportunities for sustainable economic activities, such as eco-tourism, which thrives in restored lake ecosystems. Lakes that integrate biodiversity conservation with recreation, such as Lake Vänern in Sweden, attract visitors for birdwatching, kayaking, and hiking, thereby boosting local economies and creating jobs. Furthermore, NbS enhance fisheries by restoring aquatic habitats, improving fish populations, and supporting sustainable livelihoods for local communities, as seen in the wetland rehabilitation efforts around Lake Neusiedl in Austria and Hungary. Beyond these direct benefits, NbS also contribute to climate resilience by mitigating flood risks and enhancing carbon sequestration, which can unlock economic opportunities through carbon credit markets. Improved lake environments, such as the rejuvenated shores of Lake Geneva, often lead to increased property values, as these areas become more desirable for residential and commercial development. Additionally, the implementation of NbS stimulates job creation in areas like restoration work, project monitoring, and maintenance, while also fostering community engagement and skill development through training and participatory projects. Together, these economic gains demonstrate how NbS not only safeguard lake ecosystems but also serve as catalysts for sustainable development and economic resilience in surrounding communities.

4 Conclusions

The findings from this deliverable show up the importance of tailored and integrated approaches to address the diverse challenges faced by European Natural Lakes (ENL). Chapters 1 and 2 have provided a comprehensive review of existing remediation and protection solutions, while Chapter 3 demonstrated their practical application through case studies of twelve distinct lakes across Europe.

- **Nature-based Solutions (NbS) as foundations**: NbS, such as constructed wetlands, riparian zone restoration, and sustainable agricultural practices, have emerged as effective tools in enhancing lake resilience, improving water quality, and supporting biodiversity. Case studies like Lake Balaton and Lake Vänern illustrate the multifaceted benefits of NbS in mitigating nutrient loads and combating climate impacts.

- **Adaptability to Context-Specific Challenges**: The success of interventions centers on their alignment with the unique environmental pressures and socio-economic contexts of each lake. For example, invasive species management at Lake Banyoles and hydrological restoration at Lake Neusiedl highlight the necessity of localized strategies.
- **Integration of Policy and Governance**: The role of frameworks like the EU Water Framework Directive is pivotal in fostering cross-border collaboration and stakeholder engagement. The experience of Lake Constance exemplifies how cooperative governance can drive sustainable outcomes.
- **Emerging Threats and Forward-Looking Measures**: Climate change intensifies the urgency for adaptive management. Resilience measures, including drought-resistant vegetation and carbon sequestration initiatives, as seen in lakes such as Lake Vänern and Lake Geneva, are vital in safeguarding future ecological stability.

Recommendations and Outlook

- **Investment in NbS**: Scaling up the implementation of NbS will maximize ecological, social, and economic gains across Europe's natural lake ecosystems.
- **Strengthened monitoring**: Enhanced monitoring systems are essential to track ecological changes and refine adaptive management strategies.
- **Community involvement**: Empowering local communities through education and active participation will ensure sustainable and inclusive conservation efforts.

- **Further research**: Continued research into innovative remediation techniques and climate adaptation measures will bolster the capacity to address emerging environmental challenges.

This deliverable lays a strong foundation for advancing the restoration and protection of ENL. Building on these insights, the subsequent project phases will design tailored NbS for PROCLEANLAKES demonstration sites, ensuring a practical and scalable pathway toward sustainable lake management.

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D1.6 Map of existing solutions for remediation and protection of ENL

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Annex A

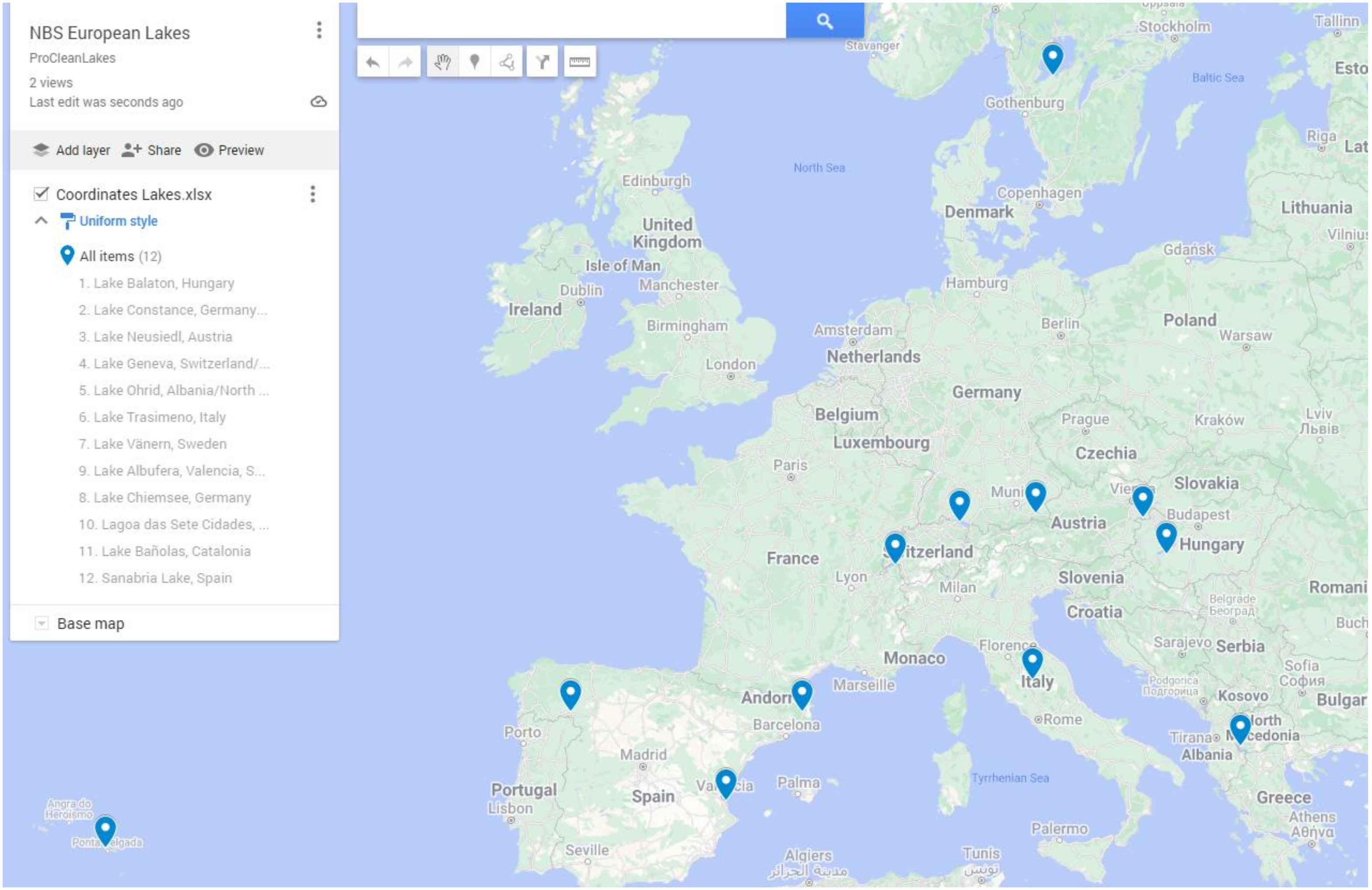

Figure Annex 14. Another view of the map of twelve natural lakes case studies considered in this deliverable for NbS solutions applied. (Source: MyMap).

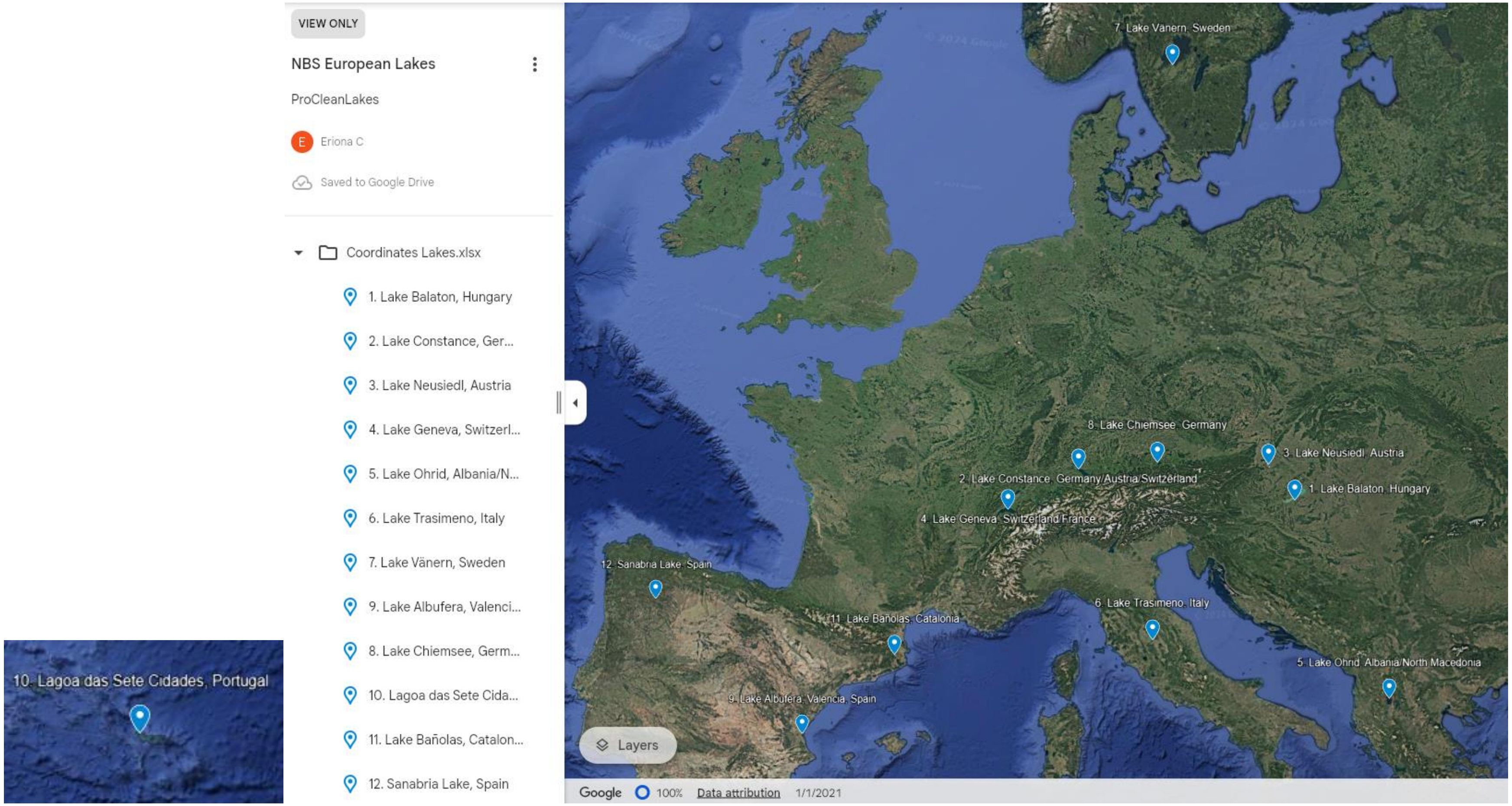

Figure Annex 15. Another view of the 12 lakes. Generated from MyMap. All the maps include data from: Data SIO, NOAA, U.S. Navy, NGA, GEBCOLandsat / CopernicusIBCAOU.S. Geological SurveyImagery from the dates:12/14/2015–newer.

End of the deliverable.