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Living Lab as a participatory framework for improving lake eutrophication mitigation policy

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Living Lab as a participatory framework for improving lake eutrophication mitigation policy

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Le Living Lab comme cadre participatif pour améliorer les politiques d'atténuation de l'eutrophisation des lacs. L'eutrophisation demeure l'une des pressions les plus persistantes et les plus complexes affectant les écosystèmes lacustres. Bien que les mécanismes de l'eutrophisation soient bien étudiés, de nombreuses stratégies de restauration des lacs continuent de rencontrer des difficultés de mise en œuvre, car l'eutrophisation n'est pas seulement un problème écologique, mais aussi un problème social, institutionnel et d'aménagement. Les apports en nutriments proviennent généralement de sources multiples, notamment l'agriculture, les eaux usées, le ruissellement urbain, l'aménagement des rives, les infrastructures touristiques et les charges internes provenant des sédiments. Par conséquent, les stratégies visant à réduire l'eutrophisation nécessitent une coordination entre différents secteurs, échelles et groupes de parties prenantes. Ce manuscrit soutient que l'approche du Living Lab peut constituer un cadre participatif utile pour l'élaboration de stratégies et de plans visant à réduire l'eutrophisation et les proliférations algales dans les lacs. Le Living Lab est compris comme un environnement multi-acteurs, co-créatif et itératif, dans lequel sont combinées les connaissances scientifiques, l'expérience locale, la responsabilité institutionnelle et l'apprentissage social. L'article examine l'importance de l'eutrophisation pour la santé des lacs, la nécessité d'approches participatives dans la gouvernance lacustre, la structure possible d'un Living Lab conçu pour traiter l'eutrophisation, ainsi que les défis théoriques et méthodologiques associés à une telle approche. L'argument central est que le principal avantage de cette approche réside dans une architecture participative organisée, grâce à laquelle le diagnostic scientifique peut être traduit en stratégies socialement légitimes, adaptatives et applicables.

Mots-clés : eutrophisation, planification participative, co-création, gouvernance lacustre, gestion adaptative, Siutghiol, Constanța.

Living Lab as a participatory framework for improving lake eutrophication mitigation policy. Eutrophication remains one of the most persistent and complex pressures affecting lake ecosystems. Although its mechanisms are well studied, many lake restoration strategies continue to face implementation difficulties because eutrophication is not only an ecological problem but also a social, institutional, and planning problem. Nutrient inputs usually originate from multiple sources, including agriculture, wastewater, urban runoff, shoreline development, tourism infrastructure, and internal sediment loading. Consequently, strategies to reduce eutrophication require coordination across sectors, scales, and stakeholder groups. We argue that the Living Lab approach can provide a useful participatory framework for developing strategies and plans to reduce eutrophication and algal blooms in lakes. The Living Lab is understood as a multi-actor, co-creative, and iterative environment in which scientific knowledge, local experience, institutional responsibility, and social learning are combined. The article discusses the importance of eutrophication for healthy lakes, the need for participatory approaches in lake governance, the possible structure of a Living Lab designed to address eutrophication, and the theoretical and methodological challenges associated with such an approach. The central argument is that the main advantage of this approach is in organised participatory architecture through which scientific diagnosis can be translated into socially legitimate, adaptive, and implementable strategies.

Keywords: eutrophication, participatory planning, co-creation, lake governance, adaptive management, Siutghiol, Constanța.

1. INTRODUCTION

Lakes are among the most valuable components of inland and coastal landscapes (Popa et al., 2023). They support biodiversity, regulate local hydrological and bio-geochemical processes, provide cultural and recreational services, sustain fisheries and tourism, and contribute to the identity of many communities (Popa et al., 2020). Their ecological condition is therefore not a narrow environmental concern but a broader question of territorial quality, public health, local development, and social well-being (Walker et al., 2013; Cheval et al., 2020). Healthy lakes depend on maintaining water clarity, oxygen balance, nutrient equilibrium, aquatic vegetation, functional food webs, and resilience to disturbance (Pavelescu et al., 2014). When these conditions are disturbed, the degradation of lake ecosystems can rapidly become visible through declining water quality, unpleasant odours, fish mortality, algal scums, bathing restrictions, loss of landscape attractiveness, and conflicts among users (Skolka, 2024).

Among the pressures affecting lakes, eutrophication remains one of the most widespread and difficult to manage (Popa et al., 2023). Eutrophication is generally defined as the enrichment of aquatic systems with nutrients, especially phosphorus and nitrogen, resulting in increased primary production and often in excessive algal or cyanobacterial growth (Popa et al., 2023). The process can occur naturally over long timescales. However, the current environmental concern is primarily related to cultural or anthropogenic eutrophication, in which human activities accelerate nutrient inputs beyond the assimilative capacity of the lake ecosystem (Smith et al., 1999; Schindler, 2006). The consequences are well documented: loss of water transparency, changes in phytoplankton composition, expansion of cyanobacteria, reduction of submerged macrophytes, oxygen depletion, release of nutrients from sediments, alteration of trophic relationships, and decline in the ecological and social value of lakes (Carpenter et al., 1998; Scheffer et al., 1993; Søndergaard et al., 2003).

The difficulty of eutrophication management derives from the fact that it is rarely produced by a single source or solved by a single technical intervention (Popa et al., 2023). Nutrients can enter lakes through agricultural runoff, wastewater discharges, stormwater systems, soil erosion, septic tanks, aquaculture, atmospheric deposition, and the remobilisation of legacy phosphorus stored in sediments (Popa et al., 2020). In many cases, external nutrient reduction is necessary but not sufficient for rapid ecological recovery, because internal feedback can maintain turbid, bloom-dominated states for long periods (Jeppesen et al., 2005; McCrackin et al., 2017). In addition, climate warming may intensify the risk of algal blooms by increasing water temperatures, strengthening stratification, altering hydrological regimes, and favouring cyanobacteria under certain conditions (Paerl, Otten, 2013). The result is a complex socio-ecological problem that requires both scientific understanding and coordinated governance.

Traditional approaches to eutrophication control have often been based on expert diagnosis, regulatory instruments, technical measures, and sectoral planning (Yan et al., 2024). However, the long-term success of lake restoration also depends on public legitimacy, stakeholder cooperation, institutional coordination, behavioural change, and the ability to adapt strategies as ecological responses unfold (Walker et al., 2013). This is why participatory approaches have become increasingly important in environmental management (Newig et al., 2023).

Participation can improve the quality of environmental decisions by integrating diverse forms of knowledge, increasing transparency, identifying conflicts early, and fostering ownership among actors expected to implement or to support management measures (Reed, 2008). At the same time, the literature on environmental governance shows that participatory processes vary considerably in quality and outcomes, and that poorly designed participation may remain symbolic, selective, or dominated by powerful actors (Koontz, Thomas, 2006; Newig, Fritsch, 2009).

In this context, the Living Lab approach offers a promising framework for developing strategies and plans to reduce lake eutrophication. Living Labs emerged in innovation studies and participatory design as real-life environments in which users, researchers, public authorities, companies, and other actors co-create, test, and evaluate solutions (Bergvall-Kåreborn, Ståhlbröst, 2009; Leminen et al., 2012; Hossain et al., 2019). More recently, Living Labs have been applied to sustainability transitions, urban governance, agroecosystems, and complex socio-ecological challenges (Voytenko et al., 2016; McCrory et al., 2020; McPhee et al., 2021). Their relevance for eutrophication lies in their ability to connect scientific monitoring, local knowledge, institutional responsibility, experimentation, and adaptive planning within a structured participatory process (Papadaki et al., 2026).

This study proposes and discusses the Living Lab as a participatory approach for developing strategies and plans to reduce the impacts of eutrophication processes in lakes. It aims to clarify: why eutrophication matters for healthy lakes; why participatory approaches are important in addressing this problem; how a Living Lab for eutrophication could be structured; and what theoretical and methodological challenges should be considered when designing such an instrument to address this issue.

2. EUTROPHICATION IMPACT

Lake health should be understood as the capacity of its ecosystem to maintain ecological structure, functional processes, biodiversity, water quality, and resilience under natural and anthropogenic pressures (Popa et al., 2023). In this sense, eutrophication is one of the most important threats to healthy lakes because it simultaneously affects several components of ecosystem integrity (Paraschiv et al., 2013).

The first and most direct effect of eutrophication is an increase in primary production due to excessive nutrient availability (Popa et al., 2023). In many freshwater systems, phosphorus has historically been identified as a key limiting nutrient, although nitrogen also plays an important role in many contexts and it can influence algal community composition and bloom dynamics (Schindler, 2006; Conley et al., 2009). When nutrient inputs exceed ecological thresholds, phytoplankton biomass increases, water transparency decreases, and the underwater light climate deteriorates (Florescu et al., 2022). Reduced light availability affects submerged aquatic vegetation, which is essential for habitat complexity, sediment stabilisation, nutrient uptake, and the maintenance of clearer-water conditions (Matsuzaki et al., 2021).

This process is especially important in shallow lakes, where interactions between sediments, aquatic vegetation, fish communities, and phytoplankton can produce alternative stable states (Scheffer et al., 1993). However, once the turbid state is established, simply reducing nutrient loading may not immediately restore the clear-water state, as internal feedback mechanisms continue to sustain high phytoplankton biomass (Dunalska, 2025). This nonlinearity is central to the management of eutrophication because it shows that prevention is often easier and less costly than restoration (Dunalska, 2025).

A second major consequence of eutrophication is oxygen depletion (Wurtsbaugh et al., 2019). As algal biomass increases, a larger quantity of organic matter eventually settles and decomposes (Carstea et al., 2013). Microbial decomposition of organic matter consumes dissolved oxygen, especially in bottom waters, while low-oxygen conditions can stress or kill fish and benthic organisms (Paraschiv et al., 2013), alter nutrient cycling, and stimulate the release of phosphorus from sediments (Moore et al., 2003). Søndergaard et al. (2003) emphasised the role of sediments and internal phosphorus loading in shallow lakes, showing that sediments are active components of the eutrophic dynamics, so the legacy of past nutrient loading can continue to influence the lake long after external inputs have been reduced.

Proliferation of cyanobacteria is another important effect of eutrophication, and one of its most visible and socially problematic symptoms (Popa et al., 2023). Cyanobacterial blooms can form dense surface scums, reduce recreational value, produce unpleasant odours, and, in some cases, release toxins that threaten humans, domestic animals, livestock, and wildlife (Florescu et al., 2022). Paerl and Otten (2013) described harmful cyanobacterial blooms as a major challenge for freshwater ecosystems, linking their occurrence to nutrient enrichment, hydrological alteration, and warming conditions. Thus, cyanobacteria are not only indicators of degraded conditions but also active drivers of ecological deterioration, affecting the suitability of lake water for recreation and other uses (Ho et al., 2019).

Social and economic impacts accompany the ecological effects of eutrophication as lakes affected by algal blooms may lose attractiveness for bathing, boating, fishing, waterfront tourism, and real estate development (Dodds et al., 2009). Local communities may experience reduced quality of life, economic losses, and increased costs for monitoring, water treatment, public information, and restoration (Tammeorg et al., 2024). The social effects are often seasonal and episodic, but their cumulative importance can be high; thus, a single intense bloom during the summer season may affect the public perception of a lake for years, especially where tourism and recreation are important (Walker et al., 2013). This is particularly relevant for lakes located near urban and coastal tourism areas, where ecological degradation can quickly become a planning and development issue (Bucur et al., 2012).

Recovery from eutrophication is often slow, as Jeppesen et al. (2005), based on long-term data from multiple case studies, showed that lake responses to reduced nutrient loading are variable and can take many years. McCrackin et al. (2017) further demonstrated, through a global meta-analysis, that recovery from eutrophication in lakes and coastal systems is often partial, late, and dependent on ecosystem characteristics and management context. This delayed response has important implications for strategy preparation, which requires long-term monitoring, realistic expectations, and adaptive revision.

Eutrophication of a lake also has a strong spatial dimension given that it is connected to its catchment through surface runoff, groundwater, drainage systems, land use, and human infrastructure (Hernández-Hernández et al., 2026). Nutrient loads are shaped by agriculture, urbanisation, wastewater treatment, shoreline development, and hydrological connectivity (Popa et al., 2020). For this reason, effective eutrophication strategies must consider the lake-catchment system, the distribution of nutrient sources, the institutional responsibilities across administrative boundaries, and the behaviour of users and land managers (Shkaruba et al., 2024). Carpenter et al. (1998) underlined the importance of nonpoint pollution from phosphorus and nitrogen in surface waters, showing that diffuse nutrient sources are especially difficult to regulate because they are distributed across landscapes and activities.

As Dokulil and Teubner (2010) showed, climate change accelerates eutrophication. Warmer temperatures favour cyanobacteria, extend the growing seasons, strengthen thermal stratification, and interact with nutrient enrichment to intensify the risk of blooms (Wang et al., 2025). Extreme precipitation events increase nutrient runoff, while droughts reduce flushing and concentrate nutrients (Li et al., 2018). These interactions make eutrophication management more uncertain and increase the need for adaptive planning. Strategies based only on historical conditions may be insufficient under the changing climatic and hydrological regimes (Wang et al., 2025). Healthy lakes therefore require not only nutrient reduction but also resilience-oriented governance capable of responding to uncertainty (Han et al., 2024).

The importance of eutrophication for a lake can thus be summarised through four main arguments. First, eutrophication directly degrades its ecological structure and function by altering nutrient dynamics, phytoplankton biomass, oxygen conditions, vegetation, and food webs (Popa et al., 2020). Second, it undermines ecosystem services and social values, including recreation, tourism, fisheries, landscape quality, and public health (Ho et al., 2019). Third, it is difficult to reverse the process because of internal loading, nonlinear dynamics, and delayed recovery (Jeppesen et al., 2005; McCrackin et al., 2017). Fourth, it is spatially and institutionally complex because its drivers are distributed across catchments and sectors (Wang et al., 2025). This is why a lake eutrophication mitigation strategy requires a combination of scientific, participatory, and adaptive approaches.

3. PARTICIPATION AND ENVIRONMENTAL MANAGEMENT

3.1. Advantages of participatory approach

The management of eutrophication has traditionally been strongly science-driven (Conley et al., 2009). Without lake monitoring, nutrient budgets, ecological modelling, and water-quality assessment, it is impossible to understand the sources, mechanisms, and trajectories of lake degradation (McCrackin et al., 2017). However, in addition to controlling the direct mechanisms of eutrophication, a complex mitigation strategy requires changes in land management, wastewater treatment, urban planning, shoreline use, agricultural practices, public behaviour, tourism management, and institutional coordination (Shkaruba et al., 2024). These changes involve actors with different interests, responsibilities, resources, and perceptions of the same problem. Thus, participation becomes necessary because eutrophication is not only a biophysical process but also the outcome of social practices and governance arrangements (Schindler, 2006).

Primarily, participatory approaches are important because they improve and fine-tune the definition of the environmental problem, as different actors may perceive eutrophication in different ways. So, scientists may define it through nutrient concentrations, chlorophyll-a, phytoplankton composition, oxygen profiles, or ecological status (Wurtsbaugh et al., 2019). Residents may perceive it through water colour, odour, bathing restrictions, fish mortality, or the loss of landscape quality (Drexler, Boles, 2024). Farmers may relate the issue to fertiliser management, drainage, soil erosion, or regulatory burdens (Feng et al., 2025). Municipal authorities may connect it to infrastructure, wastewater, urban development, and public complaints (Khalili, Moridi, 2025). While tourism operators may focus on destination image, seasonal attractiveness, and economic losses (Guimont, Lapointe, 2016). Overall, it results in a more complex perspective that it is useful for identifying the best management directions (Duan et al., 2026). A participatory process makes all these different problem framings explicit, but this does not mean that all perceptions are equally valid as scientific explanations. However, it does mean that strategies become more realistic when they understand how the problem is experienced and interpreted by different groups with various, often divergent, interests within the same space.

In addition, participation helps to identify sources of knowledge which are not captured by formal monitoring. Such knowledge can complement scientific data and can help formulate more relevant hypotheses and measures. Reed (2008) emphasised that stakeholder participation can improve environmental decision-making by incorporating broader information inputs and by increasing trust and learning. In eutrophication planning, local knowledge may be especially valuable where monitoring networks are limited, historical data are incomplete, or diffuse sources are difficult to trace (Schindler, 2006).

Participatory approaches can also increase decision legitimacy as the measures to reduce eutrophication may impose costs or constraints on certain actors. Agricultural nutrient reduction, restrictions on shoreline development, improved wastewater management, buffer strips, wetland restoration, stormwater redesign, or changes in recreational practices may all generate community resistance if they are perceived as imposed, unfair, or poorly explained (Reed, 2008). Participation can reduce this risk by allowing the affected actors to understand the evidence, to express their concerns in addressing the issue, to negotiate intervention priorities, and to contribute to the design of measures (Voicu-Dorobanțu, 2016).

The lake-catchment system rarely corresponds neatly to administrative boundaries. That is why it is often managed and impacted under the decision-making of multiple public institutions and communities. Water authorities, municipalities, environmental agencies, agricultural institutions, tourism bodies, protected area administrations, landowners, and private operators may all influence the lake, but each operates under a different mandate (Guimont, Lapointe, 2016). Management fragmentation can lead to inconsistent actions, duplicated efforts, or gaps in responsibility. In the era of fragmented responsibilities, participatory environmental planning supports the improvement of coordinated management by bringing actors into a shared process (Duan et al., 2026). Nonetheless, while it may contribute to environmental effectiveness, the outcome eventually depends on the institutional context, scale of action, communication structure, and the degree of actor involvement (Newig, Fritsch, 2009).

The temporal dimension of an environmental strategy implementation is often underestimated. Many eutrophication strategies fail not because the proposed measures are scientifically wrong, but because they are not maintained long enough. A plan may recommend nutrient reduction, but the implementation may weaken after a political cycle, a funding period, or a change in institutional priorities. Thus, participation can overcome this flaw by creating broader ownership and social memory around the strategy (Antaki et al., 2026).

3.2. Challenges of participatory approach

At the same time, participatory approaches must be treated critically as the environmental outcomes of collaborative management are often difficult to demonstrate, and the enthusiasm for participation in the process may exceed the evidence of effectiveness for the proposed measures (Koontz, Thomas, 2006). In the case of lake eutrophication, a participatory process may produce stakeholder meetings, reports, and consensus statements without reducing nutrient inputs or improving its ecological status. Conversely, a scientifically rigorous strategy may fail politically if community participation is weak. The challenge is therefore not to choose between expertise and participation, but to design processes where both are integrated.

Participatory governance acknowledges that power relations are a major issue, as stakeholders do not enter participatory processes with equal resources, but they are strongly backed by their technical expertise, institutional authority, financial capacity, political access, or communication skills (Antaki et al., 2026). Some relevant stakeholders may lack time, confidence, or formal recognition and they are, therefore, marginalised in the decision-making process. If these asymmetries are ignored, participation may only reproduce the existing power relations rather than to democratize decision-making (Visser, Kreemers, 2020). In eutrophication planning, powerful actors may seek to avoid responsibility for nutrient inputs, while less powerful communities may experience the consequences of lake degradation without influencing its causes. So, careful facilitation, transparent rules, and deliberate inclusion are therefore essential in a participatory governance process (Fernández-Pacheco Sáez et al., 2026).

Identifying and engaging the relevant actors in a participatory process is a challenge of representation (Visser, Kreemers, 2020). In the case of lake eutrophication, they may include water authorities, municipal administrations, wastewater operators, agricultural producers, tourism businesses, fishers, residents, environmental NGOs, schools, researchers, health authorities, protected area managers, and recreational users. In some specific contexts, seasonal users and tourists may also be relevant, although they are harder to get systematically involved (Li et al., 2025). So, the participation design must distinguish between the different involvement roles of the stakeholders: those who should be involved in decision-making; those who should be consulted; those who should receive information; and those who should contribute to monitoring or to implementation (Drexler, Boles, 2024).

Participation also requires translation between various knowledge systems (Visser, Kreemers, 2020). For the governance of lake eutrophication, scientific indicators such as total phosphorus, total nitrogen, and chlorophyll-a, may not be easily understood by the non-specialists who have decision-making responsibilities or who participate in the design of planning. Conversely, the experiential observations of different population groups may be difficult to integrate into technical assessments (Dobre et al., 2019). A participatory approach must therefore be based on boundary objects: maps, diagrams, scenarios, indicators, narratives, and monitoring dashboards, so the different actors can discuss the same problem without reducing it to purely technical language. This is a significant reason for the relevance of the Living Lab approach, as it provides a framework not only for consultation, but also for co-creation, interdisciplinary experimentation, and reciprocal learning (Fernández-Pacheco Sáez et al., 2026).

4. LIVING LABS AND EUTROPHICATION MITIGATION

The Living Lab concept has been defined in different ways, but several features recur across the literature: real-life setting; active user involvement; multi-actor collaboration; co-creation; openness to all voices; experimentation; and iterative learning, based on problem diagnosis, measure design, implementation, and evaluation to inform each other continuously (Bergvall-Kåreborn, Ståhlbröst, 2009; Leminen et al., 2012; Hossain et al., 2019). So, a Living Lab is not simply a laboratory in the conventional scientific sense; it is a structured environment in which actors jointly explore a problem, develop solutions, test them in real-life conditions, evaluate the outcomes, and adapt their actions (Müller, 2026). In sustainability contexts, Living Labs are often used to connect knowledge production with practical territorial transformation (Voytenko et al., 2016; McCrory et al., 2020).

For lake eutrophication, a Living Lab can be understood as a participatory lake-catchment platform designed to support the preparation, implementation, monitoring, and revision of strategies and plans to reduce nutrient enrichment and algal blooms. Its main function is to serve as a ground for interaction among the actors who influence or who are affected by the lake’s health.

4.1. Framework characteristics

Given the spatial specificity of lake ecosystems, a eutrophication Living Lab should begin with establishing clear territorial and institutional boundaries. The territorial boundary must include the entire lake catchment area, while the institutional boundary should identify which authorities and organisations are responsible for water quality, land use, environmental protection, public health, tourism, agriculture, infrastructure, and local development – so, the Living Lab should be lake-centred but catchment-sensitive (Dunalska, 2025).

The most important structural component of a Living Lab is the convening core, referring to the actor group responsible for initiating and maintaining the Living Lab (Bulkeley et al., 2016). It may include a municipality, a water authority, a university or research institute, an environmental agency, or a partnership among them. The convening core should ensure continuity, logistics, communication, documentation, and connection to formal planning mechanisms.

Another component is the multi-actor platform, representing the participatory body that brings together the relevant stakeholders (Chroneer et al., 2019). Following the actor-role perspective developed in the Living Lab research, the stakeholders may play four different roles in relation to lake management: users, providers, utilizers, and enablers (Leminen et al., 2012; Nyström et al., 2014). In a lake eutrophication Living Lab, the users may include residents, recreational users, farmers, fishers, tourists, and local businesses. Providers may include scientists, technical experts, monitoring agencies, and infrastructure operators. Utilizers may include municipalities, water managers, planning authorities, and organisations that will apply the results. Enablers may include funding bodies, regulatory institutions, NGOs, and educational organisations. Clarifying these roles makes responsibilities more transparent for strategy implementation.

A shared evidence base is also important for a eutrophication Living Lab, as it creates a common factual reference for discussion (Chroneer et al., 2019). It should include available water-quality data, nutrient concentrations, chlorophyll-a records, phytoplankton information, cyanobacteria observations, oxygen profiles, sediment data, land-use maps, wastewater information, hydrological data, and historical documentation of blooms. Where data is insufficient, the Living Lab can identify monitoring gaps and it can propose a further realistic monitoring plan.

The specificity of a Living Lab as a participatory governance tool is represented by the multistakeholder problem framing (Papadaki et al., 2026). So, before management measures are proposed, the involved actors should jointly discuss the main problem in relation to lake eutrophication: how it is experienced; which drivers are the most important; which uncertainties remain; and which objectives and evaluation criteria should guide the following strategy.

The stage of co-design of measures should combine catchment, shoreline, in-lake, communication, and governance actions: reducing nutrient and diffuse pollution, improving wastewater and stormwater management, restoring riparian buffers, regulating shoreline development; while carefully assessing in-lake interventions, informing the public, supporting citizen reporting, coordinating institutions, securing funding, assigning responsibilities, and defining implementation timelines (Barati, Bankaru-Swamy, 2026).

Through the experimentation phase, Living Labs are particularly useful because they support testing first the proposed measures under real-life conditions (Dobre et al., 2019). In eutrophication planning, experimentation may involve pilot buffer zones, demonstration wetlands, citizen monitoring protocols, participatory mapping of pollution sources, or educational campaigns.

Monitoring and evaluation of small-scale experimentation results allow the actors to learn what works, what is socially acceptable, what is technically feasible, and what institutional barriers exist, in order to further ensure the success of the desired strategy (Müller, 2026). Because lake recovery is slow, evaluation should combine ecological, implementation, governance, and social indicators: nutrients, chlorophyll-a, cyanobacteria, oxygen, transparency, macrophytes, completed measures, stakeholder participation, coordination, transparency, learning, public awareness, perceived quality, recreation, and user satisfaction (Khalili, Moridi, 2025). But the Living Lab decision-making should not rely solely on process indicators, as active participation does not automatically imply ecological improvement; and it should also not rely only on short-term ecological indicators, because lake recovery may lag management action (Duan et al., 2026).

As a Living Lab should operate through well-defined cycles (diagnosis, co-design, and experimentation), the monitoring and evaluation phase needs to be followed by the adapted revision of proposed measures, depending on the internal and external factors continuously impacting the lake dynamics (Armitage et al., 2008). For example, eutrophication is influenced by ecological feedback, climate variability, land-use change, and political priorities (Pavelescu et al., 2014).

A brief reference to Siutghiol Lake, a Natura 2000 site, illustrates why such a framework may be relevant in Romania. Siutghiol Lake is located on the Romanian Black Sea coastal area, partially within Constanța Municipality, and it is associated with urban, recreational, tourism, and ecological interests (Skolka, 2024). Studies on Romanian coastal lakes, including Siutghiol, have discussed eutrophication in this regional context and in terms of water-quality assessment, and it is among the lakes affected by nutrient and phytoplankton dynamics (Godeanu, Galatchi, 2007; Ghiță et al., 2023). Without entering into a detailed territorial diagnosis, Siutghiol can be considered a useful example of a lake where ecological processes are inseparable from shoreline development, urban pressures, recreation, tourism, and institutional responsibilities (Bucur et al., 2011; Bucur et al., 2012; Anton et al., 2021; Skolka, 2024).

This is why the eutrophication of Siutghiol Lake became a major focus of local research and a Living Lab would be appropriate in such a context because it could bring together scientists, local authorities, tourism actors, residents, environmental organizations, and water management institutions to develop a shared strategy to reduce the risk of blooms and to improve the lake health in relation to the sustainable development of both urban, natural and tourist areas (Li et al., 2025).

4.2. Adaptive lake management

The Living Lab approach is valuable for eutrophication mitigation because it reframes its management as an adaptive planning process. When lake strategies are prepared exclusively as static documents, they often struggle to respond to the changing ecological conditions, stakeholder conflicts, or unexpected outcomes. The Living Lab creates a structured framework in which the strategy can be interpreted, tested, evaluated, and periodically revised, in relation to the new territorial challenges and eutrophication dynamics (Azadi, 2026).

Such a management instrument is especially important for large lakes, as they are affected by multiple pressures, competing uses (urban development, tourism, agricultural runoff), and fragmented governance (Anton et al., 2021). In their case, a Living Lab may provide added value, especially by addressing the main difficulty of not only knowing what should be done, but also by bringing all the different interested parties to the same table with the unique goal of mitigating eutrophication under a sustainable development framework (Lakatos et al., 2024).

The Living Lab approach is also compatible with adaptive management, which recognises that environmental policies are implemented under uncertainty and dependence on ecosystem dynamics, and that management should be treated as a learning process based on a participation framework (Bulkeley et al., 2016). In eutrophication control, adaptive management is essential because ecological responses may be delayed or nonlinear, being under the influence of different factors, so they may not correspond to the initial planning of implementation terms to achieve the mitigation objectives.

Another important contribution of the Living Lab for sustainable lake management is the integration of both ecological and social indicators. Classic eutrophication strategies often focus on technical indicators, such as phosphorus, nitrogen, or dissolved oxygen, but a sustainable strategy should also include the quality of participation, public trust, behavioural change, institutional coordination, and the perceived value of the lake (Palmer et al., 2022). Conversely, participatory projects sometimes focus on social engagement without measuring ecological improvement, so a successful eutrophication Living Lab should combine both.

Nevertheless, the Living Lab approach should be applied carefully, in order to maintain a rigorous planning framework and to avoid the risk to only use the concept as a fashionable terminology for any simple public consultation (Voicu-Dorobanțu 2016). To avoid this, a eutrophication Living Lab aiming at sustainable lake management should satisfy the minimum conditions of having: a clear lake-catchment focus; a stable convening structure; meaningful stakeholder participation; a scientifically credible evidence base; real-life testing of measures; transparent monitoring of both ecological and social indicators; adaptive revision of planning and interventions; and strong connection to formal governance (Lakatos et al., 2024).

5. LIVING LAB CHALLENGES

5.1. Theoretical challenges

Although the Living Lab approach is promising, it raises several theoretical challenges when applied to eutrophication. The primary one concerns conceptual clarity, as the Living Lab concept has been used across many fields, including digital innovation, urban planning, sustainability transitions, health, agriculture, and education (Hossain et al., 2019). This flexibility can be useful, but it can also create conceptual ambiguity. For eutrophication, conceptual clarity requires distinguishing a Living Lab from other participatory formats. Thus, a public consultation invites stakeholders to comment on the proposed plans; a stakeholder focus group facilitates discussion among the interested actors; and a research project produces scientific knowledge. A Living Lab should integrate all these participatory forms, but it should also go beyond them by emphasising co-creation, iterative learning, and connection to implementation (Fernández-Pacheco Sáez et al., 2026).

The relation between participation and expertise is another theoretical challenge of using the Living Lab as the core of eutrophication mitigation. Eutrophication, as a scientifically complex process, involves knowledge on hydrology, nutrient cycling, phytoplankton ecology, sediment chemistry, food-web interactions, climate effects, and restoration techniques (Matsuzaki et al., 2021). A purely deliberative process cannot replace expert assessment, but it complements strategy development. At the same time, a purely expert-driven process may fail to address social practices, stakeholder responsibilities, and implementation barriers. The challenge is to create a co-production model in which scientific expertise remains rigorous while local knowledge and stakeholder perspectives are meaningfully integrated (Armitage et al., 2008).

Another challenge is the risk of depoliticising conflict. Although Living Labs focus on a positive and constructive approach to territorial problems, eutrophication may involve conflicts among the stakeholders (farmers, municipalities, tourism businesses, developers) over responsibility, costs, land use, regulation, limitations, and development priorities. A theoretically robust Living Lab must recognise that participation occurs within power relations and that consensus may not always be possible (Ersoy, Van Bueren, 2020).

Given that eutrophication processes are multi-scalar – nutrient inputs may originate upstream, while ecological impacts appear in the lake; decisions about land use may be local, while water-quality regulations may be national or European – the literature on urban and sustainability Living Labs warns on the importance of the analysis scale in order to avoid local experimentation to remain isolated while it is required to be connected to a wider governance framework and to related scaling processes (Voytenko et al., 2016; McCrory et al., 2020).

The temporal specificity of Living Labs, which are often project-based, represents an additional challenge, especially as eutrophication recovery is a long-term process (McCrackin et al., 2017). A project may last two or three years, a political cycle lasts 4 years, but ecological improvement may require decades. The mismatch between the different life cycles of management contexts can generate unrealistic expectations on the results. For a successful eutrophication mitigation strategy, the Living Lab must therefore be theorised not as a temporary participation project but as a governance infrastructure capable of persisting beyond the initial funding cycles.

The final concern is related to innovation, as a specific requirement for Living Labs (Anton et al., 2022). But eutrophication management does not always require novelty, given that many effective measures are already known: nutrient reduction, wastewater treatment, buffer zones, erosion control, wetland restoration, monitoring, and land-use regulation, to name the most important ones (Morelato et al., 2026). In the territorial context of Siutghiol Lake, for example, the problem with eutrophication mitigation is rather related to implementation than to the lack of innovative technologies. Therefore, a eutrophication Living Lab should be better organised around institutional, social, procedural, or communicative innovations (Anton et al., 2022), which does not exclude, however, using novel technologies as a tool to facilitate or to accelerate de-eutrophication processes.

5.2. Methodological challenges

The methodological design of a eutrophication Living Lab is as important as its theoretical justification, given that it brings additional challenges to address. First, the identification of relevant stakeholders needs to be as exhaustive as possible to avoid including only obvious institutional actors, while excluding groups that influence nutrient flows or that directly experience lake degradation. So, stakeholder mapping should consider influence, interest, responsibility, vulnerability, knowledge, and capacity to act within and beyond the Living Lab framework (Ersoy, Van Bueren, 2020). In the context of eutrophication management, it should also distinguish between permanent residents, seasonal users, land managers, economic actors, and public institutions.

Second, considering that participation in Living Labs must be deliberately configured, i.e. deciding on who participates, at what stage, by which methods, and to what extent, it should be done based on explicit rules. Otherwise, participant involvement may become confusing, inefficient, or dominated by those with more time and resources (Akasaka et al., 2022).

Third, scientific and participatory methods are difficult to integrate in a eutrophication Living Lab due to the combination of various research methods, such as water sampling, remote sensing, GIS mapping, nutrient-source assessment, interviews, workshops, participatory mapping, scenario planning, citizen science, and policy analysis (Ersoy, Van Bueren, 2020). Because each method has different validity standards – scientific monitoring requires precision and quality control, while participatory approaches require inclusiveness and facilitation – the methodological challenge is to connect all of them without weakening none (Ersoy, Van Bueren, 2020).

In the specific case of lake eutrophication, its dynamics is mostly unpredictable because the process depends on many highly variable factors, such as weather conditions, hydrological variability, land-use change, sediment processes, biological interactions, and climate variability (Morelato et al., 2026). So, an important level of uncertainty dominates the results of a eutrophication Living Lab. The solution would be scenario planning, as it allows the stakeholders to explore possible futures of territorial evolution and mitigation in relation to the impact of various drivers – such as increased tourism pressure, improved wastewater treatment, agricultural changes, extreme rainfall, or warmer summers – while the lake health depends mainly on their interaction rather than on isolated management measures (Anton et al., 2021).

Within a eutrophication Living Lab, the evaluation of results should be multi-layered, given that ecological recovery may be slow, and the challenge is to address it in a complex way, across all its pillars (Koontz, Thomas, 2006). Thus, the process evaluation should assess the quality of participation, representation, transparency, trust, and learning; the output evaluation should assess whether the Living Lab produced a strategy, an action plan, a monitoring protocol, pilot measures, or institutional agreements; the outcome evaluation should assess whether implementation occurred and whether the nutrient inputs declined; and, finally, the impact evaluation should assess long-term ecological improvement (Müller, 2026).

Data accessibility and communication are another challenge for successful Living Labs, as they are based on both scientific data, which are often difficult to interpret by non-specialists, and stakeholders' co-involvement (Papadaki et al., 2026). So, for an efficient participatory approach to eutrophication mitigation, a Living Lab should translate technical indicators into understandable formats without oversimplifying them, while communication must avoid creating false certainty about the lake dynamics. For example, a low bloom risk at one moment does not mean that the lake is now healthy, while the absence of visible algal scum does not necessarily indicate low nutrient pressure (Wei, 2026).

The institutionalisation of the Living Lab results is also important as the participatory framework can produce valuable knowledge and social learning, but if it is not connected to formal planning instruments, its influence may remain limited (Palmer et al., 2022). That is why eutrophication strategies must be linked to water management plans, spatial planning, municipal development strategies, wastewater investments, and agricultural policies, and the Living Lab should therefore include mechanisms for transferring co-created recommendations into official decisions.

The final methodological challenge is related to the comparability and transferability of the Living Lab results to other territorial contexts confronting the same issue of eutrophication. Although each lake is unique, every eutrophication Living Lab should produce lessons that can be compared across different spatial contexts, which requires documenting in detail the methods used, the involved actors, the chosen evaluation indicators, the decisions of mitigation made, and the expected outcomes (Müller, 2026). While the Living Lab for the mitigation of eutrophication in the case of one lake should not be copied mechanically to another, its design principles need to be transferable, especially when the territorial context is similar. Also, the general stages of work within a Living Lab – shared diagnosis, co-design, pilot testing, monitoring, and adaptive revision – are broadly applicable and they need to be respected regardless (Barati, Bankaru-Swamy, 2026), although the specific measures which result in the end differ depending on the case study characteristics.

5. CONCLUSIONS

Eutrophication is one of the most significant threats to healthy lakes because it affects the ecological structure, the biogeochemical functioning, fishing resources, biodiversity, water quality, public health, recreation, and local development (Feng et al., 2025). Its impacts are visible through algal and cyanobacterial blooms, reduced water transparency, oxygen depletion, habitat degradation, and loss of ecosystem services (Khalili, Moridi, 2025). The management of eutrophication is difficult because nutrient sources are numerous, ecological responses are nonlinear, internal loading can delay recovery, and climate change may increase the intensity and amplitude of related drivers (Morelato et al., 2026). For these reasons, this anthropogenic process should be treated as a complex socio-ecological problem rather than a narrow water-quality issue, especially due to its territorial effects in relation to all dimensions of sustainable development.

Participatory approaches are important because eutrophication management requires cooperation among all actors who influence or who are affected by the nutrient dynamics. Participation can improve problem framing, integrate local knowledge, increase legitimacy, support coordination, and strengthen long-term implementation; however, participation must be carefully designed within a functional structure (Voicu-Dorobanțu 2016).

In this sense, the Living Lab approach offers a promising participatory framework for preparing strategies and plans to reduce eutrophication and algal blooming within lakes. Its main contribution lies in organising co-creation, experimentation, monitoring, and adaptive learning – significant participatory processes – in real-life settings, at the scale of the lake-catchment system and based on a convening core, a multi-actor platform, a shared evidence base, and a participatory problem framing (Barati, Bankaru-Swamy, 2026).

Nonetheless, the theoretical and methodological challenges of Living Labs require attention and adaptation specific to each territorial context. Usually, conceptual ambiguity, power relations, the balance between expertise and participation, temporal mismatch, stakeholder representation, uncertainty, evaluation, and institutionalisation must all be addressed. Nonetheless, the value of a Living Lab lies in creating a structured participatory environment in which scientific knowledge can be translated into legitimate, feasible, and adaptive strategies.

For lakes such as Siutghiol in Romania, where ecological objectives of biodiversity conservation and of eutrophication mitigation intersect with pressures such as urbanisation, recreation, tourism, and institutional complexity, the Living Lab approach could support more integrated and participatory planning to achieve sustainable development and, thus, to harmonise all competing needs and interests (Li et al., 2025).

The objective would be to build a continuing participatory governance process, through which the lake health becomes a shared responsibility.

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