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Article

From Drivers to Responses: Local Insights and National Frameworks for Restoring Urban Lakes in Bengaluru

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Abstract

Urban freshwater ecosystems in rapidly growing cities face multiple, interlinked pressures. This paper synthesises 411 academic, policy, and practitioner studies on lake degradation and restoration in Bengaluru, India, to examine how these pressures are understood and addressed in research and practice. Using Content Configuration Analysis, we pursue four lines of inquiry: typifying dominant research approaches; mapping how key drivers—urbanisation, expanding consumption, climate change, and governance fragmentation—generate cascading pressures, analysing sewage treatment plants (STPs) as responses that can themselves become new stressors, and comparing national restoration guidelines with locally developed strategies. Our analysis shows that lake problems are frequently framed as discrete technical issues, whereas degradation unfolds through recursive driver-pressure-response dynamics that cut across ecological, institutional, and social domains. The STP cases illustrate this mismatch: mandated solutions can generate unintended pressures when institutional capability, accountability, or ecological integration is weak. Comparison between national guidelines and locally grounded practices reveals broad alignment in restoration principles but persistent gaps in implementation capacity, coordination, financing, and integration with land-use and urban resilience planning remains. We argue for reconceptualising urban lakes as embedded socio-ecological systems rather than bounded technical units. Such a perspective supports restoration strategies that are nationally coherent yet locally attuned, strengthening ecological function, social equity, and urban resilience. More broadly, the findings contribute to debates on the restoration and governance of urban water bodies by demonstrating how national policy frameworks can be reinforced through locally grounded socio-ecological knowledge.

Keywords: urban lake restoration; urban freshwater ecosystems; socio-ecological systems; problem-solution chains; Bengaluru; water governance; urban resilience

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> *The city is at the present time worse off for water than at any previous period in its history. It is difficult to conceive what would result on continuance of the failure of the north east monsoon. Prudence dictates that it is better to prevent the calamity than to battle with it after it overtakes a community and experience teaches that the people who drink such water as is now consumed in the city cannot do so with impunity for long.* KARNATAKA STATE ARCHIVES 1892 (CITED IN Mundoli, Manjunatha and Nagendra, 2018)

1. Introduction

Few cities confront the politics of water as acutely as Bengaluru. Perched atop the Deccan Plateau with no perennial river, the city once relied on a network of manually constructed "lakes", also called tanks, *kere*, *katte*, and *kunte*, to collect monsoon rain (Deeksha, 2024; D'Souza, 2014;

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Nagendra and Unnikrishnan, 2018). These tanks persist, but their meanings and utility have fractured. While some have become biodiversity zones, sources for drinking water, recreational areas, or flood buffers, others are pools of sewage, dried-up lake-beds, or fenced off by encroachment.

The contestation of what their utility is or should be is not simply over land or pollution, but over how freshwater systems are imagined, governed, and repurposed under pressure. Recent state amendments seeking to reduce buffer zones around lakes triggered a legal and civic backlash, highlighting a deeper instability in how lakes are "valued" (*Deccan Herald*, 2025; Gowda, 2025). While courts recognise lakes as commons, on-the-ground enforcement and practices remain fragmented (Brinkmann et al., 2020).

At the national level, the Central Pollution Control Board's (CPCB) *Guidelines for Restoration of Water Bodies* (2019) call for coordinated, science-based planning informed by international frameworks, such as the World Lake Vision (The wlv is a call to action that provides a road map for achieving the transition to sustainable lake management. Developed by the Scientific Committee of the International Lake Environment Committee Foundation during the World Water Forums (2000-2003), it highlights seven principles that form the core of lake revitalisation (Herschy 2012). The Seven Principles of Sustainable Lake Management are: "(1) A harmonious relationship between humans and nature is essential for the sustainable use of lakes; (2) A lake drainage basin is the logical starting point for planning and management actions for sustainable lake use; (3) A long-term, preventive approach directed to preventing the causes of lake degradation is essential; (4) Policy development and decision making for lake management should be based on sound science and best available information; (5) The management of lakes for their sustainable use requires the resolution of conflicts among competing users of lake resources taking into account the needs of present and future generations and of nature; (6) Citizens and other stakeholders should be encouraged to participate meaningfully in identifying and resolving critical lake problems; and (7) Good governance, based on fairness, transparency and empowerment of all stakeholders, is essential for sustainable lake use." (CPCB, 2019, p. 10-11)). They promote phased interventions, long-term governance mechanisms, and technical integration across agencies. However, as our analysis will show, the task of aligning these goals with the lived institutional and ecological realities on the ground remains a challenge. In this sense, Bengaluru is a particularly instructive case. Lake degradation and restoration have been intensely debated across institutional fora for nearly three decades. Rapid growth, combined with governance gaps, has made these water bodies vulnerable to multiple pressures, which are not isolated and thus cannot be addressed through isolated responses. Unsurprisingly, considerable academic and practitioner-oriented output exists that aims to formulate responses to lake pressures, as illustrated in Figure 1.

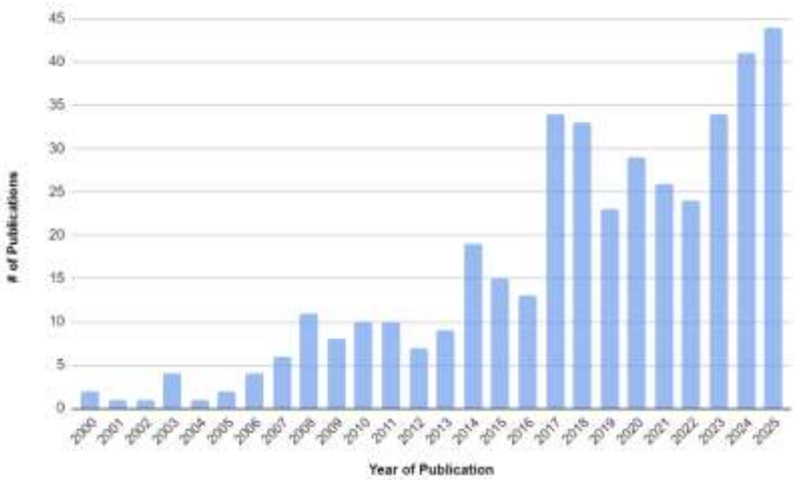

Figure 1. Distribution of lake-relevant publications in the Bengaluru region from 2000-2025.

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Yet, the growth in lake-related research has not always produced clarity. As we will show in more detail, most studies follow larger scholarly patterns where fragmentation of knowledge is reinforced by disciplinary divisions, both within the social sciences (for instance between economics and sociology) and the epistemological rupture between social and natural sciences. As a consequence, researchers often isolate individual pressures or interventions and few trace interdependencies or recursive effects. Fewer still ask what political, economic, technical, or socio-cultural assumptions underlie these framings. Instead, they often reproduce the fragmentation they seek to address. For example, Bengaluru lake research documents proximate pressures, such as sewage inflows, eutrophication, encroachment, and biodiversity loss. However, it tends to treat socio-cultural drivers or governance as either background context or a single explanatory variable. What remains under-specified is how governance, institutional conditions, and a socio-cultural ecosystem translate into repeatable breakdowns (or successes) in restoration efforts. This study bridges "what interventions are recommended" with "how interventions fail or succeed in practice." To understand the current fragmentation, its causes and its consequences on lake revitalisation, we thus need to ask more basic questions: What is a lake?, and What is it for? Drawing on 411 academic, policy, and practitioner documents, we synthesise a typology of implementation failures, mechanisms through which responses are weakened, redirected, or converted into new pressures. Because our concern is not only how lake degradation is described but how restoration knowledge translates into practice, we compare Bengaluru's locally grounded restoration strategies with the CPCB framework. This comparison serves as a cross-scale diagnostic. It reveals which locally observed restoration principles are already institutionalised in national guidance, which recurring governance and implementation failures remain weakly captured, and where local innovations point to possible policy improvements. By making these mechanisms explicit, we offer a governance-and-design lens for interpreting why technically plausible solutions translate only partially between lakes, and why "successful" restoration can mean different things for different lakes and time-points under future growth and climate variability. In doing so, this study contributes to wider discussions on the restoration and governance of urban freshwater ecosystems under conditions of rapid urbanisation and climate change. By synthesising a large body of research and linking local practices with national policy frameworks, the paper provides insights relevant to cities facing similar challenges in managing urban lakes and other water bodies.

The following section examines the shifting imaginaries, stories about what lakes are for and what should be done about them, that have shaped the lakes of Bengaluru over time as a first step in understanding how different interventions, governance approaches, and problem framings take root.

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2. Background

Bengaluru, historically known as "the City of a Thousand Lakes," never had naturally formed lakes. They are engineered tanks that once formed part of a vast interlined hydrological system designed to intercept monsoon flows in a rain-fed plateau landscape (Singh and Hebale, 2019). But their meanings—like their functions—have shifted through development, crises, governance change, and evolving epistemologies.

The earliest imaginary, dating back more than a thousand years, saw tanks as productive irrigation infrastructure. Lakes were functional nodes in an irrigation network, linked to agrarian livelihoods and governed locally through land tenure and stewardship arrangements (Gurunathan, Shanmugham, and Ramappa, 2007; Ankith, 2022). Their main purpose was agricultural. The 1870s famine disrupted this system (Jash, 2025). When monsoons failed for three consecutive years, tanks ran dry, crops failed, and famine swept across the Mysore region resulting in more than a million deaths (Jash, 2025; Nagendra, 2016a). A new imaginary emerged from this devastating crisis: lakes as urban drinking water sources, prompting the construction of new tanks. But as cholera and malaria outbreaks escalated, stagnant tanks were recast as sources of disease (Nagendra, 2016a). Consequently, a sanitation imaginary took hold, informed by germ theory and promoted by colonial commissions (Ramesh, 2018). Tanks became health risks rather than assets, justifying their abandonment in favour of piped water systems such as the Hesaraghatta reservoir and, later, the Cauvery river (Nagendra, 2016a). Lakes were neglected and abandoned, becoming repositories for waste.

By the 1980s, with urban biodiversity under threat and most lakes in decline, ecological value and wildlife habitat became a new, competing imaginary. Initiated in part by Bengaluru's active birdwatching community and formalised in the Laxman Rao Committee Report (1985), this view positioned lakes as biodiversity zones and recommended transferring their control to the forest department. This, however, collided with the reality that tanks are not forests. Governance structures shifted again, passing through multiple bodies, such as municipal corporations, the Lake Development Authority, and the Karnataka Tank Conservation and Development Authority (Lakshmisha and Nagendra, 2025; Luna, 2014). Each shift introduced a new, competing vision of what a lake is.

In the early 2000s, privatisation experiments in Nagawara, Vengaiyana Kere, Hebbal, and Agara Lake reframed tanks as revenue-generating public-private spaces, limiting access and sparking a public backlash (Mandal and Mansi, 2025). Judicial rulings reasserted lakes as commons but excluded the involvement of many NGOs (Sen and Nagendra, 2020). Meanwhile, middle-class environmentalism and elite capture recast lakes as aesthetic and recreational assets, sidelining traditional users such as fisherfolk, grazers, and washer communities (Sen and Nagendra, 2022). Two further imaginaries are present today. One is based on water scarcity mitigation, which re-emerges each time water shortages intensify. The quote from 1892 at the beginning of this article shows how long this imaginary has been woven into Bengaluru's water narrative. During the most recent water crisis in 2024, the city was portrayed as "the next Cape Town" and tanks were re-invoked as untapped resources—symbols of mismanagement, failure, and latent potential (Prasad, 2024; Shah, 2024). Yet this imaginary ignores scale. Even in the 19th century, a thousand tanks failed to sustain a city one-hundredth the size it is today (Jash, 2025; Nagendra, 2016a). Population growth has consistently outpaced water infrastructure over the course of Bengaluru's development trajectory. The other is based on the mitigation of climate change. Urban flooding, exacerbated by encroachment on lowlands and tank beds, has re-centred attention on lakes and drains as buffers (Alex *et al.*, 2020; Salah, 2024). In this variant, tanks are imagined as solutions to flooding, encroachment, erratic rainfall, groundwater recharge, and temperature regulation.

This catalogue of often overlapping and sometimes lake-specific imaginaries reflect shifting relations between people, water, infrastructure, and the environment. They filter what becomes visible and actionable, and what is obscured. They shape which drivers of degradation are highlighted or dismissed, such as whether urbanisation is viewed as pressure or opportunity,

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consumption as a matter of lifestyles or livelihoods, or governance failure as a temporary or systemic condition. These imaginaries also variably cast climate change as temporary, local, regional, a mitigatable threat, an emergency, or an inevitability. Each imaginary, whether tied to survival, disease, biodiversity, aesthetics, crisis management, or climate adaptation, has the potential to redefine how lakes are understood and, thus, what technologies need to be developed or applied, how socio-economic activities need to be restructured accordingly, and what forms of governance all this requires. Taken together, imaginaries reveal how the lakes are continually remade through the interplay of four forces: climate change, urbanisation, expanding and changing consumption, and institutional fragmentation. These dynamics raise questions about how urban freshwater ecosystems can be protected and restored—and for what purpose. In Bengaluru, lakes now have become ecological, economic, legal, and political battlefields. Interestingly missing are socio-cultural and historical considerations. Once referred to as "the City of a Thousand Lakes" or the "Garden City," Bengaluru is now more commonly referred to as "Silicon Valley of India," "IT Capital of India," "Electronic City," "Science City," and "Space City" (Mandal and Manasi, 2021; Singh and Hebale, 2019; Nair, 2008). In line with this, technical interventions are popular and widespread, while community involvement is fragmented.

In this context, a synthesis is needed that goes beyond individual case studies or disciplinary silos to examine how drivers and pressures of lake degradation and responses to restoration accumulate and contradict across time, institutions, and ecosystems. Accordingly, our study is structured around four lines of inquiry:

1. What types of research has been conducted on lake degradation and restoration in Bengaluru to date?
2. What are the main drivers, pressures, and responses linked to lake degradation in the region, and how do they interact?
3. How do interventions aimed at restoring lakes generate new pressures or contradictions, employing two sewage treatment plants as examples?
4. How do locally grounded strategies align with and challenge national restoration guidelines?

In this paper, we aim to provide a conceptual synthesis and a practical contribution to the ongoing challenges of freshwater restoration by treating lake degradation and restoration as a recursive system: drivers generate pressures and responses both address them and can also produce unintended consequences that become new pressures. Accordingly, we shift from the plurality of lake imaginaries to a systematic accounting of how contemporary documents construct problem-solution chains, including which drivers dominate, which pressures are treated as actionable, and how feedback loops and response-induced secondary pressures shape what works. The next section details how we assembled and analysed a multi-source, cross-domain document corpus.

3. Methods

3.1. Data Collection

We compiled a dataset of 411 research documents on lake degradation and restoration in the Greater Bengaluru region, published between 2000 and 2025. Searches were conducted between November 2024 and December 2025, using combinations of keywords (example: 'Bengaluru' AND 'lake*' AND ('restor*' OR 'revital*')). After deduplication, records were screened by title/abstract. Inclusion criteria were thematic focus (lake restoration, degradation, or revitalisation), geographic scope (Greater Bengaluru), language (English), and timeframe (2000-2025). We identified relevant research across academic platforms including CrossRef, PubMed, DataCite, arXiv, Google Scholar, and Sciforum, and supplemented them with manual searches and citation snowballing from reference sections of relevant studies. The final corpus included a diverse mix of peer-reviewed publications, policy briefs, technical and NGO reports, community project documents, blogs on lake research, and relevant books. Table 1 provides an overview of the temporal distribution of the included studies.

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3.2. Data Analysis

Data was analysed using Content Configuration Analysis (CCA; Bergman and Bergman, 2011; Bergman, Bergman and Gravett, 2011; Bergman, 2020). Related to thematic and content analyses, CCA is a qualitative method that can be adapted to analyse non-numeric data, including textual, audio, and visual data. One of the method's greatest strengths is its flexibility to adapt to different research foci and researcher needs (Bergman and Bergman, 2011; Bergman, 2020). Coding was conducted by two senior and two junior researchers. An initial phase of duplicate coding was followed by consensus meetings to resolve discrepancies, iteratively refine the coding scheme, and strengthen inter-coder reliability and coding quality. In this study, we used CCA to conduct a four-step analysis that aligned with our four lines of inquiry:

In step 1 we conducted an exploratory, inductive analysis of the thematic orientation and methodological approaches of lake revitalisation research and policy documents. The outcome of this analysis yielded a meta-typology of five distinct types of lake-related research in Bengaluru. These findings are presented in Results 1.

To analyse our second line of inquiry, we coded the data to identify and extract verbatim excerpts related to lake degradation drivers, associated pressures, and responses proposed to address them. These categories draw on the Driver-Pressure-Response (D-P-R) elements of the Driver-Pressure-State-Impact-Response (DPSIR) framework, a widely used analytical approach in water resource management and environmental assessment. While DPSIR offers a broader causal framing, we focus on the Driver-Pressure-Response (D-P-R) subset to focus on how interventions ('responses') can themselves generate new pressures and feedback effects. Here, D-P-R is used not as a rigid model but as a heuristic for capturing the interlinked nature of lake degradation and restoration efforts. Accordingly, we defined drivers as structural, system-level forces (climate change, urbanisation, expanding consumption, and governance failure), pressures as the more immediate or visible symptoms of degradation (for example, encroachment, pollution, sewage inflow), and responses as the technical, institutional, or community actions proposed or implemented to address these pressures. We then conducted a systematic thematic analysis to examine how primary drivers give rise to pressures and then lead to responses. The recursive D-P-R chains we identified form the basis of a conceptual network model of systemic lake degradation, which is presented in Results 2.

Step 3: Our third line of inquiry aimed to deepen our understanding of the complexity of these recursive chains by examining one issue, sewage treatment plants (STPs), as a microcosm of lake degradation and restoration. Here we use two cases, from Yelahanka and South City, to trace how STPs function both as intended responses to water pollution and as inadvertent lake degradation pressures. These cases were selected for their exemplary value. They mirror broader patterns across the dataset and offer fine-grained insight into how pressure-response dynamics unfold in practice. The case comparison as an illustration of D-P-R cycles is presented in Results 3.

Step 4: Our final line of inquiry moved from local diagnosis to cross-scalar policy translation. Using the CPCB's Guidelines for Restoration of Water Bodies (2019) as a reference framework, we examined whether the response and implementation strategies identified in the Bengaluru dataset are already anticipated, only partially accommodated, or absent from national guidance. The purpose here was to assess the fit between a national restoration framework and the institutional, ecological, and social realities documented in local research. We classified local recommendations into four correspondence categories: full alignment with CPCB guidance, partial overlap with local extension, CPCB elements absent from local research, and local innovations not reflected in the CPCB framework.

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4. Results

4.1. Results 1: A Typology of Lake-Related Research in the Bengaluru Region

Our first line of inquiry focuses on how Bengaluru's lakes have been studied in the context of their revitalisation in order to systematise dominant research approaches. Across the corpus, we observed a wide range of perspectives although the majority of studies frame lake degradation through specific pressures, such as pollution, encroachment, and biodiversity loss, presenting them as urgent problems requiring immediate, targeted intervention. The excerpt below illustrates this recurring focus, where, in this exemplary instance, degradation is cast as a contamination problem requiring specific technical intervention:

> *Bellandur lake is facing severe pollution threat with chemicals and organic load being added every day. This lake with minimal dissolved oxygen is not providing a good habitat for aquatic organisms to survive. The presence of high levels of heavy metals not only contaminates the lake ecosystem but also the underground water in the vicinity. There is urgent need to apply management measures to retain this lake free from pollution and also to provide suitable habitat for the organisms associated with this lake ecosystem.* (Rajanna et al., 2023, p. 38)

To make sense of how such problem framings recur across lake-related research in Bengaluru, we classified them into five broad types. These categories are not mutually exclusive but capture dominant analytical orientations and research aims that structure how lake degradation and restoration are understood.

1. **Discipline-Focused Studies**: Many studies are organised around specific disciplinary lenses. For example, historical analyses trace socio-political drivers of lake degradation (see, for example, Sen, Unnikrishnan and Nagendra, 2020; Shah, 2003, 2008; Unnikrishnan et al., 2016, 2021; Unnikrishnan, Sen and Nagendra, 2017). Governance and policy studies (for example, Bahadure and Sangeetha, 2014; Chengappa and Manaswi, 2020; Nagendra and Ostrom, 2014; Nath, 2021) examine institutional fragmentation and regulatory gaps as key pressures, while urban studies highlight encroachment and land transformation as primary contributors to lake decline (see, for example, Birawat et al., 2021; Dhanush and Devakumar, 2019; Gopinath, Cu and Me, 2022; Manoharan and Tarun, 2022; Mukhopadhyay and Das, 2023). These studies aim to refine problem framings and field-specific debates. Rather than developing integrative synthesis of lake-related pressures, they tend to advance more detailed, disciplinary debates.
2. **Thematic Studies on Water Quality and Flooding**: Another output stream is dedicated to analysing specific water body pressures, namely water quality (Jumbe and Nandini, 2009; Kodli et al., 2022; Kumar, 2023; Mir et al., 2024; Muniraja, 2018; Niazi and Prakash, 2020; Padmanabhan et al., 2025; Raghav and Richard, 2023; Raj B, Hegde and Kadre, 2021; Rao and Mogili, 2021; Salahuddin, 2023; Sarkar et al., 2017; Sudarshan, Mahesh and Ramachandra, 2020; Sundar Navamany, Narayan and Scholten, 2022; Tamia, 2021; Veenashree, Kumar and Nandini, 2022; Vikram and Reddy, 2014), and flood dynamics (Mukhopadhyay and Das, 2023; Tazyeen and Nyamathi, 2015; xxx find more citations). While these studies generate valuable empirical evidence, they typically isolate symptoms rather than tracing them back to structural or institutional drivers. Their analytical purpose lies in deepening specialist knowledge of particular ecological pressures, often in support of targeted technical or regulatory interventions.
3. **Technological and Digital Interventions**: A growing strand of research explores technological responses to lake degradation. These include tools for real-time monitoring, digital mapping, and machine learning-based assessments (Prathibha et al., 2022; Ramachandra et al., 2024; Ramachandra et al., 2023; Santhanam and Majumdar, 2022; Siva et al., 2019; Somya, 2024). In these studies, remote sensing, ecological modelling, and autonomous bots are examined as technical responses to manage pollution, track hydrology, and prevent encroachment. Here, degradation is primarily framed as a data problem, to be solved by detection, prediction, or

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control, to be solved by increasing or improving available metrics through technological innovation. The research aim in this strand tends to develop and test innovative techniques that promise more efficient surveillance and management of lake systems, often with limited engagement with governance or societal dynamics.

4. **Lake-Specific Case Studies**: Numerous studies adopt a case-based approach, examining individual lakes or conducting comparative case studies. While they often integrate elements from other categories discussed here, they nevertheless remain bounded to specific geographies. Examples include work on Jakkur Lake (Vishwanath, 2025), Kaikondrahalli and Kasavanahalli Lakes (Nagendra, 2016b; Ramachandra et al., 2015), Yele Mallappa Shetty Lake (Reddy, Naik and Chandra Mohana, 2016), Madiwala Lake (Salah, 2023), Hebbal Lake (Salahuddin, 2023), Chikkabanavara Lake (Sneha et al., 2019), Sunkalpalya Lake (Nagabhushan et al., 2022), Ulsoor Lake (Meenu et al., 2015; Prathibha et al., 2022), or Bellandur and Varthur Lakes as emblematic cases of lake degradation and governance failure (Baradwaj, 2014; Deepak et al., 2019; Singh, 2023; Sona and Priyadarshini, 2019). Although these lake-specific case studies often draw on multiple disciplinary and analytical perspectives, they remain geographically bounded. Their contribution lies in revealing the situated, path-dependent nature of lake degradation and restoration, grounding broader debates in specific socioecological contexts.
5. **Community-Oriented Research**: Another body of research focuses on responses led by civil society and community actors. These include local conservation efforts (Mandal and Manasi, 2021; 2025; Wirth, 2017), community stewardship of urban commons (Mundoli, Manjunath and Nagendra, 2014; Mundoli, Unnikrishnan and Nagendra, 2017; Sen, Dechamma and Nagendra, 2022), and the emergence of citizen collectives and advocacy networks (Baradwaj, 2014; Enqvist, 2015; Lakshmisha and Thiel, 2022; 2023). Here, lakes are analysed as socio-political spaces shaped by civic engagement, collective action, and contestation. The analytical focus shifts from diagnosing degradation to understanding how social mobilisation and institutional experimentation reshape possibilities for restoration and long-term sustainability.

Table 1. A Typology of Lake Research in the Bengaluru Region.

Type of research	Examples of research studies
Discipline focus	Historical or policy analyses, lake governance, or urban studies
Thematic focus	Water quality and pollutions studies, lake eutrophication, urban flood dynamics, biodiversity
Technological/digital interventions	Autonomous bots for lake monitoring and maintenance, and digital tools for monitoring and governance of lakes including Global Positioning System (GPS) mapping, and remote sensing
Lake-specific studies	Single or comparative case studies of lakes such as, Jakkur, Kaikondrahalli and Kasavanahalli, Hebbal, and Bellandur
Community approaches	Local, community-based conservation efforts, environmental stewardship and civic agency, community resilience and the urban commons

The typology of lake research associated with the Bengaluru region (Table 1) provides an overview of research that has been conducted on the drivers and pressures of lake degradation and the responses these have generated. While this classification reveals a rich and varied landscape of research activities, it also shows how problem definitions often remain compartmentalised within disciplinary, thematic, or case-specific boundaries. Many studies isolate specific pressures, such as pollution, encroachment, biodiversity loss, or water scarcity, without tracing how these pressures emerge from broader drivers or how these pressures interact with one another. Only a small number of studies, mostly confined to monographs or technical reports, adopt integrative perspectives that link ecological, infrastructural, and institutional dynamics (see for example, Baradwaj, 2014; Enqvist,

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2015; Grönwall, 2008; Luna, 2014; Raju et al., 2018; Ramachandra et al., 2015, 2016). As a result, the cumulative and recursive nature of degradation is rarely examined, and responses to pressures usually neglect the new pressures they may generate. What is needed, therefore, is not simply more research, but analytical approaches capable of recognising lakes as embedded socioecological systems shaped by feedback loops and cross-scale interactions.

The sections that follow begin to address this gap. Results 2 maps how key drivers and pressures co-occur across Bengaluru's lakes. Results 3 uses sewage treatment plants (STPs) as a focused illustration of how responses can generate unintended pressures. Finally, Results 4 compares national guidelines and locally developed restoration strategies to identify areas of alignment, divergence, and innovation.

4.2. Results 2: Interdependence of Drivers, Pressures, and Responses in Lake Degradation

Although research often examines lake degradation through single-issue lenses, such as pollution, encroachment, or governance lapses, our analysis shows that these issues seldom operate in isolation. Instead, they form interdependent systems, where multiple drivers give rise to pressures that interact with, and at times overwhelm, attempted responses. This section synthesises research findings to trace these recursive, system-level patterns in order to build a cumulative picture of interdependencies. It does not claim to exhaustively map every possible connection. Rather, our analysis identified four interdependent, primary drivers from the literature: climate change, urbanisation, expanding consumption, and governance failure. Each driver generates pressures that shape ecological decline and condition the effectiveness of restoration efforts.

Climate Change as a Structural Driver: While references to monsoon variability and changing hydrological regimes surface across multiple research studies, explicit treatment of climate change as a systemic driver remains limited. Hydrological fluctuations, such as more intense rainfall, longer dry spells, and shifting seasonal timings interact with already urbanised environments to produce heightened flood and drought risks. Bareuther, Klinge, and Buerkert (2020) and Santhanam and Majumdar (2022), for example, document how changes in rainfall patterns and built-up land reduce the buffering function of lakes. Without sufficient wetland margins or catchment connectivity, lakes struggle to regulate inflows, leading to either rapid overflow during storms or extended stagnation during dry periods. This is underlined by Bothra, Gowda, and Gowda (2025) who stress that once hydrological stability is compromised, even minor system stresses can cascade into major ecological failure. In this context, climate change is increasingly recognised as a primary driver of lake degradation. While its impacts have so far manifested mainly by amplifying pressures from urbanisation, consumption, and governance fragmentation, projected shifts in rainfall, temperature, and extreme events suggest that climate change will play a more direct and dominant role in shaping degradation pathways in the near future. Despite these risks, the Environmental Management and Policy Research Institute (2018) notes that lakes remain vulnerable due to a general lack of climate resilient infrastructure or forecasting tools.

Urbanisation as a Spatial-Hydrological Driver: Urbanisation remains one of the most widely documented drivers of lake degradation. As the City of Bengaluru expands, permeable surfaces are replaced by concrete, and catchment inflow channels are encroached upon, diverted, or blocked, leading to stormwater runoff increases in volume and speed. Vishwanath (2025) observes that "only about 30% of the lake area is fed by rainwater, while the rest is dominated by domestic sewage," a direct result of encroachment and upstream land conversion. Gopinath, Cu, and Me (2022) show how encroachments into lake beds and stormwater drains obstruct inflows, decreasing retention capacity, and turn lakes into shallow basins for sewage accumulation. These structural changes directly generate pressures such as eutrophication, algal blooms, and fish mortality, documented in numerous water quality and ecological assessments (Kumar, 2023; Sudarshan, Mahesh, and Ramachandra, 2020; Veenashree, Kumar and Nandini, 2022). Urbanisation, therefore, sets in motion multi-stage pressure chains: catchment conversion leads to inflow obstruction, which in turn leads to sewage dominance that creates the ecological collapse of a lake.

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Expanding Consumption as a Socio-Metabolic Driver: Complementing urbanisation is the rising consumption burden, both in terms of lifestyle-driven resource use and the basic service requirements of a rapidly growing population. Bengaluru adds approximately 500,000 new residents per year (World Population Review, 2025), intensifying demand for housing, water, sanitation, and waste systems. This growth translates into increased water extraction and wastewater generation, intensified solid waste discharge into stormwater drains, and heightened development pressure on lake catchments. Where sewage and waste infrastructure have not expanded at the same pace, residential developments channel untreated or partially treated waste into lakes (Chidanandaswamy, 2017; Gupta, 2025; Prasad et al., 2024). At the same time, private and community-led lake management frequently prioritises aesthetic enhancement, paved bunds, walking paths, or lighting, over ecological functioning (Bhushan, 2025; Deivanayagam, M and Varma, 2025; Lakshmisha and Thiel, 2023; Mundoli et al., 2014; Narain, Banerjee and Anand, 2014). As Derkzen and colleagues (2017) describe, many lakes have been transformed into "recreational landscapes" with diminished ecological resilience. Consumption, therefore, is a silent driver: diffuse, cumulative, and intertwined with infrastructural and governance constraints. It increases pressures not only within but well beyond urbanisation.

Government Failure as an Institutional Driver: Governance failures consistently appear across the dataset as enablers, amplifiers, and generators of pressures. For example, jurisdictional fragmentation creates unclear roles and weak accountability (Nath, 2021; Unnikrishnan et al., 2021), while policy enforcement remains uneven, and maintenance responsibilities are routinely transferred or neglected (B.PAC, 2021). In instances where fragmented planning and ineffective enforcement is the norm, both routine maintenance and long-term interventions are hampered (Bothra, Gowda and Gowda, 2025; B.PAC, 2021; Raj, 2013; Sundar Navamany, Narayan and Scholten, 2022). In this way, governance failure does not simply weaken existing responses, but operates as a structural driver that generates new pressures. When agencies lack coordination, enforcement mechanisms lapse, or maintenance responsibilities fall through bureaucratic cracks, even well-intentioned responses, such as infrastructure upgrades or pollution controls, can produce counterproductive outcomes. In these cases, responses fail to alleviate pressures and instead become new pressures themselves, such as leaking STPs, obstructive bunds, or poorly managed diversion channels. This leads to a compounding of physical, institutional, and ecological pressures across the lake system, reinforcing degradation rather than reversing them. Thus, governance is not merely a background condition but a systemic driver of degradation dynamics. The interconnections discussed thus far are visualised in Figure 2:

Figure 2 illustrates how, exploring our database of research articles together, lake degradation in the Bengaluru region is not the outcome of one or a small set of factors but rather the entangled effects of multiple drivers, interacting recursively to produce persistent degradation pathways. As illustrated in Figure 2, we identified four interconnected structural drivers—climate change, urbanisation, expanding consumption, and governance failure, which initiate distinct pressures on lake systems. Their interactions amplify stress on urban freshwater ecosystems in ways that are often cyclical and self-reinforcing. Urbanisation obstructs hydrological flows and increases pollution loads, consumption patterns intensify these burdens by generating more wastewater, solid waste, and land use conversion, while institutional fragmentation prevents coordinated mitigation, and climate change renders these systems more vulnerable to flooding, drought, and ecological collapse. Responses introduced to address any of these pressures, such as infrastructure upgrades or restoration programmes, are frequently misaligned with local conditions, poorly implemented, or insufficiently supported over time. For example, measures against droughts may lead to future flooding or they may be misaligned with urban planning associated with sprawl. When this occurs, well-meaning responses often generate new pressures, reinforcing rather than interrupting degradation. The result is a set of recursive driver-pressure-response (D-P-R) chains in which institutional, ecological, and infrastructural breakdowns become tightly interwoven, and interventions targeting individual pressures often become entangled with one another.

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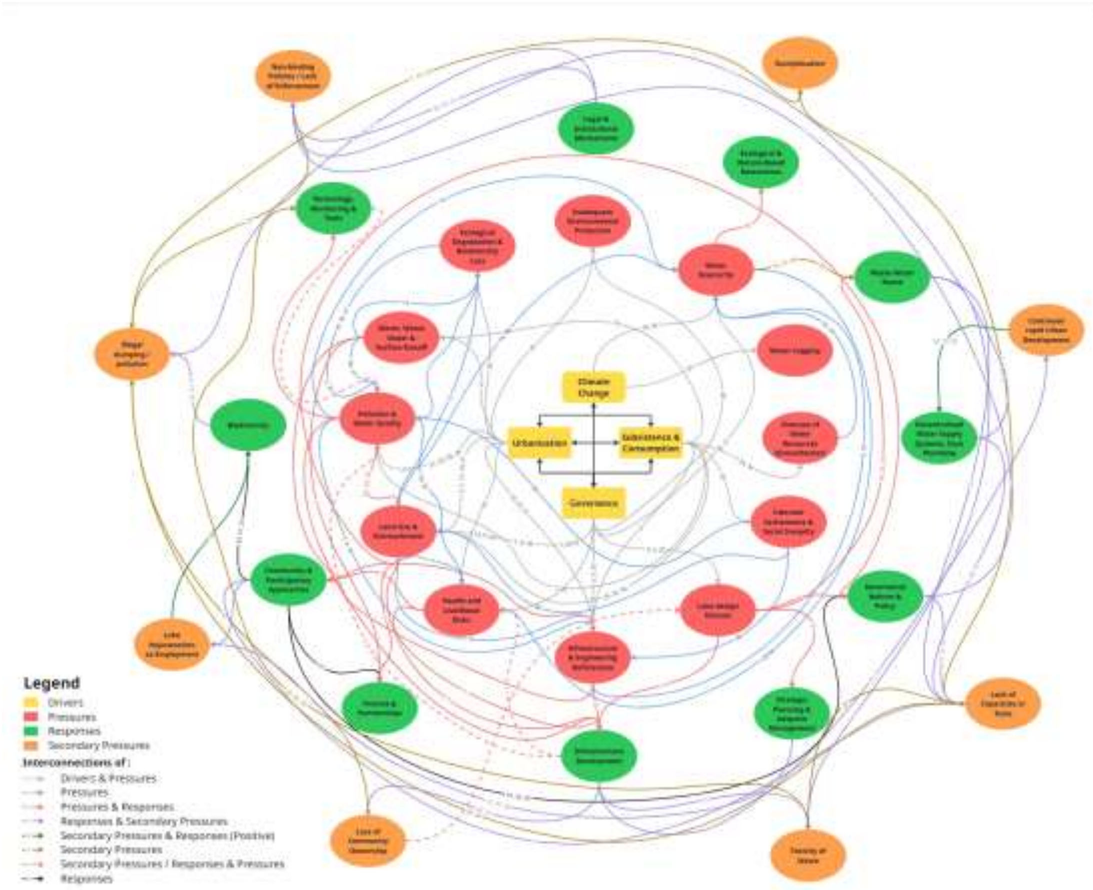

Figure 2. Conceptual network model of lake degradation, linking structural drivers (climate change, urbanisation, expanding consumption, governance failure) to associated pressures, responses, and consequences. Arrows indicate recurring D-P-R pathways, including responses that generate secondary pressures feeding back into the system.

These dynamics are not only visible at the level of the urban lake system as a whole but crystallise around specific interventions. To make this recursive logic more tangible, we turn to the specific example of sewage treatment plants (STPs), widely promoted as responses to urban lake pollution. As we will show, STPs also embody the contradictions and complexities of the broader lake revitalisation system. They emerge as responses but frequently evolve into pressures, revealing how even technically sound solutions can falter when embedded in fragmented, under-resourced, or misaligned contexts.

4.3. Results 3: Sewage Treatment Plants (STPs) as a Microcosm of Response-Induced Pressures

STPs are treated here not simply as a technical response to sewage inflows, but as an illustrative exemplar of a broader class of governance-sensitive interventions whose performance depends on context-sensitive implementation. Across the dataset, mandated infrastructure repeatedly produces divergent outcomes depending on the integrity of ownership transitions, the availability of operational expertise, the stability of maintenance and its financing, and the presence of monitoring and enforcement. Where some of these elements are absent, the response often becomes a secondary pressure. Where they align, the response can lead to positive and stable outcomes. This mechanism clarifies a central finding of our research: restoration outcomes are not properties of individual regulation or technologies, but of context-sensitive socio-technical delivery, and these fail or succeed in patterned ways that recur across Bengaluru's restoration programmes.

Central to Bengaluru's lake restoration strategies, STPs are mandated (Karnataka State Government regulation for Sewage Treatment Plants (STPs) issued in January 2016 (Notification No.

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FEE 316 EPC 2015), amended 3 April 2024) as a response to the chronic inflow of untreated sewage into lakes. Yet, across the dataset, STPs repeatedly emerge as double-edged interventions. While intended to improve water quality, they often generate new or contribute to other, known pressures. To illustrate these dynamics, we examine two contrasting cases.

Cascading Failures of Yelahanka (Prasad et al., 2024): Despite mandates requiring residential buildings to install decentralised STPs, implementation in Yelahanka has been uneven. Of the 325 decentralised STPs approved by the Karnataka State Pollution Control Board, only 174 had been built at the time of the study, and most were found to be underperforming or defunct (Prasad et al., 2024). Builders, acting under compliance pressure, often install minimal infrastructure with little regard for long-term operation. Ownership is then passed to Resident Welfare Associations (RWAs), who typically lack expertise, funds, or institutional support to ensure proper functioning. In some instances, security staff serve as untrained operators, maintenance is ad hoc, and water quality testing is rare or rudimentary. As a result, Prasad et al. (2024) found that approximately 60% of treated wastewater was being released into the surrounding stormwater system, ultimately affecting lake ecosystems, although legal frameworks prohibit discharge of treated water.

Cascading Successes of South City (Author case study): In contrast to Yelahanka, the South City residential complex demonstrates how decentralised STPs can become anchors of an effective restoration strategy, when infrastructure mandates are supported by capable ownership transitions, technical expertise, and integration into broader water systems. Although only part of the complex was built when the STP mandates came into force in 2007, residents later retrofitted and expanded infrastructure to treat 9 lakh (1 lakh is equal to 100 000) litres per day. The South City Maintenance Committee (SCMC) mapped existing assets, leveraged inhouse engineering expertise, and expanded the dual-piping system to supply treated wastewater for non-potable use to the entire complex. Complementary measures, such as rainwater harvesting, groundwater recharge, and low-cost water saving technologies further enhanced the system's efficiency. In 2015, this culminated in a Memorandum of Understanding with the Bruhat Bengaluru Mahanagara Palike (BBMP), allowing surplus treated wastewater to replenish nearby Puttenahalli Lake, thus demonstrating how decentralised STPs can support both household needs and lake restoration when effectively managed (see Figure 3, below).

Figure 3. Photographs taken during fieldwork in South City. The images illustrate key components of the local wastewater management system that supports both residential water reuse and lake restoration. **Left**: filtration and pumping infrastructure distributing treated wastewater for non-potable use within the residential complex or discharge toward the nearby lake. **Top right**: aeration tanks at the decentralised sewage treatment plant (STP),

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where wastewater undergoes biological treatment. **Bottom right**: Puttenahalli Lake, which periodically receives treated effluent from the South City STP, contributing to water level maintenance and ecological restoration.

Despite their different outcomes, both cases revolve around mandates for decentralised treatment, transfers of ownership from developers to residents, the presence or absence of technical expertise, commitments, and funds, and the challenges of connecting isolated systems to broader lake health. From this, insights emerge in relation to, first, a broader pattern across lake restoration efforts in Bengaluru, highlighted at a landscape level, that are also evident here at a micro level. A proliferation of fragmented responses that rarely scale or integrate into cohesive restoration strategies, and how responses fail not in isolation but in chains as technical, social, and institutional shortcomings cumulate. Second, the South City case reveals the potential of positive cascades. When infrastructure, governance, and community resources and commitments align, responses can support broader ecological functions. This shifts the focus from isolated technical fixes to the multidimensional conditions that enable success.

More generally, these two cases suggest that the central problem is often not the absence of technical solutions, but weak alignment between technical prescriptions and the governance arrangements required to operate, finance, monitor, and adapt them over time. This raises a broader policy question: To what extent do existing national restoration guidelines already recognise these enabling conditions and recurring failure modes? The next section addresses that question by comparing the Bengaluru database with the CPCB framework in order to identify where national guidance captures local realities, where it remains silent, and where local practice offers innovations that could strengthen regional and national policy.

4.4. Results 4: Comparing National and Local Strategies for Lake Restoration

Building on Results 2 and 3, this section examines whether the D-P-R dynamics identified in the Bengaluru-associated literature, and especially the governance and implementation conditions that determine whether responses succeed or become new pressures, are recognised in national restoration guidance. We compared the strategies proposed in the Bengaluru dataset with the Central Pollution Control Board's Guidelines for Restoration of Water Bodies (CPCB, 2019). Using the CPCB's five restoration phases—Recognition, Restoration, Protection, Improvement, and Sustenance—as a reference framework, we assessed the match between national guidance and the local socioecological realities identified across the preceding results. This comparison also shows which forms of local research mainly reproduce national technical prescriptions and which contribute additional governance, community, and planning insights. Our analysis revealed four patterns of correspondence between national recommendations and local insights:

1. Full alignment with CPCB guidelines
2. Partial overlap with local expansions
3. National-level responses missing in local research
4. Local innovations not reflected in CPCB guidelines

We summarised the results in Table 2 and provide associated illustrative examples. Rather than serving as a simple checklist comparison, our results indicate where national policy captures restoration actions, where local research adds enabling conditions for implementation, and where each level leaves important gaps.

Table 2. Comparison between CPCB Lake Revitalisation Guidelines and Local Strategies.

Phases	Recommendations
(i) Recognition Phase (Analyse problem and its effects)	• Historical analysis • Hydrological description • Geographical • Catchment
(ii) Restoration Phase	• "Designated Best Use"

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(Designate best use)	• Gap analysis • Water quality assessment by State/Union Territories (UTs)
(iii) Protection Phase (Long term action plan)	• Desk and reconnaissance • Identify associated issues • Preparation of Action Plans: o Sewage management o Management of waste o Deweeding o Stabilize bunds & drainage channels o Removal of encroachment o Industrial effluents management o De-siltation o Prohibit and penalise o Protection & restoration of drainage basins & channels o Flood control measures
(iv) Improvement Phase (of water body & uses)	• In situ remediation • Green/buffer zone • Monitoring action plans • Drainage basin management • Creation of biodiversity
(v) Sustenance Phase (post restoration of ecosystem)	• Post ecosystem treatment (Good governance, empower stakeholders, ownership, etc.) • Dissemination of information • Recreational centre • Awareness • Periodic training • Promoting public participation

Full Alignment Between CPCB and Local Strategies: Marked in green in Table 2, this category includes cases where local lake restoration strategies align closely with CPCB guidelines. Three of the five CPCB phases are fully reflected in local research, and only three of the remaining eleven CPCB guidelines in Phases two and four lack a clear local counterpart. This overlap suggests shared views on key restoration responses to many environmental pressures. For example, both the CPCB and local researchers call for mapping pollution sources and conducting public awareness campaigns:

CPCB: "*All the possible sources of pollution should be identified which may* [include] *…encroachment of waterbodies due to urbanization.*" (CPCB, 2019, pp. 12, 14)

Local: "*…identify activities for developmental works. They should prioritise collection of data based on … encroachments and other illegal activities in the lake premises.*" (Subbarao, 2024, p. 7)

CPCB: "*Awareness for … protection of the water bodies should be organized periodically … through campaigns, electronic media in vernacular languages.*" (CPCB, 2019, p. 38)

Local: "*A specific awareness programme should be initiated to educate publics and resource users to protect waterbirds [from] threats due to lake encroachment/habitat loss … and other pollution causing factors* i.e., *filling up of lake outer edges with scrap materials, domestic solid wastes, garbage and polythene bags or polyvinyl plastics, hardened cement bags and destroyed house materials.*" (Rajashekara and Venkatesha, 2014, p. 76)

These overlaps reflect a broad consensus between national and local strategies around basic technical responses and citizen engagement that function as the basic building blocks to lake restoration. What aligns most here are responses to identifiable pressures. By contrast, the recursive and governance-dependent dynamics highlighted in Results 2 and 3 remain underspecified.

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Partial Overlap with Local Expansion: In many instances, local strategies not only mirror national recommendations but go beyond them, particularly in addressing context-specific pressures and constraints, such as institutional fragmentation and chronic underfunding. Here, the challenge of fragmented governance is a dominant theme (see, for example, Anand et al., 2024; Apoorva, Srinivasan and Ramachandran, 2020; Bothra, Gowda and Gowda, 2025; Enqvist and Ziervogel, 2021; Khambete, 2016; Lakshmisha and Nagendra, 2025; Mandal and Manasi, 2025; Nath, 2021; Ragavan et al., 2024; Raju et al., 2018). While the CPCB recommends regular water quality monitoring at least eight times per year, local researchers highlight that fragmented governance and weak institutional coordination often obstruct even routine environmental management. In this sense, research shows that institutional fragmentation in Bengaluru's water and environmental governance produces inefficiencies and weak coordination, often resulting in overlapping mandates and duplicated regulations. Departments and agencies operate with limited capacity to develop or sustain long-term environmental strategies, which in turn undermines consistent commitment to sustainability goals. At the same time, local bodies and development authorities face chronic shortages of stable and predictable resources. Many important institutions, including the Lake Development Authority (LDA), remain understaffed and underfinanced, creating structural imbalances within the governance network, constraining effective environmental management (Raju et al., 2018, pp. 102-103). To respond to this, local researchers propose one of three structural governance reforms, which fall outside of the CPCB's technical action-plan model:

> Institutional Reform: "*A serious recalibration of institutional processes and structures is necessary to address underlying fragmentation of urban and urban governance, to create more holistic governance and institutional arrangements for the future.*" (Ragavan et al., 2024, p. 66)
>
> A Single Statutory Body: "*The need for good governance systems in place with a single agency with statutory and financial autonomy to act as the custodian of lakes for maintenance and action against polluters.*" (Khambete, 2016, p. 3)
>
> Or, Multistakeholder Councils: "*The involvement and collaboration of various stakeholders, specifically government agencies, environmental organizations, local communities, and citizens, are essential for addressing complex challenges and achieving meaningful outcomes. A collective understanding of the value and significance of Bengaluru's lakes can be fostered through stakeholder engagement. This shared awareness can lead to coordinated efforts and the allocation of resources for lake conservation initiatives.*" (Mandal and Manasi, 2025, p. 278)

Local research extends CPCB guidance where Bengaluru's restoration efforts most often falter, specifically in relation to coordination across institutions, stable financing, accountability, and long-term stewardship. In other words, local studies contribute not just additional responses, but the enabling conditions that determine whether responses interrupt degradation or become secondary pressures.

National-level Responses Missing in Local Research: Three national guidelines were not reflected in the local dataset, highlighting possible gaps in research or adequate empirical evidence. These include:

- Designated Best Use (DBU): The CPCB calls for identifying the DBU for each water body and aligning restoration efforts with the specific DBU water quality standards provided in Annexure I (CPCB, 2019, pp. 8, 41). Local studies typically assess water quality but do not adopt a consistent benchmarking framework.
- Long-term Gap Analysis: The CPCB recommends anticipating infrastructure needs over 15 to 20 years relative to urbanisation and population growth projections; local studies tend to focus on present-day pressures and constraints, often shaped by immediate urban growth.
- Monitoring Committees: The CPCB advocates formal institutional monitoring mechanisms. In contrast, local initiatives rely more on decentralised, community-driven models.

While the absence of these elements in the local dataset may reflect practical constraints rather than conceptual neglect, their omission helps explain why much local work remains focused on

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immediate pressures rather than longer causal chains. Designated benchmarks, forward-looking gap analyses, and formal monitoring could strengthen the evaluation, monitoring, and longitudinal research dimensions that are necessary to prevent repeated implementation failure.

Local Innovations not Reflected in CPCB Guidelines: While Bengaluru's lake restoration responses largely align with national guidelines (CPCB, 2019), the final category highlights strategic innovations from local research that go beyond the CPCB framework. Two key contributions stand out:

Framing Lakes as Socioecological Systems: Some of the most effective local restoration strategies explicitly recognise lakes as interdependent ecological, social, and economic systems, not just physical sites of pollution. This wider ecosystem approach, sometimes referred to locally as the "holy grail of conservation", enables more participatory and durable interventions:

> *"Water conservation expert Vishwanath Srikantaiah identifies a tripartite holy grail of conservation: the harmonization of ecological, social, and economic considerations … Notably, the citizen-driven collective known as Jala Poshan has been instrumental in fostering collaboration among stakeholders, orchestrating the activities of fishermen, greenkeepers, and laborers, entwining ecological ramifications with economic sustenance. The lake also emerges as a social nexus, drawing together diverse individuals to envision enhancements"* (Sharma, 2023, p. 1)

Embedding Restoration in Urban Planning: In contrast to the CPCB's action plan model, which focuses on lake-level planning and monitoring, local researchers propose integrating lake restoration into land use, transport, and infrastructure planning (Drangert and Sharatchandra, 2017; Garikaparthi, 2021; Khambete, 2016; Mundoli, Unnikrishnan and Nagendra, 2017; Ragavan et al., 2024; Siva et al., 2019):

> *"A foundational principle while making water sensitive plans is the integration of water and urban planning. Currently urban land use, economic development, transport planning, and water planning are usually parallel processes … Water planning must include blue, green, grey and black waters in the urban settlement since governance of these types of water is intrinsically linked to urban land management."* (Ragavan et al., 2024, p. 64)

> *"A comprehensive urban-level lake-restoration plan incorporating technological(autonomous) and bio-inspired solutions need to be formulated to save the dying lakes of Bangalore City."* (Siva et al., 2019, p. 134)

These innovations directly address the limitations identified in the preceding results. Framing lakes as socioecological systems and embedding restoration in wider urban planning shifts restoration away from isolated site-level interventions toward cross-scalar governance capable of managing the dynamics mapped in Results 2 and illustrated through STPs in Result 3. Seen in relation to Result 1, these innovations also emerge mainly from the more integrative, community-oriented, and governance-sensitive strands of the literature rather than from narrowly technical studies.

Taken together, the comparison shows that CPCB guidance captures much of the technical components of restoration, but only partially addresses the governance, financing, community stewardship, and spatial-planning conditions that shape implementation in Bengaluru. Local research is strongest precisely where Results 2 and 3 locate recurrent failure modes: coordination across agencies, long-term operation and maintenance, and integration with broader socio-urban systems. The contribution of local knowledge is therefore not to contradict national policy, but to specify the socioecological and institutional conditions under which national prescriptions can work better in practice.

5. Discussion and Conclusions

Result 1 shows a fragmented research field organised around discrete problems, methods, and case sites. Result 2 reconstructs how those apparently separate issues combine into recursive D-P-R chains. Result 3 demonstrates, through the example of STPs, that restoration outcomes depend less on technical design alone than on the governance arrangements through which responses are

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implemented, financed, monitored, and adapted. Result 4 then shows that national guidance and local practice are not in conflict, but operate at different levels: CPCB guidance codifies core technical actions, while local research contributes context-specific knowledge about implementation conditions, institutional bottlenecks, and socioecological integration.

The recursive D-P-R chains traced in this study illustrate that neither degradation nor restoration proceed linearly. Lake trajectories emerge from the entangled interaction of multiple drivers, pressures, and responses that accumulate over time. Urbanisation, expanding consumption, governance fragmentation, and climate variability reinforce one another, producing persistent degradation pathways that resist isolated intervention. In this context, solutions travel poorly. Technical fixes that appear effective in one setting may generate new pressures elsewhere, particularly where institutional capacity, accountability, or ecological integration is weak. As a result, responses often do not merely fail but become secondary pressures themselves, reinforcing rather than interrupting degradation.

These findings caution against technocratic solutionism. While technologies matter across the lake restoration process, they are embedded in historical and institutional imaginaries that continue to privilege visible, large-scale infrastructure and short-term problem solving over long-term coordination, distributive equity, and everyday management. Our synthesis shows that lake restoration efforts frequently reproduce exclusionary outcomes, for example, when ecological "improvement" simultaneously drives land conversion, rising real estate pressures, and the marginalisation of lake-dependent livelihoods. In this sense, lake cleaning can become self-defeating in that ecological success under prevailing governance conditions may accelerate precisely the social and spatial dynamics that undermine long-term sustainability. Managed well, Bengaluru's lakes can buffer floods, cycle treated wastewater, sustain biodiversity, supplement groundwater recharge, and provide critical water security at the urban periphery where pipe networks are unlikely to reach and where lakes may remain the primary source of water. Realising this potential requires lake governance to move beyond narrow project-based logics toward integrated hydrological, institutional, and socio-political systems thinking, a shift for which current institutional architectures remain poorly equipped. Our findings suggest that effective restoration of urban water bodies therefore requires policy frameworks that integrate ecological restoration, institutional coordination, and community stewardship moving beyond purely technical interventions.

This has implications for research. Our typology reveals a field dominated by micro-problem framings, where scholars isolate individual pressures or showcase local initiatives but rarely trace how drivers, pressures, and responses accumulate. This raises a broader challenge for the field: transforming lake research from a collection of diagnostic silos into a shared knowledge base capable of informing coordinated restoration and governance efforts. Addressing sustainability challenges increasingly requires closer cooperation and intellectual exchange between the social and natural sciences, and greater attention to how their different approaches can be brought into productive dialogue. This imperative is particularly acute in urban lake contexts, where ecological degradation and institutional fragmentation are tightly coupled. Based on our synthesis, three priorities stand out. First, research must foreground politics and power, not only pollution and hydrology, by systematically engaging with questions of land control, class, caste, gender, and institutional authority. Second, case-based research should evolve holistic, lake-attached analytical tools that connect ecological function, governance capacity, livelihoods, and distributional effects. Case studies should expand beyond single issues, presenting approaches that connect ecological function, institutional capacity, livelihoods, and distributional effects in ways that support the translation of knowhow and best practices between and across lakes. Third, restoration must be understood as a long-term socio-technical, political, and economic process. Given that lakes are likely to remain polluted for decades, research should resist becoming an implicit partner in extractive "lake revitalisation" industries and instead support empirically grounded, context-specific governance learning.

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From a policy perspective, the CPCB comparison suggests that the central deficit is not the absence of restoration guidance, but the incomplete translation of guidance into governance architectures able to carry effective interventions through time. National frameworks provide standards, categories, and technical scaffolding while local research reveals the need to add coordination mechanisms, stable financing, community stewardship, land-use integration, and adaptive learning. A stronger restoration model would therefore combine national benchmarking and long-horizon planning with locally grounded socioecological design and institutional experimentation. These insights are relevant not only for Bengaluru but also for rapidly urbanising regions worldwide where lakes and other urban water bodies are being repositioned as key components of climate adaptation, water security, and urban resilience strategies.

In conclusion, Bengaluru's lake crisis is less a shortage of restoration techniques than a problem of governing recursive socioecological chains. Lakes deteriorate (or remain deteriorated) when drivers, pressures, and responses are treated separately. They recover when technical measures are embedded in durable arrangements for coordination, financing, monitoring, and social legitimacy. The broader implication is that effective restoration requires moving beyond project-based remediation toward institutions capable of linking lake-scale technical interventions with catchment processes, urban development, and long-term stewardship.

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Abbreviations

The following abbreviations are used in this manuscript:

CCA	Content Configuration Analysis
STP	Sewage Treatment Plants
D-P-R	Driver-Pressure-Response
CPCB	Central Pollution Control Board
IT	Information Technology
FBL	Federation of Bengaluru Lakes
NGO	Non-Governmental Organisations
DPSIR	Driver-Pressure-State-Impact-Response
GPS	Global Positioning System
ML	Machine Learning
BLIS	Bangalore Lake Information System
RWA	Resident Welfare Association
TDS	Total Dissolved Solids

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WLV	World Lake Vision
UT	Union Territory
LDA	Lake Development Authority
DBU	Designated Best Use

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