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Review

Shifting paradigms: towards dynamic approaches to sustain Anthropocene lake ecosystems

Ke Zhang [a,*], Lindsey Gillson [b,c], Yuan Jin [a], Suzanne McGowan [d,e], Jemma Finch [f,g], Zhengwen Liu [a], Yaoyao Han [h], Ji Shen [i], Michael E. Meadows [i,j], David Taylor [k]

[a] Key Laboratory of Lake and Watershed Science for Water Security, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 211135, China
[b] Leverhulme Centre for Anthropocene Biodiversity, Department of Biology, University of York, York YO10 5DD, UK
[c] Plant Conservation Unit, University of Cape Town, Rondebosch 7701, South Africa
[d] Department of Aquatic Ecology, Netherlands Institute of Ecology, Droevendaalsesteeg 10, Wageningen 6708PB, the Netherlands
[e] Departments of Biology and Physical Geography, University of Utrecht, Postbus 80125, 3508 TC Utrecht, the Netherlands
[f] School of Agricultural, Earth and Environmental Science, University of KwaZulu-Natal, Durban 4041, South Africa
[g] South African Environmental Observation Network (SAEON), Grasslands, Forests, Wetlands Node, Montrose 3201, South Africa
[h] School of Emergency Management, Henan Polytechnic University, Jiaozuo 454003, China
[i] School of Geography and Ocean Science, Nanjing University, Nanjing 210023, China
[j] Department of Environmental & Geographical Science, University of Cape Town, Rondebosch 7701, South Africa
[k] Department of Geography, National University of Singapore, Kent Ridge 119077, Singapore

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ABSTRACT

Protecting, managing, and restoring freshwater ecosystems in the Anthropocene is essential to tackling the triple planetary crises of biodiversity loss, pollution, and climate change. However, conventional restoration frameworks often struggle to account for the rapid and nonlinear dynamics that characterize ecological transitions today. In this review, we synthesize emerging insights from freshwater restoration research and propose a novel bivariate framework that integrates both the rate and magnitude of change from a long-term, evolutionary perspective. By examining multidecadal to centennial trajectories and dynamics using paleoenvironmental records, our framework offers a more nuanced classification of ecosystem status along a degradation continuum. Specifically, we categorize four ecosystem types based on their state (from minimally disturbed to highly degraded) and their rate of change (from slow to fast). Each type is associated with distinct system dynamics, restoration potentials, and strategic considerations. To demonstrate practical utility, we apply the framework to a representative Anthropocene lake undergoing severe ecological degradation. While centered on freshwater systems, the framework offers broader relevance for understanding and guiding restoration in other ecosystem types. We conclude by identifying key knowledge gaps and future research directions needed to enhance ecosystem resilience and inform adaptive management in a rapidly changing world.

1. Introduction

As the world crosses the halfway point toward the 2030 deadline for the Sustainable Development Goals (SDGs), recent assessments reveal that many targets related to freshwater ecosystems are either making limited progress or continuing to deteriorate [1]. The degradation of freshwater ecosystems, especially lakes, poses significant challenges in the Anthropocene [2]. Nearly 965 million people live within a 3 km radius of a lake, accounting for more than 12% of the global population [3]. Maintaining high-quality freshwater is not only core to SDG6 (Clean Water for Sanitation for All), but also contributes towards other SDGs, such as SDG15 (Life on Land) and SDG12 (Sustainable Consumption and Production). Bold commitments and initiatives that promote freshwater ecosystem restoration and conservation have been made globally [4], including the first-ever UN resolution specifically relating to lakes in March 2022 (UNEP, 2022) (Fig. 1). Despite these efforts, many restoration initiatives have had mixed success [5]. For instance, more than half of European freshwater bodies still do not meet the criteria for Good Ecological Status set by the Water Framework Directive (WFD, 2000) [6,7]. This alarming trend underscores the necessity for radical thinking and a paradigm shift to accelerate progress.

* Corresponding author.
E-mail address: kzhang@niglas.ac.cn (K. Zhang).

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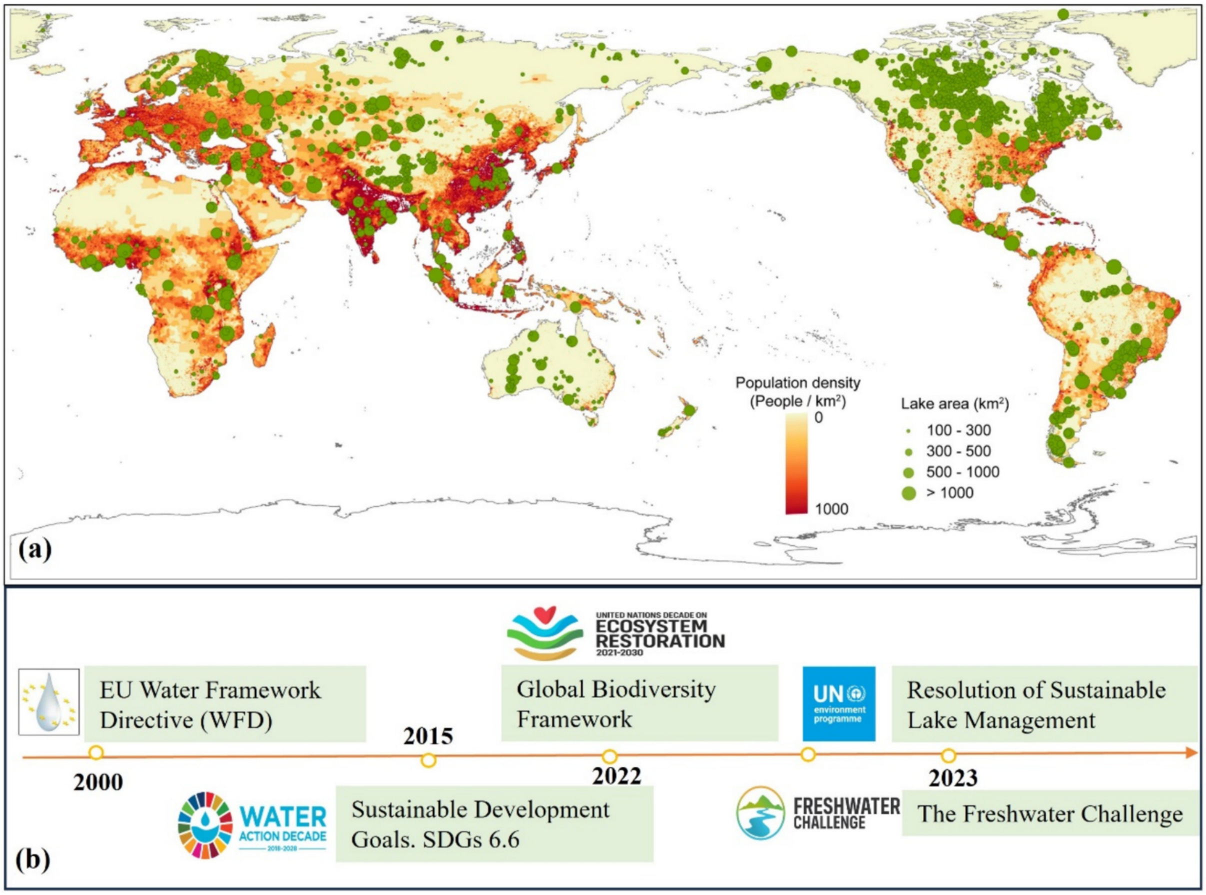

Fig. 1. (a) Global distribution of lakes (> 100 km^2) overlaid with population density, indicating the proportion of lakes located within highly populated areas [8,9]; (b) timeline of key global initiatives for freshwater ecosystem restoration and sustainability since 2000.

Managers of freshwater ecosystems are faced with making decisions about how best to restore or manage systems in various states of alteration. Various theories and frameworks have been developed to underpin ecosystem restoration efforts. These range from static approaches that aim to maintain ecosystems in idealized, less disturbed states [10,11], to more dynamic approaches that aim to accommodate ecosystem dynamics, resilience, and alternative stable states [12,13]. Current restoration theories and frameworks, such as Nature Based Solutions [14,15], rewilding [16], or transformation management [17], typically accept that ecosystems are dynamic rather than static. However, available toolkits remain unsuited to the task, in part because they apply linear logic and trend extrapolation, and assume nature is reactive and insensitive to multiple time horizons [18]. Restoration may be an important foundation for conservation efforts, yet many of the latter lack clear guidance on setting appropriate restoration targets and strategies based on sound scientific evidence [19], leading to widespread confusion about objectives and desirable outcomes [4,20].

The Anthropocene is characterized by rapid and unprecedented rates of change [21], and the Earth system is evidently transitioning to unknown futures with no historical analogue. Within this context, the dynamic and transient nature of ecosystems demands a paradigm shift towards more adaptive and holistic restoration frameworks [22,23]. One of the key limitations of current frameworks is their sole focus on state variables (e.g., threshold/tipping point, or how far degraded from reference condition), while neglecting underlying dynamics (i.e., the rate of degradation, or how fast they are changing) [24]. This state-only focus of current evaluation approaches fails to capture the transitional characteristic of many Anthropocene freshwater ecosystems, leading to widespread confusion and uncertainty about the current status of targeted ecosystems [25]. There are increasing calls to shift focus from a state-targeted to a rate-targeted approach to confront the Anthropocene challenge [26,27]. However, these concepts remain largely theoretical, and current restoration principles seldom prioritize the rate of change as a central issue and objective of management. Incorporating the rate of change allows for a transition from abstract, conceptual discussions of Anthropocene dynamics to concrete, action-oriented insights, thereby informing and supporting future decision-making for stakeholders.

Here we develop a novel bivariate framework for freshwater ecosystem restoration that integrates both state and underlying dynamics (rate of change) considerations from a historical perspective. By assessing the long-term trajectory and dynamics of lake ecosystems, our framework aims to provide a more comprehensive understanding of their past, present, and future dynamics, thereby guiding more effective restoration and management strategies. We illustrate the application of this framework using Taihu Lake as a detailed case study of a highly degraded system, with additional examples of other lake types provided in the Supplementary material, following which we consider research recommendations for sustaining lakes into an uncertain future. A key aspect of this work is differentiating distinct phases of ecosystem status across a degradation continuum, each characterized by unique system dynamics and potential management objectives and strategies.

2. Revisiting current restoration frameworks: challenges and opportunities

Traditional approaches to ecosystem restoration have historically focused on restoring ecosystems to less disturbed or "historical" baseline conditions [10,28,29]. Increasingly, these static and baseline-based approaches have been criticized for subjectivity in determining restoration goals, inapplicability to dynamic ecosystems, and their apparent inability to restore certain irreversible losses [30–32]. In response, there has been a shift towards more process-oriented approaches that acknowledge ecosystems as non-stationary systems with potential tipping points and alternative states [32,33]. Others argue for more flexible and site-specific approaches to managing and restoring targeted ecosystems, such as the resist-accept-direct (RAD) framework [34,35], and the resistance-resilience-transformation (RRT) framework [36]. These approaches accommodate the possibility that a return to former conditions may not be possible and that directing novel states towards more desirable biodiversity and ecosystem service outcomes may be more realistic (Table 1). Despite these advances, translation into practical restoration strategies remains a challenge [11]. Policymakers and managers often lack clear guidance on whether to resist change and restore past ranges of variability or direct change and guide the emergence of novel ecological conditions [37,38]. Such a conundrum is expected to be exacerbated by future climate change.

This problem is further exacerbated by the lack of long-term preindustrial reference data that span beyond the onset of intensive human activities [33]. Ecosystems undergo continuous evolution from the past through the present into the future (Fig. 2). It is increasingly recognized that current ecosystem transitions are embedded within longer-term dynamics, spanning from multi-decadal to centennial scales [13]. In the absence of sufficient empirical evidence for these temporal dynamics, critical issues such as the timing of abrupt transitions, the underlying characteristics of transient behaviours, and the identification of potential driving factors remain inadequately addressed [39]. A comprehensive understanding of the mechanisms through which pathways of persistence, adaptation, or transformation emerge and evolve is crucially required. Disregarding this temporal variability by solely considering snapshots can lead to inaccurate impact quantifications, a phenomenon also associated with the shifting baseline syndrome, whereby perceptions of ideal reference conditions differ inter-generationally as ecosystems change [40]. Many restoration projects are guided by short-term baselines rooted in the most recent past, perhaps only a few decades at most, which therefore may be premised on fundamentally flawed assumptions and fail to capture the full range of ecosystem dynamics and the extent of human influence [13]. The paucity of multi-decadal records represents a significant information gap that hampers the development of realistic restoration strategies or targets in the Anthropocene context [28].

Paleolimnological records offer a valuable tool for extending the temporal perspective of restoration efforts by providing longer-term, continuous, and high-resolution data on ecosystem changes [41]. These records, derived from lake or wetland sediment cores, enable researchers to reconstruct past environmental conditions and identify historical trajectories of ecosystems over centuries to millennia [42,43]. They provide comprehensive data on indicator species, community composition, diversity, and ecosystem structure and function, including the provision of ecosystem services [42,44], together with independent biophysical data from complementary geochemical studies. Lakes, from around the world and in a variety of contexts, represent valuable sedimentary archives. Moreover, new molecular methods are rapidly emerging, including ancient sedimentary DNA-based approaches and palaeoproteomics [45], to assess past biodiversity dynamics. Paleoecological databases, such as the Neotoma Paleoecology Database [46],

Table 1
Summaries of key theories and frameworks underpin current global ecosystem restoration.

Concepts and framework	Key purpose	Underlying assumption	Targeted indicators	Approaches	Examples/Key reference
Historical baseline/ reference condition, historical range of variability	Restore/maintain to a historical (pre-disturbance) ecological state	Ecosystem change is linear and stationary, reversible	Focus on single state variable, calculate baseline/reference value, such as percentage of change, magnitude of change	Paleo-records, survey and monitor (space for time approaches), expertise knowledge, documentary	European Water Framework Directive [6,7]; US Clean Water Act [29]
Novel ecosystem, Anthropocene baseline	Accept the non-historical configuration or novel ecosystem for restoration	Ecosystem can shift to alternative stable state when crossing tipping point/threshold; with irreversible change	State variable, quantify threshold value, early warning signals, or define threshold of potential concern	Long-term data, identify regime shift, expertise knowledge	Australia Murray-Darling Basin Authority [13,30]
Rewild, Nature based solutions	Maintain ecosystem process and structure, function, integrity, and ecosystem services	Ecosystems is complex adaptive system, enhance heterogeneity, modularity, biodiversity to cope future changes	Structure or function indicators, such as connectivity, similarity, modularity	Maintain ecosystem process and structure, function, integrity, and ecosystem services	Perino et al., [16]; Seddon et al., [14]
Resist-Adapt-Redirect (RAD), Resistance-Resilience-Transformation (RRT)	Provide flexible choices to resist, adapt or redirect changes for managers; Categorized conservation adaptation actions on a change continuum ranging from resistance to transformation	Ecosystem restoration needs diverse strategies based on ecosystem dynamics along its trajectories and society needs	Both state variable, and dynamic variables, for instance, rate of change	Indigenous knowledge, long-term data, expertise knowledge; define six categories of the RRT scale based on project primary objective	The Upper Mississippi River Basin [35]; Peterson et al., [36]; Williams et al., [50]
Transition management, Future management	Facilitate and accelerate transitions through participatory process of visioning, learning and experimenting	Ecosystem degradation is a dynamic, multidimensional, multi-actor and multi-level problem that is in a constant state of flux	Alternative regime indicator, type of transient indicators, length of transient	Long-term monitor data, mechanistic models of intermediate complexity	Francis et al., [17]; Gleick et al., [23]

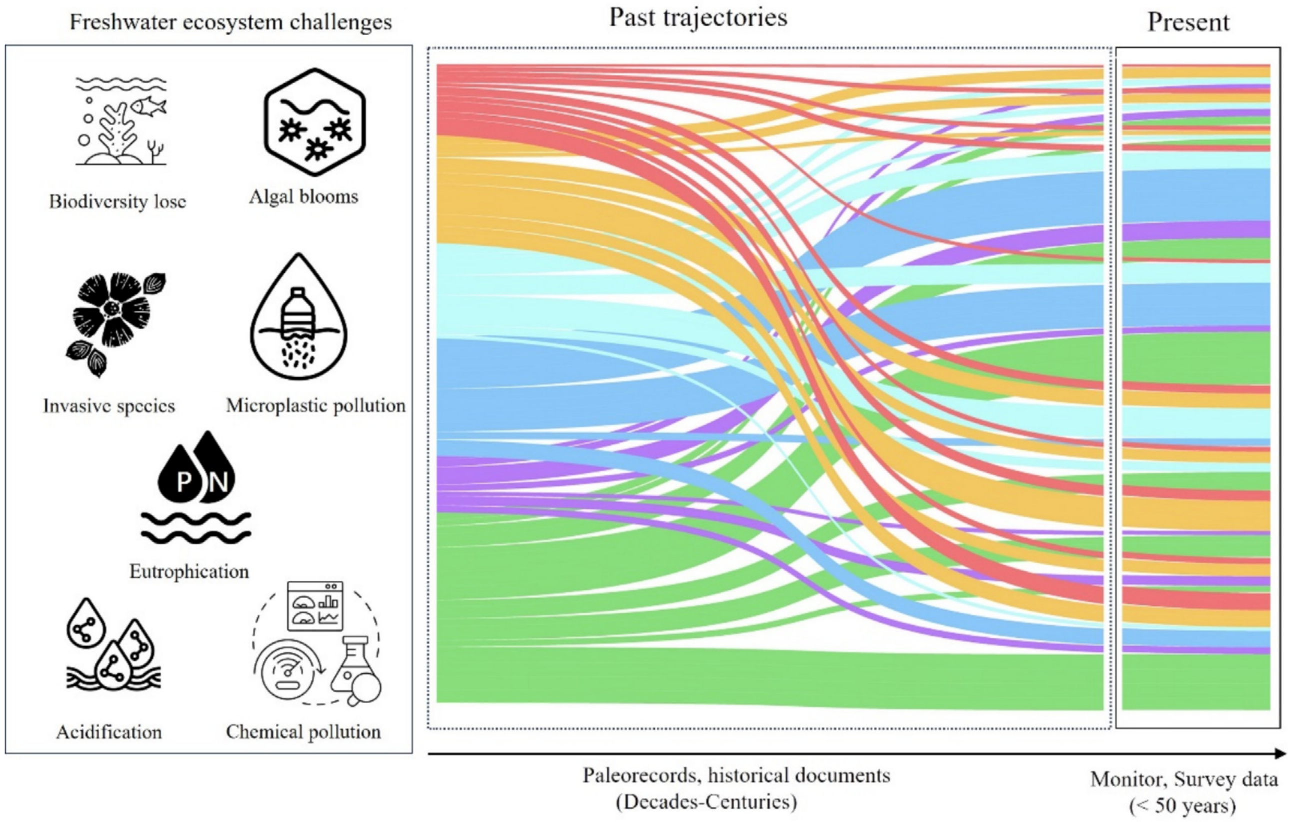

Fig. 2. Schematic diagram illustrating the challenge of assessing current ecosystem status and developing restoration strategies without a comprehensive understanding of long-term trajectories (e.g., accelerating, decelerating, stable, fluctuating, linear decline/increase). The different trajectories over time are shown in the central panel, derived from paleo-records and historical data, which contrast with the more limited scope of snapshot data from monitoring or surveys (< 50 years) on the right. The freshwater ecosystem challenges on the far left (e.g., biodiversity loss, eutrophication, microplastic pollution) highlight key stressors, but the color bands in the trajectories do not correspond to specific challenges, instead representing general trends in ecosystem change.

which standardize proxy-based datasets and important associated data such as chronologies, improve accessibility to a wide range of users and offer valuable information for restoration. Despite their potential, paleolimnological records are so far primarily used to define baseline or historical ranges of variability [47] and so their deployment has remained largely within the framework of static, baseline-based conservation approaches. However, paleolimnological records also provide crucial information about long-term dynamics, such as rates of change, tipping points, early warning signals, and novel ecosystem states that have been largely untapped within the restoration/management framework [48].

3. Novel framework: integrating rate and state of change

Our proposed novel bivariate framework integrates both the rate and magnitude of change, viewed through a historical lens, to guide freshwater restoration efforts. By evaluating (1) the current state of the ecosystem and (2) the rate of change along long-term trajectories, we aim to provide a comprehensive classification of lake ecosystem status from an Anthropocene perspective, focusing on the last 100–200 years. This timeframe captures the most intensive period of human-driven transformations in the Anthropocene and provides consistency across sites and ensures comparability while remaining meaningful for management applications. We distinguish four discrete types of lake status dynamics based on their state (from minimally disturbed to highly degraded) and the rate of change (from slow to fast) (Fig. 3):

Type I: These lake ecosystems exhibit relatively stable and less disturbed conditions (ecological state is good/acceptable), characterized by state variables fluctuating within their historical range of variability. The rate of change is small and remains close to the long-term equilibrium.

Type II: Lake ecosystems in this category display a discernible trend of increasing divergence from the initial state, with variables progressively shifting away from their historical range of variability. The rate of change increases gradually compared to the historical mean average.

Type III: Lakes categorized as Type III demonstrate significant deviations from their long-term baseline conditions, with a potential crossing of thresholds. Type III can be further divided into two subtypes: Type IIIa (fast transition), where lakes exhibit degradation at an accelerating rate of change; and Type IIIb (slow transition), where the decline in state variables shows an increasing trend, albeit with a slower rate of change compared to Type IIIa (Fig. S1 online). These long, smooth transitions between equilibrium states are easy to miss, ignore, or deny, confounding management and governance.

Type IV: Ecosystems classified as Type IV are already highly degraded, with minimal observable change in state variables. These systems display high resistance or inertia and are likely locked into a new stable or equilibrium state, having already crossed a critical threshold or tipping point. They are characterized by stability (slow/no rate of change), and highly altered structure, composition, and functions.

Our framework is underpinned by generic system dynamics behaviours, such as the differentiation between fast and slow rates of change and the magnitude of change. It acknowledges the inadequacy of short-term or snapshot information in capturing

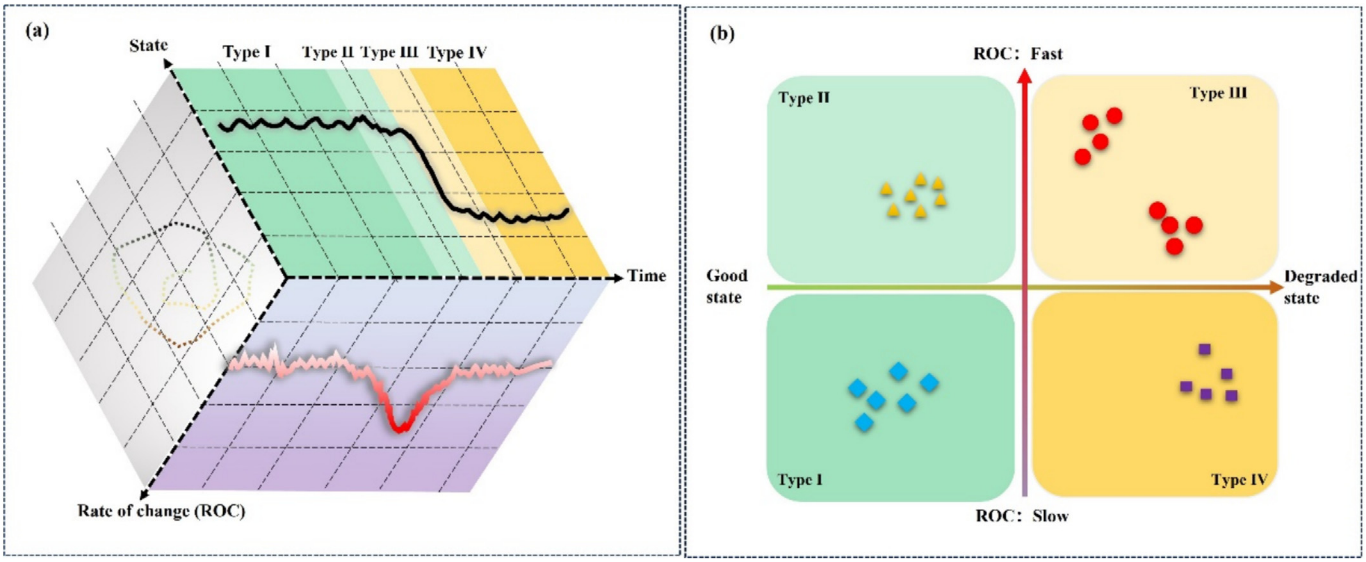

Fig. 3. Conceptual framework for classifying lake ecosystem dynamics. (a) Schematic illustration of ecosystem state trajectories relative to the rate of change over time. Different colors represent contrasting dynamic regimes (e.g., stable, accelerating, or declining states). Solid black and pink lines show example trajectories of ecosystem variables through time, while the red-highlighted section indicates a rapid transition event. The dotted curves represent underlying stability landscapes, illustrating how ecosystems may shift between alternative states. (b) Bivariate classification of ecosystems into four types based on their ecological state (horizontal axis, from minimally disturbed to highly degraded) and rate of change (vertical axis, from slow to fast). Type I: low rate of change, minimally disturbed state; Type II: increasing rate of change, relatively less disturbed state; Type III: high rate of change and significantly degraded state; Type IV: low rate of change, highly degraded state.

long-term ecosystem behaviour, emphasizing the importance of considering the past-present-future continuum and the rate of change. Importantly, the framework does not presuppose a linear progression through each type; for instance, Type I lakes may transition directly to Type III through rapid transitions.

4. Proposed management strategies within an evolutionary framework

Following the classification of a lake into a particular category within the evolutionary framework, different strategies can be employed towards restoration. Each typology has unique characteristics and requires distinct restoration strategies and approaches. Understanding the dynamic and transient nature of these lake ecosystems shifts expectations about management strategies and their impacts [49]. In addition, managers need to consider whether a return to a former state is possible or desirable, and, if not, how ecosystem functionality and services could be optimized. This new framework is considered alongside feasibility, likely future states, and stakeholder needs, and can also generate practical and scientific information to further enhance other restoration frameworks (Fig. 4). For example, the RAD framework helps managers to decide whether to attempt to stop (resist) transitions, direct them to more desirable states or accept novel states [50].

4.1. For Type I and Type II lakes (lakes that are currently less disturbed)

Traditional approaches can be adopted to maintain or restore historical conditions and services, using time series information to capture the historic range of variability over the past two to three centuries (depending on the history of the landscape). Type I lakes require prioritization for protection and close monitoring to ensure that ecosystem changes remain within the range of historical variability [13]. This involves sustaining existing conditions or, where change has occurred, restoring historical or "natural" characteristics through actions that increase or maintain ecological resistance and resilience [51]. For Type II lakes that exhibit early stages of degradation relative to past centuries, immediate intervention should be prioritized to reverse the trend. Strategies should be anticipatory and focus on preventing the crossing of tipping points. This phase, compared to lakes that have already crossed thresholds, presents the best window of opportunity to prevent degradation at low-cost and with a high degree of effectiveness. Key activities include improving knowledge (such as understanding drivers, threshold values, and prevention options), assessing system risk and vulnerability, and developing early warning systems [5], as well as identifying drivers of degradation and taking measures to ameliorate sources of change e.g., controlling land-use in the catchment and ameliorating sources of pollution. Assessing how sensitive a Type II system is to ongoing pressures is also important, as higher sensitivity would warrant earlier and more intensive intervention, whereas lower sensitivity may allow for more gradual or adaptive management responses. Management strategies should also incorporate information about the rate of change and aim to minimize directional transformation to maintain ecological resilience against increasing anthropogenic pressures.

4.2. For Type III lakes (lakes that are in transition)

Management strategies for Type III lakes, which have undergone transition dynamics having already crossed a tipping point, must consider potentially prolonged transient trajectories, such as slow or abrupt transitions [17,52]. Strategies should focus on preparing for, minimizing, and responding to various impacts. Incorporating a range of foresight and scenario-building approaches is essential to understand and anticipate potential future trajectories, assess different risks, and minimize risks across multiple possible futures [18,49]. This strategy contrasts with Type

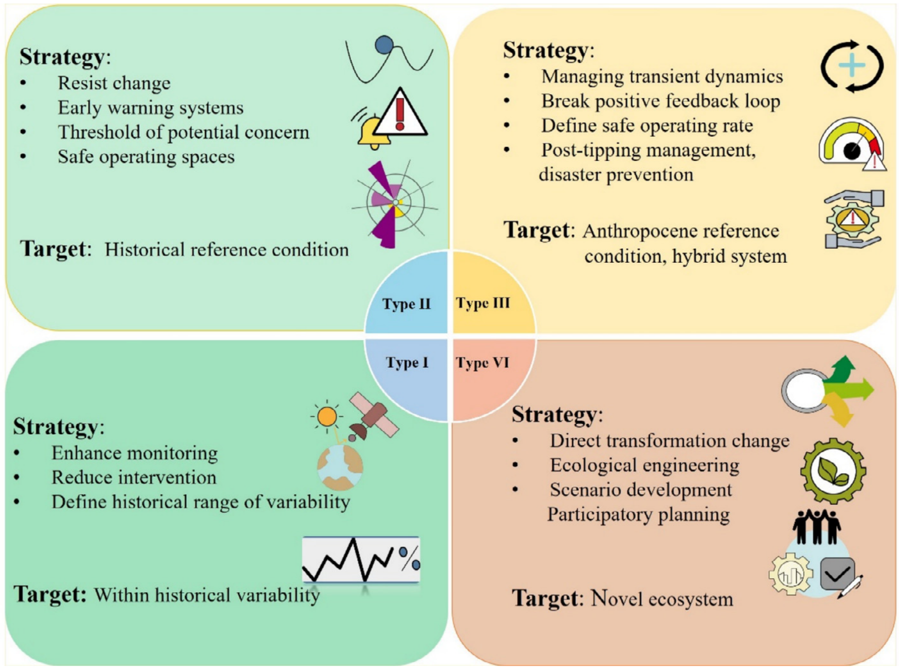

Fig. 4. Strategic framework for managing lake types based on ecological state and rate of change, each type requires specific restoration strategies based on their ecological condition and the rate of environmental change, ranging from maintaining historical states to managing novel ecosystems.

I and Type II lakes, where prevention, system stabilization, and harm avoidance are more feasible.

For Type IIIa lakes exhibiting an accelerating rate of change, the priority is to identify and, where possible, control and reduce the particular drivers of change that contribute to positive feedback mechanisms that are driving the transition. Immediate attempts to halt the decline or restore the lake to its pre-disturbance state may be impractical and costly. Instead, the focus should be on making the system more predictable, allowing for the anticipation of issues and effective risk management to avoid catastrophic collapse. Employing a range of diverse strategies to manage transient behaviours is crucial. For example, rather than fully eliminating algal blooms or restoring lake health entirely, it may be more practical to maintain lower incidence rates and control the size of transition outbreaks. Additionally, mitigating the risk of extreme disturbances, such as climate-related events (heatwaves, flooding), can help prevent catastrophic outcomes [53].

For Type IIIb lakes undergoing slow, smooth transitions, timely interventions offer a chance to reverse ongoing shifts. Despite weak stabilizing feedbacks, these lakes may still return to less disturbed conditions if addressed promptly [17,52]. Recent studies suggest that detecting and monitoring late-warning signals can prevent slow transitions from becoming irreversible [49]. This transitional period presents an opportunity to revert to safer conditions before a new equilibrium state becomes entrenched. Restoration targets should consider contemporary or Anthropocene reference conditions for a more practical approach [10].

4.3. For Type IV lakes

Restoring Type IV lakes to historical states is unfeasible, as not only these ecosystems themselves, but also the surrounding social-ecological systems are locked into alternative stable states, due to hysteretic changes and significant modifications in composition, structure, and function. While the ecosystems might theoretically shift if all human pressures were removed, achieving this is impractical, especially with ongoing climate change. Radical actions are therefore necessary to guide these lakes toward new, more preferable ecological configurations, such as hybrid or novel ecosystems [18]. This transformation may require geoengineering and biotechnological innovations to establish new ecological conditions that are more stable and better adapted to climate change. During this stage, exploring multiple ecological trajectories and scenarios through participatory approaches can help clarify the most plausible futures, relevant processes, scales of change, and prioritise ecosystem services valued by the stakeholders [54]. Monitoring the rate of recovery is crucial for evaluating the success of these projects in the absence of historical analogues.

Thus, in terms of investment required and prioritization of restoration efforts, Types I and II require the least investment with the highest reward, and should therefore be given top priority. Lake Types III and IV require greater investment with lower returns, indeed in the most extreme case Type IV lakes may be irreversibly degraded. Restoration efforts may be possible for Type IIIb lakes, while for Type IIIa lakes, immediate restoration to a historical state may be impractical, and should rather aim to stabilize the lake system, thereby lessening the risk of extreme disturbance or change. Where restoration to former states is not possible or practical, novel and creative approaches are required to restore some level of ecosystem function [55].

5. Case study: Taihu Lake in the Anthropocene

In this paper, we focus on Taihu Lake as a detailed case study to demonstrate the application of the framework to a highly degraded system (Type III). Brief illustrative examples for other types are provided in the Supplementary material. Taihu Lake stands as a pertinent symbol of China's struggle with degraded lakes in the Anthropocene. As China's third-largest freshwater lake, spanning approximately 2340 km^2, Taihu Lake is nestled within a heavily urbanized region, the Yangtze River Delta, with over 40 million inhabitants [56]. Taihu Lake has faced severe degradation and is plagued by water and ecological crises. In May 2007, the lake suffered a catastrophic cyanobacterial bloom that overwhelmed its drinking water purification plants, leaving millions of residents without potable water for nearly a week [57]. Despite considerable efforts and approximately 100 billion RMB invested in restoration projects, tangible improvements remain elusive [58,59]. Scientists, managers, and policymakers continue to grapple with the complexities of restoring this vital ecosystem.

Empirical evidence spanning the last several centuries indicates that Taihu Lake falls into Type IIIa within our proposed framework, characterized by an accelerating rate of change and a highly degraded state, as evidenced by indicators such as chlorophyll-a concentration levels and rate of change (Fig. 5, Fig. S2 online) [56]. Attempting to restore the lake to its historical baseline is deemed unattainable, as the socioeconomic limitations also constrain the ecological possibilities, yet this remains the prevailing principle guiding current policies [60]. A paradigm shift is imperative, necessitating a renewed focus on resisting further degradation and mitigating short-term catastrophic disasters, while closely monitoring the rate of change. Furthermore, it is crucial to temper expectations regarding the restoration of Taihu Lake at this stage rather than solely fixating on static state variables from the past. Management efforts should prioritize disrupting sediment nutrient release--algal bloom feedback loops that drive the current transition [59], and implement adaptive strategies to navigate the uncertain trajectory of the lake ecosystem using a range of foresight and scenario building approaches, such as participatory scenarios development [61].

6. Future outlook and recommendations

As the number of freshwater ecosystems undergoing transition increases in the Anthropocene, sustaining lakes globally will require a conceptual shift away from the current emphasis on protecting, conserving, or restoring stable lake ecosystems at equilibrium. Instead, we must acknowledge the reality that lake ecosystems are inherently dynamic and more variable in the Anthropocene context and develop typologies of lake systems based on their long-term dynamics to guide restoration initiatives. To navigate these dynamic landscapes, we highlight three research avenues that are crucial for the future management of lake ecosystems, particularly at the time scales most relevant for effective management.

6.1. Define safe operating rates for freshwater transformation management

We recommend the development of more flexible strategies focused on managing transitional behaviours and prompting more desirable transformations. While defining a safe operating space

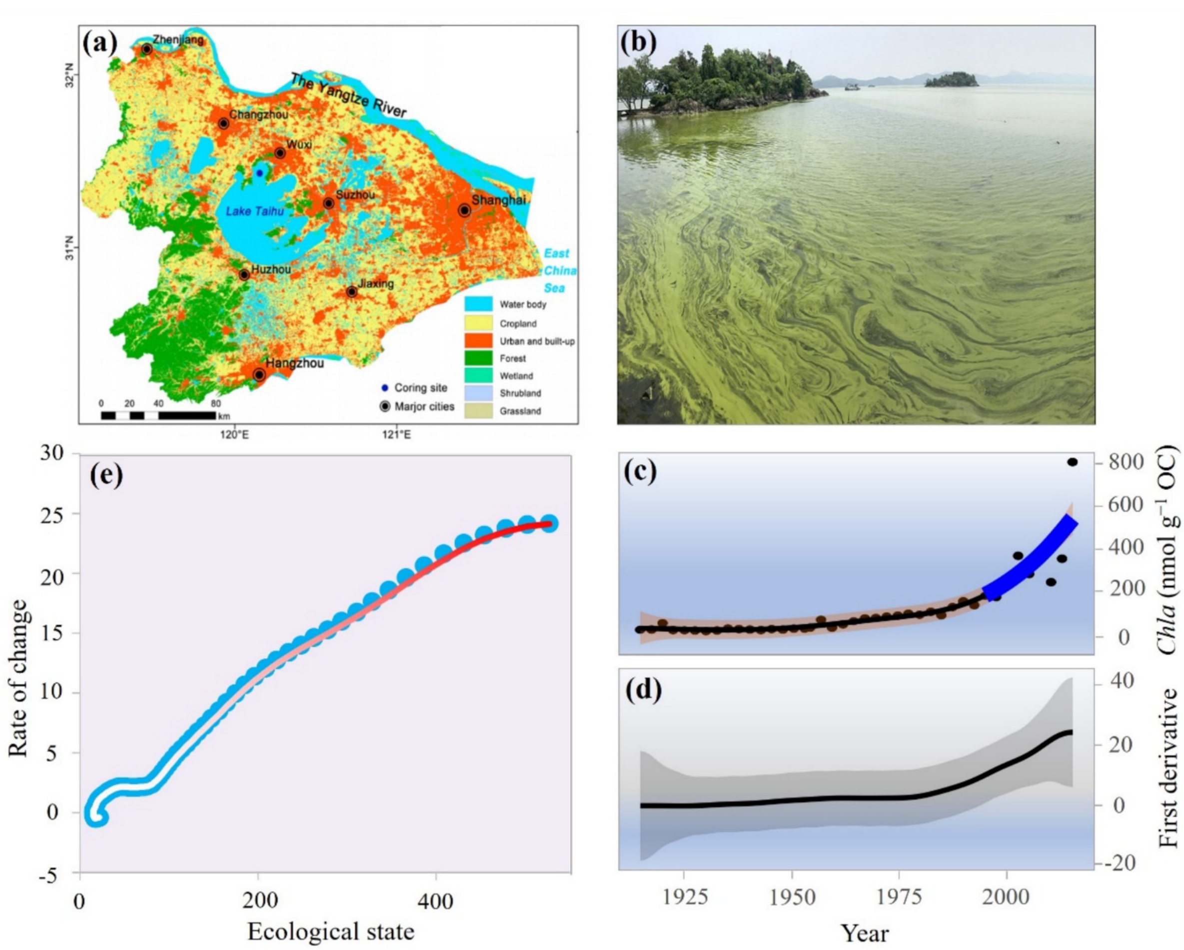

Fig. 5. Case study of Taihu Lake from a highly disturbed Anthropocene landscape in east China. (a) Land use change map of the Taihu Lake catchment, (b) algal bloom in Taihu Lake, (c) *Chlorophyll-a* (*Chla*) changes, and (d) rate of change (ROC) of the lake ecosystem over the past centuries reconstructed from sediment pigment analysis [56]. (e) Biplot of state and rate of change of Taihu Lake *Chla*, indicating the current lake status with a high rate of change and poor state, suggesting Taihu Lake is currently classified as Type IIIa over the studied period.

[62] is a reasonable strategy suitable for Type I and II lakes that are in good condition, it may not serve for lakes that have already crossed critical boundaries (Types III and IV). Therefore, new rules and measurements need to be developed. In practical terms, safe operating rates may be estimated by comparing long-term rates of change against historical baselines, the natural range of variability in reference systems, or rates associated with known ecological tipping points, thereby helping to distinguish between "safe" and "unsafe" trajectories in applied lake management. Focusing on managing dynamic rates of change may offer novel insights to guide transformation for sound ecosystem management in the Anthropocene.

6.2. Utilize "Big Data" from the past to assist in Anthropocene lake restoration

Developing guidelines and principles to combine multiple sources of data, including time-series data that covers the past decades and centuries, is essential to uncovering the dynamic trajectories of lake ecosystems in the Anthropocene. As demonstrated here, paleolimnological data can be used to guide restoration and lake management. However, a gap exists between paleoecological research and its application in freshwater management. The approach developed here could be applied more widely by combining data from palaeoecological databases [46] with contemporary monitoring surveys and model outputs through data assimilation [63], thereby enabling the development of practical and realistic restoration strategies based on our proposed typology. Interdisciplinary collaboration, especially with paleo-scientists, is crucial to engage with conservation and restoration challenges and develop frameworks for real-world restoration initiatives.

6.3. Adopt social-ecological system approaches

The decision-making process regarding lake ecosystem restoration is not solely a biological problem but also represents a governance challenge. The science and governance of lake socio-ecological system restoration are complex and not yet fully mature. Addressing the root causes of freshwater ecosystem degradation, such as overconsumption, resource extraction, and climate change, is essential for long-term restoration success in achieving the SDGs. Maintaining good quality freshwater relies on achieving other SDGs, such as Life on land (SDG15) since water quality relies on land use change and responsible production and consumption (SDG12). Where a return to past conditions is unfeasible (Types III and IV), stakeholders need to decide which ecological functions should be maintained or restored in order to deliver critical ecosystem services and maintain or recover ecological functionality. Restoration efforts should be conceived as inclusive social-ecological processes that integrate diverse values, practices, knowledge, and restoration objectives across temporal and spatial scales and stakeholder groups. Embracing this paradigm shift will require a transformation in the governance and management of Anthropocene lakes, aimed at improving restoration effectiveness and efficiency that yield long-lasting benefits to people and nature.

7. Conclusion

As the challenges of the Anthropocene intensify, it is essential to develop innovative frameworks that address the complexities of freshwater restoration and management. This paper presents a novel bivariate framework that integrates both the rate and state of change from a long-term perspective, offering a comprehensive tool for classifying and understanding freshwater ecosystems. By providing actionable insights through the typology of four ecosystem classes, this framework not only complements existing models, such as the RAD framework, but also equips scientists, managers, and policymakers with the tools needed to implement more effective, context-specific restoration strategies. The insights gained from this work can inform broader restoration efforts globally, and we see a timely opportunity for interdisciplinary collaboration, particularly between paleoecology, limnology, and environmental governance, to further refine and apply this approach. It is our hope that this framework will catalyze new research and inspire decisive action in safeguarding freshwater ecosystems for future generations.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Ke Zhang led the conceptualization and drafting of the manuscript. Lindsey Gillson, Suzanne McGowan, and Jemma Finch contributed to the framing, thematic development, and critical revision of the manuscript. Zhengwen Liu and Ji Shen provided expertise on freshwater dynamics and contributed to structuring the review. Michael E. Meadows and David Taylor integrated socio-ecological perspectives and critically revised the text. Yuan Jin and Yaoyao Han carried out the data analysis and prepared supporting figures. All authors reviewed and approved the final manuscript.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2025.11.029.

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