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Correspondence

From elastic thresholds to predictive management: Advancing freshwater ecosystem conservation

The advent of the Anthropocene has subjected Earth's systems to unprecedented anthropogenic pressures, with critical planetary boundaries, including biosphere integrity and land system change, having been transgressed beyond humanity's safe operating space [1]. Freshwater ecosystems, despite occupying a small fraction of Earth's surface, harbor exceptionally rich and endemic biodiversity. However, populations of freshwater species at the global scale have declined by an average of 83% since 1970 [2], with recent assessments indicating that 24% of freshwater species face extinction risk [3]. This biodiversity crisis has raised fundamental questions about the long-term capacity of freshwater ecosystems to sustain human well-being. Although freshwater ecosystems are degrading at rates surpassing those of terrestrial and marine systems, they have received disproportionately limited attention within global environmental governance frameworks. This disparity underscores the urgent need to quantify the safe operating space for freshwater systems, thereby establishing a framework for reconciling human development with freshwater ecosystem conservation. Among anthropogenic stresses, land-use change has been widely identified as a primary driver of biodiversity loss and functional degradation in freshwater habitats, with greater influence than climate change or biological invasions [4]. At the watershed scale, urban expansion, agricultural intensification, and deforestation systematically degrade water quality, fragment habitats, and profoundly alter biotic community structure [5], thereby undermining food web stability and ecosystem resilience. This challenge is particularly acute in rapidly developing nations, where ongoing aquatic biodiversity loss has catalyzed urgent discourse on integrating scientific land-use planning with economic development imperatives. Such integration represents a critical prerequisite for achieving a sustainable balance between development pressures and freshwater ecosystem conservation in regions experiencing rapid urbanization and agricultural intensification.

To understand how freshwater ecosystems respond to external disturbances, the ecological threshold concept provides a critical theoretical foundation [6]. Ecological thresholds manifest predominantly as gradual, continuous processes characterized by interval-based and dynamic properties. This conceptual advancement has shifted the focus from singular critical points to dynamic threshold intervals exhibiting context-dependent resilience. When environmental pressures accumulate within the critical threshold of each interval, watershed ecosystems exhibit gradual responses. However, once pressures exceed these thresholds, ecosystems undergo accelerated, and often irreversible, degradation. At this stage, hysteresis effects prevent simple reversal through pressure reduction, as ecosystem trajectories depend not only on current conditions but also on historical pathways [7]. The acceleration of urbanization processes, intensified watershed land development, and other interacting anthropogenic pressures directly contribute to the homogenization and simplification of freshwater biodiversity. Early research in the Amazon basin demonstrated that fish communities exhibit negative threshold responses at deforestation levels below 20%, while recent studies in eastern China's lakes have revealed distinct thresholds for benthic assemblages in urban versus agricultural land-use gradients [8]. Therefore, clarifying the “elastic” threshold is essential for preserving biodiversity and formulating effective watershed management responses.

Despite the novelty and profound potential of thresholds in freshwater conservation, significant scientific challenges persist. First, the spatial heterogeneity and nonlinear dynamics of watershed ecosystems make it difficult for traditional statistical models or empirical approaches to capture rapid ecological transitions, resulting in uncertainty surrounding threshold identification. Second, climatic conditions, hydrological regimes, and community structures vary widely across different units of diverse watersheds, impeding the application of a single threshold or universal indicator over large regions. Third, existing work focuses mainly on correlations between environmental pressures and ecological responses, but rarely disentangles causal mechanisms (i.e., the specific processes or pathways through which environmental pressures directly drive ecological changes, thereby revealing how and why these effects occur beyond mere correlations). Without robust mechanistic insights, predicting abrupt changes in real-world management scenarios remains challenging. Fourth, the interactive effects of multiple interacting stressors substantially increase the complexity of threshold identification. Land-use change, for instance, rarely occurs in isolation; it co-occurs with, and often exerts non-linear, compounded effects alongside other stressors such as habitat fragmentation (e.g., dam construction), climate change, and biological invasions. Consequently, the threshold itself exhibits dynamic and context-dependent elasticity, moving beyond a fixed value to become a flexible range that shifts based on the specific combination and intensity of multiple interacting stressors. Fifth, time series or spatial coverage in datasets often proves insufficient for detecting slow processes or cumulative effects that can precipitate unexpected collapses [9]. Moreover, the inconsistent resolution of data across different pressure types further complicates the identification of robust ecological thresholds at large spatial scales.

On the management front, the major challenge involves

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shifting from “descriptive science” to “predictive management”. As watersheds typically span administrative boundaries, using an averaged threshold across an entire basin can mask critical ecological risks at local scales, leading to challenges in cross-regional management due to mismatches between watershed-scale thresholds and administrative divisions. Moreover, management strategies often prioritize physicochemical references (e.g., nutrient levels, water quality) while undervaluing key biological metrics that reflect underlying ecological processes. Combined stressors, including water extraction, pollution, and habitat destruction, may create compound threshold effects, amplifying uncertainty in decision-making. Socioeconomic imperatives such as fiscal revenue or agricultural productivity frequently conflict with aquatic protection needs, making it harder to implement effective compensation mechanisms. As a result, ecological thresholds often remain theoretical, rather than becoming pragmatic tools for guiding watershed-level management.

In light of these scientific and managerial complexities, we propose a three-pronged integrative framework, which comprises ecological monitoring, mechanism-based analysis, and threshold evaluation (Fig. 1), to transition from descriptive observation to predictive management.

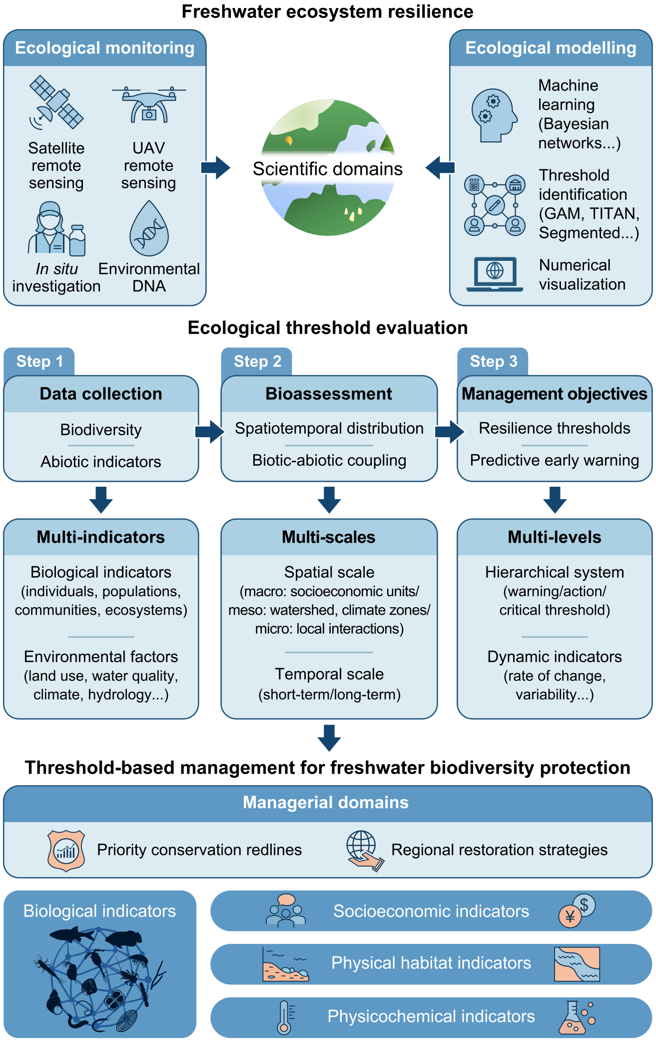

Fig. 1. Framework linking ecological monitoring, mechanism-based analysis, and threshold evaluation to predictive management of freshwater ecosystems. UAV: unmanned aerial vehicle.

Ecological monitoring with multi-source data. Systematic monitoring across spatial and temporal scales forms the critical reference for identifying elastic thresholds. By incorporating remote sensing, drone imagery, eDNA/eRNA approaches, and citizen science data [10], researchers can track land use, water quality, climate, hydromorphology, and biological community composition (e.g., fish, benthos, and plankton) and functions in near-real time. When traditional sampling offers limited temporal coverage, historical aerial photos, satellite imagery, or paleoecological archives can extend the record, ensuring that monitoring captures monthly, seasonal, and multi-year dynamics and thereby enabling better detection of gradual shifts or impending abrupt changes. Furthermore, targeting different functional zones (e.g., upstream conservation areas versus mid- or downstream agricultural segments) can help pinpoint local hotspots and spatial heterogeneity in threshold responses.

Mechanism-based analysis through multidisciplinary tools. To uncover the underlying regularities governing freshwater ecological thresholds, a synthesis of ecological, socio-economic, machine learning, and geospatial methods is required to disentangle the complex response relationships among watershed environmental variables. For instance, a remote sensing dataset coupled with model simulations can be employed to quantitatively assess the cumulative impacts of land-use pattern changes on water quality and species habitats. Socio-economic analysis and machine learning methods can be further integrated to investigate the effects of human social activities on watershed ecological disturbances, thereby revealing the relationships between land use change and the degradation of watershed ecosystems. Additionally, integrating network analysis with ecological models can illuminate the structural evolution of biological communities under multiple stressors, thereby enabling a more comprehensive understanding of stressor interactions.

Dynamic and context-specific threshold evaluation. Recognizing thresholds as dynamic transition zones, managers can establish tiered levels, such as warning, action, and critical thresholds, each triggering corresponding interventions. If a metric nears its warning threshold, decision-makers might limit additional land conversions or intensify monitoring efforts. Passing a critical threshold would require rigorous restrictions or immediate restoration measures to avert irreversible ecosystem damage. Additionally, incorporating dynamic indicators (e.g., rate of change, variability, and autocorrelation) can alert stakeholders to a system drifting toward undesirable states. Moreover, threshold evaluation should fully consider the specific response patterns of various taxa and functional groups (e.g., feeding habits of fish and benthos; behavioral traits of plankton). It is essential to integrate ecological indicators across levels, from individuals and populations to communities and ecosystems, tailored for different types of water bodies (lakes, rivers, wetlands) and various pressure source combinations (e.g., free-flowing vs. fragmented rivers, stable vs. rapidly warming climate zones, low vs. high invasion pressure environments). Customized, context-specific threshold schemes should be established to ensure management strategies are more targeted and feasible, accounting for the different stages of socio-economic development.

As global landscapes undergo rapid transformation and multifaceted anthropogenic disturbances rise, freshwater ecosystems are increasingly vulnerable. Preserving watershed biodiversity and ensuring sustainable water use are urgent priorities. The ecological threshold framework offers a novel approach for measuring the balance between development and conservation. While debate persists over the precision of threshold detection in complex systems, accumulating evidence shows that awareness of potential thresholds, even with uncertainty, can inform riskaverse decision-making and provide actionable guidance for freshwater conservation. Realizing the full integration of ecological thresholds into watershed management necessitates broader international and regional collaboration. In research, creating a global database of freshwater ecological thresholds and promoting data sharing will enable cross-regional learning and comparative studies. On the technical side, leveraging artificial intelligence, cloud computing, and big data analytics can improve the accuracy of threshold detection and enhance predictive capabilities for future scenarios. In practice, establishing differentiated, context-specific threshold standards is crucial to fundamentally shifting habitat conservation from reactive remediation to proactive prevention. Additionally, fostering widespread public engagement and social consensus will garner support from local governments, research institutions, stakeholders, and the public, thereby forging a synergistic effort to promote land-use threshold management. Such collective endeavors will transform the concept of elastic thresholds from a theoretical tenet into a cornerstone of aquatic ecosystem governance, ultimately securing both long-term biodiversity and societal well-being.

CRediT authorship contribution statement

Huiyu Xie: Writing - Original Draft, Visualization, Conceptualization. **Xiaowei Jin:** Writing - Review & Editing, Supervision, Conceptualization. **Aibin Zhan:** Writing - Review & Editing. **Xianfu Zhao:** Writing - Review & Editing. **Andrew C. Johnson:** Writing - Review & Editing. **Fengchang Wu:** Writing - Review & Editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Huiyu Xie[a,b,c], Xiaowei Jin[c,*], Aibin Zhan[d], Xianfu Zhao[e],
Andrew C. Johnson[f], Fengchang Wu[a,**]

[a] *State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing, 100012, China*

[b] *College of Water Sciences, Beijing Normal University, Beijing, 100875, China*

[c] *China National Environmental Monitoring Centre, Beijing, 100012, China*

[d] *Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, 100085, China*

[e] *Key Laboratory of Ecological Impacts of Hydraulic-Projects and Restoration of Aquatic Ecosystem of Ministry of Water Resources, Institute of Hydroecology, Ministry of Water Resources and Chinese Academy of Sciences, Wuhan, 430079, China*

[f] *UK Centre for Ecology and Hydrology, Wallingford, Oxfordshire, OX10 8BB, UK*

[*] Corresponding author. China National Environmental Monitoring Centre, Beijing, 100012, China.

[**] Corresponding author. State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing, 100012, China.
E-mail addresses: jinxw@cnemc.cn (X. Jin), wufengchang@vip.skleg.cn (F. Wu).

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