

Toward Sustainable Biosphere Reserve Governance: A Multidimensional Approach to Social-Ecological Resilience in Gahar Lake, Iran

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Abstract

This study investigates governance and socio-ecological resilience in the Lake Gahar Biosphere Reserve, located in Iran's Central Zagros. The reserve faces increasing tourism pressure, environmental degradation, and weak institutional coordination, which have intensified tensions between conservation and development. Biosphere Reserves are designed to link biodiversity conservation with sustainable development through participatory governance. However, their effectiveness is often constrained by management systems that do not adequately integrate ecological, social, institutional, and cultural dimensions, particularly in understudied regions of the Global South. This study develops and applies a multidimensional participatory framework that combines adaptive capacity thinking with governance analysis to assess system robustness and institutional performance in Lake Gahar. Using the mixed-methods case study, the research combines semi-structured interviews, participatory workshops, and resilience-based indicators to examine ecological integrity, institutional effectiveness, socio-economic pressures, climate vulnerability, and ecosystem services. The findings show that the reserve retains considerable ecological recovery potential, but cumulative pressures, including declining water quality, biodiversity loss, invasive species, and climate-related stress, increasingly weaken this capacity. The results further indicate that tourism has exceeded the area's ecological carrying capacity while generating uneven benefits for local communities, thereby reinforcing the imbalance between environmental protection and livelihood needs. The management effectiveness assessment highlights weak regulatory enforcement, institutional fragmentation, and limited stakeholder participation, all of which constrain adaptive management and undermine long-term socio-ecological capacity. The analysis argues that Lake Gahar's vulnerability is shaped not only by ecological pressures but also by institutional deficiencies that impede coordinated and inclusive decision-making. The study concludes that strengthening adaptive capacity requires a transition from fragmented, top-down management to adaptive, participatory, and locally grounded institutional arrangements capable of aligning conservation priorities with community interests and climate adaptation. More broadly, the findings suggest an analytically framework, yet context-sensitive, framework for understanding and

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strengthening socio-ecological resilience in biosphere reserves facing comparable governance and sustainability challenges.

Keywords: Socio-ecological resilience, Participatory governance, Biosphere reserve, Lake Gahar, Adaptive management

Introduction

Biosphere reserves (BRs), designated under UNESCO's Man and the Biosphere (MAB) Programme, serve as living laboratories for the integrated management of biodiversity, land, and water resources. They aim to balance conservation and sustainable development through participatory engagement between communities and ecosystems. As of 2025, the World Network of Biosphere Reserves includes 759 sites across 136 countries, facilitating knowledge exchange and collaborative governance (UNESCO-MAB 2017; UNESCO 2019).

Despite this extensive global network, important gaps remain in understanding how governance systems can effectively strengthen socio-ecological resilience in biosphere reserve. Existing research frequently examines resilience and governance as separate domains, offering limited integrative frameworks that simultaneously address ecological, institutional, social, and cultural dimensions (Lang et al., 2012; Ferreira et al., 2018). Furthermore, empirical studies that operationalize resilience-based governance in BRs remain limited, and participatory, transdisciplinary, and intergenerational approaches are still underused—despite evidence that such methods enhance governance legitimacy and adaptive capacity (Leguía-Cruz et al., 2024; Dabard et al., 2024). Recent scholarship further underscores the

need for transformative interventions and deep leverage points to secure long-term socio-ecological sustainability (Abson et al., 2017).

Recent work has begun to document the benefits of participatory governance in BRs. Intergenerational workshops in South American reserves, for instance, have improved decision-making legitimacy while bolstering ecological resilience (Leguía-Cruz et al., 2024). A review of 120 studies found that transdisciplinary approaches correlate with substantial gains in sustainability indicators (Dabard et al., 2024). Yet significant challenges persist. Climate projections suggest that a 2°C temperature rise could halve ecosystem resilience in European forests by nearly half. Although community-based management can partially offset these losses (Cantarello et al., 2024). Human pressures such as tourism and infrastructure development further erode resilience, accounting for a large share of declines documented across multiple BRs (Li et al., 2014; Schliep & Stoll-Kleemann, 2010; de Lucio & Seijo, 2021).

Despite these global insights, biosphere reserve governance in developing regions remains comparatively understudied, particularly concerning integrated, resilience-based governance frameworks and participatory assessment approaches (Plummer et al., 2020; Ferreira et al., 2018; Dabard et al.,

2024). This gap is especially evident in Iran's ecologically sensitive Central Zagros Mountains, where social-ecological systems are under growing pressure. Despite the region's ecological significance, few studies systematically integrated ecological indicators, governance arrangements, and stakeholder perspectives. Lake Gahar BR, located within the Oshtorankuh Protected Area in Lorestan, exemplifies this situation. While the reserve attracts approximately 70,000 visitors annually, research has been focused on its hydrology and tourism potential (Mehrnia and Hasanvand, 2022). The governance implications of unregulated tourism have received limited attention.

This study addresses these gaps by developing a multidimensional, participatory governance framework for Lake Gahar BR, integrating ecological, institutional, social, and cultural dimensions. Using resilience assessment tools and intergenerational knowledge co-creation, it evaluates current governance and proposes adaptive strategies. Globally, similar challenges—such as Spain's 50% reduction in managerial efficacy due to governmental constraints (de Lucio and Seijo, 2021)—highlight the need for inclusive governance. In Iran, the absence of such approaches has left Lake Gahar vulnerable, necessitating a shift toward collaborative, resilience-based management. By bridging theory and practice, this study offers a replicable framework to enhance socio-ecological resilience in understudied regions. Its findings will inform policy for Lake Gahar while serving as a model for other BRs facing conservation-development tensions. Ultimately, it advances the global

agenda for adaptive, inclusive environmental governance by identifying barriers and opportunities for sustainable management.

Material and methods

Study area

This study employs a case study approach to examine governance challenges and socio-ecological resilience in Gahar Lake, located within Iran's Oshtorankuh protected area. Building upon established frameworks for biosphere reserve research (de Lucio and Seijo, 2021; Ferreira et al., 2018), the methodology integrates qualitative and quantitative data collection techniques to provide a comprehensive assessment. The study focuses on Gahar Lake (35°36'N, 48°19'E), a permanent mountain lake at 2,350 m elevation consisting of two interconnected basins (Upper and Lower Gahar Lakes) within the 59,111 km² protected area (Mehrnia and Hasanvand, 2022). The region's hydrological system, sustained by 933mm of annual precipitation (predominantly as snow), maintains the lake's water levels and supports endemic biodiversity, making it an ecologically significant site for conservation research (Figure 1).

Data collection

Primary data collection incorporates three complementary approaches. Semi-structured interviews (n=25) with key stakeholders, including local community representatives, tourism operators, conservation managers, and provincial officials, follow participatory governance assessment methodologies (Plummer et al., 2020). These interviews investigate perceptions of management effectiveness, identify conflict ar-

eas, and assess resilience indicators using de Lucio and Seijo's (2021) eight-parameter framework. Additionally, participatory mapping workshops with intergenerational groups (Leguía-Cruz et al., 2024) document local ecological knowledge, spatial resource use patterns, and conservation priorities. This process ultimately contributes to developing a social-ecological framework tailored for biosphere reserves lacking participatory governance structures.

Framework development and analytical procedure

The analytical framework combines social-ecological systems theory (Folke et al., 2016) with institutional analysis to evaluate governance across four critical dimensions. Ecological integrity was assessed through stakeholder perceptions of water quality monitoring and endemic species inventories, while institutional capacity examines policy coherence and enforcement mechanisms. Socioeconomic resilience was assessed by exploring tourism benefit distribu-

tion and livelihood impacts, while cultural values were examined through traditional ecological knowledge and place attachment. Systematic analysis of the interview data identified key resilience dimensions, including governance effectiveness, ecosystem health thresholds, and community adaptive capacity. For each dimension, qualitative indicators were assigned to establish current conditions, perceived threat levels (low, moderate, or high), and recovery potential based on stakeholder assessments and ecological carrying capacity.

Building on these assessments, we developed strategic recommendations categorized by implementation timeframe. Short-term actions (0-2 years) prioritize immediate threat mitigation through enhanced monitoring systems and stakeholder capacity building. Medium-term strategies (2-5 years) focus on institutional restructuring and ecosystem restoration initiatives, while long-term solutions (5+ years) emphasize systemic governance reforms and climate

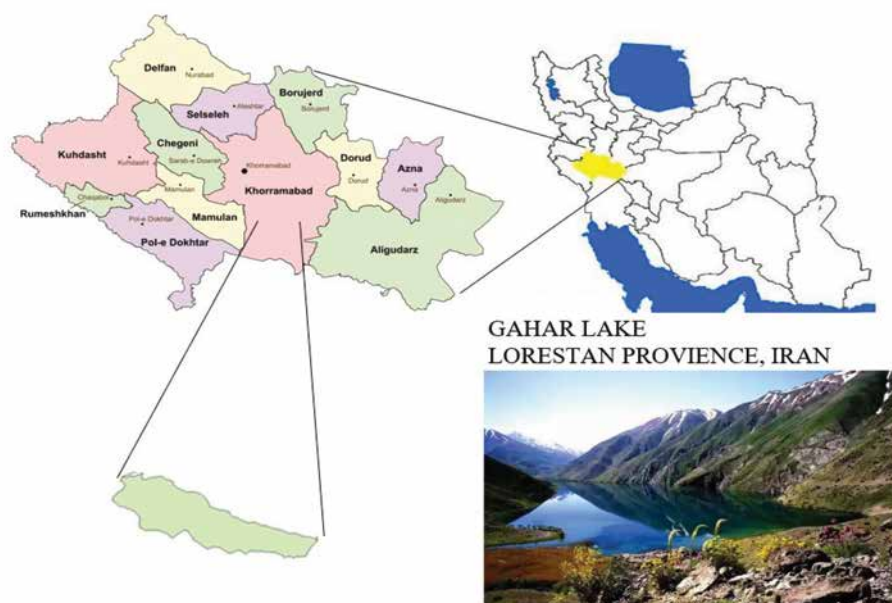


Fig 1. Gahar Lake Location, Lorestan Province, Iran

adaptation planning. Each recommendation is linked to specific resilience indicators and includes measurable targets, implementation partners, and monitoring protocols to ensure alignment with the overarching objective of enhancing governance-led resilience. A detailed implementation roadmap was co-developed with local stakeholders, featuring quarterly progress assessments, adaptive management triggers, and knowledge-sharing mechanisms to facilitate continuous improvement. While the study offers robust insights, methodological limitations include potential sampling bias and the short-term nature of resilience assessments, suggesting the need for longitudinal studies to fully capture system dynamics.

Results and discussion

Analysis of results and categorization

Analysis of the interview data revealed critical insights into the resilience and management challenges of Gahar Lake. These findings are organized into five key dimensions, including ecological health, socio-economic factors, governance effectiveness, climate vulnerability, and ecosystem services. Each dimension is discussed below with supporting evidence from the interview data.

Ecological health indicators

The ecological assessment of Gahar Lake reveals several critical indicators that reflect the overall health of this fragile ecosystem. Water quality parameters, including pH levels, dissolved oxygen concentrations, and nutrient loads (particularly nitrogen and phosphorus), show concerning trends that suggest progressive environmental degrada-

tion. Recent measurements show pH fluctuations outside optimal ranges for aquatic life, while dissolved oxygen levels periodically dip below levels required to support sensitive species. Nutrient loading from tourism-related wastewater and runoff has created conditions conducive to algal blooms, further compromising water quality.

Biodiversity metrics paint an equally troubling picture. Populations of endemic species have declined markedly, with several native fish and amphibian species now appearing on regional threatened species lists. Concurrently, invasive plant and animal species have established strong footholds along shorelines, outcompeting native vegetation and altering habitat structures. The proliferation of these non-native species has been particularly rapid in areas with heavy tourist foot traffic.

While the ecosystem demonstrates moderate recovery capacity during the fall-to-spring tourism off-season, this resilience is being progressively eroded. Sediment loading from unregulated shoreline activities has increased turbidity and smothered benthic habitats, while pollution from inadequate waste management accumulates faster than natural processes can mitigate. The lake's natural filtration systems, once capable of processing seasonal influxes, now show signs of being overwhelmed during peak visitation periods.

These ecological indicators collectively suggest an ecosystem approaching critical thresholds. The moderate recovery capacity, while still present, operates within increasingly narrow margins as cumulative stressors compound. Of particular concern is the

accelerating rate of change in these indicators - what was once a gradual seasonal variation has become more extreme and less predictable. This pattern indicates that the system's natural buffering capacity is being depleted, potentially leading to irreversible ecological shifts if current pressures continue unabated.

The ecological health assessment underscores the urgent need for intervention strategies that address both immediate stressors (particularly tourism impacts) and longer-term systemic threats. Without comprehensive management action, Gahar Lake risks crossing ecological tipping points that could fundamentally alter its character and ecological function. The indicators suggest that while recovery remains achievable; however, the opportunity for effective intervention is diminishing as cumulative pressures continue to erode the system's resilience.

Socio-economic pressures

The socio-economic dynamics surrounding Gahar Lake present a complex paradox, where tourism serves as both an economic lifeline and a significant threat to long-term sustainability. The tourism industry generates approximately €1.7 million annually (Kheyri et al., 2020), but it far exceeds the lake's ecological carrying capacity, with 70,000 visitors each year contributing to severe environmental degradation through waste accumulation, noise pollution, and habitat disturbance. While providing some economic benefits to the region, the current tourism model fails to adequately reinvest revenue into conservation efforts, leaving local communities with only marginal gains

from this economic activity. Furthermore, 85% of interviewed stakeholders identified critical gaps in environmental education, noting insufficient awareness programs for both tourists and residents. While these perpetuate unsustainable practices and undermine conservation initiatives. This imbalance between economic opportunity and environmental stewardship highlights the urgent need for a restructured approach that aligns tourism development with the lake's ecological limits while ensuring a more equitable distribution of benefits to local communities.

The governance deficiencies

The governance framework for Gahar Lake currently exhibits significant systemic weaknesses, receiving only a "weak-to-moderate" rating in management effectiveness. Critical institutional gaps persist, particularly in the severe shortage of ranger staffing, which severely limits enforcement capabilities and on-ground monitoring. This operational deficiency is compounded by fundamental policy fragmentation, where the absence of integrated zoning schemes fails to distinguish between protected areas and multi-use zones, creating conflicts between conservation and development priorities. Most critically, the governance structure systematically excludes local communities from meaningful participation in decision-making processes, despite repeated calls for the establishment of participatory management committees that could bridge this divide. This triple governance failure - operational under capacity, policy disorganization, and stakeholder marginalization - creates a self-reinforcing cycle that undermines both

conservation outcomes and sustainable development potential, mirroring challenges observed in other biosphere reserves with top-down management approaches. The current system's inability to incorporate local ecological knowledge or address community concerns not only diminishes management effectiveness but also erodes public trust in conservation institutions, making cooperative solutions increasingly difficult to implement. These governance deficiencies represent perhaps the most fundamental barrier to realizing the lake's full potential as a model of sustainable development, necessitating urgent structural reforms to establish more inclusive, adaptive, and accountable management systems.

Climate vulnerability

Gahar Lake faces mounting climate vulnerabilities that compound its existing ecological pressures, with observable impacts already altering fundamental ecosystem processes. The lake's hydrological regime has undergone significant changes, marked by a troubling reduction in snowfall - historically crucial for water recharge-coupled with increasingly erratic rainfall patterns that disrupt seasonal water level fluctuations. These hydrological shifts coincide with rising temperatures that create thermal stress for cold-water-adapted species, pushing some endemic organisms beyond their physiological tolerance limits. Local experts estimate these combined climate impacts have diminished the lake's overall resilience by approximately 40% compared to 2010 baselines, with cascading effects on water quality, species composition, and ecosystem function. Particularly concerning is

the climate system's interaction with existing anthropogenic pressures, where warmer temperatures accelerate nutrient cycling and algal growth while reduced water inflows concentrate pollutants from tourism activities. The lake's moderate natural recovery capacity, once sufficient to buffer seasonal variations, now appears increasingly inadequate against these climate-amplified stressors, suggesting the system may be approaching critical ecological thresholds. These findings underscore the urgent need for climate-adaptive management strategies that address both the symptoms and root causes of vulnerability while preparing for the projected intensification of these trends under future warming scenarios.

Ecosystem services indicators

Gahar Lake's ecosystem services demonstrate critical patterns that reflect both its ecological value and mounting pressures. Ecotourism, classified as highly important, shows a declining trend due to overcrowding and unsustainable visitor pressures, threatening the natural features that make the area attractive. Groundwater regulation, identified as critically important for regional water security, currently remains stable but faces growing risks from climate-induced hydrological variability. Biodiversity habitat, another high-priority service, exhibits concerning decline primarily driven by invasive species expansion, which undermines the lake's capacity to support native flora and fauna. These indicators collectively reveal an ecosystem under stress, in which even currently stable services may deteriorate without intervention. The trends highlight the urgent need for management strate-

Table1. Gahar Lake Biosphere Reserve Resilience Assessment and Management Framework

Dimension	Key Indicators	Current Status	Threat Level	Recovery Potential	Strategic Recommendations
Ecological Health	Water quality (pH, dissolved oxygen, nutrients)	Declining (pH shifts, nutrient loading)	High	Moderate	Implement real-time water monitoring system; establish buffer zones with native vegetation to filter runoff; conduct quarterly water quality audits
	Biodiversity (endemic species, invasive species)	Moderate (endemics at risk)	Medium	Low-Moderate	Launch invasive species removal program; create endemic species breeding zones; establish biodiversity corridors connecting a lake to the surrounding protected areas
	Vegetation cover (health, invasive species)	Degraded (invasive species dominant)	High	Moderate	Implement 5-year reforestation plan focusing on native species; establish a community nursery for indigenous plants; enforce strict penalties for illegal logging
Socio-Economic	Tourism pressure (visitor numbers, impacts)	70,000 visitors/year (over capacity)	Critical	Low	Enforce 500 visitors/day cap; implement an online booking system; develop premium ecotourism packages to increase revenue while reducing numbers
	Local community benefits	Limited (20-30% revenue share)	High	Moderate	Establish tourism revenue-sharing mechanism (40% to conservation); create local guide certification program; prioritize local hires for management positions
	Education & awareness	Insufficient (85% awareness gap)	Medium	High	Develop multilingual visitor education center; implement mandatory eco-orientation for tourists; integrate conservation curriculum in local schools
Governance	Institutional capacity (rangers, enforcement)	Weak (50% staffing shortage)	High	Moderate	Increase ranger staff by 100% with specialized training; establish a rapid response enforcement unit; implement a digital monitoring system

Table1. Gahar Lake Biosphere Reserve Resilience Assessment and Management Framework

Dimension	Key Indicators	Current Status	Threat Level	Recovery Potential	Strategic Recommendations
Climate Vulnerability	Policy integration (zoning, regulations)	Fragmented (no clear zoning)	High	Moderate	Develop an integrated zoning map (core protection vs. multi-use areas); streamline regulations across provincial/national levels; create a unified management authority
	Stakeholder participation	Minimal (local input <15%)	Critical	High	Form a multi-stakeholder governance council (40% local representation); implement participatory budgeting; establish community watchdog groups
	Hydrological changes (snowfall, rainfall)	Reduced snowfall (-30% since 2010)	High	Low	Develop a climate-adaptive water management plan; construct small-scale water retention systems; implement a snowpack monitoring network
	Temperature shifts	+1.8°C since 2000	Medium	Moderate	Establish a thermal refugia for cold-water species; modify tourism seasonality; develop heat-resilient infrastructure
Ecosystem Services	Ecotourism	Declining (quality -25%)	High	High	Implement carrying capacity-based pricing; certify 50% operators as eco-compliant; create low-impact tourism routes
	Groundwater regulation	Stable but vulnerable	Medium	Moderate	Protect recharge zones through land acquisition; regulate groundwater extraction; implement artificial recharge during wet seasons
	Biodiversity habitat	Declining (endemics -15%)	High	Low-Moderate	Establish species recovery program; create predator-free sanctuaries; implement habitat restoration incentives for landowners

gies that address both immediate threats and long-term resilience, ensuring these vital ecosystem services can be maintained for future generations.

As summarised in this perceptionbased framework, resilience at Gahar Lake is constrained by declining ecological conditions,

increasing tourism pressure with limited local benefits, weak institutional capacity, and emerging climate related risks. Nevertheless, some ecosystem services, particularly groundwater regulation, are still perceived as relatively stable, although vulnerable. The classifications presented in the table provide

a qualitative synthesis of stakeholder perspectives to facilitate comparison across resilience dimensions, rather than serving as precise quantitative measures. The following discussion uses this framework to examine to unpack how these interacting ecological, institutional, and socioeconomic factors shape the lake's room for maneuver, and to evaluate the feasibility and limitations of the proposed management options from a qualitative, interview-based perspective.

Discussion

The findings of this study show that Gahar Lake's resilience is shaped by intertwined ecological, social, and governance processes, as perceived by interviewed stakeholders. Ecological resilience refers here to the lake's capacity to absorb tourism related and climatic disturbances while maintaining key functions, particularly water quality and biodiversity support. Participants described a system that still exhibits some capacity for seasonal recovery during reduced periods of tourism, although this resilience is increasingly comprised by unregulated tourism activities, land-use pressures, and emerging climate variability. These findings are consistent with evidence from other biosphere reserves, where conservation objectives and development pressures remain closely intertwined.

The results also indicate limited social and governance resilience. Social resilience, understood as local communities' ability to cope with and adapt to ecological and economic change, is generally perceived as weak. Interviewees emphasized dependence on tourism and natural resources, few

alternative livelihood options, and limited influence over management decisions. This combination restricts local flexibility in responding to ecological degradation and regulatory changes, and reduces incentives for longterm stewardship. Governance or institutional resilience, defined as the capacity of institutions to learn, coordinate, and adapt under changing conditions, is likewise perceived as constrained by fragmented mandates, weak enforcement, and predominantly top-down decision making.

A central contribution of this study is to qualitatively linkage of governance weaknesses to observable ecological outcomes. Participants frequently linked unclear zoning and overlapping mandates to the location and intensity of tourism infrastructure near to the lakeshore. they associated these developments with increased pollution, vegetation damage, and disturbance of habitats. Similarly, limited ranger presence and ineffective sanctions were described as enabling illegal fishing, hunting, and fuel wood collection, with perceived consequences for species decline and ecosystem degradation. Although, these causal narratives are not supported by formal modelling or quantitative monitoring, they illustrate how governance failures are experienced by stakeholders as drivers of ecological change.

The Discussion also underscores that all key assessments in this study, including expressions, such as "moderate recovery capacity", "limited participation", or "over capacity tourism"—are derived from perception-based qualitative data. They capture how different actors interpret changes in the lake and its governance, rather than provid-

ing statistically measured indices or formally calculated thresholds. These perceptions are valuable because they reveal locally grounded understandings of risk, responsibility, and feasible responses. At the same time, they are subjective and may be influenced by incomplete information or strategic framing. The findings should therefore be interpreted as an interpretive synthesis of stakeholder views and the author judgment, not as a quantitative evaluation of ecological or institutional performance.

Within this qualitative frame, the proposed management options, such as visitor caps, eco certification schemes, enhanced revenue sharing and multi-stakeholder committees should be seen as perceived opportunities and priorities emerging from the interview material, rather than prescriptive solutions. Stakeholders themselves acknowledged implementation challenges, including limited institutional capacity, strong dependence on tourism income and existing power asymmetries between authorities, local communities and private operators. This suggests that any introduction of such measures would require gradual piloting, negotiation and adaptation to local constraints, rather than assuming straightforward transfer of “best practices” from other biosphere reserves.

The Gahar Lake case is embedded in Iran’s specific governance and socio-political context, characterized by strong central control over natural resources and a tourism sector linked to broader development agendas. These conditions shape power relations, governance hierarchies and the scope for participatory approaches. Consequently, the study’s insights should be viewed as illus-

trative for mountain lake biosphere reserves in similar contexts, rather than universally generalisable to all biosphere reserves or developing regions. Nevertheless, the case reinforces broader arguments about the importance of clarifying institutional mandates, increasing meaningful stakeholder participation, and better integrating conservation and tourism policy.

Climate change appears in stakeholder narratives as an additional stressor that interacts with existing pressures. Perceived reductions in snowfall and more erratic rainfall are linked to concerns about altered inflows, changing tourism seasonality, and increased pressure on water resources. At present, governance arrangements are not perceived as adequately integrating these risks into zoning, water management, or tourism planning. From a resilience perspective, this suggests that climate-related changes may accelerate ecological degradation if current governance and tourism practices persist, but also that climate-adaptive measures could strengthen both ecological and social resilience if they are developed in a participatory manner and supported by more systematic monitoring.

Overall, the study provides a perception-based, qualitative framework that makes the interconnections between ecological conditions, social vulnerability, and governance weaknesses at Gahar Lake more visible. By differentiating ecological, social, and governance resilience, and by situating stakeholder narratives within the broader literature on biosphere reserves, the findings highlight that improving ecological outcomes will require simultaneous attention to

institutional reform and community engagement. The study does not claim to provide definitive metrics or universally applicable prescriptions; rather, they offer a context-specific interpretation of how resilience is currently understood and constrained in Gahar Lake, and where stakeholders perceive potential entry points for incremental, resilience-oriented governance change.

Implementation roadmap

The conservation and sustainable management of Gahar Lake require a phased, adaptive approach that addresses both immediate pressures and longerterm resilience. Rather than proposing an optimized or prescriptive blueprint, this Implementation Roadmap offers an indicative, practice-oriented action plan that translates the study's findings and stakeholder perceptions into a sequence of contextsensitive interventions. The roadmap is organised around short-term (0–2 years), mediumterm (2–5 years), and longterm (5–10 years) time frames to reflect how participants themselves distinguished between urgent, incremental, and more structural changes.

In line with the empirical findings, the selection of proposed management actions was informed by three interrelated criteria. The first criterion was perceived urgency, reflecting the extent to which stakeholders and experts consistently described particular issues as critical or requiring immediate attention. Recurrent concerns included unmanaged visitor flows, waste accumulation, and the visible deterioration of water quality during peak tourism periods, all of which were regarded as requiring prompt management responses.

The second criterion considered contextual feasibility, with emphasis placed on actions that were perceived as compatible with Iran's existing institutional, regulatory, and socio-economic conditions. Rather than assuming the establishment of new governance structures, preference was given to measures that could be implemented through existing agencies, legal mandates, and available administrative and financial capacities.

The third criterion was the potential contribution of each action to strengthening socio-ecological resilience. Based on the qualitative evidence, greater emphasis was placed on interventions that stakeholders perceived as capable of generating complementary benefits across multiple dimensions, including ecological recovery, improved governance participation, and enhanced livelihood security. Accordingly, the proposed actions should be understood as context-specific management options emerging from stakeholder perceptions and qualitative interpretation, rather than as formally ranked priorities or prescriptive recommendations.

The analysis identified four interrelated management objectives that collectively address the principal challenges facing Gahar Lake. The first objective is the immediate mitigation of tourism-related pressures through improved visitor management, including clearer access regulations, measures to reduce peak-season overcrowding, and targeted infrastructure improvements to minimise waste generation and pollution. A second objective involves the gradual strengthening of governance by clarifying institutional responsibilities,

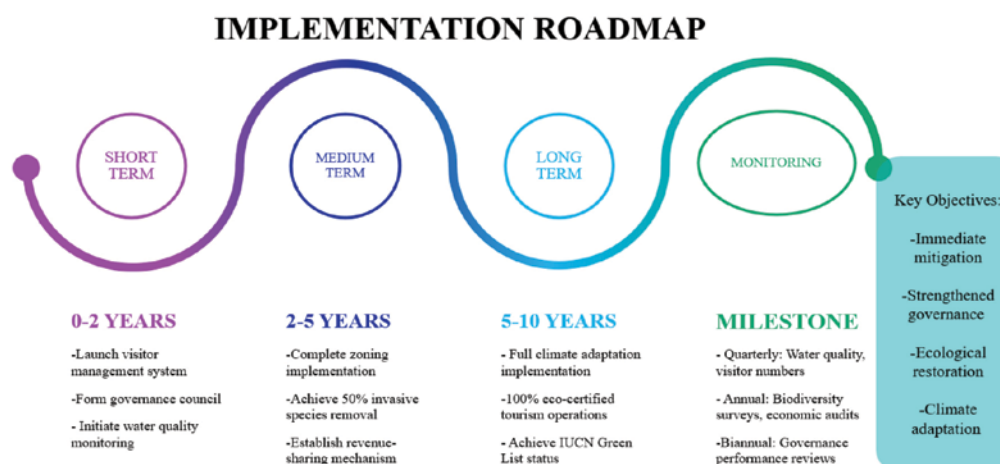


Fig. 2. Implementation roadmap including short-term, medium-term, and long-term strategies as well as monitoring to reach key objectives

promoting more systematic participation of local communities in decision-making processes, and improving the enforcement of existing conservation regulations.

The analysis further highlights the need to prioritise ecological restoration, particularly in habitats and water bodies identified by participants as being most affected by trampling, litter accumulation, and hydrological change. Finally, the findings emphasise the progressive integration of climate adaptation measures to enhance hydrological stability and reduce the vulnerability of local livelihoods to climate-related impacts. Together, these objectives represent context-specific management priorities derived from stakeholder perceptions and qualitative evidence, rather than prescriptive or universally applicable recommendations.

Figure 2 presents the Implementation Roadmap, summarizing short-, medium-, and long-term actions alongside indicative monitoring elements aligned with the study's resilience dimensions. The Table is intend-

ed as a flexible, evolving framework rather than a fixed plan. It enables managers and stakeholders to track progress across ecological, governance, and livelihood dimensions simultaneously, while revisiting priorities as new information, financial conditions, or policy opportunities arise.

This integrated but non-prescriptive approach reflects the complex interdependencies between ecological and human systems around Gahar Lake. At the same time, it acknowledges several practical constraints: dependence on public budgets and tourism revenues, the need to operate within existing Iranian environmental regulations, and the potential for stakeholder resistance to stricter visitor controls or new governance arrangements. Implementation will therefore depend on iterative negotiation among government agencies, local communities, and conservation organizations, and on adapting the pace and scope of actions to available financial and institutional capacities.

Gahar Lake's resilience is likely to remain limited if management continues to rely on

fragmented, reactive responses to individual problems. The roadmap instead points towards a more inclusive, adaptive governance trajectory that is broadly consistent with participatory principles reported in other biosphere reserves, such as transdisciplinary knowledge integration, equitable benefit sharing, and institutional flexibility, while not assuming their automatic transferability to this context. Future research and pilot projects could test specific components of the proposed governance arrangements and visitor management measures, using the resilience indicators employed in this study (e. g., water quality parameters, biodiversity trends, and perceived fairness of decision-making) to evaluate their effectiveness under real-world institutional and climatic uncertainties.

Conclusion

The findings from this study reveal a complex interplay between ecological resilience and governance challenges in Gahar Lake, highlighting both vulnerabilities and opportunities for sustainable management. The lake's moderate recovery capacity, as noted by participants, suggests that while the ecosystem retains some ability to rebound from disturbances, particularly during seasonal tourism lulls, its long-term resilience is increasingly compromised by unregulated tourism, climate change, and institutional weaknesses over time. This aligns with global observations in biosphere reserves where participatory governance has been critical in balancing conservation and development (Plummer et al., 2020; de Lucio and Seijo, 2021). However, Gahar Lake's current

governance framework lacks the integration of local communities and fails to enforce existing regulations effectively, mirroring challenges documented in other protected areas with top-down management structures (Schliep and Stoll-Kleemann, 2010).

The ecological stressors identified water quality degradation, biodiversity loss, and invasive species are exacerbated by socio-economic pressures, particularly unsustainable tourism. Tourism attracts an estimated 70,000 visitors annually, generating approximately €1.7 million in revenue (Kheyri et al., 2020). However, these economic benefits are overshadowed by environmental costs, including pollution and habitat disruption. This paradox underscores the requirement for a governance system that not only regulates tourism but also redistributes its benefits to fund conservation efforts, as demonstrated in successful biosphere reserves such as Lanzarote BR (de Lucio and Seijo, 2021). The proposed visitor caps and eco-certification programs could mitigate these impacts, but their success hinges on robust stakeholder collaboration, which is currently lacking.

Participatory governance emerges as a critical yet underutilized strategy for enhancing Gahar Lake's resilience. The interview data reveal limited community engagement, with locals deriving minimal economic benefits and holding little influence over management decisions. This exclusion contrasts sharply with best practices in biosphere reserves worldwide, where participatory approaches have improved both ecological outcomes and social equity (Leguía-Cruz et al., 2024; Ferreira et al., 2018). For instance,

the suggested formation of a multi-stakeholder management committee, comprising government agencies, local communities, and conservation groups, could foster co-designed solutions, such as zoning plans to balance tourism with habitat protection. Such committees have been reported to be effective in resolving conflicts and aligning conservation goals with livelihood needs, as demonstrated in the Alto Bernesga BR (de Lucio and Seijo, 2021).

Climate change further complicates these dynamics, with reduced snowfall and erratic rainfall altering the lake's hydrological regime. These shifts threaten the lake's role in groundwater recharge and biodiversity support, services highly valued by local communities. Adaptive strategies, such as reforestation to stabilize sediments and climate-smart tourism policies, are urgently needed. However, their implementation requires decentralized decision-making and knowledge co-production, as advocated by Folke et al. (2016). The documented success of community-based climate adaptation in Malawi's BRs (Chiotha et al., 2018) suggests that Gahar Lake could similarly benefit from integrating traditional knowledge with scientific monitoring, particularly in water management and disaster preparedness.

The decline in ecosystem services, especially ecotourism and biodiversity habitat, signals a tipping point that demands transformative governance reforms. Although the lake's current state is rated "weak-to-moderate," its potential for recovery remains viable if managed holistically. In the context of Gahar Lake, these lessons point to the importance of strengthening community en-

gagement through environmental education and stewardship initiatives, improving the enforcement of tourism regulations through greater community participation in monitoring, and establishing sustainable financing mechanisms that reinvest a proportion of tourism revenues into essential environmental infrastructure, including wastewater and sanitation systems (Alipour and Olya, 2015).

Gahar Lake's resilience is compromised by intersecting ecological and anthropogenic pressures. While its perceived moderate recovery capacity suggests some potential for recovery, urgent action is needed to strengthen governance, curb tourism impacts, and integrate climate adaptation strategies. The proposed measures align with successful models from global biosphere reserves (Ferreira et al., 2018) and may provide a useful reference for vulnerable mountain lakes in developing regions.

Gahar Lake's predicament encapsulates the quintessential Anthropocene challenge - balancing human development with ecosystem integrity. While its resilience is currently strained, our findings suggest recoverability through institutional innovation that bridges top-down regulation with bottom-up stewardship. The reserve's future hinges on adopting the "biosphere reserve" concept in practice, not just designation - transforming from a tourism hotspot to a living laboratory for sustainability. This requires nothing less than a paradigm shift in Iran's conservation approach, one that values local knowledge as much as scientific expertise, and recognizes that true resilience emerges from equitable governance systems as much as from

ecological processes. As climate pressures intensify, Gahar Lake stands as a useful case study, its lessons resonating far beyond Iran's mountainous borders to all regions grappling with the complex interplay of nature, culture, and economic development.

Implementation roadmap

The conservation and sustainable management of Gahar Lake demand a structured, phased approach that addresses immediate ecological threats while strengthening long-term resilience. This implementation roadmap presents a strategic action plan designed to translate research findings into practical interventions, ensuring the lake's ecological integrity while supporting sustainable tourism and local livelihoods. Recognizing the interconnected nature of the challenges, from water quality degradation and biodiversity loss to climate vulnerability and governance gaps, the roadmap organizes interventions according to urgency, feasibility, and potential impact. It outlines short-term (0–2 years), medium-term (2–5 years), and long-term (5–10 years) actions to systematically restore ecosystem health, enhance governance, and build climate resilience.

Key objectives include the immediate mitigation of tourism pressures through improved visitor management and infrastructure upgrades, the strengthening of governance through participatory decision-making and effective policy enforcement, the ecological restoration of critical habitats and water quality, and the integration of climate adaptation measures to safeguard hydrological stability. By aligning stakeholder efforts across government, local communities, and

conservation organizations, this roadmap provides a clear pathway to transform Gahar Lake into a model of sustainable ecosystem management. Regular monitoring and adaptive management will ensure responsiveness to emerging challenges, securing the lake's ecological and socio-economic benefits for future generations.

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