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Caspian Sea: Embracing change for a sustainable future

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ABSTRACT

The Caspian Sea, the world's largest inland body of water, has long experienced significant water-level fluctuations due mainly to natural factors, with additional impacts from human activities. Anthropogenic influences, including land- and sea-based activities, extend beyond the water level changes, severely impacting the Caspian's delicate ecosystem through pollution and unsustainable resource use. Global warming exacerbates environmental deterioration, which reduces freshwater supply and disrupts basin-wide circulation and vertical mixing, which are crucial for the Caspian bioproductivity. While scholars often focus on the complex ecological dynamics of the Caspian Sea, politicians are more concerned with the visible issue of the water level fluctuations. Although these perspectives are distinct, both overlook the need to address the Caspian's environmental system as a water body that integrated to the catchment basin. This comment argues that the future of the Caspian Sea lies in adapting intelligently to its natural cycles and prioritizing action on environmental degradation.

Keywords: Environmental challenges; Adaptive strategies; Climate change.
Article type: Report and Opinion.

INTRODUCTION

Since its isolation from the Paratethys Ocean during the Pliocene epoch, the Caspian Sea has experienced substantial sea-level fluctuations with an amplitude of around 100 m, shaped its unique biodiversity, and influenced human societies for millennia. Though landlocked, the Caspian Sea exhibits oceanic characteristics, including high waves, polar-type deep-water formation and circulation, and an oceanic crust in its southern deep basin (Karpinsky *et al.* 2005a; Forte & Cowgill 2013; Lahijani *et al.* 2023a). The Caspian's environmental changes—such as water level fluctuations, coastal lagoon formation, and desiccation—occur on a shorter time scale than those observed in oceans. Its semi-contained nature, bordered by developing societies and subject to environmental pressures including overfishing, pollution, sea surface warming and lake level changes (Mirrasooli *et al.* 2019, Lavrova *et al.* 2022; Lahijani *et al.* 2023a, 2024), allows the Caspian region to serve as a "mesocosm," or a scaled-down, controlled environment ideal for testing adaptive solutions to global challenges. This mesocosm provides insights into developing "smart" societies—communities that are flexible, resilient, and capable of adapting to the environmental, economic, and social pressures of the 21st century. These environmental dynamics and challenges, which outlines the primary environmental issues impacting the Caspian Sea and proposes adaptive strategies to mitigate these challenges. Thus, the Caspian Sea serves as an exemplary model for studying adaptive solutions to environmental challenges, offering insights with broad global relevance.

Challenges and adaptation

The Caspian Sea has experienced substantial fluctuations in water levels over the past century in a range of almost 3 m (see Fig. 1; Lahijani *et al.* 2024), driven by natural and human factors. It is also noted that the average decline

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rate for the last and current centuries is of the order of 10 cm/year which is about 25 times faster than the global mean sea rise, suggesting that the controlling forces go beyond anthropogenic water withdrawals. These changes have had significant impacts on the environment and the communities along the Caspian rim. Coastal wetlands, essential for flood regulation and carbon sequestration, are shrinking due to fluctuating water levels (Lahijani *et al.* 2023a & b). Fig. 1 illustrates these environmental challenges, including water level fluctuations, pollution, habitat loss, and invasive species, while also presenting proposed adaptive strategies aimed at mitigating these impacts and fostering resilience in the region.

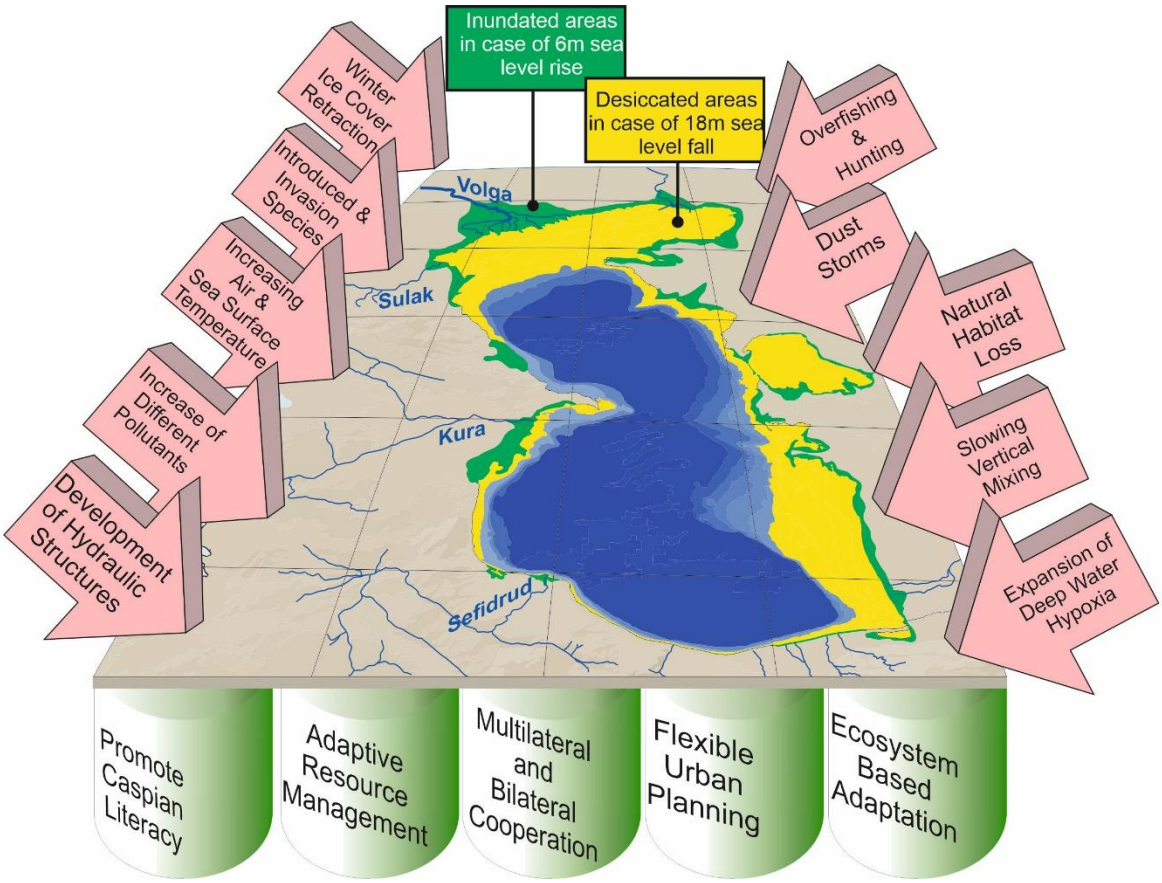

Fig. 1. Environmental Challenges and Adaptive Strategies for the Caspian Sea. This figure illustrates the Caspian Sea's environmental challenges, including water level fluctuations, pollution, invasive species, habitat loss, and hypoxia expansion. It shows areas vulnerable to inundation (green) and desiccation (yellow) under extreme scenarios. Adaptive strategies—such as promoting Caspian literacy, resource management, multilateral cooperation, flexible urban planning, and ecosystem-based adaptation—aim to build resilience and support sustainable environmental management.

Although historical records show that the Caspian has recovered from previous rises and falls—neither leading to ecocide nor catastrophe (Dumont 1995; Prange *et al.* 2020)—recent socioeconomic impacts are a major concern. Fluctuating water levels disrupt maritime and fishing industries, alter port depths, and increase transportation costs. Declining fish stocks and compromised spawning grounds now threaten food security for local communities. Historically, rapid sea-level changes and unpredictable wind and wave regimes led to bypassing the Caspian in major trade routes (Matthee 1994; Naderi Beni *et al.* 2024). In earlier times, human activities were more nature-based, utilizing small tributaries, Qanats, and multipurpose ponds for irrigation and water management. However, three major events since the mid-19th century have drastically shifted these practices: industrial exploitation of Baku's oil fields, extensive hydrologic interventions post-WWII, and the dissolution of the Soviet Union in 1991. The first two events led to significant pollution and the degradation of riverine habitats crucial for fish reproduction, while the latter event disrupted the regulatory framework previously governed by Iran and the USSR, leading to overexploitation of biological resources and increased stress on the ecosystem. Recent history highlights how sea-level changes have repeatedly reshaped the region. For instance, land reclaimed during the sea-level fall of 1940-1977 was subsequently flooded in the 1978-1995 rise, resulting in considerable

economic losses (Leroy *et al.* 2009). These events show that efforts to control or mitigate natural fluctuations are often costly and ineffective. While natural processes play a significant role, human activities exacerbate the Caspian Sea's problems. Pollution from oil and industry, agricultural runoff, and unsustainable water management have severely disrupted the environment (Tarasov 1996; Demin 2007; Akhmadiyeva & Abdullaev 2019; Lahijani *et al.* 2024). Overfishing and invasive species like *Mnemiopsis leidyi* and *Azolla pinnata* have destabilized the ecosystem further (Karpinsky *et al.* 2005b; Strukova *et al.* 2016). Additionally, dams and water diversion projects along major tributaries alter the natural discharge regime and limit fish spawning grounds. The dissolution of the Soviet Union left regulatory gaps, complicating environmental management (Lahijani *et al.* 2024). Overfishing, illegal hunting of endangered species, and unsustainable practices continue despite international bans, with sturgeon and caviar still available for consumption in the Caspian countries (IUCN 2024). Climate change, marked by warmer temperatures and reduced winter ice formation in the north, exacerbates stagnant water conditions, leading to reduced oxygen levels and higher hydrogen sulfide concentrations (Lavrova *et al.* 2022; Lahijani *et al.* 2023a).

Necessity to speed up cooperation

Several regulatory frameworks have been established to foster cooperation among the Caspian Rim countries, with the Tehran Convention (2003) as a primary agreement for pollution control and biodiversity conservation. While these frameworks and cooperative efforts exist, they are often undermined by legal ambiguities, economic priorities, and geopolitical tensions. Current cooperation remains insufficient to fully address the Caspian Sea's environmental challenges, including land-based pollution, overfishing, and the impacts of climate change on the sea's ecological health (Ghafouri 2008; Barbara 2014; Orazgaliyev & Araral 2019; Pietkiewicz 2021; Lahijani *et al.* 2024). Academic studies highlight the need for stronger enforcement of environmental laws and more effective regional collaboration to tackle these complex issues. Knowledge transfer from the scientific community to society is also lacking, and public awareness remains low. Greater Caspian literacy could foster societal concern and encourage decision-makers to prioritize environmental action. Regional cooperation has been successfully implemented in other parts of the world. For example, in the Arctic, international collaboration through the Arctic Council has promoted ecosystem-based management, climate monitoring, and sustainable development (Arctic Council 1996). These strategies, which emphasize transboundary cooperation, flexible management, and the integration of local knowledge (AMAP 1997), serve as a valuable model for the Caspian region. More than three decades have passed since cooperative efforts began among Caspian Rim countries, yet significant environmental improvements remain elusive. Instead, invasive species continue to spread, biological resources are declining, and several valuable species are endangered—all of which threaten to push the ecosystem to an irreversible tipping point. Despite existing frameworks, the persistent environmental challenges facing the Caspian Sea underscore the urgent need for enhanced cooperation and more robust adaptive strategies. The persistent environmental challenges facing the Caspian Sea emphasize the critical need for strengthened cooperation and robust adaptive strategies.

A window for adaptive strategies under climate change

For millennia, societies around the Caspian Sea have adapted to environmental changes. Ancient settlements adjusted agricultural practices and trade networks in response to fluctuations in sea levels (Naderi *et al.* 2024). However, modern infrastructure has reduced this adaptability, leaving contemporary societies more vulnerable to these shifts. The Caspian Sea's water level fluctuations are a natural part of its history and should not be viewed in isolation. Instead, they serve as valuable indicators of broader climatic shifts. Yet, modern responses have increasingly involved attempts to control or mitigate these changes in ways that do not align with natural processes. For instance, a major Soviet-era project proposed to stabilize Caspian water levels through transboundary connections in the 1960s-1970s, but it was ultimately abandoned due to environmental and economic concerns (Voropaev & Ratkovich, 1985).

Rather than seeking artificial stabilization, it is more prudent to adopt adaptive strategies that work with natural processes. Key approaches include:

Promoting Caspian Literacy: Increase awareness and understanding through educational initiatives targeting both the public and stakeholders. An informed population can advocate for sustainable policies and practices.

Flexible urban planning: Design coastal infrastructure that accommodates natural fluctuations in water levels, incorporating buffer zones and adaptable urban layouts. This approach reduces the economic and social risks associated with sudden environmental changes.

Adaptive resource management: Developing policies for fishing, water use, and land development that are flexible and responsive to changing environmental conditions. This flexibility will help communities manage resources sustainably even as conditions shift.

Ecosystem-based adaptation: Restoring wetlands and other critical habitats to strengthen ecosystem resilience against both natural and human-induced pressures. Healthy ecosystems can provide natural buffers against climate impacts and support biodiversity.

Transboundary cooperation: Given the shared nature of the Caspian Sea, prioritizing international agreements that allow for dynamic resource management and adaptable territorial boundaries. Collaborative governance is essential for managing a shared ecosystem effectively.

By embracing these strategies, we can reduce societal vulnerabilities and foster a more sustainable relationship with the environment.

CONCLUSION

The Caspian region can serve as a testing ground for innovative adaptive approaches that can be applied globally. The challenges of climate change, resource depletion, and environmental degradation are not unique to this region—they are universal. The Caspian Sea, with its semi-contained environment and developing societies, offers an ideal platform for experimenting with adaptive, flexible strategies essential for future global sustainability. The Caspian Sea's experience underscores the essential role of resilience and adaptability, offering a vital framework for regions worldwide grappling with similar environmental challenges in an era of climate change.

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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