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Biodiversity in the Caspian Basin: Ecogeographical Challenges, Ecological Restoration and Pathways toward Sustainable Development

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Abstract
The Caspian Basin represents one of the most ecologically complex and geographically diverse regions of Eurasia, characterized by unique ecosystems, rich biological resources, and significant environmental gradients. However, increasing anthropogenic pressure, rapid urbanization, industrial pollution, unsustainable land use, climate change, and hydrological alterations have intensified ecological degradation across the region. These processes have led to habitat fragmentation, biodiversity loss, soil and water contamination, and declines in endemic and economically important species. This study evaluates the major ecogeographical risks affecting biodiversity within the Caspian Basin and explores ecological restoration approaches to support sustainable regional development. The research integrates ecological observations, geospatial analysis, biodiversity assessment, and environmental monitoring data collected from different ecosystems surrounding the Caspian region. The findings show that ecosystem restoration, landscape-level conservation planning, and sustainable environmental management strategies are essential to improving ecological resilience. The study also highlights the importance of interdisciplinary scientific cooperation, modern remote sensing technologies, and ecosystem-based management approaches to preserve biodiversity and maintain ecological stability within the Caspian Basin. The obtained results provide a scientific framework for future conservation planning and sustainable development initiatives in ecologically vulnerable regions.

1. INTRODUCTION

The Caspian Basin occupies a strategically important ecological and geographical position between Europe and Asia (Washington, 2024) and contains highly diverse terrestrial, coastal, wetland, and marine ecosystems. The region supports numerous endemic plant and animal species and serves as an important ecological corridor for migratory organisms. Because of its complex climate, geomorphological diversity, and rich natural resources, the Caspian Basin has historically maintained high ecological productivity and biological diversity. In recent decades, however, the region has faced considerable environmental stress from industrialization, oil extraction, intensive agricultural expansion, population growth, urban development, and climate variability. These pressures have accelerated ecosystem degradation and disrupted natural ecological processes. Coastal erosion (World Bank Group Report, 2023), desertification, salinization, deforestation, habitat destruction, and declining water quality have become

increasingly serious environmental challenges throughout the basin. Biodiversity conservation within the Caspian region has therefore become a major scientific and environmental priority. Sustainable ecosystem management requires a comprehensive understanding of ecological dynamics, species distribution patterns, environmental risks, and restoration potential. Ecogeographical assessments (Mammadova, 2024) provide valuable information for identifying vulnerable ecosystems and developing effective environmental protection strategies. This study aims to investigate the major current risks (Zarrin, 2022) affecting biodiversity in the Caspian Basin and evaluate ecological restoration pathways that may contribute to sustainable development. The study also emphasizes the importance of integrated environmental monitoring, ecosystem-based conservation planning, and international scientific collaboration to maintain long-term ecological stability in the region.

This study aims to investigate the ecogeographical conditions of the Caspian Basin and evaluate the key environmental factors influencing biodiversity distribution, ecosystem stability, and ecological degradation processes. The study further aims to identify sustainable pathways for biodiversity conservation and ecological restoration under increasing anthropogenic and climatic pressures.

2. RESEARCH METHODS

Time and Place

The study was conducted across selected ecological zones of the Caspian Basin (Aerospace View, 2022), including coastal ecosystems, semi-arid landscapes, wetland habitats, forested territories, and anthropogenically disturbed areas. A multidisciplinary research approach was applied to evaluate biodiversity status, environmental degradation processes, and ecological restoration potential.

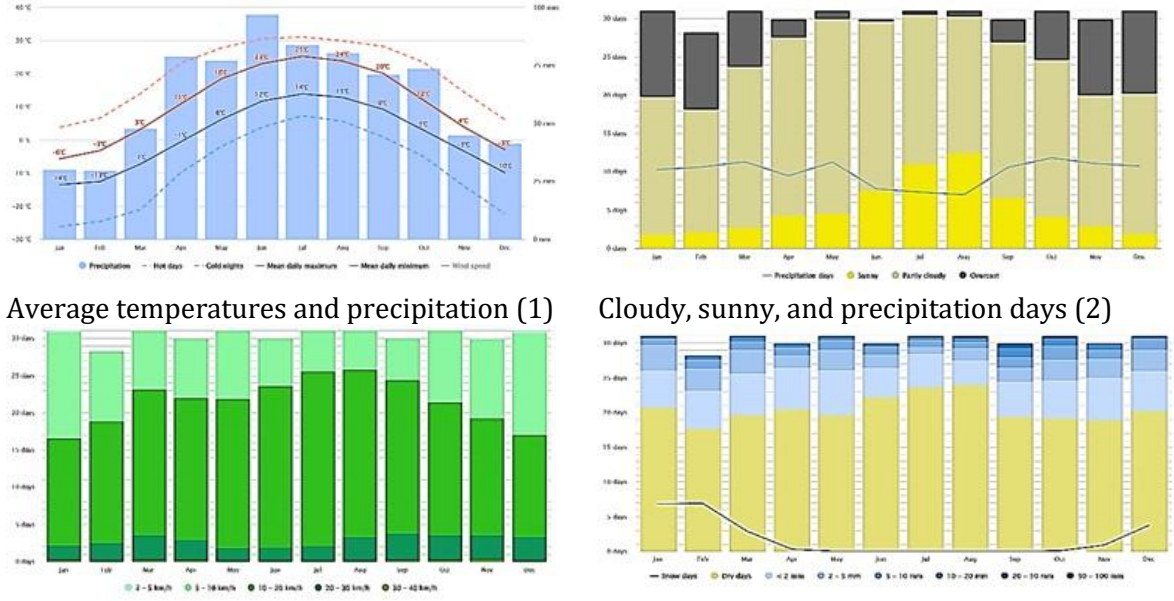


Figure 1. General natural view of the Caspian Sea

Field observations (Wallingford, 2024) and ecological surveys assessed vegetation structure, species diversity, habitat conditions, and environmental stress indicators. Sampling activities included soil analysis, water quality assessment, and vegetation monitoring within representative ecosystems. Biodiversity assessments focused on identifying dominant species, endemic taxa, and ecologically sensitive organisms exposed to environmental pressures.

Geospatial technologies and remote sensing methods were employed to analyze land-use changes, vegetation dynamics, habitat fragmentation, and spatial distribution patterns. The Caspian Sea is a unique inland water body located at the crossroads of Eastern Europe and Western Asia. It lies approximately between 36°33′00″N -47°07′00″N latitude and 46°35′00″E - 54°54′00″E longitude, forming a natural boundary shared by Azerbaijan, Russia, Kazakhstan, Turkmenistan, and Iran. With a surface area of about 371,000 km^2, it is the largest enclosed basin on Earth, combining characteristics of both a sea and a lake because of its saline water and isolated hydrological system. From a geographical perspective, the Caspian Sea shows a remarkable north-south environmental gradient (World Bank Group Report, 2022). The northern part is shallow, cold, and strongly influenced by continental conditions, while the southern basin is significantly deeper and climatically milder. This spatial contrast creates a mosaic of ecological conditions that directly shape biodiversity distribution and ecosystem structure across the basin. The Caspian region's climate is highly heterogeneous. Northern areas are dominated by a cold continental climate with long winters and temperatures that often drop below freezing.

In contrast, southern coastal zones experience a warmer, more humid subtropical influence, with significantly higher precipitation. Annual rainfall varies widely, ranging from less than 200 mm in arid eastern zones to more than 1,000 mm in the southern coastal belt. Temperature fluctuations and high evaporation rates play a crucial role in regulating the sea's water balance, making the Caspian highly sensitive to climate variability and changes in river inflow, particularly from the Volga River. As for the sea's climate, the Caspian Sea basin is predominantly semi-arid and continental, with hot, dry summers, relatively mild winters, and regionally variable precipitation patterns shaped by complex atmospheric circulation and marine-terrestrial interactions.



Average temperatures and precipitation (1) Cloudy, sunny, and precipitation days (2)

Wind speed (3) Precipitation amounts (4)

Figure 2. Main climate average annual parameters, 2025

In Figure 2, graph 1 shows a pronounced seasonal temperature regime in the Caspian region, with extremely cold winters and relatively warm summers, and mean daily maximum temperatures rising from about -6 °C in January to 25 °C in July. Precipitation shows moderate seasonal variability, peaking in late spring and autumn, while long-term extremes indicate both severe cold nights and warmer summer conditions over the past three decades. Figure 2 shows that the Caspian region is mostly partly cloudy year-round, with relatively few precipitation days and seasonal variation in cloudiness and sunshine. Figure 3 shows the wind speed variability over the Caspian Sea, indicating that average wind conditions typically range between 3-10 m/s, with occasional weak breezes of 1-3 m/s, while strong wind events reach 10-20 m/s and extreme

storm conditions can exceed 25-30 m/s, thereby playing a critical role in shaping wave dynamics, coastal processes, and atmospheric circulation patterns. Figure 3 shows mean annual precipitation over the Caspian Sea region, with values predominantly ranging from 100-400 mm across coastal and marine zones, while localized maxima of 400-600 mm occur under cyclonic and orographically enhanced conditions, reflecting a spatially heterogeneous precipitation regime that governs the basin's hydrological balance. Ecologically, the Caspian Sea is one of the most distinctive biodiversity hotspots among inland aquatic systems. Its long geological isolation has resulted in a high degree of endemism (Tatarnikov, 2022).

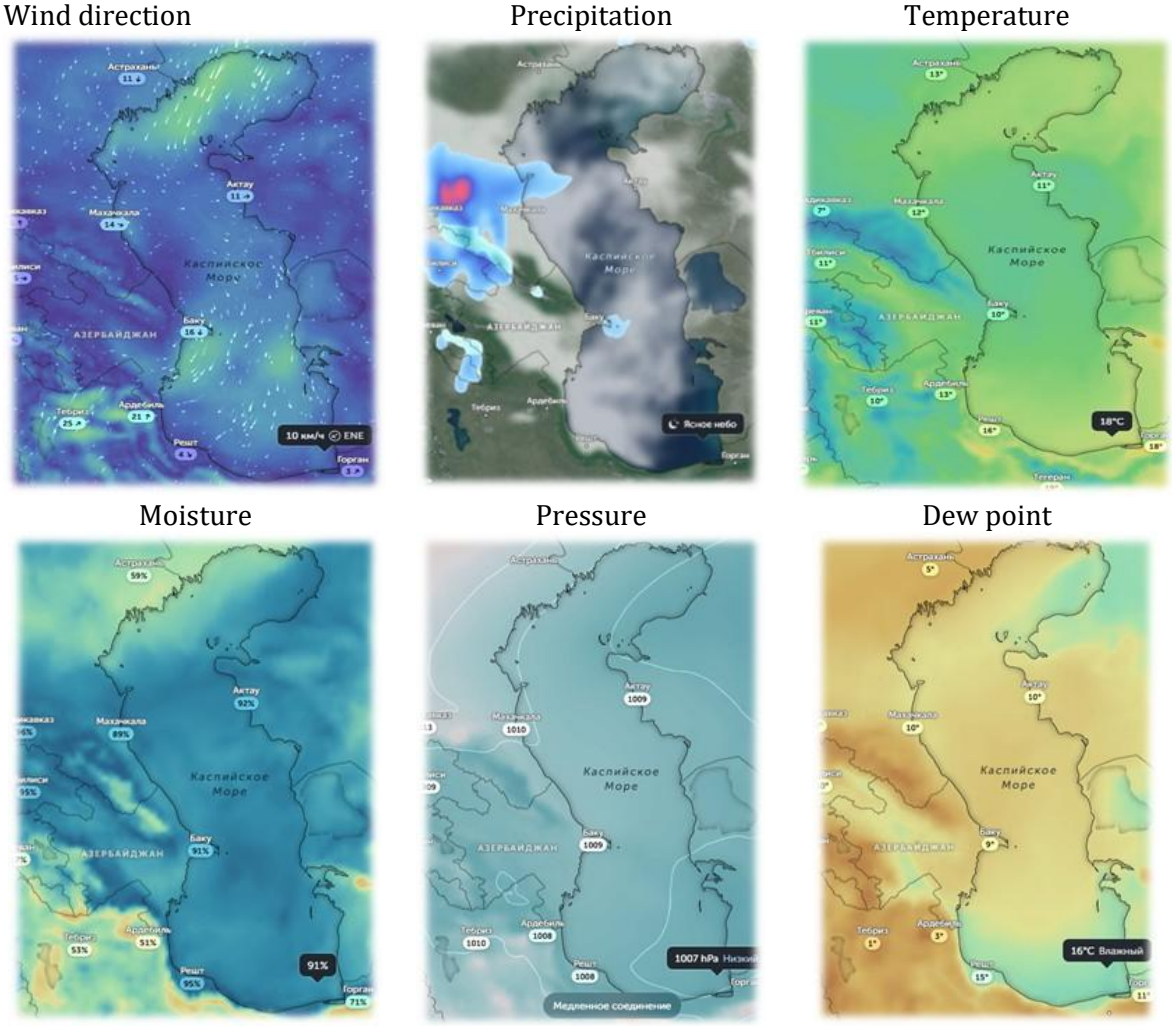


Figure 3. Daily climate map for May 15, 2026

As shown in the current maps (Climate, 2026), the same point in the southern Caspian Sea shows the same results. The ecosystem supports a wide range of species, including more than 400 recorded aquatic organisms, many of which are found nowhere else in the world. Among the most significant are Caspian sturgeon species, which have both ecological and economic importance, and the Caspian seal (*Pusa caspica*), the basin's only endemic marine mammal. The coastal and delta ecosystems, especially the Volga Delta, function as essential ecological corridors for migratory birds, supporting large populations of pelicans (*Pelecanus* spp.), flamingos (*Phoenicopterus* spp.), herons (*Ardea* spp.), and diverse waterfowl species (Anatidae family), which constitute key avian components of the Caspian Sea ecosystem, reflecting the region's high ecological productivity and the importance of coastal wetlands as critical habitats for feeding, breeding, and migratory stopover functions. Vegetation in the region is mainly composed of reed beds, halophytic plants, and salt-tolerant coastal flora (Flora, 2021) adapted to fluctuating salinity and arid conditions. However, this biodiversity richness is increasingly under pressure. Industrial pollution, oil and gas extraction, overfishing, habitat fragmentation, and climate-induced

hydrological changes are gradually destabilizing ecological balance. These pressures make the Caspian Sea (UN, 2022) not only biodiversity-rich but also highly vulnerable, requiring coordinated scientific monitoring and transboundary environmental management.

The Caspian Sea is a scientifically important natural system where geography, climate, and biodiversity are tightly interconnected. Understanding these interactions is essential for developing long-term strategies for conservation, ecological restoration, and sustainable regional development. Satellite datasets obtained from Landsat and Sentinel platforms were used to evaluate temporal environmental changes and ecological degradation processes within the region. Geographic Information System (GIS) techniques were also used to map ecological risk zones and restoration priority areas (Wallingford, 2024). We analyzed environmental parameters, including soil salinity, moisture content, organic matter levels, and water physicochemical characteristics, using standard ecological and laboratory methods. We compared relatively stable ecosystems with degraded environments to identify the main drivers of biodiversity decline. The collected ecological, geographical, and environmental datasets were integrated to evaluate restoration opportunities and develop sustainable ecosystem management recommendations for the Caspian Basin.

3. RESULTS AND DISCUSSION

The results revealed that ecogeographical conditions, climatic variability, and anthropogenic activities strongly influence biodiversity distribution (Samant, 2023) within the Caspian Basin. Areas exposed to intensive industrial operations, urban expansion, and unsustainable agricultural practices showed significantly reduced ecological stability and lower species diversity than relatively preserved ecosystems. Remote sensing analysis indicated substantial landscape transformation and habitat fragmentation in coastal and semi-arid regions. Vegetation degradation, salinity increase, and soil erosion were identified as major environmental factors contributing to ecosystem instability. Wetland ecosystems (Serykh, 2020) showed high ecological sensitivity to hydrological fluctuations and pollution stress, leading to declines in aquatic biodiversity and habitat quality. The study also showed that climate-related environmental changes, particularly rising temperatures and irregular precipitation patterns, have intensified ecological vulnerability across the basin.

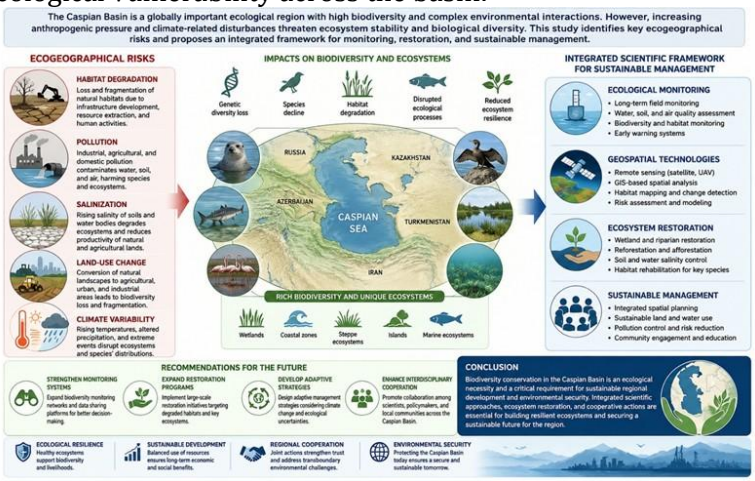


Figure 4. Biodiversity in the Caspian Basin, 2026

Alterations in water balance and seasonal ecological processes negatively affected vegetation productivity and ecosystem resilience. Ecological restoration approaches, including reforestation, wetland rehabilitation, sustainable land management, and biodiversity-oriented conservation planning, showed considerable potential to improve ecosystem functionality (Svetasheva, 2020) and environmental sustainability. Because the Caspian Basin extends across multiple national territories, transboundary environmental management and coordinated conservation policies are essential for long-term biodiversity protection. Overall, the study confirms that sustainable development within the Caspian Basin cannot be achieved without

preserving and restoring ecological integrity. Integrating ecological monitoring, geospatial technologies, and ecosystem restoration strategies provides an effective scientific framework for addressing these environmental challenges. Sustainable ecosystem management, restoration-oriented environmental planning, and interdisciplinary scientific cooperation are essential to improve ecological resilience and ensure long-term environmental sustainability.

Integrating geospatial monitoring technologies with ecological field assessments provided valuable opportunities for early detection of environmental degradation and restoration planning. The findings also emphasized the need for regional cooperation among scientific institutions, environmental organizations, and government agencies. Biodiversity conservation should therefore remain central to regional environmental policy and scientific research initiatives.

4. CONCLUSIONS

The Caspian Basin represents a globally important ecological region characterized by significant biodiversity and complex environmental interactions. Nevertheless, increasing anthropogenic pressure and climate-related ecological disturbances continue to threaten ecosystem stability and biological diversity throughout the region. This study showed that ecogeographical risks, including habitat degradation, pollution, salinization, land-use change, and climate variability, significantly affect biodiversity conservation in the Caspian Basin. Future research should strengthen biodiversity monitoring systems, expand ecosystem restoration programs, and develop adaptive environmental management strategies suited to rapidly changing ecological conditions. Protecting biodiversity in the Caspian Basin is not only an ecological necessity but also critical to sustainable regional development and environmental security.

AUTHOR CONTRIBUTIONS

UM: Conceptualization, Methodology, Investigation, Data Curation, Writing – Original Draft; ASA: Formal Analysis, Visualization, Writing – Review & Editing; IIZ: Supervision, Writing – Review & Editing.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

AI DECLARATION

AI-assisted technologies have been used in the writing process to improve the readability and language of the manuscript. No artificial intelligence tool generated primary research data.

REFERENCES

[UNDP] United Nations Development Programme. (2022). *Addressing the cost-of-living crisis in developing countries: Poverty and vulnerability projections and policy responses.* United Nations Development Programme. New York.

Aerospace View of the Caspian Sea. (2022): https://caspianpost.com/interview/can-the-caspian-sea-be-saved-exploring-solutions-for-a-regional-challenge-interview

Climate of the Caspian Sea. (2026). https://zoom.earth/places/caspian-sea/#map=dew-point/model=icon

Fauna of the Caspian Sea. (2023): https://www.azernews.az/nation/61315.html

Flora of the North Coast of the Caspian Sea, (2021): https://www.magnific.com/premium-photo/high-angle-view-rocks-by-sea_151216357.htm#from_element=cross_selling__photo

Mammadova U.F. (2024). Caspian Sea ecotourism potential: Sustainable development and conservation perspectives. *International and National Seminar of Fisheries and Marine Science, ISFM 2024 BIO Web of Conferences 136:*

Samant, R., & Prange, M. (2023). Climate-driven 21st-century Caspian Sea level decline estimated from CMIP6 projections. *Communications Earth and Environment,* 4, 357

Serykh, I.V., & Kostianoy, A.G. (2020). The links of climate change in the Caspian Sea to the Atlantic and Pacific Oceans. *Russian Meteorology and Hydrology,* 45, 430–437.

Svetasheva, D.R., Tatarnikov, V.O., Azmukhambetova, D.Kh., & Gontovayaa, I.V. (2022). The river flow projection in the Russian part of the Caspian Sea catchment basin. *Proceedings of the Scientific Conference on Climate Change in the Caspian Sea Region:* 91-93.

Tatarnikov, V.O., & Ocheretny, M.A. (2022). Long-term forecast of the Caspian Sea level in the face of global warming. *Proceedings of the Scientific Conference on Climate Change in the Caspian Sea Region:* 91-93.

Wallingford. (2024). Improving the resilience of port infrastructure, shipping and logistics to climate-related risks and disasters in the Caspian Sea. *Inception Report.*

World Bank Group Report (2022). *Europe and Central Asia Economic Update, Spring 2022: War in the Region.* World Bank Group Report. Washington, D.C

World Bank Group Report (2023). *Azerbaijan - country climate and development report.* Washington. D.C.

Zarrin, A., & Dadashi-Roudbari, A. (2022). Projected changes in precipitation intensity in the southern coast of the Caspian Sea using a CMIP6 multi-model ensemble. *Proceedings of the Scientific Conference on Climate Change in the Caspian Sea Region:* 97-100.