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THE CASPIAN SEA WATER LEVEL DECLINE: A COMPREHENSIVE REVIEW OF CLIMATE-DRIVEN IMPACTS ON ECOSYSTEMS, BIODIVERSITY, AND INFRASTRUCTURE

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Abstract. The Caspian Sea, the world's largest landlocked water body, is experiencing unprecedented water level decline driven primarily by climate change. This review synthesizes recent scientific evidence on the causes, consequences, and projected impacts of this environmental crisis. Analysis of satellite data reveals that water levels have declined by approximately 2 meters since 1996, with rates accelerating to 30 cm per year since 2020. Climate modeling projects potential declines of 9 to 21 meters by 2100 under medium to high emission scenarios, which would result in complete desiccation of the northern Caspian basin and conversion of up to 143,000 km² of water to land. Such declines critically threaten endemic species including the endangered Caspian seal (*Pusa caspica*) and six sturgeon species, while potentially reducing marine protected area coverage by up to 94%. Coastal communities, industrial infrastructure, and fisheries face billions of dollars in economic losses. The review identifies increased evaporation driven by rising temperatures as the primary driver, with anthropogenic water abstraction and dam construction on the Volga River exacerbating natural fluctuations. Effective mitigation requires adaptive, dynamic conservation planning, transboundary cooperation, and immediate policy interventions to protect both biodiversity and human livelihoods. The findings emphasize the urgent need for coordinated international action to address this environmental catastrophe, which serves as a critical test case for managing climate change impacts on major landlocked water bodies worldwide.

Keywords: Caspian Sea; water level decline; climate change; biodiversity conservation; marine protected areas; ecosystem services; transboundary cooperation; Kazakhstan.

Introduction

The Caspian Sea represents a unique and globally significant inland water body, covering approximately 387,000 km² and containing about one-third of Earth's inland surface water. Located at the crossroads of Europe and Asia, it is bordered by five countries: Kazakhstan, Russia, Turkmenistan, Iran, and Azerbaijan. This enclosed basin supports extraordinary biodiversity, including more than 300 endemic invertebrate species, 76 endemic fish species, and the endemic Caspian seal, along with globally important populations of migratory birds [1, 2].

The Caspian Sea's water level has historically fluctuated in response to climatic variations, with regressions of up to 90 meters and transgressions of 50 meters during the Quaternary period [3]. However, the current declining trend represents an unprecedented challenge in the context of anthropogenic climate change. Recent observations indicate an alarming acceleration in water level decline. Since the mid-1990s, radar altimetry data show consistent dropping water levels, with decline rates of 6.07 ± 0.26 cm per year between 2002 and 2015 [4], accelerating to as high as 30 cm per year since 2020 [5]. In July 2025, the Caspian Sea reached its lowest recorded level in the era of instrumental measurements, falling to less than 29 meters below sea level.

The fundamental mechanism driving current water level decline is climate change-induced imbalance between water inputs and evaporation. Rising surface temperatures have significantly

increased evaporation rates while precipitation and river discharge have decreased [4, 6]. Studies demonstrate that half of the water level decrease results from increased evaporation, with the remainder caused by lack of precipitation and reduced discharge from inflowing rivers. The Volga River, which accounts for approximately 80% of total water inflow into the Caspian Sea, plays a critical role in the sea's water balance [7, 8].

This review aims to: (1) synthesize current scientific understanding of the causes and mechanisms driving Caspian Sea level decline; (2) evaluate documented and projected impacts on ecosystems, biodiversity, and human infrastructure; (3) assess vulnerabilities of current conservation measures; and (4) identify critical research gaps and policy recommendations for effective mitigation and adaptation strategies.

Materials and Methods of Research. A comprehensive literature search was conducted using Web of Science, Google Scholar, and specialized databases for the period 2015–2025. Search terms included combinations of "Caspian Sea," "water level decline," "sea level change," "climate change," "biodiversity," "ecosystem," "conservation," and "infrastructure." Priority was given to peer-reviewed articles published in high-impact journals, particularly recent studies utilizing advanced climate modeling (CMIP6 projections) and remote sensing data.

Primary sources included: (1) Climate modeling studies projecting future water level scenarios [9, 6]; (2) Remote sensing and satellite imagery analyses documenting coastline recession [10, 11]; (3) Ecological assessments of biodiversity impacts [1, 2]; (4) Bathymetric projection studies evaluating spatial impacts on protected areas and infrastructure [10]; and (5) Reports from international organizations including UNEP, IUCN, and the Convention on Biological Diversity.

The review employs an IMRAD structure to systematically present findings. Climate projections are evaluated across multiple emission scenarios (SSP245, SSP585) using CMIP6 model outputs. Ecosystem impacts are assessed through spatial analysis of Ecologically or Biologically Significant Areas (EBSAs), Important Marine Mammal Areas (IMMAs), and World Database on Protected Areas (WDPA) designations. Infrastructure vulnerability is quantified through geographic information system (GIS) analysis of settlement locations, port facilities, and industrial installations relative to projected shoreline changes.

Research Results. Observed Water Level Changes and Coastline Recession. Analysis of long-term water level records reveals distinct phases of Caspian Sea level fluctuation throughout the 20th and early 21st centuries. Between 1940 and 1977, the sea level fell by an average of 4 cm per year, totaling 1.2 meters [12]. A period of rising water levels followed from 1978 to 1995, increasing by 13 cm annually for a total gain of 2.5 meters. However, since 1996, the sea has again declined, losing 8 cm per year for a total decrease of 1.83 meters by 2023 [13]. See Figure 1.

Satellite observations provide critical documentation of recent accelerated decline. NASA Worldview satellite imagery comparing 2001 to 2024 shows dramatic coastal recession in the northeastern Caspian Sea. Within a focal study area of 21,901 km², water coverage decreased from 15,194 km² in 2001 to 8,183 km² by 2024, representing a 46% reduction [10]. The coastline receded by more than 56 kilometers over this period. In some areas along the northeastern coast, the shoreline has retreated by 30-35 kilometers, severely impacting ecologically significant areas and seal habitats [13].

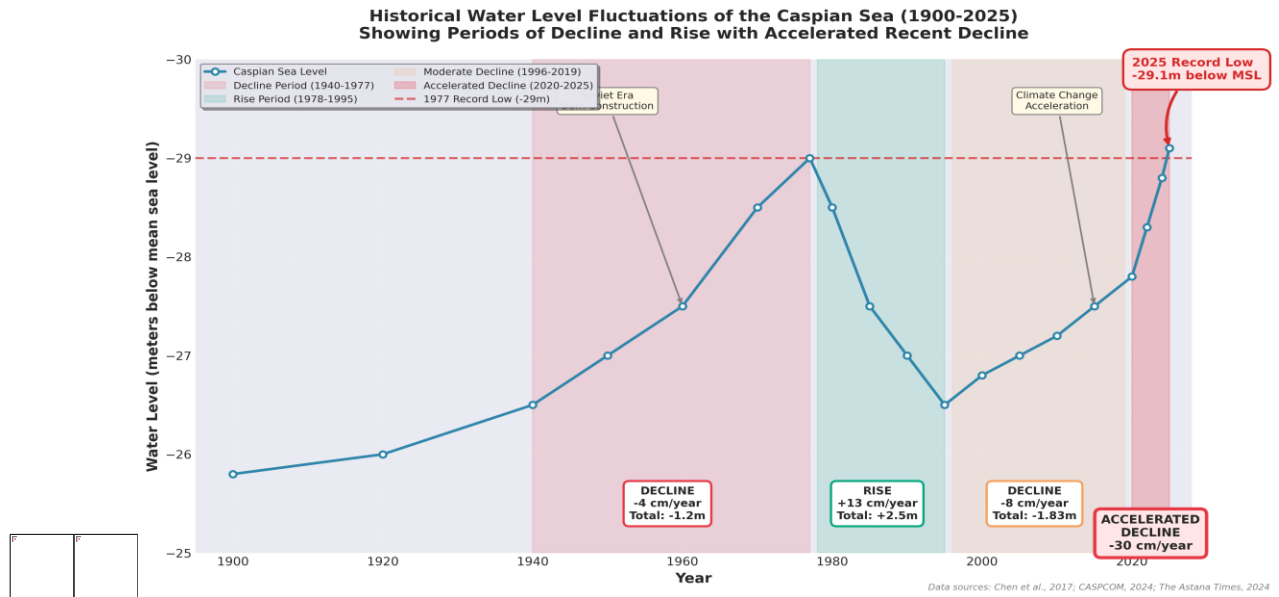


Figure 1. Historical water level fluctuations of the Caspian Sea (1900-2025)

Climate Modeling Projections. Multiple climate modeling studies utilizing CMIP6 projections consistently predict substantial future declines in Caspian Sea level. Samant and Prange [6] analyzed 15 coupled climate models across three shared socioeconomic pathways, projecting climate-driven sea level reductions of approximately 8 meters (inter-model range 2-15 meters) under the SSP245 scenario and 14 meters (inter-model range 11-21 meters) under SSP585 by 2100. Koriche et al. [9] found that accounting for human water extraction adds up to 7 meters of additional water loss beyond climate-driven decline. How it shown in Fig.2, models predict that even under optimistic emission scenarios limiting global warming to below 2°C, water levels will likely decline by 5-10 meters, with declines of up to 21 meters possible under high emission scenarios [14].

Projected Caspian Sea Level Decline Scenarios to 2100
 Based on CMIP6 Climate Models

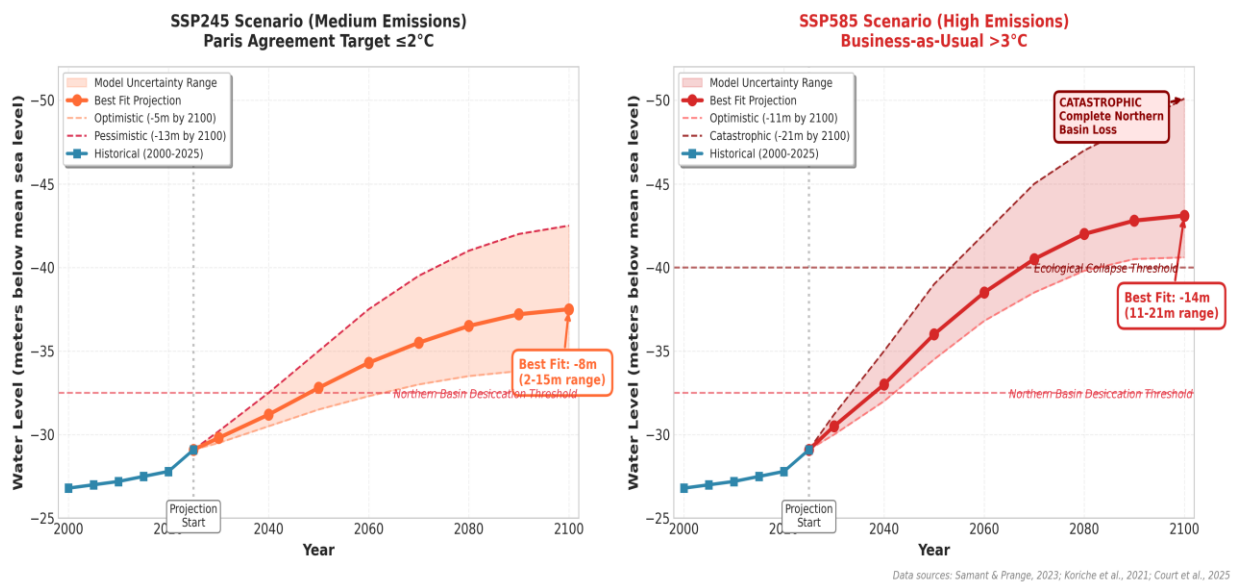


Figure 2. Projected Caspian Sea level decline scenarios to 2100

Impacts on Ecosystems and Biodiversity. The northern Caspian basin, characterized by extremely shallow bathymetry with average depths of only 5-6 meters, is exceptionally vulnerable to water level decline. Bathymetric projections indicate that a 5-meter decline would result in approximately 77,000 km² (20% of current sea surface) transitioning from water to land, with the northern basin experiencing the most dramatic changes [10].

The Komsomol Bay Ecologically or Biologically Significant Area (EBSA), recognized as an important spring molting site for Caspian seals, provides a stark example of ecosystem loss. By 2024, most of this area had become completely desiccated, forcing seals to shift to newly emergent islands to the north, though at lower densities than previously observed [10]. The endangered Caspian seal (*Pusa caspica*) faces existential threats from habitat loss. Projections indicate that a 5-meter decline could reduce the breeding Important Marine Mammal Area (IMMA) by 57-81% [10].

Six species of Caspian sturgeon, all critically endangered, face additional pressure from declining water levels. Summer and autumn sturgeon ranges could experience 25% reduction with a 5-meter decline and 45% reduction with a 10-meter decline [10].

Reduction of Protected Areas and Conservation Designations. Spatial analysis of marine conservation designations reveals catastrophic potential losses. Under a 5-meter decline scenario, 7 of 15 EBSAs would experience proportional coverage reductions exceeding 50%, with 4 completely desiccated [10]. Current marine protected area coverage stands at 16.8% of the Caspian Sea extent. However, this would decline precipitously to 7% under a 5-meter scenario and just 1% under a 10-meter decline [10]. Coastal terrestrial protected areas would experience multi-kilometer increases in distance to shore.

Infrastructure and Socioeconomic Impacts. Major Caspian ports critical for international trade face severe operational challenges. Under a 10-meter decline scenario, Baku, Anzali, and Aktau would experience increases in distance to shore of 1 kilometer or more [10]. Offshore hydrocarbon production facilities in the northern Caspian, including the Kashagan and Filanovsky oil fields, face becoming landlocked under 5-to-15-meter declines. Industrial fishing for kilka would lose at least one major fishing ground under declines above 5 meters [10]. For coastal communities, particularly in Kazakhstan and Russia, settlements would experience mean increases in distance to shore of 44-89 kilometers under a 10-meter decline scenario [10]. More than 15 million people live around the Caspian coast [15], with livelihoods deeply connected to the sea.

Conclusion. The Caspian Sea is experiencing a climate change-driven environmental crisis of unprecedented scale. Water levels have declined approximately 2 meters since 1996, with rates accelerating to 30 cm per year since 2020. Climate modeling consistently projects further declines of 9-21 meters by 2100 under medium to high emission scenarios, threatening complete desiccation of the northern basin. These changes will have catastrophic impacts on biodiversity, with the endangered Caspian seal facing potential loss of 57-81% of breeding habitat and six sturgeon species losing critical areas. Marine protected area coverage could decline from 16.8% to just 1% under conservative scenarios. Economic impacts will be measured in billions of dollars annually.

Effective response requires immediate, coordinated action: implementation of adaptive conservation planning; enhanced transboundary cooperation through strengthened legal frameworks; comprehensive monitoring systems and research programs; proactive planning for infrastructure adaptation and community support; harmonized water management across the Volga River basin; and sustained political commitment to environmental sustainability. The fate of the Caspian Sea serves as a critical test case for global capacity to address climate change impacts on major landlocked water bodies. Success requires recognition that the scale of anticipated disruption merits international attention beyond the five littoral states.

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КАСПИЙ ТЕҢІЗІНІҢ СУ ДЕҢГЕЙІНІҢ ТӨМЕНДЕУІ: КЛИМАТТЫҚ ӘСЕРЛЕРДІҢ ЭКОЖҮЙЕЛЕРГЕ, БИОӘРТҮРЛІККЕ ЖӘНЕ ИНФРАҚҰРЫЛЫМҒА ЖАППАЙ ӘСЕРІНІҢ ШОЛУЫ

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Аңдатпа. Каспий теңізі, әлемдегі ең үлкен тұйық су көлемі ретінде, климаттық өзгерістердің әсерінен су деңгейінің төмендеуін бастан өткеруде. Бұл шолу зерттеу климаттық өзгерістердің себептері, салдары және болжамды әсерлері туралы ғылыми дәлелдемелерді жинақтайды. Серіктік деректердің талдауы көрсеткендей, су деңгейі 1996 жылдан бастап шамамен 2 метрге төмендеді, ал 2020 жылдан бастап жылына 30 см жылдамдықпен төмендеу жылдамдығы артты. Климаттық модельдеу 2100 жылға қарай орташа және жоғары эмиссия сценарийлері бойынша 9-дан 21 метрге дейінгі су деңгейінің төмендеуін болжайды, бұл Солтүстік Каспий бассейнінің толық кебуіне және 143,000 км² судың құрлыққа айналуына әкелуі мүмкін. Мұндай төмендеу қауіпті түрлерге, оның ішінде қатерде тұрған Каспий итбалығына (*Pusa caspica*) және алты бекіре түріне қатер төндіреді, сонымен бірге теңіз қорықтарының қамтылуын 94% дейін қысқартуы мүмкін. Жағалау қауымдастықтары, өнеркәсіптік инфрақұрылым және балық шаруашылығы миллиардтаған доллар экономикалық шығынға ұшырайды. Шолу температураның көтерілуімен қоректенетін буланудың жоғарылауын негізгі қозғаушы күш ретінде анықтайды, ал Волга өзеніндегі су алу және бөгет салу табиғи ауытқуларды күшейтеді. Тиімді азайту бейімделгіш, динамикалық қорықты жоспарлауды, трансшекаралық ынтымақтастықты және биоалуантүрлілікті және адам өмірін қорғау үшін жедел саясат араласуларын қажет етеді.

Түйін сөздер: Каспий теңізі; су деңгейінің төмендеуі; климаттық өзгерістер; биоәртүрлілікті сақтау; теңіз қорықтары; экожүйелік қызметтер; трансшекаралық ынтымақтастық; Қазақстан.

СНИЖЕНИЕ УРОВНЯ ВОДЫ КАСПИЙСКОГО МОРЯ: КОМПЛЕКСНЫЙ ОБЗОР КЛИМАТИЧЕСКИХ ВОЗДЕЙСТВИЙ НА ЭКОСИСТЕМЫ, БИОРАЗНООБРАЗИЕ И НА ИНФРАСТРУКТУРУ

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Аннотация. Каспийское море, крупнейший в мире замкнутый водоем, переживает беспрецедентное снижение уровня воды, вызванное в первую очередь изменением климата. Данный обзор обобщает последние научные данные о причинах, последствиях и прогнозируемых воздействиях этого экологического кризиса. Анализ спутниковых данных показывает, что уровень воды снизился примерно на 2 метра с 1996 года, при этом темпы снижения ускорились до 30 см в год с 2020 года. Климатическое моделирование прогнозирует возможное снижение на 9-21 метр к 2100 году при средних и высоких сценариях выбросов, что приведет к полному высыханию северного бассейна Каспийского моря и превращению до 143 000 км² воды в сушу. Такое снижение критически угрожает эндемичным видам, включая находящегося под угрозой исчезновения каспийского тюленя (*Pusa caspica*) и шесть видов осетровых, при этом потенциально сокращая покрытие морских охраняемых территорий до 94%.

Прибрежные общины, промышленная инфраструктура и рыболовство сталкиваются с экономическими потерями в миллиарды долларов. Обзор определяет повышенное испарение, вызванное ростом температур, как основной движущий фактор, при этом антропогенный забор воды и строительство плотин на реке Волга усугубляют естественные колебания. Эффективное смягчение требует адаптивного, динамичного планирования охраны природы, трансграничного сотрудничества и немедленных политических вмешательств для защиты как биоразнообразия, так и средств к существованию людей.

Ключевые слова: Каспийское море; снижение уровня воды; изменение климата; сохранение биоразнообразия; морские охраняемые территории; экосистемные услуги; трансграничное сотрудничество; Казахстан.