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RESEARCH ARTICLE
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The Shrinking Caspian Sea: Eco-Hydrological Responses to Human and Climate Pressures

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Key Points:

- Caspian Sea water levels declined sharply in recent years
- Basin precipitation over the basin remained stable, while rising evaporation accounts for a minority share of the observed water loss
- Reduced river inflow, especially from the Volga, occurred despite stable precipitation and likely reflects within-basin water use

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The Caspian Sea, the Earth's largest inland water body, faces water level decline, drawing comparisons to the collapse of the Aral Sea. Unlike the Aral Sea, the relative roles of climatic variability, hydrological changes, and anthropogenic pressures on the Caspian Sea remain poorly understood. Here, we integrate satellite observations, in situ hydrological records and reanalysis data to examine recent drivers of the Caspian water loss. We show that total river inflow to the Caspian Sea has declined significantly, primarily due to reduced discharge from the Volga River. At the same time, precipitation over the basin has remained broadly stable, while evaporation over the sea has shown a modest upward trend. These findings point to compound anthropogenic and climatic influences on the regional water balance. We also detect a long-term increase in chlorophyll-*a* concentrations in the shallow Northern Caspian, signaling growing ecological stress associated with ongoing hydrological change. Avoiding further ecological disruption requires coordinated international action and policies to mitigate shrinkage by optimizing water allocation and environmental releases, as well as prioritizing long-term ecosystem resilience. Without urgent intervention, the Caspian Sea risks following the trajectory of other desiccating inland water bodies, with long-lasting ecological and socioeconomic consequences.

Plain Language Summary The Caspian Sea, the world's largest inland water body, has been shrinking steadily since the early 1990s. Using satellite data and river flow measurements, we show that rainfall over the region has remained largely unchanged with modest increases in evaporation. At the same time, river inflow to the Caspian Sea, particularly from the Volga River, has declined substantially. We also observe increasing signs of ecological stress in the northern Caspian Sea, including rising chlorophyll-*a* levels. These

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findings highlight the need for coordinated international water management to reduce future ecological and socio-economic risks.

1. Introduction

The Caspian Sea, Earth's largest landlocked water body and a key regional component of Eurasia's ecological and economic stability, is silently shrinking at a pace that raises concerns reminiscent of the catastrophic collapse of the Aral Sea (AghaKouchak et al., 2015; Spoor, 1998). Accounting for 41% of the total volume of saline lakes globally, this inland sea sustains over 850 endemic species, including the critically endangered Caspian seal and sturgeon populations producing 90% of the world's black caviar (Harkonen et al., 2012; Lahijani et al., 2024; Pietkiewicz, 2021; Pourkazemi, 2006; Wurtsbaugh et al., 2017). The Caspian Sea socio-ecological system supports fisheries, trade, and industries for the five states along its coasts: Azerbaijan, Iran, Kazakhstan, Russia, and Turkmenistan. Yet, in the absence of an international governance and sharing system that is supported by these littoral states, the Caspian Sea has been subject to one of the longest transboundary water and energy conflicts with major environmental implications since the collapse of the Soviet Union (Madani, Rouhani, et al., 2014; Madani, Sheikhmohammady, et al., 2014). Since the mid-1990s, the Caspian Sea's water levels have gradually declined, especially in the northern parts, with projections warning of an 8–14 m decline by 2100 (Samant & Prange, 2023). This trajectory mirrors the Aral Sea's anthropogenic shrinkage against a backdrop of a fragmented governance landscape across the neighboring states, facing competition over energy and geopolitical influence.

Hydrologically, the crisis stems from an altered water balance (Chen et al., 2017). The Caspian Sea relies on inflows from about 130 rivers, 80% of which originate from the Volga Basin in Russia (Chen et al., 2017; Gelfan et al., 2024). However, upstream operations, agricultural water withdrawals, and reservoir expansions, coupled with rising evaporation from regional warming, have reduced inflows to historic lows (Chernogaeva et al., 2023; Koronkevich et al., 2023; Lahijani et al., 2024; Roshan et al., 2012). Meanwhile, downstream Kazakhstan, Azerbaijan, Iran, and Turkmenistan, as well as south Russia, face declining fisheries, salinized farmlands, and receding shorelines, increasing geopolitical tensions over maritime boundaries and offshore oil reserves (EIA, 2013; Prange et al., 2020; Zimnitskaya & von Geldern, 2011). Since measurements began, the Caspian Sea has experienced significant fluctuations in water level (Arpe & Leroy, 2007; Arpe et al., 2000; Lahijani et al., 2023) with the most significant decrease occurring in the late 1970s. The sea level increased from 1979 to 1995, causing extensive coastal inundation and economic damage in the early 1990s (Lahijani et al., 2023). However, this upward trend reversed in 1996 as confirmed by satellite altimetry data (see Figure 2). The Caspian Sea's water level has declined from −26 to −28 m mean sea level (MSL), a drop of about 2 m since 1996 (Figure 2d). During this period, the sea has lost approximately 23,858 km^2 (5.47%) of its surface area, representing an equivalent volume of 630 km^3 based on the relationship between area, elevation and volume. The 2018 Caspian Convention, hailed as a landmark legal framework, has failed to address the unfolding hydrological crisis, leaving littoral states in deep competition for dwindling resources (Pietkiewicz, 2021).

Many studies have attempted to forecast or project the water level changes using various approaches, including water budget models, stochastic models, climate simulations, and examining the relationships between the water level changes and water budget (Arpe et al., 2014; Elguindi & Giorgi, 2006a, 2006b; Nandini-Weiss et al., 2020; Renssen et al., 2007; Vaziri, 1997). However, many of these models struggled to accurately predict the water level fluctuations (Lahijani et al., 2023), primarily due to the lack of components to capture human activities and the limited availability of ground-based data. Several studies have found the water level simulation challenging due to systematic biases in modeling approaches, simplified assumptions, data limitations, and complex human interactions (Brunner et al., 2021; Wada et al., 2017). Additionally, most previous studies that incorporated ground observations focus only on portions of the basin, as countries bordering the Caspian Sea are known for not sharing hydrological data publicly (Ayzel et al., 2022). For the first time, we have compiled ground-based observations from major rivers in all five neighboring countries, enabling a more comprehensive analysis that integrates local and satellite-based data. This expanded data set allows us to examine not only the physical drivers of water level change but also the broader socio-environmental implications.

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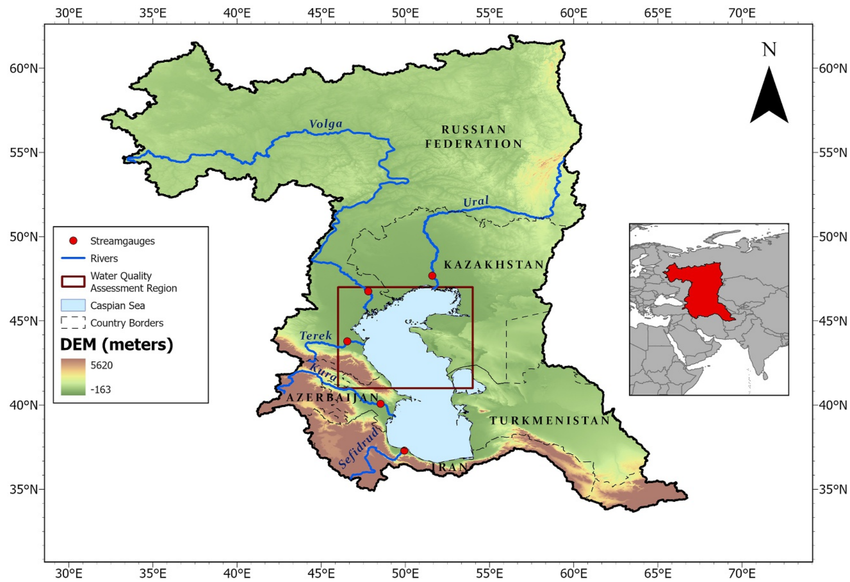

Figure 1. Map of the Caspian hydrological basin.

In large lake systems such as the Caspian Sea, hydrological changes can directly influence ecosystem health and water quality. Lakes are widely recognized as important indicators of water availability and ecological stability (Cheng et al., 2025). While much of the discussion surrounding the Caspian Sea decline focused on water quantity, the ecological consequences of these changes are equally critical, especially when considering the human dimension. In addition, the Caspian Sea is a major hotspot for the oil and gas industry, where approximately 1 million tons of oil are estimated to leak into the sea annually (Modabberi et al., 2020). These combined pressures raise concerns about how hydrological shifts and human activities may influence water quality and ecosystem functioning. In this study, we present a focused analysis of recent Caspian Sea Level (CSL) changes by examining river inflow, precipitation, evaporation, and water quality indicators within a broader hydroclimatic and human-influence context (Figure 1).

2. Materials and Methods

2.1. Discharge

We analyzed hydrologic variables, including river flows and precipitation dynamics over the Caspian hydrologic basin, focusing from 1991 to 2020 to capture a standardized 30-year timeframe. Yearly discharge data for the major rivers, from all five countries contributing to the Caspian Sea: Volga, Sefidrud, Ural, Kura, and Terek were obtained from the Caspian Sea Portal (2023). Historical flow data. Retrieved on 20 March 2024, from http://caspcom.com/%d0%b8%d1%81%d1%82%d0%be%d1%80%d0%b8%d1%8f/. To ensure consistency, discharge data were harmonized to a common temporal resolution and unit system and aggregated to annual values to minimize inconsistencies from measuring protocols. Due to missing discharge for the Kura in 2020, we restricted the total inflow analysis (sum of the five rivers) to the period 1991 to 2019, ensuring complete discharge data for all rivers. For the Volga River, which dominates the inflow, we extended the analysis from 1991 to 2020 to maintain a 30-year record. The long-term mean discharge for both the total inflow and Volga discharge, as well as the means for the first half (1991–2005) and the second half (2006–2019 for total inflow; 2006–2020 for Volga), were analyzed to assess temporal trends.

2.2. Precipitation

Monthly precipitation data were obtained from the Global Precipitation Climatology Center (GPCC) (Schneider et al., 2022) at a 0.25 grid resolution available at (https://opendata.dwd.de/climate_environment/GPCC/html/fulldata-monthly_v2022_doi_download.html), covering the Caspian hydrologic basin from 1991 to 2020. These data were aggregated to yearly means, and the first half and the second half were analyzed for both regions (the

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Caspian Sea and its hydrologic basin). Shapefiles for both basins were taken from Lehner and Grill (2013) (Table 1).

2.3. Evaporation

Evaporation data were obtained from the ECMWF Reanalysis V5 (ERA5) (Hersbach et al., 2020) data set with 0.25° resolution and similarly aggregated to yearly means to assess changes over time. The ERA5 data set can be found at https://cds.climate.copernicus.eu/.

2.4. Surface Area

This study estimated the annual surface water area using the MODIS Surface Reflectance Daily Level 2G product (MOD09GA, Version 6), which provides atmospherically corrected reflectance data at 500-m spatial resolution. The Caspian Sea region was defined by a rectangular region spanning 47.0°E–54.0°E longitude and 36.5°N–47.5°N latitude. Daily MODIS imagery from 2000 to 2020 was processed using the Google Earth Engine (GEE) platform. The Normalized Difference Water Index (NDWI) was computed from the green (Band 4) and near-infrared (Band 2) reflectance bands to detect water features. A threshold of NDWI > 0.1 was applied to identify open water pixels (McFeeters, 1996). To reduce the influence of atmospheric artifacts, cloud-contaminated pixels were masked using the state_1km QA band, retaining only clear-sky observations where the cloud state bits equaled zero.

For each year, a median composite of all valid daily water masks was generated to represent persistent annual water presence. Each composite was converted to water area by multiplying detected water pixels by pixel area and summing over the region of interest. The MODIS MOD09GA product used in this analysis is maintained by NASA's LP DAAC and was accessed via GEE (Vermote & Wolfe, 2021). We also, as a robustness check, validate the area estimates against the JRC Global Surface Water product (Pekel et al., 2016). Code to GEE can be accessed at (https://code.earthengine.google.com/9688f601518c1e9a38daa7b99e558528).

2.5. Statistical Test

Statistical significance of differences between the first and second half means is tested using the Mann-Whitney *U* test (Nachar, 2008). Long-term trends were evaluated using the Mann-Kendall test (Gilbert, 1987; Kendall, 1948; Mann, 1945).

2.6. Terrestrial Water Storage

To assess water storage within the basin, we obtained Terrestrial Water Storage Anomaly (TWSA) from the Gravity Recovery and Climate Experiment (GRACE/GRACE-FO) data set. We use GRACE and GRACE-FO monthly mascon solutions provided by NASA's Goddard Space Flight Center (GSFC), Version 2, to estimate TWSA. The GSFC mascon product provides surface mass anomalies at $1° \times 1°$ spatial resolution and is expressed directly in centimeters of TWSA, representing changes in total terrestrial water storage (Loomis et al., 2019; Luthcke et al., 2013). For the uncertainty estimate, we use the uncertainty fields provided by GSFC alongside the mascon data. These uncertainties reflect formal error propagation from the mascon inversion process and the regularization applied during the solution generation (Loomis et al., 2019). The GSFC mascon data are corrected for GIA, using the ICE6G-D mode (Richard Peltier et al., 2018). It should be noted, however, GIA models represent an additional and independent source of uncertainty, as they rely on limited observations and simplifying assumptions (e.g., ice history and Earth structure), leading to an imperfect representation of GIA-induced gravity signals (Eicker et al., 2024; Sun & Riva, 2020). Since the GSFC mascon product is designed to minimize signal leakage and does not require post-hoc rescaling, we do not apply additional scaling factors (Loomis et al., 2019; Luthcke et al., 2013).

2.7. Lake Volume Anomaly

Lake volume anomalies were initially based on the global estimates provided by Yao et al. (2023), which cover the period from October 1992 to September 2020. To extend the time series, updated lake water level data were retrieved from the Database for Hydrological Time Series over Inland Waters (DAHITI) (Schwatke et al., 2015). A height–volume relationship was established using overlapping data from 1992 to 2020, based on the comparison between DAHITI water levels and the volume anomalies reported by Yao et al. (2023). This empirical relationship was then applied to the continued DAHITI water level series, allowing for the extension of lake volume anomalies up to January 2025. We do, however, limit the analysis to 2020 for consistency. Annual storage change was then computed by differencing consecutive monthly volume anomalies and aggregating to annual totals.

2.8. Lake Water Level

Water level time series were derived from satellite altimetry data provided by DAHITI (Schwatke et al., 2015). The time series combines observations from multiple satellite missions operating along the same ground track (pass number 133), ensuring temporal consistency. Specifically, data from TOPEX/Poseidon, Jason-1 (SGDR-E), Jason-2 (SGDR-D), Jason-3 (SGDR-F), and Sentinel-6A (LR, F08) were used. The resulting time series spans from 1992 to December 2020 and provides a consistent record of lake water level variations, which was used in conjunction with a height–volume relationship to derive volume anomalies.

2.9. Contribution of Evaporation to the Observed Volume Loss

To quantify the contribution of increased evaporation to observed volume loss, we computed annual ET anomalies (mm) relative to two baseline periods: 1991–2000 (pre-decline) and 2000–2009 (early MODIS era) to isolate the long-term trend component. For each year from 2000 to 2020, we multiplied the anomalies by the annual median surface area derived from MODIS surface reflectance data to obtain annual excess evaporation volumes. Note that surface area data are only available from 2000 onwards via MODIS, hence all volumetric estimates begin from 2000. We then summed these annual volumes to calculate the cumulative excess evaporation over 2000–2020. The resulting cumulative volumes of evaporation were compared with the volume loss (630 km^3) calculated from the hypsometric relationship between water level and surface area and expressed as a percentage of total loss.

2.10. Hypsometric Curve

To calculate the hypsometric (area–elevation–volume) curve of the Caspian Sea, we used GEE to process the National Oceanic and Atmospheric Administration's Earth Topography at 1 arc min (NOAA ETOPO1 Bedrock) global relief model (1 arc-minute ∼1.8 km spatial resolution) to extract elevations within a bounding box (44.2°E–55.7°E, 31.0°N–55.0°N). The MODIS Land Water Mask (MOD44W, 24 February 2000) was additionally used to only include the permanent inland water pixels. Starting from the lowest elevations, values were binned at 0.1 m intervals, and for each bin, the area was calculated based on the pixel size ($1.85\ km \times 1.32\ km \approx 2.44\ km^2$). Cumulative area and the associated volume were then computed by summing across bins.

2.11. Water Quality

To assess harmful algal blooms (HABs) trends in the northern Caspian Sea, we utilized the MODIS Aqua Level-3 Standard Mapped Image (L3SMI) product for chlorophyll-*a* (Chl-*a*) concentration, provided by NASA's Ocean Biology Processing Group (OBPG) (NASA Ocean Biology Processing Group, 2017) (Available at: https://oceancolor.gsfc.nasa.gov/l3/). This data set spans from mid-2002 to 2021 and offers daily global coverage at a spatial resolution of approximately 4 km (9 km^2 per pixel), enabling analysis of both seasonal and interannual variability in phytoplankton biomass.

The L3SMI product aggregates Level-2 data that are atmospherically corrected and processed using the OC3M empirical band-ratio algorithm (O'Reilly et al., 2000). While the Caspian Sea is a semi-enclosed and optically complex system, prior studies (e.g., Mozafari et al., 2023) have shown that MODIS ocean color products can provide reasonable estimates of Chl-*a* in large inland water bodies, especially when temporal aggregation is used to reduce retrieval noise.

Chl-*a* values in the data set are reported in micrograms per liter (μg/L), and the standard uncertainty for MODIS-derived Chl-*a* retrievals over oligotrophic to mesotrophic waters typically ranges from ±30%–40%, with higher uncertainty over turbid, high-CDOM, or eutrophic waters such as the northern Caspian. To mitigate these issues,

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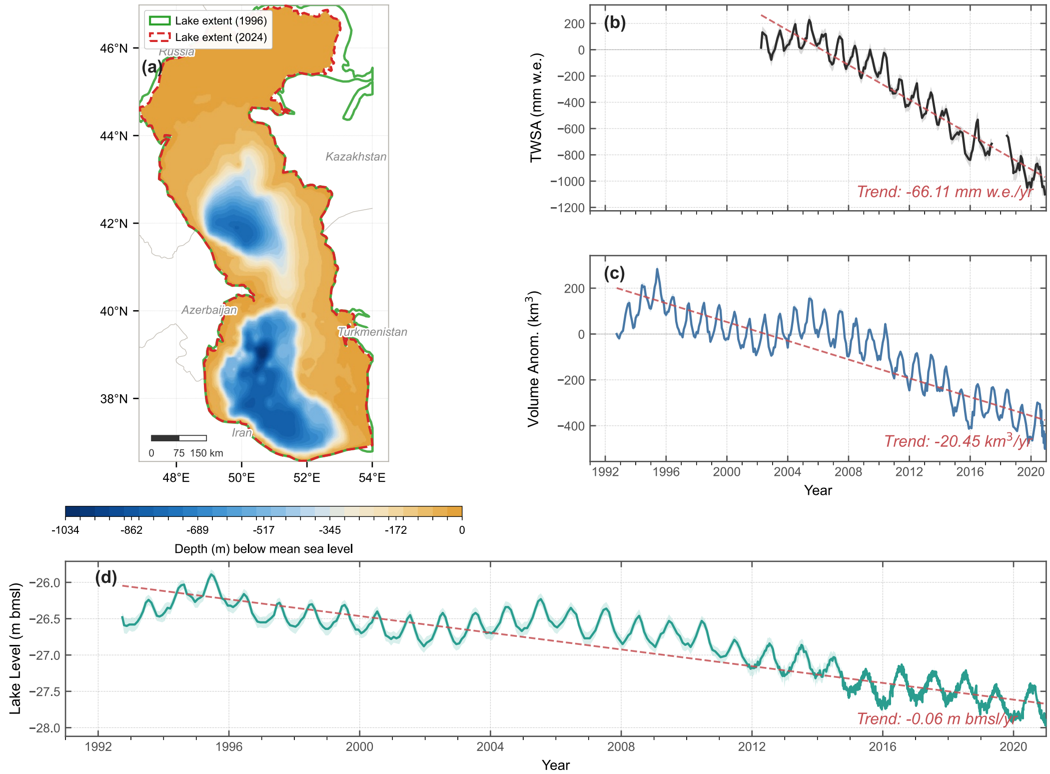

Figure 2. Long-term changes in the Caspian Sea. (a) Spatial distribution of the Caspian Sea's bathymetry with lake area changes in 1996 (green) and 2024 (red) overlaid. The observed shrinkage corresponds to an estimated loss of 23,858 km^2 (5.47%) of the lake's surface area or 630 km^3 of equivalent volume based on hypsometric conversion (see Text S1 in Supporting Information S1). (b) Total Water Storage Anomaly (mm water equivalent) from GRACE/GRACE-FO showing a negative trend. (c) Lake volume anomaly (km^3). (d) Caspian Sea water height (m) below mean sea level.

we aggregated daily observations to seasonal (May–November) and annual means, reducing the influence of atmospheric interference, sun glint, and cloud cover.

We processed the MODIS-Aqua L3SMI Chl-*a* product using the GEE platform. The analysis focused on the northern Caspian Sea (above 41°N), defined as a rectangular region spanning 46°E–54°E longitude and 41°N–47°N latitude. We calculated the average daily Chl-*a* concentration across all pixels in the northern Caspian Sea from May through November, when the probability of HAB occurrences and elevated Chl-*a* levels is typically higher. These daily values, derived from satellite observations, were then aggregated into annual averages from 2002 to 2021.

The MODIS OC3M algorithm, originally developed for open-ocean waters (O'Reilly et al., 1998), may be affected by suspended sediments and CDOM in optically complex environments such as the northern Caspian Sea. Similar limitations have been reported in previous studies of this region (Mozafari et al., 2023). Therefore, satellite-derived Chl-*a* is interpreted here as an indicative proxy of ecological variability rather than a direct measure of phytoplankton biomass.

3. Results

3.1. Long-Term Water Loss and Surface Shrinkage

Analysis of the Caspian Sea's decline is depicted in Figure 2, revealing long-term changes. Terrestrial Water Storage Anomaly shows a pronounced downward trend, reaching approximately −1,200 mm.w.eq by 2020. Our findings are consistent with (Chen et al., 2024), who also reported a decline in Caspian Sea levels based on GRACE and GRACE-FO data. It is important to note that no data-filling method was used to address missing data in the TWSA, resulting in a gap between 2017 and 2018 due to the transition from GRACE to Grace-FO. This

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Table 1
Summary of the Mean Annual Precipitation Over the Caspian and Volga Basins

Basin	Mean precipitation (1991–2005) (mm/yr)	Mean precipitation (2006–2020) (mm/yr)	Change (mm/yr)
Caspian	361.36	356.78	−4.58
Volga	566.62	578.37	+11.75

Note. Change represents the difference between the second and first half of the study period.

downward trend in TWSA is also mirrored by the lake volume anomaly (Figure 2c), which has decreased steadily. Furthermore, the water level decline (Figure 2d), supports this observation, indicating sustained water loss in the Caspian Sea.

3.2. Precipitation

For the 30-year period (1991–2020), mean annual precipitation over the Caspian basin remained stable at 359.1 mm/yr, with no significant difference between the first (1991–2005: 361.36 mm/yr) and second (2006–2020: 356.2 mm/yr) halves ($p = 0.74$) or long-term trend ($p = 0.94$). From Figure 3a, interannual variability is evident throughout the record, but without any systematic shift in the precipitation regime between the two periods (Figure 3b).

In the Volga Basin, precipitation exhibits larger interannual variability and a modest increase from 566.62 mm/yr (1991–2005) to 578.37 mm/yr (2006–2020), corresponding to a rise of 11.75 mm/yr; however, this change is not statistically significant ($p = 0.64$). Annual precipitation anomalies relative to the 1991–2020 climatology confirm the absence of any persistent wet or dry phase in either basin (Figure S3 in Supporting Information S1). To further assess whether changes in the seasonal timing of precipitation could account for altered inflow patterns, we examined seasonal totals (DJF, MAM, JJA, SON) independently. No statistically significant trends were detected in any season for either basin (MK-test, all $p > 0.05$), including Volga Spring precipitation, which showed the highest positive slope (+0.79 mm/yr) but remained non-significant ($p = 0.095$) (see Table S1 in Supporting Information S1). The absence of a declining precipitation signal in either basin, together with the lack of significant regime shift between periods or seasonal redistribution, indicates that reduced inflow to the Caspian Sea cannot be explained by precipitation trends alone.

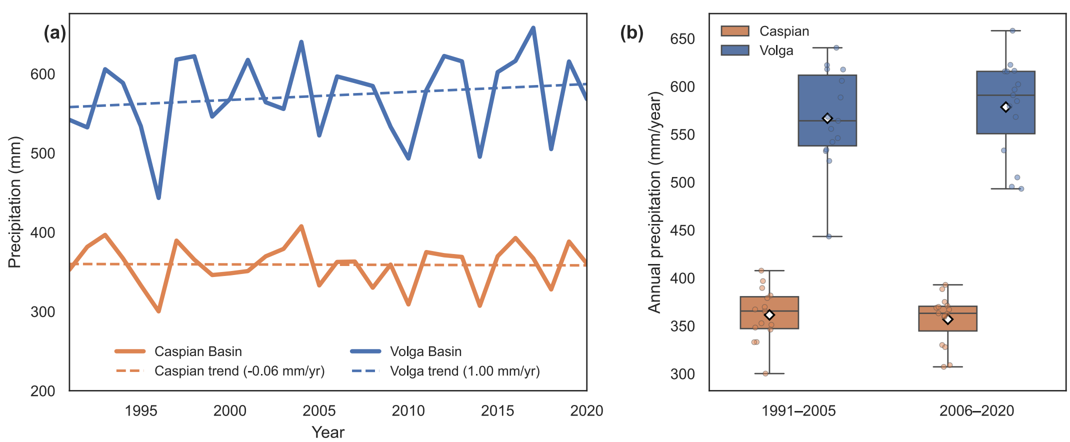

Figure 3. Precipitation variability and trends in the Caspian and Volga basins (1991–2020). (a) Annual basin-averaged precipitation time series for the Caspian (orange) and Volga (blue) basins derived from Global Precipitation Climatology Center, with dashed lines indicating linear trends. (b) Comparison of annual precipitation distributions between the first (1991–2005) and second (2006–2020) halves of the study period. No statistically significant change in precipitation is observed between periods in either basin.

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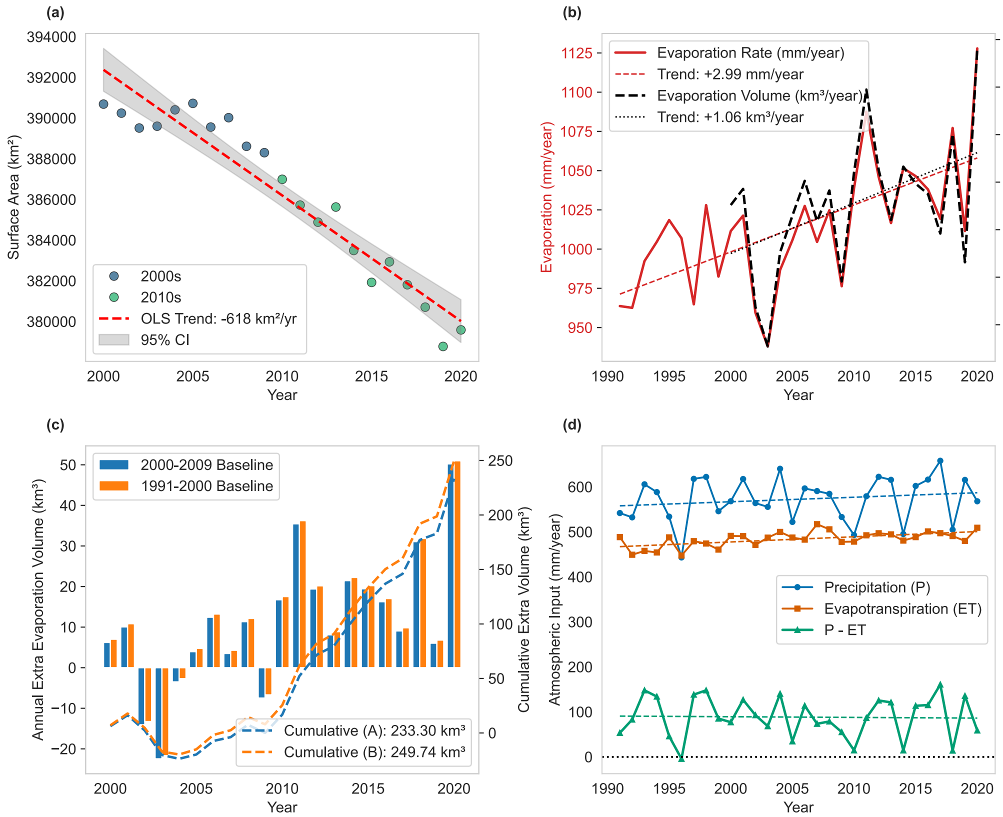

Figure 4. Evaporation flux and its contribution to the Caspian Sea water loss (1991–2020). (a) Annual median surface area of the Caspian Sea showing a decline of ~618 km^2/yr. (b) Evaporation rate (red, mm/yr) and evaporation volume (black, km^3/yr) with linear trends over the Caspian Sea showing evaporation increases over the sea. (c) Annual and Cumulative ET relative to two baselines (A: 2000–2009; B: 1991–2000). Cumulative excess evaporation explains 37%–40% of observed volume loss. (d) Annual precipitation (blue), Evaporation (orange), and net atmospheric Input over the Volga basin.

3.3. Evaporation

Figure 4 displays evaporation trends over the Caspian Sea. The evaporation rate in millimeters per year (mm/year) shows a statistically significant increasing trend of +2.99 mm/year between 1991 and 2020 ($p = 0.001$). This aligns with global reports documenting rising evaporation rates over sea surfaces, driven by increased sea surface temperatures and enhanced atmospheric moisture capacity (Ma et al., 2025; Yu et al., 2020). However, the evaporation rate alone does not capture the actual volume of water lost from the sea surface; for that, the rate must be multiplied by the surface area over which evaporation occurs. Although the evaporation rate increased, the concurrent decline in surface area (Figure 4a) means that the resulting increase in evaporation volume is more modest (+1.06 km^3/year), as the rising intensity acts over a progressively smaller water surface. We note that neither the increasing evaporation rate nor the evaporation volume can, on their own, explain the observed decline in the CSL.

We estimate the effect of increased evaporation by computing annual anomalies relative to a fixed baseline and multiplying by the annual median surface area (see Section 2). Since satellite-derived surface area is only available from 2000 onwards, all volumetric calculations were restricted to the 2000–2020 period. Using the baseline from the first decade of the MODIS record (2000–2009), the cumulative excess evaporation volume totals 233.30 km^3 over 2000–2020 (Figure 4c), explaining ~37% of the observed 630 km^3 volume loss. To test the sensitivity of this to baseline choice, we repeated the analysis using pre-MODIS ERA5 evaporation rates (1991–2000) as an alternative reference; this yielded an attribution of approximately 40% of the observed volume decline. The close agreement between these two independent baselines indicates that the estimated evaporation contribution is not strongly dependent on the choice of reference period.

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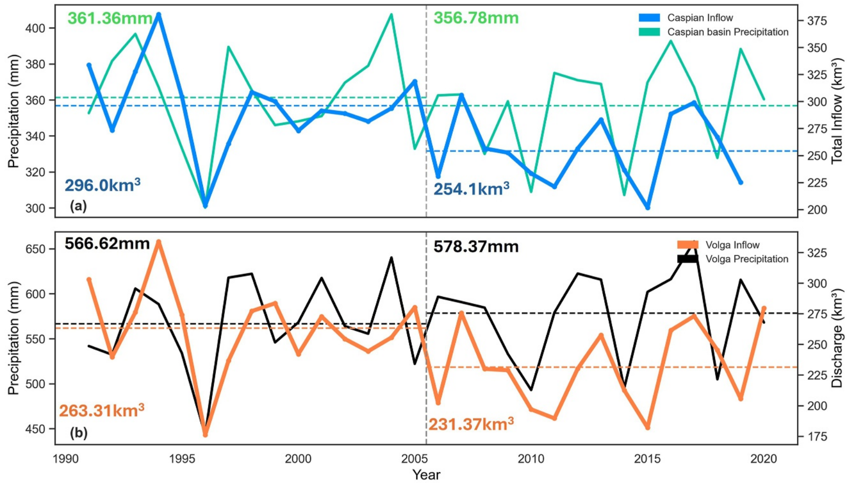

Figure 5. Hydrological Inputs to the Caspian Sea (a) Caspian Sea total inflow (blue line, km^3/year) and precipitation (green line, mm/year). (b) Volga precipitation (black line, mm/year) and discharge (orange line, km^3/year).

An independent comparison using the JRC Global surface data set produced the same qualitative conclusion, although the absolute area magnitude and slope were much smaller than in the MODIS series (see Figure S4 in Supporting Information S1). Nonetheless, the results suggest that increased evaporation alone is insufficient to explain the magnitude of the observed CSL decline.

3.4. River Inflows

River inflows have significant impacts on the variability of lakes and reservoirs (Döll et al., 2009). Within the study period, the Volga alone contributed ∼90% of the river inflow to the Caspian Sea (See Figure S2 in Supporting Information S1). Total inflow to the Caspian Sea from the five major rivers (Volga, Sefidrud, Ural, Kura, Terek) declined significantly over the study period (1991–2019) (Figure 5a), from a first-half mean of 296.0 km^3/yr to a second-half mean of 254.1 km^3/yr, a decrease of 41.9 km^3/yr ($p = 0.003$), with a significant downward trend ($p < 0.05$). Most of this decline is due to the decrease in the Volga River water flow, dropping from 263.3 km^3/yr (1991–2005) to 231.4 km^3/yr (2006–2020), a reduction of 31.9 km^3/yr (Figure 5b) ($p = 0.02$). Critically, this decline in river inflow occurred despite the absence of any significant change in precipitation over the Volga basin (Figure 3a). The divergence is further reflected in a significant decline in basin runoff efficiency (Figure S5 in Supporting Information S1). Mean runoff efficiency for the Caspian basin decreased from 0.24 in the first half (1991–2005) to 0.21 in the second half (2006–2019; $p = 0.02$), while the Volga basin declined from 0.34 to 0.29 ($p = 0.005$) (Figure S5 in Supporting Information S1). Long-term trends confirm a sustained decline rate of −0.002/yr for the Caspian basin ($p = 0.01$) and −0.003/yr for the Volga basin ($p = 0.005$) (Figure S6 in Supporting Information S1), indicating that a progressively smaller fraction of the basin precipitation is being converted to downstream runoff. To assess whether this decline could be explained by climate-driven increases in land-surface evapotranspiration, we examined net atmospheric input (P-ET) over the Volga basin (Figure 4d). No significant declining trend was detected, suggesting that increased catchment evapotranspiration alone is insufficient to account for the observed reduction in runoff efficiency (Table 2).

Table 2
Summary of Mean Annual River Inflow to the Caspian Sea

Inflow component	Mean inflow (1991–2005) (km^3/yr)	Mean inflow (2006–2020) (km^3/yr)	Change (km^3/yr)
Total inflow (5 rivers)	296.0	254.1	−41.9
Volga River	263.3	231.4	−31.9

Note. Total inflow includes the Volga, Sefidrud, Ural, Kura, and Terek rivers. Changes represent differences between the second and first half of the study period. The decline in total inflow is statistically significant (Mann-Whitney *U*-test, $p = 0.003$). The Volga River accounts for ∼76% of the total reduction.

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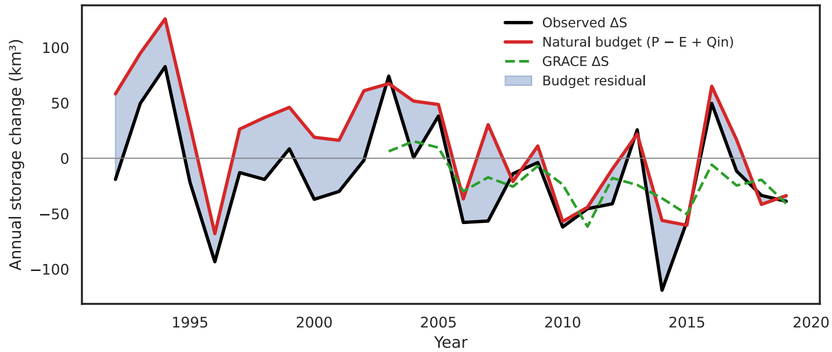

Figure 6. Annual observed storage change of the Caspian Sea derived from satellite altimetry and hypsometry (black) compared with the expected storage change from the natural water-budget component ($P - E + R$) (red). The GRACE/GRACE_FO- derived storage change (green-dashed), available from 2002 onwards, independently confirms the altimetry-based estimate. The shaded region indicates the residual between the observed and the expected storage changes, representing the unexplained component of the basin water balance. The residual averages approximately 30 km^3/yr (hypsometry) and 18 km^3/yr (GRACE).

3.5. Water Balance

Having examined each component of the Caspian Sea's water balance individually, we next evaluate their combined effect through an annual mass balance framework. We close the mass balance as $P - E + R$, where P is precipitation over the sea surface, E is evaporation, and R represents the total inflow. This budget is compared with the observed annual storage change (ΔS) derived from satellite altimetry and hypsometry (Figure 6).

Across the study period, the observed storage change reveals a persistent negative trend consistent with the long-term water loss. Independent estimates indicate a total volume decline of approximately ~630 km^3, while satellite gravimetry shows a TWSA decrease of about −1200 mm water equivalent over the period 2002–2020, corresponding to roughly ~500–520 km^3 when expressed over the Caspian Sea surface area. The close agreement between these independent estimates provides strong confidence in the magnitude of the observed decline. When comparing the observed storage change with the expected natural budget ($P - E + R$), a systematic discrepancy emerges (Figure 6). In most years, the natural budget suggests positive or near-neutral storage gains, whereas the observed storage change is consistently lower.

The residual averages approximately ~30 km^3/yr (18 km^3/yr when validated against GRACE). This residual does not correspond to the net volume loss of the sea itself, but rather reflects the annual imbalance between observed storage change and the sum of measured hydrological inputs. The persistence of this residual indicates that the measured components of the water balance—precipitation, evaporation, and gauged river inflow—are insufficient to fully explain the observed decline. Given that precipitation shows no significant long-term trend and increased evaporation accounts for an estimated ~37%–40% of the total volume loss, the remaining deficit is most plausibly attributed to reductions in effective river inflow and unmeasured fluxes in the budget components.

This interpretation is consistent with the observed decline in river discharge, particularly from the Volga River, and the concurrent reduction in runoff efficiency across the basin. Additional contributors to the residual may include surface outflow to the Kara-Bogaz-Gol and systematic uncertainties in reanalysis evaporation (ERA5) and gridded precipitation data sets (GPCC). The consistency between independent storage estimates confirms the magnitude of the observed decline. Together, these findings indicate that anthropogenic alterations to the hydrological system play a major role in the Caspian Sea's ongoing decline.

3.6. Water Quality

Water quality in the Caspian Sea is shaped by pollutant loads from major inflows including the Volga, Kura, Ural, and Sefidrud rivers, where elevated concentrations of nutrients, heavy metals, and organic pollutants have been documented (Amirgaliev et al., 2022; Zefrehei et al., 2021), contributing to eutrophication and the periodic occurrence of HABs. As an indicator of ecosystem response to ongoing change, we examined trends in Chl-*a*, a widely used proxy for algal activity and trophic state (Paerl & Otten, 2013).

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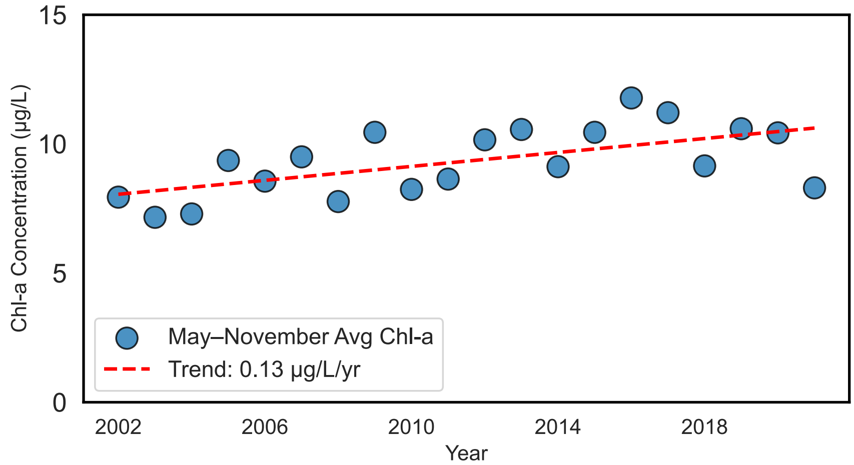

Figure 7. Annual average chlorophyll-*a* (chl-*a*) concentrations in the northern Caspian Sea (at latitudes above 44°) from 2002 to 2021 from MODIS L3SMI.

Using MODIS AQUA satellite L3SMI data (2002–2021) (NASA Ocean Biology Processing Group, 2017) over the Northern Caspian Sea (north of 41°N latitude), we found no significant trend in annual mean Chl-*a* for the region as a whole. However, results show a significant trend over 44° latitude, where historical records indicate that HABs have been most prominent (Mozafari et al., 2023). Over the 20-year period, the average Chl-*a* concentration ranged from 7 to 11 μg/L, with an upward trend of approximately 1.3 μg/L per decade at latitudes above 44° (Figure 7). A Mann–Kendall trend test indicates a statistically significant increase in Chl-*a* concentrations over the study period ($Z = 2.72$, $p = 0.006$). Spatial mean maps for 2002–2010 and 2011–2021 confirm that the increase is concentrated in the northernmost regions of the Caspian Sea, while changes in the southern portion are minor or slightly negative (Figure 8).

Given known uncertainties in satellite retrievals over optically complex waters and the potential for declining water depth to enhance sediment resuspension, these observations are interpreted cautiously as a proxy for ecological variability rather than a direct measure of phytoplankton biomass. They provide complementary evidence of ecological stress in the northern Caspian alongside the hydrological changes in recent years.

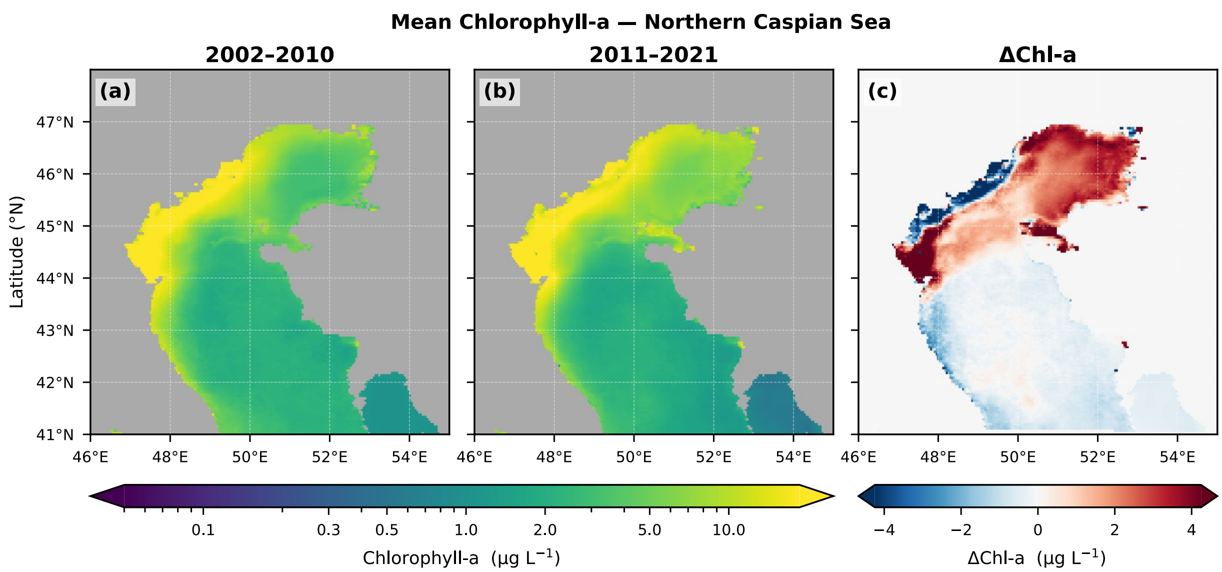

Figure 8. Mean chlorophyll-*a* (Chl-*a*) concentration in the northern Caspian Sea from MODIS Aqua L3SMI data for (a) 2002–2010 and (b) 2011–2021, and (c) their difference (ΔChl-*a*).

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4. Discussion and Conclusion

The decline of the Caspian Sea has become a topic of growing concern and debate, both scientifically and politically. While there is widespread agreement that the sea's water levels have dropped significantly in recent decades, the underlying causes remain contentious. It is common in the political or decision-making spheres to attribute the decline to climate change, an external, global driver seemingly beyond local human control. In contrast, this study aimed to investigate both the drivers of Caspian Sea shrinkage, illuminating that human actions and local anthropogenic impacts may play a far more significant role than publicly acknowledged.

Our results demonstrate that the observed volume loss cannot be attributed to changes in atmospheric forcing alone. Precipitation over both the Caspian and Volga basins showed no significant trend, either annually or seasonally. Increased open-water evaporation, while statistically significant, accounts for 37%–40% of the total volume loss. In contrast, river inflow declined by 41.9 km^3/yr between the first and second halves of the study period, with the Volga alone accounting for 31.9 km^3/yr of this reduction despite stable basin precipitation (Figure 5). The annual mass balance confirms a persistent residual of approximately 30 km^3/yr on average between the natural budget and the observed storage change (Figure 6) representing a deficit consistent with water consumption within the basin, though partially attributable to observational uncertainties. Taken together, these findings point to within-basin water consumption as plausibly the major contributor to the Caspian Sea's decline.

Contrary to recent climate modeling studies that attribute Caspian Sea decline primarily to Climate-driven evaporation increase (Court et al., 2025; Samant & Prange, 2023), Our results indicate that the observed water level decrease over the recent years cannot be fully explained by atmospheric forcing alone. We find no significant declining trend in long-term precipitation or net atmospheric input signal (P-ET) over the Volga Basin that could account for the observed water-level decrease (Figure 4d). While climate change undoubtedly exacerbates stress on the system, our results indicate anthropogenic impacts likely play a larger role in the recent CSL decline (Modaresi Rad et al., 2022).

Fluctuations in the Caspian Sea's volume have been documented, with historical records indicating changes exceeding three m over the years (Chen et al., 2017). However, the sustained decline observed over the past 30 years appears to be different in both character and cause, driven not only by climate variability but also, and perhaps more critically, by intensive human activities (Mineeva et al., 2021).

Additionally, although groundwater exchange may locally influence lake levels, available evidence suggests that such fluxes are small relative to river inflow and are unlikely to account for the magnitude of the observed multi-decadal Caspian Sea decline (Zekster, 1995). Engineering interventions in the Volga River and its tributaries over the last 70 years, undertaken to support agricultural expansion, navigation, industrial growth, and hydropower generation, have dramatically altered the basin's hydrology (Interim Secretariat of the Framework Convention for the Protection of the Marine Environment of the Caspian Sea, 2012). These interventions have fragmented the riverine system, reduced freshwater inflows, and disrupted the natural seasonal flow regimes, particularly in the northern Caspian (Koronkevich et al., 2023). Declining water levels may also have ecological consequences, particularly in the shallow northern Caspian Sea. Lower depths can enhance sediment resuspension, which can influence apparent increases in Chl-*a* concentrations.

Although the northern part of the Caspian Sea constitutes only about 1% of the sea's overall volume, it covers around 29% of the total sea area and has an average depth of 6 m, supporting a rich diversity of aquatic and riparian species (Byholm et al., 2022; Xenarios et al., 2025). The intra-annual variability of water flow in the Volga River has diminished significantly over the past 50 years, a pattern shaped not only by climate but also by shifts in agricultural practices and irrigation (Gusarov & Beylich, 2025). While the importance of human activities is evident, detailed data on water withdrawals, especially for irrigation, industrial, and municipal use by country, are not publicly available, limiting the ability to fully quantify anthropogenic impacts. Despite these data limitations, the evidence of human-induced decline is compelling.

The dichotomy between post-Soviet economic development and hydro-ecological sustainability is widening in the Caspian Sea basin, pushing the region beyond its hydrologic carrying capacity to sustain the sea and its ecological functions. The construction of dams, inter-basin transfers, and increasing withdrawals for irrigation and urban supply have significantly reduced inflows from major rivers. Meanwhile, intensified economic activity following the collapse of the USSR has placed additional stress on the fragile ecosystem. The development of new pipelines, refineries, and drilling operations, initially in Azerbaijan and subsequently in Kazakhstan and

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Turkmenistan, dramatically increased hydrocarbon production compared to Soviet times, attracting foreign investors and partners (Caspian Policy Center (CPC), 2023). The increased export of Caspian hydrocarbon resources to Europe, Russia, and Asia has intensified local water use and increased the environmental risks associated with oil spill incidents along energy corridors throughout the sea (Pentayev et al., 2025). Pollution and reduced river inflow have also devastated the sturgeon population, undermining the region's world-renowned caviar industry (Berman, 2024; Interim Secretariat of the Framework Convention for the Protection of the Marine Environment of the Caspian Sea, 2012; Leummens, 2016).

The Volga–Don Canal adds another dimension, both human and geopolitical. While most of its operational water is drawn from the Don River, the Volga's flow has also been regulated to support the canal and shipping logistics. The canal is of strategic importance, enabling the movement of Russia's Caspian Flotilla between the Caspian and Black Seas, especially since Turkey restricted naval passage under the Montreux Convention during the Ukraine conflict. Moreover, trade corridors such as Russia's North-South route and China's Belt and Road Initiative rely on the Caspian as a vital marine link. Falling water levels pose serious risks to these corridors, reducing cargo capacity, increasing dredging costs, and hindering port operations.

Beyond its ecological and economic consequences, the Caspian Sea's decline mirrors patterns of human-driven hydrological collapse seen elsewhere (Wurtsbaugh et al., 2017). The Aral Sea experienced catastrophic shrinkage due to massive irrigation diversions from the Amu Darya and Syr Darya (Duan et al., 2024; Spoor, 1998; Touge et al., 2024). Similarly, Lake Urmia in Iran has shrunk dramatically due to extensive dam construction and unsustainable agricultural withdrawals (AghaKouchak et al., 2015). Another notable example is Lake Chad, which also lost over 90% of its surface area since the 1960s due to combined climate and human pressures (Jedwab et al., 2023). These cases underscore a recurring theme: unsustainable water management, particularly excessive withdrawals and uncoordinated infrastructure development, can drive the collapse of inland water bodies with far-reaching consequences for ecosystems and human livelihoods (Hassani et al., 2020; Wurtsbaugh et al., 2017). A common pattern across the region, especially in Iran and Turkmenistan, is heavy investment in agriculture to create jobs, which in turn increases water withdrawals and reduces inflows to these lakes.

The array of human stressors threatening the Caspian Sea socio-ecological system extends beyond hydrology and also includes illegal and overfishing, increasing urban and tourism-related pollution, and unregulated waste disposal. For example, tourism infrastructure, notably along Iran's southern Caspian coast, has expanded rapidly, often without adequate planning or wastewater treatment (Mola et al., 2012). The resulting discharge of untreated wastewater further deteriorates water quality and accelerates ecological degradation (Nurmatov et al., 2025). Shifts in the phenology of primary producers, including the timing, magnitude, and composition of algal blooms, have been observed, jeopardizing food webs and economic activities reliant on ecosystem stability (Fendereski, 2023).

The geopolitical reconfiguration of the region, often referred to as the “new Great Game” (Atal, 2005; Bayramov, 2020), risks prioritizing short-term economic gains over long-term environmental security. While the five littoral states have taken steps toward cooperation, such as the 2006 Framework Convention for the Protection of the Marine Environment and the 2018 Aktau Convention, the effectiveness of these agreements remains limited. In particular, the lack of transparency in water accounting and binding mechanisms complicates sustainable inflow management and the prevention of further degradation from oil and gas development.

In essence, the Caspian Sea's response to combined human and climatic drivers of change signals a precarious trajectory and the disruption of socio-ecological functions. Our findings underscore that the decline is not simply a byproduct of climate change, but rather a complex, multi-dimensional issue in which human activities (e.g., dam construction, water withdrawal, energy development, and poor environmental governance) play a major role. Unless transparent and coordinated efforts are urgently undertaken by all five riparian countries, the Caspian Sea may face long-lasting ecological damage. Learning from the example of other regional collapses, such as the Aral Sea, immediate investment in sustainable water governance, data sharing, and environmental safeguards is critical to protecting the Caspian Sea's future.

5. Limitations

While this study provides a multi-component assessment of the CSL decline, several limitations should be acknowledged. The most fundamental limitation is the absence of publicly available data sets on water

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withdrawal across the Caspian basin. Detailed records of irrigation, industrial, and municipal water use are not publicly accessible to the research community, which limits the ability to close the Caspian water budget and adequately partition the observed sea level decline between climatic drivers and direct anthropogenic consumption. Without such data, the anthropogenic component of the water balance can only be estimated indirectly through residual analysis or coarse national statistics, both of which carry considerable uncertainty.

The evaporation estimates also used in the study are derived from ERA5 reanalysis, which may carry systematic biases over large inland water bodies due to uncertainties in surface energy balance, lake-atmosphere interactions, and the influence of salinity on latent heat flux. Exploratory comparison with the GLEAM data set yielded broadly consistent but more variable estimates, highlighting the inherent uncertainty in open-water evaporation estimation. Groundwater exchange between the Caspian Sea and surrounding aquifer systems also remains poorly constrained and is often treated as a minor residual term, though its true magnitude is uncertain. These limitations underscore the urgent need for coordinated transboundary monitoring and data sharing across the Caspian basin, encompassing its hydrology, water use and broader ecosystem health to support more robust assessments of the sea's ongoing decline.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

All data sets used in this study are publicly available. Precipitation data were obtained from the Global Precipitation Climatology Center (Schneider et al., 2022) available at (https://opendata.dwd.de/climate_environment/GPCC/html/fulldata-monthly_v2022_doi_download.html). Evaporation data were retrieved from ERA5 reanalysis (Hersbach et al., 2020). River discharge data for the Volga and other major tributaries were obtained from the Caspian Sea Portal available at http://caspcom.com/. Satellite-derived lake areas and water level products were sourced from publicly available remote sensing datasets. Analysis scripts supporting the findings of this study are archived on Zenodo available at https://doi.org/10.5281/zenodo.19265284 (Duku & AghaKouchak, 2025).

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