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Temporal analysis of the Caspian Sea level changes and their environmental consequences

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ABSTRACT
The Caspian Sea has experienced significant water level fluctuations, making its changes and ecosystem impacts a crucial concern in recent decades. This study analyzed the long-term trend of Caspian Sea water levels from 1990 to 2023, along with their environmental, social, and economic consequences. Using Landsat 5 (1990) and Landsat 8 (2023) imagery within Google Earth Engine (GEE), the research revealed a 2.34-meter sea level decline across the North, Middle, and South Caspian Sea during this period, dropping from -26.18 m in 1990 to -28.52 m in 2023. Recent Caspian Sea level fluctuations pose multifaceted threats. Infrastructure, economic activities (ports, seafaring, fishing), and social uses are disrupted. Wetlands and bays are drying, coastal areas are expanding, and human encroachment on the sea is increasing, negatively impacting coastal aquifers. Geopolitically, declining sea levels imperil the International North-South Transport Corridor (INSTC), a key strategic link for Iran and Russia. This "silent legal trap" of falling sea levels, though under-addressed by geopolitical analysts, is poised to become a significant source of conflict among littoral states. A cross-sectoral and comprehensive integrated coastal management approach is crucial to address these challenges.

Keywords: Remote sensing, Water level variations, Caspian Sea, Threats and impacts, Environment.

INTRODUCTION

Caspian Sea is the largest land-locked water body that is not naturally connected to other open seas (Court *et al.* 2025). The Caspian basin is extended from the dry desert region in the southeast to the humid temperate regions in high geographical latitudes. The length of the Caspian Sea watershed is about 2500 km from north to south and about 1000 km from west to east, which has influenced the Caspian Sea level in accordance with the climatic conditions of the basin (Ezam *et al.* 2020; Akbari *et al.* 2020). The Volga River basin, with a relatively humid climate in its northern part, covers approximately 1.38×10^6 km² and constitutes a major portion of the Caspian Sea drainage basin. Despite representing only about 40–45% of the Caspian Sea's contributing area, the Volga River provides approximately 80% of the riverine inflow to the Caspian Sea (Chen *et al.* 2017). During many centuries, the Caspian Sea level has changed based on the amount of water entering from the Volga River, which is dependent upon the amount of precipitation and evaporation in the watershed of the river. The level of these changes is a function of the variations cycle and the atmospheric and weather conditions of the North Atlantic Ocean, which is extended over thousands of kilometers in the north and west. All these factors have made the

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Caspian Sea a region with high sensitivity to the impacts of climate change (Nandini-Weiss *et al.* 2020; Prange *et al.* 2020).

Water level reduction has pervasive impacts and may influence water circulation, aquatic and coastal ecology, navigation and coastal infrastructure (Lahijani *et al.* 2023). Many researchers believe that water level variations in the landlocked seas and natural lakes can result into disrupting the different ecosystems exchanges that depend on them. The sea level changes are caused by the water balance of inland seas (or lakes) or there may be other causes such as the increase in sea surface temperature, harvesting above the amount of nutrition, temperature changes of land and global climate changes (Chen *et al.* 2023). Hence, the impact of these changes on the Caspian Sea level has extensive consequences on the coasts and coastal ports and can indirectly influence the livelihood and economy of millions of people.

The studies indicate that the increase in temperature during the 21st century has increased the evaporation of the Caspian Sea and local lakes (Cretaux *et al.* 2016; Yazdanpanah Dero *et al.* 2020). Temperature variations are regarded to be one of the factors of low water level of enclosed seas such as the Caspian Sea, which is worsened by the decline in rainfall. In this regard, natural lakes without any outflow indicate high sensitivity to climate change, since their water level is determined by the balance between rainfall and discharge of runoff into the lake and the lake surface evaporation (Duku *et al.* 2026). Besides, these changes can be caused by a considerable increase in water evaporation, indiscriminate harvesting, and a decline in the amount of water flowing into the Caspian Sea with the policy of dam construction in some upstream countries such as Russia, which is not balanced by the increase in river discharge or rainfall (Kostianoy *et al.* 2025).

Considering the disturbing conditions of the variations in the Caspian Sea and also the tensions created on its surrounding ecosystems, including wetlands, which have occurred based on the decreased water level of this sea, a comprehensive plan to reduce future crises has not yet been designed in the surrounding countries (Research Center Islamic Council, 2020). Thus, following these fluctuations, a chain of other environmental challenges including wetland ecosystems dependent on the Caspian water (e.g. international important wetlands of Anzali, Miankale Wetland and Amirkalai Wetland in Iran and the wetlands of the northern part of the sea located in the Volga Delta), wildlife around the wetlands related to this sea, significant changes in the coastline of the Caspian Sea, various risks to the ports located on its shores, can be major threats to more than several million individuals who indirectly depend on fishing (Hamzeh *et al.* 2017; Khoshravan *et al.* 2020). On the other hand, the decrease in the water level of the Caspian Sea has geopolitical consequences and affects the entire economy of the region. So, it is expected that there are international political tensions regarding the re-assignment of the geo-political divisions of the Caspian Sea, national water harvesting and desalination programs to meet the increasing demands of the agricultural, industrial and domestic sectors in water-stressed areas (Islamic Parliament Research Center, 2020).

Caspian Sea level variations are caused by mutual hydro-meteorological processes, which are not only at the level of the entire watershed, but also go far beyond it (Chen *et al.* 2017). Accordingly, the present study monitors the fluctuations of the Caspian Sea level in a long-term period, the trends of these changes during the period 1990 to 2023 were investigated using the Landsat image set.

Given the importance of this topic, some studies have been performed in this field so far, for example, Shojaei Nouri *et al.* (2023) on the impact of ehe Caspian Sea level fluctuations on the local changes of coastal lines of Nour and Royan urban region, North Iran. Their results demonstrated that a large part of the coastal lands of Noor and Royan cities have been submerged due to the rise in the sea level. In another study, Alizadeh *et al.* (2023) analyzed the changes of western coastal line of the Caspian Sea from Talesh to Anzali, North Iran. The obtained results indicate that 77% of the coastline has encountered water receding, among which human activities have partially caused the changes of the coastline due to the sea fluctuations. Chen *et al.* (2023) also examined the Caspian Sea level variations. They stated that the changing trend of the Caspian Sea has accelerated since 2005. Suzanne *et al.* (2022) investigated the changes in the Caspian Sea level in the last 2200 years, in its southeastern region. The Caspian Sea's level has fluctuated by over 15 meters, with a maximum annual change rate of 14 cm. This accelerating trend is linked to temperature shifts, human diversion of rivers, and increasing environmental hazards.

This study analyzes the Caspian Sea level fluctuations from 1990 to 2023, examining their environmental, social, and economic impacts. It contributes to long-term monitoring efforts by addressing two key questions: 1) What

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are the Caspian Sea level variations during this period? 2) What are the effects of these fluctuations on the surrounding environment?

MATERIALS AND METHODS

Study area

The Caspian Sea, the world's largest lake, covers approximately 400,000 km². It is bordered by five coastal countries: Iran, Russia, Azerbaijan, Kazakhstan, and Turkmenistan. Iran's political borders span 992 kilometers of the southern coast, extending from the Astara River to Hosseingjoli Bay, and from Astara to the Atrak River (Jannatov & Talibli 2026). The sea experiences diverse climates, bordered by the Ural and Volga rivers to the north, the arid plains of Kazakhstan and Turkmenistan to the east, and the Alborz mountains and the humid Caucasus regions to the south and west (Nasrollah Zadeh *et al.* 2016). The Caspian Sea is a biodiverse region with over 2,000 identified species. It also holds estimated oil reserves of 17-33 billion barrels, comparable to Qatar at the lower end and the United States at the higher end (Ghaderi azizi & Dehkordi 2015).

Fig. 1. Geographical location of the studied area.

Methodology

This study analyzed the changing trend of the Caspian Sea level from 1990 to 2023 using Landsat 5 (1990) and Landsat 8 (2023) imagery. The random forest algorithm, known for its effectiveness in classifying satellite images at various spatial resolutions, was employed for image classification, demonstrating superior results compared to traditional support vector machine and neural network methods (Ao *et al.* 2018; Zhang *et al.* 2019). Random Forest is a supervised classification technique that employs an ensemble of diverse decision trees for classification and decision-making. Each tree in the forest independently processes and evaluates data. This machine learning method is popular for its speed with large datasets and its ability to operate without requiring explicit training data (Fischer *et al.* 2023). This method first determines network parameters, including the number of trees and nodes per tree. Then, subsets of input data are randomly selected for each tree. After individual tree decision operations, results are integrated via majority vote for classification. Accuracy is determined by the trees' power and their correlation: better decision-making and lower correlation lead to higher final accuracy.

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Changing monitoring and accuracy evaluation

Detection and monitoring of changes, in fact, is the identification of changes in a place, which is performed in the process of remote sensing, using two- or multiple-time images (Liu *et al.* 2007; Munthali *et al.* 2020). The current study investigates the accuracy of classification based on Kappa index and overall accuracy as shown in Table 1.

Table 1. Evaluation of the accuracy of images based on overall accuracy and Kappa coefficient during the studied years.

Satellite images	Year	Overall accuracy	Kappa coefficient
L5-TM	1990	0.93	0.85
L8, OLI-TIRS	2023	0.98	0.90

The Caspian Sea level changes were monitored using Google Earth Engine (GEE). Data processing involved extracting monitoring maps based on the Normalized Difference Water Index (NDWI), classifying areas into water and non-water. NDWI uses visible green and near-infrared bands to detect water and exclude vegetation/soil. Values range from +1 (water) to -1 (non-water; Sagar *et al.* 2017). This index was calculated using Equation 1, with LANDSAT satellite images. Specifically, the visible green (band 3) and near-infrared (band 5) sub-bands were utilized. On the resulting maps, blue zones are coded as 0 and non-blue classes as 1.

Selection of training points

Sampling is a crucial stage in image classification, significantly impacting its quality and accuracy. This study visually and randomly selected 1500 sampling points per class within the GEE web system. Of these, 800 samples were used for algorithm training and 700 for classification testing.

RESULTS AND DISCUSSION

Caspian Sea level variations

To accurately monitor Caspian Sea water levels, satellite imagery of its northern, middle, and southern regions was acquired and analyzed as shown in Figs. 2, 3 & 4.

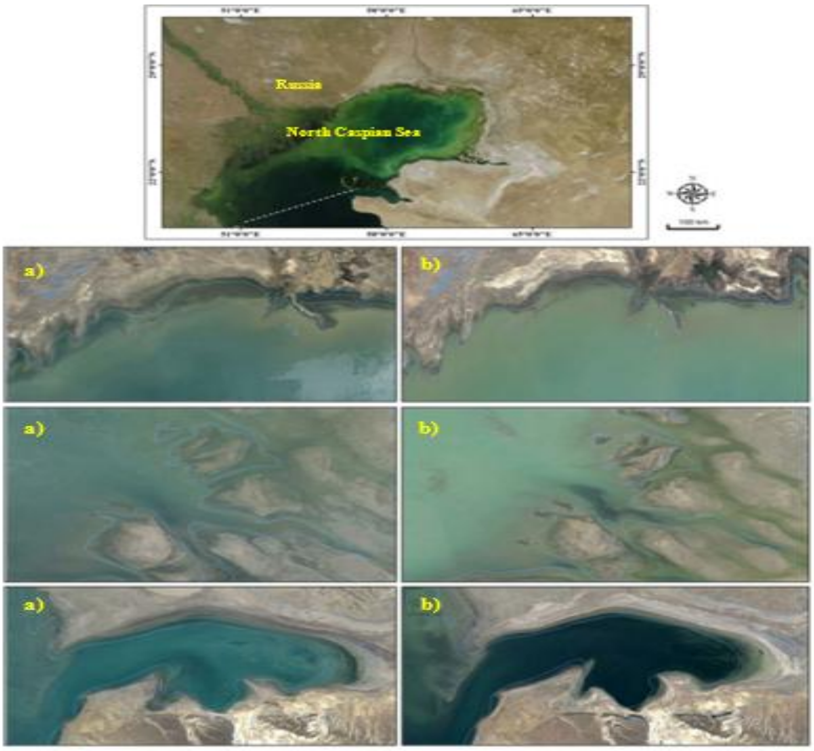

Fig. 2. Map of the fluctuation of the North Caspian Sea level during the years: a) 1990, b) 2023.

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From 1990 to 2023, the Caspian Sea level, encompassing its North, Middle, and South variations, experienced a total decline of 2.34 meters, dropping from -26.18 meters in 1990 to -28.52 meters in 2023 (Fig. 2). This period saw continuous fluctuations, with a decrease from -26.18 meters to -26.61 meters between 1990 and 2000, and a further drop from -26.18 meters to -28.63 meters between 2000 and 2010. Visual representations of this decline across the Caspian Sea's regions are presented in Fig. 5.

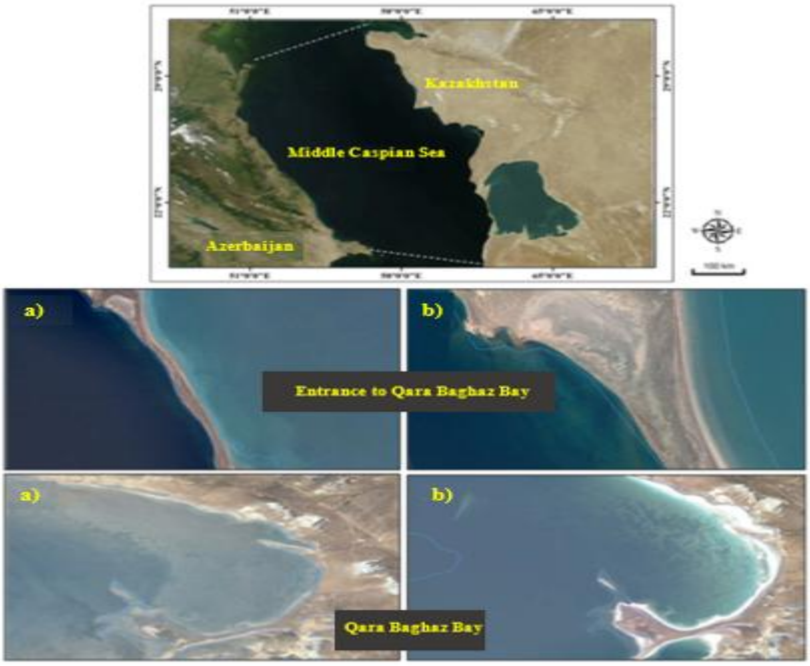

Fig. 3. Map of the fluctuation of the Middle Caspian Sea level during the years: a) 1990, b) 2023.

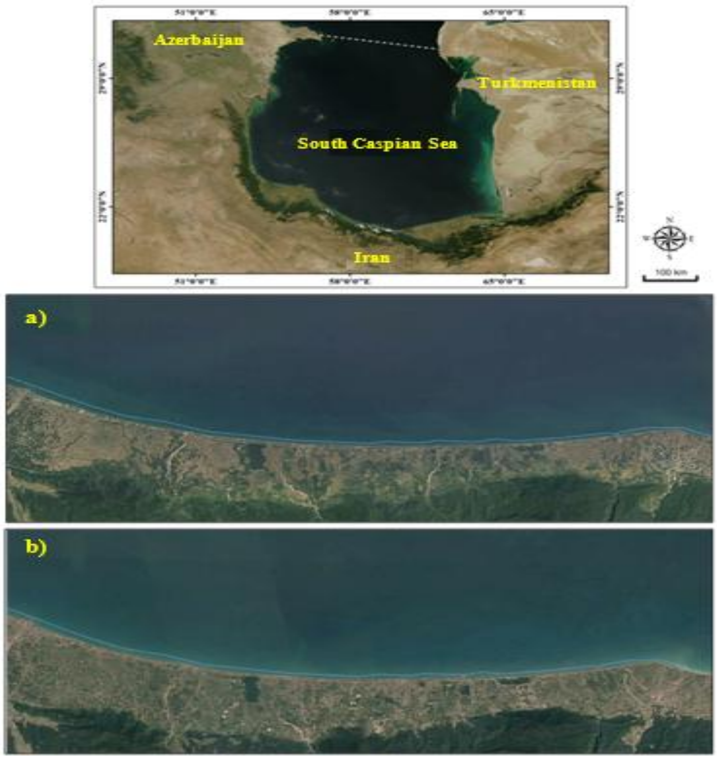

Fig. 4. Map of the fluctuation of the South Caspian Sea level during the years: a) 1990, b) 2023.

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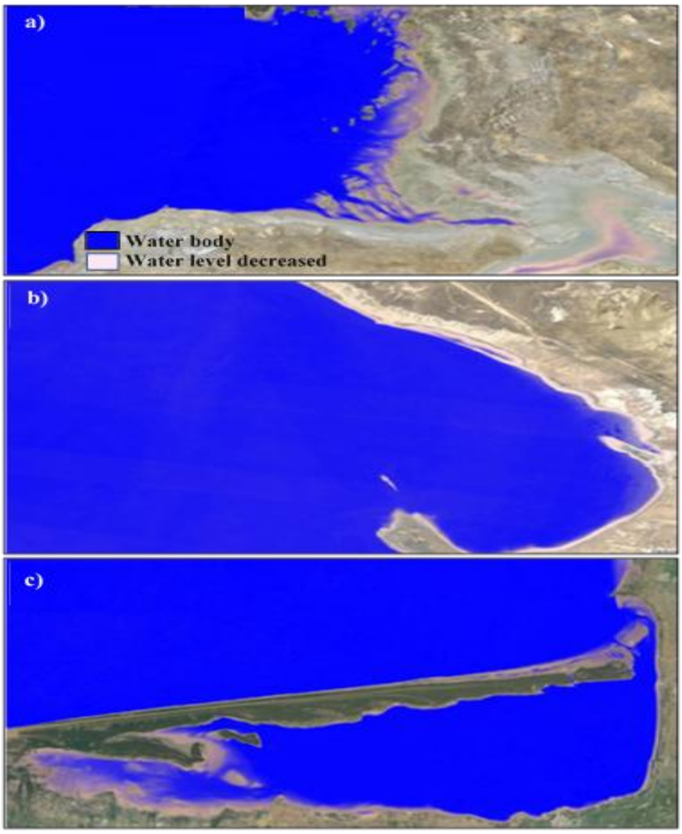

Fig. 5. Images of the reduced water area of Caspian from 1990 to 2023
a) North, b) Middle, c) South

The fluctuations of Caspian Sea level from 1990-2023

This study analyzed Landsat satellite imagery from 1990-2023 to investigate monthly Caspian Sea level fluctuations across three periods: 1990-2000, 2000-2010, and 2010-2023. The most significant fluctuations observed were: -26.7 meters in January 2000 (1990-2000 period, Fig. 6), -26.89 meters in January 2009 and 2010 (2000-2010 period, Fig. 7), and a -28.58 meter decrease in January 2023 (2010-2023 period, Fig. 8).

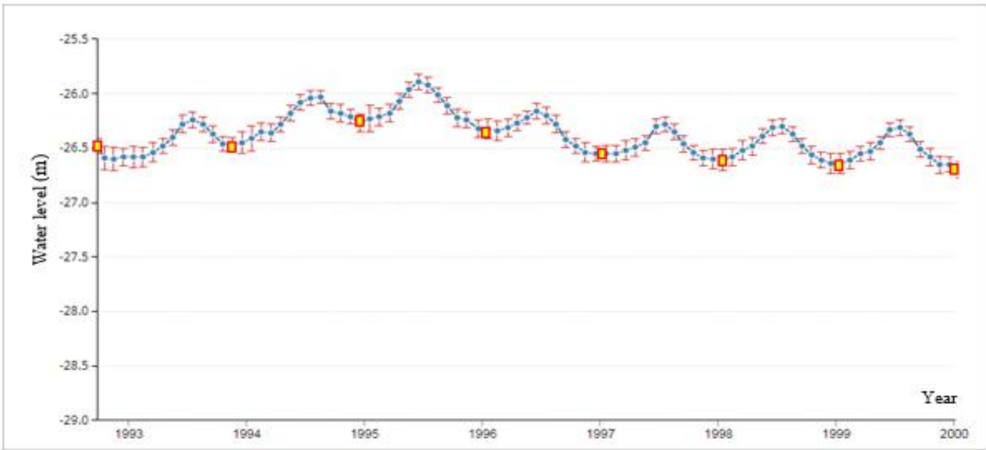

Fig. 6. Graph of Caspian Sea level fluctuations during the years 1990 to 2000.

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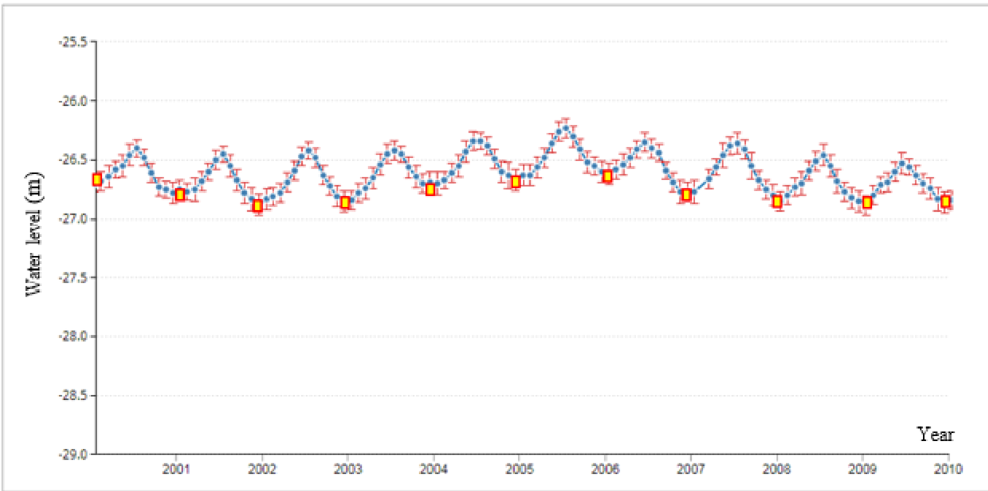

Fig. 7. Graph of Caspian Sea water level fluctuations during the years 2000 to 2010.

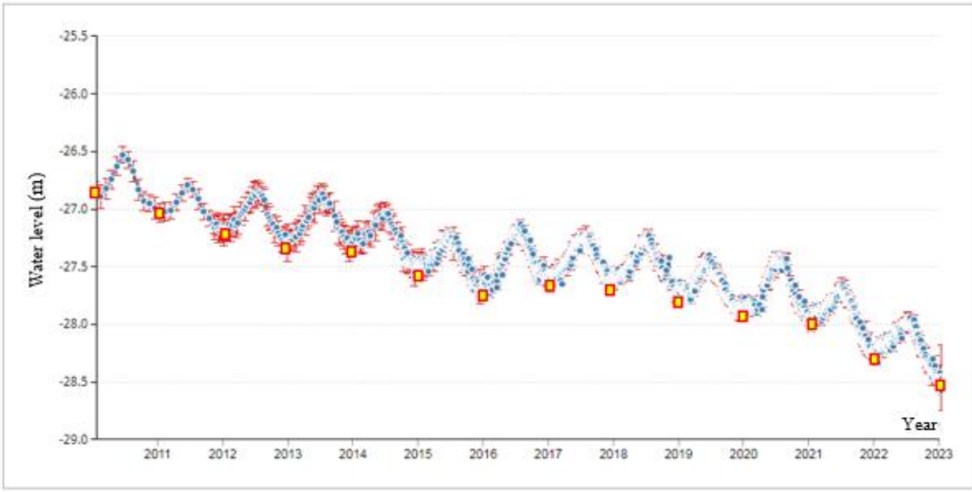

Fig. 8. Graph of Caspian Sea water level fluctuations during the years 2010 to 2023.

Based on the investigations, Caspian Sea level has increased at a rate of 0.15 m per year during the 1990s, and has encountered a decreasing trend since 1992 at the rate of 0.11 m per year. Due to the severe summer drought in the Volga basin in 2010, a significant decline in the trend of these changes was observed, and the continuation of the decreasing trend until 2023 was recorded (httpps://hydroweb.theia-land.fr/). This sharp decline based on the phenomenon of climate change and the increase of human activities shows a more problematic situation compared to the past.

Due to global warming, increased variations in precipitation processes, evaporation and wind regime can have a considerable impact on the Caspian Sea level until the end of this century. Therefore, the predictions indicate that by the end of the 21st century, the reduction of Caspian Sea level will reach 9 m to 18 m. So, the water level of the Caspian Sea is reduced by 23% to 34%, so that the vast plateau of the Northern Caspian Sea, the Turkmen plateau in the southeast and all the coastal areas in the middle and south of Caspian Sea are out of the sea level range, and the Qara Bay Boghaz also completely will be dried in the eastern margin (Fig. 9).

Effective factors on the Caspian Sea level changes

The Caspian Sea level variations are affected by a set of different factors such as precipitation in the neighboring basins, precipitation on the sea, the volume of water flowing the Volga River, the level of evaporation from the surface, and human harvesting from the catchment basin (Sala, 2019). Various studies (Arpe *et al.* 2019; Akbari *et al.* 2020; Koriche *et al.* 2021) have shown that the main factors of changes in the Caspian Sea level are caused by temperature, precipitation and evaporation.

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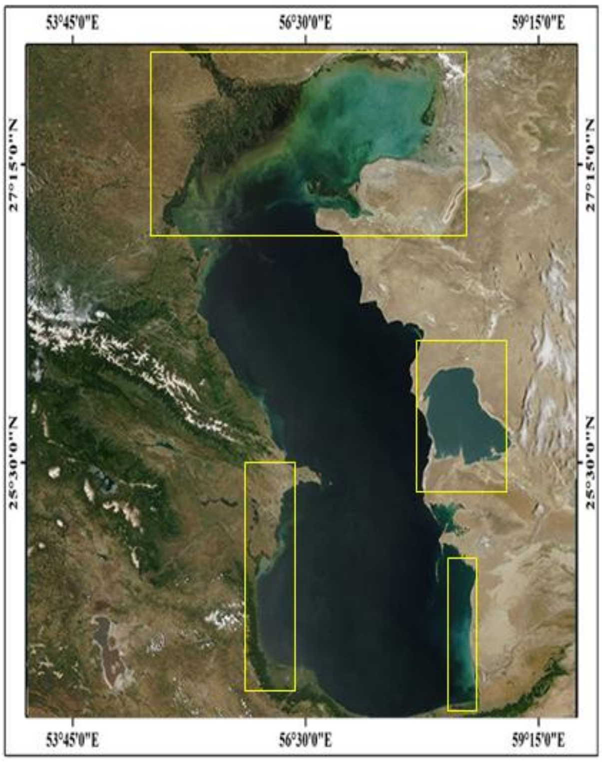

Fig. 9. The reduction of the Caspian Sea level by the 21st century
(**Source:** Esri, Maxar, and Earthstar Geographics).

Also, the dependence of the Caspian level on solar activities also shows the future increase of the sea level (Kaftan et al. 2018). The main part of the watershed of Caspian Sea is located in the European part of Russia. This section of the watershed has a crucial role in the water balance of the Caspian Sea. Climate predictions indicate an increase in precipitation and temperature in this region. Therefore, the increase in temperature has made some changes in the spring flooding of the Volga River from spring to winter. As mentioned, the changes in the inflow of the rivers into the Caspian Sea, namely the Volga River, as well as the level of evaporation from the sea level are considered to be the main factors of the changes in the sea level (Chen *et al.* 2023). Indeed, the short-term fluctuations of these changes are affected by factors such as meteorological and hydrological components in coastal areas, which depend on the climatic conditions of different coastal areas. On the other hand, the two factors of wind and sea flows can also make temporary changes in the Caspian Sea level, in which in the northern part of the sea, the northwest winds have caused the sea level to decline, while the southeast winds can increase the sea level. In addition, other factors affecting the changes in the Caspian Sea level are the increase in greenhouse impacts, changes in solar radiation, tectonic movements of the earth and the rise of the sea bed, anthropogenic factors and the reduction of evaporation from the surface of the sea due to oil pollution, the construction of the Qare Boghaz Bay dam, the construction of the Volga Canal, the deviation of riverbeds and the water transported from the lakes of the northern parts (the construction of dams and artificial lakes).

The Iranrud project, involving the transfer of Caspian Sea water, exacerbates fluctuations and challenges facing the sea. This water transfer devastates ecosystems, including desert areas, and its destruction would lead to salt dust in northern Iran, destruction of Alborz Forests, and overall ecological degradation. Furthermore, a 6 cm drop in Caspian water necessitates 100,000 m^3 of dredging, creating significant navigation issues for northern Iranian ports due to high costs and impracticality of excessive dredging. The declining Caspian Sea level also impacts surrounding bays and wetlands, particularly the Gorgan Gulf. To address this, the Ports and Maritime Organization, with government funding and National Wetlands Committee approval, dredges the Gorgan Gulf to maintain its connection with the Caspian Sea. Additionally, the difference in water levels between the Caspian Sea and open waters could increase fluctuations, potentially submerging northern Iranian lands and posing challenges like crossing the Alborz Mountain Range.

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The impacts of Caspian Sea level changes

- **The biological processes disturbance in river mouth**: Reduced rainfall, increased temperatures, and human activities in the Caspian watershed have decreased river flow into the sea. This has disturbed the biological processes in the river mouths, particularly the deltas formed by the Sefidroud and Gorganroud rivers, which are crucial for the reproduction of Caspian aquatic species. Additionally, wave action creates sandbars at the river mouths, hindering water exchange and the migration of aquatic creatures (Khoshravan *et al.* 2020).

- **Impact on water salinity**: Caspian Sea salinity varies significantly, from 1‰ in the northern delta to 13‰ in the eastern basins, with higher values in some bays. Salinity in the shallow North Caspian is particularly sensitive to fluctuations in water level. Short-term changes in the North Caspian's water level or Volga River flow can alter salinity. Long-term data indicate that Caspian Sea salinity is directly influenced by Volga water inflow and sea level, with salinity peaking during periods of lower sea level (Matishov *et al.* 2018).

-**Impact on water hydrochemistry**: The Caspian Sea exhibits a higher pH than other sea basins, primarily due to abundant alkaline inputs from rivers and its unique seawater composition (Karbassi *et al.* 2014). Surface pH ranges from 8.3-8.6, decreasing to 7.3-8 near the seabed. The highest pH is found at the Volga River mouth in the North Caspian. From 1961 to 1983, a decline in water levels led to a 0.2 pH decrease in the North Caspian, while the Central and Southern basins experienced an increase, indicating an accelerated water cycle in deeper areas due to sea-level reduction.

- **Impact on the coastline**: The Caspian Sea's water level fluctuates more rapidly than other seas and lakes, leading to significant shoreline shifts. In recent decades, a 30,000 km^2 increase in water level has submerged coastal areas (Ataei *et al.* 2018). Conversely, past decreases exposed new land, caused sedimentation, and altered the southeastern shoreline's morphology. Rising levels inundate coastal lands, destroy existing landforms, and displace sediments. These changes profoundly impact the numerous communities and activities along its shores, causing damage and displacement of settlements and facilities.

- **Impact on ecosystem**: Caspian Sea level fluctuations significantly impact its ecosystem. Rising levels expand coastal wetlands, creating new habitats for aquatic life and migratory birds. However, increased water levels can slow the water cycle, reducing nutrient and dissolved oxygen cycling, negatively affecting biological production. Conversely, decreasing water levels shrink wetlands, dry up smaller ones, limit aquatic and migratory bird habitats, and restrict fish spawning access to rivers.

- **Impact on pollutant reprocessing**: Caspian Sea level fluctuations significantly influence the distribution of pollutants. The receding waters, particularly in Iran's northern basins, have led to severe environmental issues, most notably impacting Golestan and Miankaleh provinces and the northern wetlands.

- **Increase of coastal sediments in the shallow areas of the basin**: Frequent fluctuations in the Caspian Sea level have led to sediment accumulation in shallow areas. These shallow areas, including coastal regions, terraces, and marine-coastal deltas (such as the northern Caspian Sea basin with a water depth of approximately 5 meters), are easily accessible and highly susceptible to natural risks, particularly along the Volga and Ural coasts and river delta coastal parts.

- **Impact on the aquatics of the Caspian Sea**: Nutrients from the Northern Caspian Sea nourish numerous aquatic organisms, including fish, migratory birds, and non-native species in the sea. Fluctuations in Caspian Sea levels directly impact these food resources, potentially causing widespread death among these species.

- **Impact on the ecosystem services of the Caspian Sea:** Changes in the Caspian Sea's level threaten the ecosystem services that support coastal communities. For instance, a decline in the sea level, particularly in the northern areas, significantly reduces fishing and aquaculture, impacting livelihoods. This also jeopardizes cultural services like tourism, leading to a loss of coastal visitors and, ultimately, endangering the region's food security.

- **Impact on the border countries**: The continuing decline in the Caspian Sea's water level poses a significant threat to bordering nations. Should this trend persist, hundreds of kilometers of coastline will be lost. Among the five Caspian littoral states (Iran, Turkmenistan, Kazakhstan, Russia, and Azerbaijan), Russia faces the most severe impact due to its shallow coastal areas, rendering vast stretches unusable. With depths along the Russian coast ranging from 4 to 5 meters, a further drop in sea level would critically disrupt many Russian ports and their commercial activities.

- **Impact of geo-political**: The shrinking Caspian Sea carries significant geopolitical and economic consequences. Lower water levels hinder maritime traffic, causing business losses for bordering nations and globally. Shifting coastlines, adding land in some areas, could reignite border disputes, as the 2018 Convention on the Legal Regime

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of the Caspian Sea, based on current coastlines, doesn't account for such changes. Although gradual, this decline poses a direct threat to Russia's and Iran's geo-economic competition against rival transport routes (Suez Canal, Western-controlled routes). If the North-South Corridor (INSTC) becomes uncompetitive due to these technical issues, Russia's trade route to the Indian Ocean and southern markets will be undermined.

CONCLUSION

Climate change and human activity are causing significant water level fluctuations in the Caspian Sea, the world's largest closed water basin. These changes are not merely environmental, but a strategic geopolitical and geo-economic factor in the region. The accelerated decline in water levels over recent decades threatens coastal infrastructure, ports, shipping, the fishing industry, and vital water reserves like wetlands and bays. This retreat exposes new lands, potentially leading to legal disputes, disrupts ecological balance, and impacts coastal groundwater. These transboundary challenges affect all five littoral states. Geopolitically, the receding sea directly jeopardizes the International North-South Transport Corridor (INSTC), a key strategic link for Iran and Russia to the Indian Ocean and southern markets. The 2018 Convention on the Legal Regime of the Caspian Sea, after 22 years of negotiations, lacks a clear mechanism for redrawing borders when coastlines change. This legal void, exacerbated by rapid water recession, creates a potential governance crisis. This "silent legal trap" of declining sea levels is an under-addressed geopolitical issue, poised to become a major conflict point among littoral states in the next decade. Iran, particularly vulnerable due to its southern, shallow-water geography, faces significant threats to its northern coastal provinces' economic vitality, encompassing food security, ecological balance, freshwater, aquatic life, and tourism. The destruction of this southern coast would not only undermine Iran's regional economy but also intensify migration and social instability in its northern provinces.

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