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Research Article

Caspian Sea Level Decline by 2035: Mathematical and Regional Assessment

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Abstract

The Caspian Sea is the world's largest endorheic water body and has experienced substantial fluctuations in water level during the twentieth and twenty-first centuries. Recent climate projections indicate that increasing temperature, enhanced evaporation, and changes in riverine inflow may intensify the long-term decline in Caspian Sea level. This study builds on the mathematical and geometrical framework presented by Ghorbani (2025) for assessing shoreline and geometric changes along Iran's Mazandaran coast and applies a 3-m water-level decline by 2035 as a regional scenario for the entire Caspian Sea. The main objectives are to estimate the potential changes in the total surface area and water volume of the Caspian Sea and to assess the potential consequences for coastal geometry, navigation, ports, and offshore oil and gas infrastructure in the five littoral states: Iran, Kazakhstan, Russia, Turkmenistan, and Azerbaijan. The present Caspian Sea surface area is approximately 389,000 km^2 and its volume is approximately 78,000 km^3. Because the relationship between water level and surface area is strongly nonlinear, a 3-m decline cannot be converted into an area loss using a simple linear relationship. Nevertheless, historical observations and recent bathymetric studies suggest that a decline of this magnitude could result in the loss of several tens of thousands of square kilometers of water surface, particularly in the shallow northern Caspian. In this study, an initial scenario range of approximately 30,000-45,000 km^2 of surface-area loss is proposed, while the corresponding reduction in water volume is estimated at approximately 1,000-1,200 km^3. The consequences are not spatially uniform. Kazakhstan and Russia are expected to face the greatest direct risks to shallow-water offshore energy infrastructure because of fields such as Kashagan and Vladimir Filanovsky. Turkmenistan may also face substantial risks because of offshore developments in the Cheleken area and the shallow eastern Caspian. In Azerbaijan, major fields such as Azeri-Chirag-Gunashli are located in considerably deeper waters, making their direct exposure to a 3-m reduction relatively limited; however, ports, coastal terminals, navigation routes, and logistics infrastructure may be affected. In Iran, the principal impacts are expected to involve shoreline retreat, ports, wetlands, fisheries, tourism, and coastal infrastructure rather than large-scale offshore hydrocarbon production. The results indicate that a 3-m decline, although substantially smaller than the 8-14 m best-fit projections and the upper-end projections of up to 21 m by the end of the twenty-first century, should be considered an important early-warning scenario for regional infrastructure and energy planning. The study further demonstrates the potential value of extending the mathematical shoreline framework developed by Ghorbani (2025) toward a basin-wide model of energy-infrastructure vulnerability.

Keywords

Caspian Sea, Water-level Decline, Shoreline Retreat, Oil and Gas, Offshore Infrastructure, Mathematical Modeling, Climate Change

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1. Introduction

The Caspian Sea is the world's largest endorheic water body and is surrounded by five countries: Iran, Azerbaijan, Kazakhstan, Russia, and Turkmenistan. Because the Caspian Sea has no natural connection to the global ocean, its water level is strongly controlled by the balance between river inflow, precipitation, evaporation, and other relatively minor components of the regional hydrological system. The Volga River is particularly important because it provides a major proportion of the riverine inflow to the Caspian Sea. Changes in climate, precipitation, evaporation, and water management within the Volga basin can therefore have substantial consequences for the long-term Caspian water balance.

The Caspian Sea has experienced large multidecadal fluctuations during the twentieth century. A decline of approximately 3 m occurred during an earlier period of the twentieth century, demonstrating that a multi-meter decline is not unprecedented in the history of the basin. However, the current concern is associated with the combination of observed recent decline and projected future warming, which may increase evaporation and produce an increasingly negative water balance.

Recent climate modeling has significantly increased scientific concern regarding the future of the Caspian Sea. Samant and Prange (2023) analyzed 15 Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models and three shared socioeconomic pathways. Their best-fit estimates suggested a decline of approximately 8 m by the end of the century under SSP2-4.5 and approximately 14 m under SSP5-8.5, with model ranges extending to approximately 21 m in the high-emission scenario.

A major multi-author study published in 2025 further investigated the spatial consequences of Caspian Sea level decline. Court et al. (2025) considered a series of decline scenarios and demonstrated that even relatively moderate declines can have substantial consequences for shallow coastal areas, ecosystems, infrastructure, ports, navigation, and human activities. The study considered scenarios ranging from 2.5 m to much larger declines and emphasized that previous climate projections have included possible declines of up to approximately 21 m by 2100.

Ghorbani (2025) investigated the geometrical response of the Caspian Sea to water-level decline, with particular emphasis on Iran's Mazandaran coast. That study examined the relationship between vertical water-level changes and horizontal shoreline migration and discussed the implications for ports, wetlands, fisheries, agriculture, and coastal activities. The study also emphasized the importance of the shallow coastal geometry of the Caspian Sea and demonstrated that relatively small vertical changes can produce substantial horizontal changes in shoreline position.

The present study is a continuation and regional extension of that research. Rather than focusing exclusively on the Mazandaran coast, this paper considers a 3-m decline as a basin-wide scenario and investigates its possible consequences for the five Caspian littoral states, with particular emphasis on oil and gas infrastructure. [1, 2].

2. Objectives and Research Framework

The main objective of this study is to assess the potential consequences of a 3-m decline in Caspian Sea level by 2035.

Three main research questions are considered.

First, if the Caspian Sea level declines by approximately 3 m, how much of its surface area and water volume could potentially be lost?

Second, how could this decline modify the shoreline, shallow-water areas, ports, navigation routes, and coastal infrastructure in the five littoral states?

Third, considering the presence of offshore oil and gas fields in several Caspian countries, which countries and which types of infrastructure are likely to be most vulnerable?

The 3-m decline should be interpreted as a scenario rather than a deterministic prediction. Current climate projections provide a broad range of possible future changes, and the actual trajectory by 2035 will depend on temperature, evaporation, precipitation, river discharge, water extraction, and other components of the Caspian water balance.

The selection of 3 m is nevertheless scientifically useful because it represents a substantial but plausible near-term stress scenario and is comparable in magnitude to historical multi-meter fluctuations of the Caspian Sea. [3].

3. Methodology

The methodology combines three main categories of information: historical Caspian Sea level variations, climate projections, and the bathymetric and geometric characteristics of the Caspian basin.

The present surface area of the Caspian Sea is approximately 389,000 km^2, while its total water volume is approximately 78,000 km^3. These values vary somewhat among studies depending on the reference water level, measurement period, and definition of the water boundary.

A critical feature of the methodology is that the relationship between water-level decline and surface-area reduction is nonlinear. The northern Caspian is extremely shallow, whereas the central and southern basins contain very deep water. Consequently, a 1-m reduction in water level can produce a much larger loss of surface area in shallow regions than an equivalent reduction in deeper regions.

For a simple first-order volume estimate, the following relationship can be used:

$$V = A \times h$$

where V is the approximate volume of water affected, A is the effective surface area, and h is the water-level change.

For a 3-m decline, using an effective area in the approximate range of 360,000-390,000 km^2 gives a first-order volume change on the order of approximately 1,000-1,200 km^3.

However, the same approach cannot be used directly to calculate the surface-area reduction because the bathymetry is highly heterogeneous. Published historical and bathymetric studies indicate that several tens of thousands of square kilometers may be removed from the water surface following a multi-meter decline, particularly in the northern Caspian. Recent modeling has shown that a 5-m decline can produce a very substantial loss of surface area.

Accordingly, this study proposes an initial scenario range of approximately 30,000-45,000 km^2 of surface-area loss for a 3-m decline. This range is intended as a scenario estimate rather than a definitive bathymetric calculation. A future study using high-resolution digital bathymetry and a detailed hypsometric curve should be used to refine this estimate. [4-6].

4. Potential Basin-Wide Consequences of a 3-m Decline

If the Caspian Sea level declines by 3 m, one of the most important consequences will be a substantial reduction in the total water-covered surface.

Assuming an initial area of approximately 389,000 km^2 and a potential loss of 30,000-45,000 km^2, the remaining water-covered area could fall approximately within the range of:

$389{,}000 - 30{,}000 = 359{,}000\ km^2$

to

$389{,}000 - 45{,}000 = 344{,}000\ km^2$

Thus, the remaining water surface could be approximately 344,000-359,000 km^2.

This corresponds to a reduction of approximately 8-12% of the present water-covered area.

The volume reduction is much smaller in percentage terms. A reduction of approximately 1,000-1,200 km^3 from a total volume of approximately 78,000 km^3 corresponds to roughly 1-1.5% of the total water volume.

This difference is scientifically important. A relatively small percentage reduction in total water volume can produce a much larger percentage reduction in surface area because large portions of the Caspian coastline consist of shallow shelves.

Therefore:

A 3-m vertical decline does not mean a 3-m horizontal shoreline retreat.

In shallow regions, the horizontal retreat can be many kilometers, depending on the local slope and bathymetry.

The strongest geometric changes are expected in the northern Caspian, particularly along the Kazakhstan and Russian coasts, followed by parts of the eastern Caspian and the shallow coastal areas of Turkmenistan. In the central and southern Caspian, the primary effect will generally be a reduction in water depth rather than the complete disappearance of large areas of open water. [7].

5. Five-Country Assessment

5.1. Azerbaijan

Azerbaijan is one of the most important oil and gas countries in the Caspian region. A significant part of its energy infrastructure is associated with offshore fields and the coastal industrial complex surrounding Baku.

One of the most important hydrocarbon areas is the Azeri-Chirag-Gunashli (ACG) complex. The ACG fields are located in the deeper central Caspian, with water depths approximately in the range of 150-450 m. Consequently, a 3-m decline would have a relatively small direct effect on the water depth above the main field infrastructure.

For example, a 3-m reduction in a location with 300 m water depth represents approximately:

$3 \div 300 \times 100 = 1\%$

of the existing water depth.

Therefore, it is unlikely that a 3-m decline alone would make the main deep-water ACG platforms inaccessible.

However, this does not mean that Azerbaijan would be unaffected.

The regional energy system should be considered as a chain:

Offshore field → platform → subsea pipeline → coastal terminal → port → maritime transportation

A decline in Caspian Sea level can affect the coastal and logistical components of this chain even when the offshore production platforms remain in deep water.

Ports, terminals, navigation channels, service facilities, and coastal industrial infrastructure may experience declining water depths and changing distances to the new shoreline.

This distinction is particularly important for Azerbaijan because the country has a highly developed energy and maritime infrastructure around Baku and other coastal areas.

Therefore, under the 3-m scenario, Azerbaijan can be characterized as having:

relatively low direct vulnerability of deep offshore fields, but moderate and potentially significant vulnerability of coastal and logistical infrastructure.

This distinction is important for future regional risk assessments.

5.2. Kazakhstan

Kazakhstan is potentially one of the most vulnerable countries under a 3-m Caspian Sea level decline.

The principal reason is the extremely shallow northern Caspian and the location of major hydrocarbon infrastructure in shallow water.

The most important example is the Kashagan field.

The Kashagan field is located in the northern Caspian, where water depths in the field area are approximately 3-4 m. Studies using remote sensing and satellite observations have emphasized the extremely shallow nature of the field and the associated logistical and navigation challenges.

Under a simplified scenario, if the existing water depth in a particular area is 3-4 m and the sea level declines by 3 m, the remaining water depth could theoretically approach approximately 0-1 m.

This does not mean that the entire Kashagan field would necessarily become dry. Water depth is spatially variable, engineered navigation channels are maintained, and the field infrastructure is designed to operate under shallow-water conditions.

Nevertheless, the scenario would create major engineering and logistical challenges.

Potential consequences include:

1) increased dredging requirements;
2) reduced navigation depth;
3) greater difficulty for service vessels;
4) increased transportation costs;
5) more difficult maintenance operations;
6) restricted access for heavy equipment;
7) modification of navigation channels;
8) increased distance between some coastal facilities and the new shoreline.

The importance of Kashagan demonstrates why a basin-wide decline should be evaluated not only from an environmental perspective but also from an energy-security perspective.

The 2025 study by Court et al. identified shallow northern Caspian hydrocarbon infrastructure, including Kashagan, among the energy assets that could face serious accessibility problems under larger decline scenarios.

The city and port of Aktau also require attention because changes in shoreline position and water depth can affect maritime connectivity and port operations.

Consequently, Kazakhstan should be considered one of the countries with the highest vulnerability to a 3-m decline, particularly with respect to shallow-water offshore oil and gas infrastructure.

5.3. Russia

Russia controls a substantial part of the northern Caspian and has developed several offshore oil and gas fields in relatively shallow waters.

One of the most important examples is the Vladimir Filanovsky field, operated by LUKOIL.

The field is located in the northern Caspian where water depths are approximately 7-11 m. Under a 3-m decline, the reduction would therefore represent approximately 27-43% of the existing water depth.

For example, in a location with 10 m of water:

$3 \div 10 \times 100 = 30\%$

Thus, a 3-m decline could remove approximately one-third of the existing water depth.

This is a substantial engineering change.

The principal concern would not necessarily be the oil reservoir itself, because the reservoir lies beneath the seabed. Instead, the main risks would concern surface operations and marine logistics.

Potential consequences include:

1) reduced navigation depth;
2) greater dredging requirements;
3) more difficult access for service vessels;
4) increased maintenance costs;
5) logistical restrictions;
6) challenges for offshore construction and repair;
7) potential changes in the operation of subsea pipelines and associated infrastructure.

Other Russian offshore fields in the northern Caspian should also be evaluated under the same framework.

The 2025 regional study identified northern Caspian hydrocarbon fields such as Vladimir Filanovsky among infrastructure locations that could become increasingly isolated from normal maritime access under larger water-level decline scenarios.

Therefore, Russia should also be classified among the countries with high vulnerability of shallow offshore energy infrastructure.

5.4. Turkmenistan

Turkmenistan has developed substantial offshore oil and gas resources in the eastern Caspian Sea.

One of the most important offshore areas is the Cheleken Contract Area, including fields such as Lam and Zhdanov.

The Cheleken region contains significant offshore infrastructure, including platforms, wells, subsea pipelines, and associated coastal facilities.

Compared with the very deep-water fields of Azerbaijan, many of these operations are located in relatively shallow and intermediate-depth environments. Consequently, a 3-m decline could have a more noticeable effect on navigation and offshore logistics.

The potential consequences include:

1) reduced water depth around offshore facilities;
2) increased dredging requirements;
3) greater difficulty for supply vessels;
4) changes in navigation routes;
5) increased distance between some facilities and the new shoreline;
6) increased pressure on coastal industrial infrastructure.

Another major issue for Turkmenistan is Kara-Bogaz-Gol.

This very shallow water body is highly sensitive to changes in Caspian Sea level. Large-scale water-level declines can produce substantial transformations in this region and along the eastern Caspian coast.

The 2025 study by Court et al. identified the eastern Caspian and Kara-Bogaz-Gol among regions that may undergo major changes under declining water levels.

Therefore, the implications for Turkmenistan extend beyond oil and gas.

They include:

oil and gas + ports + navigation + coastal industry + shallow-water ecosystems

Under the 3-m scenario, Turkmenistan can therefore be classified as having moderate-to-high vulnerability, particularly in shallow offshore and coastal areas.

5.5. Iran

Iran differs from Kazakhstan, Russia, and Turkmenistan because its current offshore oil and gas production in the Caspian is not comparable in scale to the major offshore hydrocarbon developments of those countries.

Consequently, the primary effects of a 3-m decline in Iran are expected to involve:

1) shoreline retreat;
2) ports;
3) wetlands;
4) fisheries;
5) tourism;
6) coastal infrastructure;
7) navigation channels;
8) agricultural areas close to the coast.

The Mazandaran coast is particularly important because it was the focus of Ghorbani (2025), which examined the relationship between vertical water-level decline and horizontal shoreline movement. The study emphasized that the relatively gentle coastal geometry of parts of Mazandaran can translate relatively small vertical changes into substantial horizontal shoreline movement.

Ports such as Amir-Abad may experience increased sedimentation and navigation challenges as water levels decline. The reduction in water depth at port entrances and navigation channels may increase the frequency and cost of dredging.

Wetlands and coastal lagoons are also particularly vulnerable.

The Gorgan Bay region, for example, is sensitive to changes in Caspian Sea level because its connection to the open Caspian depends strongly on coastal morphology and water depth.

Thus, for Iran, the 3-m scenario represents primarily a coastal and environmental infrastructure problem, rather than a direct threat to a large offshore oil and gas production system.

At the same time, the Iranian case is scientifically important because the mathematical framework developed by Ghorbani (2025) provides a starting point for linking vertical water-level decline with horizontal shoreline migration. [1, 8, 9].

6. Regional Comparison of the Five Countries

The five Caspian countries are not equally vulnerable to a 3-m decline.

Kazakhstan is likely to be among the most vulnerable because of the extremely shallow northern Caspian and the presence of Kashagan, where water depths are only a few meters.

Russia also has high vulnerability because of shallow offshore fields such as Vladimir Filanovsky and other northern Caspian infrastructure.

Turkmenistan has moderate-to-high vulnerability because of the Cheleken offshore development, shallow eastern Caspian waters, and the highly sensitive Kara-Bogaz-Gol region.

Azerbaijan has relatively lower direct vulnerability of its major deep-water offshore fields, but significant coastal and logistical exposure because of its ports, terminals, navigation infrastructure, and energy transportation network.

Iran has relatively limited direct offshore hydrocarbon exposure but potentially substantial vulnerability in coastal infrastructure, ports, wetlands, fisheries, and tourism.

If the assessment is restricted to direct vulnerability of offshore oil and gas infrastructure, an initial qualitative ranking can therefore be proposed as:

Kazakhstan → Russia → Turkmenistan → Azerbaijan → Iran

However, this ranking changes if the assessment includes the entire coastal economy.

When ports, wetlands, tourism, fisheries, cities, and coastal industrial infrastructure are included, all five countries face significant risks. [10, 11].

7. Discussion

The most important finding of this study is that a 3-m decline should not be interpreted simply as a 3-m vertical change in the Caspian Sea.

In an enclosed basin such as the Caspian, vertical water-level changes are translated into horizontal shoreline migration.

The magnitude of horizontal migration depends strongly on local bathymetry and coastal slope.

Thus:

3 m vertical decline $\neq$ 3 m horizontal shoreline retreat.

In shallow coastal areas, a 3-m decline may cause shoreline retreat of several kilometers or more.

This is particularly important for oil and gas infrastructure because an offshore field may remain underwater while the supporting maritime infrastructure becomes increasingly difficult to access.

For example, a production platform may remain surrounded by water, but the nearest port may become too shallow for the original class of service vessel.

Similarly, a subsea pipeline may remain functional while the coastal terminal connected to that pipeline faces new navigation constraints.

Therefore, the future risk should be evaluated at the level of the entire energy infrastructure chain:

Offshore field → platform → subsea pipeline → coastal terminal → port → maritime transportation

Damage or operational impairment at any point in this chain may affect the functionality of the entire system.

This approach provides an important extension of the work presented by Ghorbani (2025), which demonstrated the relationship between water-level change and coastal geometry along the Mazandaran coast.

The next logical step is therefore to combine shoreline geometry, bathymetry, and the spatial distribution of offshore energy infrastructure.

A simple preliminary vulnerability concept can be written as:

Vulnerability = Shallow water + Nearshore location + Dependence on maritime access.

This is not intended to be a final mathematical index. Rather, it represents a conceptual framework that can be developed into a quantitative regional index.

Additional factors could subsequently include distance to the nearest port, pipeline length, navigation-channel depth, dredging requirements, production capacity, and estimated adaptation costs. [12, 13].

8. Limitations of the Study

Several limitations should be acknowledged.

First, the 3-m decline by 2035 is a scenario and should not be interpreted as a deterministic prediction.

Second, the estimated loss of 30,000-45,000 km^2 of surface area is an initial scenario range rather than a result of a new high-resolution bathymetric model.

Third, water depth is not spatially uniform around offshore fields. Therefore, subtracting 3 m from a single average depth cannot provide a precise estimate of operational accessibility.

Fourth, the rate of water-level decline may not be constant. Interannual variability in evaporation, precipitation, river discharge, and regional climate conditions can produce substantial year-to-year changes. [14].

Fifth, the study does not yet incorporate detailed geospatial information for every oil and gas platform, pipeline, port, and navigation channel.

Therefore, the present research should be regarded as a regional scenario framework and a first-stage assessment.

9. Recommendations for Future Research

Future research should develop a geospatial database containing the major oil and gas fields and associated infrastructure throughout the Caspian Sea.

For each field, at least the following information should be collected:

1) field name;
2) country;
3) geographic coordinates;
4) current distance from shoreline;
5) water depth;
6) distance to the nearest port;
7) platform type;
8) subsea pipeline connections;
9) production capacity;
10) current production status;
11) maritime transportation requirements.

The next stage should evaluate several water-level scenarios, for example:

1 m, 2 m, 3 m, 5 m, 10 m, and 15 m

For each scenario, the new shoreline should be estimated using high-resolution bathymetry.

The resulting shoreline positions could then be overlaid with the locations of offshore platforms, pipelines, ports, and terminals.

This would make it possible to develop a Caspian Offshore Energy Infrastructure Vulnerability Index.

Such an index could identify the degree of vulnerability of each field and infrastructure component under different water-level scenarios.

Three regions should receive particular attention in the first stage:

Kashagan in Kazakhstan, Vladimir Filanovsky in Russia, and Cheleken/Lam in Turkmenistan.

Major Azerbaijani fields such as ACG, Shah Deniz, and Absheron should then be included to compare shallow-water and deep-water infrastructure. [15].

This approach would allow future studies to move beyond a general environmental assessment toward a quantitative regional risk model.

10. Conclusions

A 3-m decline in Caspian Sea level, although substantially smaller than the 8-14 m best-fit projections and the upper-end projections approaching 21 m by the end of the twenty-first century, could represent a major change in the geometry and functioning of the Caspian coastal system.

Based on current surface area, volume, historical behavior, and published bathymetric studies, such a decline could potentially result in the loss of several tens of thousands of square kilometers of water surface and approximately 1,000-1,200 km^3 of water volume. A preliminary scenario range of 30,000-45,000 km^2 of surface-area loss is proposed in this study.

The most significant geometric changes are expected in shallow areas, particularly in the northern Caspian.

The consequences will differ substantially among the five littoral countries.

Kazakhstan is likely to experience very high vulnerability because of the extremely shallow northern Caspian and the presence of the Kashagan field.

Russia is also highly vulnerable because of shallow offshore fields such as Vladimir Filanovsky and other northern Caspian infrastructure.

Turkmenistan faces moderate-to-high vulnerability because of the Cheleken offshore development, shallow eastern waters, and the highly sensitive Kara-Bogaz-Gol region.

Azerbaijan's major deep-water fields, including ACG, are less directly affected by a 3-m decline in terms of water depth. However, the country's coastal ports, terminals, navigation routes, and energy logistics may experience important consequences.

Iran has relatively limited direct exposure to large-scale offshore hydrocarbon production but may face substantial consequences for ports, wetlands, fisheries, tourism, and coastal infrastructure.

The most important conclusion is that Caspian Sea level decline should not be treated exclusively as an environmental issue. It should also be considered a mathematical, geographical, engineering, economic, energy, and infrastructure-security problem.

Ghorbani (2025) demonstrated that vertical changes in Caspian Sea level can translate into significant horizontal changes in shoreline geometry along the Mazandaran coast. The present study extends this concept to the entire Caspian region and proposes that the same mathematical framework can ultimately be integrated with bathymetry and offshore energy infrastructure data.

Such an integrated approach could provide a quantitative basis for identifying vulnerable oil and gas fields, navigation corridors, ports, and coastal terminals before the most severe impacts occur.

The 3-m scenario should therefore be regarded as an early-warning threshold for regional planning, rather than merely a hypothetical environmental event.

Abbreviation

ACG	Azeri Chirag Gunashil
SSP	Shared Socioeconomic Pathway
NDWI	Normalized Difference Water Index
CMIP6	Coupled Model Intercomparision Project Phase 6

Author Contributions

Majid Ghorbani: Conceptualization, Formal Analysis, Investigation, Supervision, Writing – original draft, Writing – review & editing

Conflicts of Interest

The author declares no conflicts of interest.

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