Adapting Caspian Sea ports to climate-induced water level declines: The case of Aktau

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Abstract

The Caspian Sea is the world's largest inland body of water. It is critical for regional trade through the Trans-Caspian International Transport Route (TITR), which links South-East Asia and China to Europe. Aktau Port in Kazakhstan is strategically important, located on key international transport routes like the TITR. Over the past 30 years, the Caspian Sea's water levels have dropped from -26.6 m Baltic Datum (BD) in 1995 to -29.66 m BD in October 2024. This decline has damaged about 70% of Aktau Port's fenders, which have been replaced with temporary ones and ships can only be loaded to 80% of their capacity to avoid grounding in shallow berths. Climate projections indicate a further 7 m potential decline by 2100 owing to reduced inflows and increased evaporation. This research provides the first integrated assessment of climate-driven water level decline and port adaptation in the Caspian region, combining hydrological modelling with engineering adaptation pathways to inform climate-resilient infrastructure planning. This paper outlines the adaptation options for Aktau Port for the following times scales: immediate; medium-term; and long-term. Immediate measures include dredging, coupled with new fendering systems, for the port to operate at its full capacity. Medium-term options involve quay wall modifications and introducing shallow-draft vessels. Long-term strategies require a critical decision between major infrastructure upgrades or relocating operations offshore or to a new port.

Keywords: adaptation; Aktau Port; Caspian Sea; climate change

1. Introduction

The Caspian Sea is located between Europe and Central Asia. It is the largest inland body of water in the world with a surface area of ~371,000 km^2 and a coastline of ~7,000 km in length [1]. It is bordered by five countries: Russia and Kazakhstan in the north; Iran in the south; Turkmenistan in the south-east, and Azerbaijan in the south-west (Figure 1). The Caspian Sea not only provides a maritime link that connects the Persian Gulf and the Indian Ocean to northern Europe but is also key to the Middle Corridor, also known as the Trans-Caspian International Transport Route (TITR). The TITR connects South-East Asia and China to Europe. The route traverses Kazakhstan, the Caspian Sea, Azerbaijan, Georgia, and Türkiye and serves as an alternative to the Northern Corridor through Russia and the sea route via the Suez Canal. Since the Russo-Ukrainian war began, cargo traffic along the TITR has increased substantially [2]. In recent years investments in maritime and rail infrastructure investments on both shores of the Caspian Sea have accelerated [3].

Water levels in the Caspian Sea have fluctuated by tens of metres over historical time scales and by hundreds of metres over geological ones [4-6]. The surface area of the Caspian Sea means that it is sensitive to global and regional climate changes and variability [1]. The causes of the Caspian Sea's substantial fluctuations in historical water levels over the past several hundred years are uncertain [7].

Aktau Port in Kazakhstan holds significant strategic and economic importance for the country and the broader Central Asian, Caucasus and Europe regions. It is located at the intersection of major international transport corridors, including the TITR. The port is ice-free and navigable throughout the year, and comprises 23 specialised berths for handling different cargo types [8]. In the past 120 years, water levels have ranged from -26.00 m referenced to the Baltic Datum (BD) at Aktau Port in Kazakhstan to around -29.66 m BD in October 2024. In the past three decades, water levels at Aktau Port have declined on average by almost 10 cm/year from a level of around -26.6 m BD in 1995. It has been estimated that approximately 70% of Aktau Port's fenders have been damaged and replaced by temporary ones as a result of the decline in water levels (Figure 2) [9]. The absence of fenders with design parameters adapted to the current sea level could result in significant damage to port structures and vessels' hulls. Compared to the situation in 2000, vessels are currently only loaded to 80% of their capacity to prevent grounding in the shallow berths [10].

Although previous studies have explored historical variations in Caspian Sea water levels and their underlying causes, limited attention has been given to the risks posed to critical infrastructure and the development of actionable adaptation strategies. This research presents the first comprehensive assessment integrating climate-driven water level projections and engineering-based adaptation pathways for Aktau Port for the short-, medium- and long-terms (i.e. 2030s, 2050s and 2090s epochs). By combining hydrological modelling with infrastructure planning and operational insights, the research provides a transferable approach for similar ports on the Caspian Sea.

2. Implications of changes in the Caspian Sea's water levels for port infrastructure

Ports are inherently exposed to climate risks through their fixed location, longevity, irreversibility and high initial capital cost. The lifetime of their infrastructure is measured in decades. For example, quay walls and breakwaters are often designed to last for 50 years or more, and can function well beyond their initial design life [11, 12]. Any future decreases in the Caspian Sea's water levels are likely to have significant implications for the viability of the water transportation sector [13], rendering most present-day port infrastructure obsolete. Even ports that maintain shoreline access will have insufficient water depth for present-day vessels. The quay and harbourside infrastructure will be inappropriate for safe ship navigation and mooring, as well as limiting efficient cargo handling operations. This in turn will have both national and international ramifications for the east-west transportation of goods and energy across the Caspian Sea. Adaptation and resilience measures, such as dredging, quay wall modifications, and offshore loading facilities, for Caspian Sea ports could easily extend to several US$100 millions. Such interventions need to be planned over a long-time scale on the basis of climate-based projections but also need to be responsive to the observed rate of change in both sea level and other climate hazards. Understanding the drivers of any future changes in the Caspian Sea's water level is critical for developing robust adaptation measures for ports.

3. Drivers of water level fluctuations in the Caspian Sea

The present-day water level variations in the Caspian Sea are mostly controlled by contributions from around 100 rivers which discharge into it, although approximately 80% to 90% of the total river flow to the Caspian Sea comes from the River Volga [1, 14] which drains an area of ~1.3 million km^2. The flows from these rivers are affected by hydro-climatic processes at global and regional scales. There have been numerous studies of the water level fluctuations in the Caspian Sea over the past century [7, 15-18]. The Caspian Sea's water balance comprises five main components (Figure 1):

1. Fluvial flows into the sea of which around 80% to 90% is supplied by the River Volga.
2. The inflow and outflow of groundwater.
3. Precipitation falling directly on the sea.
4. Evaporation from the water surface.
5. Outflow of water to the Kara-Bogaz-Göl (KBG), a shallow, highly saline lagoon connected to the Caspian Sea by a narrow channel, which is located in north-western Turkmenistan.

Figure 1: Map of the Caspian Sea and the main components of its water balance

Figure 2: Photograph showing the changes in water levels at Aktau Port between 1999 and 2021 and the use of temporary fenders

Table 1 summarises the mean values of these five components and corresponding water levels for the Caspian Sea for six time periods between 1900 and 2012. Over this time period, the fluvial inflow accounted for between 75% and 82% of the water entering the sea, and evaporation for 95% to 98% of water losses. These figures highlight the Caspian Sea's sensitivity to hydro-climatic variability, particularly changes in river discharge and evaporation rates. Future climate change is expected to intensify this imbalance by reducing inflows and increasing evaporation, leading to further declines in water levels.

Table 1: Mean values of the components of the Caspian Sea's water budget and water levels referenced to the Baltic Datum (BD)

Period	River discharge (km^3/year)	Precipitation over the sea (km^3/year)	Ground water discharge (km^3/year)	Evaporation from sea surface (km^3/year)	Outflow to Kara-Bogaz-Göl (KBG) (km^3/year)	Water level (m BD)
1900-1929	332.4	69.8	5.5	389.4	21.8	-26.18
1930-1941	268.6	79.2	5.5	394.8	12.4	-26.80
1942-1962	285.4	74.1	4.0	356.3	10.6	-28.18
1970-1977	270.5	87.6	4.0	374.9	7.1	-28.64
1978-1995	315.0	86.1	4.0	348.7	8.6	-27.80
1996-2012	283.0	75.2	4.0	381.6	19.5	-27.10

Source: [19, 20]

Assessing the anthropogenic impacts on river flows into the Caspian Sea, especially from the Volga, is complex owing to multiple factors (e.g., dam releases, water abstractions) and the large natural flow variations. There is a paucity of data on water losses and abstractions, especially for the Volga. Before 1940, inflow to the sea was nearly natural, with abstractions from contributing rivers estimated to be only 2.2% of the normal inflow under natural conditions [21]. Significant reductions in flows in the Volga began in the 1950s with the creation of Volga-Kama reservoirs [21]. It has been estimated anthropogenic activities have reduced inflows to the sea ~40 km³/year (~13%), mainly due to water abstracted for irrigation and increased evaporation from reservoirs [21] . Without these changes, the Caspian Sea's water levels would have been 1.0 m higher by 1972 and 1.6 m higher by 1990 compared to the observed water levels [21].

The rise in the Caspian Sea's water levels from 1979 to 1995 was primarily driven by increased precipitation over the Volga River basin [7], and to a lesser degree the closure of the KBG's connection to the sea in 1980 [20]. However, research has indicated that the dominant factor behind the subsequent decline in water levels was the significant increase in evaporation rates over the Caspian from 1996 onwards [7] coupled with the reconnection of the KBG to the Caspian Sea in 1992 [20].

Understanding the historical and physical drivers of Caspian Sea water level fluctuations provides the foundation for projecting future trends. Given the dominant role of river inflows, particularly from the River Volga, and the sensitivity of the water balance to evaporation and precipitation, any changes in regional climate and hydrology will have profound implications for the sea's level. The next section explores how these drivers are expected to evolve under different climate change scenarios and what this means for water levels in the coming decades.

4. Modelling future Caspian Sea water levels under climate change

4.1 Model framework and governing equations

To assess potential changes in water levels at Aktau Port under a range of climate futures, a process-based water balance model was developed that couples the Caspian Sea and the Kara-Bogaz-Göl (KBG) lagoon. The model resolves the dominant fluxes at annual to decadal scales and is intentionally parsimonious to support transparent calibration and scenario analysis.

For the Caspian Sea, the governing balance is:

$$\Delta H = (Qr - Lv + P) - (E + Q_{KBG})$$

where ΔH is change in sea level (m), Qr is the total river inflow (dominated by the Volga), Lv are the net losses between the most downstream Volga flow gauging station and the sea, P is the precipitation falling directly on the sea surface, E is the evaporation from the sea surface, and Q_{KBG} is the net outflow to the KBG.

For the KBG, the balance is:

$$\Delta H_{KBG} = (Q_{in} + P_{KBG}) - E_{KBG}$$

where Q_{in} is the exchange flow from the Caspian Sea through the connecting channel, and P_{KBG} and E_{KBG} are the precipitation and evaporation over the lagoon, respectively.

The exchange of water between the Caspian Sea and the KBG is represented using standard broad-crested weir formulations for free and drowned (submerged) flow conditions, with period-specific hydraulic coefficients calibrated to observations. Free flow occurs only briefly when the KBG level is sufficiently depressed (e.g., shortly after re-opening in 1992); otherwise, drowned flow predominates owing to the submergence at the outlet control [22].

Drowned flow for a weir = (coefficient of discharge).(width of opening).(depth of water above invert)$^{0.5}$

Free flow for a weir = (coefficient of discharge). (width of opening) (depth of water above invert)$^{1.5}$

4.2 Data

The water balance model and subsequent projections relied on multiple datasets covering hydrology, climate, and observed water levels:

- Observed water levels: Historical water level data for the Caspian Sea at Aktau and Baku were obtained from Kaz Hydromet, the national hydro-meteorological service of Kazakhstan for the period 1980–2024.

- River discharge: Monthly discharge data for the River Volga and other major tributaries (Ural, Terek, Kura) were sourced from Kaz Hydromet.
- Climate forcing: Precipitation and evaporation estimates were derived from ERA-5 reanalysis [24], with adjustments applied to account for known wind speed biases affecting evaporation estimates.
- Future climate projections: Climate change scenarios were based on the Coupled Model Intercomparison Project, Phase 6 (CMIP6) multi-model ensemble (median) for three Shared Socioeconomic Pathways (SSP1-1.9, SSP2-4.5, SSP5-8.5), downscaled to the Caspian Sea region.
- Kara-Bogaz-Göl data: Channel geometry and historical flow estimates were taken from [22, 23].
- Ancillary data: Information on groundwater exchange, ungauged tributaries, and delta losses was compiled from [4] and related literature.

All datasets were harmonized to a common temporal resolution (monthly) for calibration and scenario simulations. Uncertainties in data quality and coverage were addressed through sensitivity analysis during model calibration.

4.3 Flux representation and key assumptions

The inflow to the Caspian Sea comprises river flows which are dominated by the Volga (~80 to 90% of the total), with additional contributions from the Ural, Terek, Kura and other tributaries. A net Volga delta loss term of 6 to 8 km^3/year accounts for evaporation, seepage, evapotranspiration, and temporary storage in channels and floodplains between the most downstream gauge and the sea [4]. Precipitation over the sea surface is taken from reanalysis-derived climatologies.

The largest loss of water from the Caspian Sea is via evaporation. This is driven primarily by air temperature, wind speed and humidity, and the evolving sea surface area. The ERA5 wind data was corrected for its known underestimation by testing small multiplicative adjustments during calibration [24]. Outflow to the KBG was computed dynamically from the contemporaneous head difference between the two water bodies and the connecting channel geometry.

4.4 Calibration and validation

The water balance model was calibrated against observed sea levels at Aktau and Baku between 1980–2020, using three goodness-of-fit metrics: Nash–Sutcliffe Efficiency (NSE), Mean Squared Error (MSE) and r^2. Calibrated parameters included: (i) effective width/depth and hydraulic coefficients for the KBG channel; (ii) net Volga delta losses; (iii) small adjustments to evaporation to account for ERA-5 wind biases; and (iv) a residual term for groundwater and ungauged inflows.

Across the calibration experiments (Table 2; Figure 3), the parameter set in Run 4 (Volga loss = 6 km^3/year; +2% evaporation adjustment) provided the best multi-site performance against the average of Aktau and Baku levels, yielding NSE = 0.82, MSE = 0.051, and r^2 = 0.89 for the average series. This configuration was adopted for scenario simulations. (For NSE, values > 0.75 are considered excellent; for MSE, lower is better; r^2 ranges from 0 to 1.)

Table 2: Parameters used to calibrate the Caspian Sea water balance model and the comparison to observed water levels at Baku and Aktau using Nash-Sutcliffe Efficiency (NSE), Mean Square Error (MSE) and r-squared

Calibration run	Calibration parameter		Nash-Sutcliffe Efficiency*			Mean Squared Error**			r-squared***		
	River loss (km^3/ year)	Percentage increase in ERA-5 evaporation	Fit to Baku observed water level	Fit to Aktau observed water level	Fit to average water levels at Aktau and Baku	Fit to Baku water level	Fit to Aktau water level	Fit to average observed water levels at Aktau and Baku	Fit to Baku water level	Fit to Aktau water level	Fit to average observed water levels at Aktau and Baku
Run 1	6	0%	0.68	0.13	0.49	0.082	0.238	0.138	0.92	0.93	0.95
Run 2	8	0%	0.76	0.38	0.66	0.061	0.169	0.093	0.90	0.94	0.95
Run 3	6	3%	0.32	0.81	0.67	0.173	0.053	0.095	0.71	0.88	0.82
Run 4	6	2%	0.66	0.80	0.82	0.087	0.055	0.051	0.80	0.92	0.89
Run 5	6	1%	0.78	0.58	0.77	0.056	0.115	0.064	0.87	0.94	0.93

*For NSE, values less than 0.36 are considered unsatisfactory, while values between 0.36 to 0.75 are classified as good, and values greater than 0.75 are regarded as excellent.
**For the MSE, the lower the value the better the model. A MSE of 0 means the model is a perfect fit.
***The value of r-squared ranges between 0 and 1, 0 corresponds to no correlation and 1 provides perfect correlation between the observed and the modelled water level.

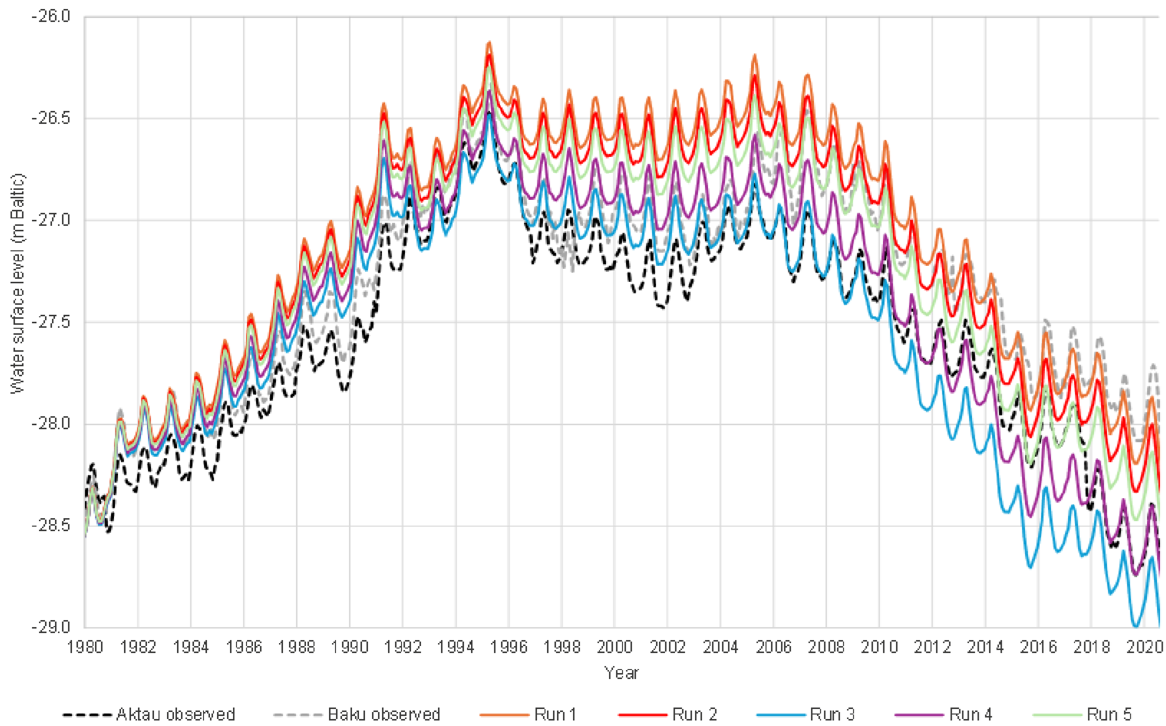

Figure 3: Calibration simulations of the water balance model of the Caspian Sea for the period 1980 to 2020

4.5 Scenario design and climate forcing

Future simulations were driven by the CMIP6 multi-model ensemble (median) under three Shared Socioeconomic Pathways (SSPs) for the 2030s, 2050s and 2090s epochs, referenced to the 1995 to 2014 baseline (consistent with IPCC AR6 practice [25]:

- SSP1-1.9: very low greenhouse gas (GHG) emissions with rapid decarbonization (<1.5 °C by 2100).
- SSP2-4.5: "middle-of-the-road" development and moderate GHG emissions (~ 2.5 to 3 °C by 2100).
- SSP5-8.5: fossil-fuelled growth with high GHG emissions (> 4 °C by 2100).

4.5. Projected water levels

All the modelled scenarios indicated a continued decline in Caspian Sea levels at Aktau relative to the 1995–2014 baseline (Table 3; Figure 4). These findings align with other recent studies [26-29]. By the 2090s, the projected reductions in water levels range from −2.4 m (SSP1-1.9) through −2.9 m (SSP2-4.5) to −7.4 m (SSP5-8.5). SSP1-1.9 and SSP2-4.5 are similar through to the middle of this century before diverging, while SSP5-8.5 produces the steepest decline throughout.

The period 1995 to 2014 was used as a reference period with which to compare future Caspian Sea water level conditions. It was chosen because it aligns with key international climate assessments, such as those used in the Intergovernmental Panel on Climate Change's Sixth Assessment Report (AR6) [25]. Figure 4 shows how the water levels in the Caspian Sea could change for the three SSPs in the 2030s, 2050s and 2090s. The results of the water balance model are provided in Table 3. Table 4 provides the projected water levels for the 2030s, 2050s and 2090s if they continue to decline at the same rate as they have done between 2006 and October 2024.

For context, the October 2024 level at Aktau was −29.66 m BD, already 2.6 m below the 1995 to 2014 average of −27.0 m BD. Short-term variability (e.g. in precipitation, inflows, evaporation), model structural and forcing uncertainties, and extreme events can cause deviations from the long-term trajectory, but the decadal downward trend is robust across scenarios.

Table 3: Caspian Sea water levels and reductions under different climate change scenarios

Climate change scenario	Average water level (m BD) for the median of the climate model ensembles compared to the 1995 to 2014 reference period			Average change in the water level for the 2030s, 2050s and 2090s compared to the 1995 to 2014 reference period		
	2030s	2050s	2090s	2030s	2050s	2090s
SSP1-1.9	-28.23	-29.03	-29.63	-1.0	-1.7	-2.4
SSP2-4.5	-28.03	-28.83	-30.23	-0.8	-1.5	-2.9
SSP5-8.5	-28.93	-31.43	-34.83	-1.7	-4.1	-7.4

4.6 Continuation of the recent decline in water levels

If the mean rate of decline observed from January 2006 to October 2024 were to persist, water levels would reach −32.8 m BD by the 2050s and −38.3 m BD by the 2090s, i.e. an additional −3.14 m and −8.64 m relative to October 2024 water level, respectively (Table 4). This "constant-trend" counterfactual is not a climate scenario, but it highlights the severity of recent declines relative to the CMIP6 forced projections.

Table 4: Future Caspian Sea water levels if the rate of decline between 2006 and 2024 continues at a constant rate until the 2090s

Water level (m BD)			Change in water level in metres compared to October 2024 level of -29.66 m BD		
2030s	2050s	2090s	2030s	2050s	2090s
-30.1	-32.8	-38.3	-0.44	-3.14	-8.64

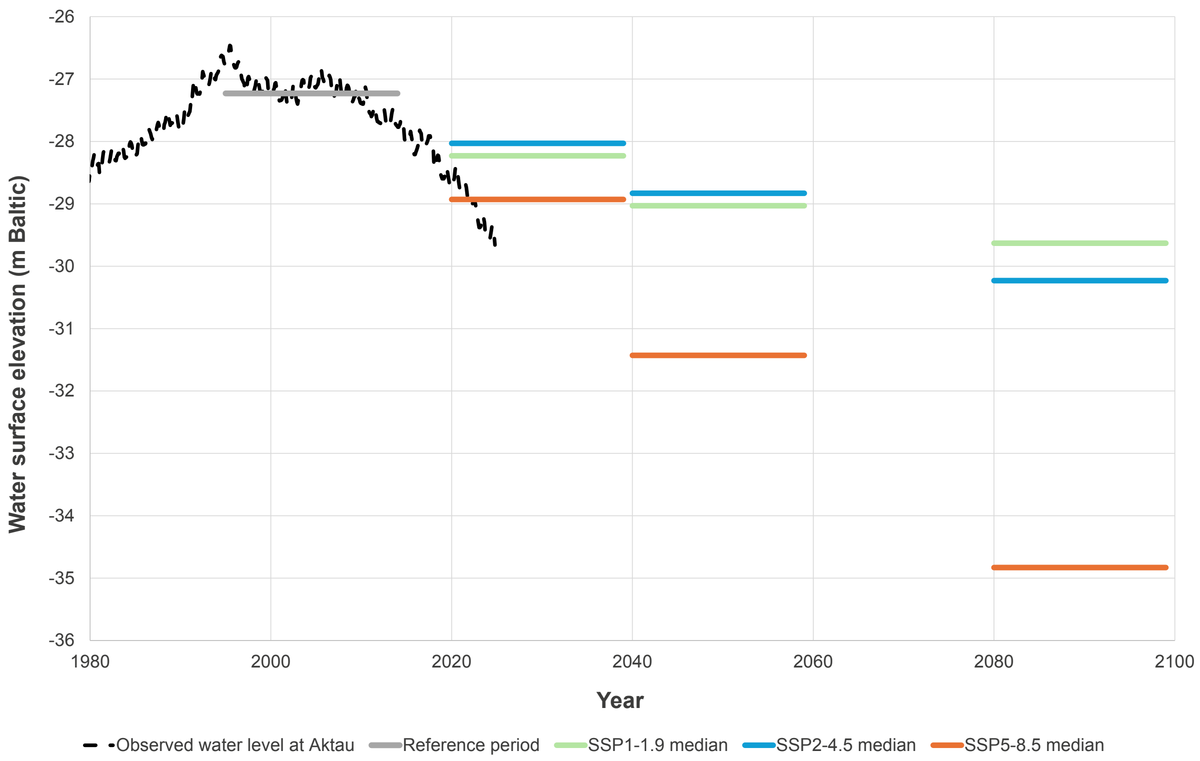

Figure 4: Future changes in the Caspian Sea's water levels for 2030s, 2050s and 2090s epochs under three different climate change scenarios for Aktau Port

4.7 Sensitivity to the connection to the Kara-Bogaz-Göl (KBG)

The sensitivity of sea levels to closing the KBG channel (i.e., eliminating outflow) was assessed. The water level in the KBG is consistently 0.5 m to 3.0 m below that of the Caspian Sea [22]. The estimated outflows from the Caspian Sea to the KBG can reach up to 20 km³ per year [23]. In 1980, in response to the rapidly dropping sea level, a dam was constructed on the channel connecting the KBG to the Caspian Sea to prevent water from flowing into it, resulting in the drying up of the KBG [22]. This resulted in significant environmental consequences, including an increase in dust storms which affected people's respiratory health, deaths of pink flamingos, and adverse impacts on the population of sturgeon [26]. In 1992, the dam blocking the connection between the KBG and the Caspian Sea was demolished at the instruction of the Turkmenistan Government [22]. Simulations show that closure of the channel connecting the KBG to the Caspian Sea raises future water levels by ~0.45 to 1.10 m, depending on scenario and epoch (Table 5), compared to if the channel remained open. Based on the available topographic data once the water level in the Caspian Sea falls below -32 m BD, water is unlikely to be able to flow into the KBG.

Table 5: Caspian Sea's water levels and reductions under different climate change scenarios with the closure of the channel between the Kara-Bogaz-Göl and Caspian Sea

Climate change scenario	Average water level (m BD) for the median of the climate model ensembles compared to the 1995 to 2014 reference period			Average change in the water level for the 2030s, 2050s and 2090s compared to situation where water is allowed to continue to flow into the Kara-Bogaz-Göl		
	2030s	2050s	2090s	2030s	2050s	2090s
SSP1-1.9	-27.13	-27.93	-28.53	+1.10	+1.10	+1.10
SSP2-4.5	-26.98	-27.78	-29.38	+1.05	+1.05	+0.85
SSP5-8.5	-27.98	-30.48	-34.38	+0.95	+0.95	+0.45

4.8. Effects of water abstractions for desalination

Water abstraction from the Caspian Sea for desalination is expected to increase over the next decade (2025 to 2035). Azerbaijan and Kazakhstan have already begun utilising the sea to address their own water shortages. Kazakhstan plans to construct nine additional desalination plants. Iran and Turkmenistan are also considering similar developments [3]. The capacity of the Caspian Desalination Plant in Aktau is set to double from 20,000 m^3 to 40,000 m^3 per day, while a new plant with a daily capacity of 5,000 m^3 is likely to be built in Fort-Shevchenko [3]. Even if 10 more plants are added, each abstracting 20,000 m^3 of water per day, the total annual abstraction would amount to just 0.073 km^3/year, an amount that remains negligible in the context of the Caspian Sea's overall water balance.

4.9 Uncertainties and limitations

Uncertainties in the water balance modelling of the Caspian Sea arise from (i) climate forcing (spread across CMIP6 models and scenarios); (ii) hydrological representation (e.g., groundwater and ungauged tributaries); (iii) parameter estimation (e.g., KBG channel hydraulics, Volga delta losses); and (iv) meteorological reanalysis biases (e.g., ERA5 wind underestimation affecting evaporation [23]. The median projections have been reported to reduce model-specific artefacts, but the tails of the distribution (particularly under SSP5-8.5) could yield more extreme outcomes. Despite these uncertainties, all median projections point to a sustained, decadal-scale decline in water levels, with the magnitude strongly dependent on emissions pathways.

5. Measures to allow Aktau Port to adapt to a reduction the Caspian Sea's water levels

Aktau Port, located on the eastern coast of the Caspian Sea, plays a crucial role in Kazakhstan's transportation infrastructure. It is strategically positioned for a number of reasons. It provides landlocked Kazakhstan with maritime trade routes to Azerbaijan, Iran, Russia, and Turkmenistan [30] and forms a key part of the TITR. In addition, Aktau Port benefits from a relatively mild climate, allowing for year-round operation without significant disruptions from severe weather conditions [30]. The layout of Aktau Port is shown in Figure 5.

Aktau Port needs to adapt to decreases in the Caspian Sea's water levels. The port needs to increase water depths to continue to accommodate the existing fleet of ships, and investigate the use of new vessels that maintain or increase cargo deadweight tonnage (DWT) whilst reducing the drafts of ships. The falling water levels in the Caspian Sea have reduced the available draft for vessels that use Aktau Port and this is already limiting the throughput, in particular from oil tankers, which is not efficient or sustainable. The container, grain and general cargo ships have shallower drafts of around 4.5 m, but these are also starting to be draft limited. The current decline in Caspian Sea water levels has already led to a decreases in vessels' capacities, which has reduced the port's performance and productivity which may lead to shifting routes to longer marine or overland routes. This section discusses the possible adaptation measures for Aktau Port for the following time scales: immediately; short- to medium-term (i.e. 2027 to 2050); and long-term (post 2050). The adaptation measures investigated focused on engineering considerations and capital dredging. This is because maintenance dredging requirements at Aktau Port are minimal. The velocity of the currents in the vicinity of the port are very low and as a result sediment transport in the area is negligible compared with the effects of the falling water levels.

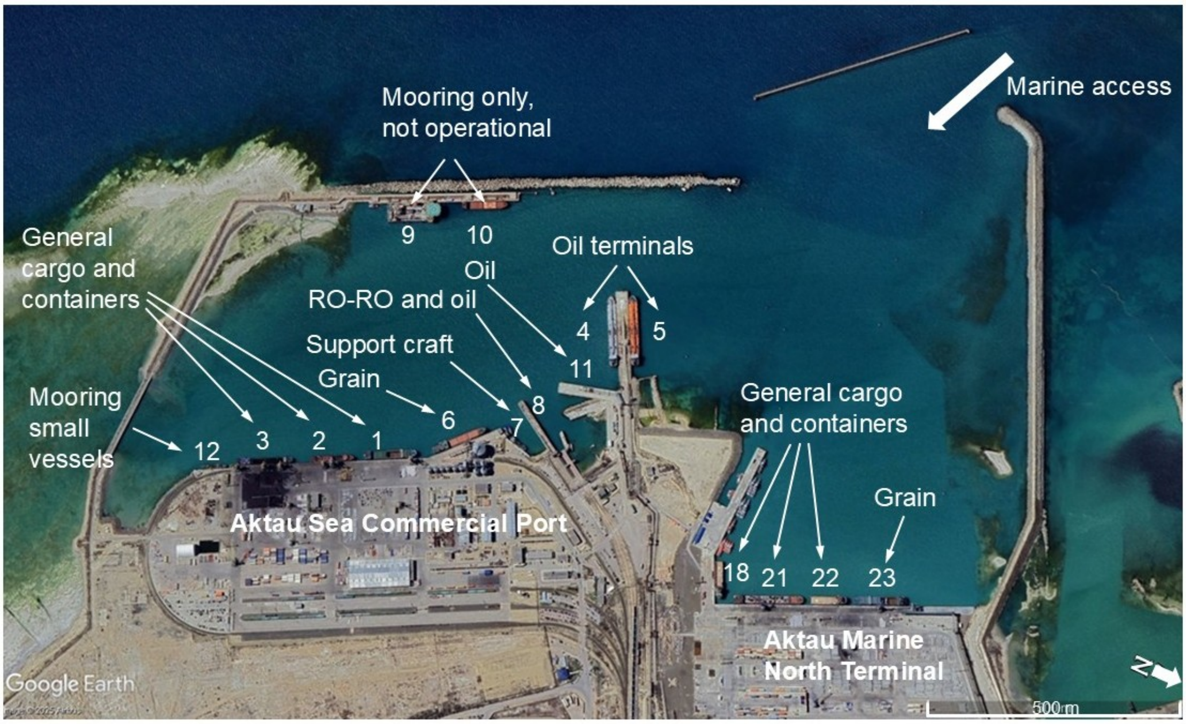

Figure 5: Layout of Aktau Port showing the berth numbers and their uses

5.1 Immediate measures: Maintaining operability with low-regret actions

The immediate priority for Aktau Port is to restore and maintain navigable depths while protecting quay structures, without incurring significant capital expenditure. Dredging is required to maintain the required water depths for ships to access the berths. In combination with the dredging there is a need for new . There are different approaches for adapting the fendering systems to enable berth deepening. The viability of these options depends on the condition of the berths and their structural capacity.

An assessment of Aktau Port indicated that dredging cut depths range from to ~0.9 to ~0.9 m adjacent to the berths, and from 1.06 to 2.45 m in the basins and access channel. Dredging would be beneficial at berths 1 to 6, 18, and 21 to 23, where existing quay structures can accommodate some deepening. Berths 7 to 12, however, are at structural capacity and would require a stability buffer zone of up to 14 m from the quay wall, prohibiting dredging in their immediate vicinity. Consequently, these berths would not benefit from adjacent basin deepening. Significant structural upgrades would be necessary to enable future dredging in these areas. Additionally, dredging operations in the Caspian Sea are constrained by the availability of local equipment, which is often outdated and limited in capacity. Contractors need to be engaged well in advance to secure equipment, given the high regional demand.

Concurrently, the port's fendering system requires upgrading urgently. Falling water levels have lowered berthing elevations relative to the fender contact points, leading to reduced energy absorption, altered load paths into the quay, and heightened risk of structural damage. Temporary tyre fenders currently in use (Figure 2), are not suitable for sustained operations.

Replacement fender systems can both restore energy absorption performance and, critically, move the berthing line away from the existing quay face to permit limited deepening in front of the wall In practice, the gain in dredged depth enabled by new fenders is berth specific, but typically of the order of 1.0 to 1.5 m. Further deepening close to the wall risks undermining stability and can conflict with crane reach, mooring geometry and cargo handling layouts. Four conceptual fendering options could be considered:

1. Option 1. Fender frames, retrofitted to the cope, to provide a modest stand-off.

2. Option 2. Fender piles, depending on vessel size and loading these may or may not be connected to the quay cope. These can be installed relatively quickly and can be combined with floating fenders.
3. Option 3. Floating (pneumatic) fenders that adapt to fluctuating levels but require periodic maintenance of chains and floats.
4. Option 4. Dolphin structures which are independent structures that can help move the berthing line several metres seaward, enabling deeper dredging at the cost of more extensive construction and potential knock-on requirements such as crane reach upgrades.

All these options require equipment and mooring compatibility assessments to confirm that the ships can be loaded and unloaded efficiently. An assessment of the mooring arrangements is needed to confirm that the fendering structures do not interfere with the mooring arrangements so the ships can safely attach ropes to the mooring bollards. Adaptation measures such as roller fairleads or anti-chafe protection on the cope beam edges may be required. Figure 6 shows the four potential fendering options and Table 6 provides an overview of their advantages and disadvantages.

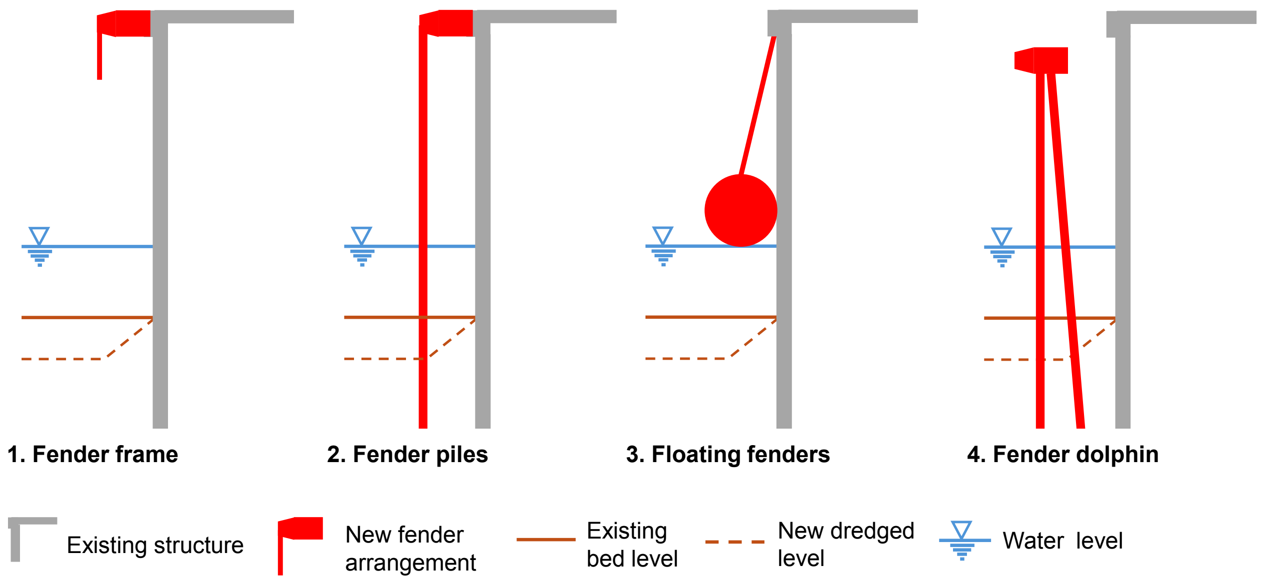

Figure 6: Examples of conceptual fender adaptation options for berths at Aktau Port

Table 6: Advantages and disadvantages of fender adaptation options

Fender adaptation option	Advantages	Disadvantages
1. Fender frame	Can be fitted to existing quay cope	Limited to 1 to 2 m extension from the berth Limited potential to dredge Adds significant new loads to the structure
2. Fender piles	Can be installed quickly, with or without fender to connect to quay cope	If combined with pneumatic fender limited to 2 to 3 m extension from the berth
3. Floating fender	Range of sizes available Can adapt to fluctuating levels Quick to install	Durability, may need chain and float replacements through quay life Loads imparted to sheet piled wall, albeit spread
4. Fender dolphin	Can push berthing line several metres providing scope for deeper dredging than the other options Berthing structure is independent of the existing structure	More extensive construction required Costs can be significant Raked or battered piles could clash with the existing wall Large offset of the berthing line would increase the required crane reach to load/ unload the vessel Added potential cost of equipment upgrades

5.2 Short- to medium-term measures (2027–2050): Structural upgrades for deeper dredging

The implementation of dredging and new fenders for the berths at Aktau Port provides an additional depth of 1.0 to 1.5 m, depending on the berth. This provides time to assess, design and implement more significant and costly adaptation measures that could extend the life of the port by several decades. The main adaptation measure required are to the quay walls and possibly also to the breakwaters in the vicinity of the navigational channel. These quay adaptation measures are costly but could potentially allow the depth of dredging to be significantly increased. Five conceptual quay wall options were considered (Figure 7; Table 7):

1. Option 1. New sheet piled toe.
2. Option 2. Anchored toe.
3. Option 3. New independent quay wall.
4. Option 4. New anchored sheet piled wall.
5. Option 5. New piled deck.

While Options 1 and 2 incur lower costs compared to Options 3, 4, and 5, they are limited in the maximum dredging depth that can be achieved. Examples of these potential modifications are shown in Figure 7 and their advantages and disadvantages are given in Table 7. Decreases in water levels could also lead to compatibility issues for loading and unloading cargo related to crane reach limits. For all these options, detailed interface management is essential. Changes to the berthing line and quay geometry must be reconciled with crane outreach, rail alignment, conveyor positioning, utilities, drainage, and safety systems to ensure that navigational and cargo-handling performance is preserved or enhanced during and after construction.

Table 7: Advantages and disadvantages of quay wall adaptation options

Quay wall adaptation option	Advantages	Disadvantages
1. New sheet piled toe	Can provide additional depth near to quay wall Limited modifications to quay wall Commonly used by international contractors Cheaper than Options 3, 4 and 5	Difficult to pile underwater and near to existing structure Needs to be accompanied by a fendering upgrade Reliant on existing quay being in good condition Potential underwater hazard to ships Interim solution that does not allow dredging as deep as Options 3, 4 and 5
2. Anchored toe	Can be installed from dry by long reach rig No modifications to quay wall Cheaper than Options 3, 4 and 5	New and unproven technology, limited examples of application Reliant on existing quay being able to be deepened and in good condition Interim solution that does not allow dredging as deep as Options 3, 4 and 5
3. New independent quay wall	Wall can be independent of existing structures so there is limited demolition Allows dredging to a greater depth than Options 1 and 2	Equipment compatibility Expensive as new wall needs to have large sections Quay level may increase
4. New anchored sheet piled wall	Proven approach at Aktau Allows dredging to a greater depth than Options 1 and 2	Equipment compatibility Requires demolition so disruptive to port operations
5. New piled deck	Potential to lower deck (if required) and reduce retaining pressure (including with soil nailing) New piles to transfer deck loads can be arranged around existing anchor ties Allows dredging to a greater depth than Options 1 and 2	Quay wall will still have retained earth pressures to withstand, which may limit dredging Piling may be limited by existing construction or infrastructure Potential high cost of demolition and piling

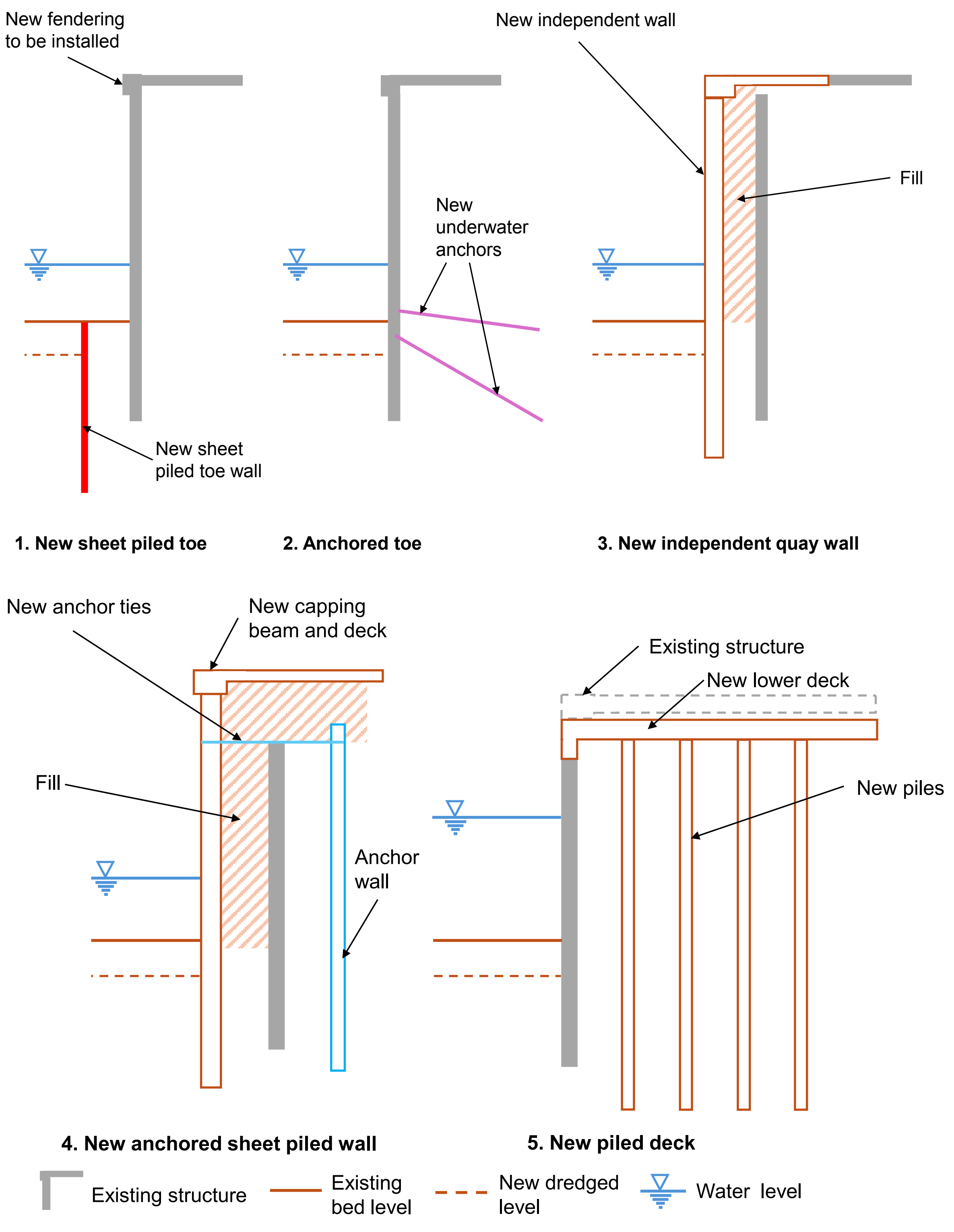

Figure 7: Examples of conceptual quay wall adaptation options for berths at Aktau Port

5.3 Complementary adaptation of the Caspian Sea's fleet of vessels

In addition to modifications to Aktau Port's physical infrastructure, changes in the design of the Caspian Sea's fleet of vessels could help the adaptation to falling water levels. For newbuilds, reducing the design draft and increasing the beam of new vessels could help to retain or enhance their DWT capacity. Operational adjustments that increase service speeds, (e.g., from ~10 knots to ~15 knots where feasible), can boost route capacity and reduce transit times, subject to fuel, emissions and maintenance trade-offs. These considerations apply across the principal vessel classes using Aktau, (i.e. oil tankers, Roll-On Roll-Off (RO-RO) ferries, container vessels, dry bulk vessels, and general cargo ships) and should be developed in tandem with berth geometry, fender lines and mooring layouts to ensure safe, efficient turnaround.

5.4 Adaptation pathways for Aktau

The current variations in the Caspian Sea's water levels means that adaptation pathways will need to be developed for Aktau Port to take into account the future variations in water levels. Adaptation pathways for infrastructure projects help decision-makers plan for uncertain future climate conditions by identifying flexible, phased options for development and investment. Developing adaptation pathways for a port such as Aktau, which faces uncertain future water levels owing to varying future GHG emissions, is a complex challenge. There are a range of outcomes and, depending on the emissions scenarios, the Caspian Sea's water level could decline by between -1.5 to -4.1 m by the 2050s. Port infrastructure (e.g., quays) often have a design life of at least 50 years, requiring decisions made today to remain robust under future uncertainty. There is the potential for "lock-in risk" whereby early decisions may constrain future options or lead to maladaptation if sea levels decline faster or more slowly than expected, or even start rising again.

A theoretical example of an adaptation pathway for Aktau Port is shown on Figure 8. This is based on the assumption that the Caspian Sea's water level decline to the median levels estimated under the SSP5-8.5 scenarios which are -31.43 m BD and -34.83 m BD for the 2050s and 2090s epochs respectively. There is a requirement to immediately carry out dredging, constrained by the condition not to modify the port's quay wall and implement a new fendering system, as well as some limited adaptation to equipment. This first phase of adaptation to water level decline offers around 1 m of additional water depth (it includes dredging, new fendering, and some equipment adaptation). In the example shown in Figure 8, these adaptation measures provide a 15 year window to plan, design and adapt the existing quay walls (Figure 7) and carry out a significant amount of additional dredging. These adaptations to the quay walls together with further dredging would have between a 30 and 40 year design life.

A threshold-based and scenario-driven approach should be used to determine when to implement each measure, based on water depth with critical depth levels set for different vessel types and berths, monitoring reductions in cargo volume owing to navigability issues, as well as ongoing maintenance costs. Adaptation measures should be developed for low, medium, and high water level decline scenarios. For some of the adaptation measures, there is a need to evaluate the economic trade-offs of early versus delayed adaptation measures, and no-regret options (e.g., implementation of new fenders) should be prioritised.

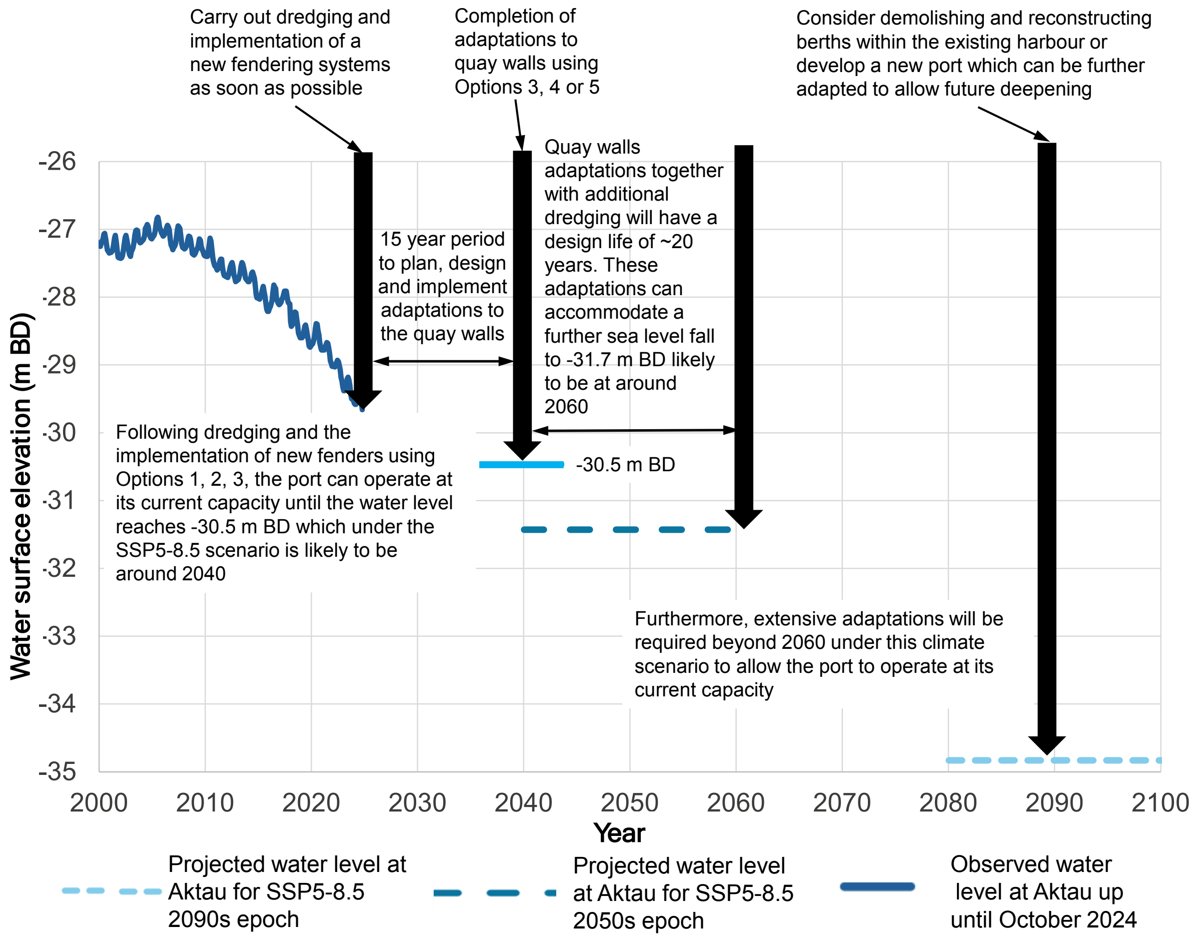

Figure 8: Example of a theoretical adaptation pathway for Aktau Port based on the assumption that the Caspian Sea's water levels projected decline follows the SSP5-8.5 median scenario

6. Conclusions and recommendations

This research demonstrates that the Caspian Sea is highly likely to experience continued water level decline over the coming decades, driven by increased evaporation and reduced inflows from the River Volga under changing climatic conditions. Aktau Port, as Kazakhstan's principal maritime hub and a critical link in the TITR, is particularly vulnerable to these changes. The observed and projected reductions in water depth have significant implications for port operability, cargo throughput, and regional trade connectivity. It is interesting to note that several recent studies on the TITR and Aktau Port [31, 32] do not mention decreasing water levels in the Caspian Sea as being an issue .

Current evidence shows that falling water levels have already reduced available draft at Aktau, forcing vessels, particularly oil tankers, to operate underloaded, thereby reducing efficiency and increasing costs. Around 70% of the port's fenders have become ineffective owing to the lower water levels and have had to be replaced with temporary solutions. The existing quays and mooring systems are not designed for such low water levels, leading to increased wear and operational risk. If water levels continue to decline at the rates projected under high-emission scenarios, the window for implementing major adaptation measures will be limited to approximately 15 years.

Adaptation planning for Aktau Port needs to adopt a phased and flexible approach. Immediate measures should focus on low-regret actions such as installing new fendering systems and undertaking targeted dredging to maintain operability. These interventions can provide an additional 1.0 to 1.5 m of depth and create a short-term buffer while more substantial works are designed. In the medium-term, structural modifications to the existing quay walls and associated infrastructure will be necessary to enable deeper dredging and sustain cargo capacity. Long-term strategies may include major reconstruction, offshore loading facilities, or the development of new port infrastructure, depending on realized water levels and trade patterns. A threshold-based, scenario-driven approach is required to guide decision-making, incorporating critical depth thresholds for different vessel types, cargo throughput indicators, and maintenance cost trends. Adaptation pathways should be developed for low, medium, and high water-level decline scenarios, with priority given to no-regret measures that deliver benefits under all futures. Coordination with other Caspian ports, particularly Baku, will be essential to ensure operational compatibility and maintain efficient regional trade. In parallel, vessel design should evolve to accommodate lower water levels, for example by reducing draft and increasing beam while maintaining or improving DWT.

In summary, the decline of the Caspian Sea represents a systemic challenge requiring proactive, phased, and collaborative adaptation planning. Immediate interventions can sustain operations in the short term, but strategic investments and regional coordination will be critical to safeguarding Aktau Port's role as a key trade and energy hub in the decades ahead.

Further research is needed to refine projections of Caspian Sea water levels by improving the representation of hydrological processes, particularly groundwater interactions, deltaic losses, and the influence of anthropogenic water withdrawals. Enhanced regional climate modelling and downscaling would reduce uncertainty in evaporation and inflow estimates. Future work should also include economic analyses of adaptation options, considering life-cycle costs, financing mechanisms, and trade-offs between early and delayed interventions. Finally, integrated studies that couple port infrastructure planning with fleet modernization strategies and regional coordination frameworks will be essential to ensure resilient and cost-effective adaptation across the Caspian basin.

7. References

1. Rodionov, S.N. (1994) Global and regional climate interaction: The Caspian Sea experience, Springer Science & Business Media, Dordrecht.

2. Georgi, C., (2023). The Trans-Caspian International Transport Route through the Caspian region. German International Journal of Modern Science/Deutsche Internationale Zeitschrift für Zeitgenössische Wissenschaft, (54) doi: 10.5281/zenodo.7845315

3. Hutson, N. and Taganova, J. (2023). A new strategy for merging the environmental and commerce challenges of the Caspian, Central Asian Journal of Water Research (2023) 9(2): 76-102, https://doi.org/10.29258/CAJWR/2023-R1.v9-2/76-102.eng

4. Lahijani, H., Leroy, S.A.G., Arpe, K. and Crétaux, J-F. (2023) Caspian Sea level changes during instrumental period, its impact and forecast: A review, Earth-Science Reviews 241 104428. https://doi.org/10.1016/j.earscirev.2023.104428

5. Naderi Beni, A., Lahijani, H., Mousavi Harami, R., Arpe, K., Leroy, S.A.G., Marriner, N., Berberian, M., Andrieu-Ponel, V., Djamali, M., Mahboubi, A. and Reimer, P.J. (2013) .Caspian sea-level changes during the last millennium: historical and geological evidence from the south Caspian Sea. Climate of the Past, 9(4), pp.1645-1665. https://doi.org/10.5194/cp-9-1645-2013

6. Leroy, S.A.G, Reimer, P.J., Lahijani, H.K., Naderi Beni, A., Sauer, E., Chalié, F., Arpe, K., Demory, F., Mertens, K., Belkacem, D., Kakroodi, A.A., Omrani Rekavandi, H., Nokandeh, J. and Amini, A. (2022). Caspian Sea levels over the last 2200 years, with new data from the S-E corner, Geomorphology, vol. 403, 108136 https://doi.org/10.1016/j.geomorph.2022.108136

7. Chen, J.L., Pekker, T., Wilson, C.R., Tapley, B.D., Kostianoy, A.G., Cretaux, J.F. and Safarov, E.S. (2017). Long-term Caspian Sea level change. Geophysical Research Letters, 44(13), pp.6993-7001. https://doi.org/10.1002/2017GL073958

8. Joshi, R. (2022). 7 major ports in Kazakhstan, Marine Insight, 16 April 2022, available at: https://www.marineinsight.com/know-more/7-major-ports-in-kazakhstan/ (accessed 21 July 2025)

9. Aktau Port Authority (2024) Personal communication with Aktau Port Authority February 2024

10. Gasimov, K. (2025). Kazakhstan's Aktau port to launch dredging works in June, 24 April 2025, Azerbaijan Report News Agency, available at: https://report.az/en/infrastructure/kazakhstan-s-aktau-port-to-launch-dredging-works-in-june/ (accessed 21 July 2025)

11. Yang, L., Li, K. and Pang, X., (2013). Design and optimization of maintenance strategies for a long life-span port project. Materials and structures, 46(1), pp.161-172.

12. Taneja, P., Ligteringen, H., and Van Schuylenburg, M. (2010). Dealing with uncertainty in design of port infrastructure systems. Journal of Design research, 8(2), 101-118.

13. Yazdanpanah Dero, Q., Yari, E. and Charrahy, Z., (2020). Global warming, environmental security and its geo-economic dimensions case study: Caspian Sea level changes on the balance of transit channels. Journal of Environmental Health Science and Engineering, 18(2), pp.541-557.

14. Arpe, K., Leroy, S.A.G., Lahijani, H. and Khan, V. (2012.) Impact of the European Russia drought in 2010 on the Caspian sea level, Hydrological and Earth System Sciences 16 (2012), pp. 19-27. https://doi.org/10.5194/hess-16-19-2012

15. Apollov, B.A. (1935). Water balance of the Caspian Sea and possible changes. Report of TSIEGM. Issue. 2 (44), 11–18.

16. Apollov, B.A. and Alekseeva, K.I. (1959). Caspian Sea water level forecast. Report of Oceanographic Commission of the Academy of Sciences USSR, Vol. 5, pp. 63–78.

17. Kritsky, S.N., Korenistov, D.V. and Ratkovich, D.Y. (1975) Caspian Sea level fluctuations. Nauka, Moscow, 159 p.

18. Medvedev, I.P., Kulikov, E.A., Fine, I.V. and Kulikov, A.E. (2019). Numerical modeling of sea level oscillations in the Caspian Sea. Russian Meteorology and Hydrology, Vol 44, pp.529-539.

19. Voropaev, G.V. (1986). The Caspian Sea: Hydrology and hydrochemistry. Nauka, Moscow, p. 262p.

20. Nesterov, E.S. (2016.) Water balance and level fluctuations of the Caspian Sea, modelling and prediction. Russian Hydrometcenter, 378 p.

21. Shiklomanov, I.A., Georgievsky, V.Y. and Kopaliani, D. (1995). Water balance of the Caspian Sea and reasons of water level rise in the Caspian Sea central Caspian part, UNESCO-IHP-IOC-IAEA Workshop on sea level rise and the multidisciplinary studies of environmental processes in the Caspian Sea region Paris, France 9-12 May 1995.

22. Varushchenko, A.N., Lukyanova, S.A., Solovieva, G.D., Kosarev, A.N. and Kurayev, A.V., (2000). Evolution of the Gulf of Kara-Bogaz-Göl in the past century. Dynamic Earth Environments: Remote Sensing Observations from Shuttle-Mir Missions, pp.201-210.

23. Ginzburg, A.I., Kostianoy, A.G. and Sheremet, N.A., (2022) On the dynamics of waters in Kara-Bogaz-Göl (satellite information). Cosmic Research, 60(Suppl 1), pp.S27-S37. https://doi.org/10.1134/S0010952522700046

24. Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horanyi, A., Munoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Holm, E., Janiskov, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S. and Thepaut, J.-N. (2020). The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), pp.1999-2049. https://doi.org/10.1002/qj.3803

25. Kikstra, J.S., Nicholls, Z.R., Smith, C.J., Lewis, J., Lamboll, R.D., Byers, E., Sandstad, M., Meinshausen, M., Gidden, M.J., Rogelj, J. and Kriegler, E., (2022). The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: from emissions to global temperatures. Geoscientific Model Development, 15(24), pp.9075-9109. https://doi.org/10.5194/gmd-15-9075-2022

26. Court, R., Lattuada, M., Shumeyko, N., Baimukanov, M., Eybatov, T., Kaidarova, A., Mamedov, E.V., Rustamov, E., Tasmagambetova, A., Prange, M. and Wilke, T., (2025). Rapid decline of Caspian Sea level threatens ecosystem integrity, biodiversity protection, and human infrastructure. Communications Earth & Environment, 6(1), p.261. https://doi.org/10.1101/2024.11.08.622693

27. Eeslami, Z. and Ghanghermeh, A. (2022). Forecast of water levels in the Caspian Sea based on the sixth IPCC report. Physical Geography Research, 54(2), pp.257-272.

28. Hoseini, S.M., Soltanpour, M. and Zolfaghari, M.R. (2025). Projected changes in Caspian sea level under CMIP6 climate change scenarios: probabilistic and deterministic approaches. Climate Dynamics, 63(1), p.44.

29. Samant, R. and Prange, M. (2023). Climate-driven 21st century Caspian Sea level decline estimated from CMIP6 projections. Communications Earth & Environment, 4(1), p.357.

30. Gunnar, P. (2024) The South Caucasian transport corridor: A new Eurasian transport option, Wismarer Diskussionspapiere, No. 03/2024, ISBN 978-3-948862-16-9, Hochschule Wismar, Fakultät für Wirtschaftswissenschaften, Wismar

31. Beifert, A. and Moldabekova, A. (2023). The readiness of port logistics services in the Caspian Sea within the Eurasian Transport Corridor–case study of the Port of Aktau. In International Conference on Reliability and Statistics in Transportation and Communication (pp. 233-246). Cham: Springer Nature Switzerland.

32. Prause, G. (2024). The South Caucasian transport corridor: A new Eurasian transport option (No. 03/2024). Wismarer Diskussionspapiere.

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