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Rapid decline of Caspian Sea level threatens ecosystem integrity, biodiversity protection, and human infrastructure



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The Caspian Sea is the world's largest landlocked waterbody, providing habitat for hundreds of endemic and migratory species, along with ecosystem services that sustain millions of people. Global warming is projected to drive declines in water levels of up to 21 m by 2100. Using geospatial analyses, we assessed the impact of sea level decline on habitats, protected areas, and human infrastructure. We show that a water level decline of just 5–10 m will critically disrupt key ecosystems (including habitats for endemic Caspian seals and sturgeon), reduce existing marine protected area coverage by up to 94%, and render billions of dollars of civil and industrial infrastructure obsolete. Replacing traditional static conservation planning with a pre-emptive, dynamic approach that allows protected areas to track shifting ecosystems, is recommended to help endemic Caspian Sea biodiversity adapt to these changes, and to avoid conflicts with mitigation efforts directed at protecting human activities.

Climate change is driving environmental crises for landlocked water bodies and rivers globally, with profound consequences for biodiversity, agriculture, fisheries, infrastructure and other economic activity, as well as human health and wellbeing^{1,2}. Increased rates of evaporation and changes to precipitation patterns are leading to declines in the levels of lakes and landlocked seas^{3–5}, meaning that current spatial conservation measures need to be adapted to remain relevant as key habitats shift to track changing water levels^{6–8}. Substantial changes in lake/inland sea ice phenologies are also expected⁹. Adapting protected areas for these ecosystems to make them fit for purpose in future will need to account for conflicts with concomitant actions to mitigate impacts on civil and industrial infrastructure and economic activity. However, the systematic evaluations needed to balance conservation and socioeconomic interests

in mitigation planning are missing for most major inland waterbodies. Here we assess vulnerability to water level decline for key ecosystems, protected areas, and human infrastructure in the Caspian Sea, the world's largest landlocked waterbody, and its relevance to developing a pre-emptive, temporally dynamic, spatial marine conservation strategy for the region.

Today, the Caspian Sea (Fig. 1) extends approximately 1150 km by 450 km, and is bordered by five countries: Azerbaijan, Iran, Kazakhstan, Russia, and Turkmenistan. Covering an area of around 387,000 km², it has three sub-basins: the northern Caspian has average water depths of 5 m, while the middle and southern basins reach 788 m, and more than 1000 m, respectively. The Caspian Sea receives water from around 130 rivers, with more than 80% of the inflow via the Volga and Ural rivers in the north^{10,11}.

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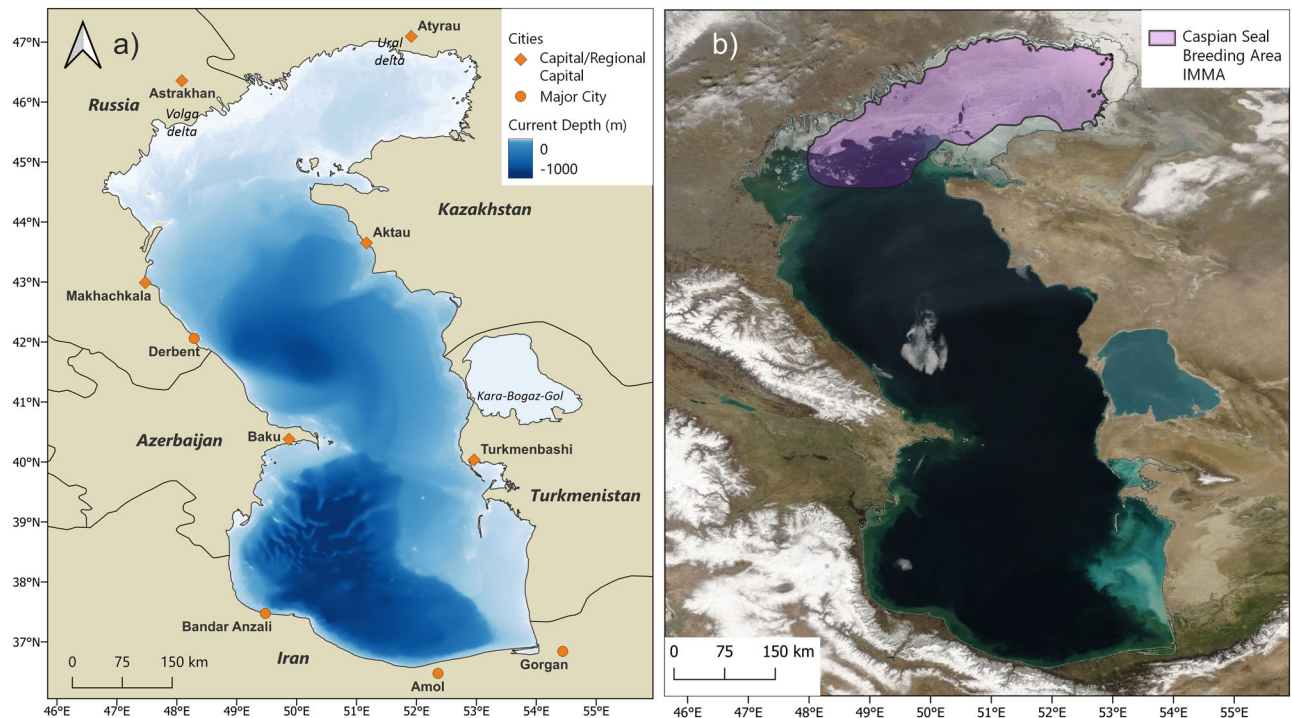


Fig. 1 | Current physical environmental conditions of the Caspian Sea.

a Bathymetry of the Caspian Sea with a datum of -27.5 m against global mean sea level. **b** NASA Worldview satellite image of the Caspian Sea region showing typical

winter ice coverage of the northern Caspian basin, which is the breeding habitat for the endemic Caspian seal (*Pusa caspica*). The pink polygon indicates the Caspian seal breeding Important Marine Mammal Area (IMMA; see Methods).

The depth and surface area of the Caspian Sea have varied over time, with regressions of up to 90 m and transgressions of 50 m during the Quaternary¹². At the beginning of the 20th century, Caspian Sea level (CSL) was approximately -25.8 m below global mean sea level. It then decreased by 2 m, stabilised during the 1950s and 1960s, before reducing rapidly between 1970 and 1977, reaching its lowest level in 100 years at -29 m. The level then rose to -26.5 m by 1995, subsequently declining again by around 2 m^{13,14}. The 20th Century variations are attributed to changes in water inflow rates (due to natural factors and human abstraction) and precipitation, and their balance against evaporation. The current declining trend is linked to global warming driving reduced precipitation, and a sharp increase in sea surface temperature and evaporation^{13,15,16}. CSL declined by -6.07 ± 0.26 cm per year between 2002 and 2015¹³, a negative rate 20 times greater than global sea level increase. Declines as high as 30 cm per year have been measured since 2020¹⁷. Early modelling studies predicted climate-driven CSL declines of around 5 m by 2100^{18,19}, but more recent projections predict reductions of 9 to 21 m by the end of the century under medium to high emission scenarios^{20–22}.

The Caspian Sea is of high importance for biodiversity in Central Asia and Europe, supporting more than 300 species of endemic invertebrates, 76 endemic fishes²³, as well as the endemic Caspian seal (*Pusa caspica*)²⁴. The coastal margins provide habitats for globally significant populations of water and migratory birds, with major flyways connecting Europe, Asia, and Southern Africa²⁵. The Caspian Sea has experienced substantial anthropogenic impacts and stressors including habitat destruction, pollution, introduction of invasive species and overexploitation of natural resources^{26–29}; leading to extinctions and displacement of native fauna³⁰, and collapse of commercial fisheries³¹ and the seal population³². CSL decline threatens already impacted ecosystems, the winter sea ice breeding habitat of Caspian seals in the northern basin³³, and the stability of regional climate³⁴. While concerns over the consequences of CSL decline for biodiversity have been raised previously^{22,35}, little systematic evaluation has been carried out on vulnerabilities of ecosystems and conservation protections arising from CSL decline.

More than 15 million people live around the Caspian coast³⁶. The projected sea level decline presents major economic and societal implications. Shipping routes, civil and industrial infrastructure, including ports and hydrocarbon production facilities, could become obsolete or unviable, while industrial and artisanal fisheries face severe disruption. As with the Aral Sea, increased exposure to pollutant contaminated sediment dust, arising from desiccation, could have serious impacts on human health³⁷. Adverse societal consequences from changes in CSL have previously been reported¹⁰ but are largely unrecognised in current policy and conservation spatial planning³⁵.

Quantitative assessments of vulnerabilities are required for Caspian countries to develop effective mitigation plans that can help sustain ecosystem services and functions in the face of impacts arising from CSL declines. To address this gap, we first quantify the extent of coastal recession in the northeastern Caspian Sea from 2001 to 2024 to establish current impacts on vulnerable ecosystems and areas of ecological importance. Next, we use bathymetric projections to estimate how CSL decline will reduce coverage of key ecosystems and existing spatial conservation designations in the Caspian region under different future decline scenarios, and evaluate vulnerabilities of human infrastructure and marine areas important for economic activity. Finally, we suggest policy priorities for effective, integrated, and sustainable responses to the environmental pressures that will soon unfold in the region. We find that since 2001 the coastline in the northeastern Caspian Sea has regressed by more than 56 km, and areas previously designated as of ecological significance have already become desiccated leading to loss of important habitats. Our bathymetric mapping projections indicate that the 5–10 m water level declines expected for low to medium emission climate change scenarios will critically disrupt key ecosystems, will reduce existing marine protected area coverage by up to 94%, and could render billions of dollars of civil and industrial infrastructure obsolete. We recommend replacing traditional static conservation planning with a pre-emptive, dynamic approach that allows protected areas to track shifting ecosystems. This will support adaptation of endemic Caspian Sea biodiversity to these changes, and help avoid conflicts with mitigation efforts directed at protecting human activities.

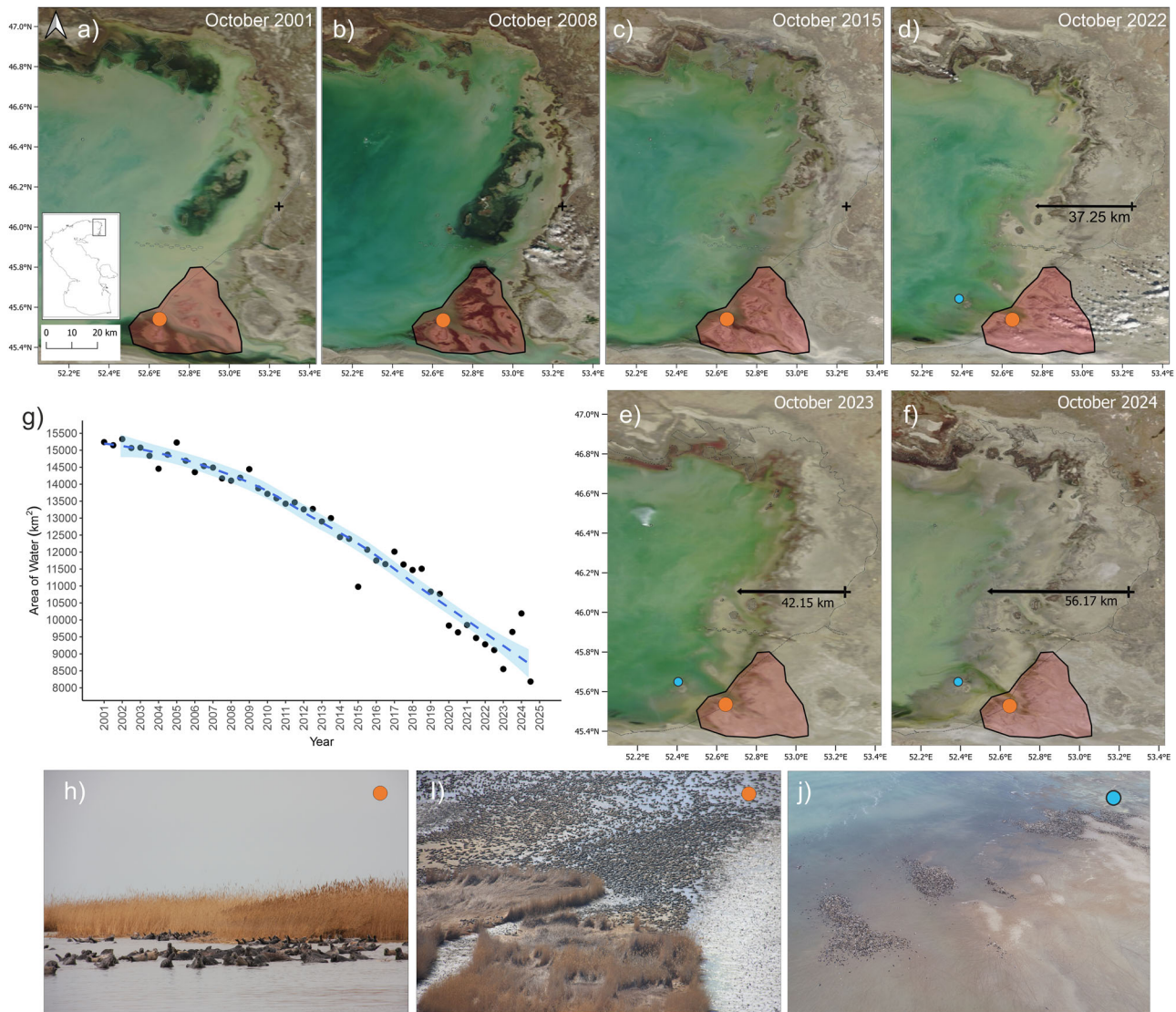


Fig. 2 | Coastal regression in the northeastern Caspian Sea. a–f Time series of NASA Worldview satellite images from 2001 to 2024 showing sea level recession; the polygon indicates boundary of the Komsomol Bay Ecologically or Biologically Significant Area (EBSA). The orange point marks the location of Caspian seal moulting aggregations in April 2011, and the blue point indicates the location of moulting aggregations in April 2022. **g** Plot of time series of measured water area within the focal polygon (area shown in Worldview satellite image) from 2001 to 2024. Points indicate measurements for March and October in each year, line and

shading indicate Loess best fit line and 95% confidence interval. **h** Caspian seal moulting aggregation among reed beds in Komsomol Bay at location of orange dot on satellite images, April 2011 (Photo: (©) Simon Goodman, University of Leeds). **i** Aerial view of dense Caspian seal moulting aggregations in Komsomol Bay, April 2011 (Photo: (©) Lilia Dmitrieva, University of Leeds). **j** Moulting aggregations of Caspian seals on newly emergent islands April 2022, at location of blue dot (Photo: (©) Assel Baimukanova, Institute of Hydrobiology and Ecology).

Results

Sea level recession in the northeastern Caspian Sea 2001–2024

The northeastern Caspian (Fig. 2) is an area with extremely shallow bathymetry (typically less than 1 m), consisting of extensive reed beds, sandbanks, muddy shoals, and water channels. It provides important habitats for water and migratory birds, fish spawning areas, as well as moulting and resting sites for Caspian seals^{38,39}, including an area formally recognised as an ‘Ecologically and Biologically Significant Area’ (EBSA), under the Convention on Biological Diversity²⁹. As one of the shallowest areas of the Caspian Sea, it is also one of the most vulnerable areas to changes in water level. Using a time series of NASA Worldview satellite imagery (2001–2024), we measured the change in area covered by water, in a focal polygon with bounds 47.12° N, 53.43° E to 45.27° N, 52.05° E, with a total area of 21901 km².

The area within the focal polygon covered by water in 2001 was 15,194 km² (Fig. 2). By October 2022, this had decreased by 39% to 9197 km², at approximately 285 km² per year (Fig. 2a–d and g). Relative to the

Worldview datum coastline, the shore receded by at least 37.25 km between 2001 and 2022. By the end of 2024, there was further rapid recession of the coastline, with water coverage decreasing by a total of 46% (8183 km² of water remaining), and a total shoreline recession of 56.17 km relative to 2001.

By 2024, most of the area within the Komsomol Bay EBSA boundary, recognised as an important spring moulting site for Caspian seals^{38,39} (Fig. 2h, i), had become desiccated, and seals could no longer access islands for moulting. Aerial surveys and field observations during spring 2018–2023 indicate moulting seals have shifted to newly emergent islands to the north, but with lower densities than observed in Komsomol Bay⁴⁰ (Fig. 2j).

Overview of impact from sea level decline scenarios across the Caspian Sea region

Previous climate modelling analyses^{20–22} have projected water level declines for the Caspian Sea of up to 21 m against the –27.5 m datum by 2100, but there is uncertainty over the maximum decline depending on climate model

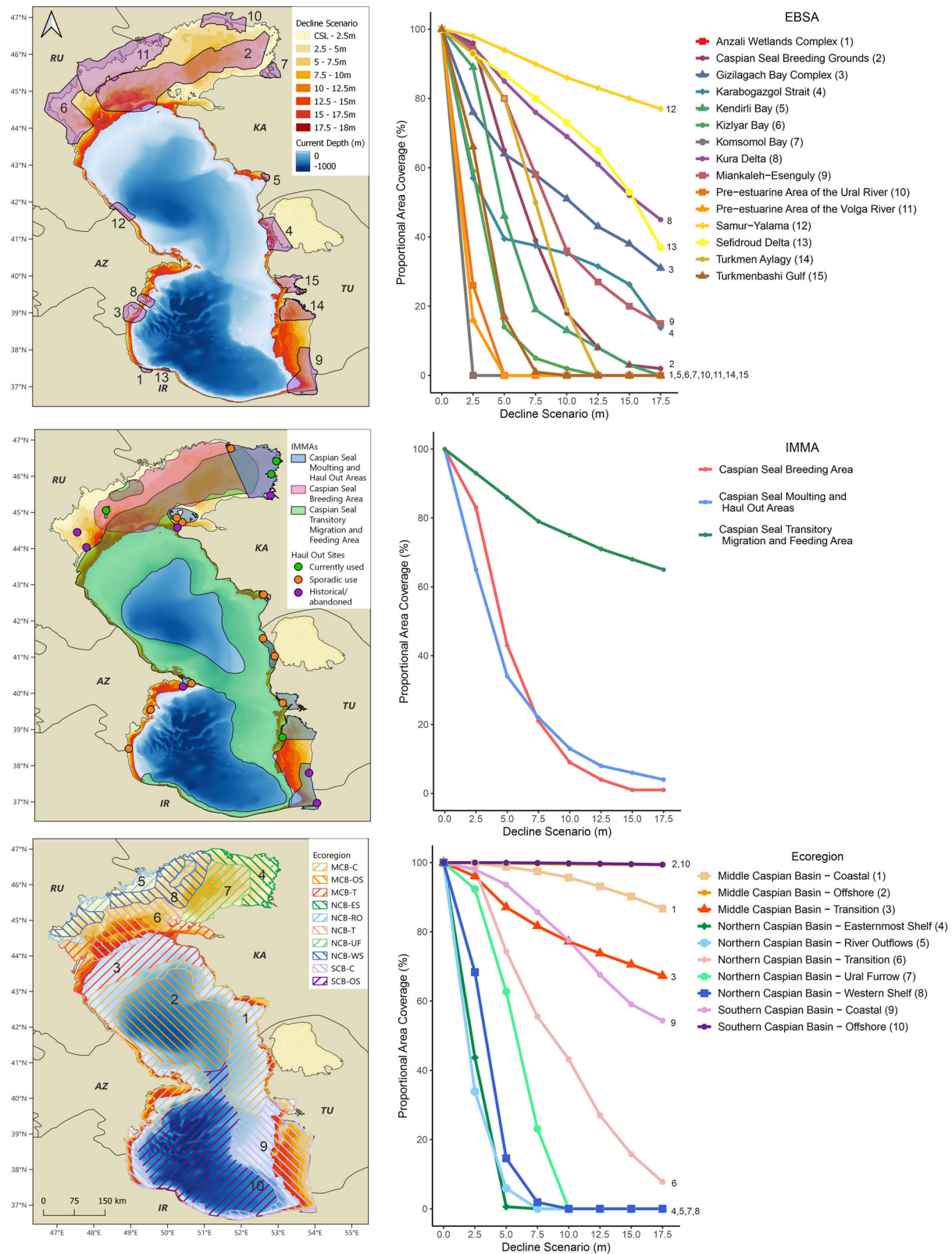


Fig. 3 | Area reductions arising from sea level decline scenarios for ecologically important areas in the Caspian Sea. Area reductions arising from different sea level decline scenarios for Ecologically, or Biologically Significant Areas (EBSAs; top); Important Marine Mammal Areas (IMMAs; middle); and Caspian Ecoregions

(bottom). Left column: maps of decline scenario overlain with polygons showing spatial area designations. Right column: charts showing proportional reduction in sea area covered by current spatial area designations under the different decline scenarios.

Table 1 | Total percentage coverage remaining for Ecologically and Biologically Significant Areas (EBSAs) and Marine Protected Areas (MPAs), for each of the Caspian countries, for 5, 10 and 15 m Caspian Sea level decline scenarios

Country	EBSAs % coverage remaining			MPAs % coverage remaining		
	5 m	10 m	15 m	5 m	10 m	15 m
Azerbaijan	77.86	65.65	39.10	0	0	0
Iran	86.44	72.45	16.07	0.64	0	0
Kazakhstan	60.40	16.75	2.34	36.30	5.16	2.92
Russia	5.02	0.57	0	0.33	0.15	0.03
Turkmenistan	63.42	27.02	11.12	15.10	0.05	0

assumptions and future greenhouse gas emission rates. Current best fit models suggest declines of 8 m to 14 m by 2100 under medium to high emission scenarios²². To evaluate the potential impacts of CSL decreases across the range predicted by these modelling studies on Caspian ecosystems, existing spatial conservation designations and human infrastructure, we defined eight sea level decline scenarios in increments of 2.5 m (−2.5 m, −5 m, −7.5 m, −10 m, −12.5 m, −15 m, −17.5 m and −18 m decline) relative to the −27.5 m datum, and generated models of the resulting Caspian Sea bathymetry at these water levels. We then calculated changes in the relative position of coastlines and coverage of land and water areas for each projection.

A 2.5 m decline leads to a substantial loss of water coverage around the margins of the northern basin (Fig. 3 and Supplementary Fig. 1). Following a 5 m decline, approximately 77,000 km² of current water area (around 20% of the present Caspian Sea surface) will become land, with the most affected areas being the northern basin, Kara-Bogaz-Gol, and Turkmenistan shoreline (Fig. 3 and Supplementary Fig. 1). Under the most extreme decline scenario considered of 18 m (Fig. 3 and Supplementary Figs. 1a–h), as much as 143,000 km² of water could transition to desert; a loss of 37% relative to the current Caspian Sea area.

Reduction of Caspian ecoregions and areas with ecological significance

We next used our bathymetry projections to evaluate how existing marine coverage of Caspian Sea ecosystems and regions of ecological significance would be reduced under each CSL decline scenario, considering (i) Ecologically or Biologically Significant Marine Areas (EBSAs; $n = 15$)³⁹; (ii) Important Marine Mammal Areas (IMMAs; $n = 3$)³⁸; and (iii) Caspian Ecoregions ($n = 10$; Supplementary Table 1), which are a synthesis of distinct Caspian Sea habitat types based on ecological and physical parameters⁴¹. EBSAs are designated under the Convention on Biological Diversity, and IMMAs by the IUCN Joint SSC-WCPA Marine Mammal Protected Areas Task Force. They are not legally defined protected areas, rather they are areas of high biodiversity importance identified by expert working groups and are intended to inform spatial planning decisions by policy makers. They may encompass other areas recognised as ecologically significant under other designations such as Ramsar sites or national classifications.

Most ecoregions and all area designations with recognised ecological significance (EBSAs, IMMAs) would experience increasing reductions in marine coverage (i.e., conversion to land) as sea level declines (Fig. 3 and Supplementary Tables 3–5). Under a decline of just 5 m, 7 of 15 EBSAs would experience proportional coverage reductions exceeding 50%, with 4 completely desiccated, and similar outcomes for 2 of 3 IMMAs. Among ecoregions, 3 of 5 in the northern Caspian would experience reductions exceeding 80% under a 5 m decline. With a 10 m decline, 5 EBSAs and 4 ecoregions would be completely eliminated, while IMMAs would see reductions ranging from 25% to more than 80% (Fig. 3 and Supplementary Tables 3–5). At the national level, remaining coverage for EBSAs with a 10 m

decline would range from 0.57% for Russia, to 72.5% for Iran (Table 1), although absolute EBSA area coverage for Iran is already low (Fig. 3).

Impacts on Caspian seal breeding and sturgeon habitats

Our bathymetry projections indicate that water level declines of 2.5 m to 5 m will make all current and historical Caspian seal haul-out sites inaccessible to seals (Fig. 3). Shifts in haul-out site use due to sea level recession are already observed in the northeastern Caspian Sea (Fig. 2). The current Caspian seal breeding area in the northern Caspian is extremely vulnerable to sea level reduction. The area of the breeding IMMA covered by water and winter sea ice, and therefore accessible to seals, could be reduced by around 57% with a decline of just 5 m, but this could be as much as 81%, if the deeper sub-basin of the northern Caspian becomes isolated from the main portion of the Caspian Sea by a land barrier (Figs. 3, 4 and Supplementary Table 4).

Similarly, the summer/autumn ranges of Caspian sturgeon species overlap considerably with shallow water areas²³, and could experience a 25% reduction with a 5 m decline and around a 45% reduction with a 10 m decline (Fig. 4 and Supplementary Table 6). Sturgeon winter/spring ranges are less dependent on shallow water areas, reducing by around 5% at 10 m CLS decline.

Effects on current marine and coastal terrestrial protected areas

Using spatial data for Caspian region protected areas derived from the World Database on Protected Areas (WDPA)⁴², our bathymetry projections show that all but one WDPA-listed marine protected area would see coverage reductions exceeding 50% at 5 m, with 11 of 16 protected areas transitioning completely to land. Declines of 10 m and above eliminate marine coverage for most currently designated conservation areas (Fig. 5a, b and Supplementary Table 7). The current total coverage of Caspian Sea marine protected areas is 16.8% of the sea area. A 5 m decline would decrease coverage to 7%, and a 10 m decline to just 1% (Fig. 5c). At the national level, remaining MPA coverage with a 10 m decline would be less than 0.2% for all countries, except for Kazakhstan at 5.16% (Table 1), which would retain a portion of the 'State Nature Reserved Zone in the Northern Caspian Sea' (polygon 16, Fig. 5).

Under a 5 m decline, coastal terrestrial protected areas (shore-based ecosystems that depend on the sea for their function) will experience a multi-kilometre increase in their distance to shore (Fig. 5d and Supplementary Table 8). Under a 10 m decline, 3 of 12 sites will experience an increase of more than 10 km, increasing to 6 sites with a 15 m decline. The greatest increase in distance to shore would be expected for the Aktau-Buzachi State Nature Sanctuary in Kazakhstan, with an increase of 61.7 km under the 18 m decline scenario.

Impacts on human infrastructure and activity

Coastal settlements in all Caspian countries will experience increases in distance to shore, requiring major adaptation of civil infrastructure for declines of 2.5 m and above (Fig. 6 and Supplementary Table 9). Coastal settlements in the northern Caspian basin, within Kazakhstan and Russia, will experience the greatest increase in their distance to the Caspian shoreline (Fig. 6b). Under a 10 m decline scenario, the mean increase in distance to shore for Russian and Kazakh settlements is 44 km (range: 18.8–102.2 km) and 89 km (range: 0.87–259.7 km), respectively.

More than one third (8 out of 22) of all industrial infrastructure facilities included in this study, comprising ports, oil refineries and gas processing plants, will experience an increase greater than 5 km in their distance to the Caspian shoreline, under a 10 m sea level decline scenario (Fig. 6 and Supplementary Table 10). Ports that are critical for trade or industrial logistics will be impacted in all countries, with Baku (Azerbaijan), Anzali (Iran), and Aktau (Kazakhstan), experiencing increases in distance to shore of 1 km or more, while Turkmenbashi (Turkmenistan), and Lagan (Russia; planned future site), could see worst case increases of 16 km and 126 km respectively (Fig. 6d).

The Kashagan (Kazakhstan) and Filanovsky (Russia) oil fields in the northern Caspian are two of the region's most important hydrocarbon

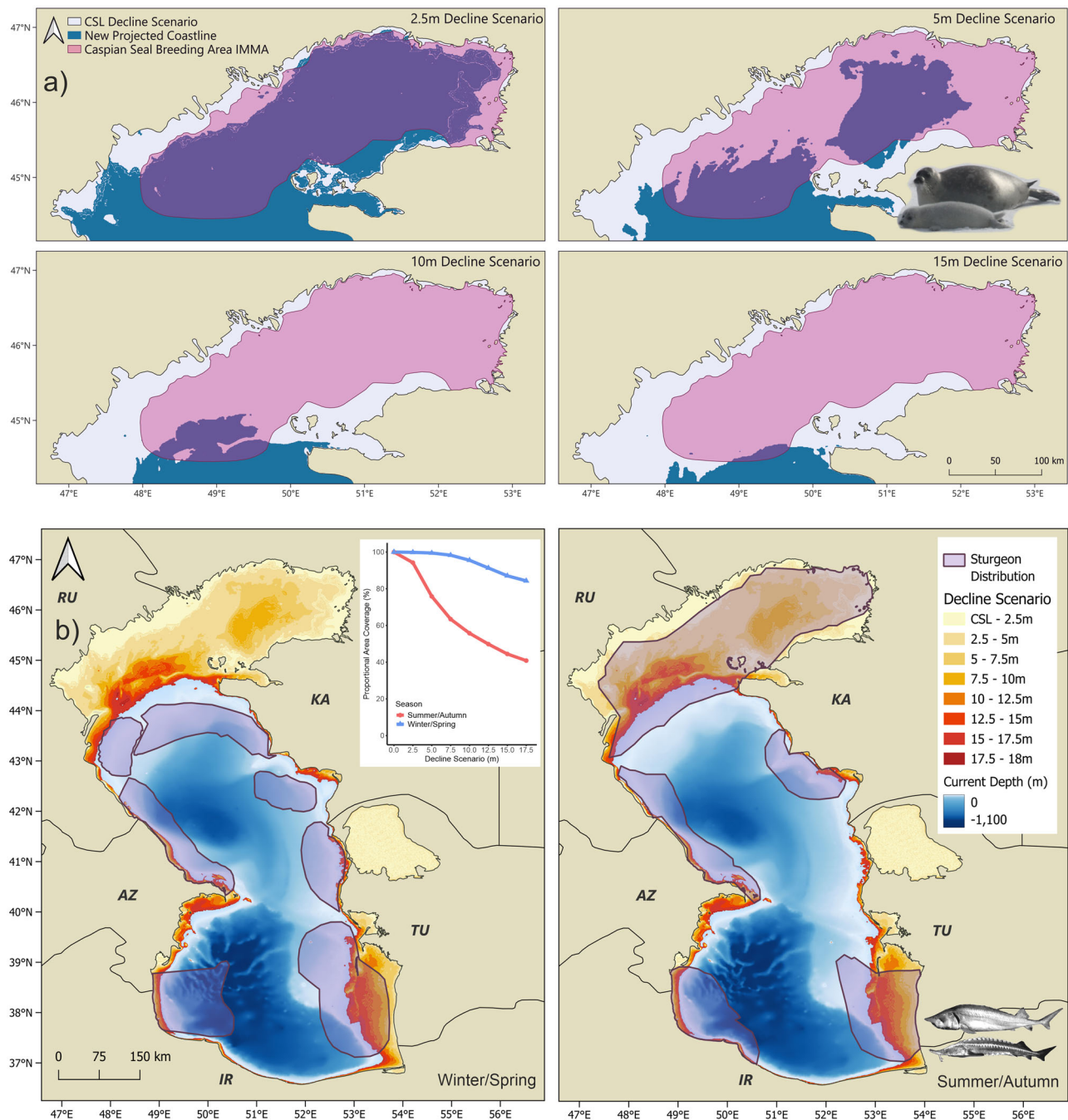


Fig. 4 | Area reductions under Caspian Sea level decline for Caspian seal breeding and sturgeon habitats. Maps showing: **a** Sea area reduction from the Caspian seal breeding Important Marine Mammal Area (IMMA), under 2.5 m, 5 m, 10 m and

15 m decline scenarios; and **b** Summer/Autumn and Winter/Spring sturgeon ranges under estimated Caspian Sea level decline scenarios; inset graph quantifies percentage area reduction for each season group.

production sites. Production currently occurs at offshore installations, with ship-based logistics (Fig. 6a, b), but these will become landlocked under 5 to 15 m CSL declines. Access to the Caspian Sea for international shipping via the Volga River will also be critically impacted by a decline of 5 m (Fig. 6c), with major consequences for navigation and trade.

Industrial fishing for kilka (*Clupeonella* spp.) is presently focused on relatively deep waters off the coast of Dagestan, but one fishing ground on the boundary between the northern and mid Caspian basin could disappear with declines above 5 m (Fig. 6a). Artisanal fisheries, which primarily use shallower waters, will also be heavily impacted, particularly in the northern

Caspian Sea, where declines of 5 m can be expected to eradicate most fishing activity.

Discussion

We made a quantitative assessment of impacts from projected 21st Century water level decline on Caspian Sea ecosystems, spatial conservation designations, and human infrastructure. Our analyses suggest that CSL declines of 5 to 10 m, as projected for medium emissions scenarios by the end of this century, will cause losses exceeding 80% of current extent for many ecosystem types and ecologically important areas. These declines will also eliminate or substantially reduce the

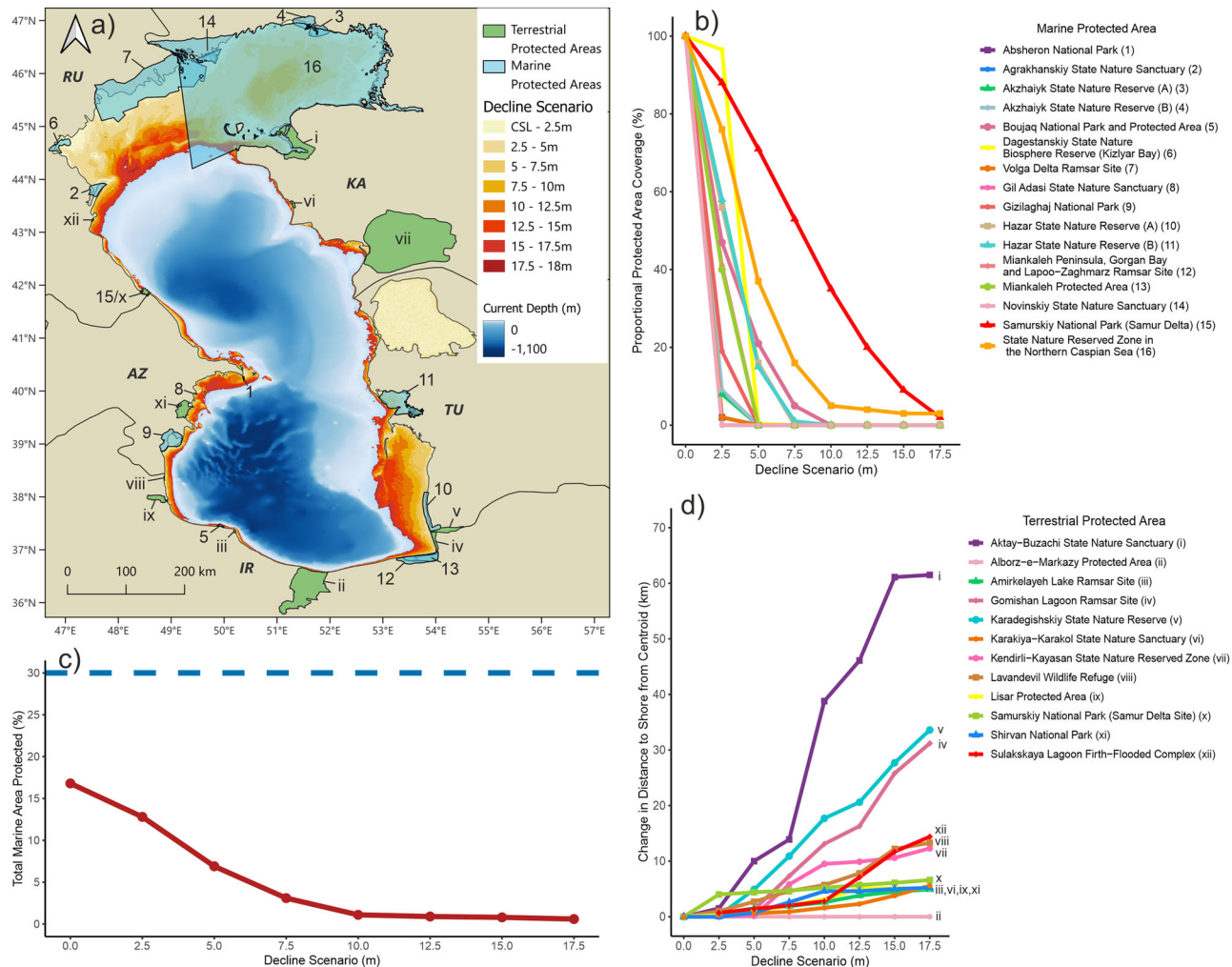


Fig. 5 | Area reductions under Caspian Sea level decline for Caspian Sea region protected areas. Area reductions arising from different sea level decline scenarios on current areas with legislative environmental protections listed in the World Database on Protected Areas (WDPA); **a** Map of decline scenario overlap with spatial area designations; **b** Plot showing proportional reduction in sea area covered by current spatial area designations under the different decline scenarios; **c** Decline in

overall marine protected area coverage relative to Caspian Sea area for the -27.5 m datum, dashed reference line indicates the Kunming-Montreal Global Biodiversity Framework (GBF) target of 30% area coverage of inland water, coastal, and marine environments; **d** Increase in distance to shore for Caspian coastal terrestrial protected areas, under sea level decline scenarios of 2.5 m to 17.5 m relative to the study datum.

marine coverage of most current spatial conservation designations in the Caspian Sea. In parallel, 5 to 10 m declines will have dramatic consequences for coastal communities, industrial infrastructure and economic activity, as settlements, ports, and offshore energy installations become stranded tens or hundreds of kilometres from new shorelines.

The sensitivity of Caspian region protected areas to climate change has previously been recognised^{43–45}, but to the best of our knowledge, there has been no previous quantitative evaluation of their vulnerability to CSL decline. We find that without mitigation, marine protected area coverage will reduce from 16.8% of the Caspian Sea extent at the -27.5 m datum to 7% and 1% for 5 m and 10 m decline scenarios respectively. The high sensitivity of current spatial conservation designations arises because they are aligned with ecologically significant areas, and regions of high habitat diversity around coasts and transition zones into deeper waters in the northern Caspian basin, and other shallow shelf areas. The northern basin has a mean depth of just 5 m, and although it accounts for only 1% of the total Caspian Sea water volume, with an extent of approximately 115,000 km², it represents one-third of the total sea surface area.

As CSL decline proceeds, current marine areas will shift from permanent water coverage, to transitory inundation, and eventual desiccation, with water associated vegetation such as reed beds and *Salicornia* (a genus of

succulent, halophytic, flowering plants) transitioning to desert or steppe⁴³. Shallow shelf and transition zone ecosystems will be greatly reduced, without replacement, since areas with remaining water coverage have steeper bathymetry. Habitats for endemic benthos will be displaced and diminished as water levels reduce because they are constrained to specific bathymetry ranges, substrate types, water oxygen levels, and experience competition from invasive species³⁰. New terrestrial habitats such as emergent islands may develop, but the succession process and their suitability to sustain displaced species is poorly studied. Current coastal terrestrial protected areas will experience multi-kilometre increases in their distance to shore, meaning the ecosystems they encompass (lagoons, reed beds, salt marshes and beaches) will also transition to steppe and desert. Overall, there will be substantial loss of internationally important habitats (recognised by their EBSA and Ramsar designations) for fish, birds and benthos, with potential for cascading effects throughout Caspian Sea ecosystems and beyond, for example due to loss of fish spawning areas and habitats supporting migratory birds.

Such changes are already visible around the margins of the northern Caspian Sea and other areas with shallow bathymetry such as Turkmenbashi Bay (Turkmenistan), Gorgan Bay and Gomishan Lagoon (Iran), and the Ghizil Agaj Bay (Azerbaijan)⁴³. In our focal northeastern Caspian study

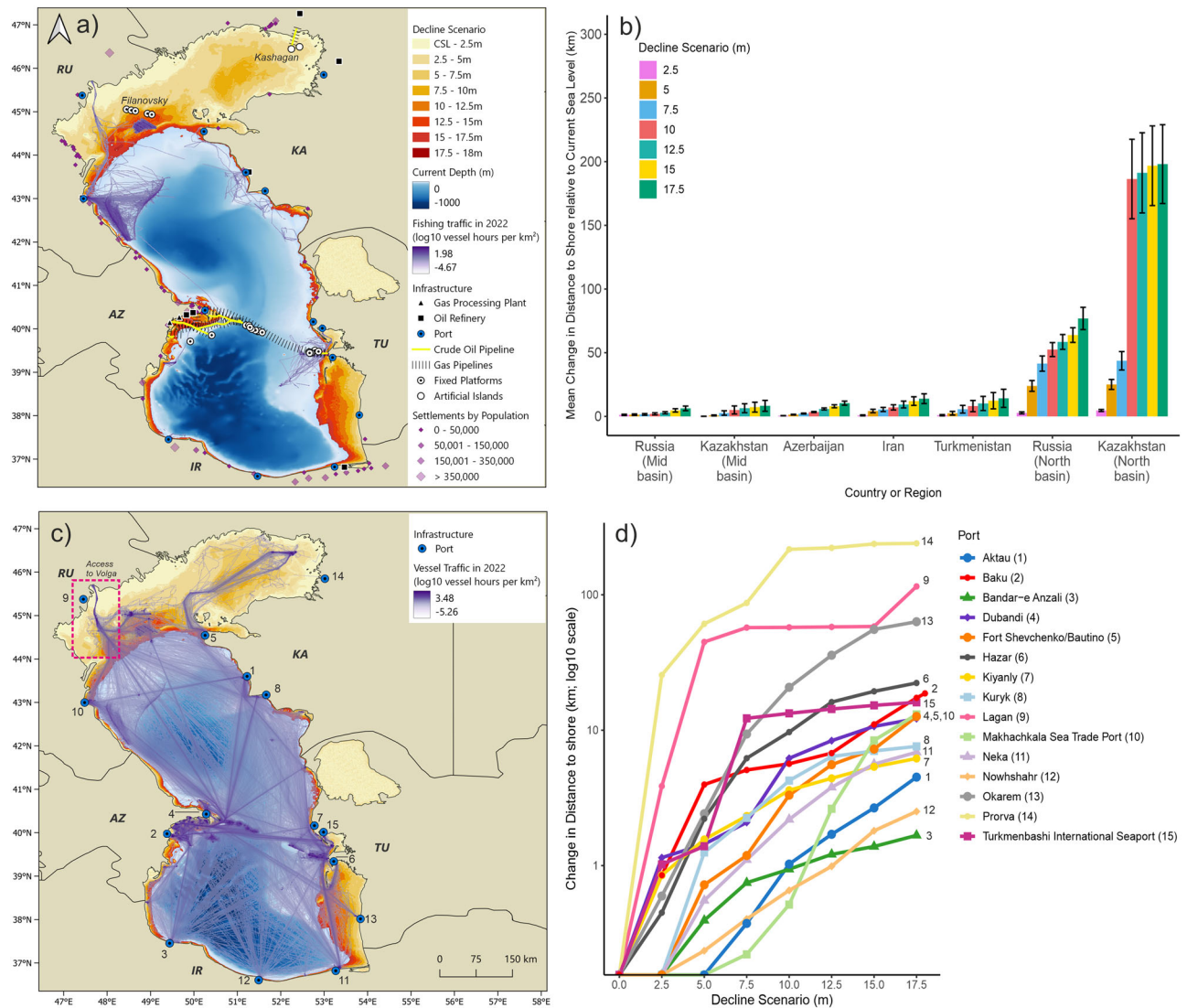


Fig. 6 | Impact of Caspian Sea level decline on human civil and industrial infrastructure and activity. a Map showing locations of coastal settlements, industrial infrastructure and commercial fishing activity relative to sea level decline scenarios; **b** Bar chart summarising mean increase in distance to coast for settlements relative to the -27.5 m datum (error bars show standard deviation; values for

individual settlements can be found in Supplementary Tables 9, 10), in different Caspian coastal regions; **c** Map showing shipping density and port locations relative to decline scenarios; **d** Plot showing increase in distance to coast relative to the -27.5 m datum for ports.

zone water coverage has decreased by approximately 7000 km^2 (46%), between 2001 and 2024, leading to displacement of Caspian seal moulting and haul-out sites in the Komsomol Bay EBSA, which is now nearly completely desiccated. Recession is also visible within the Volga and Ural deltas, including the 3410 km^2 Akzhayik State Nature Reserve close to Atyrau. Caspian seal haul-out sites on the Zyud-Vestovye Shalygas Islands, located in the buffer zone of the Akzhayik State Nature Reserve, have also been lost⁴⁰.

The endangered Caspian seal²⁴, is vulnerable to loss of its present breeding area. The species pups on the winter ice sheet that currently forms in the northern basin December to March each year³³. A 5 m decline would lead to reductions between 57% and 81% of the current breeding IMMA. How climate warming and sea level reduction will interact to influence the Caspian ice regime, and to what extent winter sea ice might persist around the northern coast of a reduced Caspian Sea is poorly understood^{46,47}, as is whether Caspian seals can successfully adapt to terrestrial breeding in the absence of ice, for example on newly emergent islands. Historically, births of up to 50 pups have been observed on Ogurja Ada Island in Turkmenistan⁴⁸, and small numbers of white coat pups have stranded dead in Iran⁴⁹, but to our knowledge, there are no documented cases of Caspian seal pups born on

land surviving to weaning. The northern Caspian basin also provides important foraging areas for Caspian seals⁵⁰, and other culturally and economically important species such as Caspian sturgeon⁵¹. Loss of the area may compromise access to important sturgeon spawning rivers such as the Ural, and spawning habitat of the commercially important common kilka (*Clupeonella caspia*)^{23,26,51}.

CSL decline will also cause consequential impacts for human wellbeing, infrastructure, and economic activity. The economic cost of disruption could exceed tens of billions of dollars per year. Millions of tons of cargo are shipped through the Volga River each year, the only external maritime connection, to and from the Caspian⁵². Access to the Volga could be compromised by declines of as little as 5 m, with dredging already implemented to keep passage for larger vessels open⁵³. Similarly, operators of offshore oil production facilities in the northern Caspian basin are dredging channels to maintain shipping logistics⁵⁴, and operations at Aktau port and the intake for the city's water desalination plant have been disrupted due to declining water levels⁵⁵.

For artisanal and coastal fishing communities in the northern basin, economies could collapse entirely as fishing grounds disappear. Alternative

incomes sources from aquaculture, horticulture, and ecotourism⁵⁶, may also become inviable posing risks to the social integrity of communities. Commercial fisheries will shift to deeper waters where possible, with consequent changes in maritime zones of jurisdiction and exclusive fishing rights. However, they may be vulnerable to economic losses if fish stocks fall due to loss of spawning habitats and other cascading CSL decline related impacts.

Ecosystem services provided by the Caspian Sea to the surrounding region will also be altered by sea level reductions. The cumulative effects of decreased ice cover, increased surface water temperatures, and changes in sea level will cause alterations in mixing-regimes and deep ventilation, with consequences for nutrient cycling². Physical atmospheric changes in precipitation and moisture may increase aridity of the regional climate, exacerbating water scarcity across central Asia³⁴. Desiccation of inland lakes can also pose health risks to local inhabitants. Previous evaporation events following restriction of the connection from the Caspian into Kara-Bogaz-Gol, and in the Aral Sea, led to toxic dust and salt exposure from the emerged seabed, causing serious concerns for respiratory health and land degradation³⁷. For similar reasons, along with anticipated harsh climatic conditions, it is unlikely that newly exposed land would be suitable for agriculture³⁷.

Our assessments are based on projections of CSL decline derived from the latest generation of climate models that suggest reductions in water levels of up to 21 m by 2100 under high emission scenarios. Lesser declines (5 to 12 m), drying most of the northern Caspian basin will still occur even if global temperature rises are kept below 2 °C under the Paris Climate Accord^{20–22}. Current progress on meeting emission reduction targets suggests global temperature rises could exceed this threshold⁵⁸. Timelines for CSL reductions are uncertain, but water levels fell by 1.4 m in the 16 years 2006 to 2021, and approximately 75 cm 2022 to 2024¹⁷, a rate that if sustained, implies declines may be on track to reach the upper range of current model predictions (18 m or more by 2100). Changes in land-use and increases in water abstraction (e.g., for desalination) may further compound climate-driven declines^{22,59}. The behaviour of potential isolated sub-basin remnants in the northern Caspian Sea is also highly uncertain as this will depend on whether they maintain river connections (e.g., with the Ural), and flow volumes, with implications for ecosystem persistence and conservation management in the early stages of the drying of the northern basin.

We employed bathymetry data with a resolution of 15 arc seconds (equivalent to less than 1 km). This is sufficient to assess risks to broadscale ecosystem coverage and large protected areas, but finer scale bathymetry data is required for detailed assessments for specific local areas and individual pieces of infrastructure. We used remaining water coverage as a proxy measure for an area's ability to sustain habitats and ecosystem processes. However, habitat suitability and ecosystem sustainability may scale non-linearly as water levels decrease, and ecosystem functionality could fail at smaller proportional reductions if environmental factors exceed species tolerances, for example, minimum water depth, water temperature ranges, oxygen and/or nutrient availability, substrate type, or loss of co-dependent species.

Conclusions and recommendations

Sea level decline will amplify existing anthropogenic threats to Caspian biodiversity^{27,28}. For example, species range shifts may increase species exposure to degraded habitats, existing industrial activities, or other forms of human-wildlife conflict such as fisheries^{56,60}. Similarly, mitigation of CSL decline in relation to human infrastructure and activities has the potential to create new impacts, or conflicts with conservation priorities. Current Caspian Sea spatial conservation designations have varying levels of protections and enforcement, and there are few marine protected areas that prohibit all human economic activity. They will require substantial adaptation to remain relevant and fit for purpose.

Addressing CSL decline impacts on biodiversity will require adaptive, temporally dynamic approaches to spatial conservation planning. Rather than having fixed spatial boundaries, protected areas will need to track shifting species ranges and ecosystems over time, similar to proposals

suggested in the context of coral reef conservation^{61,62}. Planning processes need to be forward-looking, so that areas predicted to host important habitats and ecosystems in future receive pre-emptive protection that can be considered when planning for concomitant mitigation for impacts on human infrastructure and activity. For example, conflicts may arise between ecosystem conservation and relocation/adaptation of ports or shipping routes. Such an approach will be essential to allow temporal and spatial contiguity of ecosystems, and for maintaining commitments under the Kunming-Montreal Global Biodiversity Framework (GBF) such as conserving 30% of inland water, coastal, and marine areas through area-based conservation measures⁶³.

Legislation such as the Kazakh EcoCode⁶⁴, in principle allows for some dynamic protections, but Caspian countries may need to revise legal frameworks on protected areas to formalise the status of adaptive as opposed to fixed boundaries. It will also be necessary to collect more comprehensive species and community occurrence data and establish monitoring, to support development of detailed species distribution models for Caspian taxa, evaluations of species vulnerabilities, and predictions of species range shifts through time. Such models will be necessary to inform spatial planning and decisions on other types of conservation interventions such as assisted translocations or ecosystem restoration, coupled with detailed risk assessments for civil and industrial infrastructure, and their associated mitigation plans⁴⁴. Investment to enhance regional expertise in biodiversity and conservation spatial planning should also be prioritised.

Commitment to economic diversification and sustainable development goals will be essential to the survival of coastal communities. Sources of income such as fishing are likely to become unviable for communities in the north. Ensuring human prosperity will be central to maintaining both social stability and sustainable biodiversity⁵⁶. Communication and consultation with communities will be essential for finding equitable solutions.

Effective responses to CSL declines will require rapid and coordinated transboundary cooperation on governance. Since the end of the Soviet Union in the early 1990s, the Caspian states have made progress on establishing legal frameworks for environmental governance under the Tehran Convention. However, they have often prioritised national economic and political interests over transboundary cooperation to address ecological degradation⁶⁵. The Caspian Sea serves as an example of the urgent need to address climate change impacts on major landlocked waterbodies worldwide, where pre-emptive, adaptive planning will be required to keep spatial conservation relevant and manage inevitable conflicts with parallel mitigation to protect human populations. Successfully adapting to these impacts in the Caspian region will require a level of transboundary political cooperation beyond that achieved to date. The anticipated scale of environmental disruption in the Caspian Sea will potentially have global consequences, and therefore warrants attention and support from the wider international community.

Methods

Data sources

Spatial data were compiled from open access sources. All spatial data processing and analyses were conducted using QGIS 3.22.12⁶⁶.

A Caspian Sea boundary polygon was constructed using data from the Global Administrative Areas 2015 (v2.8) dataset (<http://purl.stanford.edu/zb452vm0926>). Gridded bathymetric data was obtained from the General Bathymetric Chart of the Oceans (GEBCO) repository at a spatial resolution of 15 arc seconds (equivalent to less than 1 km at 40 °N; www.gebco.net/data_and_products/gridded_bathymetry_data/)⁶⁷, and clipped to the Caspian Sea boundary, representing the 2010 coastline at a datum of −27.5 m below mean global sea level¹¹.

Spatial data on key ecosystems, ecologically important areas and current spatial conservation designations within the Caspian region were compiled as follows: (i) Ecologically or Biologically Significant Marine Areas (EBSAs; $n = 15$; <https://www.cbd.int/ebsa/>)³⁹; (ii) Important Marine

Mammal Areas (IMMA; $n = 3$; www.marinemammalhabitat.org/immas/)³⁸; (iii) Caspian Ecoregions ($n = 10$; as defined by Fendereski et al.⁴¹; See supplementary Table 1); (iv) Seasonal ranges of Caspian sturgeon species²³; (v) Marine Protected Areas ($n = 16$) and Terrestrial and Inland Waters Protected Areas, ($n = 12$), listed in the WDPA (www.protectedplanet.net/en/thematic-areas/wdpa)⁴², and records from local nature protection agencies. Additional curation of names, designation, and polygon boundaries for protected areas is described in Supplementary Table 2.

Locations of key Caspian seal haul-out sites were taken from the Caspian Sea IMMA documents. These sites had been previously categorised into (1) Currently used sites; (2) Established seal habitat that is no longer used regularly or by a significant number of seals; and (3) A known historical area of seal habitat that is no longer used at all.

Caspian Sea oil and gas infrastructure (on and offshore production and processing facilities, pipelines and ports) and settlements were georeferenced from map data at the University of Texas at Austin GeoData service (<https://geodata.lib.utexas.edu/catalog/princeton-736666054>), and supplemented with literature and Google Earth searches.

Monthly vessel density data (vessel hours per km² per month) within the Caspian Sea for the calendar year of 2022 was obtained from Global Maritime Traffic (<https://globalmaritimetraffic.org/gmtds.html>). 'No data' values were set to zero, and monthly values summed to give annual values, before being log10 transformed.

Estimation of shoreline recession in the northeastern Caspian Sea (2001–2024)

To document ecosystem transition due to sea level change, satellite images (250 m per pixel) were sourced from the NASA Worldview application (2023, www.worldview.earthdata.nasa.gov/), part of the NASA Earth Science Data and Information System, for March and October of each year between 2001 and 2024. The first cloud-free image closest to the 15th day of each month was selected for analysis. In QGIS, for each image, within a polygon with bounds 47.12° N, 53.43° E to 45.27° N, 52.05° E, the coastline was georeferenced manually to distinguish separate land and water polygons, based on the visible land-water boundary. The area (km²) for each part was then calculated using the QGIS polygon area tool. To evaluate measurement error, one image (March or October) was selected at random for each year, and the water area for each image was remeasured independently. The difference between the first and the second measurement was divided by the mean of the two measurements, and multiplied by 100 to yield a percentage value. The mean measurement error percentage across all images was 3.6%, which is an acceptable level of precision given the 250 m pixel resolution of the imagery and short-term variation in water distribution due to local weather conditions.

Calculating decline scenario bathymetry

Based on recent climate modelling projections^{20–22}, we defined eight sea level decline scenarios in increments of 2.5 m (–2.5 m, –5 m, –7.5 m, –10 m, –12.5 m, –15 m, –17.5 m, and –18 m decline) relative to the –27.5 m Caspian Sea datum (relative to global mean sea level). Individual scenarios were generated by reclassifying the GEBCO bathymetry raster as 0 or 1 for cells above/below the specified depth of a decline scenario (e.g., –30 m for a 2.5 m decline). The reclassified raster was multiplied by the original bathymetry values, and the new sea level (e.g., –30 m) was added to reach the true depth (where 0 m is the surface).

Reduction in area of marine habitat and conservation zones

For each individual marine zone, the proportional reduction in area covered by water was calculated under the eight sea level decline scenarios, relative to coverage at the –27.5 m datum. First the bathymetry scenario rasters were converted to polygons and clipped to the Caspian Sea boundary polygon. Proportional coverage of conservation areas under each decline scenario was then measured using the 'Overlap Analysis' tool which calculates area and percent cover of overlaying layers. This returned the area of each

conservation site under each decline scenario which were then divided by the original site area.

Changes in distance to shore

The nearest distance to the shoreline (km) for human settlement and infrastructure georeferenced points was calculated under each decline scenario using the 'v.distance' tool in QGIS GRASS. For terrestrial coastal protected areas, distance to shore was calculated from the centroid of the area polygon.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data used in this study were derived from publicly available sources as specified in the text. GIS shape files for spatial resources generated or georeferenced for this study including: decline scenarios, Caspian ecoregions, sturgeon habitat areas, and human infrastructure, along with text files of numerical results and image files are available from: <https://doi.org/10.5518/1656>. A Shiny app to support visualisation of the spatial data from the paper is available: <https://chassall.shinyapps.io/CaspianShinyApp/>.

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References

1. Sayer, C. A. et al. One-quarter of freshwater fauna threatened with extinction. *Nature*. <https://doi.org/10.1038/s41586-024-08375-z> (2025).
2. Woolway, R. I. et al. Global lake responses to climate change. *Nat. Rev. Earth Environ.* **1**, 388–403 (2020).
3. Dai, A., Zhao, T. & Chen, J. Climate change and drought: a precipitation and evaporation perspective. *Curr. Clim. Change Rep.* **4**, 301–312 (2018).
4. Wang, W. et al. Global lake evaporation accelerated by changes in surface energy allocation in a warmer climate. *Nat. Geosci.* **11**, 410–414 (2018).
5. Yao, F. et al. Satellites reveal widespread decline in global lake water storage. *Science* **380**, 743–749 (2023).
6. Markovic, D. et al. Europe's freshwater biodiversity under climate change: distribution shifts and conservation needs. *Diversity Distrib.* **20**, 1097–1107 (2014).
7. Parks, S. A. et al. Efficacy of the global protected area network is threatened by disappearing climates and potential transboundary range shifts. *Environ. Res. Lett.* **17**, 054016 (2022).
8. Pittock, J., Hansen, L. J. & Abell, R. Running dry: freshwater biodiversity, protected areas and climate change. *Biodiversity* **9**, 30–38 (2008).
9. Li, X., Peng, S., Xi, Y., Woolway, R. I. & Liu, G. Earlier ice loss accelerates lake warming in the Northern Hemisphere. *Nat. Commun.* **13**, (2022). 5156.
10. Rodionov, S. N. Global and regional climate interaction: The Caspian Sea experience. In *Water Science and Technology Library* 1th edn, Vol. 11, 1–243, <https://doi.org/10.1007/978-94-011-1074-7> (Springer Dordrecht, 1994).
11. Leroy, S. A. G., Lahijani, H. A. K., Crétau, J.-F., Aladin, N. V. & Plotnikov, I. S. Past and Current changes in the largest lake of the world: the Caspian Sea. In *Large Asian Lakes in a Changing World* Springer Water (ed Steffen Mischke) 65–107 <https://doi.org/10.1007/978-3-0> (Springer International Publishing, 2020).
12. Krijgsman, W. et al. Quaternary time scales for the Pontocaspian domain: interbasinal connectivity and faunal evolution. *Earth-Sci. Rev.* **188**, 1–40 (2019).

13. Chen, J.L. et al. Long-term Caspian Sea level change. *Geophys. Res. Lett.* **44**, 6993–7001 (2017).
14. Lahijani, H.A.K., Leroy, S.A.G., Arpe, K. & Cretaux, J.F. Caspian Sea level changes during instrumental period, its impact and forecast: a review. *Earth-Sci. Rev.* **241**, (2023).
15. Arpe, K. et al. Prediction of the Caspian Sea level using ECMWF seasonal forecasts and reanalysis. *Theor. Appl. Climatol.* **117**, 41–60 (2014).
16. Wang, J. et al. Recent global decline in endorheic basin water storages. *Nat. Geosci.* **11**, 926–932 (2018).
17. CASPCOM. Information bulletin on the state of the Caspian Sea level, No. 27, 15 May 2024. http://www.caspcom.com/files/CASPCOM%20Bulletin%20No.%2027_2.pdf. (2024).
18. Elguindi, N. & Giorgi, F. Projected changes in the Caspian Sea level for the 21st century based on the latest AOGCM simulations. *Geophys. Res. Lett.* **33**, (2006). 2006GL025943.
19. Renssen, H. et al. Simulating long-term Caspian Sea level changes: the impact of Holocene and future climate conditions. *Earth Planet. Sci. Lett.* **261**, 685–693 (2007).
20. Koriche, S. A., Singarayer, J. S. & Cloke, H. L. The fate of the Caspian Sea under projected climate change and water extraction during the 21st century. *Environ. Res. Lett.* **16**, 094024 (2021).
21. Nandini-Weiss, S. D., Prange, M., Arpe, K., Merkel, U. & Schulz, M. Past and future impact of the winter North Atlantic Oscillation in the Caspian Sea catchment area. *Int. J. Climatol.* **40**, 2717–2731 (2019).
22. Samant, R. & Prange, M. Climate-driven 21st century Caspian Sea level decline estimated from CMIP6 projections. *Commun. Earth Environ.* **4**, 357 (2023).
23. Karpinsky, M. G. The Caspian Sea benthos: Unique fauna and community formed under strong grazing pressure. *Mar. Pollut. Bull.* **61**, 156–161 (2010).
24. Goodman, S. & Dmitrieva, L. Pusa caspica. *IUCN Red List of Threatened Species*, e.T41669A45230700. <https://doi.org/10.2305/IUCN.UK.2016-1.RLTS.T41669A45230700.e> (2016).
25. Veen, J. et al. An atlas of movements of Southwest Siberian waterbirds. Wetlands International. https://www.academia.edu/download/45276101/An_Atlas_of_Movements_of_Southwest_Siber20160502-26464-qlzw4t.pdf. (2005).
26. Mammadov, E. et al. Management of Caspian biodiversity protection and conservation. In *The Handbook of Environmental Chemistry*. 1–34. https://doi.org/10.1007/978-2016_463 (Springer, 2016).
27. Lahijani, H. A. K. et al. A note on the silent decline of the Caspian environment. *Mar. Pollut. Bull.* **205**. <https://doi.org/10.1016/j.marpolbul.2024.116551> (2024).
28. Lattuada, M., Albrecht, C. & Wilke, T. Differential impact of anthropogenic pressures on Caspian Sea ecoregions. *Mar. Pollut. Bull.* **142**, 274–281 (2019).
29. Khodorevskaya, R. et al. State and Dynamics of the Bioresources in the Caspian Sea. In *Environment and Bioresources of the Caspian Sea Ecosystem, Handbook of Environmental Chemistry* (ed Velikova, V.) 1–84. https://doi.org/10.1007/978-2014_287 (Springer, 2014).
30. Lattuada, M. et al. Endemic Caspian Sea mollusks in hotspot and non-hotspot areas differentially affected by anthropogenic pressures. *J. Gt. Lakes Res.* **46**, 1221–1226 (2020).
31. Strukova, E. et al. Exploitation of the Caspian Sea bioresources (with focus on economics of bioresources utilization). In *The Handbook of Environmental Chemistry*. https://doi.org/10.1007/978-2015_452 (Springer, 2016).
32. Härkönen, T. et al. Collapse of a marine mammal species driven by human impacts. *PLoS ONE* **7**, e43130 (2012).
33. Wilson, S. C. et al. Breeding behavior and pup development of the Caspian seal, *Pusa caspica*. *J. Mammal.* **98**, 143–153 (2017).
34. Koriche, S.A. et al. Impacts of variations in Caspian Sea surface area on catchment-scale and large-scale climate. *JGR Atmos.* **126**, (2021). e2020JD034251.
35. Prange, M., Wilke, T. & Wesselingh, F.P. The other side of sea level change. *Commun. Earth Environ.* **1**, 69 (2020).
36. United Nations Environment Programme. Caspian Sea, State of the Environment 2010: Report by the Interim Secretariat of the Framework Convention for the Protection of the Marine Environment of the Caspian Sea and the Project Coordination Management Unit of the “CaspEco” Project. <https://www.unep.org/resources/report/caspian-sea-state-environment-report> (2011).
37. Bennion, P. et al. The impact of airborne dust on respiratory health in children living in the Aral Sea region. *Int. J. Epidemiol.* **36**, 1103–1110 (2007).
38. IUCN-MMPATF. Global Dataset of Important Marine Mammal Areas (IUCN-IMMA). October 2022. Made available under agreement on terms and conditions of use by the IUCN Joint SSC/WCPA Marine Mammal Protected Areas Task Force and accessible via the IMMA e-Atlas. <https://www.marinemammalhabitat.org/imma-eatlas> (2022).
39. Secretariat of the Convention on Biological Diversity. Report of the regional workshop to facilitate the description of Ecologically or Biologically Significant Marine Areas in the Black Sea and Caspian Sea. <https://www.cbd.int/ebsa/> (2018).
40. Baimukanov, M. T., Sirazhitdinova, M. K. & Baimukanova, A. M. Atlas of Caspian seal (*Pusa caspica* Gmelin, 1788) haulouts in the Kazakh part of the Caspian Sea (information and analytical guide). 122 pages. https://ihe.kz/images/publication/mirgaliy/2022_7.pdf (2022).
41. Fendereski, F. et al. Biogeographic classification of the Caspian Sea. *Biogeosciences* **11**, 6451–6470 (2014).
42. UNEP-WCMC and IUCN. Protected Planet: the world database on protected areas (WDPA)/OECD Database [On-line], [October 2022 downloaded], www.protectedplanet.net. (Cambridge, UK: UNEP-WCMC and IUCN, 2022).
43. Lahijani, H.A.K. et al. Tracking of sea level impact on Caspian Ramsar sites and potential restoration of the Gorgan Bay on the southeast Caspian coast. *Sci. Total Environ.* **857**, (2023). 158833.
44. Tulloch, V.J.D. et al. Linking threat maps with management to guide conservation investment. *Biol. Conserv.* **245**, (2020). 108527.
45. Zheng, Y. et al. Assessing the ecological vulnerability of protected areas by using Big Earth Data. *Int. J. Digit. Earth* **14**, 1624–1637 (2021).
46. Naurozbayeva, Z. et al. Determining factors for changes in the ice regime of the Caspian Sea. *Int. J. Water Resour. Dev.* <https://doi.org/10.1080/07900627.2023.2231099> (2023).
47. Tamura-Wicks, H., Toumi, R. & Budgell, W.P. Sensitivity of Caspian sea-ice to air temperature. *Quart. J. R. Meteor. Soc.* **141**, 3088–3096 (2015).
48. Krylov, V.I. Ecology of the Caspian seal. *Finnish Game Res.* **47**, 32–36 (1990).
49. Shirazi, A.S. et al. First confirmed records of white-coat pups of the Endangered Caspian seal *Pusa caspica* on the coast of Iran. *Oryx* **57**, 784–787 (2023).
50. Dmitrieva, L. et al. Individual variation in seasonal movements and foraging strategies of a land-locked, ice-breeding pinniped. *Mar. Ecol. Prog. Ser.* **554**, 241–256 (2016).
51. Pueppke, S.G. et al. Re-establishing naturally reproducing sturgeon populations in the Caspian basin: a wicked problem in the Ural River. *Water* **15**, 3399 (2023).
52. Akbulaev, N. & Bayramli, G. Maritime transport and economic growth: Interconnection and influence (an example of the countries in the Caspian Sea coast; Russia, Azerbaijan, Turkmenistan, Kazakhstan and Iran). *Mar. Policy* **118**, 104005 (2020).
53. Akhundov, K. Shipping in shallowing Caspian Sea - challenges and solutions. *Caliber.az*. <https://caliber.az/en/post/239068/> (2024).
54. North Caspian Operating Company. NCOC updates on the progress of dredging activities to support Kashagan offshore operations. *NCOC News*. <https://www.ncoc.kz/en/news/news-373> (2022).

55. Amangeldina, A. The Caspian Sea is under the threat of desertification. What are the causes and consequences? *beda.media* <https://beda.media/en/articles/caspian-sea> (2024).
56. Svolkinas, L. et al. Stakeholder consensus suggests strategies to promote sustainability in an artisanal fishery with high rates of poaching and marine mammal bycatch. *People Nat.* **5**, 1187–1206 (2023).
57. Issanova, G. et al. Assessment of the soil cover in the dried Aral Seabed in Kazakhstan and climate change in the region. *Water Air Soil Pollut.* **233**, 525 (2022).
58. IPCC. Climate change 2023: synthesis report. In *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, eds Lee, H. & Romero, J.J.]. 35–115. <https://www.ipcc.ch/report/ar6/syr/> (2023).
59. Hutson, N. & Taganova, J. A New strategy for merging the environmental and commerce challenges of the Caspian. *Cent. Asian J. Water Res.* **9**, 76–102 (2023).
60. Dmitrieva, L. et al. Assessment of Caspian seal by-catch in an illegal fishery using an interview-based approach. *PLoS ONE* **8**, e67074 (2013).
61. Beger, M. et al. Demystifying ecological connectivity for actionable spatial conservation planning. *Trends Ecol. Evol.* **37**, 1079–1091 (2022).
62. Buenafe, K.C.V. et al. A metric-based framework for climate-smart conservation planning. *Ecol. Appl.* **33**, (2023). e2852.
63. Secretariat of the Convention on Biological Diversity. Kunming-Montreal Global Biodiversity Framework 2030 - Targets and Guidance Notes. <https://www.cbd.int/gbf/targets> (2023).
64. Parliament of the Republic of Kazakhstan. Ecological code of the Republic of Kazakhstan. <https://adilet.zan.kz/eng/docs/K2100000400> (2021).
65. Bayramov, A. The reality of environmental cooperation and the Convention on the Legal Status of the Caspian Sea. *Cent. Asian Surv.* **39**, 500–519 (2020).
66. QGIS.org. QGIS Geographic Information System. Open source geospatial foundation project. <http://qgis.org> (2023).
67. GEBCO Bathymetric Compilation Group. The GEBCO_2022 Grid - a continuous terrain model of the global oceans and land. https://www.bodc.ac.uk/data/published_data_library/catalogue/10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c (2022).

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Competing interests

The authors declare no competing interests.

Additional information

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