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CASE STUDY

Rapid sea-level decline, regional hydrochemical change and lower-trophic richness trajectories revealed by long-term environmental monitoring

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ABSTRACT

BACKGROUND AND OBJECTIVES: Caspian monitoring is reported separately, limiting distinction between basin-scale physical change, regional hydrochemical responses, and biological variability. The study objectives were to integrate sea-level dynamics, hydrochemical properties, and lower-trophic taxonomic richness across Kazakhstan's aquatic ecosystems, while distinguishing empirically supported trends from exploratory cross-domain co-variation. Furthermore, observed concurrence was not interpreted as direct causality, biodiversity loss, or community-leve turnover.

METHODS: Observations from 2010 to 2023 were analysed as annual summaries because station-level metadata were inconsistently available across archives. Units were harmonized, missing values were not interpolated, and partial-year 2023 observations were flagged. Mann-Kendall tests and Sen slopes quantified trends, a Wilcoxon signed-rank test assessed temperature differences, and five pre-specified Spearman correlations examined exploratory co-variation. Hydroclimatic compression designated exclusively concurrent sea-level decline and regional hydrochemical deterioration; it did not serve as a causal mechanism or a composite index.

FINDINGS: Caspian Sea level declined by 1.13 metres from minus 27.57 metres in 2012 to minus 28.70 metres in 2022; the approximately 1.16 metre estimate refers to decline from the highest early-period level. The Sen slope was minus 0.110 metres per year, with a probability below 0.001. During 2016 to 2023, dissolved oxygen declined in Mangistau by 0.295 milligrams per litre per year, with a probability of 0.009, while potential of hydrogen declined in Atyrau by 0.191 units per year, with a probability of 0.031. Neither temperature nor salinity exhibited uniform, basin-wide deterioration. Although zooplankton richness declined monotonically, it failed to reach predefined significance criterion, with a probability of 0.050. Similarly, temporal trajectories for both phytoplankton and macrozoobenthos remained nonsignificant. Of five exploratory Spearman associations, only potential of hydrogen versus phytoplankton richness remained significant after Holm correction, with an adjusted probability of 0.005.

CONCLUSION: The evidence supports basin-scale sea-level decline accompanied by spatially heterogeneous hydrochemical change in Kazakhstan waters. Although lower-trophic recorded richness exhibited directional shifts, disparities in sampling effort and incomplete taxonomic-composition metadata preclude interpreting these trends as quantified biodiversity loss or demonstrated community reorganization. Cross-domain associations remain exploratory and non-causal. This study successfully differentiates robust physical and regional hydrochemical trends from ambiguous biological dynamics, thereby establishing key priorities for standardized, depth-resolved, and taxonomically consistent monitoring frameworks, taxonomically consistent monitoring frameworks.

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INTRODUCTION

The Caspian Sea is the world's largest enclosed inland water body and one of the most hydroclimatically sensitive aquatic systems because its level responds directly to the balance among river inflow, precipitation and evaporation. Historical syntheses have established that Caspian Sea levels exhibit profound sensitivity to regional hydroclimatic forcing and long-term water-balance variability (Kosarev and Yablonskaya, 1994; Rodionov, 1994; Kostianoy and Kosarev, 2005; Kosarev, 2005). Furthermore, numerical modelling studies have linked Caspian Sea-level variability to large-scale atmospheric forcing and shifts in regional water balance (Arpe *et al.,* 2000; Elguindi and Giorgi, 2006; Arpe *et al.,* 2012; Roshan *et al.,* 2012). Subsequent analyses utilizing instrumental, gravimetric and satellite-based telemetry have revealed marked temporal variability alongside a sustained contemporary contraction (Chen *et al.,* 2017a; Chen *et al.,* 2017b; Nandini-Weiss *et al.,* 2020; Prange *et al.,* 2020). More recent analyses continue to identify climate-linked sea-level decline as a major basin-scale concern (Serykh and Kostianoy, 2020; Lahijani *et al.,* 2023; Samant and Prange, 2023). The northern basin is especially vulnerable because of its shallow bathymetry, whereas the Kazakhstan coastline supports fisheries, ports, hydrocarbon production, recreation and rapidly changing coastal infrastructure. Consequently, the physical contraction of the basin interacts synergistically with water-quality degradation and habitat restructuring, rather than functioning as an isolated hydrological anomaly. Recent assessments increasingly describe the Caspian as a coupled social-ecological system exposed simultaneously to climate forcing, pollutant inputs, shoreline modification, biological invasions and resource extraction (Lahijani *et al.,* 2024; Kostianoy and Pešić, 2024). Kazakhstan's sector is of particular significance, as the shallow Northern Caspian is subject to substantial fluvial influence, whereas the Mangistau coast of the Middle Caspian exhibits a contrasting hydrographic regime. Regional monitoring has documented substantial variability in temperature, salinity, potential of hydrogen (pH), dissolved oxygen (DO) and contaminants, and independent water-quality studies along the Kazakhstan coast have identified spatially heterogeneous ecological and human-use risks (Kenzhetayev *et al.,* 2020; Costantini *et al.,* 2021; Ramazanova *et al.,* 2022; Esmaeilzadeh and Mehdinia, 2024). Furthermore, satellite observations additionally reveal recurrent oil-pollution pressure adjacent to major ports and industrial zones, underscoring the increasing utility of systematic remote sensing for Caspian basin monitoring (Mityagina and Kostianoy, 2024; Kostianoy *et al.,* 2024; Lavrova *et al.,* 2024b). Most monitoring reports, however, remain organized as separate descriptions of individual variables, which makes it difficult to distinguish persistent directional change from ordinary seasonal variability. While isolated anomalies, such as an elevated summer temperature in a given year, a depressed oxygen concentration in another, or a localized decline in plankton richness, carry individual significance, their ecological interpretation shifts fundamentally when evaluated jointly against a coherent temporal baseline. Robust non-parametric trend methods are well suited to such monitoring series because they tolerate non-normality, small samples and outliers while preserving interpretable effect sizes (Mann, 1945; Kendall, 1975; Theil, 1950; Sen, 1968). Consequently, a multi-domain synthesis can therefore evaluate whether the physical contraction of the sea coincides with synchronized hydrochemical and ecological shifts. Plankton and benthic communities provide an especially useful ecological layer because they respond to water-column conditions over shorter timescales than many higher-trophic indicators. While variations in phytoplankton richness primarily reflect shifts in nutrient availability, optical regimes, salinity and carbonate chemistry, zooplankton and macrozoobenthos assemblages encapsulate

broader habitat suitability and food-web restructuring. The Caspian Sea is widely recognized as susceptible to ecological restructuring driven by climatic stress, harmful algal blooms, and biological invasions (Shiganova *et al.,* 2023; Lavrova *et al.,* 2024a). Yet long-term hydrochemical and community datasets from the Kazakhstan sector have rarely been analyzed within one quantitative framework. The primary contribution of this study lies in the explicit integration of sea-level trajectory, regional hydrochemistry, and lower-trophic community metrics within a unified statistical framework, while strictly interpreting cross-domain correlations as hypothesis-generating rather than causal evidence. This study reanalyzes multi-source observations from 2010 to 2023 to determine whether the Kazakhstan sector of the Caspian Sea exhibits a coherent hydroclimatic-ecological transition. Ultimately, the proposed framework is designed to transition descriptive environmental monitoring into robust evidence base capable of supporting adaptive management strategies. The specific objectives of this study are to quantify the magnitude and significance of sea-level change; identify robust trends in temperature, salinity, pH and DO; compare trajectories between Mangistau in the Middle Caspian and Atyrau in the northern Caspian; assess long-term changes in macrozoobenthos, phytoplankton and zooplankton richness; and evaluate exploratory associations between physical-chemical conditions and community indicators during overlapping years. The study was conducted in the Kazakhstan sector of the Northern and Middle Caspian Sea using observations collected from 2010 to 2023, including field campaigns undertaken in 2022 and 2023.

MATERIALS AND METHODS

Study domain and data architecture

The study concerns the Kazakhstan sector of the Northern and Middle Caspian Sea, with regional comparisons centered on the coastal zones of Atyrau Region in the Northern Caspian and Mangistau Region in the Middle Caspian. The compiled archive integrates historical records sourced from Kazekoproekt, the Kazakhstan National Hydrometeorological Service (Kazhydromet), and Yessenov University. Because the compiled source archive did not preserve a complete station-by-year inventory, exact station counts, coordinates, sampling frequencies, detection limits and laboratory quality-control metadata cannot be reported consistently for every variable and year. The datasets were therefore not pooled at the raw station level. Each source-specific time series was maintained within its original spatial and temporal bounds, while quantitative integration was restricted to harmonized annual summaries featuring directly comparable variables and units. Long-term records span 2010-2023; the 2022-2023 field observations are treated separately as a contemporary observational check. Fig. 1 delineates the designated monitoring domains, Fig. 2 outlines the analytical workflow, and Table 1 itemizes the respective study domains and periods.

Sea-level and hydroclimatic variables

The basin-scale hydroclimatic component comprised 11 annual Caspian Sea-level observations for 2012-2022 and evaporation information available only for 2016-2020. Sea level was designated as the primary physical-response variable because it constitutes the longest internally consistent physical time series in the compiled database. The sea-level series was evaluated with Mann-Kendall and Sen-slope procedures. The five-year evaporation record was retained strictly as qualitative water-balance context rather than subjected to formal correlation with sea level; its brief, non-equivalent coverage would yield an underpowered comparison risk implying a causal linkage unsupported by the observational design.

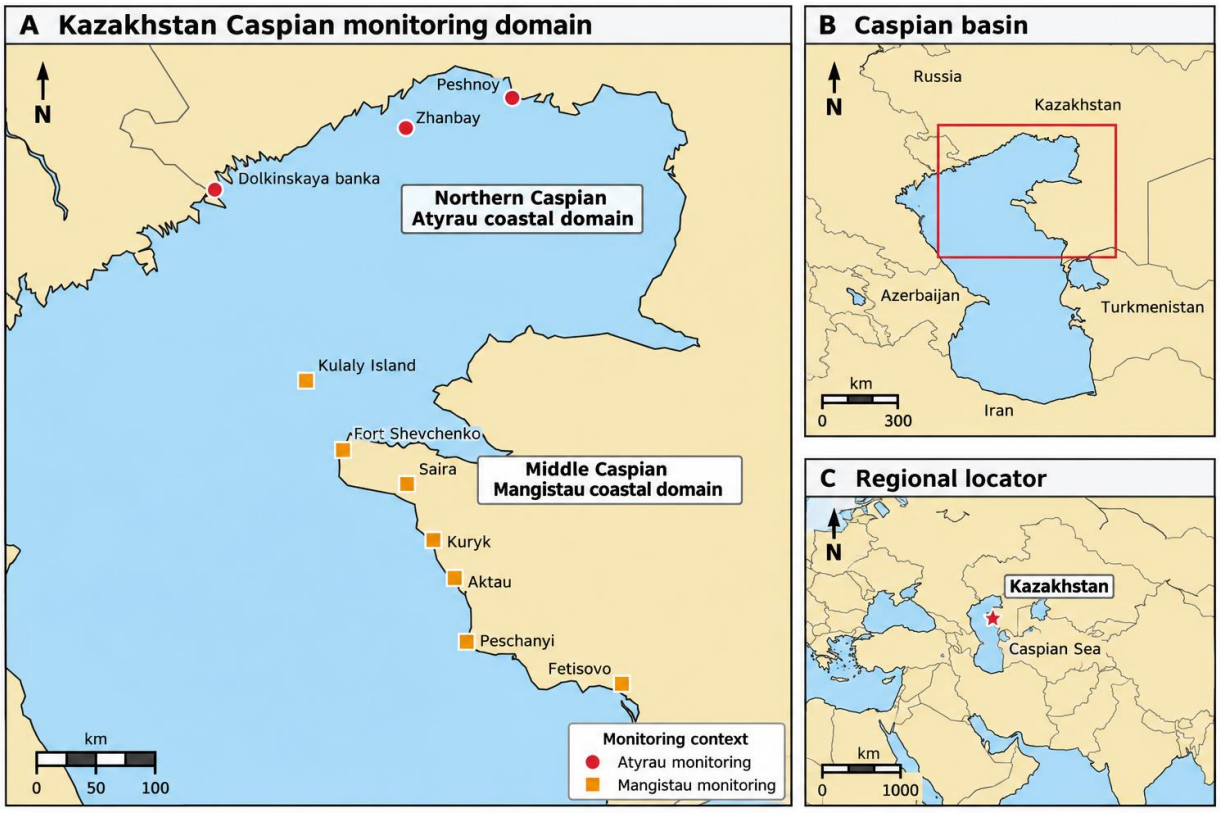

Fig. 1: Geographical location of the study area in the Kazakhstan sector of the Caspian Sea

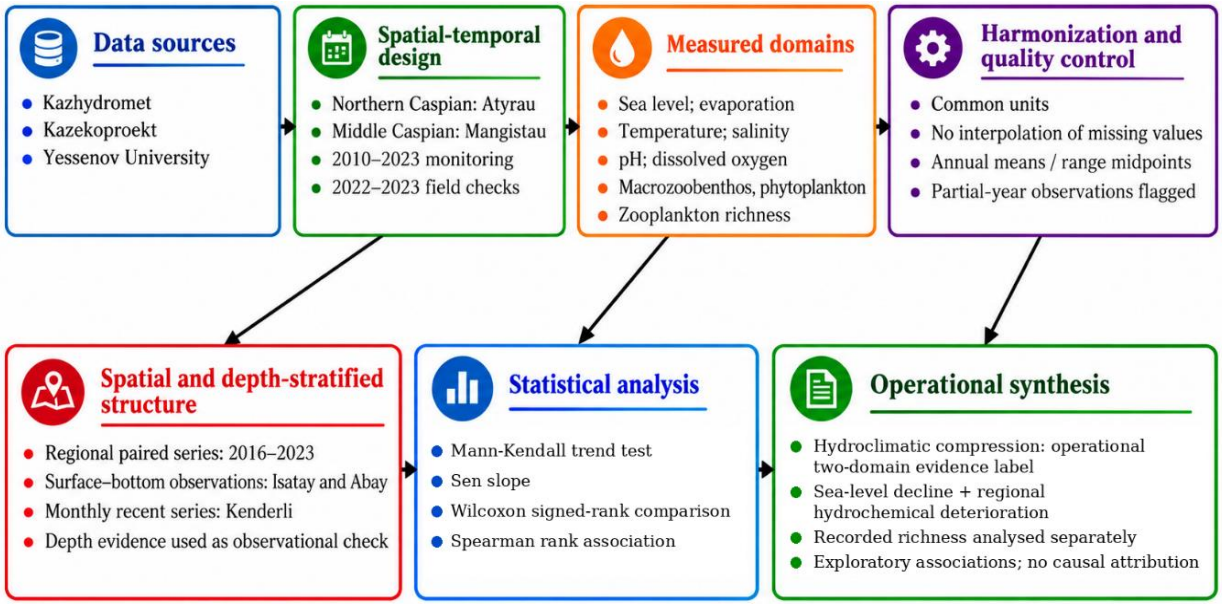

Fig. 2: Methodological schematic of the study design, data sources, spatial-temporal structure, measured domains, data harmonization, statistical analyses and operational synthesis

Table 1: Data domains used in the multi-source study

Domain	Variables	Primary period	Spatial scale	Analytical role
Hydroclimate	Caspian Sea level; evaporation	2012-2022; 2016-2020	Basin / regional	Basin-scale physical response and hydroclimatic context
Hydrochemistry	Temperature; salinity; pH; DO	2012-2023	Northern and Middle Caspian	Trend and regional contrast
Ecology	Macrozoobenthos, phytoplankton, zooplankton richness	2010-2022	Kazakhstan sector	Recorded-richness trajectory analysis
Recent field observations	Surface/bottom hydrophysics; Kenderli monthly chemistry	Kenderli: October 2022-August 2023; Isatay and Abay: 2023	Isatay, Abay, Kenderli	Qualitative contemporary context

Hydrochemical measurements and indicators

Water temperature, salinity, pH and DO were selected as the principal hydrochemical indicators because they had the most continuous annual coverage across the monitoring archive. Aggregate annual series were evaluated across a common long-term interval characterized by adequate data coverage, whereas regional trajectories for Mangistau and Atyrau were assessed specifically over the 2016 to 2023 period. Turbidity, transparency, conductivity and current velocity were retained as supporting observations where available but were not forced into the long-term trend analysis when temporal coverage was discontinuous. This separation prevents sparsely observed variables from being interpreted as equivalent to the core annual hydrochemical series.

Spatial and depth-stratified analysis

Spatial analysis distinguished the Atyrau coastal domain of the Northern Caspian from the Mangistau coastal domain of the Middle Caspian. For the paired 2016 to 2023 regional temperature series, corresponding annual values were compared directly to ensure that the evaluated regional contrast remained free from temporal confounding by unmatched years. Regional pH and DO were evaluated as separate monotonic trajectories rather than pooled paired contrasts. The recent field component retained surface and bottom observations from Isatay and Abay in 2023 and the monthly Kenderli series from October 2022 to August 2023. Because these depth-resolved observations lack a repeated multi-year design, surface-bottom differences served strictly as a qualitative check on vertical heterogeneity rather than being incorporated into long-term inferential trend tests. After locating the monitoring domains geographically in Fig. 1, the Fig. 2 summarizes the methodological sequence from data sources and spatial-temporal design through variable selection, harmonization, statistical analysis and operational synthesis. The workflow in Fig. 2 is complemented by the compact study inventory in Table 1, which specifies the variables, observation periods, spatial scales and analytical roles used in the evidence synthesis.

Data harmonization and quality control

Harmonization was deliberately conservative. Decimal commas were standardized to decimal points, and units were standardized to degrees Celsius (°C), practical salinity units (PSU), milligrams per liter (mg/L) and nephelometric turbidity units (NTU), as applicable. No missing annual observation was interpolated. Where the source archive provided a reported annual mean, that value was retained. When only a minimum–maximum range was available, the midpoint was used strictly as a descriptive annual locator for regional visualization and comparison, not as a station-weighted mean. This distinction is

important when interpreting hydrochemical observations from coastal aquifers, where hydrochemical characterization depends on the available measurements and their spatial representation (Satrio *et al.,* 2024). The compiled archive lacked the constituent station-level records necessary to recalculate alternative range summaries, precluding a formal sensitivity analysis across minimum, midpoint, and maximum parameters; consequently, results derived from midpoint are not treated as sole support for the primary conclusion. Partial-year 2023 values were retained only when explicitly identified and are flagged as a source of uncertainty. The archive does not support reconstruction of a uniform station-level detection-limit or quality-control protocol across all three data providers, so the analysis makes no claim of complete methodological equivalence among programs.

Hydroclimatic compression assessment

Hydroclimatic compression was operationalized as an interpretive two-domain evidence rule rather than a composite numerical index: 1) the basin-scale sea-level series must show a statistically significant monotonic decline, and 2) at least one regional hydrochemical series must show statistically significant deterioration in a direction relevant to water quality. Temperature and salinity are preserved as contextual parameters and are not constrained to exhibit monotonic increases or decreases. This approach distinguishes the interpretation of observed environmental indicators from classification frameworks developed for other environmental applications, including neural network-based classification of geological properties and seismic vulnerability (Mamyrbekova *et al.,* 2026). A simple leave-one-component robustness check was applied to this rule. Removing the sea-level criterion eliminates the classification by definition, whereas removing either the Mangistau DO signal or the Atyrau pH signal individually leaves the other statistically supported hydrochemical criterion in place. Accordingly, the interpretation relies on multiple hydrochemical lines of evidence rather than a single variable, while remaining strictly an observational framework rather than a demonstrated causal process. Biological recorded-richness trajectories are evaluated independently and are not part of the defining rule.

Trend and regional-comparison analysis

Directional trends were evaluated with the Mann-Kendall rank test (Mann, 1945; Kendall, 1975), and trend magnitude with the Sen slope (Theil, 1950; Sen, 1968). A two-sided $p<0.05$ was treated as statistically significant; $p=0.050$ therefore does not meet the stated criterion and is described as nonsignificant. To evaluate the paired 2016-2023 regional temperature data, the Wilcoxon signed-rank test was applied, with the median paired difference reported as an indicator of effect-size. Annual sample sizes are small ($n=8$ for regional 2016-2023 series, $n=10$ for 2012-2021 aggregate/cross-domain series, $n=11$ for sea level, and $n=13$ for 2010-2022 richness series), limiting power and making p-values sensitive to individual years. Formal confidence intervals for Sen slopes and the paired effect were not recoverable from the compiled summary archive and are therefore not presented. Serial-dependence correction or prewhitening was omitted because the brief annual series preclude stable autocorrelation estimation; this methodological constraint is explicitly integrated into interpretation. Accordingly, the outcomes serve strictly as indicators of monotonic trajectory within each individual series rather than as validation of independent causal mechanisms.

Recorded-richness assessment

The ecological analysis is restricted to annual recorded richness of macrozoobenthos, phytoplankton and zooplankton during 2010-2022 (up to $n=13$ annual values per group). The archive does not contain a complete year-by-year record of standardized sampling effort, station coverage, season, taxonomic resolution, nomenclatural revision, abundance, biomass, dominance or

species-turnover matrices. Consequently, the analytical framework is incapable of quantitatively decoupling intrinsic ecological shifts from variations in sampling effort or shifts in taxonomic methodology. Richness values represent the annual sector-level values reported in the compiled monitoring archive; they are not standardized rarefied richness and are not interpreted as station-normalized estimates. Mann-Kendall and Sen-slope procedures quantify only monotonic trajectories of recorded richness. Beginning-to-end changes are descriptive. Formal trend analyses of abundance and biomass were omitted because inconsistencies in measurement units, sampling effort, and temporal coverage precluded robust annual comparisons.

Cross-domain association analysis

Five pre-specified Spearman rank associations were evaluated over the common 2012-2021 interval (n=10 paired annual observations each): pH-phytoplankton richness, pH-zooplankton richness, sea level-phytoplankton richness, sea level-zooplankton richness and salinity-zooplankton richness. Unadjusted p-values are reported for transparency, together with Holm-adjusted p-values for the five-comparison family. The adjusted p-values are 0.005, 0.104, 0.126, 0.126 and 0.298, respectively. Only the pH-phytoplankton association remains below 0.05 after correction. Detrended, partial and lagged correlations were omitted because a decade of annual data is inadequate for a stable multivariable or lagged time-series modeling, particularly given discrepancies in monitoring effort. Consequently, shared temporal structure may produce spurious association; therefore, all cross-domain findings are treated strictly as exploratory and non-causal.

Statistical software and reproducibility

Calculations were performed using annual values from the compiled monitoring archive, following a fixed sequence of data extraction, unit harmonization, missing-value screening, robust trend estimation, matched regional comparison and exploratory rank association. The analytical sample size is reported for each principal trend, with unavailable station-level metadata distinguished from available annual summaries. Reproducibility is limited by data-holder restrictions and the unavailability of a comprehensive station-level dataset; missing metadata and observations were not reconstructed or imputed.

RESULTS AND DISCUSSION

Rapid sea-level decline is the strongest basin-scale physical signal

The sea-level series decreased from -27.57 meters (m) in 2012 to -28.70 m in 2022, giving the principal tabulated end-point decline of 1.13 m. A decline of approximately 1.16 m is obtained when the highest early-period level is used as the baseline; the 2012-2022 end-point decline of 1.13 m is the primary estimate. The Mann-Kendall test (n=11) showed a strong monotonic decline (τ=-0.782, $p<0.001$), with a Sen slope of -0.110 meters per year (m/y). The short 2016-2020 evaporation record is retained only as water-balance context. Although this contemporary decline aligns with documented evidence of climate-driven changes in the Caspian water-balance (Chen *et al.,* 2017a; Lahijani *et al.,* 2023; Samant and Prange, 2023), the Caspian basin has experienced substantial historical fluctuations; consequently, the present assessment characterizes a rapid decline within the 2012-2022 monitoring window rather than asserting historical uniqueness. Fig. 3 and Table 2 report the observed trajectory and trend statistic.

Hydrochemical change is region-specific rather than uniform

The aggregate 2012-2021 series (n=10 where complete) did not show statistically significant monotonic trends in temperature (Sen slope -0.150 °C/y, p=0.381), salinity (+0.140 PSU/y, p=0.727) or DO (-0.006 mg/L/y, p=0.727), whereas pH declined (Sen slope -0.0725 pH/y, p=0.029). The pH findings are restricted to an empirical

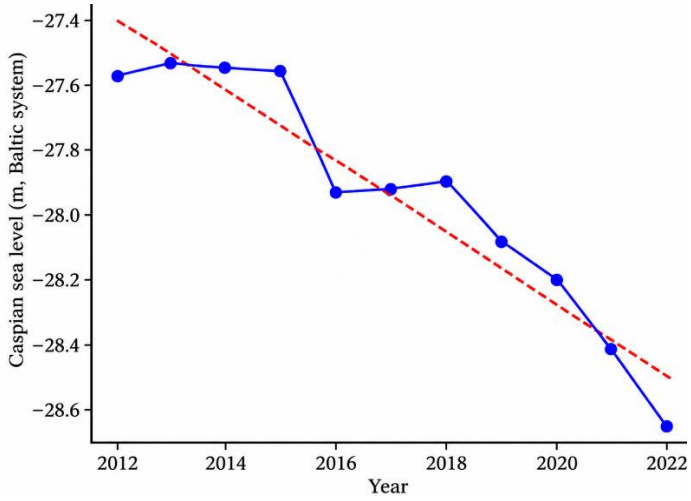

Fig. 3: Caspian Sea level during 2012-2022. The dashed line is a visual linear guide; inferential trend estimates are based on the Mann-Kendall test and Sen slope

Table 2: Principal robust trend results

Series	Period	Kendall τ	p-value	Sen slope	Interpretation
Sea level	2012-2022 (n=11)	-0.782	<0.001	-0.110 m/y	Significant decline
Aggregate pH	2012-2021 (n=10)	-0.556	0.029	-0.0725 pH/y	Significant decline
Mangistau temperature	2016-2023 (n=8)	+0.571	0.061	+0.798 °C/y	Increasing tendency
Mangistau DO	2016-2023 (n=8)	-0.764	0.009	-0.295 mg/L/y	Significant decline
Atyrau pH	2016-2023 (n=8)	-0.643	0.031	-0.191 pH/y	Significant decline
Macrozoobenthos richness	2010-2022 (n=13)	-0.116	0.582	-0.417 species/y	No significant monotonic trend
Phytoplankton richness	2010-2022 (n=13)	-0.297	0.160	-1.625 species/y	No significant monotonic trend
Zooplankton richness	2010-2022 (n=13)	-0.416	0.050	-1.93 species/y	Not significant at p<0.05

evaluation of directional pH trend; because measurements of alkalinity, DO carbon and complementary carbonate-system parameters were inconsistently available, broader carbonate-system deterioration cannot be inferred. Furthermore, regional responses exhibited notable heterogeneous. In Mangistau, the 2016-2023 temperature series (n=8) showed a nonsignificant increasing tendency (Sen slope +0.798 °C/y, p=0.061), while DO declined (-0.295 mg/L/y, p=0.009). In Atyrau, pH declined (-0.191 pH/y, p=0.031), while the available DO trajectory was negative but not statistically significant. The matched temperature comparison showed a median Mangistau-minus-Atyrau difference of -2.8 °C (Wilcoxon p=0.039). Not every region-variable combination could be reconstructed from the annual summary archive; combinations lacking a complete recoverable series are not assigned inferential statistics. These findings indicate spatially heterogeneous responses occurring alongside a basin-wide physical decline, rather than uniform hydrochemical degradation across all variables or a demonstrable causal link from sea level to wáter chemistry. The regional trajectories in Fig. 4 are summarized in Table 2, which reports the analytical sample size for every listed trend. Only region-variable combinations with complete, recoverable annual series in the compiled archive are included.

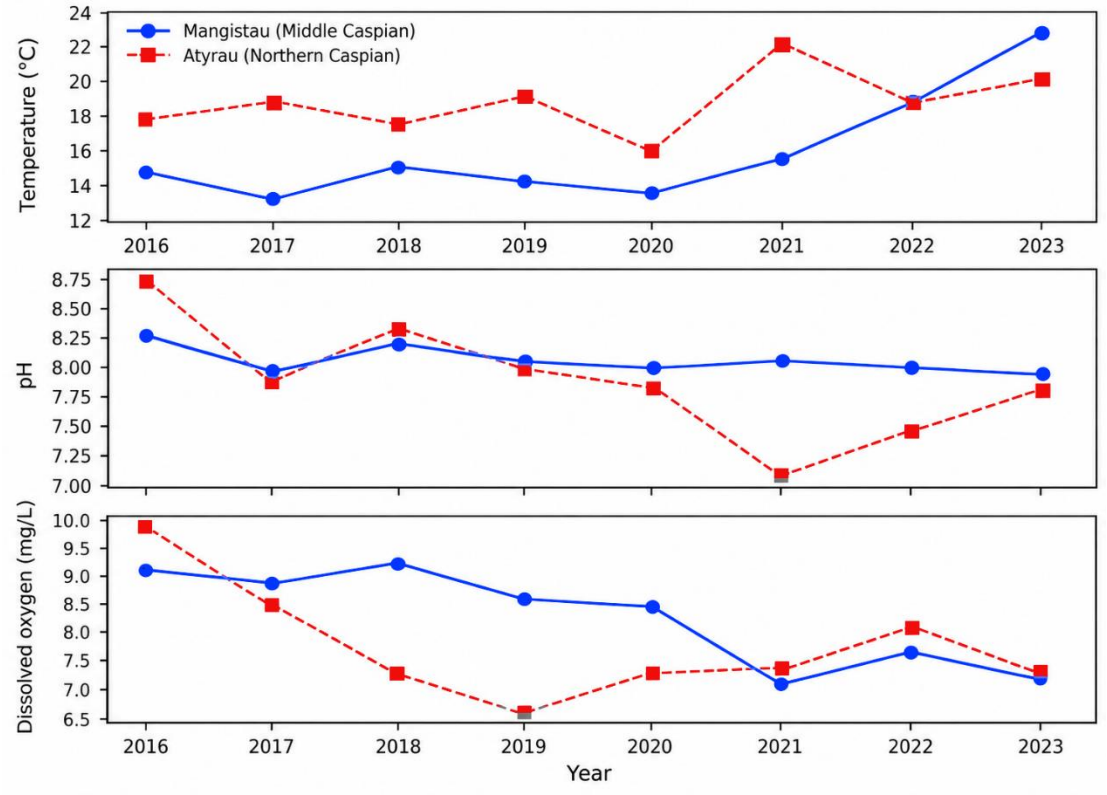

Fig. 4: Regional trajectories of temperature, pH and DO oxygen in Mangistau (Middle Caspian) and Atyrau (Northern Caspian), 2016-2023

Lower-trophic recorded-richness trajectories are heterogeneous

Recorded annual richness declined descriptively between the first and last reported values, from 39 to 18.7 taxa for macrozoobenthos, 74 to 22 for phytoplankton and 32 to 11.7 for zooplankton. These end-point divergences are not interpreted as measures of true ecological loss, as temporal variations in sampling effort, spatial station coverage, seasonal timing, and taxonomic consistency preclude standardized multi-year comparisons. Formal rank tests (n=13 annual values where complete) did not identify a significant monotonic trend for macrozoobenthos (τ=-0.116, p=0.582; Sen slope -0.417 species/y) or phytoplankton (τ=-0.297, p=0.160; Sen slope -1.625 species/y). Zooplankton had the strongest negative direction (τ=-0.416; Sen slope -1.93 species/y), but p=0.050 does not meet the predefined p<0.05 criterion and is therefore reported as nonsignificant. The available evidence indicates spatially heterogeneous shifts in recorded richness, rather than demonstrable alterations in community composition, taxonomic turnover, shifts in dominance structure, or ecosystem-wide biodiversity loss. Fig. 5 presents the descriptive annual record of the compiled sector-level richness values.

Cross-domain associations are exploratory and vulnerable to shared time structure

Across the ten overlapping annual observations (2012-2021), the unadjusted Spearman coefficients were positive for pH-phytoplankton richness (ρ=0.863, p=0.001), pH-zooplankton richness (ρ=0.695, p=0.026), sea level-phytoplankton richness (ρ=0.650, p=0.042) and sea level-zooplankton richness (ρ=0.616, p=0.058), while salinity-zooplankton richness was negative and weak (ρ=-0.366, p=0.298). Holm

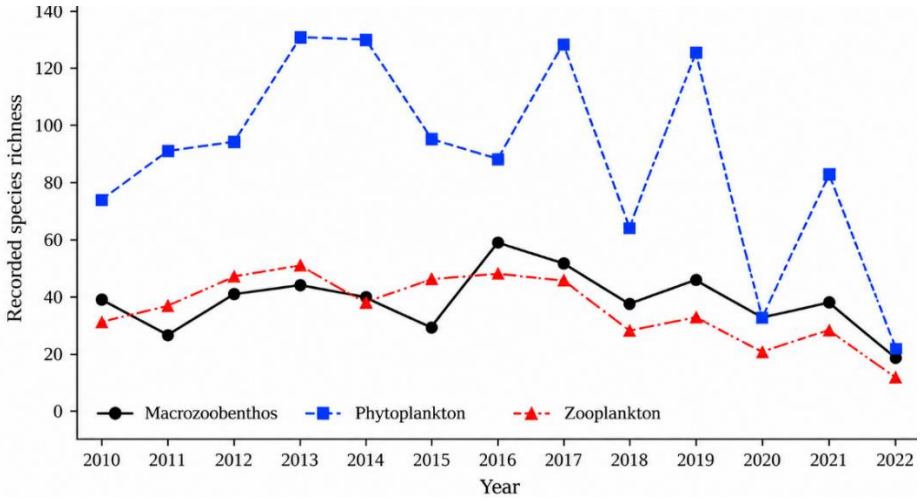

Fig. 5: Annual recorded sector-level richness values for macrozoobenthos, phytoplankton and zooplankton in the compiled Kazakhstan monitoring archive, 2010-2022. Values are not standardized for sampling effort, station coverage or taxonomic resolution and should not be interpreted as rarefied or station-normalized richness estimates

adjustment for the five comparisons gives adjusted p=0.005, 0.104, 0.126, 0.126 and 0.298, respectively; only the pH-phytoplankton pairing remains statistically significant after correction. Even this association fails to establish a causal mechanism, as the time series are brief, share common temporal structure, and originate from non-stationary monitoring designs. Detrended, partial and lagged models were not fitted because n=10 is insufficient for stable multivariable time-series inference. The associations therefore identify hypotheses for future standardized monitoring rather than causal ecological linkages. Table 3 reports the five Spearman rank coefficients and unadjusted p-values. Because the analyses form one exploratory family, interpretation of the associations is based on the Holm-adjusted p-values reported in the text. Effect sizes are reported alongside significance thresholds to emphasize magnitude, and all identified associations are interpreted strictly as non-causal.

Recent field observations provide qualitative spatial and depth context

The 2023 Isatay and Abay observations and the October 2022-August 2023 Kenderli series provide contextual evidence that conditions vary with depth, season and location. Because the compiled archive lacks a complete, recoverable tabulation of field sample sizes, paired surface-bottom metrics, parameter ranges, and sampling depths, a formal quantitative comparison is precluded. These observations do not validate the long-term trends, and no inferential claim is based on them. They motivate future depth-resolved sampling and illustrate why annual coastal averages fail to capture short-term vertical heterogeneity.

Study limitations and implications

The source archive was assembled from multiple monitoring programs rather than a single fixed design. Exact station counts, geographic coordinates, sampling frequencies, analytical detection limits and quality-control procedures are not consistently preserved for every variable and year in the compiled archive. Consequently, temporal coverage, station density, and monitoring effort exhibit spatial and temporal variability; furthermore, certain annual regional metrics are derived from ranges, and several 2023 observations are restricted to partial-year records. Biological recorded richness is particularly sensitive to effort, season, location, taxonomic

Table 3: Exploratory cross-domain rank associations. Reported p-values are unadjusted; Holm-adjusted p-values for the five-association family are provided in the text. n is the number of paired annual observations

Association	n	Spearman ρ	p-value (unadjusted)	Interpretation
pH vs phytoplankton richness	10	0.863	0.001	Strong positive co-variation
pH vs zooplankton richness	10	0.695	0.026	Positive co-variation
Sea level vs phytoplankton richness	10	0.650	0.042	Positive co-variation
Sea level vs zooplankton richness	10	0.616	0.058	Positive tendency
Salinity vs zooplankton richness	10	-0.366	0.298	No clear association

resolution, nomenclatural revision and identification protocol. Additionally, the restricted length of the annual series constrains statistical power, precludes reliable estimation of autocorrelation or lagged-models, and complicates the reconstruction of confidence intervals from summary-level data alone. Major potential drivers including river discharge, precipitation, evaporation, pollution loading, eutrophication, coastal development, habitat modification and invasive species were not jointly modelled. These methodological constraints preclude direct causal attribution, the formal partitioning of climate-driven versus local anthropogenic drivers, and the derivation of precise estimates regarding biodiversity loss. The defensible contribution is therefore a transparent separation of statistically supported trends, descriptive directional changes and exploratory cross-domain co-variation. Observed evidence and management implications are separated in Table 4. The empirical evidence is strictly confined to the trends and associations quantified herein; furthermore, the proposed monitoring frameworks represent recommendations for future design rather than experimentally validated protocols. Applying the operational two-domain rule, the record is compatible with hydroclimatic compression because the significant basin-scale sea-level decline coincides with statistically supported regional deterioration in DO and pH in Atyrau. The absence of significant aggregate temperature and salinity trends demonstrates that this label does not mean uniform degradation. A leave-one-out sensitivity analysis across hydrochemical-signals indicates that the interpretation relies exclusively on neither oxygen nor pH alone; however, it remains contingent upon the sea-level criterion and must therefore be evaluated strictly as an interpretive framework (Fig. 6). Future monitoring should use fixed stations, standardized effort and taxonomic quality assurance, explicit surface-bottom profiles, and region-specific pH measurements supplemented by alkalinity and dissolved inorganic carbon if carbonate-system assessment is intended. River discharge, nutrient and pollutant loads, shoreline modification and invasive species should be measured concurrently so that causal pathways can be tested rather than inferred from coincident trends. The synthesis treats the operational hydroclimatic-compression designation independently from observed changes in biological richness. The former is substantiated by the significant drop in sea level, alongside region-specific oxygen and pH trajectories, in accordance with the specified evidentiary criteria. The biological series show heterogeneous and mostly nonsignificant monotonic trajectories and therefore do not justify a claim of demonstrated community-level ecological reorganization. Recent field observations provide qualitative context only, and cross-domain correlations remain exploratory after multiplicity correction. This evidentiary hierarchy serves as the foundation for the monitoring priorities outlined in Table 4 and informs the overarching conclusions.

Table 4: Monitoring implications of the analysis

Monitoring priority	Observed evidence	Risk of simple averaging	Recommended design
Sea level	Strong 2012-2022 decline	Masks physical habitat loss	Annual basin trend plus shoreline exposure mapping
DO	Significant decline in Mangistau	Annual means can hide bottom-layer minima	Seasonal surface-bottom profiles
pH	Significant aggregate/Atyrau decline	May be diluted by regional pooling	Region-specific pH monitoring; add alkalinity and dissolved inorganic carbon for carbonate-system assessment
Plankton richness	Heterogeneous recorded-richness trajectories; no significant monotonic decline at $p<0.05$	Sampling effort and taxonomic inconsistency can confound year-to-year values	Standardized effort, fixed stations, seasonal coverage and taxonomic quality assurance

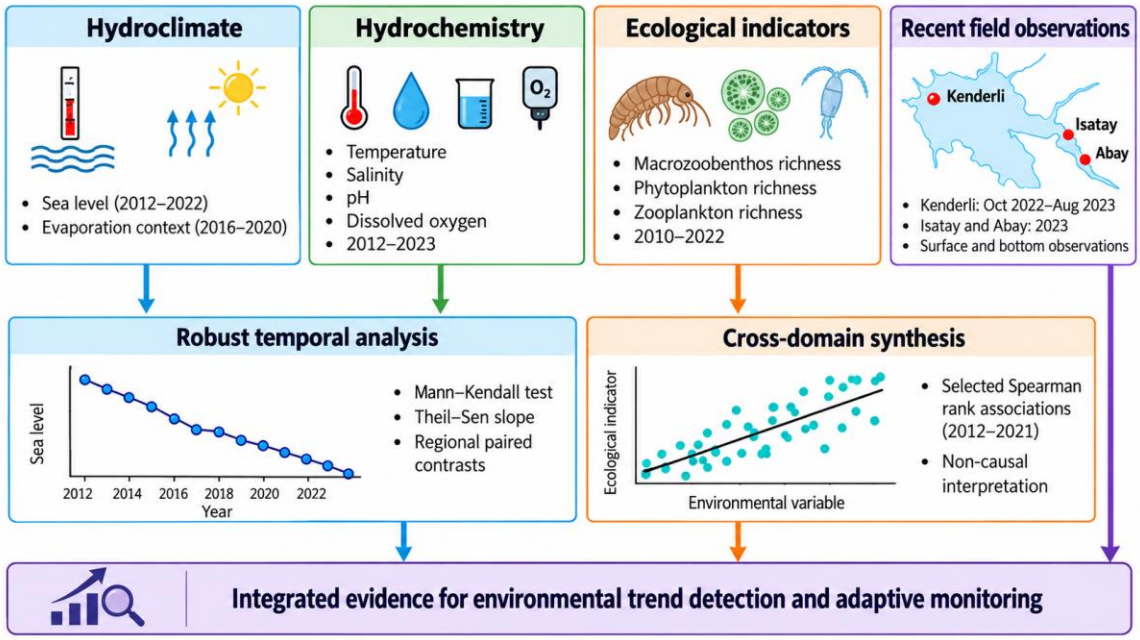

Fig. 6: Integrated synthesis of observed basin-scale sea-level decline, spatially heterogeneous hydrochemical trends, uncertain lower-trophic recorded-richness trajectories and qualitative recent field context. Exploratory cross-domain associations are shown as hypothesis-generating rather than causal evidence

CONCLUSION

The integrated synthesis reveals a coherent yet spatially heterogeneous environmental transition across the Kazakhstan sector of the Caspian Sea. The strongest basin-scale signal is the rapid decline in sea level during 2012 to 2022. Within the coastal water column, statistically supported hydrochemical deterioration is expressed differently by region: dissolved oxygen declines in the Mangistau series of the Middle Caspian, whereas pH declines in the Atyrau series of the Northern Caspian. Lower-trophic richness trajectories exhibit marked heterogeneity: zooplankton display a borderline monotonic decline, phytoplankton demonstrate a non-significant downward shift, and macrozoobenthos maintain no significant monotonic trend despite pronounced descriptive end-point reductions.

These findings underscore the analytical utility of synthesizing physical, chemical and ecological observations within a unified environmental evidence framework rather than treating them as disconnected monitoring variables. The evidence does not support a simplistic narrative of uniform warming, uniform salinization or a single pollution trajectory. Instead, the combined record supports hydroclimatic compression, defined here by physical contraction of the basin together with statistically supported regional hydrochemical deterioration. Although ecological reorganization was assessed independently and unfolded concurrently with this compression, it is not employed as a defining classification criterion. The cross-domain associations strengthen the case for targeted mechanistic monitoring, particularly the positive co-variation of plankton richness with pH and sea level, while remaining explicitly non-causal because the annual series are short, share temporal structure and originate from monitoring programs with unequal sampling intensity. Accordingly, this study distinguishes statistically robust directional trends from exploratory ecological associations that necessitate targeted mechanistic validation. The principal management implication is that future Caspian surveillance should move beyond isolated annual averages and threshold exceedances. A robust monitoring framework requires maintaining fixed long-term stations, standardizing sampling effort alongside taxonomic quality assurance, resolving seasonal surface-to-bottom oxygen gradients, regionally tracking pH and the carbonate dynamics, and integrating biological indicators with shoreline exposure metrics and satellite observations. Such a design would make it possible to detect persistent directional change even when individual measurements remain within regulatory ranges. Consequently, this synthesis bridges the gap between descriptive environmental reporting and integrated early-warning monitoring. Continued application of this architecture with harmonized station-level data would allow future work to test mechanisms, separate climate forcing from local anthropogenic pressure and determine whether observed ecological reorganization accelerates as sea-level decline continues.

AUTHOR CONTRIBUTIONS

L. Taizhanova, the corresponding author, has contributed to the compilation and analysis of hydrochemical data, interpretation of the results, and manuscript preparation. S.E. Koibakova conducted the field measurements and seawater-quality analysis and prepared the original manuscript. S. Syrlybekkyzy contributed to the conceptualization and methodology, supervised the study, participated in field analysis, interpreted the results, and reviewed and edited the manuscript. Z. Altybaeva contributed to hydrochemical data compilation, analysis, interpretation of the results, and manuscript preparation. A. Kurbaniyazov participated in manuscript review and approved the final manuscript. F. Nurbayeva participated in manuscript review and approved the final manuscript. N. Janaliyeva participated in manuscript review and approved the final manuscript. K. Muzbayeva participated in manuscript review and approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare no conflict of interest. This study involved analysis of environmental monitoring records and field measurements and did not involve human participants or experimental animals. The authors affirm responsibility for the integrity of the data analysis, interpretation and reporting and compliance with the journal's publication-ethics requirements.

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ABBREVIATIONS

%	Percent
°C	Degree Celsius
°C/y	Degree Celsius per year
AI	Artificial intelligence
CC BY	Creative Commons Attribution
DOI	Digital object identifier
ID	Identifier
km	Kilometre
m	Metre
m/y	Metre per year
mg/L	Milligram per liter
mg/L/y	Milligram per liter per year
n	Number of paired observations
NA	Not available
NTU	Nephelometric turbidity unit
ORCID	Open Researcher and Contributor ID
p	Probability value
pH	Potential of hydrogen
pH/y	pH unit per year
PSU	Practical salinity unit
PSU/y	Practical salinity unit per year
species/y	Species per year
URL	Uniform resource locator
ρ	Spearman rank correlation coefficient
τ	Kendall rank correlation coefficient

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