Journal of Innovative Technology and Education, Vol. 12, 2025, no. 1, 15 - 27
HIKARI Ltd, www.m-hikari.com
https://doi.org/10.12988/jite.2025.1165

Mathematical Modeling of the Caspian Sea Geometry under Water Level Decline: Evidence from Iran's Mazandaran Coast

Majid Ghorbani

Department of Mathematics, Azad University
Central Tehran Branch, Tehran, Iran
ORCID: https://orcid.org/0000-0003-0143-9616

Abstract

The Caspian Sea is the world's largest endorheic water body and serves as a natural laboratory for examining the interaction between hydroclimatic forcing and coastal geomorphic response. Over the last century, the basin has experienced multi-decadal oscillations, with an accelerated decline observed since the mid-1990s. Projections indicate that this downward trend will continue throughout the twenty-first century [1–3]. This meta-analysis synthesizes peer-reviewed evidence on shoreline migration, vertical water-level change, and areal transformation, and evaluates how these processes reshape the basin's large-scale geometry—approximated locally by parabolic or saddle-shaped (hyperbolic-paraboloid) surfaces—while generating cascading socioeconomic risks.Our analysis combines quantitative shoreline metrics (Digital Shoreline Analysis System, DSAS), spectral water delineation (NDWI/MNDWI), sediment-transport theory (Exner equation), and water-balance diagnostics to: (i) characterize recent and projected Caspian water-level trajectories; (ii) capture planform curvature and alongshore variability along Iran's Mazandaran coast; (iii) contrast Caspian dynamics with those of China's coastal systems, including the South China Sea littoral and the Yangtze River delta; and (iv) assess risk pathways for agriculture, navigation, fisheries, and wetlands [4–8].Findings from the literature highlight a persistent negative water balance, primarily due to evaporation exceeding precipitation and inflows, superimposed on high interannual variability. The Volga River—regulated by reservoirs such as Volgograd—remains the dominant control on riverine input [6]. Shoreline retreat and shallow-water expansion have already disrupted port operations in Mazandaran (e.g., Amir-Abad), accelerating dredging needs and exposing wetlands such as Gorgan Bay to desiccation and dust-storm hazards [7,8]. Comparative analysis further shows that while China's open coasts are strongly influenced by marine processes, the Caspian's closed-basin geometry transmits water-level anomalies more uniformly, amplifying parabolic and saddle-like morphodynamic responses [9–13].The study concludes with practical adaptation options for Mazandaran, including channel realignment, dynamic coastal zoning, ecological buffer systems, and flexible port layouts, aligned with realistic twenty-first-century scenarios of continued decline [3,7,8].

Keywords: Caspian Sea, Mazandaran coast, shoreline change, DSAS, NDWI, Exner equation, Volga discharge, Yangtze River delta, South China Sea, hyperbolic paraboloid, water balance, fisheries risk, port dredging, Gorgan Bay

1. Introduction

The Caspian Sea (CS) has experienced pronounced multi-decadal fluctuations in water level, primarily governed by the basin's closed hydrological balance—river inflow plus precipitation minus evaporation and minor losses to Kara-Bogaz-Gol—further influenced by climate variability and human regulation [1–5]. Since the mid-1990s, observations have shown a persistent decline in water level. This trend is strongly associated with increased evaporation driven by warming, which outpaces precipitation gains across the catchment. Projections indicate that this downward trajectory is likely to continue throughout the twenty-first century under multiple forcing scenarios [2,3]. Even moderate declines of 5–10 m are expected to disrupt ecosystems, protected areas, and coastal infrastructure significantly [3].

Beyond vertical changes, the Caspian shoreline has undergone substantial horizontal adjustments, including delta progradation and retreat, beach profile translation, and lagoon desiccation. These processes collectively reshape the basin's planform geometry [7,8].

The southern littoral of the CS, particularly Mazandaran Province (Iran), is a hotspot of vulnerability. Here, small vertical changes in sea level translate into disproportionately large horizontal shoreline shifts due to the low coastal gradient, extensive shallow shelves, and engineered navigation channels. Ports such as Amir-Abad already report sedimentation and draft limitations, requiring frequent dredging and operational adaptations [7]. Neighboring wetlands, including Gorgan Bay and Miankaleh, are also highly sensitive to water-level fluctuations, with evidence of circulation weakening, habitat loss, and the emergence of dust sources during low stands [8].

The Volga River, which contributes the majority of CS inflow, is heavily regulated by a cascade of reservoirs, including Volgograd. Consequently, upstream hydrological changes propagate into the basin's overall water balance and shoreline evolution [6].
To capture the geometric transformation of the CS, an integrated approach is required: (i) a vertical water-balance framework; (ii) shoreline metrics derived from long-term satellite records (Landsat, Sentinel) using robust spectral indices; (iii) areal changes analyzed through DSAS transect statistics; and (iv) morphodynamic process models constrained by sediment-continuity principles (Exner equation). This study performs a meta-analysis of these components, with a particular focus on Mazandaran's coastal zone, while drawing comparative insights from two Chinese systems: the Yangtze River delta—an example of sediment-starved, post-dam shoreline retreat—and the South China Sea's open coasts, where marine forcing and large-scale reclamation dominate shoreline dynamics [9–13].
By contrasting these contexts, the analysis clarifies how the Caspian's closed-basin geometry produces unique parabolic and saddle-like shoreline responses, which cannot be directly extrapolated from open-ocean coasts. Beyond the scientific synthesis, the study also highlights practical implications for Mazandaran's irrigated agriculture, fisheries, and navigation systems. Falling water levels, combined with shifting wave climates and sediment dynamics, are likely to increase the frequency of channel closures, expand mudflats, and degrade critical habitats. These processes, in turn, elevate both economic costs and ecological risks [3,7,8,12].

2. Methodology

2.1 Water balance and vertical change

The vertical variation of the Caspian Sea (CS) is described through a volumetric balance equation that accounts for inflows and losses:

$$\frac{dV}{dt} = Q_R + \mathrm{P\,A} - \mathrm{E\,A} - Q_K - Q_G,$$

$$\frac{d\mu}{dt} = \frac{Q_R + \mathrm{P\,A} - \mathrm{E\,A} - Q_K - Q_G}{\frac{dV}{d\mu}} \quad (1)$$

Where V is water volume, μ is mean water level, Q_R represents river inflow (dominated by the Volga),P is precipitation over the basin, E is evaporation, Q_K denotes outflow to Kara-Bogaz-Gol, and Q_G represents groundwater exchange [1–6]. This formulation provides a diagnostic framework for evaluating long-term water-level changes.

2.2 Shoreline extraction and horizontal change

To assess horizontal shoreline shifts, we applied a standard spectral workflow based on multi-decadal Landsat and Sentinel time series. Water–land boundaries were delineated using the Normalized Difference Water Index (NDWI) and its modified version (MNDWI):

(2) NDWI+ $\frac{G-NIR}{G+NIR}$, MNDWI= $\frac{G-SWIR}{G+SWIR}$

Where G is the green band, the near-infrared band, NIR the near-infrared band, and SWIR the shortwave infrared band. Shoreline displacement is estimated as a function of water-level change ($\Delta\mu$) and local slope (β):

$$\Delta x \approx \frac{\Delta\mu}{\beta}$$

This approach enables the quantification of horizontal shoreline migration under different water-level scenarios [14,15,17–19].

2.3 Areal change and basin-scale geometry

The areal response of the CS to vertical fluctuations is approximated from published hypsometry and thermohaline budgets [4,5]. Locally, nearshore bathymetry is represented by quadratic surfaces, while at broader scales the basin planform is idealized by parabolic and saddle-shaped (hyperbolic-paraboloid) geometries:

z(x,y) = a x^2+ by^2 + c,

z(x,y) = a x^2 - by^2+ c (3)

These formulations allow the characterization of basin geometry and its role in amplifying or moderating shoreline response.

2.4 Sediment continuity and littoral transport

Morphodynamic adjustments along Mazandaran's coast are governed by sediment continuity, expressed by the Exner equation:

(1- α_p) $\frac{\partial_{\alpha_s}}{\partial_t}$ + $\nabla. q_s$ = 0 (4)

Where α_p is porosity, α_s is sediment concentration, and q_s is sediment flux [16]. This framework captures shoreline reorganization, bar migration, and accommodation-space changes in response to base-level decline.

2.5 Scope of meta-analysis

The meta-analysis synthesized peer-reviewed studies that met at least one of the following criteria:

(i) Documentation of shoreline or level time series;

(ii) Explicit focus on the Caspian Sea or Mazandaran Province; and/or

(iii) Transferable insights from coastal-morphodynamic studies in the Yangtze River delta and Chinese open coasts.

Data sources included:

DSAS documentation for shoreline-change metrics [14,15];

Spectral-index fundamentals for water delineation [17–19];

Hydrologic diagnostics for basin water balance [1–6];

Case-specific studies of Mazandaran ports and wetlands [7,8].

All cited works carry DOIs and are listed in the reference section.

3. Results and Discussion

3.1 Vertical (level) change: observations and projections

Instrumental records and gravimetry indicate substantial twentieth-century CS oscillations followed by a post-1995 decline [1]. Multi-model projections show evaporation increases outpacing precipitation, yielding a persistently negative basin-integrated P - E and continued level fall through 2100 across emissions pathways [2]. Ecosystem risk assessments conclude that even 5–10 m of decline would drastically reduce marine protected area coverage, displace biota (e.g., Caspian seals), and strand infrastructure [3]. Thermohaline analyses also describe feedbacks between surface area, evaporation, and circulation that modulate budgets as the lake contracts [4, 5]. In a water-balance view (Section 2.1), these combine to maintain $\frac{d\mu}{d_t} < 0$unless Volga discharge compensates, which is unlikely given climatic and regulatory trajectories [6].

3.2 Horizontal change along Mazandaran

Because Mazandaran's shelves are shallow and gently sloping, shoreline position is highly sensitive to vertical changes in water level (Δμ) [14,15]. Empirical DSAS analyses from the southern Caspian report multi-decadal shoreline migration of tens to hundreds of meters, closely synchronized with water-level oscillations [14,15]. High-resolution monitoring at Amir-Abad Port shows shoaling and morphological instability, which limit berth accessibility. Under declining water levels, nearshore bars migrate shoreward, and navigation channels intersect with littoral drift, requiring frequent dredging [7]. To the east, Gorgan Bay and Miankaleh have experienced circulation weakening, nutrient shifts, and exposure to dust-source formation during low stands. Modeling suggests that inlet deepening or realignment could partially restore hydrological exchange under continued decline [8]. These observations align with Exner-governed adjustments, in which gradients in alongshore sediment transport ($\nabla . q_s$) reorganize bars and spits while base-level fall reduces accommodation space [16].

3.3 Areal transformation and basin geometry

Areal contraction A(μ) accelerates asfalls across gently sloping shelves, producing large areal loss per unit level in Mazandaran relative to steeper margins. The parabolic vs saddle idealizations (Section 2.3) help interpret this: regions approximated by an elliptic paraboloid (both principal curvatures positive) withdraw more uniformly, whereas saddle regions (opposing curvatures) can localize exposure along one axis while retaining submergence along the other. This geometry aligns with observed anisotropy between Iran's wide southwestern shallows and steeper eastern flanks [4, 5]. Practical implication: hazard footprints elongate along the gentle curvature direction, magnifying agricultural land exposure and expanding intertidal mudflats that hinder small-craft navigation and fishing.

3.4 Volga regulation (Volgograd) and catchment forcing

The Volga River provides the majority of Caspian inflow, but its cascade of reservoirs—including Volgograd—modifies both discharge timing and sediment delivery [6]. While long-term sea-level decline is primarily driven by evaporation, reduced river discharge exacerbates water-balance deficits and decreases deltaic sediment supply, which could otherwise partially offset local shoreline retreat. Under the storage balance (Section 2.1), the long-term outlook is continued $\frac{d\mu}{d_t}$ negative with amplified seasonality, complicating navigation management and port operations along Mazandaran.

3.5 Comparative lens: Yangtze River delta and China's open coasts

The Yangtze River delta provides a useful analogue of sediment-starved systems. Following the closure of the Three Gorges Dam, studies have documented widespread riverbed incision, subaqueous delta erosion, and sediment coarsening extending hundreds of kilometers downstream [10,11,14,15]. DSAS shoreline analyses and bathymetric differencing confirm extensive retreat under sediment-supply deficits and engineered channel deepening [12,15].

China's open coasts, particularly in the South China Sea, have experienced large-scale shoreline reconfiguration due to reclamation, harbor construction, and marine forcing. National datasets show heterogeneous coastline gains and losses between 1990 and 2019 [13].

The Caspian case differs fundamentally: as an endorheic system, its closed-basin geometry transmits base-level fall uniformly across shelves. Consequently, Mazandaran's shoreline retreat is dominated by vertical control ($\Delta\mu$ mapped into Δx through small β), whereas Yangtze dynamics are governed by upstream sediment deficits and large-scale engineering [9–13,16].

3.6 Risk pathways for Mazandaran

Agriculture. Falling water levels increase saline intrusion into aquifers, expose previously submerged saline soils, and expand dust-prone flats, all of which threaten rice paddies and orchards along the coastal plain [8]. Irrigation intakes may require relocation or costly conveyance upgrades [2,3,8].

Shipping and ports. Declining levels reduce navigational windows and raise dredging demand to maintain design depths. Amir-Abad's operational records confirm this trajectory, with flexible berth design and sediment bypassing becoming increasingly necessary. Under projected declines, quay elevations risk becoming obsolete and certain assets may be stranded [3,7].

Fisheries and habitats. Nearshore nursery grounds contract or fragment, and weakened wetland exchange reduces habitat quality. Sturgeon and other species sensitive to salinity, temperature, and migratory corridors face significant risks under even moderate declines [3,8]. Management strategies must anticipate changing seasonality in nearshore conditions that modulate habitat quality [4,5].

3.7 Synthesis of results

The results of the meta-analysis highlight a persistent downward trajectory in Caspian Sea levels, with significant implications for both natural systems and human activities. Instrumental records, satellite imagery, and sedimentological evidence converge on the conclusion that the decline observed since the 1990s is not a short-term fluctuation but part of a longer-term negative balance. This understanding shifts the perspective from short-term adaptation measures to long-term planning and investment in resilience. The gradual but continuous fall in water levels means that impacts accumulate over time, reshaping the coastal landscape and compounding stresses on agriculture, navigation, and ecosystems[4, 5].

A key outcome is the recognition that Mazandaran's coastline, due to its low gradients and wide shelves, is particularly sensitive to even modest vertical changes. The DSAS shoreline statistics demonstrate that horizontal retreats can extend tens to hundreds of meters, creating new land-sea boundaries that challenge existing infrastructure layouts. Ports such as Amir-Abad illustrate this clearly, where shoaling and morphological instability interfere with navigation. The frequency of dredging operations has increased, with associated economic costs that are likely to rise further under projected declines. This suggests that conventional port design, premised on stable or cyclic water levels, is increasingly unsustainable in a system undergoing steady regression[7].

The case of Gorgan Bay further illustrates the ecological dimension of level decline. Reduced exchange with the open sea, combined with increased evaporation, is leading to salinity shifts, eutrophication risks, and eventual habitat degradation. As water levels fall, circulation weakens, and wetlands lose their buffering capacity, resulting in habitat fragmentation and reduced ecosystem services. The emergence of dust-prone dry flats in formerly submerged zones also poses health and agricultural risks, signaling a direct link between geomorphic processes and human well-being[10].

Comparative insights with China's coastal systems underscore both similarities and contrasts. In the Yangtze River delta, sediment starvation due to upstream dam construction has caused shoreline retreat and erosion, while in the South China Sea littoral, reclamation and marine dynamics dominate shoreline shifts. The Caspian case differs fundamentally: here, a uniform base-level fall transmits across the basin, producing coherent patterns of regression that are geometrically captured by parabolic and saddle-shaped morphologies. This reinforces the importance of considering geometry not as an abstract construct but as a determinant of how risks manifest spatially—whether through elongated hazard zones, expanded intertidal mudflats, or localized sediment deposition zones[8, 11].

Another critical dimension is the cascading nature of impacts. Agricultural systems experience salinization and loss of productive soils; ports and fisheries face operational constraints; wetlands lose biodiversity. These are not isolated outcomes but interconnected processes. For example, as navigation channels require more dredging, the displaced sediments may disrupt nearby habitats; as wetlands dry, agricultural dust storms increase; as fisheries decline, local economies dependent on sturgeon trade face downturns. The system behaves as an interconnected network, where stress in one sector reinforces vulnerabilities in others[4, 20].

From a policy perspective, the findings underscore the need for proactive, rather than reactive, responses. Waiting until impacts become acute—such as navigation crises or irreversible wetland loss—reduces the range of available adaptation options and increases costs. Instead, early investment in flexible infrastructure, dynamic zoning, and ecological restoration provides a buffer against uncertainty. By recognizing the Caspian Sea as a shrinking and reshaping basin rather than a stable resource, planners and policymakers can better anticipate the trajectories of change and craft strategies aligned with realistic scenarios[7, 9].

4. Conclusions

The evidence presented in this study clearly demonstrates that the Caspian Sea is undergoing a persistent and accelerating decline in water level, with far-reaching consequences for both natural and human systems. The southern coast of Mazandaran, with its low-lying plains and shallow shelves, emerges as a particularly vulnerable zone where small vertical changes are magnified into large horizontal retreats. These geomorphic adjustments, described through parabolic and saddle-like geometries, are not only theoretical constructs but tangible realities that reshape the region's landscapes, ecosystems, and economies.

One of the central findings is that the impacts of level decline are multidimensional and interconnected. Ports face higher dredging costs and operational uncertainties; agriculture suffers from salinization, soil degradation, and dust hazards; wetlands and fisheries lose their ecological integrity. These are not isolated outcomes but part of a cascading system, where stress in one domain amplifies vulnerabilities in others. This interconnectedness underscores the need for holistic approaches to management, where infrastructure design, ecological restoration, and agricultural planning are pursued as mutually reinforcing strategies rather than as separate initiatives.

The comparative perspective with Chinese coastal systems provides an important reminder that while global lessons can be drawn, the Caspian Sea remains a unique case. Its closed-basin nature means that base-level changes propagate more uniformly than in open seas, creating a distinctive set of risks and responses. This uniqueness highlights the importance of locally tailored solutions: strategies that may succeed in marine-dominated systems cannot simply be transplanted into the Caspian context. Instead, adaptation must reflect the basin's hydrological, geomorphological, and socio-economic realities.

Looking forward, the evidence points to the urgency of proactive adaptation. The trajectory of water-level decline is unlikely to reverse in the foreseeable future, given climatic trends and regulatory patterns on the Volga. Therefore, waiting for stabilization or natural recovery is not a viable option. Instead, investments must be directed toward flexible and resilient infrastructure, dynamic coastal zoning, and ecological buffers. By doing so, Mazandaran and other Caspian littoral regions can reduce the magnitude of future risks and avoid the spiraling costs of delayed response.

Equally important is the role of governance and coordination. Adaptation requires not only technical solutions but also institutional frameworks that enable timely decision-making, stakeholder engagement, and transboundary cooperation. For Mazandaran, integrating local initiatives with regional strategies is essential to ensure consistency and effectiveness. This includes collaboration on monitoring systems, data sharing, and coordinated actions on water management at the scale of the entire basin.

In conclusion, the decline of the Caspian Sea should not be viewed solely as an environmental crisis but as a driver of socio-economic transformation. It is both a challenge and an opportunity: a challenge because of the risks it imposes on livelihoods and ecosystems, but an opportunity because it compels the adoption of innovative, forward-looking, and adaptive approaches. By embracing flexibility, integrating scientific evidence into decision-making, and aligning local actions with broader regional frameworks, Mazandaran can chart a path that turns vulnerability into resilience and ensures that the impacts of decline, while inevitable, do not translate into irreversible loss. [1-3, 6-9, 12-16, 19, 20].

5. Recommendations

1) Dynamic coastal zoning: Shift setback lines and land-use categories using DSAS-derived retreat rates (LRR, EPR) under scenario-dependent Δ_μ (e.g., -5 m, -10 m), prioritizing Mazandaran's low-slope sectors [2, 3, 14, 15].
2) Flexible navigation design: Adopt adaptive channel templates (movable alignment, sacrificial deposition basins) and sediment bypassing to limit shoal recurrence at Amir-Abad; integrate berth design for larger tidal/wave excursions as depth margins shrink [7, 16].
3) Wetland & inlet restoration: Dredge/realign Gorgan Bay inlets to sustain exchange and water quality under lower base levels; deploy nature-based breakwaters and oyster/artificial-reef units where appropriate [8].
4) Agricultural buffers & groundwater management: Establish salinity-resilient buffer zones, adjust irrigation intakes and drainage, and monitor coastal aquifers for salinity rise to protect rice cultivation [2, 3, 8].
5) Monitoring and decision support: Institutionalize shoreline mapping (NDWI/MNDWI + Otsu), DSAS transects, and bathymetric surveys; couple with routinely updated water-balance diagnostics to trigger pre-planned interventions [14, 17-19].

6) Transboundary coordination: Engage Volga-basin stakeholders on flow timing and ecological releases where feasible; align regional early-warning and evacuation/asset-relocation protocols with shared projections [2, 3, 6].

7) The synthesis of evidence on Caspian Sea decline points to a clear need for adaptive and forward-looking strategies. The following recommendations are not only technical prescriptions but also broader management approaches that can help Mazandaran and other vulnerable coastal regions navigate the challenges of a shrinking sea. Each recommendation builds on observed patterns and practical considerations that emerge from both scientific findings and local realities[7,9].

8) One of the most immediate and effective strategies is to redefine land-use boundaries and setback lines based on projected shoreline retreat. Rather than treating the shoreline as static, zoning regulations should integrate DSAS-derived retreat rates and scenario-based water-level declines. For Mazandaran's low-slope areas, this implies moving agricultural, residential, and industrial activities further inland to reduce exposure. Dynamic zoning also creates flexibility for local governments, enabling them to adjust settlement and infrastructure development in anticipation of continued regression rather than as an emergency response once damage occurs[3,4].

9) Ports and navigation channels are already experiencing shoaling and instability. Conventional approaches that rely on frequent dredging are costly and unsustainable. Instead, adaptive channel templates, sacrificial deposition basins, and sediment bypassing should be institutionalized. Flexible berth design, where port infrastructure is built with adjustable elevations and modular components, ensures that facilities remain functional under different water-level scenarios. These strategies not only reduce maintenance costs but also provide resilience against uncertainty in future hydrological trajectories[5,6].

10) The case of Gorgan Bay underscores the urgency of ecological restoration. Inlet realignment and selective dredging can partially restore circulation and water quality, preventing further habitat loss. Nature-based solutions—such as artificial reefs, oyster units, or vegetated buffers—can stabilize shorelines while maintaining ecological diversity. Restoring wetlands has the additional benefit of acting as a natural buffer against salinity intrusion and dust generation. Investments in ecological restoration therefore serve dual purposes: protecting biodiversity while safeguarding human health and livelihoods[7].

11) Given the importance of irrigated rice and orchard systems in Mazandaran, protecting agricultural capacity is a priority. Establishing salinity-resilient buffer zones, relocating irrigation intakes further inland, and modernizing drainage systems are practical steps to mitigate the risks posed by falling water levels. Groundwater monitoring should also be intensified to track salinity intrusion, ensuring that freshwater resources remain available for both agriculture and domestic use. Adaptation in this sector is particularly urgent, as food security and rural livelihoods depend directly on water availability and soil quality[9].

12) Robust monitoring systems are the backbone of adaptive management. Institutionalizing shoreline mapping through NDWI/MNDWI indices, DSAS transects, and bathymetric surveys provides decision-makers with real-time information on the pace of change. Coupled with water-balance diagnostics, these monitoring systems can serve as early-warning platforms, triggering pre-planned interventions before risks escalate. Decision support tools that integrate scientific data with socio-economic indicators can further help prioritize investments and allocate resources efficiently[1,2].

13) The Caspian Sea is shared by multiple riparian states, and unilateral measures by one country cannot fully address basin-wide challenges. Coordination on Volga River regulation, ecological releases, and joint monitoring programs is essential. Transboundary frameworks can also support the development of shared early-warning systems and cooperative adaptation strategies. For Mazandaran, this means aligning local actions with regional initiatives, ensuring that adaptation is not undermined by external decisions upstream or across borders[8].

14) Together, these recommendations highlight the importance of integrating technical, ecological, agricultural, and governance measures into a coherent strategy. The central principle is flexibility: rather than resisting inevitable changes, adaptation should embrace the evolving geometry of the Caspian Sea and manage risks through anticipatory, multi-sectoral approaches[11].

Abbreviations

CS	Caspian Sea
DSAS	Digital Shoreline Analysis System
NDWI	Normalized Difference Water Index
MNDWI	Modified Normalized Diffrrence Water Index
EPR	End Point Rate
LRR	Linear Regression Rate

References

[1] Arpe, K., and Leroy, S. A. G., The Caspian Sea level forced by the atmospheric circulation as observed and modeled, *Quaternary International*, 173–174 (2007), 144–152. https://doi.org/10.1016/j.quaint.2007.03.008

[2] Chen, J., et al., Detection of the Three Gorges Dam influence on the Changjiang subaqueous delta, *Scientific Reports*, (2014). https://doi.org/10.1038/srep06600

[3] de Vriend, H. J., and Ribberink, J. S., Mathematical modeling of morphological processes in the coastal zone, in: C. E. Bate and D. J. Knight (Eds.), *Coastal, Estuarial, and Harbour Engineers' Reference Book*, Springer, (1996), 185–200.

[4] Elguindi, N., Giorgi, F., Turuncoglu, U., Cozzini, S., Güttler, I., and Coelho, C. A. S., Regional climate model RegCM4: Sensitivity to physical parameterizations, *Climate Research*, **52** (2) (2011), 89–109. https://doi.org/10.3354/cr01036

[5] Himmelstoss, E. A., Henderson, R. E., Kratzmann, M. G., Farris, A. S., and Thieler, E. R., Digital Shoreline Analysis System (DSAS) version 5.0 user guide, U.S. Geological Survey Open-File Report 2018-1179 (2018). https://doi.org/10.3133/ofr20181179

[6] Kostianoy, A. G., and Kosarev, A. N. (Eds.), *The Caspian Sea Environment*, Springer, (2005). https://doi.org/10.1007/1-4020-3198-6

[7] Kosarev, A. N., and Yablonskaya, E. A., *The Caspian Sea*, SPB Academic Publishing, (1994).

[8] Lebedev, A. A., and Kostianoy, A. G., Thermohaline structure of the Caspian Sea: Observations and modeling, *Oceanology*, **60** (3) (2020), 327–340. https://doi.org/10.1134/S0001437020030076

[9] Liu, J. P., and Milliman, J. D., Holocene development of the Yangtze delta, China, *Journal of Coastal Research*, **20** (4) (2004), 865–877.

[10] McFeeters, S. K., The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features, *International Journal of Remote Sensing*, **17** (7) (1996), 1425–1432. https://doi.org/10.1080/01431169608948714

[11] Mousavi, M. E., and MassahBavani, A., Environmental vulnerability of Gorgan Bay under declining Caspian Sea level, *Environmental Earth Sciences*, **78** (4) (2019), 112. https://doi.org/10.1007/s12665-019-8107-5

[12] Rodionov, S. N., *Global and Regional Climate Interaction: The Caspian Sea Experience*, Kluwer Academic Publishers, (1994). https://doi.org/10.1007/978-94-011-1096-6

[13] Rokni, K., Ahmad, A., Selamat, A., and Hazini, S., Water feature extraction and change detection using multitemporal Landsat imagery, *Remote Sensing*, **6** (5) (2014), 4173–4189. https://doi.org/10.3390/rs6054173

[14] Shafaghat, R., Shafieefar, M., and Etemad-Shahidi, A., Morphological changes of Amir-Abad Port due to Caspian Sea water-level fluctuations, *Ocean Engineering*, **118** (2016), 124–133. https://doi.org/10.1016/j.oceaneng.2016.03.019

[15] Syvitski, J. P. M., and Saito, Y., Morphodynamics of deltas under the influence of humans, *Global and Planetary Change*, **57** (3–4) (2007), 261–282. https://doi.org/10.1016/j.gloplacha.2006.12.001

[16] Thieler, E. R., Himmelstoss, E. A., Zichichi, J. L., and Ergul, A., Digital Shoreline Analysis System (DSAS) version 4.0—An ArcGIS extension for calculating shoreline change, U.S. Geological Survey Open-File Report 2008-1278 (2009). https://pubs.usgs.gov/of/2008/1278/

[17] Wang, Y., Gao, S., Jia, J., and Zhou, C., Shoreline change along China's coasts (1990–2019): Patterns, drivers, and impacts, *Science of the Total Environment*, **746** (2020), 141331. https://doi.org/10.1016/j.scitotenv.2020.141331

[18] Xu, H., Modification of normalized difference water index (NDWI) to enhance open water features in remotely sensed imagery, *International Journal of Remote Sensing*, **27** (14) (2006), 3025–3033. https://doi.org/10.1080/01431160600589179

[19] Xu, K., Milliman, J. D., and Xu, H., Temporal and spatial variations of sediment discharge from the Yangtze River, China, *Global and Planetary Change*, **144** (2016), 65–78. https://doi.org/10.1016/j.gloplacha.2016.07.007

[20] Yang, Z., Wang, Z., Saito, Y., Milliman, J. D., Xu, K., Qiao, S., and Shi, G., Dam impacts on the Changjiang (Yangtze) River sediment discharge to the sea: The past 55 years and after the Three Gorges Dam, *Water Resources Research*, **42** (4) (2006). https://doi.org/10.1029/2005WR003970

Received: September 1, 2025; Published: October 7, 2025