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Coupled SWAN-ROMS Numerical Modeling of Nearshore Hydrodynamics and Rip Current Formation Along the Southern Caspian Sea

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ABSTRACT

Understanding and modeling coastal currents are crucial for assessing coastal hazards, mitigating human risks, and minimizing structural damage. The southern Caspian Sea, with its diverse geomorphology, variable climatic conditions, and dynamic coastal processes, serves as a key region for the development of various coastal currents. Statistical analyses of drowning incidents in coastal cities indicate that nearshore currents, particularly rip currents, are among the primary contributors to coastal hazards. These currents, which include longshore currents, rip currents, and undertow, are primarily generated by wave breaking in shallow coastal zones. This study aims to identify high-risk coastal areas where specific wave conditions contribute to the formation of strong rip currents, posing significant threats to swimmers and coastal safety. To achieve this, a coupled numerical modeling framework integrating the SWAN (Simulating WAves Nearshore) and ROMS (Regional Ocean Modeling System) models was employed to simulate nearshore current dynamics in four key coastal regions: Nowshahr, Chaboksar, Anzali, and Talesh, located along the southern Caspian Sea. Wind field data were obtained from the ERA5 reanalysis dataset, while boundary conditions were derived from SWAN simulations performed on a mesoscale grid covering the entire Caspian Sea. The results indicate that under prevailing hydrodynamic conditions, longshore currents dominate across all study sites, with rip currents forming in specific localized areas. The orientation of longshore currents is primarily controlled by wind-driven wave propagation patterns, exhibiting an eastward direction in Nowshahr and Chaboksar, while flowing westward in Anzali and Gisum Forest coastal zones. Furthermore, the spatial variability in coastal bathymetry, both alongshore and cross-shore, significantly influences the extent and intensity of these currents, as observed through drifter trajectories. The maximum recorded current velocities range between 0.7 and 1.1 m/s, highlighting the potential hazard posed by these currents in nearshore environments. These findings provide a scientific basis for improving coastal safety measures, informing hazard mitigation strategies, and enhancing numerical modeling frameworks for rip current prediction in the Caspian Sea region.

1. Introduction

The study of hydrodynamic processes along the southern Caspian Sea coastline has long been of scientific and practical significance due to its direct implications for coastal erosion, sediment transport, navigation safety, and the sustainability of coastal ecosystems. In particular, wave-driven nearshore circulation plays a fundamental role in shaping shoreline morphology and influencing the occurrence of hazardous currents, such as rip currents, which pose substantial risks to swimmers and coastal infrastructure. Despite its critical importance, research on nearshore hydrodynamics in the Caspian Sea remains relatively underdeveloped compared to other enclosed or semi-enclosed basins, such as the Black Sea or the Mediterranean.

For many years, hydrodynamic investigations in the region have predominantly focused on port environments and harbor hydrodynamics, with limited emphasis on open-coast nearshore processes. The Integrated Study of Iranian Seas and Waves (ISWM) (PMO, 2009) provided an extensive analysis of wave conditions in the Caspian Sea, but it largely neglected nearshore current dynamics. In general, past studies have either been regionally constrained or have focused primarily on large-scale circulation and wave characteristics, rather than on the finer-scale nearshore current systems that govern sediment transport and hydrodynamic hazards.

Recent years have seen a growing interest in nearshore hydrodynamics, with several field monitoring campaigns and numerical modeling efforts conducted by research institutions and governmental agencies. Among these, the rip current investigations along the southern Caspian Sea coastline (Akbarpour Jannat et al., 2012, Akbarpour Jannat et al., 2014, Lahijani, H.A.K., 2006, Terziev at al. 2005, Lahijani, H.A.K., 2006, Noraniyan Isfahani, M., 2017, Noraniyan Isfahani, M., 2018) and the Coastal Monitoring Program for the northern shores of Iran (PMO, 2015) have contributed valuable observational data. However, while these studies have provided important insights into nearshore circulation, they remain limited in spatial and temporal coverage and have not fully incorporated high-resolution numerical models capable of capturing the complex interactions between waves and currents.

A notable effort in this direction was the study by Akbarpour Jannat et al., 2012, which represented the first attempt to deploy coastal drifters for rip current tracking in the region. Their work, which combined in situ measurements of current velocity profiles, wave characteristics, and seabed topography with Boussinesq-based numerical modeling (BOSS2D), successfully identified multiple rip current channels extending offshore to depths of approximately 5 meters. However, the reliance on Boussinesq models, while accurate for nearshore wave-current interactions, posed computational challenges, limiting their feasibility for large-scale applications.

Similarly, Akbarpour Jannat et al, 2014 applied a coupled ROMS-SWAN model to investigate nearshore circulation along the southwestern Caspian coastline, incorporating wave spectra derived from ECMWF ERA-Interim wind forcing. Their nested grid simulations provided high-resolution insights into the structure of nearshore currents, confirming the presence of eastward-directed flows and rip current cells along the Kiashahr–Bandar Anzali coastal stretch. These findings were consistent with observational datasets from the Northern Iran Coastal Monitoring Program (PMO, 2015), reinforcing the role of wind-driven circulation in shaping the hydrodynamics of the region.

Beyond numerical modeling efforts, field-based monitoring programs have further contributed to our understanding of nearshore hydrodynamics. A series of observational campaigns along the Nowshahr, Roudsar, Anzali, and Astara coastlines involved current velocity measurements at multiple depths (5 m, 10 m, and 15 m), which were subsequently used to validate numerical models. Comparative analyses between measured current patterns, wind climatology, and numerical simulations confirmed a strong correlation between coastal wind forcing and nearshore circulation dynamics. The prevailing westerly winds were identified as the dominant driver of eastward coastal currents, while statistical assessments indicated that nearshore currents exhibited velocities below 0.1 m/s in 50% of cases, with longshore currents rarely exceeding 0.5 m/s.

Despite these advancements, significant knowledge gaps remain in the understanding of wave-current interactions, particularly in rip current generation, alongshore current variability, and nearshore sediment transport processes. Given the localized nature of rip currents and their dependence on fine-scale bathymetric features, achieving a higher-resolution numerical representation necessitates the use of nested and structured grid systems. However, while unstructured grid models offer enhanced resolution, their computational cost remains prohibitive, limiting their applicability for long-term simulations. To overcome these challenges, this study employs a nested structured grid system, providing an optimized balance between computational efficiency and spatial resolution, representing a novel application for the region.

This study aims to advance the understanding of nearshore hydrodynamics in the southern Caspian Sea by utilizing a coupled SWAN-ROMS modeling framework to simulate nearshore circulation under various wave forcing conditions. By focusing on key transition zones along the Nowshahr, Chaboksar, Anzali, and Talesh coastlines, this research provides a comprehensive assessment of short-term hydrodynamic variations, emphasizing the spatial and temporal evolution of wave-driven currents, rip current formation, and coastal circulation patterns.

The remainder of this paper is structured as follows: Section 2 provides a detailed description of the numerical modeling approach, including grid configurations, boundary conditions, and external forcing mechanisms. Section 3 presents a comparative analysis of the modeled nearshore circulation with observational drifter buoy data, offering validation and insight into model performance. Section 4 discusses the key hydrodynamic processes governing model outputs and field observations, with a focus on wave-driven coastal dynamics and their implications for nearshore circulation patterns. Finally, Section 5 synthesizes the key findings of this study and outlines recommendations for future research, emphasizing the need for improved coastal hazard mitigation strategies, refinements in numerical modeling techniques, and the development of an observational network for continuous monitoring. This research provides critical insights into the spatial variability of wave-induced currents, highlighting their dependence on coastal morphology, bathymetry, and wind forcing. The findings contribute to improved hazard assessment, coastal risk management, and numerical modeling accuracy, offering a foundation for future studies in the Caspian Sea and other semi-enclosed basins.

2. Numerical Model Configuration

2.1 Computational Grid

Accurate numerical modeling of nearshore hydrodynamics requires a well-defined computational grid that captures the complex interactions between wave forcing, coastal topography, and hydrodynamic circulation. Given the socioeconomic and environmental significance of the southern Caspian Sea coastline, four key study sites were selected to ensure comprehensive spatial coverage and to represent diverse hydrodynamic conditions. These sites include Nowshahr (Hosseini Beach), Chaboksar (Serolat), Anzali (Eastern Shores), and Talesh (Gisoom), each of which experiences distinct nearshore processes, including wave-driven currents, rip currents, and alongshore transport dynamics.

The computational grid system was developed using high-resolution terrain and bathymetric datasets to ensure accurate representation of both land topography and underwater morphology. Land elevation data were obtained from the 30-meter resolution Shuttle Radar Topography Mission (SRTM) dataset, while bathymetric data were sourced from the half-degree resolution General Bathymetric Chart of the Oceans (GEBCO). To improve the accuracy of nearshore depth variations, these datasets were further refined using local hydrographic surveys, ensuring precise bathymetric representation within the wave-breaking and sediment transport zones.

A multi-scale nested grid approach was implemented to achieve an optimal balance between computational efficiency and spatial resolution. To accurately capture the hydrodynamic processes across different spatial scales, two primary grid systems were developed. The first is a large-scale computational grid covering the entire Caspian Sea, which serves as the offshore boundary condition provider for localized simulations. This ensures that energy transfer from deep water to nearshore regions is accurately represented, maintaining physical consistency between different spatial domains. The second consists of high-resolution nested grids tailored for each study site, specifically designed to resolve small-scale nearshore circulation features such as rip currents, wave-induced setup, and alongshore drift. These localized grids enable precise modeling of wave-driven current dynamics and enhance the accuracy of nearshore hydrodynamic predictions.

The Caspian Sea-wide grid was structured as a curvilinear and orthogonal grid, with a horizontal resolution of 2 km × 2 km, covering a total of 604 × 346 computational cells (Figure 1). This grid serves as the offshore forcing domain, allowing energy transfer from deep water to nearshore regions while maintaining physical consistency between different spatial scales.

For localized simulations, four high-resolution nested grids were developed, corresponding to the selected coastal regions. These grids, referred to as N1 (Nowshahr), N2 (Chaboksar), N3 (Anzali), and N4 (Talesh), were designed to ensure numerical stability and accurate representation of coastal hydrodynamics. Each nested grid was developed with a 20 m × 20 m horizontal resolution, ensuring that grid axes remained parallel and perpendicular to the coastline to maintain depth contour consistency and minimize interpolation errors. The key specifications of these nested grids, which are identical for both the SWAN (wave model) and ROMS (hydrodynamic model), are summarized in Table 1.

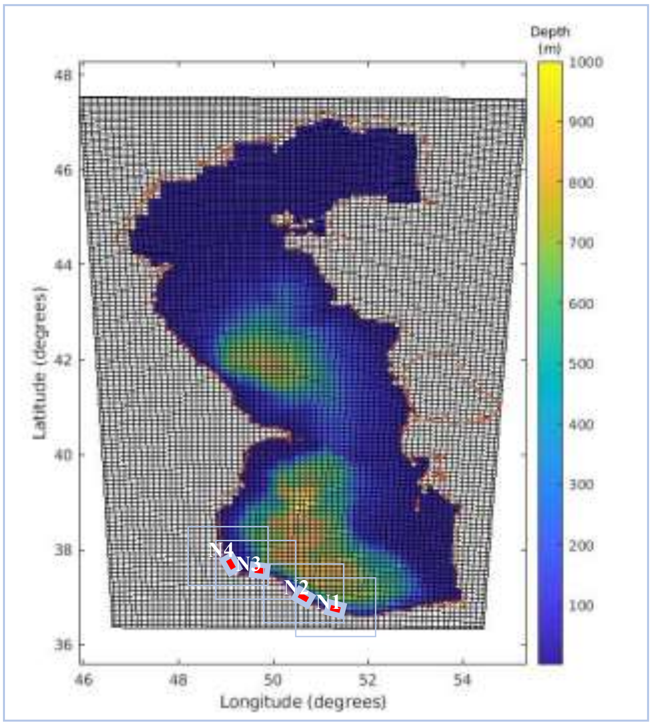

Figure 1 - Computational grid of the wave model in the Caspian Sea with a horizontal resolution of 2 km × 2 km, depicted with a 5:1 cell ratio. The geographical locations of the nested computational grids along the coasts of Nowshahr (N1), Chaboksar (N2), Anzali (N3), and Talesh (N4) are indicated.

Table 1. General specifications of the computational grids for the models in the entire Caspian Sea and the sites of Nowshahr, Chaboksar, Anzali, and Talesh.

Area	*Number of Cells*		*Rotation Angle Relative to True East* (°)	*Horizontal Resolution* (m)	*Maximum and Minimum Depths* (m)	*Wave Breaking Depth with a 5-year Return Period* (m)*
	Perpendicular to Shoreline	*Along Shoreline*				
Caspian Sea	604	346	-	2000	2 1005	--
Nowshahr	178	498	14.6	20	0.5 27	7.22
Chaboksar	248	778	32.6	20	0.5 24	6.7
Anzali	148	368	7	20	0.5 22	7.05
Talesh	118	498	60	20	0.5 ١٣	5.89

* Derived from the monitoring studies of the northern coastal areas of the country, the report on the approximate determination of the wave-breaking zone along the coastline.

2.1.1 Grid Orientation and Spatial Resolution

To optimize computational accuracy, each nested grid was carefully oriented based on local coastline alignment and prevailing wave energy pathways, ensuring a realistic representation of nearshore hydrodynamics. The Nowshahr (N1) grid is rotated 14.6° counterclockwise from true east, consisting of 178 × 498 cells (Figure 2). This orientation aligns with the local wave approach angle, effectively minimizing errors in wave refraction calculations and improving the accuracy of nearshore current simulations. The Chaboksar (N2) grid, with a 32.6° counterclockwise rotation, consists of 248 × 778 cells (Figure 3). Given the steeper bathymetry in this region, the higher grid resolution enables the precise detection of rip current channels and wave-driven circulation patterns, ensuring a more refined simulation of nearshore processes. The Anzali (N3) grid is rotated 7° counterclockwise, comprising 148 × 368 cells (Figure 4). As this region is characterized by a gently sloping seabed, this grid configuration is particularly effective in capturing the broader nearshore circulation patterns typically observed in wave-dominated environments. Lastly, the Talesh (N4) grid is rotated 60°

counterclockwise, consisting of 118 × 498 cells (Figure 5). This significant rotation accounts for coastal curvature and prevailing current directions, which play a crucial role in shaping wave-driven flow structures and sediment transport in this region. These carefully designed grid orientations ensure that the numerical model accurately captures the complex hydrodynamic interactions along the southern Caspian Sea coastline, enhancing the reliability of simulated nearshore circulation and sediment transport patterns.

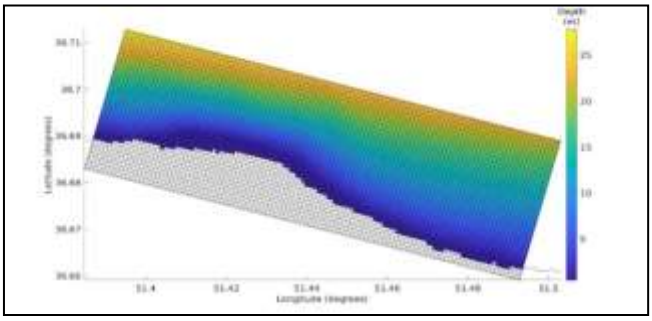

Figure 2 - Computational grid of the model along the Nowshahr coast with a horizontal resolution of 20 meters, depicted with a 4:1 cell ratio.

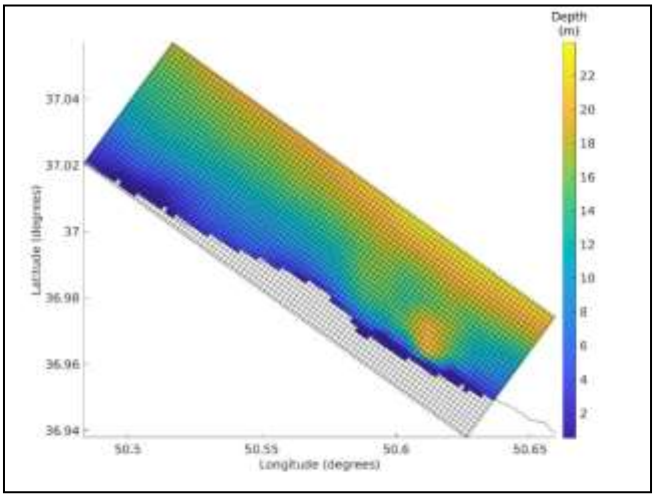

Figure 3 - Computational grid of the model along the Chaboksar coast with a horizontal resolution of 20 meters, depicted with an 8:1 cell ratio.

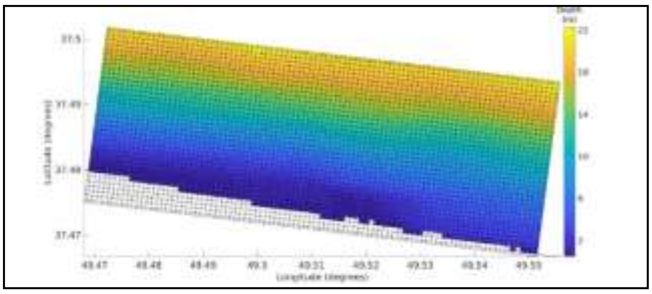

Figure 4 - Computational grid of the model along the Anzali coast with a horizontal resolution of 20 meters, depicted with a 4:1 cell ratio.

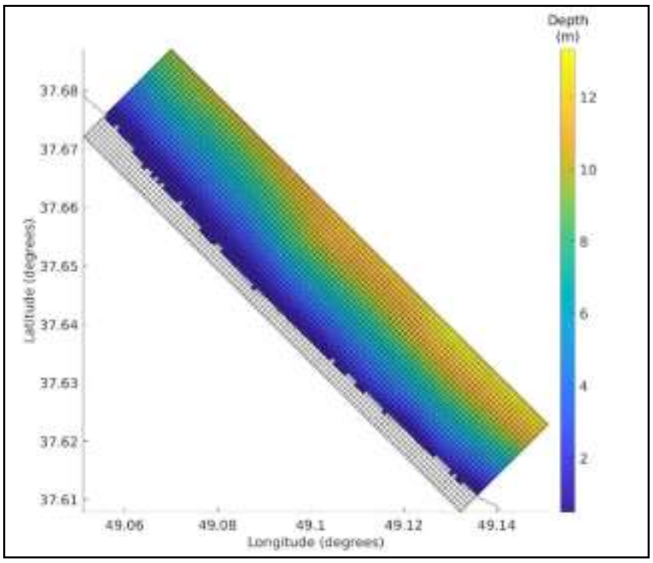

Figure 5 - Computational grid of the model along the Talesh coast with a horizontal resolution of 20 meters, depicted with a 4:1 cell ratio.

2.1.2 Advantages of the Nested Grid Approach

The use of nested grids provides several key advantages for accurately simulating nearshore hydrodynamics, particularly in complex coastal environments such as the southern Caspian Sea. One of the primary benefits is the improved resolution in coastal zones, where the fine-grid resolution (20 m × 20 m) enables the precise simulation of nearshore circulation features, including rip currents, longshore drift, and wave-induced set-up. This high resolution ensures that small-scale hydrodynamic processes critical for coastal hazard assessment and sediment transport modeling are accurately represented.

Another significant advantage is the seamless offshore–nearshore coupling, facilitated by the large-scale Caspian Sea grid, which provides stable boundary conditions for localized high-resolution simulations. This setup ensures a smooth transition of hydrodynamic forcing between deep water and shallow nearshore zones, preserving physical consistency across different spatial scales.

Moreover, the structured nested grid approach offers a computationally efficient alternative to unstructured grid models, which, despite their flexibility, impose significant computational costs. The nested framework maintains high numerical accuracy while significantly reducing computational demand, making large-scale, high-resolution simulations more feasible.

Additionally, the optimized grid orientation plays a crucial role in maintaining numerical stability. Aligning grid axes parallel to depth contours minimizes numerical diffusion, enhances bathymetric consistency, and ensures that modeled currents and wave transformations remain physically realistic. This approach prevents artificial distortions in simulated wave and current patterns, improving model reliability. Finally, the nested grid framework is highly adaptable for future studies, allowing for easy refinement and expansion. This flexibility makes it particularly suitable for long-term hydrodynamic modeling, enabling researchers to incorporate higher-resolution bathymetric data, refine grid domains, and extend simulations to include sediment transport, climate change impacts, and extreme event forecasting. Given these advantages, the nested grid approach represents a robust and efficient methodology for advancing nearshore hydrodynamic research in the Caspian Sea and other semi-enclosed basins.

2.1.3 Computational Stability and Accuracy Considerations

To ensure numerical stability and accuracy, the grid system was meticulously designed with several key considerations. Bathymetric smoothing was applied by maintaining the slope parameter (r-factor) below 0.2 in the ROMS grids, which helped prevent numerical instabilities arising from abrupt depth variations and steep gradients. This adjustment ensures a more stable simulation environment, reducing errors in the computation of pressure gradients and bottom stress forces.

Additionally, time-step optimization was implemented using a two-level nested time-stepping approach, which allowed for efficient temporal resolution while ensuring that the Courant-Friedrichs-Lewy (CFL) condition was satisfied across all grid scales. This approach was critical in maintaining numerical stability, particularly in areas with high velocity gradients and rapid wave transformations.

Furthermore, wave-current coupling consistency was ensured by fully integrating the SWAN (wave model) and ROMS (hydrodynamic model), allowing synchronized exchanges of wave radiation stresses, bottom shear stress, and turbulent kinetic energy (TKE) between grids. This coupling mechanism was essential for accurately capturing wave-induced circulation patterns, particularly in regions influenced by strong rip currents, longshore transport, and offshore-directed return flows. By incorporating these stability measures, the computational framework effectively enhances the reliability, efficiency, and physical realism of nearshore hydrodynamic simulations, ensuring that the model remains robust under various wave and current conditions.

2.1.4 Expected Contributions of the High-Resolution Grid System

The high-resolution computational grid system developed in this study represents a significant advancement in nearshore hydrodynamic modeling for the Caspian Sea, providing a more refined understanding of wave-driven circulation patterns and sediment transport processes. By employing a multi-scale, nested framework, this study achieves a higher level of precision in simulating rip currents, nearshore circulation, and wave-induced flow structures, which are crucial for hazard prediction, beach safety, and coastal management. The ability to accurately resolve rip current behavior enhances coastal risk assessments, aiding in the development of mitigation strategies to prevent swimmer hazards and structural damage.

Beyond hydrodynamic hazard assessment, the model significantly contributes to the understanding of wave-driven sediment transport dynamics, which is essential for evaluating coastal erosion trends and designing effective engineering solutions. The integration of high-resolution bathymetric data with advanced wave-current interaction modeling allows for a more realistic representation of sediment transport pathways, supporting sustainable coastal development and shoreline protection efforts.

Moreover, the flexibility and computational efficiency of the nested grid approach ensure that this methodology can be adapted and expanded for future hydrodynamic, ecological, and climate impact studies in the region. The model can be further refined to investigate long-term shoreline evolution, storm surge impacts, and climate-driven coastal changes, making it a valuable tool for regional coastal planning and environmental conservation. Through this comprehensive modeling approach, the study provides a strong foundation for future research in semi-enclosed basins such as the Caspian Sea, advancing the field of coastal hydrodynamics and numerical ocean modeling.

The structured multi-scale grid approach adopted in this study ensures a high degree of spatial accuracy, enabling the detailed assessment of hydrodynamic processes along the southern Caspian Sea coastline. The integration of high-resolution SRTM and GEBCO bathymetric datasets, local hydrographic surveys, and advanced grid nesting techniques allows for state-of-the-art numerical modeling of wave-current interactions. These methodological advancements provide a solid foundation for future nearshore hydrodynamic research in semi-enclosed basins such as the Caspian Sea.

2.2 Model Configuration

2.2.1 Flow Model

To increase the stability of the model in each grid, bathymetric data were corrected such that, according to the Backman-Hydogle cell slope criterion [19], the depth ratio between any two adjacent cells does not exceed 0.25. In the vertical direction, each grid is composed of 5 depth layers (sigma) with uniform vertical distribution. The distribution of the grid cell thickness for bathymetry was determined by selecting vertical stretching functions (Uchiyama et al., 2010) equal to 4 and a transfer function (Shchepetkin et al., 2005) equal to 2. In this way, the Haney criterion [21], which defines the maximum hydrostatic compatibility of vertical stratification, was obtained as less than 5.6. Meeting these criterion values ensures the model's stability.

Considering the longitudinal characteristics of the grids and the number of layers created in the local model, the coupled wave-current model was executed for a one-month period in July 2018, using a Baroclinic time step of 300 and 10 fast Barotropic time steps in each of the grids. The model was implemented using third-order upstream numerical schemes for horizontal propagation and fourth-order for vertical propagation. The Generalized Length Scale (GLS) turbulence model, a generalized two-equation model, was applied for turbulence. The ROMS ocean model supports three types of boundary conditions: closed, open, and periodic for the horizontal boundaries. This model solves the dynamics of the bottom boundary layer processes based on the drag method, which includes linear friction, second-order friction with a constant coefficient, and second-order friction with a logarithmic coefficient.

2.2 Model Configuration

2.2.1 Flow Model

To ensure numerical stability and accuracy, bathymetric data were carefully processed and corrected in each computational grid. This correction was performed in accordance with the Backman-Hydogle cell slope criterion [19], which specifies that the depth ratio between any two adjacent cells should not exceed 0.25. Adhering to this criterion helps prevent numerical instabilities associated with abrupt bathymetric changes, which could otherwise introduce artificial pressure gradients and computational errors.

The vertical discretization of the model was structured using a sigma-coordinate system, where each grid consists of five uniformly distributed vertical layers. The grid cell thickness was determined by selecting vertical stretching functions (Uchiyama et al., 2010) with a parameter value of 4, along with a transfer function (Shchepetkin et al., 2005) value of 2. These parameters were chosen to optimize the vertical resolution, ensuring accurate representation of thermocline structure, bottom boundary layer dynamics, and internal wave propagation. Additionally, the Haney criterion (Haney, R. L., 1991), which defines the maximum hydrostatic compatibility of vertical stratification, was maintained at a value of less than 5.6, further reinforcing model stability by minimizing numerical errors in vertical pressure gradient calculations.

Given the longitudinal characteristics of the grids and the layering structure within the local model, the coupled wave-current simulations were conducted for a one-month period in July 2018. To maintain computational efficiency and accuracy, a baroclinic time step of 300 seconds was used, with 10 fast barotropic time steps executed within each baroclinic step across all grids. The choice of time-stepping strategy ensures that the model accurately captures fast-moving surface gravity waves while maintaining numerical stability for slower baroclinic motions.

For spatial discretization, the model employed high-order numerical schemes to improve accuracy and reduce numerical dissipation. A third-order upstream scheme was applied for horizontal propagation, ensuring precise resolution of advective processes, while a fourth-order scheme was used for vertical propagation, minimizing truncation errors in vertical mixing and stratification processes. To model turbulence closure, the Generalized Length Scale (GLS) turbulence model was implemented. This generalized two-equation approach accounts for mixing length variations, improving the simulation of turbulent kinetic energy (TKE) dissipation rates and subgrid-scale mixing effects, which are crucial for accurate representation of coastal hydrodynamics.

The Regional Ocean Modeling System (ROMS), utilized in this study, supports three types of horizontal boundary conditions: closed, open, and periodic. The appropriate boundary condition type was selected based on the dynamical requirements of each computational domain, ensuring a seamless interaction between offshore forcing and nearshore circulation. Additionally, the bottom boundary layer dynamics were resolved using drag-based formulations, which account for bottom frictional processes critical for wave-current interactions, sediment transport, and bottom stress calculations. Three different formulations were considered for bottom friction: linear friction, second-order friction with a constant coefficient, and second-order friction with a logarithmic coefficient. These formulations help to parameterize seabed roughness effects, improving the accuracy of near-bottom velocity predictions and shear stress computations, which are essential for modeling rip current formation and sediment resuspension.

By incorporating these advanced numerical schemes, turbulence closures, and bottom boundary formulations, the flow model configuration in this study ensures a high degree of accuracy, stability, and physical realism. These methodological refinements contribute to an improved representation of nearshore circulation processes, making the model highly suitable for coastal hazard assessment, sediment transport studies, and future hydrodynamic forecasting applications in the southern Caspian Sea.

2.2.2 Wave Model

The wave modeling component of this study was conducted using a combination of high-resolution wind forcing datasets derived from the ECMWF-ERA Interim global model, which provides spatial resolution of 0.125° and a temporal resolution of 3 hours. This dataset offers reliable global atmospheric reanalysis and forecasting products, ensuring an accurate representation of wind forcing as a key driver of wave generation and transformation in the Caspian Sea.

To simulate wave growth, energy dissipation, and bottom interactions, well-established parameterizations were applied within the spectral wave model. The KOMEN formulation (Akbarpour Jannat et al, 2012) was used to model wave energy growth due to wind input, capturing the influence of wind stress on wave amplitude and spectral evolution. Additionally, KOMEN's approach was employed to parameterize wave energy dissipation due to whitecapping, a critical process affecting wave energy decay and spectral peak attenuation in coastal environments.

For the representation of bottom friction effects, the MADSEN formulation (Akbarpour Jannat et al, 2014) was implemented. This method provides an improved estimation of wave energy dissipation over the continental shelf and shallow-water regions, where bottom roughness and frictional drag significantly influence wave transformation, energy dissipation, and sediment transport dynamics. By integrating these well-established physical formulations, the wave model effectively captures the key processes governing wave propagation, dissipation, and bottom interactions, ensuring a high level of accuracy and physical realism in nearshore wave dynamics simulations.

This comprehensive wave modeling approach provides a robust foundation for understanding wave-induced hydrodynamics, which is essential for coastal hazard assessment, rip current modeling, and shoreline stability studies in the southern Caspian Sea.

2.3 Forcing Mechanisms

The Caspian Sea, as the world's largest enclosed inland body of water, exhibits unique hydrodynamic characteristics, particularly in terms of forcing mechanisms that drive its wave and current systems. Unlike open ocean environments, the Caspian Sea lacks significant tidal fluctuations, resulting in a hydrodynamic regime primarily governed by wind forcing and atmospheric interactions. Due to its vast surface area of approximately 371,000 square kilometers, the sea is highly responsive to synoptic-scale wind patterns, which play a dominant role in wave generation, current formation, and water mass movement.

In coastal waters, the primary mechanism driving nearshore circulation is the interaction between incoming waves and the swash zone. As waves propagate toward the shoreline and break in the surf zone, they generate wave-driven currents, which contribute to longshore transport, rip current formation, and cross-shore exchange processes. The momentum transfer associated with wave breaking is a key driver of coastal circulation, leading to the development of rip channels, wave setup, and alongshore drift.

Additionally, wind-driven currents outside the breaking zone significantly influence coastal circulation, particularly through their role in the undertow current cycle. In this process, wind stress over the water surface generates large-scale surface currents, which, upon reaching the nearshore zone, interact with return flows beneath the wave-breaking layer, resulting in the development of undertow currents. These currents contribute to sediment resuspension, cross-shore mixing, and nearshore water mass exchange, playing a crucial role in coastal morphodynamics.

In this study, the coupled hydrodynamic-wave model explicitly accounts for these key forcing mechanisms by incorporating wind forcing for wave generation and wave-induced forcing for coastal current formation. This approach ensures that both atmospheric-driven large-scale circulation and wave-driven nearshore hydrodynamics are accurately represented, providing a comprehensive understanding of the dominant forcing processes that govern coastal dynamics in the southern Caspian Sea.

2.4 Initial and Boundary Conditions

Accurate initial and boundary conditions are essential for ensuring the physical realism and numerical stability of hydrodynamic and wave simulations. In this study, the initial and boundary values for velocity components (u and v), water level, temperature, and salinity were extracted from the Caspian Sea circulation model (Akbarpour Jannat et al, 2014), which provides a detailed representation of large-scale oceanographic processes within the basin. The initial conditions were derived from the HYCOM (Hybrid Coordinate Ocean Model) data bank, a widely used global oceanographic dataset that offers high-resolution representations of temperature, salinity, and current structures.

For wave modeling, the initial and boundary conditions for wave characteristics at the local grid boundaries were obtained from the SWAN wave model, which was run over the entire Caspian Sea basin (Akbarpour Jannat et al, 2014). By nesting local wave simulations within the larger-scale SWAN model, the approach ensures that energy transfer, spectral wave evolution, and offshore forcing conditions are accurately represented within the high-resolution nearshore grids. The model was forced using wind data from the ECMWF-ERA Interim global reanalysis/forecasting model, which provides a spatial resolution of 0.125° and a temporal resolution of 3 hours. These data include horizontal wind components at a height of 10 meters above the water surface, ensuring an accurate representation of wind-driven wave generation and atmospheric forcing.

Since there are no significant riverine inputs within the domain of the local grids, the predicted nearshore flow patterns primarily consist of wave-driven currents. Despite the extension of the model domain to depths beyond the wave-breaking zone, wind-driven currents were not explicitly incorporated into the local-scale circulation modeling due to their minimal impact on nearshore hydrodynamics compared to wave-induced forcing. By adopting this approach, the model effectively captures the dominant hydrodynamic mechanisms governing coastal circulation, sediment transport, and rip current dynamics in the southern Caspian Sea.

2.5 Calibration

To ensure the accuracy and reliability of the numerical simulations, the model was calibrated and validated using observational datasets from multiple sources. The calibration process involved adjusting the wave and current model coefficients to achieve the best agreement between simulated results and measured field data. For this purpose, data from tracking buoys, wave buoys operated by the Ports and Maritime Organization, and the Acoustic Doppler Current Profiler (ADCP) deployed by the National Institute of Oceanography and Atmospheric Sciences were utilized. The observational datasets, recorded in 2011, provided critical insights into wave height, period, and current velocity, enabling a robust statistical evaluation of model performance.

A comparative analysis of statistical wave characteristics was conducted at both deep and shallow water points along the southern Caspian Sea shoreline, with results summarized in Table 2. This assessment allowed for the refinement of key wave and current model parameters, ensuring that the numerical model accurately reproduced real-world hydrodynamic conditions. By integrating high-quality observational data into the calibration process, the study enhances the credibility and predictive capability of the coupled wave-current model, making it a valuable tool for coastal hydrodynamic research, hazard assessment, and marine engineering applications in the southern Caspian Sea.

Table (2): Statistical Parameters of Waves Based on Mean Bias Error (MBE), Root Mean Square Error (RMSE), Scatter Index (SI), Correlation Coefficient (CC), and Agreement Index (AA), at the Wave Buoy Station of the Ports and Maritime Organization (Deep Water) and at the ADCP Wave Buoy Station of the National Institute of Oceanography and Atmospheric Sciences (Shallow Water).

	M1		M3	
	H_s (m)	T_p (s)	H_s (m)	T_p (s)
MBE	-0/05	0/8	0/02	0/03
RMSE	0/23	1/09	0/1	1/42
SI	0/47	0/24	0/27	0/25
CC	0/76	0/51	0/81	0/67
IA	0/87	0/65	0/82	0/8

Based on Figure 6, the comparison between measured flow velocity at Bandar Anzali and the corresponding numerical model outputs provides a critical assessment of model accuracy. The time series analysis demonstrates how well the simulated results align with the ADCP field measurements recorded at a depth of 3 meters from the surface. Meanwhile, the simulated velocity data corresponds to the fourteenth vertical layer in the model, ensuring a direct comparison of near-surface current dynamics.

The validation results indicate a strong correlation between measured and simulated flow velocities, confirming the model’s ability to capture nearshore circulation dynamics in the region. Minor discrepancies observed between the two datasets may be attributed to spatial variability in current patterns, uncertainties in bathymetric data, and subgrid-scale turbulence effects that are not fully resolved in the model. However, the overall agreement supports the robustness of the hydrodynamic model in reproducing wave-driven currents and wind-induced flows along the southern Caspian Sea coastline. This validation strengthens the model’s applicability for coastal hazard assessment, rip current prediction, and sediment transport studies, providing a reliable framework for future hydrodynamic forecasting in the region.

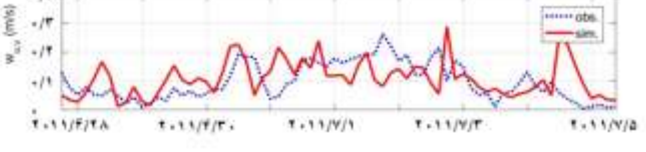

Figure (6): Time series of horizontal flow velocity measured and simulated at Bandar Anzali. The ADCP data corresponds to a depth of 3 meters from the surface, while the simulated data corresponds to the fourteenth layer (from the surface).

3. Results and Discussion

Coastal currents influenced by wave forcing along the coasts of Nowshahr, Chaboksar, Anzali, and Talesh were investigated using coupled ROMS-SWAN models for a one-month period in July 2018. The results were extracted from the model at one-hour time intervals to ensure high temporal resolution. Using the modeled data, the current vectors and the vorticity derived from horizontal currents were calculated and plotted for times corresponding to the measurements from the drifter trackers, allowing for direct comparison between simulated and observed patterns.

The wave-driven current averaged at depth for the Nowshahr coast is shown in Figure (7). The coastal flow pattern in this region indicates the presence of a dominant easterly alongshore current, which is primarily driven by wave-induced forces and modulated by local bathymetric variations. The velocity of these currents exhibits spatial variability, with stronger flows observed in the western sector compared to the eastern region. This gradient in current intensity could be attributed to variations in coastal morphology, wave energy dissipation, and local sediment transport dynamics.

Notably, multiple cells of rotational currents are evident, indicative of rip current activity. These rip currents, formed due to wave breaking and nearshore bathymetric features, play a critical role in nearshore circulation by redistributing sediment and energy. In the eastern section of the domain, the spacing between rip current channels is approximately 700 meters, and their influence extends offshore to a depth of about 2 meters. This suggests the presence of rhythmic topographic features, such as sandbars, which regulate the formation and spacing of rip currents.

The vorticity field (Figure 8) derived from horizontal currents further supports these observations. The dominant flow regime remains coastal, characterized by persistent alongshore currents, yet several localized zones of elevated vorticity correspond to the rip currents identified in the velocity field. The intensity and penetration depth of these rip currents appear to vary along the coast, with a noticeable increase in offshore penetration in the central part of the study area. This enhancement is likely linked to the geomorphological characteristics of the coastline, including variations in seabed slope and nearshore bathymetry, which can channelize wave energy and enhance the offshore-directed return flow.

These findings highlight the complex interactions between wave forcing, coastal morphology, and nearshore circulation processes, emphasizing the importance of high-resolution numerical modeling in assessing hydrodynamic behavior in dynamic coastal environments.

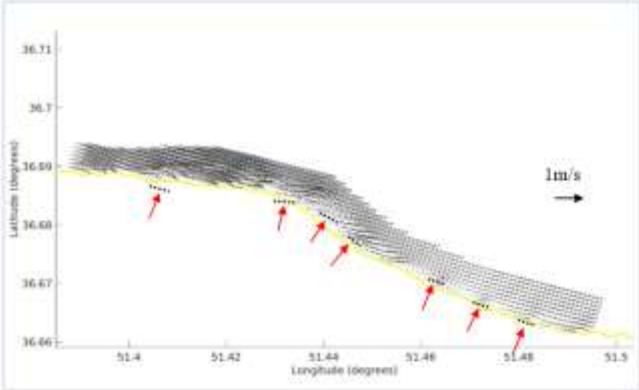

Figure (7): Coastal currents resulting from the modeling at the Nowshahr coast, confined to a depth of 6 meters up to the shoreline.

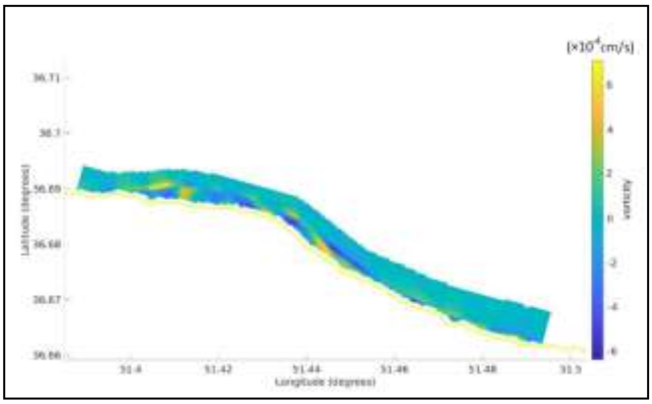

Figure (8): Vorticity field resulting from the modeling at the Nowshahr coast, confined to a depth of 6 meters up to the shoreline.

At the Chaboksar coast (Figure 9), the coastal slope is steeper than in the Nowshahr region, leading to a more confined nearshore zone and narrower coastal currents. This steep slope influences the wave transformation and energy dissipation, resulting in a more concentrated and intensified nearshore flow. Similar to the Nowshahr region, the coastal current pattern exhibits a dominant onshore component and an eastward-alongshore flow, primarily driven by wave forcing and local bathymetric constraints. However, in contrast to Nowshahr, the variation in the onshore current velocity remains relatively uniform across the region, indicating that the steep bathymetry may play a role in stabilizing the nearshore flow field.

Rip currents are clearly visible along almost the entire coastline, marked by distinct vortices embedded within the broader coastal current system. These rip currents exhibit greater offshore penetration than those observed at Nowshahr, extending to depths of 5–6 meters. This increased offshore reach suggests that stronger wave breaking and nearshore circulation processes are at play, likely facilitated by the steeper slope and channelized return flows. The rip currents are particularly pronounced in the western section, where their intensity surpasses that of those in the eastern region. This asymmetry in rip current strength may be

attributed to regional variations in incident wave energy, bottom roughness, and shoreline morphology.
Several rotational cells, spaced between 700 and 1000 meters apart, are identified along the coastline. These rotational features are indicative of rip current dynamics and their associated vorticity structures. The study of the vorticity field (Figure 10) further corroborates these findings, revealing that the western region is characterized by stronger and more persistent rip currents, as indicated by the higher vorticity values. In contrast, the eastern section displays weaker, more diffuse rip current signatures.

In the central part of the study area, the vortices appear more consolidated and well-defined, suggesting that localized geomorphological factors, such as submerged sandbars or rocky outcrops, may be contributing to the spatial organization of these currents. Despite the dominance of stronger rip currents in the western section, weaker rip currents are still present throughout the region, underscoring the variability and complexity of nearshore hydrodynamics along the Chaboksar coast.

These results highlight the critical role of bathymetry in shaping rip current dynamics and emphasize the need for high-resolution hydrodynamic modeling to improve our understanding of nearshore circulation patterns in steep-slope coastal environments.

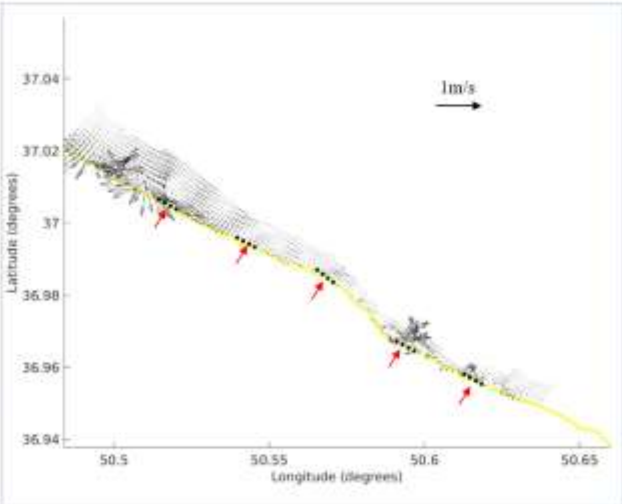

Figure (9) Coastal currents resulting from modeling at the Chaboksar coast, limited to depths of 8 meters from the shoreline.

At the Anzali coast, the shoreline currents exhibit relatively weak intensity at the selected simulation time (Figure 11). The gentle coastal slope plays a significant role in shaping the nearshore circulation, resulting in a broader, more diffused current band. Unlike regions with steeper bathymetry, where currents are more concentrated and energetic, the gradual slope at Anzali facilitates the dissipation of wave energy over a wider area, leading to a more uniform and less intense coastal flow.

While offshore currents have developed, there is limited evidence linking them to well-defined rip currents. Only two rip currents are distinctly visible, and their influence on offshore transport appears to be weak compared to other study areas. The offshore-directed currents extend to a depth of approximately 8 meters, suggesting that while some rip current activity is present, it lacks the pronounced intensity observed in regions with steeper slopes, such as Chaboksar. This subdued rip current activity may be attributed to weaker wave forcing, reduced wave breaking intensity, or a more uniform seabed profile that lacks the morphological features necessary to generate strong rip channels.

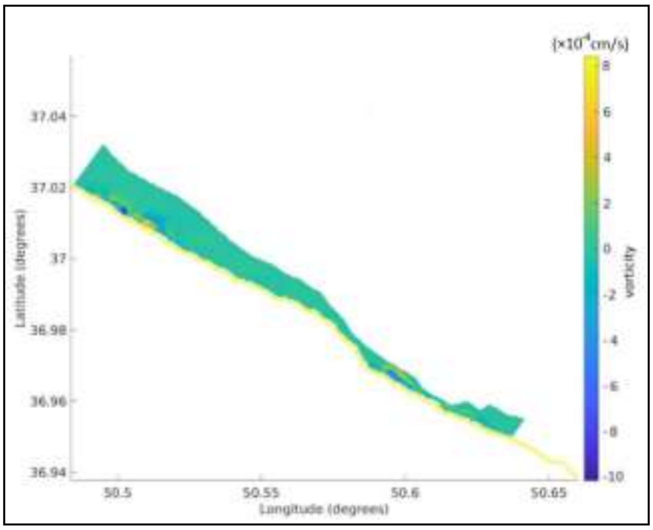

Figure (10) Vorticity field resulting from modeling at the Chaboksar coast, limited to depths of 8 meters from the shoreline.

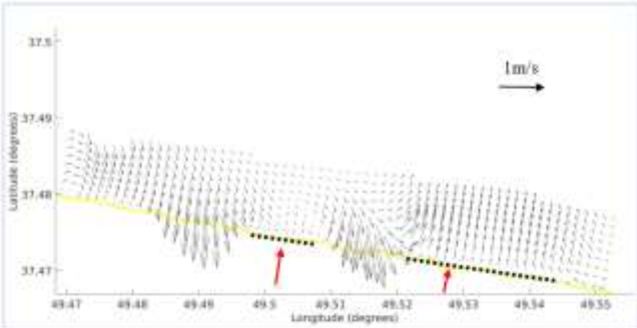

Figure (11) Coastal currents simulated at the Anzali coast, limited to a depth of 8 meters from the shoreline.

The vorticity field (Figure 12) further supports these findings. The analysis indicates that rip currents in the eastern part of the area exhibit stronger vorticity signatures than those in the western region. This spatial variation suggests that local geomorphological factors or variations in wave energy distribution may be influencing the development of rip currents. The weaker rip activity in the western section could be due to the presence of alongshore sediment transport

processes that redistribute wave energy, preventing the formation of well-defined rip channels.
Overall, the results for the Anzali coast highlight the influence of coastal slope on nearshore hydrodynamics. The broader current band and weaker rip currents observed in this region underscore the importance of local bathymetry in modulating wave-driven circulation patterns. These findings provide valuable insights into the spatial variability of nearshore currents along the Caspian coastline and emphasize the necessity of detailed hydrodynamic modeling for improved coastal hazard assessment and management.

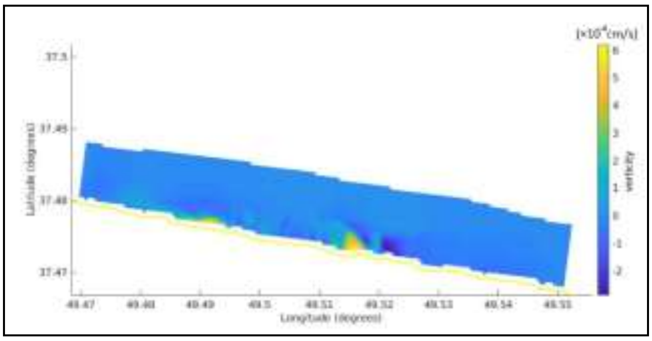

Figure (12) Vorticity field simulated at the Anzali coast, limited to a depth of 8 meters from the shoreline.

Based on Figures 13 and 14, which depict coastal currents and the vorticity field at the Talash coast, the hydrodynamic characteristics of this region are closely linked to the gently sloping seabed and extended wave-breaking zone.
The broader current band observed in Figure 13 confirms that wave breaking occurs farther offshore, leading to a gradual transition between wave-induced and offshore-directed flows. This is characteristic of regions with low-gradient bathymetry, where wave energy dissipation is more evenly distributed across a wider area. The dominant onshore current directed westward suggests that wave-induced setup plays a major role in driving coastal circulation, with coastal morphology acting as a secondary influence.
A distinctive feature of the Talash nearshore circulation is the presence of cyclonic upwelling currents, consistently observed along the entire coastline. Figure 14 (vorticity field) reinforces this observation, highlighting spatial variations in current intensity. The relatively uniform bathymetry supports the formation of broad, persistent upwelling currents, contrasting with localized rip currents that typically emerge in regions with pronounced topographic irregularities. The penetration depth of these upwelling currents, extending 3–4 meters offshore, suggests their potential role in nutrient transport and sediment redistribution, influencing coastal productivity and seabed stability.
The western sector of the study area exhibits stronger current intensities, as indicated by higher vorticity values in Figure 14. This intensification may result from regional variations in wave energy dissipation, localized wind-driven circulation patterns, or subtle bathymetric differences that enhance flow acceleration. The eastern section, in contrast, shows weaker upwelling activity, suggesting a more diffuse flow regime with less concentrated current structures.
Overall, the hydrodynamic regime of the Talash coast is characterized by a broad, low-energy nearshore current system, with persistent upwelling rather than strong rip current formation. These findings highlight the critical role of coastal slope and wave forcing in shaping nearshore circulation and underscore the importance of morphological considerations in assessing coastal hydrodynamics. Future studies incorporating high-resolution field measurements and three-dimensional flow analysis would provide further insights into the mechanisms governing upwelling and sediment transport in gently sloping coastal environments.

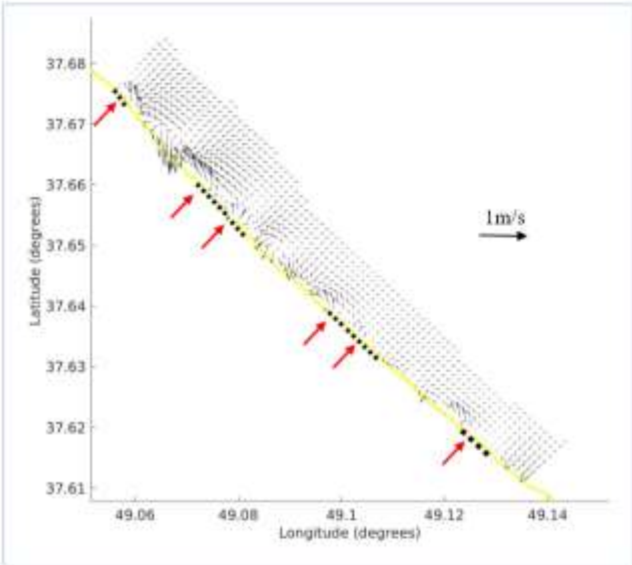

Figure (13) Coastal currents obtained from modeling at the Talash coast, limited to a depth of 8 meters to the shoreline.

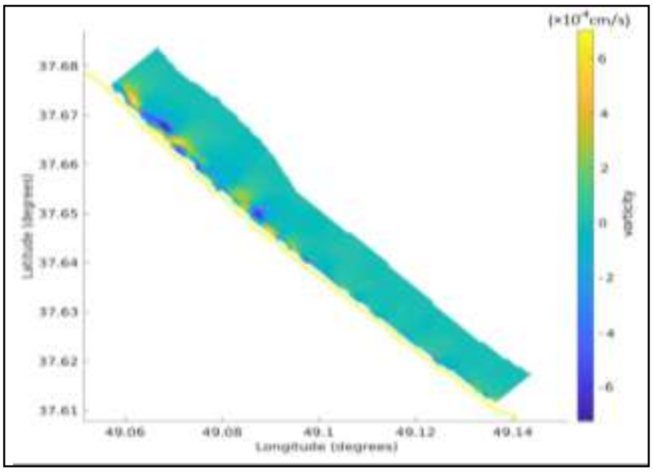

Figure (14) Vorticity field obtained from modeling at the Talash coast, limited to a depth of 8 meters to the shoreline.

4. Conclusion

This study utilized coupled SWAN-ROMS numerical modeling to analyze wave-driven nearshore currents along the southern Caspian Sea, focusing on four coastal regions: Nowshahr, Chaboksar, Anzali, and Talesh. The results demonstrated that wave-induced circulation is a dominant hydrodynamic feature throughout these coasts, significantly influenced by coastal morphology, bathymetric characteristics, and wave forcing. The interaction between wave energy dissipation, shoreline slope, and nearshore bathymetry plays a crucial role in shaping current intensity and distribution patterns.

A key finding of this study is the spatial variability in current intensity, which decreases from east to west along the study domain. This trend is primarily governed by differences in coastal slope and the width of the wave-breaking zone. In regions with steeper bathymetry, such as Chaboksar, the nearshore current system is more concentrated, generating stronger alongshore and rip currents. Conversely, in areas with gentler slopes, such as Anzali and Talesh, wave breaking occurs farther from the shoreline, leading to broader, more diffused current bands with weaker intensities. The extent of offshore-directed currents also varies accordingly, with steeper regions exhibiting deeper penetration of rip currents, while in gently sloping regions, the return flows are more gradual and widespread.

Rip currents were observed as a significant hydrodynamic feature in the study area, with their presence particularly pronounced along the Nowshahr and Chaboksar coasts. These currents exhibited well-defined circulation cells, penetrating offshore up to 5–6 meters in depth, with spacing between rip channels ranging from 700 to 1000 meters. The variation in rip current intensity and distribution is closely linked to local bathymetric variations and wave forcing mechanisms. In contrast, the Anzali and Talesh coasts exhibited fewer and weaker rip currents due to their more uniform seabed morphology, which limits the formation of strong, concentrated return flows.

Current velocities reached up to 1 m/s in certain sections, emphasizing their potential implications for sediment transport, beach morphology, and coastal erosion processes. These findings highlight the necessity for high-resolution bathymetric datasets to enhance the accuracy of hydrodynamic modeling and improve the identification of high-risk zones for rip current hazards. Given the dynamic and regionally variable nature of nearshore circulation, periodic updates to bathymetric surveys are essential to capture evolving seabed features that influence current formation.

Moreover, the results underscore the need for establishing a dedicated observation network for waves and shallow water currents across the southern Caspian Sea. The absence of continuous in situ measurements poses a challenge for accurately validating numerical models and improving the predictive capability of hydrodynamic simulations. Implementing a real-time monitoring system with drifter deployments, ADCP measurements, and wave buoys would provide critical data to refine model accuracy and enhance coastal hazard assessments.

From a practical perspective, the insights from this study have direct implications for coastal zone management, maritime safety, and beachgoer risk mitigation. The identification of strong rip currents in certain areas necessitates the implementation of targeted public safety measures, such as warning systems, designated safe swimming zones, and enhanced coastal surveillance. Additionally, the influence of nearshore currents on sediment transport processes highlights the need for integrated coastal engineering strategies to mitigate erosion and shoreline instability.

Overall, this research provides a comprehensive understanding of wave-driven nearshore circulation in the southern Caspian Sea, emphasizing the interplay between bathymetry, wave forcing, and current dynamics. The findings serve as a foundation for future studies focusing on coastal hydrodynamics, wave-current interactions, and hazard mitigation strategies in similar semi-enclosed basins. Further research incorporating high-resolution field measurements and data assimilation techniques is recommended to enhance the predictive accuracy of numerical models and support sustainable coastal management efforts in the region.

5. Acknowledgements

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"Hazard Zonation of Rip Currents and Associated Mortality Risks along the Iranian Caspian Coastline (Gilan and Mazandaran Provinces: Talesh, Anzali, Chaboksar, and Nowshahr)."

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