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ORIGINAL PAPER

Hydrodynamic modeling and risk assessment of surge events in the Kazakh sector of the Caspian Sea

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Abstract
The Caspian Sea, a crucial economic resource for its littoral states, is increasingly affected by sea level decline and surge phenomena. Oil and gas extraction, fisheries and maritime transport are among the primary economic activities in the region. However, decreasing water levels and recurrent surges, particularly in the northeastern part of the sea, pose growing risks to these operations. This study investigates the spatial and temporal characteristics of 1836 surge events recorded in the Kazakh sector from 1940 to 2022, comprising 1086 up surges and 750 down surges. Up surges predominantly occurred in spring and autumn, while down surges peaked in September. To evaluate the potential impact of these surges, a hydrodynamic model (MIKE 21) was applied, utilizing ERA5 reanalysis data for surface wind and atmospheric pressure. Model validation against in situ measurements showed excellent performance ($R^2=0.98$, RMSE = 0.11 m). Simulations of 14 extreme events revealed that up surges can cause inland flooding up to 33.5 km, while down surges can induce coastal retreats up to 32.2 km. These results demonstrate the need for robust early warning systems and integrated coastal risk management to mitigate the socio-economic impacts of surge events in the Caspian region.

Keywords Caspian Sea · Surge · Hydrodynamic modeling · MIKE 21

1 Introduction

The Caspian Sea, an endorheic body of water, holds significant socioeconomic importance for the Caspian region. The development trajectory of Kazakhstan, particularly the Atyrau and Mangystau regions bordering the Caspian Sea, is heavily influenced by the hydrocarbon reserves within the Caspian Basin (Akhmadeev and Brylov 2020). It should be noted that the hydrological and meteorological regime of the sea is the main determinant of safe operations at sea.

The Caspian Sea is an enclosed body of water subject not only to multi-year water level fluctuations, but also to short-term changes in sea level under the influence of meteorological factors. The northeastern Caspian Sea, particularly its coastal zone, exhibits unique

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hydrological and morphological dynamics, including prominent up and down surge fluctuations, unlike other parts of the sea (Terziev et al. 1992; Lahijani et al. 2023). Surges are wind-induced variations in water levels near the coast (Adam et al. 2017; Lavrova and Kostianoy 2020; Pineau-Guillou et al. 2023). Air circulation over the North Caspian is predominantly driven by continental baroclinic formations such as the Siberian winter maximum and the Iranian-Afghan summer minimum (Terziev et al. 1992; Pavlova et al. 2020).

In the Kazakh sector of the Caspian Sea, an average of 3–4 up surges and 4–5 down surges occur monthly, regardless of the season. This results in nearly continuous coastal migration for 80–85% of the year (Terziev et al. 1992). Under typical wind conditions, the extent of this migration ranges from 3 to 5 km. However, extreme conditions, such as severe down surges, can lead to coastal retreat of 8–12 km, while extreme up surges can cause inland inundation of up to 15 km (Ivkina 2013; Ivkina et al. 2019). In the period 2003–2017, 370 surge events were observed in the North Caspian Sea, of which more than 80 per cent occurred during the cold season (Nesterov et al. 2018).

The ongoing sea-level decline has accelerated the drying of extensive shallow water areas in the northeastern part of the sea (Chen et al. 2017; Akbari et al. 2020; Medvedev et al. 2020). The combination of strong winds, shallow depths, and gentle sea and land slopes creates ideal conditions for significant wind-driven surges. These surges have a substantial impact on human economic activities in the coastal regions of Atyrau and Mangistau, causing significant material damage and environmental consequences (Terleeva and Ivanov 2015; Lavrova et al. 2021). According to hazard criteria (Kazhydromet 2024), during high sea levels, critical up surges exceeding 50 cm can lead to coastal flooding. Conversely, down surges exceeding 50 cm can impair navigation conditions for small vessels, damaging economic assets and disrupting ecological balance.

Storm surge events represent one of the most significant natural hazards for coastal areas and infrastructure. Early studies highlighted the key role of wind in redistributing water masses and generating extreme sea levels (Huang et al. 2002), while recent research has focused on improving surge prediction models and integrating them with socioeconomic risk management frameworks (Ghorbanzadeh et al. 2021; Rugminiamma et al. 2021; Huang et al. 2022; Vijayan et al. 2023).

Due to the frequent storm surge events and the limited observation network in the North Caspian Sea, it is necessary to use a storm surge prediction model to issue warnings. There are a number of numerical models that are mainly used for storm surge prediction, such as ADCIRC (Pavlova et al. 2020, 2021), ADCIRC + SWAN (Vijayan et al. 2023), FVCOM (Chen et al. 2006, 2013, 2022), Delft3D (Bloemendaalet al. 2018), MIKE 21 (Ivkina and Stroyeva 2007; Yeltay and Ivkina 2024). For the northern part of the Caspian Sea, the ADCIRC model (Pavlova et al. 2020) and the three-dimensional hydrodynamic model (Popov and Lobov 2017) reproduce the surge sea level changes well, with correlation coefficients between modelled and observed data of 0.77 and 0.90, respectively. The results of modelling with MIKE 21 in the Kazakh part of the sea near the port of Aktau showed a correlation of 0.66–0.95, an absolute error of 3–8 cm (Yeltay and Ivkina 2024).

The frequent occurrence of surge events in the northeastern Caspian Sea complicates marine operations and necessitates precise predictions of maximum water surface fluctuations. This study aims to analyze surge phenomena and determine the potential water surface positions in the northeastern Caspian Sea through numerical simulations of past extreme surge events. The findings will contribute to the effective planning of marine operations, navigation, and tourism in this region.

2 Materials and methods

2.1 Description of study area

The Caspian Sea, situated at the crossroads of Europe and Asia, borders Kazakhstan, Turkmenistan, Iran, Azerbaijan, and Russia (Fig. 1). Its total coastline extends approximately 7500 km, with roughly 2p 000 km falling within Kazakhstan's territory. The Caspian shelf is limited to an average depth of about 100 m. The northern part of the sea under consideration is shallow, with an average depth of 5–6 m and maximum depths of 15–20 m at the boundary with the central part of the sea (Terziev et al. 1992). The shores of the Caspian Sea, on the other hand, are varied. In the northern part of the sea there are bays and harbours, peninsulas and large islands such as Kulaly and Tyuleniy (Terziev et al. 1992).

The Caspian Sea receives water from over 130 rivers, contributing an annual inflow of approximately 270–300 km3. The Volga, Terek, Sulak and Samur rivers, originating in Russia, flow into the Caspian Sea. The Volga, with an average annual discharge of 270 km3, accounts for approximately 80% of the total surface inflow (Terziev et al. 1992; Nesterov 2016). In Kazakhstan, the Zhaiyk (Ural) River, which rises on the slopes of the Round Sopka peak in the Ulytau Mountains of Russia, is the primary river feeding the Caspian Sea (Terekhov et al. 2020).

Coastal sea-level fluctuations pose a substantial threat to human populations, wild-life, and infrastructure, making it a critical research area (Nesterov 2016; Kulp and Strauss 2019;

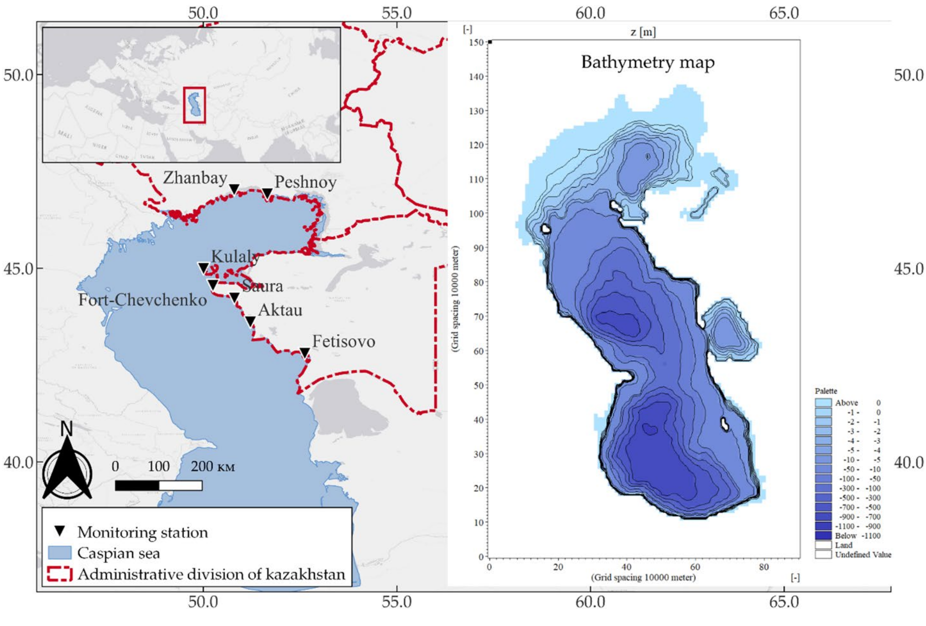

Fig. 1 Study area. Location of marine stations and posts

Hermans 2022; Terekhov et al. 2024). These fluctuations significantly impact water transport infrastructure. In Kazakhstan's deep-water Caspian Sea, the ports of Bautino, Aktau, and Kuryk facilitate the transportation of cargo, oil, and oil products to Iran, Turkey, Russia, Azerbaijan, and Turkmenistan (Aktau port 2024; Kuryk port 2024). In the period 1900–2022, the average level of the Caspian Sea fluctuated around minus 27.34 m BS, and in Kazakhstan's north-eastern part of the sea was minus 27.70 m BS (for 1929–2022). Level fluctuations are caused by several factors such as anthropogenic activities, climate change effects, and geological and tectonic processes.

2.2 Datasets

The characteristics of surge phenomena, including sea level, wind speed, and direction, were obtained through the analysis of data from seven marine stations and posts within Kazakhstan's National Observing Network (Fig. 1) for the period 1940–2022. At present, coastal marine observations of hydrometeorological characteristics (sea level, water and air temperature, wind speed and direction, wave height and direction, salinity) in Kazakhstan are carried out at four marine hydrometeorological stations: Peshnoy, Kulaly Island, Fort-Shevchenko, Aktau and six marine hydrometeorological posts: Zhanbay, Igolkinskaya Banka, Fetisovo, Kuryk, Saura and Peschanyi (Kazhydromet 2022). Marine observations are conducted 4 times a day (00, 06, 12, 18 h UTC).

However, only 7 of them are experiencing surge events. Surge phenomena are observed only at 7 of them. Due to the fact that particularly dangerous surge phenomena are most partly observed from data of the Peshnoy sea station for further modelling the initial sea level values before the surge phenomena were applied only for this station.

Bathymetry, wind and pressure data, and calculation point coordinates are essential inputs for numerical modeling. In this work, the bathymetric model with a grid spacing of 10 km (Ivkina et al. 1997; Ivkina and Stroyeva 2007; Yeltay and Ivkina 2024) is used as the bathymetric grid of the Caspian Sea water area for calculations using the MIKE 21 model (Fig. 1). The construction of a high-quality computational grid is an important step in obtaining valid and reliable modelling results. The previously developed bathymetric model of the Caspian Sea was used as a basis for the construction of a computational grid for the entire Caspian Sea water area.

Meteorological conditions were derived from ERA5 reanalysis data, providing hourly data on single-level wind fields at 10 m height (meridional and zonal) and atmospheric pressure with a 0.25° resolution (Hersbach et al. 2018).

For storm surges, the National Hydrometeorological Service (NHMS) establishes the criteria for hazardous events at each location (Dzhenyuk 2019). According to NHMS research (Kazhydromet 2000; 2002), the primary criteria for identifying up and down surge events are a sea level rise or fall of at least 15 cm and a wind speed exceeding 5 m/s blowing towards or away from the coast. According to the storm surge hazard criteria for the north-eastern coastline (Bloemendaal et al. 2018), a critical rise or fall is assessed at 50 cm, dangerous at 65 cm and particularly dangerous at 100 cm.

During the period from 1940 to 2022, approximately 1086 up surges and 750 down surges meeting these criteria were observed from observation stations and posts in the Kazakh part of the Caspian Sea (Table 1). Of these, 11.2% were classified as dangerous and 1.6% as particularly dangerous.

2.3 Hydrodynamic modeling methodology

Statistical and numerical models enable the calculation and prediction of various hydrometeorological characteristics of the marine environment, directly impacting humans, coastal areas, structures, and other elements. Numerical modeling, particularly hydrodynamic modeling, is widely employed in methods for predicting sea level fluctuations (Gurumoorthi and Venkatachalapathy 2017; Symonds et al. 2017; Hanapiah et al. 2020; Lyubitsky et al. 2020; Nguyen et al. 2020; Serikbay et al. 2023). The quantitative characteristics of past up and down surge events in the Kazakh sector of the Caspian Sea were assessed using statistical methods and descriptive data analysis (Ministry of Education and Science of the Russian Federation 2015). Additionally, hydrodynamic calculations using the MIKE 21 flow model (DHI 2017a; b) were employed to determine the areas susceptible to up and down surge phenomena.

The hydrodynamic module of the MIKE 21 flow model within the MIKE Zero software package is based on solutions to the three-dimensional Reynolds-averaged Navier–Stokes equations, comprising the local continuity Eq. (1) and momentum in projections on the x-axis (2) and y-axis (3) (DHI 2017b).

$$\frac{\delta u}{\delta x}+\frac{\delta \nu}{\delta y}+\frac{\delta w}{\delta z}=S \tag{1}$$

$$\frac{\delta u}{\delta t}+\frac{\delta u^2}{\delta x}+\frac{\delta vu}{\delta y}+\frac{\delta wu}{\delta z}=fv-g\frac{\delta \eta}{\delta x}-\frac{1}{\rho_0}\frac{\delta p_a}{\delta x}-\frac{g}{\rho_0}\int_z^{\eta}\frac{\delta \rho}{\delta x}dz-\frac{1}{\rho_0 h}\left(\frac{\delta S_{xx}}{\delta x}+\frac{\delta S_{xy}}{\delta y}\right)+F_u+\frac{\delta}{\delta z}\left(v_t\frac{\delta u}{\delta z}\right)+u_s S \tag{2}$$

$$\frac{\delta v}{\delta t}+\frac{\delta v^2}{\delta y}+\frac{\delta uv}{\delta x}+\frac{\delta wv}{\delta z}=-fu-g\frac{\delta \eta}{\delta y}-\frac{1}{\rho_0}\frac{\delta p_a}{\delta y}-\frac{g}{\rho_0}\int_z^{\eta}\frac{\delta \rho}{\delta y}dz-\frac{1}{\rho_0 h}\left(\frac{\delta S_{yx}}{\delta x}+\frac{\delta S_{yy}}{\delta y}\right)+F_v+\frac{\delta}{\delta z}\left(v_t\frac{\delta v}{\delta z}\right)+v_s S \tag{3}$$

Table 1 Number of observed surge events in the Caspian Sea area

Observation station	Observation period	Number of cases				Total number
		up to 49 cm	50–64 cm (critical)	65–99 cm (dangerous)	over 100 cm (particularly dangerous)	
Up surge						
Zhanbay	2005–2022	26	1	2	1	30
Peshnoy	1940–2022	285	180	112	18	595
Kulaly	1961–2022	22	16	1		56
Fort-Shevchenko	1961–2022	21	6	1		80
Saura	2013–2022	103	1			104
Aktau	1985–2022	31	1			32
Fetisovo	2006–2022	186	3			189
Down surge						
Zhanbay	2005–2022	25	1			26
Peshnoy	1940–2022	264	105	88	10	467
Kulaly	1961–2022	22	7			59
Fort-Shevchenko	1961–2022	32	1			94
Saura	2013–2022	37				37
Aktau	1985–2022	26	5	2		33
Fetisovo	2006–2022	33	1			34

where, u, v, w—x, y, z components of velocity vector, x, y, z—Cartesian coordinates, S—water inflow rate from sources, t—time, η—deviation of free surface from undisturbed level, d—depth at undisturbed state of liquid, h = η + d—total depth of water, f = 2ΩsinΦ—Coriolis parameter (Ω—angular velocity of Earth rotation, Φ—geographic latitude), g—gravity, ρ—water density, $S_{xx}, S_{xy}, S_{yx}, S_{yy}$—components of radiation stress tensor, v_t—vertical turbulent (vortex) viscosity, p_a—atmospheric pressure.

The main calibration parameters of the model are (DHI 2017b):

1. Bottom stress or roughness, determined from the quadratic law of friction (expressed by the Chézy coefficient or Manning number):

$$C = \frac{1}{n} R^{1/6} \tag{4}$$

   where R is the hydraulic radius, n is the roughness coefficient.
2. Wind stress or wind friction determined from the quadratic law of velocity.
3. Turbulence calculated based on eddy viscosity concentration (expressed through the Smagorinsky coefficient) (Smagorinsky et al. 1965).
4. If the water depth values are less than the drying depth (in this case 0.2 m), an element is considered to be flooded (Yeltay and Ivkina 2024; DHI 2017b).

Previously, Yeltay and Ivkina (2024) calibrated the MIKE 21 Caspian Sea current model for the years 1980, 1990, 2000, 2010, 2020, 2021 by calculating the sea level change when the calibration parameters of the model were changed. As a result, it was determined that the optimal value of the Smagorinsky turbulent viscosity coefficient is 0.5, and the optimal value of the Manning roughness coefficient is 0.031 $m^{-1/3}$ s. Verification of the model was carried out for a multi-year period from 2000 to 2020, for which the coefficient of correlation between observed and modelled water levels was 0.97 for Fort-Shevchenko and 0.95 for Aktau marine stations.

As a result, it was obtained that calibration and validation of the model (Yeltay and Ivkina 2024) indicated that a Manning roughness coefficient of 0.031 m⁻1/3 s and a Smagorinsky turbulent viscosity coefficient of 0.5 were most suitable for the region under study.

The algorithm for calculating and constructing maps of water surface position changes using the MIKE 21 Flow Model FM and QGIS is illustrated in Fig. 2.

To assess the variations in the water surface position of the Caspian Sea under surge events, calculations were carried out for 14 particularly hazardous events with an average duration of 4.5 days. The bathymetry of the Caspian Sea with spatial resolution of 10 km was used as the input data (Fig. 1). The initial sea level conditions were derived from the data of the Peshnoy sea station (Fig. 1) (Kazhydromet 2022), which is located in the north-eastern part of the sea. The wind conditions during the considered periods of the surge events are obtained from ERA5 reanalysis data, which provide hourly data on single-level wind fields at 10 m height (meridional and zonal) with a resolution of 0.25° (Hersbach et al. 2018).

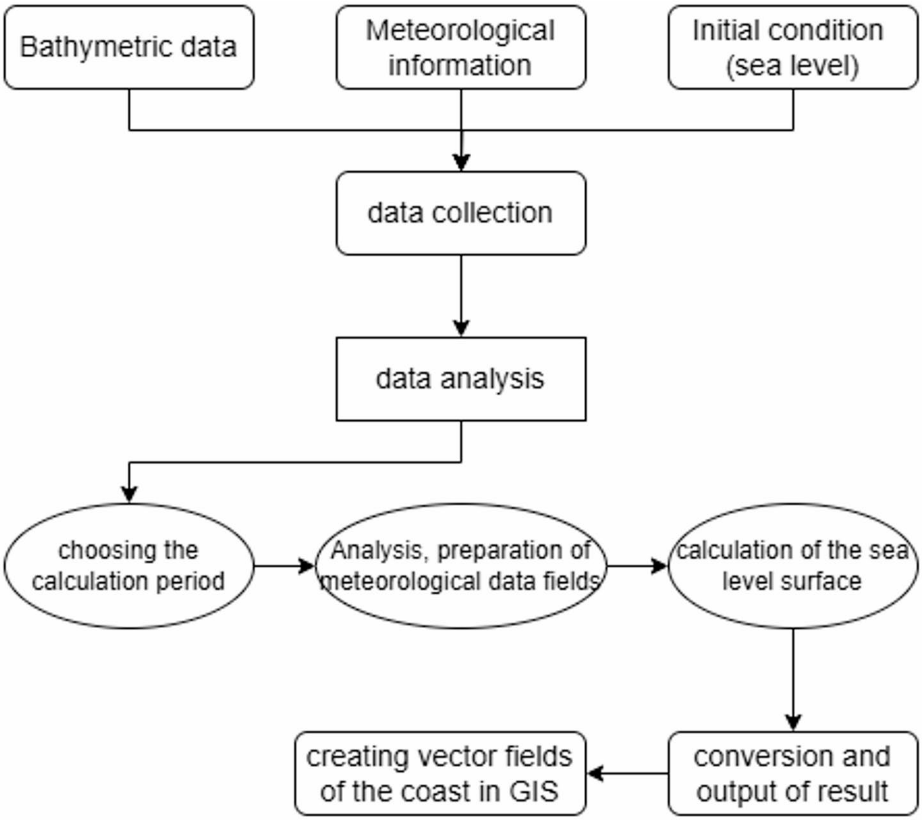

Fig. 2 Hydrodynamic model calculation algorithm

3 Results

Statistical analysis of surge events in the Kazakh sector of the Caspian Sea from 1940 to 2022 revealed an increasing trend in recent years (Fig. 3). The northern part of the sea experienced an average of 7–28 up surges and 8–24 down surges annually, while the central part recorded 4–16 up surges and 3–7 down surges. For instance, at Peshnoy Station, 467 down surges and 595 up surges were observed, with the periods 2010–2019 and 2020–2022 accounting for 26%, 23%, 19%, and 8% of down surge and up surge events, respectively.

The seasonal distribution of up surges correlates with periods of stormy winds. The highest frequency of up surges occurs during spring (March–May, 33%) and autumn (September–November, 26%) when prolonged and strong winds prevail (Fig. 4). In contrast, the lowest frequency occurs in February, the coldest month, when the North Caspian Sea is largely ice-covered, inhibiting the development of up surge waves. The intensity of seawater intrusion during up surges depends on factors such as wind strength, coastal topography, and sea level. In the Kazakh sector of the Caspian Sea, sea level rises of up to 1 m have been observed under wind speeds of 12–28 m/s sustained for 10–12 h to 1–2 days.

Statistical analysis of down surge events indicates that autumn, particularly September, experiences the highest frequency. The majority of down surges (59%) result in water level

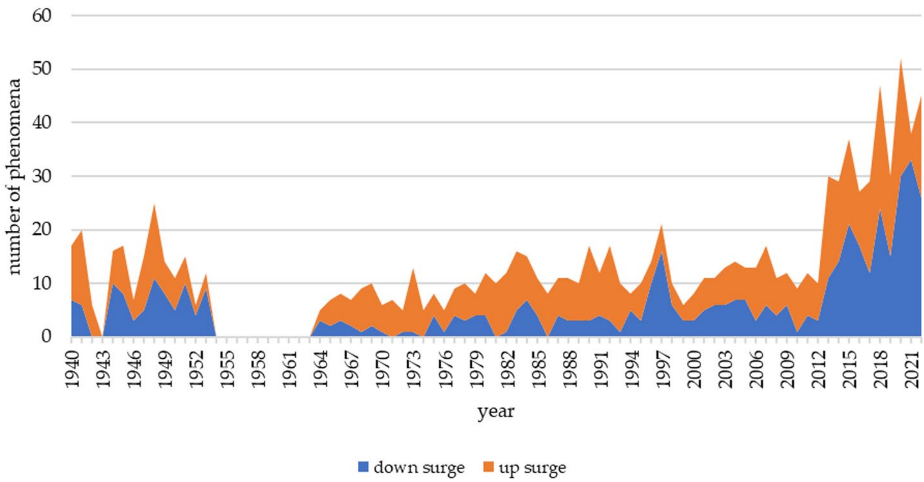

Fig. 3 Dynamics of the number of up and down surge events according to Peshnoy Station data

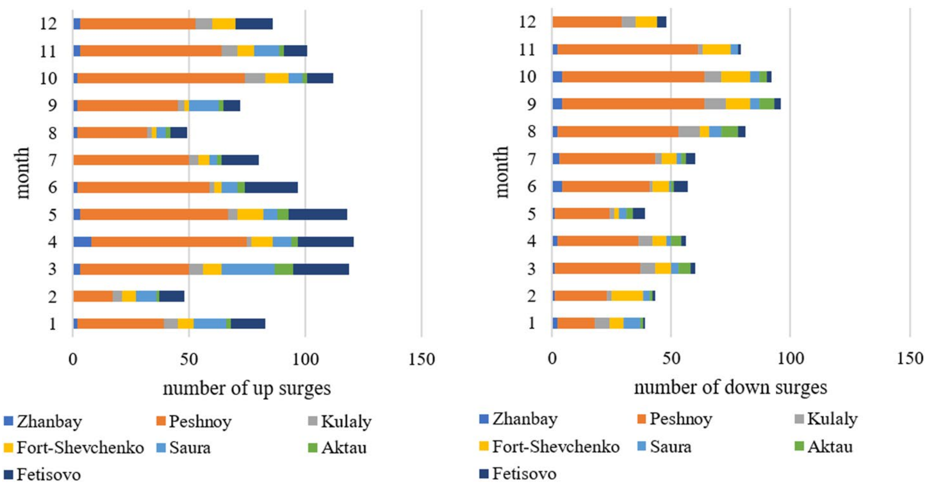

Fig. 4 Distribution of surge events within the year

drops of up to 50 cm, while those exceeding 100 cm are relatively rare (1%). The duration of these events varies significantly, ranging from several hours to several days, with most lasting 1–2 days and the extremes ranging from 6 h to 10 days. Quantitative characteristics of the surge events observed in the Kazakhstan Sector of the Caspian Sea for the period 1940–2022 are shown in Table 2.

The average monthly wind speeds during the observed up surges ranged from 9.1 m/s (in July) to 11.6 m/s (in April), with maximum values reaching up to 28 m/s. In contrast, the average monthly wind speeds during periods of down surge on the Caspian Sea ranged from 7.4 m/s (in July) to 10.5 m/s (in March and December), with maximum values reaching up to 22 m/s.

Table 2 Monthly up and down surge characteristics for 1940–2022

Characteristic	Month												For the full period
	01	02	03	04	05	06	07	08	09	10	11	12	
Up surge													
Number of cases (for the whole period)	84	48	119	121	112	96	85	45	63	118	95	99	1086
Repeatability, %	8	4	11	11	10	9	8	4	6	11	9	9	100
Number of up surges > 100 cm	–	–	1	5	3	1	1			4	1	3	19
Average up surge height, cm	34	32	37	46	41	42	38	40	45	48	46	41	41
Highest up surge height, cm	69	60	184	172	145	119	105	83	95	124	110	129	184
Maximum wind speed, m/s	24	20	28	21	24	20	20	18	17	20	17	24	28
Average wind speed, m/s	10.4	9.5	11.3	11.6	10.3	10.0	9.1	9.3	9.5	10.1	10.5	10.2	10,1
Down surge													
Number of cases (for the whole period)	39	43	60	56	39	57	60	81	96	92	79	48	750
Repeatability, %	5	6	8	7	5	8	8	11	13	12	11	6	100
Number of down surges > 100 cm						1	1	2	1	1	1	2	10
Average down surge height, cm	34	34	39	44	34	37	39	47	40	47	47	41	40
Highest down surge height, cm	67	81	85	86	80	115	110	123	117	119	114	106	123
Maximum wind speed, m/s	18	24	20	16	16	16	16	16	16	17	24	20	24
Average wind speed, m/s	8.7	8.5	10.5	10.3	9.2	8.8	7.4	8.6	8.2	9.0	8.9	10.5	9.0

The development and intensity of surge events are influenced not only by wind speed but also by wind direction. Peaks of up surges are most frequently observed during south-westerly (26%), westerly (26%), and south-easterly (19%) winds, whereas northerly winds occur much less often (3–6%). In other side, down surge events are most commonly associated with northerly (26%), north-westerly (21%), north-easterly (16%), and easterly (16%) winds.

According to Table 2, the average height of sea level change during surge events is 40–41 cm, with the maximum fluctuations ranging from 60 to 184 cm.

Significant up surges exceeding 1 m in height were recorded 19 times. Notable instances include Zhanbay in April 2008 (1.0 m), Peshnoy in March 1946 (1.84 m), April 1965, 1987, 1999, and 2000 (1.16 m, 1.11 m, 1.29 m, and 1.72 m, respectively), May 1944, 1967, and 1990 (1.04 m, 1.09 m, and 1.45 m, respectively), June 1996 (1.19 m), July 1946 (1.05 m), October 1969, 1970, 1975, and 1985 (1.24 m, 1.08 m, 1.09 m, and 1.0 m, respectively), November 1978 (1.1 m), and December 1991, 1998, and 2017 (1.29 m, 1.0 m, and 1.28 m, respectively).

Ten down surge events exceeding 100 cm were recorded, predominantly in August, October, and December at Peshnoy Station. These include June 1996 (1.15 m), July 2021 (1.1 m), August 2020 (1.05 m and 1.23 m), September 2015 (1.17 m), October 1953 and 1967 (1.19 m and 1.31 m, respectively), November 2017 (1.14 m), and December 2017 and 2020 (1.06 m and 1.04 m, respectively).

For the Kazakh sector of the Caspian Sea, up surge winds primarily originate from the southwest, west, and southeast directions. Wind speeds during up surges remain relatively consistent across seasons and directions, averaging around 10 m/s. The dominant wind directions during up surges vary seasonally: winter (southeast, southwest, west), spring (southwest, west), summer (southwest, west), and autumn (west, southeast). Up surges exceeding 100 cm in height are most frequently associated with southwest and west-southwest winds.

Down surge winds predominantly originate from the north and northwest directions, accounting for 26% and 21% of the total, respectively. The seasonal distribution of down surge winds is as follows: winter (north, northwest), spring (north, northwest), summer (north), and autumn (north, northeast, northwest, east). Among the stations analyzed, Peshnoy Station exhibits the highest frequency of surge events. Figure 5 illustrates the monthly occurrence of surges at Peshnoy Station, with the highest frequency of up surges observed in March–May. In other months, maximum up surge heights range from 60 to 129 cm. This suggests that up surges of 60 cm can occur year-round, while those exceeding 100 cm are more likely during spring and autumn.

The maximum short-term sea level decline occurs between June and November. In other months, the maximum sea level rise ranges from 72 to 106 cm. This suggests that up surges of approximately 70 cm can occur year-round, while those exceeding 100 cm are more likely during summer and autumn (Fig. 5). The statistical analysis of surge events that took place in the period 1940–2022 in the Kazakhstan part of the Caspian Sea revealed that the mean height of the level change is 40 cm, with the highest-level fluctuations recorded at up to 184 cm. It is also noteworthy that surge events are observed on a monthly basis, with the majority occurring during the spring and autumn months, and a significant proportion of these surges manifesting in autumn.

A distinctive characteristic of surge fluctuations is their rapid temporal and spatial variability. Therefore, when planning economic development in the open and coastal areas of

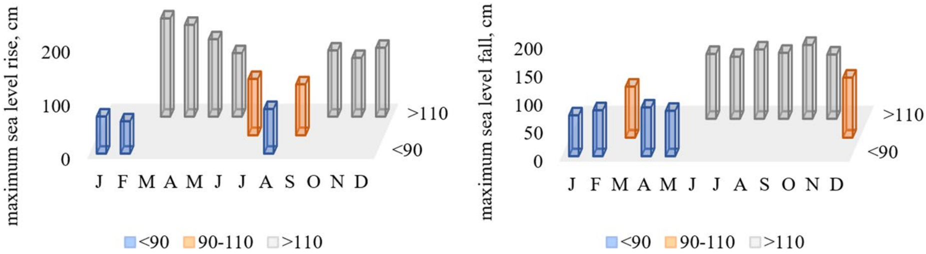

Fig. 5 Statistics of up and down surge according to Peshnoy Station for the period 1940–2022

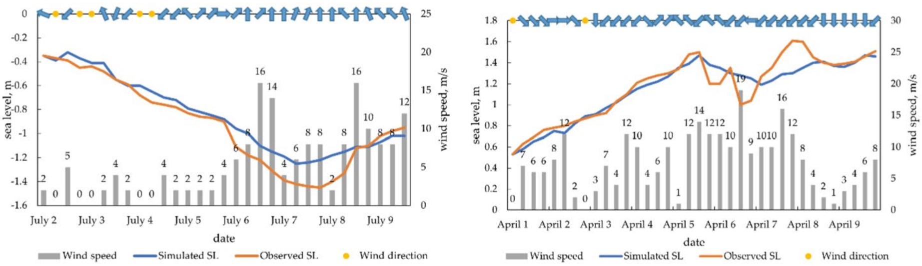

Fig. 6 Sea level at Peshnoy marine station

the Caspian Sea, it is crucial to consider not only statistical characteristics but also the maximum heights of up and down surges and their spatial extent. Given the limited number of sea level observation stations along the Kazakh coast, it is essential to complement observational data with numerical modeling and Earth remote sensing techniques.

In this regard, the present work proposes a retrospective calculation of the positions of the water surface in the north-eastern part of the Caspian Sea during 14 cases of particularly hazardous surge events from 1946 to 2021. These events resulted in sea level changes exceeding 1 m, as presented in Table 4.

The modelling results showed a sufficiently high convergence with the observed data at the Peshnoy station. Multiple regression analysis revealed that sea level variations during storm surges are largely explained by wind characteristics (speed and direction). For example, the down surge situation that occurred in the period from 4 to 10 July 2021 due to the northerly wind with a speed of 16 m/s (Fig. 6). The agreement between the observed and modelled data was sufficiently high, the correlation coefficient was 0.98, RMSE 0.11, coefficient of determination 0.95, coefficient of efficiency 0.86, index of agreement 0.97, MAE 0.09 m. Correlation between the modeled levels and wind speed was 0.66, while accounting for wind direction increased it to 0.91. The strongest influence was exerted by northern and north-eastern winds. These results confirm the key role of northern winds in short-term sea level drops and underscore the importance of considering not only wind speed but also wind direction when forecasting hydrological conditions. The modelling of the up surge formed on 1–9 April 1999 under the influence of an easterly wind of 12 m/s (with gusts of wind to 19 m/s) and its comparison with the observed data showed that the correlation coefficient was 0.93, the RMSE 0.11, the coefficient of determination 0.86, the coefficient of efficiency 0.83, the index of agreement 0.96, and the MAE 0.07 m (Fig. 6). During the up surge period, sea level rises under the influence of southerly winds, while northerly winds cause it to fall. The relationship between wind speed and direction and sea level was found to be statistically significant (R2 = 0.71, p < 0.001).

As a result of modelling, maps of changes in the water surface position of the north-eastern part of the Caspian Sea were constructed (Fig. 7). Zones of drying and flooding during dangerous surge events were determined. According to Table 4, during the particularly hazardous surge events, peak wind speeds reached up to 20 m/s. It should be noted, however, that wind speeds as high as 28 m/s have been observed over the Caspian Sea during surge events, although the associated sea level variations didn't attain critical thresholds. This discrepancy attributed the prevailing wind direction: southerly winds were predominantly associated with up surge events, whereas northerly winds were more characteristic of down surge conditions.

The simulation results were validated against satellite images to assess deviations from the actual coastline. This comparison involved analyzing the water surface area of the north-eastern Caspian Sea using Sentinel satellite images and the Normalized Water Difference Index (NDWI). However, due to limited image availability and cloud cover, the comparison was restricted to two episodes. Despite these limitations, the comparison revealed a 3–4% deviation between the simulation results and actual data (Table 3).

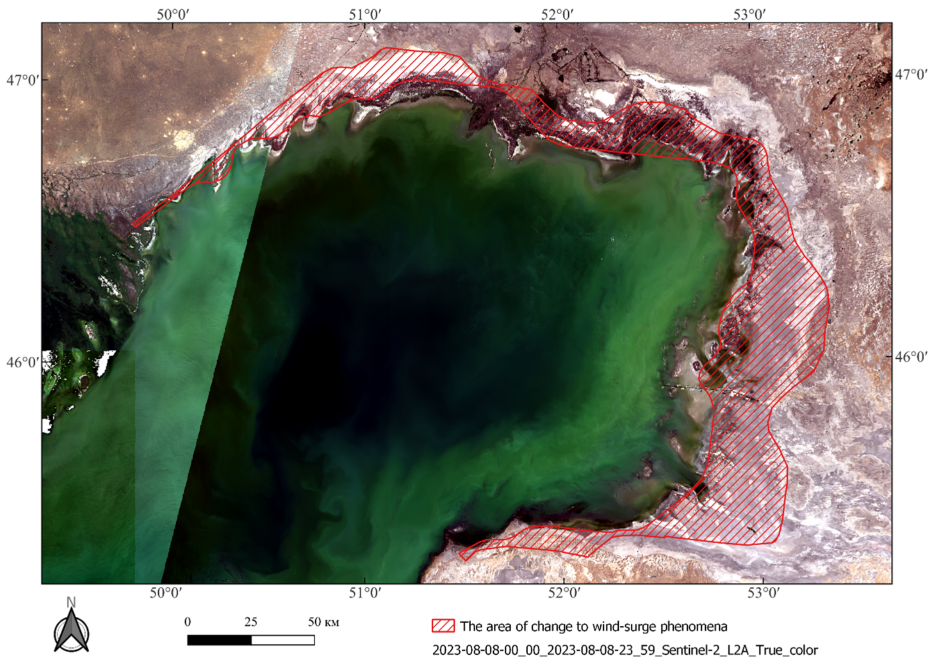

Fig. 7 Vulnerability to surges in the Kazakh Sector of the Caspian Sea

Table 3 Monthly up and down surge characteristics for 1940–2022

Date of occurrence of the phenomenon	The area of the water mirror according to remote sensing data, km^2	Area of the water mirror according to the simulation results, km^2	Deviation, km^2 (%)
December 1–8, 2020	23,407	24,130	723 (3)
July 4–10, 2021	23,174	22,278	896 (4)

Table 4 Characteristics of surge phenomena

Date of occurrence of the phenomenon	Sea level change, cm	Prevailing wind direction and maximum wind speed	The maximum distance of changing the position of the coastline, km
July 1–4, 1946	+105	west southwest, 20 m/s	33.5
October 22–24, 1953	−119	northwest, 9 m/s	20.5
October 3–6, 1967	−131	southeast, 7 m/s	19.5
October 27–29, 1969	+124	west, 12 m/s	29.9
October 30–31, 1975	+109	south southwest, 16 m/s	16
April 16–22, 1987	+111	southwest, 12 m/s	20.3
December 12–15, 1991	+129	southwest, 16 m/s	29.2
June 20–23, 1996	−115	northeast, 14 m/s	32.2
April 1–7, 1999	+129	southwest 16 m/s	19.6
April 10–12, 2000	+172	southwest 16 m/s	21.7
December 2–5, 2017	+128	southeast, 12 m/from	29.6
December 6–9, 2017	−106	the southeast, 12 m/s	14.6
December 1–8, 2020	−104	northeast, 10 m/s	10.2
July 4–10, 2021	−110	north, 16 m/s	17.2

4 Discussion

The modeling results yielded maps illustrating changes in the water surface position (drainage and flooding zones) within the northeastern Caspian Sea (Fig. 7). Additionally, the maximum distances of these changes were calculated and presented in Table 4.

Hydrodynamic simulations for the Atyrau region in the northeastern Caspian Sea reveal that particularly hazardous up surge events—although infrequent—can result in extensive inland flooding ranging from 16 to 33.5 km, driven by the combination of high wind energy and extremely gentle coastal slopes. Conversely, down surges may cause shoreline retreat of up to 32.2 km into the sea. These findings demonstrate the spatial severity of surge impacts and underscore the vulnerability of the region's low-lying coastal zones (Fig. 7).

Mapping coastline changes during recent extreme events has enabled a detailed analysis of coastal evolution under high-energy meteorological forcing. While the simulation results generally exhibit strong agreement with observed sea levels and satellite-derived shoreline data, it is important to acknowledge that model uncertainty may result in underestimation of flood extents, particularly in flat topographies with complex wetting and drying dynamics. The statistical and modeling results underscore the multifaceted nature of surge dynamics in this region. Although a decline in the number of surges exceeding 0.5 m has been observed in recent years—consistent with trends reported by Pavlova et al. (2021)—surge events exceeding 1 m have occurred approximately 30 times between 1940 and 2022, indicating that extreme events remain a persistent hazard.

One of the key insights derived from this study is the temporal variability of surge events. The observed seasonal peaks—up surges predominantly occurring in spring and autumn and down surges reaching their highest frequency in autumn—are indicative of the critical role played by atmospheric dynamics in surge generation. The correlation between surge frequency and wind patterns aligns with previous research that attributes surge events to the prevailing atmospheric circulation systems, including the Siberian winter maximum and Iranian-Afghan summer minimum. Such findings reaffirm the necessity of incorporating seasonally driven wind dynamics into predictive models.

Spatially, the gentle coastal slopes and shallow bathymetry of the northeastern Caspian Sea amplify the impacts of surge events, as evidenced by the extensive coastal flooding (up to 33.5 km inland) and retreat (up to 32.2 km offshore) observed during extreme events. These spatial dynamics underscore the vulnerability of the region to both up and down surges, with implications for coastal infrastructure, ecosystems, and human settlements. The study's use of high-resolution hydrodynamic modeling has provided granular insights into these spatial impacts, facilitating the identification of high-risk zones.

From an environmental standpoint, surge events threaten both terrestrial and aquatic ecosystems. Up surges can inundate large tracts of land, altering salinity profiles and degrading freshwater resources, while down surges intensify erosion processes and cause habitat loss for estuarine and marine species. These dual processes contribute to ecological instability, particularly in sensitive transitional zones. From an infrastructure perspective, the findings highlight significant risks to ports, oil and gas extraction facilities, and coastal communities. The study's identification of high-risk zones provides a valuable tool for policymakers and engineers tasked with designing resilient infrastructure. For instance, the observed correlation between surge height and wind speed suggests that infrastructure designs should account for extreme wind scenarios to mitigate damage. Additionally, the data underscore the importance of maintaining robust observation networks and predictive models to support early warning systems.

The methodological framework employed in this study—combining historical data, hydrodynamic modeling, and satellite-based validation—represents a significant advancement in surge event analysis. The use of ERA5 reanalysis data for wind and pressure inputs has ensured high temporal and spatial resolution, enhancing the accuracy of model outputs. Furthermore, the retrospective modeling of extreme events has provided valuable insights into the historical dynamics of surge phenomena, enabling the calibration and validation of predictive models. Despite these strengths, the study identifies several limitations. The sparse spatial coverage of sea level observation stations along the Kazakh coast constrains empirical validation at broader scales, requiring reliance on modeled estimates. Although satellite-derived shoreline mapping using NDWI provided validation within a 3–4% deviation, the availability of high-quality, cloud-free imagery remains a limiting factor. Enhancing the observational network and incorporating alternative remote sensing sources (e.g., radar) would significantly improve future assessments.

Finally, while the focus on the northeastern sector is justified due to its unique morphological and hydrodynamic conditions, the generalizability of these findings to other regions of the Caspian Sea is limited. Extending this methodological framework to other sectors—such as the southern and western coastal zones—will support the development of a basin-wide surge hazard understanding and enable transboundary coastal risk planning.

5 Conclusions

This study provides a comprehensive contribution to understanding surge phenomena in the northeastern Caspian Sea. Integrating long-term historical records, hydrodynamic modeling with MIKE 21, and satellite-based validation allowed for the analysis of the spatial and temporal dynamics of 1836 surge events between 1940 and 2022, leading to the identification of critical risks to coastal ecosystems, infrastructure, and socio-economic activities. The modeling of 14 particularly hazardous cases revealed that surge-induced coastal flooding can extend up to 33.5 km inland, while down surges can cause shoreline retreat up to 32.2 km, especially in areas characterized by extremely gentle coastal slopes.

The Caspian Sea's closed hydrological nature makes it highly sensitive to sea level fluctuations. Resulting changes in coastline position directly affect habitats of rare flora and fauna and disrupt key human activities such as fishing, maritime transport, oil and gas operations, and recreation. Understanding the magnitude and frequency of surge-related changes is essential for informed decision-making aimed at minimizing environmental and socio-economic impacts, particularly under future climate change scenarios. Intensified storm activity and sea level shifts—whether rising or falling—are expected to accelerate coastal erosion and morphological deformation, amplifying regional development challenges.

The variable duration of storm events, combined with the shallow bathymetry and low topographic gradients of the region, amplifies the impacts of both up and down surges. These findings underscore the need for protective infrastructure and adaptive coastal management strategies.

The results highlight the importance of continuous monitoring and forecasting of surge dynamics in order to manage risks related to coastline changes and ensure long-term sustainability of coastal areas. They offer practical tools for authorities and planners to prevent environmental degradation and economic losses across the Caspian region.

Future research should focus on incorporating climate change projections into hydrodynamic models to assess how surge dynamics might evolve under different greenhouse gas scenarios. Rising sea levels and increased storm intensity driven by global warming are likely to exacerbate surge impacts, requiring adaptive and forward-looking coastal planning. Additionally, coupling hydrodynamic models with ecological and economic modules could enable more holistic assessments of surge-related consequences, including habitat loss, fishery disruption, and infrastructure vulnerability. Finally, the integration of machine learning techniques for pattern recognition and predictive enhancement could complement traditional numerical and statistical tools, opening new perspectives in the analysis and forecasting of surge events.

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Author contributions All authors contributed to the presented study. Conceptualization, S.B.S. and A.G.Y.; methodology, S.B.S. and A.G.Y.; software, A.G.Y., N.T.S. and T.A.T.; formal analysis, S.B.S. and A.G.Y.; investigation, A.G.Y., J.R.-I. and M.-E.R.-C.; resources, A.G.Y. and JR-I.; data curation, T.A.T. and D.B.R.; writing—original draft preparation, A.G.Y. and S.B.S..; writing—review and editing, A.G.Y. and M.-E.R.-C.; visualization, N.T.S., J.R.-I. and M.-E.R.-C.; supervision, S.B.S. and A.G.Y.; project administration, S.B.S. All authors have read and agreed to the published version of the manuscript.

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Declarations

Conflicts of interest Not applicable.

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