MODELING OF BERM FORMATION AND EROSION AT THE SOUTHERN COAST OF THE CASPIAN SEA

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Cross-shore beach profile data from field measurements performed at six locations on the southern coast of the Caspian Sea are used to investigate bathymetry change due to various wave conditions. Beach profile measurements are analyzed and subsequently compared with the results of a berm formation and erosion model. The model comprises distinct empirical sediment transport equations for predicting the cross-shore sediment transport rate under various wave conditions. To yield a berm formation and erosion model, empirical cross-shore sediment transport equations are combined with the mass conservation equation. Simulations results obtained from the model compared well with the measurements, proving the capability of the model in simulating berm formation and erosion evolution.

Keywords: berm formation and erosion modeling; cross-shore sediment transport; field measurements

INTRODUCTION

Coastal regions experience different waves and tidal levels continuously; therefore, beach face responds to fluid motion. According to wave characteristics and tidal conditions, sediment moves either landward or seaward. Berms typically form during mild wave conditions and erode during storms. When the fluid motion is low, the sand grains move as a bed-load sediment transport. If the fluid motion increases, then a saturated layer of sediment starts moving as sheet-flow sediment transport. Once the fluid motion becomes sufficiently high, the hydrodynamic forces lift the sand particles into the water column, and suspended sediment transport will be dominant.

The berm encounters uprush and backwash. Consequently, intermittent flows vary rapidly in this wet/dry zone and high gradients and values of sediment concentration and transport are yielded. Because of the high gradients of the flow velocities, all mechanisms of sediment transport should be considered and expected to contribute to berm formation and erosion analysis. In other words, all the mechanisms may affect berm formation and erosion. However, because of the complex mechanisms between water and sediment layers, it is difficult to model and calculate all the relationships.

To predict berm formation and erosion, several numerical models have been developed and applied in many coasts in recent years. Many different complex processes from offshore to onshore should be considered when modeling sediment transport mechanisms and beach profile responses. Owing to these complexities, morphodynamic models generally cannot resolve morphodynamic processes explicitly. Therefore, most morphodynamic models cannot reproduce the results correctly under various wave conditions in different coastal regions. Nevertheless, researchers (e.g., Larson and Kraus 1989; Southgate and Nairn 1993; Roelvink et al. 2010; Kobayashi et al. 2008; Jayaratne et al. 2014; Tabasi et al. 2017) have continued their efforts to propose morphodynamic models to obtain reasonable results by improving hydrodynamic and morphodynamic calculations. The hydrodynamic and morphodynamic equations of these models include free parameters that should be calibrated for each specific site to achieve reasonable results.

In this study, a numerical model was used to predict berm formation and erosion under various wave conditions and timescales. The model simulates the evolution of the berm in connection to erosion and accretion based on different wave conditions. It is noteworthy that multiple simulations of berm formation and erosion in various locations with different wave conditions can offer a better judgment regarding the model performance. Therefore, a number of cross-shore beach profiles in the Caspian Sea were measured in different seasons of the year to validate the numerical model.

In the first section of this paper, field measurements, their locations, and wave datasets for evaluating the performance of the proposed morphodynamic model are described. The second section presents the fundamental governing equations for the calculation of the hydrodynamics and morphodynamics. The structure of the computer program for the model setup is provided in the third section. Section fourth summarizes the results of the model for different cross-shore beach profiles in the Caspian Sea. In addition, the model performance is compared with the field measurement results in this section.

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BEACH LOCATIONS AND DATA DESCRIPTION

The southern coasts of the Caspian Sea located in Iran were selected for this study (see Fig. 1). The coastline stretches from 49˚E to 59˚E latitude for a distance of 820 km and is partitioned into three provinces. Furthermore, the southern coastlines of the Caspian Sea are primarily composed of sandy beaches. The cross-shore beach profiles considered in this study were those from Ataei et al. (2018). They reported that these profiles were predominantly composed of sediment, with the median grain size varying from 0.17 to 0.23 mm. Coastal regions with a significant distance in each province were selected for the field measurements. The coastal regions investigated were as follows:

- Astara and Dastak in the Guilan province
- Namakabrud, Mahmudabad and Larim in the Mazandaran province
- Miankaleh in the Golestan province

Cross-shore beach profiles were measured for each coastal region from 2013 to 2014. Although the profiles were measured from offshore to onshore, only the nearshore elevations of the measured profiles were required for modeling. In fact, the measurement of profiles in areas close to the shoreline should be easy as those areas are easily reachable, and the flow is extremely shallow. Nonetheless, compared with the offshore zone, the bed profile near the shore changed rapidly owing to the high gradient of the flow velocity and the sediment concentration in the nearshore zone. Therefore, the frequency of the measurements in the nearshore region should be significantly higher compared to other regions.

Owing to insufficient measured filed data, a hindcast dataset comprising every-three-hour intervals was employed to obtain wave parameters such as significant wave height and mean period in the present study. The values of each wave parameter provided in the dataset were from 1998 to 2003, i.e., a five-year average of wave parameters was used in the simulation. Fig. 2 shows box plots of the hindcast wave height and the period for the abovementioned locations. The wave heights and periods corresponded to different periods of the year. Hence, the wave characteristics differed according to season. The whiskers above and below the boxes indicate the maximum and minimum values, respectively, of the wave height and period in the time histories of the datasets. The central marks on each box plot indicate the median, whereas the top and bottom edges of the boxes represent the 25th and 75th percentiles for each dataset, respectively. The mean wave heights ranged from 0.7 to 1 m, whereas the wave periods ranged from 4.8 to 5.3 s. Additionally, 75% of the wave heights and periods were approximately below 1 m and 5.3 s, respectively. This reflects that both wave heights and periods are within a reasonable margin.

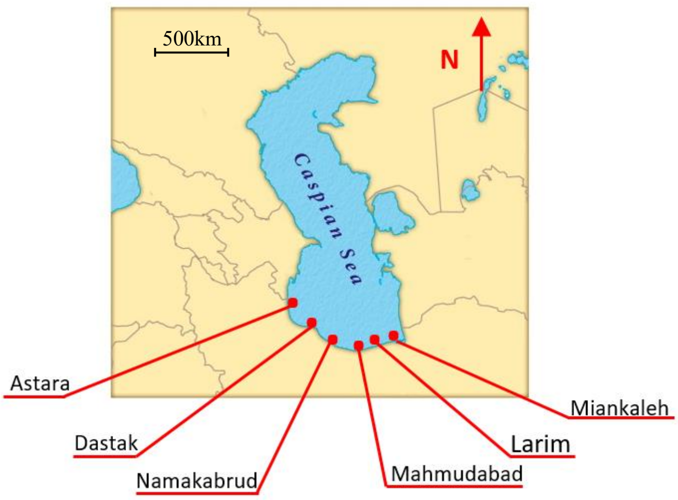

Figure 1. Locations of measured (field) beach profiles in the Caspian Sea (Iran).

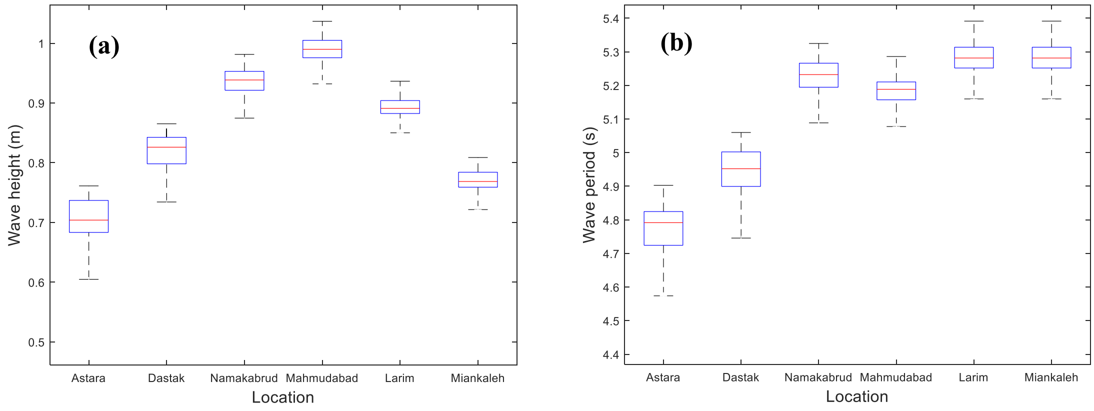

Figure 2. Wave condition for each coastal region of Caspian Sea; (a) significant wave height and (b) mean wave period.

MODEL DESCRIPTION AND BOUNDARY CONDITIONS

Several studies regarding berm formation and erosion have been published. In some research studies, berm formation and erosion were investigated qualitatively as well as quantitatively (e.g., Duncan 1964; Strahler 1966; Thomas and Baba 1986; Larson et al. 2004). Meanwhile, some researchers have proposed various empirical relationships between wave conditions and berm characteristics (e.g., Bagnold 1940; Bendixen et al. 2013). To simulate the effects of various wave conditions on beach morphology, numerous numerical morphodynamic models have been developed and formulated with various levels of complexity. Generally, morphodynamic models determine bed-level changes in association with the quantification of volumetric sediment transport. The model formulation can be classified into analytical, behavioral, empirical, semi-empirical, and process-based categories. In the present study, the numerical model proposed by Suzuki and Kuriyama (2008) pertaining to the relationship between berm formation and erosion was applied.

To investigate the correlation between hydrodynamic parameters and morphological changes, different thresholds for berm formation and erosion have been proposed. Larson and Kraus (1989) utilized data from Japanese, American, and Canadian beaches for the classification of erosion and accretion events. They hypothesized a relationship between sand fall velocity and wave characteristics. Similarly, Wright and Short (1984) proposed a dimensionless fall velocity parameter using data from three years of observation at 26 beaches around Australia. Furthermore, they classified beaches into dissipative, intermediate, and reflective based on a dimensionless fall velocity. Flater profiles tend to be formed as dissipative beaches by high energy wave conditions, whereas steeper profiles with a greater amount of sand volume tend to form as reflective beaches. In this study, the model comprised different berm formation and erosion sub-modules based on wave run-up to estimate the sediment transport rate. If the wave run-up reaches the top of the berm, then berm erosion will occur. Otherwise, the berm will form and further develop (see Fig. 3).

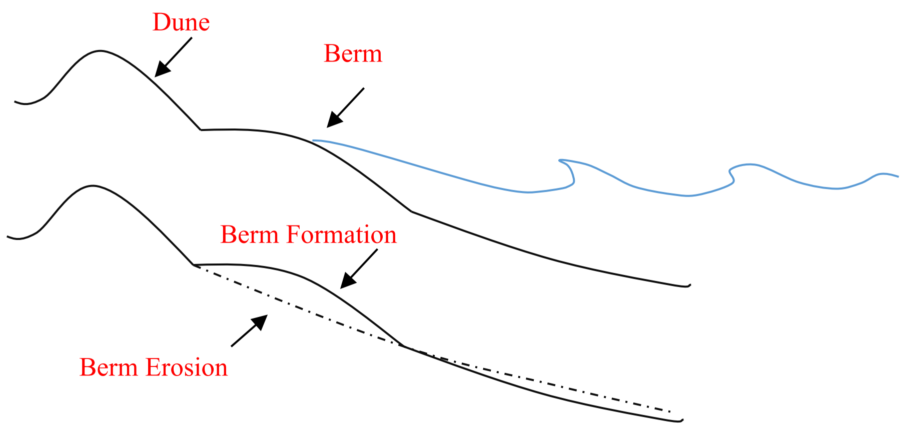

Figure 3. Schematic diagram of berm formation and erosion

Berm formation

To manage coastal zones, the formation and evolution of berm accretion processes must be predicted. Generally, berm forms after a storm event (beach recovery) and in seasonal variable conditions. However, the simulation of berm formation in numerical models has not been achieved at a high degree of accuracy owing to the deficient understanding of associated highly complex processes, such as the different characteristics of waves, currents, and morphologies.

Numerous studies that involve the physics of berm formation have been conducted. Hine (1979) presented a comprehensive study regarding berm formation and classified berm formation processes into three different mechanisms based on hydrodynamic and morphodynamic characteristics. Weir et al. (2006) added two more modes of berm formation to Hine's theory. Sunamura and Horikawa (1974) proposed a threshold by considering the median grain size (D_{50}) for berm formation. Jensen et al. (2009) performed a study to identify the main factor controlling berm formation on gentle slope beaches.

In this study, for the modeling berm formation, the foreshore was partitioned into two zones. The offshore boundary was defined at the shoreline location and set as $x/X = 1$, where x and X are the cross-shore position and distance between boundaries, respectively. Furthermore, the onshore boundary was defined at the cross-shore location of the maximum wave run-up elevation and set as $x/X = 0$. The boundary between the lower and upper zones was defined as $x/X = 0.7$ (see Fig. 4).

The sediment transport rate tended to increase gradually from $x/X = 0$ to 0.7 in the form of a quadratic relationship. Meanwhile, the rates from $x/X = 0.7$ to 1 were assumed to be constant. The sediment transport rate at $x/X = 0.7$ is expressed as shown in Eq. (1).

$$Q_{f\_0.7} = 1.15 \times 10^{-7} E_f + 0.49. \quad (1)$$

The offshore energy flux is expressed as $E_f = \frac{1}{16}\rho g (H_{1/3})^2 C_g$, where ρ is the seawater density, g the gravitational acceleration, $H_{1/3}$ the significant wave height, and C_g the group velocity.

Berm erosion

In this study, for the berm erosion cases, the model partitioned the foreshore into three distinct zones (see Fig. 4). The sediment transport rate increased from $x/X = 0$ to 0.15 and decreased from $x/X = 0.15$ to 0.7.

$$\begin{cases} Q_{e\_0.15} = 2.06 B_h - 0.29 \\ Q_{e\_0.7} = -3.07 B_h - 1.17 \end{cases} \quad (2)$$

where $Q_{e\_0.15}$ and $Q_{e\_0.7}$ are the sediment transport rates for berm erosion at $x/X = 0.15$ and $x/X = 0.7$, respectively, and B_h is the berm height. The free parameters included in the sediment transport equations for both berm formation and erosion conditions can be calibrated based on the characteristics of the sites.

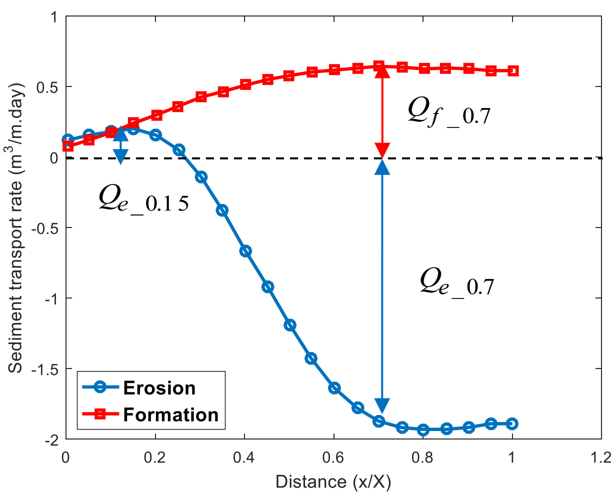

Figure 4. Sediment transport rate by Suzuki and Mochizuki (2014).

Bed level update

The final step in the bed profile simulation is the bed-level update. In this step, bed level changes due to the total sediment transport rate should be calculated using the mass conservation equation as follows:

$$\frac{\partial z_b}{\partial t}+\frac{1}{1-p}\left(\frac{\partial q_x}{\partial x}\right)=0, \quad (3)$$

where z_b is the bed level, ∂t the time step for simulation, p the porosity, q_x the sediment transport rate, and x the cross-shore distance.

MODEL SETUP

A computer program was written in MATLAB to simulate berm formation and erosion. The model grids had a constant cell spacing of $dx = 1\ m$. The model can be used for irregular waves for the full duration of modeling. The bed level changed owing to the spatial gradient of cross-shore sediment transport. Therefore, the model was sensitive to the free parameters included in the sediment transport equations. In other words, to simulate the bed level changes accurately, the free parameters of the sediment transport equations should be optimized via trial and error during the calibration process. Measured cross-shore profiles, offshore wave heights, and water levels were defined as the inputs to the program. The program comprised three tiers for the calculation of beach profile changes, as follows:

1. The offshore energy flux was calculated and the wave run-up levels estimated;
2. Erosion/formation was determined, and related relationships (Eqs. 1 or 2) were employed for the sediment transport rate calculations;
3. Beach profile updated using sediment mass conservation equation.

In this computer program, waves were classified into destructive and constructive types based on the wave run-up threshold; subsequently, seaward and landward sediment transport fluxes were estimated using the distinct modules.

RESULTS AND DISCUSSION

This study focused on berm formation and erosion at the southern coasts of the Caspian Sea. Fig. 5 and 6 show the comparison results of the model simulations and field measurements during different seasons for all beaches. According to the wave conditions, berm formation and erosion occurred. Furthermore, the results of the field sites justified the performance and reliability of the numerical model.

The Brier skill score (BSS) is a useful method for evaluating model performance. The BSS has been widely applied in beach profile modeling by Splinter et al. (2014), Berard et al. (2017), and Tabasi et al. (2018). The BSS applied to the prediction of beach erosion and formation can be expressed as follows:

$$BSS = 1-\frac{\sum(|Z_m-Z_s|)^2}{\sum(|Z_m-Z_i|)^2}, \quad (4)$$

where Z_m is the bed elevation after erosion and formation, Z_s the final simulated bed elevation, and Z_i the initial bed level. Using BSS values, Van Rijn et al. (2003) categorized the performance of coastal morphodynamic models, as listed in Table 1. A BSS value approaching 1 indicates better model performances compared with lower values. The BSS values revealed that the model agreed well with the field measurements for both berm formation and erosion conditions.

Table 1. Classification of Brier Skill Score (BSS) by Van Rijn et al. (2003).

Score	Bad	Poor	Fair	Good	Excellent
Classification	<0	0–0.3	0.3–0.6	0.6–0.8	0.8–1.0

The erosional conditions for the Mahmudabad and Namakabrud beach profiles were dominant during the periods July 6–November 6, 2013, and November 25, 2013–January 8, 2014, respectively. Meanwhile, berm formation was the most effective during the periods May 6–October 19 and June 29–November 1, 2013; December 21, 2013–January 13, 2014; and October 12, 2013–January 16, 2014, at Miankaleh, Larim, Dastak, and Astara beaches, respectively. The durations of model simulations and wave characteristics for each site are summarized in Table 2.

Table 2. Duration of model simulation and wave parameters for selected beach profiles.

Beach	Mahmudabad	Namakabrud	Miankaleh	Larim	Dastak	Astara
Duration of Simulation (days)	123	44	166	125	23	96
Mean Wave Height (m)	0.71	0.80	0.64	0.71	0.71	0.62
Mean Wave Period (s)	4.85	4.95	4.50	4.80	4.65	4.77
Mean Wave Direction (°)	192.5	87.6	293.0	250.0	93.0	77.0

As shown in Table 2, the model incorporates the ability for onshore and offshore sediment transport with beach profile predictions ranging from short to medium time scales. As an example, for berm formation modeling, the model demonstrated high performance in simulating the Dastak profile in 23 days as well as the Miankaleh profile in 166 days. However, the duration of simulation for berm formation is expected to be relatively longer than that for berm erosion.

The net sediment transport rates for the Miankaleh, Larim, Dastak, and Astara beaches during the study were primarily landward, and berm formation occurred continuously across the beach profile (see Fig. 5). Although berm was formed in the Miankaleh, Larim, Dastak, and Astara profiles, the net sediment transport rates were not completely landward, and the direction of sediment transport shifted between onshore and offshore based on the wave conditions. Therefore, berm erosion/formation couplet patterns frequently appeared during the measurements. Similarly, in the Mahmudabad and Namakabrud profiles (see Fig. 6), the sediment transport was primarily seaward and erosion occurred; however, berm erosion/formation couplet patterns appeared during the model simulation.

The calculated BSS values are shown in Figs. 5 and 6. As depicted in Fig. 5, the model performance was excellent for all the berm formation cases except that of Astara. In addition, the BSS values in Fig. 6 show that the model performance was excellent and good for the Nakamabrud and Mahmudabad cases, respectively. The average BSS values for berm formation and erosion were 0.80 and 0.77, respectively. These values signified satisfactory performances for both the berm formation and erosion cases. Meanwhile, as no significant difference was observed between the average BSS values, it was difficult to judge the case in which the model performed better.

Finally, the accurate prediction of the sediment transport rate is crucial for simulating beach profile changes. The sediment transport rate relationships comprise the wave energy flux, berm height, and numerical (free) constants. They can be fitted with the field observations using a time series of wave characteristics with daily intervals and by changing the numerical constants.

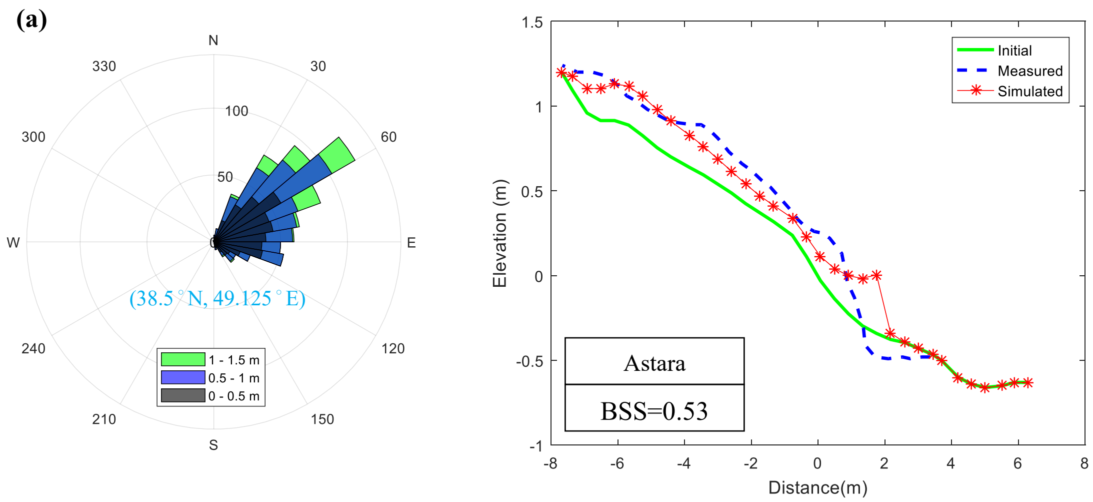

Figure 5. Right panels: Evolution of berm formation in Astara (a), Dastak (b), Larim (c), and Miankaleh (d) for measured (blue dashed line) and simulated beach profiles (red asterisk line). Green lines represent initial beach profiles. Left panels: Hindcast wave rose.

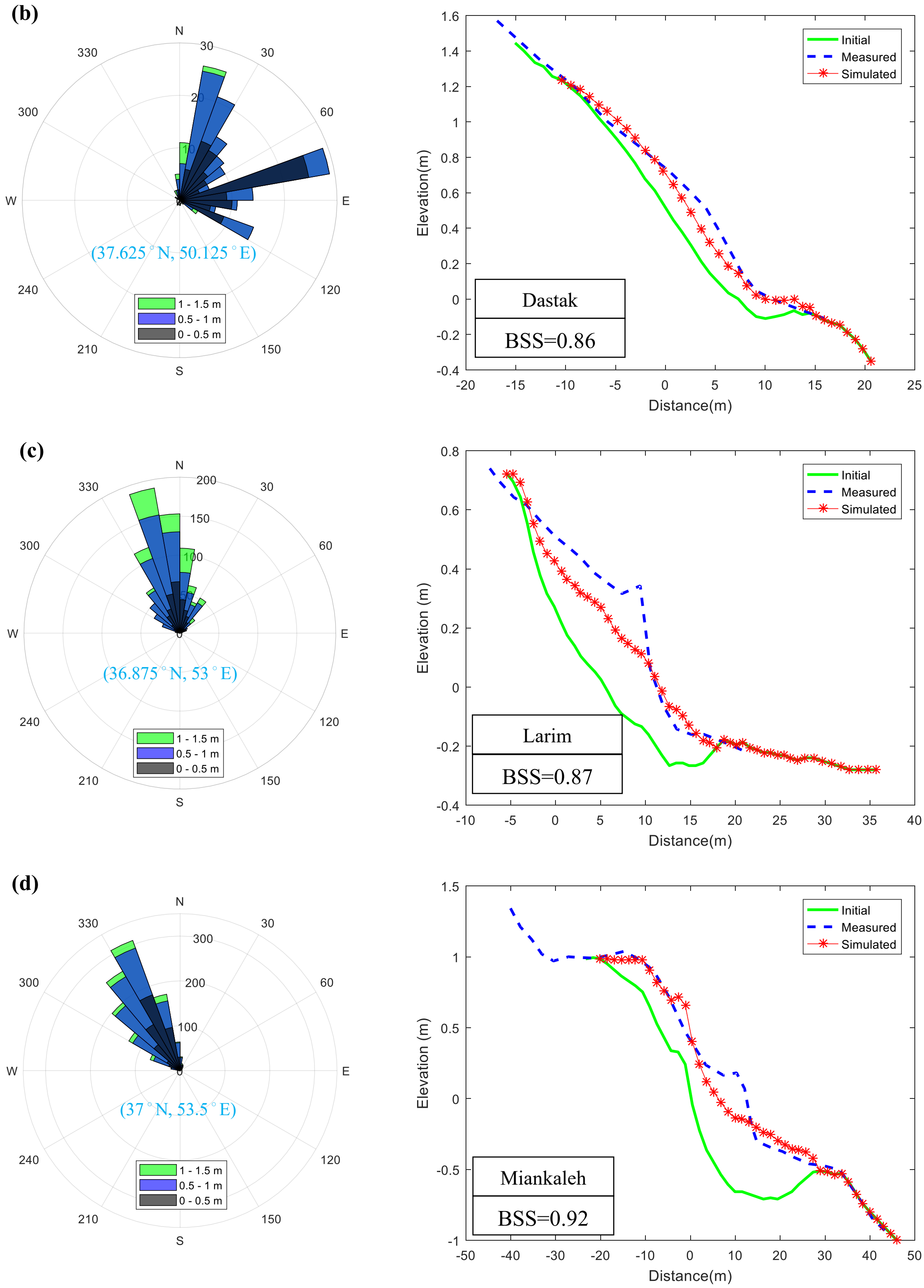

Figure 5. (Continued)

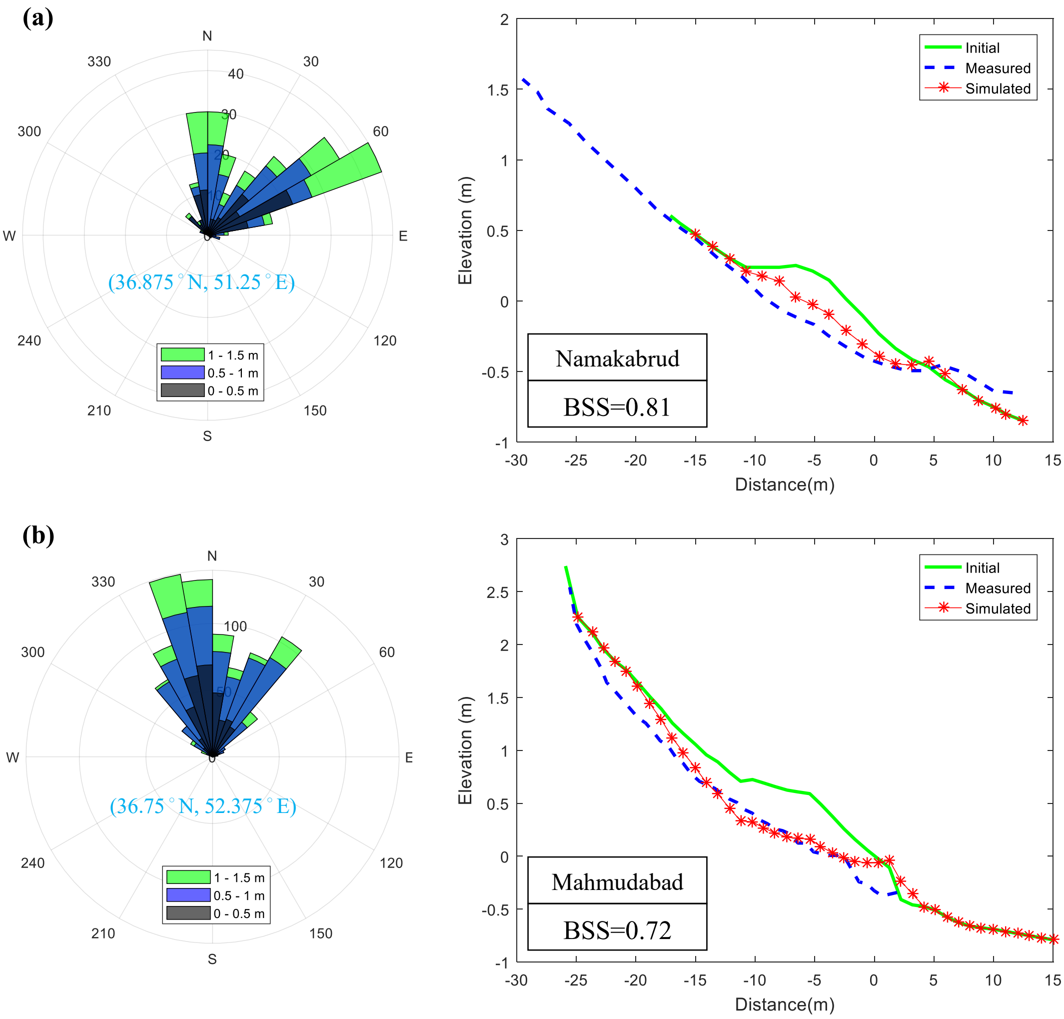

Figure 6. Right panels: Evolution of berm erosion in Namakabrud (a) and Mahmudabad (b) for measured (blue dashed line) and simulated beach profiles (red asterisk line). Green lines represent initial beach profiles. Left panels: Hindcast wave rose.

CONCLUSION

Numerous studies and numerical coastal erosion models have been performed and developed with varying levels of complexity. It was discovered that beach profile evolution models performed better in simulations of berm erosion compared with those of berm formation. In other words, the lack of capability for predicting berm formation or beach recovery is still a significant challenge for most coastal morphodynamic models. Meanwhile, the BSS values proved that the model used in this study performed reliably in simulating both berm formation and erosion. Additionally, multiple erosion/formation couplets that appeared within the modeled period were simulated successfully. Finally, the model computation time was low, and depending on the simulation duration, the model compiling time was within seconds to minutes.

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