CROSS-SHORE MODELLING FEATURES: CALIBRATION WITH EXTENSIVE DATABASES

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Coastal areas face continuous changes due to natural and anthropogenic influence. These dynamic environments experience short- and long-term fluctuations due to erosion, accretion and alterations in sediment transport patterns. Understanding and predicting these changes is important for coastal management and for mitigation of the risks associated with flooding, shoreline retreat and land loss. In the present work, a medium-term cross-shore numerical model (CS-Model) was applied for four profiles in IJmuiden beach (north and south), The Netherlands, over 40 years, and the model performance was evaluated, considering extensive datasets. The long period of analysis was divided into 3 smaller periods, each of them subdivided in 5-, 10-, 15- and 20-years' time intervals considered for model calibration, and 2 other selected periods, for model validation. By evaluating the Mean Absolute Error (MAE), the numerical model results show that the berm position (Y_B) is more sensitive to changes than the seaward dune toe position (Y_S), and this behavior is related to the contribution of alongshore sediment transport and its gradients in the study area. The model calibration presents good agreement between observed and modeled values of Y_B and Y_S. The validation time assumed in simulations shows a deviation trend of the calibration time, increasing the MAE. The use of the most recent years to calibrate the model leads to best model performance, reenforcing the importance of data acquisition and updated datasets. Also, when smaller and consistent periods of data are used to calibrate the model, better are the results, allowing to discuss the data extension used for model calibration. The correct calibration and good validation of numerical models using the observed conditions is important to obtain better modelling results, allowing proper coastal management.

Keywords: CS-Model; Accretion Rate; Wind Data; Model Validation; Dunes

INTRODUCTION

Coastal areas are very attractive due to their specific characteristics (abundant amenities, aesthetic value and ecosystem services they provide), being highly densely populated (Luijendijk *et al.*, 2018). The shoreline is naturally influenced by the interactions between climate forcing, sediment dynamics and morphodynamics (Passeri *et al.*, 2015). The dynamic of the shoreline makes coastal areas highly vulnerable to erosion and accretion caused by storms, cyclones, waves action, wind action, tides effect, sea level variations and flooding (Ghadamode *et al.*, 2024). Nowadays, these areas are also affected by population growth, urbanization, industrialization and other anthropogenic activities (Shaik *et al.*, 2024). The communities who live in coastal areas are facing the consequences of the impacts of climate change, especially the combination of rising sea levels and the increase of the storm events frequency, causing significant destruction and changes (Santra *et al.*, 2024).

Numerical modelling is an important tool for representing and understanding the complex dynamic processes that operate in natural or semi-natural environments (Karssenberg *et al.*, 2001). Process-based numerical models are commonly applied in coastal areas for simulating expected morphologic changes. These models have the ability to directly simulate relevant feedback between the shape of the landscape and the hydrodynamics (Saunders *et al.*, 2024). However, model calibration is necessary to find the optimal hydrodynamic, morphodynamic and sediment transport parameters that best represent the physical processes relevant to the space and time scale under analysis (Saunders *et al.*, 2024). The variables of the model must be calibrated with site-specific measured data, to ensure accurate results. The use of site-specific data for model calibration is useful for model precision (Güner & Başaran, 2024).

Different methods can be applied for model calibration. For instance, models can be calibrated using a deterministic approach with simple random sampling over a broad user specified parameter range (Simmons *et al.*, 2017). Another method for calibration was defined by Saunders *et al.* (2024) using a predetermined number of simulations or a convergence tolerance to initiate the calibration process, but this resulted in large number of simulations. In most cases, the simulations performed during model calibration are discarded after the optimal parameter value is determined. Considering the number of completed simulations (large sample size) and the knowledge of all free parameter assignments, there is an opportunity to leverage these trials for subsequent statistical analysis.

Some practical examples of model's calibration can be found in the literature. One example is the work of Güner & Başaran (2024), which have used site-specific measured data to calibrate XBeach model. This model is influenced by numerous free parameters, offering a wide range for evaluating its accuracy when comparing observed and modelled data. The optimal value of each parameter was calibrated through a trial-and-error process, considering the range of values provided in XBeach manual. After the identification of the best parameter value that results in the lowest statistical error, the

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calibration continues by considering other parameters for calibration. Another example is the work of Ma *et al.* (2024) that applies the XBeach model to understand the interactions between wave, dune and vegetation in hurricane attenuation, based on dune profile data collected before and after the event. The vegetation drag coefficient (C_D) is a crucial model parameter to calculate the wave dissipation through the vegetation. This parameter was especially calibrated considering laboratory experiments to analyze the model performance in predicting the interactions between vegetation, waves and dunes against extreme storm conditions. Other method was present in Simmons *et al.* (2019), that calibrates the SBEACH model using Monte Carlo sampling to determine the validity of combinations of model parameters to simulate a real event, calculating the model's skill for each run.

In this work, the CS-Model was chosen to evaluate morphological changes in a specific study area, using long-term profile and wave climate datasets. The model was calibrated through a trial-and-error process to determine the best value that minimizes error by comparing modelled and observed data. Previous studies have calibrated the CS-Model using 40 years of available datasets, showing good agreement between observed and modelled profiles but, the model performance was better when 5-10 years of data were used, instead of long-term datasets (Romão *et al.*, 2024). The calibration process adopted in the present study consisted in the definition of 3 scenarios for model calibration (dividing the available data into 3 different calibration periods) and 2 scenarios for model validation. The model performance in representing the evolution of the berm and seaward dune toe position (Y_B and Y_S, respectively) was evaluated by comparing the differences between the simulated and observed results. Considering the amount of available data, 4 cross-shore profiles were considered in the simulations.

Considering the previous, this document is organized as follows: the study area, the data available, the model description and the initial modeled conditions were defined in the Methodology section; the Results section presents the numerical model simulation results for the calibration and the validation scenarios; after, in the Discussion section, the results are discussed and compared with other numerical studies, emphasizing the time intervals used for model calibration and validation; and finally, the Conclusions section summarizes the main findings of the study.

METHODOLOGY

This section provides a description of the study area, the data available to calibrate and validate the numerical model and the description of the model applied in the simulations. After the description of the model, the initial modeling conditions are described, also including the parameters used in the calibration scenarios, considering the different time periods of analysis.

Study Area

The area chosen to perform the analysis was IJmuiden, located in the central part of the Holland coast, in The Netherlands (Figure 1).

Figure 1. IJmuiden study area, in The Netherlands, also including the cross-shore profiles location (P1 to P4).

Four cross-shore profiles were chosen to represent the study area: two profiles are located at north of the northern groin (P1 and P2) and the other two profiles are located at south of the southern groin (P3 and P4). In this coastal zone, typical wave heights range from 0.1 to 1.5 m, coming mainly from southwest (from 225º counting north, clockwise, on average). Tidal levels are between 1 and 2 m, considering a neap-spring tide cycle (Van Rijn, 2023). Alongshore sediment transport comes from south to north, and was estimated to vary between 115 000 and 395 000 m^3/year (in IJmuiden southern area), with sediments grain size ranging between 0.20 and 0.25 mm. In the northern part of IJmuiden shoreline, it is observed an erosion rate of about 40 000 m^3/year (near P2). However, the erosion is mitigated with continuous yearly beach nourishments (around 200-600 m^3/m in eroding coastal stretches) (Stronkhorst *et al.*, 2018).

Data Available

For the study area, 57 years of profile data (between 1965-2022), 51 years of wave climate data (between 1971-2022), that encompasses wave height, period and direction from an offshore station (52.55º N, 4.06º E) (Rijkswaterstaat, 2024), and 20 years of tide levels (between 2002-2022) are available. Considering the combined range of the available data, the larger time period of the analysis was defined to be between 1979-2020 (the tide level series was replicated to the past, to complete the dataset). Smaller periods of calibration and validation were defined in-between this range. More detailed information about the available data is presented in Romão *et al.* (2024).

Model Description

The model chosen for the analysis was CS-Model (Cross-Shore Model, by Larson *et al.*, 2016), developed to characterize the evolution of the cross-shore profile in a medium-term perspective (few number of years). The typical CS-Model cross-shore profile scheme is presented in Figure 2, with a small number of morphological variables used to represent the shape of the profile: dune toe position (Y_L and Y_S, from land- and seaward sides, respectively); berm position (Y_B), shoreline position (Y_G); depth of closure (D_C); dune height (S); and berm height (D_B). The dune slope is defined by β_L and β_S (land- and seaward sides, respectively) and the berm slope by β_B. The model considers processes related to sediment transported by the wind (q_{WL} and q_{WS}, from land- and seaward sides, respectively), overwash and sediment removed from the dune (q_L and q_S, from land- and seaward sides, respectively), and exchanges between the bar and the berm (q_B), so a bar volume can initially be given (V_B) (Larson *et al.*, 2016).

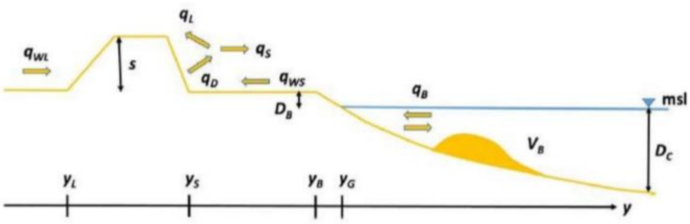

Figure 2. Schematic representation of a beach profile in CS-Model, with the parameter's dune toe position (Y_L and Y_S, from land- and seaward sides, respectively), berm position (Y_B), shoreline position (Y_G), depth of closure (D_C), dune height (S) and berm height (D_B) (adapted from Larson *et al.*, 2016).

Initial Modelled Conditions

The year 1979 was selected as the initial year for model calibration and the 4 cross-shore profiles at that time were approximated to the CS-Model scheme. The dune and berm slopes are determined considering the average value of all the 41 cross-shore profiles available (Table 1).

Table 1. Initial parameters adapted in CS-Model, for all profiles.

Profile	P1	P2	P3	P4
Y_L (m)	55.00	130.00	5.00	0.00
Y_S (m)	195.00	215.00	215.00	170.00
Y_B (m)	210.00	217.82	263.13	182.70
S (m)	9.32	12.92	15.30	16.67
D_B (m)	5.00	3.50	2.00	2.00
β_L (rad)	0.4361	0.3124	0.2152	0.1465
β_S (rad)	0.1324	0.4067	0.2312	0.3949
β_B (rad)	0.0246	0.0279	0.0108	0.0195

An extensive calibration of the CS-Model was conducted, considering all the 41 years of data, to evaluate the model's performance. The Accretion Rate (m/time step), aeolian sediment transport contribution (QWINDS, in m^3/s/m) and the coefficient of dune erosion due to wave impact (CIMPACT) were used to calibrate the model. The results were evaluated through the Mean Absolute Error (MAE), that represents the average differences between the modelled results (Pi) and the observed values (Oi), according to Equation 1.

$$MAE = \frac{1}{N}\sum_{i=1}^{n}|P_i - O_i| \quad (1)$$

For the 41 years, the berm (Y_B) and seaward dune toe (Y_S) positions evolution was determined, considering the best value of MAE. It was expected to observe a seaward advance in berm position in P3 and P4 profiles related to the trapping effect promoted by the south groin. Also, in P1 profile, an advance in berm position was expected, related to the frequent artificial nourishments performed in the location. In P2 profile, an erosion trend was expected, related to the shadow effect promoted by the northern groin. Results for the calibration of Y_B lead to good agreement between the observed and modeled values, with values of MAE $\leq$ 5.54 m. The only profile where this is an exception is P3 profile, located close to the southern groin, which presented a MAE = 49.75 m. Therefore, in this initial calibration, the simulations of P3 profile were divided into two parts, representing two main periods of accretion trends, one from 1979 until 1997 and the other, between 1997 and 2020, which decreased the MAE to 23.30 m. This have highlighted the importance of the time periods considered for the models' calibration. The Y_S position of all the 4 profiles demonstrates good agreement between the observed and modeled evolutions, with MAE $\leq$ 4.25 m. More details about the initial calibration of Y_B and Y_S positions are presented in Romão *et al.* (2024).

Calibration Scenarios Definition

After the long-term calibration of CS-Model (41 years), the model was again calibrated using 3 different time periods of 20 years: one between 1980-1999; another between 1990-2009; and the last one between 2000-2019. The periods of 2000-2019 and 2010-2019 were considered for results evaluation and validation. On each 20 years' time period considered to model calibration, different time ranges (5, 10, 15 and 20 years) were used to evaluate the model performance and response to the different calibration ranges. New values of Accretion Rate (m/time step), QWINDS (m^3/s/m) and CIMPACT were selected to evaluate the best value of MAE for the seaward dune toe and berm positions. The calibration was performed in 3 steps: first, the minor value of MAE was achieved while varying the Accretion Rate parameter to calibrate the Y_B position; second, the QWINDS was changed to achieve the best value of MAE, for Y_S position; finally, the CIMPACT parameter was altered to achieve reduced MAE for the 2 variables, Y_B and Y_S; additionally, if the Y_B presented significant changes, the Accretion Rate was again calibrated. This process was applied to P1, P3 and P4 profiles.

The P2 profile was calibrated considering the Y_B and Y_S positions and the dune height (S), that also reduces along time, due to overtopping events. Therefore, in this cross-shore profile, the Accretion Rate parameter was changed to calibrate the Y_B position. Next, the CIMPACT parameter was used to calibrate the dune height (S) and finally, the QWINDS parameter was used to calibrate the Y_S position. Once more, if the Y_B position presented significant changes, the Accretion Rate was again calibrated to achieve a lower value of MAE. To calibrate the bar volume parameter, an initial value equal to the observed profile from the first year was assigned. This value was calculated based on the sediment volume exceeding the slope threshold defined for the initial profile. Also, a d50 of 2.5×10^{-4} m was used based on the medium sediment diameter encountered in the study area (Van Rijn, 2023; Romão *et al.*, 2024). Table 2 summarizes all the values assumed for each parameter, to better represent the Y_B and Y_S positions, with the lower MAE, for the calibration time ranges of 5, 10, 15 and 20 years, in each time periods of 20 years.

Table 2. Values adopted for the parameters used to calibrate the profiles in the different calibration periods: Accretion Rate (AR), Aeolian Sediment Transport (QWINDS) and Wave Impact Coefficient (CIMPACT).

		AR ($\times10^{-6}$ m/time step)				QWINDS ($\times10^{-9}$ m^3/s/m)				CIMPACT ($\times10^{-6}$)			
Time Range		P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
1980 to1999	1980-1999	2.70	-0.71	9.60	0.55	85	80	73	270	100	250	0.20	8
	1985-1999	3.30	-1.00	8.10	0.66	37	2.60	92	260	230	340	1.60	9
	1990-1999	2.50	-0.79	8.50	1.40	82	410	91	250	100	320	0.20	7
	1995-1999	2.10	-0.29	4.40	1.20	67	85	150	270	100	0.49	21	11
1990 to 2009	1990-2009	2.30	-0.47	6.00	1.30	55	120	92	280	80	280	0.20	9
	1995-2009	2.10	-0.09	3.20	1.10	55	150	130	270	90	250	18	10
	2000-2009	2.30	-0.00	2.90	0.96	76	1100	49	270	50	660	0.30	10
	2005-2009	3.40	-0.15	0.00	2.80	92	100	750	220	70	10	110	8
2000 to 2019	2000-2019	2.30	-0.00	2.30	0.84	49	650	55	270	1.00	350	0.20	11
	2005-2019	2.70	-0.20	0.60	1.20	62	41	140	230	1.00	50	22	10
	2010-2019	2.30	-0.05	3.10	0.21	90	130	33	270	40	100	0.20	11
	2015-2019	2.00	-0.00	9.50	1.40	90	2100	40	280	100	1200	0.40	13

Analyzing Table 2, it is possible to observe that the P3 profile is more sensitive to the Accretion Rate (values ranging from 0.00×10^{-6} to 9.60×10^{-6} m/time step, corresponding to 0 cm/year to 2.8 cm/year).

The P2 profile is highly dependent on QWINDS (values ranging from 3×10^{-9} to 2100×10^{-9} $m^3/s/m$), being also dependent on CIMPACT, with the values that best calibrate the model in the different time periods ranging from 0.49×10^{-6} to 1200×10^{-6}.

RESULTS

The results of Y_B for all calibration and validation time periods are presented in Figure 3, for each cross-shore profile. The blue areas and the blue solid lines represent the calibration period from 1980 to 1999, the green areas and solid lines represent the calibration period from 1990 to 2009 and the red areas and solid lines represent the calibration period from 2000 to 2019. The dashed lines represent the validation periods for each calibration periods (blue for the period 2000-2020 and green for the period 2010-2020).

Looking to Figure 3, two conclusions can be highlighted: i) the validation period of Y_B evolution presents a deviation from the calibration period, representing different behaviors observed in the 40 years of profile evolution; and ii) when more recent years are used for model calibration, better results are obtained to represent the Y_B evolution.

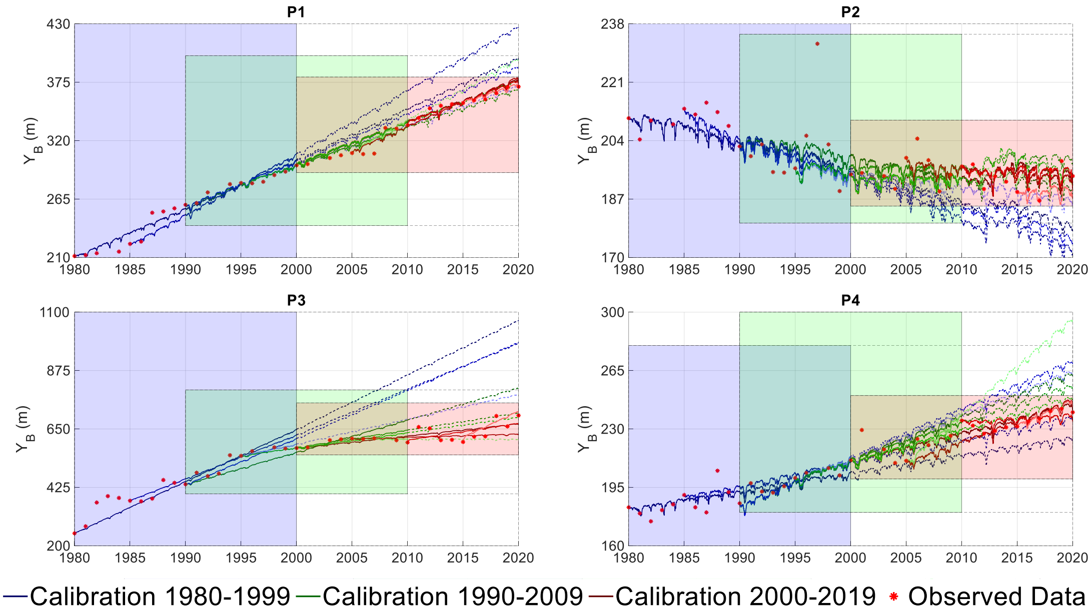

Figure 3. Berm position (Y_B) evolution considering different calibration and validation periods, for all profiles.

The Y_S evolution is represented in Figure 4, using the same graphical features considered in Figure 3. The amplitude of the position variation over the analyzed period is much smaller, when compared to the ones of the berm position. For instance, in the P1 profile, small variations in Y_S are observed (final changes of about 0.55 m). In spite of these small scales' amplitude, the validation period shows a deviation from the calibration period.

To better understand the differences between the observed and modeled Y_B and Y_S evolution, the MAE was calculated for the calibration and validation periods, and the results are summarized in Table 3. The values marked in green represent the minimum value of MAE obtained for the calibration and the validation scenarios and, in other hand, the values marked in red represents the maximum value of MAE obtained for the calibration and validation scenarios.

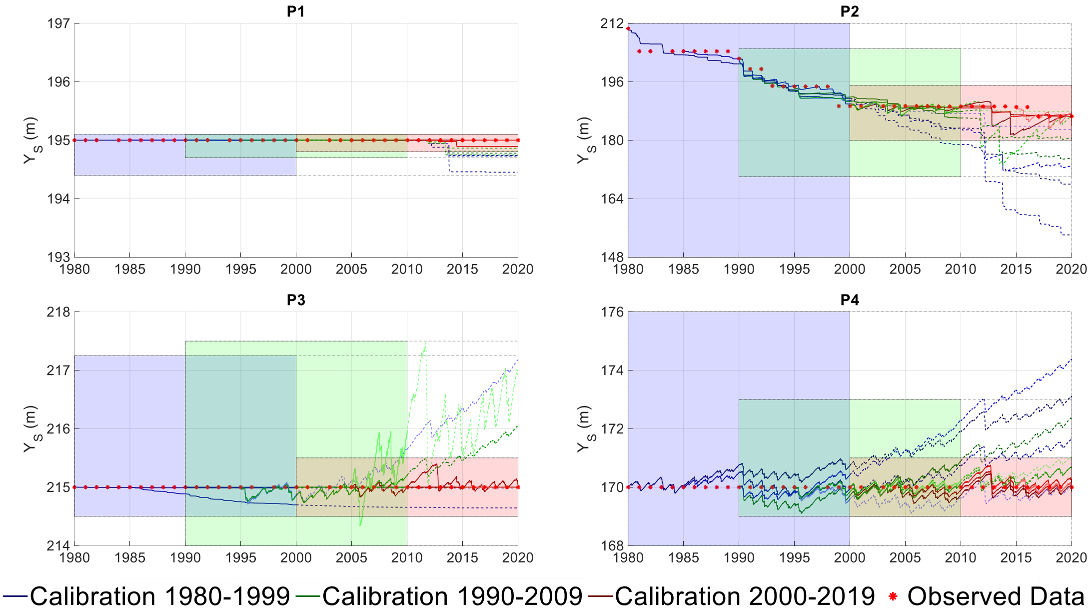

Figure 4. Seaward dune toe position (Y_S) evolution considering different calibration and validation periods, for all profiles.

Table 3. Mean Absolute Error of berm (Y_B) and seaward dune toe (Y_S) positions evolution (in meters), for all calibration and validation periods, considering all the profiles.

	Time Range		Y_B (m) P1	Y_B (m) P2	Y_B (m) P3	Y_B (m) P4	Y_S (m) P1	Y_S (m) P2	Y_S (m) P3	Y_S (m) P4
Calibration	1980-1999	1980-1999	5.78	5.21	28.35	4.58	0.00	1.76	0.01	0.38
		1985-1999	8.00	5.74	18.05	4.66	0.00	1.26	0.16	0.17
		1990-1999	2.42	7.24	19.45	3.69	0.00	1.49	0.00	0.27
		1995-1999	1.57	9.68	6.07	2.06	0.00	2.34	0.08	0.13
	1990-2009	1990-2009	3.88	5.67	30.19	5.27	0.00	1.66	0.00	0.38
		1995-2009	4.02	6.01	11.14	4.94	0.00	1.25	0.09	0.12
		2000-2009	5.41	4.05	10.92	5.88	0.00	0.67	0.00	0.08
		2005-2009	4.65	3.29	4.60	3.39	0.00	0.02	0.35	0.08
	2000-2019	2000-2019	4.05	4.29	21.07	3.94	0.00	1.55	0.00	0.25
		2005-2019	4.71	3.49	22.87	4.20	0.00	0.50	0.10	0.17
		2010-2019	2.32	3.36	25.78	3.11	0.06	0.72	0.00	0.18
		2015-2019	1.32	3.94	16.91	1.75	0.00	1.05	0.00	0.04
Validation	2000-2019	1980-1999	13.44	7.75	234.66	14.35	0.08	8.66	0.01	1.80
		1985-1999	30.86	11.67	179.65	6.41	0.18	14.76	0.34	0.66
		1990-1999	8.88	9.08	174.42	14.79	0.09	8.18	0.00	2.24
		1995-1999	6.52	4.66	63.45	11.71	0.09	2.46	0.77	0.45
	2010-2019	1990-2009	2.79	4.13	101.05	14.09	0.15	9.51	0.00	1.46
		1995-2009	7.43	4.96	38.66	8.92	0.17	5.56	0.51	0.26
		2000-2009	2.76	5.37	34.90	4.53	0.09	6.68	0.00	0.31
		2005-2009	10.55	3.17	34.38	29.56	0.13	1.01	1.10	0.46

For 1980-1999, the calibration of profile P1 resulted in better agreement between the observed and modelled Y_B position when considering a 5 years' time range (MAE = 1.57 m), instead of the 20 years (MAE = 5.78 m). The higher MAE = 8.00 m for the period between 1985 and 1999 can be related to the observed Y_B position, which have changed from 225.00 m in 1986 to 252.14 m in 1987, making difficult to adequately model this behavior and therefore, increasing the error of the simulation. The period 1990-2009 presented a more irregular behavior. The calibration performed considering 20 years of data resulted in a MAE = 3.88 m, which increases when 10 years of data are used (MAE = 5.41 m) and decreases to a MAE = 4.65 m when 5 years of data are considered. In this time period, the observed Y_B presented a variation from 307.85 m in 2007 to 332.02 m in 2008, with significant influence in the obtained MAE. Finally, for the time range of 2000-2019, the calibration of Y_B using 20 years of data resulted in a higher MAE (= 4.05 m) instead of the calibration using 5 years of data (MAE = 1.32 m).

An exception is observed in 2005-2019 calibration period (MAE = 4.71 m), which consider again the variation in Y_B position from 2007 to 2008 (307.85 m to 332.02 m), difficult to simulate in the model and with significant impact in the MAE. The better results of MAE when using 5 years of data are in agreement with the conclusion observed in Romão *et al.* (2024). The calibration of 1980-1999 period resulted in a wick validation of the model results, far of well represent the observed values in 2000-2019 (increasing the MAE). The validation period (2000-2019) presents a similar behavior of the calibration period, which is a decreasing of MAE from 13.44 m when using 20 years to MAE = 6.52 m when considering 5 years. The MAE is 30.86 m when using 15 years. The same conclusion can be made to the validation period of 2010-2019, as when 20 years of data are used, the MAE = 2.79 m, increasing to MAE = 10.55 m when 5 years are used, with an exception when 10 years are used (MAE = 2.76 m). This represents an increase of MAE from the calibration period to the validation period. For this P1 profile, the Y_S evolution shows the MAE approximately equal to 0.00 m, which defines a good model representation of the dune evolution along time, in the calibration period. However, the MAE increases in the validation period, especially in 1985-1999 and 1995-2019 time ranges, that shows the bigger MAE (0.18 m and 0.17 m, respectively).

The calibration of P2 profile, for the 1980-1999 time period, resulted in an increase of MAE from the 20 years interval of data (5.21 m) until the 5 years of data used (MAE = 9.68 m). This behavior can be related to the observed Y_B position evolution, which presents a higher dispersion, when compared to the other profiles. The fast advance and retreat of the Y_B position are associated to the existence of artificial nourishments in the area, which may lead to this behavior. The calibration for the 1990-2009 period presents the opposite behavior, resulting in a higher MAE when 20 years of data are used (MAE = 5.67 m), instead of 5 years used to calibrate the model (MAE = 3.29 m). An exception is observed in the 1995-2009 time range, as the MAE is 6.01 m. The final calibration period (2000-2019) presented a MAE of 4.29 m, when 20 years of data are used, and a MAE = 3.36 m, when 10 years are used. This value increases to 3.94 m, when 5 years are used. The validation period of 2000-2019 resulted in a decrease of MAE from 7.75 m to 4.66 m, for respectively 2000-2019 and 2015-2019 time ranges. The validation period also resulted in an increase of MAE, when compared to the calibration period. Same behavior is observed for the validation period of 2010-2019, resulting in a decrease of MAE from 4.13 m to 3.17 m, for 2010-2019 and 2015-2019 time ranges, respectively. The calibration of Y_S for P2 location shows the highest MAE (MAE equal to 2.34 m), observed in time period between 1995-1999 (5 years of calibration). The validation period increases the MAE for all time-ranges, especially for 1985-1999 time range, that has a MAE = 14.76 m.

Considering the P3 profile, the first model calibration period (1980-1999) resulted in better representation of Y_B when 5 years are used (MAE = 6.07 m), increasing this value to 28.35 m when 20 years are used. An exception is observed when 10 years of data are used, presenting a MAE = 19.45 m, related to the observed evolution, which changes from 478.33 m in 1993 to 548.89 m in 1994. The second calibration period (1990-2009) resulted in a reduction of the MAE from 30.19 m when 20 years are used, to 4.60 m when 5 years are used. The final calibration period (2000-2019) presents an MAE that changes from 21.07 m to 25.78 m when 20 and 10 years are used to calibrate the model. The calibration using 5 years decreases the MAE to 16.91 m. The validation of 2000-2019 period shows results far from being well represented with the model (high values of MAE). When 20 years are used in the validation period, the MAE is 234.66 m, which decreases to 63.45 m using 5 years. Same behavior is observed for the validation period of 2010-2019, decreasing the MAE from 101.05 m when 20 years are used, to 34.38 m, when 5 years are used in validation period. In this case, the validation of P3 profile resulted in better representation when less years are used to evaluate the model performance. The Y_S calibration shows good agreement between the observed and modeled values, with the highest MAE being 0.35 m, in 2005-2009 period (5 years of calibration from 1990-2009). The higher MAE in the validation scenario for Y_S evolution shows a value of 1.10 m, corresponding to a 5-year calibration period (between 2005-2009).

P4 profile results vary from MAE = 4.58 m, using 20 years to calibrate the model, to MAE = 2.06 m when 5 years are used, for 1980-1999 time range. An exception is observed between 1985-1999 period (MAE = 4.66 m), related to the fast evolution of observed Y_B position, from 180 m to 205 m, between 1987-1988. The calibration period of 1990-2009 shows a decrease of the MAE from 5.27 m, when 20 years are used to calibrate the model, to 3.39 m, when 5 years are used to calibrate the model. Other exception is observed (between 2000-2009), when the MAE increases to 5.88 m, related to the evolution of Y_B from 211.25 m to 229.38 m, between 2000-2001. Finally, the calibration period between 2000-2019 resulted in a decrease of MAE from 3.94 m to 1.75 m, when, respectively, 20 and 5 years are used to calibrate the model. The changes from the observed Y_B position in 2005 to 2006 (from 210.96 m to

224.03 m) and in 2009 to 2010 (from 225.91 m to 235.00 m) are responsible for increasing the MAE to 4.20 m when 15 years are used in model calibration (for the time range between 2000-2019). The validation period of 2000-2019 shows a decrease of the MAE from 14.35 m to 11.71 m when, respectively, 20 and 5 years are used to calibrate the model. This evolution was not regular, decreasing the MAE when 15 years are used to validate the model (MAE = 6.41 m), but increasing the MAE when 10 years are used in validation (MAE = 14.79 m). Finally, the validation period of 2010-2019 presented a MAE which decreases from 14.09 m to 4.53 m, when 20 and 10 years are used to calibrate the model, respectively, increased again the MAE to 29.56 m, when 5 years are used to validate the model. Good agreement between the observed and modeled values of Y_S evolution are detected, with the higher MAE registered in 1980-1999 and also in 1990-2009, when 20 years are used to calibrate the model (MAE = 0.38 m). The validation period increases the MAE from the calibration period, showing MAE = 1.80 m and MAE = 1.46 m for the highest MAE scenarios observed in the calibration period (1980-1999 and 1990-2009, respectively) but, the highest MAE is registered in 1990-1999 validation period, with MAE = 2.24 m (when 10 years are used to calibrate the model).

The principal conclusions of this analysis are: the validation period leads to an increase of the MAE, comparing to the calibration period, representing different behaviors observed in the 40 years of profile evolution; in general, the use of recent years to calibrate the model, leads to a better representation of the Y_B position evolution and often, using 5 years to calibrate the model presented lower values of MAE, when comparing to the use of 20 years of data to calibrate the model.

The calibration of Y_S depends on the calibration of the Y_B position, and the values of MAE are up to 2.34 m in the calibration period. In the validation period, the results are less than 2.24 m, in P1, P3 and P4 profiles, maintaining good agreement between observed and modeled Y_S position. The P2 profile presented the highest values of MAE for Y_S position (MAE between 1.01 m to 14.76 m). This behavior is also related to the dune erosion, which transported sediments to the beach, increasing the Y_S position. However, due to the erosion rate, those sediments are transported to out of the profile, reducing the Y_B and Y_S positions.

DISCUSSION

The obtained research results were compared and discussed with other works referred in the literature, which have considered calibration/validation processes in medium-term analysis. For instance, CS-Model was previous calibrated using 41 years of data, for IJmuiden, The Netherlands, by Romão *et al.* (2024), showing good agreement between observed and modeled profiles for the available surveys. In their work, the authors have realized that P3 profile was located close to a coastal structure, showing different behaviors in time and a high MAE (49.75 m), due to the fast evolution along the initial observed years, related to the longshore sediment transport accumulation. This difficulty was a motivation for the present research.

Hallin *et al.* (2019) have also applied the CS-Model, in Kennemer dunes (IJmuiden, The Netherlands), to evaluate the effect of sediment supply in decadal dune evolution. A 22-years period of analysis was selected based on the available profile, wind, water level and deep-water wave observations, from 29th March 1994 to 16th February 2016. The model simulations were divided into a calibration and a validation period. The calibration period was considered between 29th March 1994 and 11th March 2010 (approx. 16 years) and the validation period between 12th March 2010 and 16th March 2016 (approx. 6 years). The optimal calibration values were selected by a process of try and error, changing the characteristics of wind (speed and direction), water levels and waves (heights, periods and directions), sediment characteristics (median grain size), the cross-shore profile characteristics (dune toe elevation, depth of closure, beach width and seaward dune slope), and other calibration parameters. The numerical model performance was evaluated looking to different determinations of errors, also including the MAE, comparing the modeled results with observations. According to the authors, CS-Model effectively captured the variability in dune evolution across the study area, with consistent calibration parameters. This work also demonstrates the sensitivity of the results to the aeolian sediment transport and the alongshore sediment transport.

In the study of Palalane *et al.* (2016), CS-Model was applied in 3 different locations: Barra-Vagueira coastal stretch, located in Aveiro, Portugal; Macaneta beach, located in Maputo, Mozambique; and in Ängelholm beach, located in Skälderviken, Sweden. The authors considered different periods of analysis: 2009-2013 (4 years); 1997-2015 (18 years); and 1995-2015 (almost 20 years), respectively to each location, based on the available data. The model calibration also considered the aeolian sediment transport, the CIMPACT coefficient and the Accretion Rate (except for Barra-Vagueira beach), among other calibration parameters. The model performance was evaluated considering the deviations between observed and modelled results of Y_B and Y_S positions, also considering the changes in bar and dune volumes (modeled and observed). In general, the cross-shore model results show good agreement between modeled and observed profiles. The simplified model scheme allowed an efficient medium-term practical analysis, but their design fails in representing sloping profiles or the absence of berms. The work does not have any validation period. Palalane *et al.* (2016) highlighted the importance of available data for model calibration. They considered that Barra-Vagueira beach has sufficient profile data for successful model calibration instead of Ängelholm and Macaneta, that has limited profiles measurements.

Marinho (2018) have applied the CS-Model in 4 study areas: Barra-Vagueira coastal stretch (Aveiro, Portugal); Duck beach (NC, USA); Silver Strand coast (CA, USA); and Cocoa Beach (FL, USA). Her main goal was to simulate a 2 bar-system evolution. The model was calibrated for each study area considering the respective available data: about 4 years at Barra-Vagueira; 4 years at Duck; 2 years at Silver Strand; and just 1 year at Cocoa Beach. A validation of the model performance was only executed for Duck beach, considering a 4-years period. The calibration parameters included the CIMPACT coefficient, the aeolian sediment transport (considered constant along time), and other parameters related to the bar-berm sediment exchanges, and good model results were obtained (minor least square error). Marinho (2018) have used less years for model calibration (maximum of 4 years), but a validation is effectuated to Duck beach (4 years) due to the available data. This underscores the importance of the existence of calibration and validation periods.

The study of Pombo *et al.* (2022) evaluates the performance of two shoreline evolution models, LTC (Coelho, 2005) and GENESIS (Hanson, 1989), over a 15-year period (2003–2018) along the Poço da Cruz – Praia de Mira coastline in Aveiro, Portugal. Both models simulate shoreline changes influenced by wave-driven alongshore sediment transport, but the differences are in how they consider cross-shore dynamics. LTC updates the active cross-shore profile dynamically, while GENESIS keeps it fixed. The models were calibrated from 2003 to 2008 and validated using field data, from 2008 to 2018. In this case, long-term wave climate characterization provided better predictions by capturing the wave energy distribution more accurately. The artificial nourishments performed at the study area during the analyzed period, reducing erosion, were better represented by LTC, underscoring the importance of integrated human actions into model simulations. The LTC model tends to overestimate shoreline retreat when the human interventions were not considered, while GENESIS underestimates shoreline retreat. The results show that accurate shoreline evolution modeling requires proper wave climate data and consideration of human interventions. This is easier to achieve when a medium period of data is adopted.

CONCLUSIONS

The CS-Model was previously calibrated in the study presented by Romão *et al.* (2024), considering 41 years of profiles evolution, wave climate and tide levels data. The results of the indicated study suggested good agreement between observed and modeled values of berm position (Y_B) evolution, with MAE up to 5.54 m (considered profiles P1, P2 and P4). Profile P3 presented the highest MAE (equal to 49.75 m). For seaward dune toe position evolution (Y_S), all the profiles presented good agreement between observed and modeled values, with MAE not exceeding 4.30 m. The conclusion of that work shown that model performance was better when 5-10 years were used for calibration, instead of using 40 years. Therefore, the study presented in this paper focused on investigating the CS-Model performance for the same profiles (P1 to P4) when the model is calibrated with different periods of data. For that, three periods were considered to calibrate the model (1980-1999, 1990-2009 and 2000-2019). For each period, the last 20, 15, 10 and 5 years of data were considered to evaluate the calibration process. At the same time, two periods were chosen to validate the model performance, one between 2000-2019 (20 years) and other between 2010-2019 (10 years).

The results of Y_B evolution show that the validation period leads to an increase of the MAE, compared to the calibration period, representing different behaviors observed in the 40 years of profile evolution. When recent years are used to calibrate the model, the lower values of MAE for Y_B evolution are achieved and in general, using the period of the most recent 5 years to calibrate the model presented lower MAE, instead of using 20 years to calibrate the model.

For Y_S evolution, MAE up to 2.34 m are registered (for the P2 profile) in the calibration process, which corresponds to good agreement between observed and modeled values. The validation period increases the MAE up to 2.24 m for P1, P3 and P4 profiles, maintaining the good representation of Y_S by the model. However, the P2 profile shows a MAE between 1.01 m and 14.76 m in the validation period, related to the dune erosion.

The Y_B evolution is more sensitive than the Y_S evolution, related to the contribution of the alongshore sediment transport in the study area, more important for P3 and P4 profiles (IJmuiden south). Recent years to model calibration led to better modeling performance, highlighting the importance of data acquisition and updated datasets. The time periods used for model calibration were discussed and, in general, using smaller periods of time to calibrate the model leads to better results.

CS-Model does not need extensive datasets to describe a specific study area. However, it is important the existence of data for model calibration and validation. The model performance parameters are more sensitive to the Accretion Rate, related to the contribution of longshore sediment transport, especially important for P3 profile, when different trends are observed. This can be related to the presence of the southern groin, which interrupts the alongshore sediment transport (from south to north), promoting an advance of the Y_B in offshore direction, more intense in the first years, and reducing the variation rate in the most recent years (related to the clogged effect). When there are significant variations over time and it is intended to model them, it may be difficult to replicate the larger changes in cross-shore profiles and so, the datasets do not need to be very extensive, but should reflect the most recent trends observed at the study area.

Accurate calibration of numerical models and validation against observed conditions are crucial for obtaining reliable results that closely represent reality. These results are essential for understanding the primary processes influencing the medium-term evolution of cross-shore profiles simulated using numerical tools, identifying the processes controlled by the model, and determining which processes can be simplified. Updated datasets are crucial for better representation of cross-shore evolution but, is necessary to consider the historical coastal interventions in the datasets (artificial nourishments and groins, for instance). Monitoring campaigns are important to collect data for calibration and validation of numerical models. Observations permits an effective performance of the numerical models, enabling to implement proper coastal management strategies, such artificial nourishments, for coastal protection.

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REFERENCES

Coelho, C., 2005. Riscos de exposição de frentes urbanas para diferentes intervenções de defesa costeira (Exposure risk of urban waterfronts, for different coastal defense interventions). Ph.D thesis University of Aveiro, Portugal, p. 404 pp. (In Portuguese).

Ghadamode, V., Kondarathi, A.K., Pandey, A.K. & Srivastava, K. 2024. Shoreline and land use-land cover changes along the 2004-Tsunami-Affected South Andaman coast: Understanding changing hazard susceptibility. *Natural Hazards and Earth System Sciences*, 24(9), pp. 3013–3033. https://doi.org/10.5194/nhess-24-3013-2024.

Güner, H.A.A. & Başaran, B. 2024. Modeling cross-shore profile evolution in response to climate change: A case study for the Southwestern Black Sea Coast. *Regional Studies in Marine Science*, 78, 103794. https://doi.org/10.1016/j.rsma.2024.103794.

Hallin, C., Huisman B.J., A.; Larson, M., Walstra, D.-J.R. & Hanson, H. 2019. Impact of sediment supply on decadal-scale dune evolution - Analysis and modelling of the Kennemer dunes in the Netherlands. *Geomorphology*, 337, 94–110.

Hanson, H., 1989. GENESIS: a generalized shoreline change numerical model. *Journal of Coastal Research*. 1–27.

Karssenberg, D., Burrough, P.A., Sluiter, R. & de Jong, K. 2001. The PCRaster Software and Course Materials for Teaching Numerical Modelling in the Environmental Sciences. *Transactions in GIS*, 5(2), Pages 99-110.

Larson, M., Palalane, J., Fredriksson, C. and Hanson, H. 2016. Simulating cross-shore material exchange at decadal scale. Theory and model component validation. *Coastal Engineering*, 116, 57–66.

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G. & Aarninkhof, S. 2018. The State of the World's Beaches. *Scientific Reports*. 2018, 8, 6641.

Ma, M., Huang, W., Jung, S., Oslon, C., Yin, K. & Xu, S. 2024. Evaluating Vegetation Effects on Wave Attenuation and Dune Erosion during Hurricane. *Journal of Marine Science and Engineering*, 12(8), 1326. https://doi.org/ 10.3390/jmse12081326.

Marinho, B. 2018. Alimentações Artificiais Como Solução de Defesa Costeira: Abordagens de Monitorização e Modelação. Ph.D. Thesis, University of Aveiro, Aveiro, Portugal, p. 359. (In Portuguese).

Palalane, J, Fredriksson, C., Marinho, B., Larson, M., Hanson, H., & Coelho, C. 2016. Simulating cross-shore material exchange at decadal scale. Model application. *Coastal Engineering*, 116, 26–41.

Passeri, D.L., Hagen, S.C., Bilskie, M.V., Medeiros, S.C., 2015. On the significance of incorporating shoreline changes for evaluating coastal hydrodynamics under sea level rise scenarios. *Natural Hazards* 75, 1599–1617.

Pombo, R., Fernández-Fernández, S., Baptista, P., Coelho, C. & Bernardes, C. 2022. Old forecasts vs actual shoreline evolution: Assessing model's performance and projections accuracy. *Coastal Engineering*, 175, 104143. https://doi.org/10.1016/j.coastaleng.2022.104143

Rijkswaterstaat, 2024. Ministerie van Infrastructuur and Waterstaat. Available online: https://www.rijkswaterstaat.nl/ (accessed on 15 July 2024).

Romão, F., Coelho, C., Lima, M., Ásmundsson, H. and Myer, E.M. 2024. Cross-Shore Modeling Features: Calibration and Impacts of Wave Climate Uncertainties. *Journal of Marine Science and Engineering*, 12, 760. https://doi.org/10.3390/jmse12050760.

Santra, M., Dwivedi, C.S., Pandey, A.C. 2024. Quantifying shoreline dynamics in the Indian Sundarban delta with Google Earth Engine (GEE)-based automatic extraction approach. Tropical Ecology, 65(3), pp. 426–442. https://doi.org/10.1007/s42965-023-00321-w.

Saunders, T.M., Cohn, N. & Hesser, T. 2024. Insights into nearshore sandbar dynamics through process-based numerical and logistic regression modeling. *Coastal Engineering*, 192, 104558. https://doi.org/10.1016/j.coastaleng.2024.104558.

Shaik, I., Suhail, M. & Nagamani, P.V. 2024. Shoreline delineation and change analysis in response to sea level rise and coastal bathymetry along the coast of Visakhapatnam, India using high-resolution optical imagery. Acta Geophysica, 72(6), pp. 4453–4472. https://doi.org/10.1007/s11600-024-01341-3.

Simmons, J.A., Harley, M.D., Marshall, L.A., Turner, I.L., Splinter, K.D. & Cox, R.J. 2017. Calibrating and assessing uncertainty in coastal numerical models. *Coastal Engineering*. 125, 28–41. https://doi.org/10.1016/j.coastaleng.2017.04.005.

Simmons, J.A.; Splinter, K.D.; Harley, M.D.; Turner, I.L. 2019. Calibration data requirements for modelling subaerial beach storm erosion. Coastal Engineering, 152, 103507.

Stronkhorst, J., Huisman, B., Giardino, A., Santinelli, G. and Santos, F.D. 2018. Sand nourishment strategies to mitigate coastal erosion and sea level rise at the coasts of Holland (The Netherlands) and Aveiro (Portugal) in the 21st century. *Ocean and Coastal Management*, 156, 266–276.

Van Rijn, L. 2023. Improvement of Coastline Modelling Software Using Field Data. AX-COAST Report (non-published).