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ORIGINAL RESEARCH ARTICLE

Defining a single set of calibration parameters and prestorm bathymetry in the modeling of volumetric changes on the southern Baltic Sea dune coast

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Abstract The studies described herein aimed to estimate the accuracy of determination of the volumetric changes on the dune coast of the southern Baltic Sea through the application of the XBeach numerical model, which is crucial for coastal engineering. In the first phase of the study, the profile (1D) mode of the model was adapted to 19 cross-shore profiles located along the Dziwnów Spit.

The model was calibrated with a storm event in 2009 that caused significant changes to dunes and beaches. Cross-shore profiles were measured approximately one and a half months before and after the storm. An evaluation of model performance was made based on the Brier skill score (BSS), the visual match of the profile shape (VMS), the absolute volumetric change error (m^3/m) and the relative volumetric change error (%). In this study, parameters related to the asymmetry transport (*facua*) and the dune erosion algorithm (*wetslp*) were taken into account. The best results for model calibration on all 19 cross-shore profiles were obtained with *facua* values ranging from 0.16 to 0.40 and *wetslp* values from 0.35 to 0.60. The calibration of individual profiles yielded good results, with an average absolute error of approximately 4 m^3/m and an average relative error of ca. 20%. The poorest results were collected for the profiles situated near coastal engineering structures, where the average absolute error was 10 m^3/m and the relative error was 60%. The possibility of accepting one set of parameter values for all the profiles at once was also investigated. These studies revealed that the application of one

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set of *facua* and *wetslp* values for all profiles simultaneously resulted in a relative volumetric change error of ca. 25% on average, with the maximum of about 40%.

Due to the difficulty of collecting data just before and after the storm event, complex studies using all available bathymetric data were performed. Using a joint dataset composed of prestorm topography recorded before that storm and bathymetry from different years, a simulation of the 2009 storm event was carried out. The studies revealed that the prestorm bathymetry and the randomness of the selection of calibration parameters have similar effects on the accuracy of volumetric changes.

Moreover, the impact of the nearshore bathymetry (to a depth of 2 m) on modeling the volumetric changes in the terrestrial part of the shore is evident. A change in the sea bottom inclination and a successive change in the nearshore sediment volume can increase the difference between modeled and actual volumetric changes.

1. Introduction

Sea level rise and the increasing frequency of storm events, which are two phenomena that have been observed recently in some regions, have become real hazards in coastal areas, especially those with low dune berms as their first line of defense. If coastal parameters are insufficient to resist these phenomena, the continuous dune berm may be breached, leading to inland flooding. Therefore, to mitigate the adverse effects of coastal hazards, it is necessary to develop a tool that would allow emergency units to be ready to launch specific procedures to mitigate these hazards.

Coastal zone studies are increasingly supported by numerical models that determine shoreline displacement and volumetric changes. These models are used for both early warning systems and for coastal zone modeling systems that are convenient tools for coastal zone management (Barnard et al., 2014; Furmańczyk et al., 2014; Haerens et al., 2012). However, it should always be kept in mind that models have limitations in reflecting the natural processes that occur in coastal zones. These limitations result from simplified assumptions or equations that describe coastal processes and from the insufficient availability of up-to-date datasets; hence, these models may generate errors.

A vast number of models, both analytical (Bruun, 1954; Dean and Maurmeyer, 1983; Edelman, 1972; Kriebel et al., 1991) and numerical (Larson and Kraus, 1989; Seetzel, 1993), that concern coastal erosion have been developed so far. XBeach (Roelvink et al., 2009), which is a process-based model, is the most widely used. It was created to simulate the processes that occur in the coastal zone during storm events in line with storm impact regimes (Sallenger, 2000). It has been adapted and tested all around the world to simulate wave runup (Palmsten and Splinter, 2016) as well as morphological changes in profiles (1D mode) (Dissanayake et al., 2014; Harley et al., 2011; Pender and Karunarathna, 2013; Vousdoukas et al., 2011) and domains (2D mode) (McCall et al., 2010; Williams et al., 2015). XBeach has become a tool for the long-term simulation of volumetric changes (Pender and Karunarathna, 2013) and for simulations of storm groups rather than single storm events only (Karunarathna et al., 2014).

The XBeach model (*XBeach Quatorze_Juillet, revision 1241*) was applied on the southern Baltic coast for the first time by Bugajny et al. (2013). Further studies to widen the applicability of the model were performed in Bugajny et al. (2015). The results of these studies confirmed that XBeach is a relevant model for predicting beach and dune changes on the dune coast of a tideless sea and proved the usefulness of that model in creating an efficient tool to predict hazards in the Baltic Sea coastal zone.

Despite being quite versatile, XBeach requires site-specific calibration (Splinter and Palmsten, 2012), since the good calibration of process-based models improves their efficiency, making them optimal tools for simulating storm events that end in dune erosion (Armaroli et al., 2013; Harley et al., 2011). One of the most common calibration methods is ‘trial and error’. Having over 100 ‘free’ parameters to tune, this process may become time-consuming, yet it is crucial for the proper application of the model. Studies performed for the Baltic coast have so far revealed that the most significant influence on volumetric change simulations have *facua* and *wetslp* parameters.

In technical terms, the application of the model should cover the largest area possible. However, the application of the model is limited to case studies due to the time-consuming calibration process. Model calibration in 1D mode raises the following questions: What is the variety of calibration parameters along the coast? How would the one set of parameters work if used for other profiles along a given section of the coast? Is there a set of parameters that would be optimal for a given case study? To answer these questions, the model was calibrated focusing on selected parameters and then the influence of calibration parameter sets on the modeled volumetric changes was analyzed based on the selected measures.

Furthermore, the availability of data, both pre- and post-storm, is another point of concern. Is it possible to predict the recorded volumetric changes on the coast using the model without a valid prestorm bathymetry? To answer that question, storm simulations were carried out by changing the prestorm bathymetry recorded in different years on the selected profiles used in the research and the errors of modeled volumetric changes were calculated. Therefore, the goals of this study were:

- to study the influence of a set of calibration parameters on modeling volumetric changes on a dune coast and on the accuracy of the model predictions;
- to study the influence of prestorm bathymetry on the accuracy of modeling volumetric changes in a dune coast.

These studies took place on a several-kilometer-long section of the dune coast of the southern Baltic Sea. As a result, two issues were discussed: the selection of a set of calibration parameters and their impact on the accuracy of the model results and the influence of the underwater morphology of the nearshore on the subaerial volumetric changes of the coast that was modeled.

2. Study area and materials

2.1. Dziwnów Spit

The Dziwnów Spit is a barrier that separates Kamieński Lagoon from the Baltic Sea (Figure 1). It includes a 12 km-long section of the Baltic dune coast that is pushed into a Pleistocene cliff high plain between km 385 and 397 of chainage as set out by the Maritime Office. The spit is divided at its central point by a manmade channel dug at the turn of the 19th and 20th centuries (Racinowski and Seul, 1999) that flows southwards into a natural part of the Dziwna inlet. The Dziwnów Spit may thus be split into two parts: eastern and western. The eastern part is narrow. It is not wider than 0.5 km at its narrowest segment. The dune berm height there ranges from 3 to 4 m. In turn, the western part is wider and reaches approximately 2 km in width. The dune berm system is well developed, with dunes reaching 12 m. The entire spit is gently inclined toward the northwest and has the shore with a wide (30—50 m) sandy beach. In the nearshore region, a system of 2—3 underwater bars can be observed (Dobracki and Zachowicz, 2005; Musielak et al., 2007).

The new channel that replaced the natural Dziwna inlet and the construction of jetties on both sides disrupted alongshore sediment transport, causing intensified erosion that led to the construction of the coastal defense system. Currently, the spit is well protected by diverse coastal engineering structures such as groynes, seawalls and beach nourishment that modify the course of natural processes (Dudzińska-Nowak, 2015). Despite these efforts, alternating accumulative and erosive systems tend to appear here, with dominating erosion (Dudzińska-Nowak, 2006a,b; Zawadzka-Kahlau, 1999). The greatest loss of the dune berm due to storm events is observed at km 388 (seawalls), km 391 (jetties) and km 394 (the area adjacent to groynes) (Furmańczyk and Dudzińska-Nowak, 2009; Furmańczyk et al., 2011). The comparison of volumetric changes caused by weak storms (that do not cause dune erosion) along protected and natural sections has shown that, in such weak wave conditions, groynes do not increase the volumetric change dynamics on the protected coast, while their protective function leads to both seaward shoreline displacement and positive values of volumetric changes. As the wave action intensifies, groynes lose their protective function, causing the protected coast to behave like a natural coast, showing landward shoreline displacement and negative values of volumetric changes (Bugajny and Furmańczyk, 2017).

Due to its size and geographical location, as well as the limited water exchange between the Danish Straits and the North Sea, the tides in the Baltic Sea are weak, limited to a few centimeters (Sztobryn et al., 2005). Hence, the Baltic Sea is considered a nontidal sea. Because of the negligible impact of tides, it seems that the most important hydrodynamic factor influencing morphological changes on the coast is wave action (Zeidler et al., 1995) accompanied by a storm surge.

The western coast of the southern Baltic Sea, where the study area is located, is classified in the range 1.96—2.22 m above AMSL due to maximum storm surges in the period 1811—2006 (Musielak et al., 2017), while the monthly maximal deep-water significant wave height in the years 1998—99 for the Pomeranian Bay ranged between 2.89—4.22 m (Paplińska and Reda, 2001).

2.2. Morphological and hydrodynamic data

As a part of the annual monitoring of the coastal zone, the morphology of the coastal zone was recorded in the form of bathymetric-topographic profiles that are shared by the Maritime Office in Szczecin. The profiles are taken perpendicular to the coast at intervals of 500 m and reach no further than 2000 m toward the sea from base points located on land. The numbering of profiles increases every 1 km from east to west and receives a number according to the chainage along the coast. Topographic measurements of the profiles (the subaerial part and to a depth of −1 m) were made using geodetic methods with a vertical precision of ±5 cm. Bathymetric measurements were made from a depth of −1 m to approximately −15 m using an echo sounder with vertical precision of ±8 cm and a horizontal precision of ±20 cm (Bugajny et al., 2013). In these studies, profiles measured in late August of 2009 were used to calibrate the model, as a prestorm registration, while profiles from 2004, 2006, 2008, 2010 and 2012 for the study area, i.e., 395.5—386.5 km (Figure 1), were used to study the influence of bathymetry on the volumetric changes on the coast.

In addition, data from an airborne laser scanner (red LIDAR — topographic), acquired on November 30, 2009, by a TopEye scanner were used. The dataset is characterized by a density of 8 pt/m^2 and horizontal and vertical accuracy x, y, z of ±20 cm and was made as part of the annual monitoring of the coastal zone by the Maritime Office in Szczecin (Bugajny et al., 2013, 2015; Dudzińska-Nowak and Wężyk, 2014). The data were used as the poststorm morphological data.

Water level data from 2009 (12—16.10) were registered every 4 hours by a tide gauge located in the port of Dziwnów and provided by the Maritime Office in Szczecin.

Basic wave parameters were derived from the WAM model (WAMDI Group, 1988), shared by the Interdisciplinary Centre for Mathematical and Computational Modeling, University of Warsaw (ICM UW). Due to a very good correspondence between the modeled and measured wave parameters for the Baltic Sea (Cieślikiewicz and Herman, 2001,

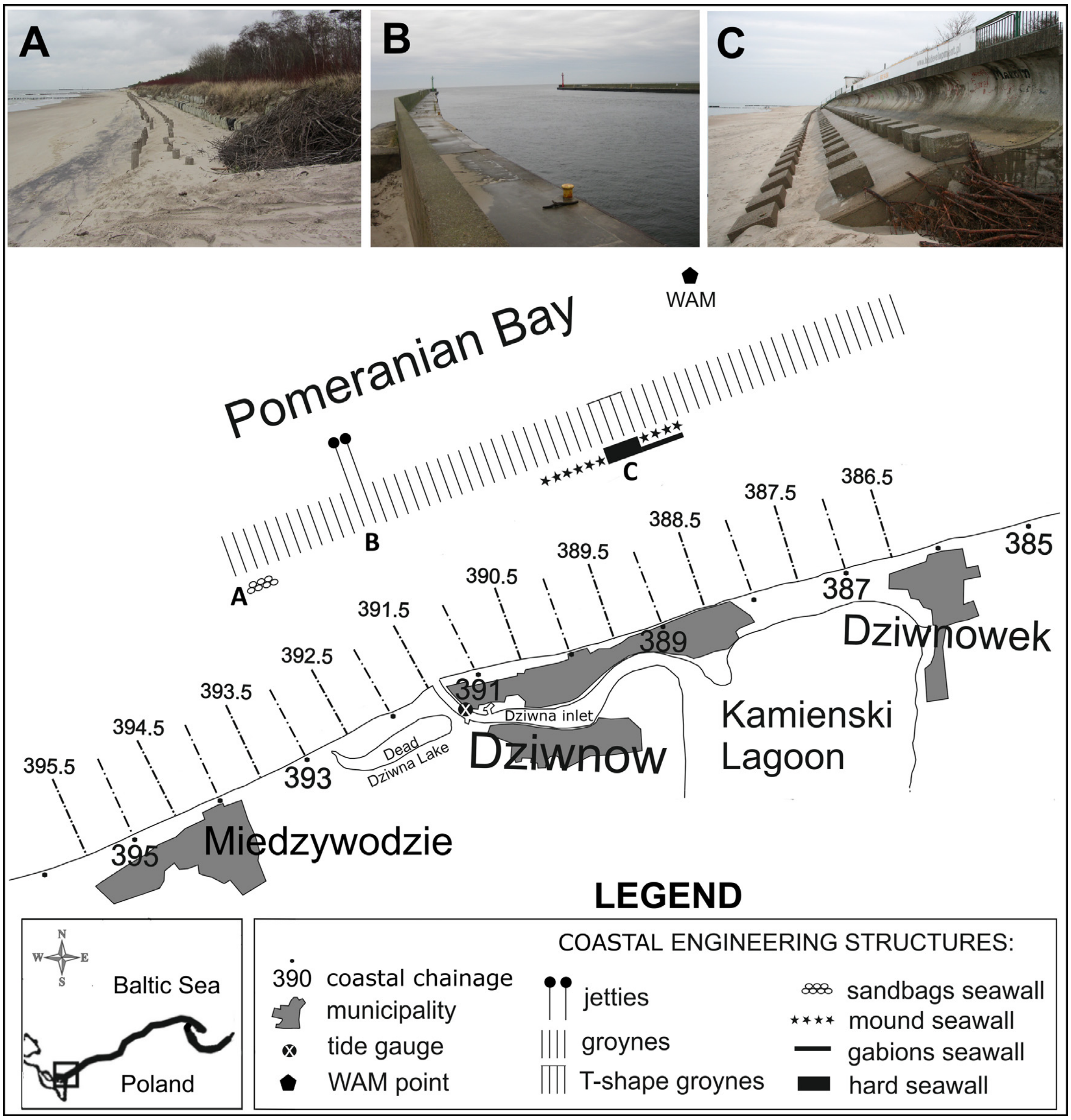

Figure 1 Study area with the location of bathymetric-topographic profiles, hydrodynamic data and coastal engineering structures.

2002; Paplińska, 1999, 2001), it was decided to use the WAM model data in this study.

This study is focused on a storm event that took place on 12—16 October 2009. It caused significant changes in a shore in the form of intense erosion of both the beach and the dunes (Furmańczyk and Dudzińska-Nowak, 2009). The maximum water level reached +0.76 m AMSL, while the maximum significant wave height (Hs) was 3.75 m at a peak period of 11.17 s. A time series demonstrating the changes in the values of these parameters throughout the storm event is provided in Figure 2.

3. Methods

3.1. Model performance evaluation

The performance of a model is estimated on the basis of comparison of field measurements with model simulation results at the same location. Various measures can be used for this purpose (Sutherland et al., 2004).

The **Brier skill score** (BSS) is the most commonly used nondimensional measure and relies on an analytical comparison of the profile measured in the field before and after the storm and the profile after the simulation (Sutherland et al., 2004). The correlation of the measured profiles (prestorm — x_b and poststorm — x_p) and the modeled profile (x_m) can be expressed as follows:

$$BSS=1-\left(\frac{\langle|x_m-x_p|^2\rangle}{\langle|x_p-x_b|^2\rangle}\right)$$

The interpretation of BSS values was described by van Rijn et al. (2003). They classified the model performance as bad when BSS < 0, poor when BSS = 0—0.3, reasonable/fair when BSS = 0.3—0.6, good when BSS = 0.6—0.8 and excellent when BSS = 0.8—1. Ideally, when the predicted changes are the same as the observed changes, the BSS value = 1. This indicator is sensitive to small changes

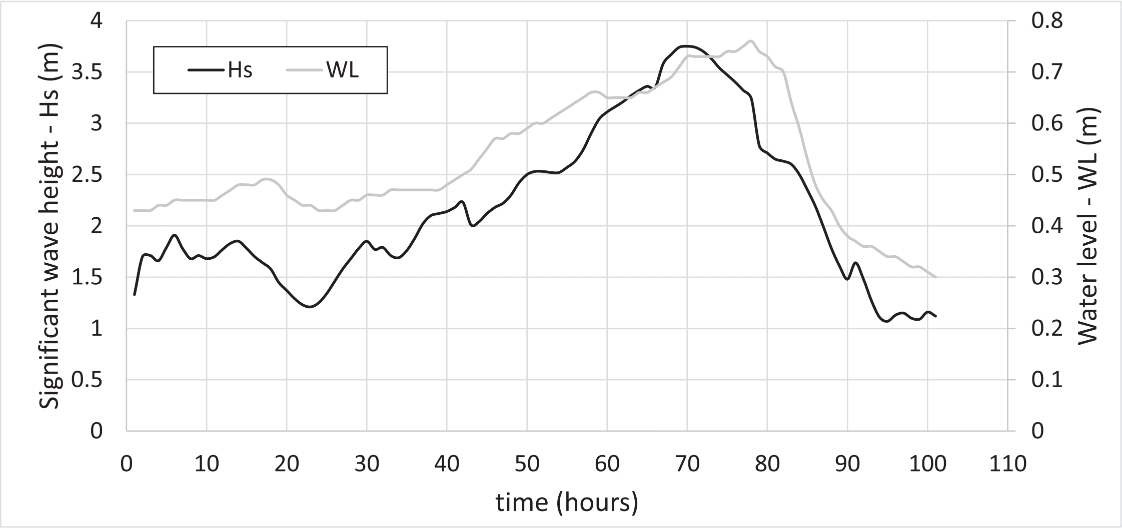

Figure 2 Time series of 2009 storm parameters (significant wave height — Hs and water level — WL) used in the XBeach simulations.

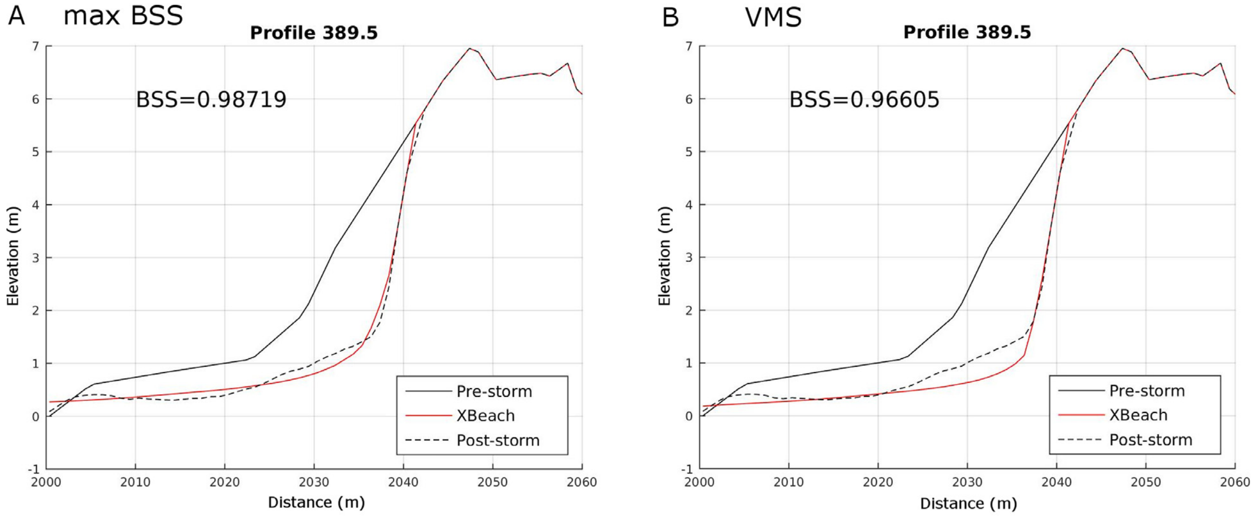

Figure 3 Comparison of calibration results for profile 389.5 in simulations with maximum BSS (A) and based on the visual match profile shape (VMS) (B).

when the denominator takes small values. Therefore, low values of BSS can be obtained with small real changes, even if the model correctly simulates these changes (Sutherland et al., 2004). In this study, BSS values were calculated only for the land part of the profile, taking into account changes to the beach and the dunes.

The **visual match of the profile shape** (**VMS**) after the storm with the model result was also performed. The BSS values do not always best reflect the model fit, especially when a long time interval occurred between the storm and the poststorm measurement in the field. After the storm, a successive reconstruction of the coastal profile in the form of the beach bar and aeolian transport, especially in the area of the upper beach near the dune foot, was observed. In this case, more attention should be paid to the VMS result than to the BSS. In the current research, an assessment was carried out using both measures, BSS and VMS and a comparison of the correctness of the model calibration for the 389.5 profile is shown in Figure 3.

The simulation result for a very good match (BSS = 0.987) and of a simulation where the modeled profile coincides with the measured one in an area located behind a beach bar toward the dune (beach lagoon) is presented in Figure 3A and 3B, respectively. The beach bar that is not included in the numerical simulation and the aeolian accumulation in the upper beach area is clearly visible. For this approach, the BSS value is slightly lower, equals to 0.966, but the simulation reflects better the actual process that was modeled; the poststorm survey took place approximately 1.5 months after the storm event.

Moreover, the accuracy of the determination of the volumetric changes on the coast was also calculated. XBeach was used to calculate the volumetric changes caused by the storm event conditions. Therefore, two additional measures were applied to assess the model performance: the absolute error and the relative error of volumetric changes.

The absolute error of volumetric changes (m_b). The sum of changes in the height of the profiles multiplied by 1 m of alongshore distance was used as the volumetric change in these profiles. The error is calculated on the basis of the volumetric change in the coast between the profiles measured in the field before and after the storm and the modeled volume changes in the profile and is expressed in the absolute values of the following difference:

$$m_b = |x_i - x_m|$$

where x_i is the measured volume and x_m is the modeled volume.

Relative error of volumetric changes (m_w). This is the ratio of the absolute error to the measured volumetric changes. It can be expressed as a percentage:

$$m_w = \frac{m_b}{x_i} \times 100\%$$

where m_b is the absolute error and x_i is the measured volume.

3.2. XBeach model calibration parameters

The XBeach model was developed to simulate the impact of extreme events on dune coasts. It is a process-based model, which makes it more complex and computationally more intense than equilibrium-type models (Ciavola et al., 2014). The XBeach (*Easter release*) was used in this study. It has approximately 100 parameters that can be significant and that should be specified in the calibration process. The default values for most parameters were used, as suggested in the model manual (Roelvink et al., 2010). However, taking into account the results obtained in previous studies on the application of XBeach on the Polish coast (Bugajny et al., 2013, 2015) and the changes in the default values of parameters in the version of the model used in this work, particular attention was paid to the following parameters:

- *wetslp*, critical wet slope, is a parameter related to the dune erosion algorithm. As the critical slope between two neighboring cells of the calculation grid is exceeded, sediment is transported between these cells until the critical slope is reached. The algorithm is a relatively simple tool for describing the complex process of dune erosion (van Thiel de Vries, 2009). The default value of the *wetslp* parameter is 0.3, which results from a study on the profile of equilibrium for a seashore by Vellinga (1986), tests performed at Oregon State University and the Zwin experiment (Roelvink et al., 2009, 2010).
- *facua* (u_a), a dimensionless calibration parameter, was introduced into the model to take into account the size of sediment transported due to the wave shape. It can take values from 0 to 1. High values of *facua* lead to higher onshore flow, which results in greater sediment transport in this direction. Therefore, *facua* = 0.5 is suitable for medium wave conditions, whereas *facua* = 0 or low values correspond to storm conditions (Voukouvalas, 2010). The default value of this parameter was set at 0.1 on the basis of studies carried out by van Thiel de Vries (2009).
- *morfac*, the morphological acceleration factor, is a parameter that accelerates the morphological time scale in relation to the hydrodynamic scale. This parameter can take values from 0 to 1000 (Roelvink et al., 2010). In this research, a value of 10 was used, similar to those in the work of McCall et al. (2010), Ranasinghe et al. (2011) and Pender and Karunarathna (2013).
- *smax*, is a parameter specifying the maximum value of the Shields coefficient. It was introduced into the model to balance the overestimation of dune erosion observed in McCall et al. (2010). As a result of the recommendation of McCall et al. (2010), that an *smax* between 0.8—1.2 results in small differences in BSS, this parameter was set at a constant value of 1 in this study.

3.3. XBeach model setup

The storm event that took place on 12—16.10.2009 was used for model calibration. This event caused significant changes to the coast, such as intense dune and beach erosion (Furmańczyk and Dudzińska-Nowak, 2009). A simulation of the storm event of 2009 was run for 19 cross-shore profiles (395.5, 395, 394.5, 394, 393.5, 393, 392.5, 392, 391.5, 391, 390.5, 390, 398.5, 389, 388.5, 388, 387.5, 387, and 386.5 km) located every 500 m along the study area (Figure 1).

For each profile, a variable computational grid was created with a cell size of approximately 20 m offshore and 1 m onshore. The application of this variable grid minimized the computing time.

The wave boundary conditions were implemented as a time series of hourly JONSWAP spectra (instat=41) perpendicular to the coast. The average spectral parameters for the Baltic Sea, obtained in Paplińska (1994), did not differ much from those adopted for the North Sea, which confirmed the possibility of using the JONSWAP spectrum to describe the wind waves in the Baltic Sea. In addition, the water level at the model boundary was assumed to be the same as that recorded by a tide gauge at the mouth of the Dziwna River (Figure 1). Furthermore, average values of $D_{50} = 0.25$ mm and $D_{90} = 0.375$ mm for medium-sized sand were adopted.

The boundary conditions for flows at both the offshore and the onshore boundaries were set to absorbing-generating ones, while at the lateral boundaries, they were set to no flow (wall). Directional wave propagation was not taken into account in this case.

In this study, the accuracy of the volumetric change calculations performed by the XBeach model was assessed on the basis of the four measures described earlier. For each of the 19 profiles located in the study area, using the ‘trial and error’ approach for model calibration, approximately 300 simulations were run, changing the values of *wetslp* from 0.3 to 0.6 by increments of 0.05 and of *facua* from 0 to 1 by increments of 0.1. The *morfac* parameter was set to 10, and the *smax* parameter was set to 1 for all simulations. The remaining parameters were introduced with their default values. Next, on the basis of the BSS obtained from the simulations for particular profiles, the profiles with the highest BSS (max BSS) values were selected. Furthermore, the visual match of the profile shape (VMS) was assessed for those profiles to identify those in which the shape after the simulation better matched the morphological changes.

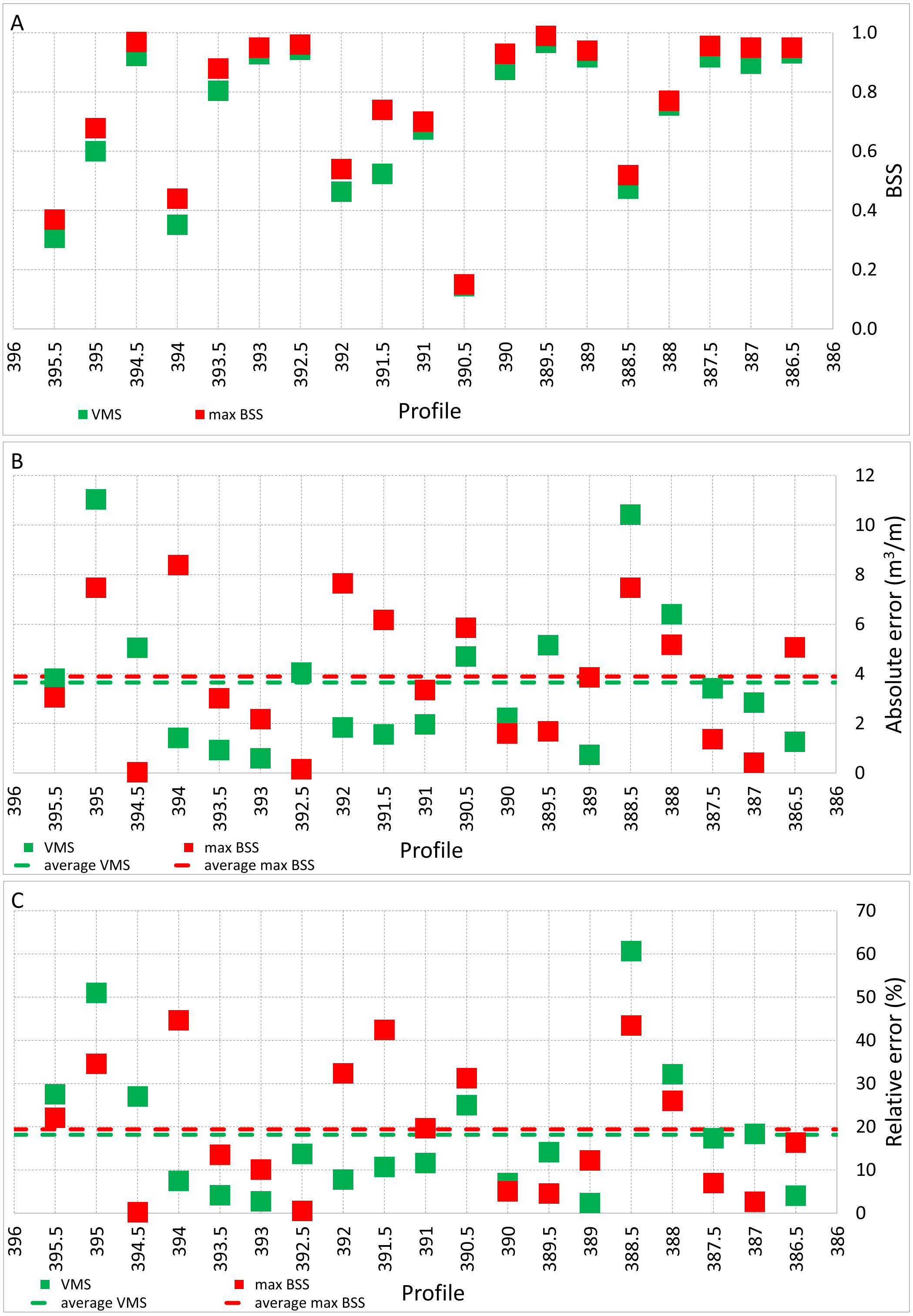

Figure 4 XBeach 1D calibration results for particular profiles. A: Model match in line with BSS; B: Absolute error of volumetric changes for max BSS and best VMS simulations; C: Relative error of volumetric changes for max BSS and best VMS simulations.

4. Results

4.1. Model performance and accuracy

The results of model calibration using BSS values for individual profiles are shown in Figure 4. The BSS values for simulations with the maximum BSS value are marked in red (max BSS), while those that are in line with the VMS are marked in green. In Figure 4A, for maximum values of the BSS, 10 profiles take values ≥ 0.8, which means a 'perfect' fit.

For four profiles, the fit of the model varies in the range of 0.6—0.8, which means a 'good' fit, and four profiles are at the 'reasonable' level in the range of 0.3—0.6. Only one profile (390.5) displayed a BSS of < 0.3, which means a 'weak' fit. In turn, the BSS values identified as being in line with the visual match of the profile shape (VMS) do not differ much from those with the maximum BSS; moreover, they reflect the profile shape better. The distinction of BSS values for max BSS and VMS simulations for each profiles is presented in Figure 4A. It is evident that values of BSS for VMS approach are lower.

The distribution of the absolute error of the volumetric changes is shown in Figure 4B. For simulations with a maximum BSS (max BSS), this error takes values from 0.04 m^3/m to 8.38 m^3/m, with an average value of 3.89 m^3/m. However, for the VMS simulations, this error ranges from 0.59 m^3/m to 11.04 m^3/m, and its average value is 3.65 m^3/m, which is slightly lower than that for max BSS. The high error values in the 388.5 profile result from its proximity to a heavy concrete seawall located in Dziwnów.

The analysis of the distribution of the relative error of volumetric changes (%) in individual profiles (Figure 4C) showed that the error ranges from 0.20% up to 44.69% for simulations with max BSS, and its average value is 19.40%. For VMS simulations, this error can be up to 60.64%, with an average value of 18.14%. Thus, it is concluded that simulations based on the maximum BSS value or the visually matched profile shape VMS give somewhat similar results, with an average relative error of approximately 20%.

Taking into account the absolute error, for simulations carried out on the basis of the max BSS, in 8 out of 19 profiles, the absolute error values are higher than the average error. For simulations performed on the basis of VMS, only 6 out of 19 profiles have higher error values than average. Similarly, the relative error values for simulations based on the max BSS are higher than the average in 8 out of 19 profiles, while for simulations based on VMS, only 6 out of 19 profiles obtained error values higher than average.

Analyzing the absolute and relative error values of the volumetric changes, it can be seen that there may be several reasons for this situation. The XBeach model is a short-term model used to simulate the volumetric changes to the coast that occur under the influence of hydrodynamic conditions such as storm events. This model is not able (using calibration parameters that are constant in simulation time) to simulate the accumulation process, which usually occurs during the storm calming and is represented by a beach bar.

Ideally, the data before and after the storm should be collected in the shortest possible time from the event. However, for calibration purposes, the only available survey data were data collected approximately 1.5 months before and after the event. Fortunately, the accumulated beach bar is very visible in most of these profiles. Apart from the accumulation related to storm calming, the shape of the cross-shore profile and thus its volume are affected by aeolian accumulation. The effects of aeolian accumulation may be observed in different parts of a beach profile. The XBeach model does not include aeolian accumulation in its simulation. Similarly, alongshore sediment transport is also not considered. Small waves and changes in water level that occur outside the time of the storm also affect the final shape of the profile.

In summary, it can be stated that the calibration of the model for each profile was carried out optimally. Simulations performed on the basis of VMS show slightly smaller absolute and relative error values than those based on the max BSS. Therefore, the simulation results from VMS were used in the further analyses in this work. The calibration results for each profile are presented individually in Table 1 as a set of *facua* and *wetslp* parameters.

4.2. Impacts of the calibration parameter set: profile-specific vs. site-specific

Another aspect analyzed in the research was the impact of the adopted set of calibration parameters (*facua* and *wetslp*) on the predicted volumetric changes on the coast. Based on the VSM simulation results, parameter sets (*facua* and *wetslp*) were obtained for each of the 19 profiles; these sets are shown in Table 1. The *facua* parameter values range from 0.16 to 0.40, while the *wetslp* parameter values range from 0.35 to 0.60. Their average values are 0.27 and 0.57, respectively. The varying parameter values result from the research area, which is a complex coastal system where natural processes are modified by various coastal protection measures (Figure 1).

The most common approach for 1D modeling is to determine the optimum model parameters for one profile (surveyed before and after the storm event) and to apply them to the selected coast section as long as the alongshore characteristics are sufficiently uniform. In the case of the study area, many natural and anthropogenic conditions could affect the optimum values of the parameters. Therefore, we examined how the adoption of one set of optimum parameters (*facua* and *wetslp*) affects the level of the relative error of the modeled volumetric changes along the study area for all 19 profiles. Based on the VMS simulation (Table 1), the average values of the *facua* and *wetslp* parameters were calculated from all profiles (0.27 and 0.57, respectively), and these became set no. 1 for further research (Table 2).

Theoretically, each of the 19 profiles could be taken separately and its parameters used as the optimum model parameters (*facua* and *wetslp*) for the study area. The values of *facua* and *wetslp* parameters for each profile calibration (Table 1) were applied to all other profiles in each combinations, creating 361 simulations. BSS values were then calculated for these simulations. The profile sensitivity to changes in model parameters, on the base of the average, minimum and maximum BSS values for particular profiles with the application of sets of parameters that are optimal for other profiles is presented in Figure 5A. It can be seen that five profiles with average BSS values close to 0 or negative (395.5, 394, 390.5, 388.5 and 388) are very sensitive (least resistant) to changes in model parameters.

In sum, profiles with little BSS amplitude are stable; for these profiles, the application of an optimal set of parameters from other profiles did not affect the obtained results. On the other hand, profiles of high amplitude and low average BSS values that are located either near coastal engineering structures or at a different type of shore show improved results after the application of optimal sets, but only by a small increase in BSS value, since the specific features of their location are not included in the simulations.

Table 1 The values of *facua* and *wetslp* parameters for the 'visual matching profile shape (VMS)' simulation for individual profiles with the average value (Figure 4A).

Profile	395.5	395	394.5	394	393.5	393	392.5	392	391.5	391	390.5	390	389.5	389	388.5	388	387.5	387	386.5	average
facua	0.40	0.37	0.20	0.27	0.26	0.24	0.17	0.23	0.24	0.27	0.31	0.19	0.16	0.19	0.40	0.32	0.30	0.30	0.23	0.27
wetslp	0.55	0.60	0.60	0.60	0.60	0.60	0.55	0.60	0.60	0.45	0.35	0.60	0.60	0.60	0.60	0.60	0.60	0.55	0.55	0.57

Table 2 Parameter sets used for all profiles at once.

Set no.	Profile no.	BSS	*facua*	*wetslp*	Description
1	all	0.70	0.27	0.57	profile calibration average parameters (VMS, Table1)
2	387	0.62	0.30	0.55	the highest average BSS
3	387.5	0.62	0.30	0.60	the highest average BSS
4	388	0.61	0.32	0.60	one of the highest average BSS
5	390.5	0.61	0.31	0.35	one of the highest average BSS
6	389.5	−0.41	0.16	0.60	the lowest average BSS
7	all	−2.42	0.10	0.30	default average BSS

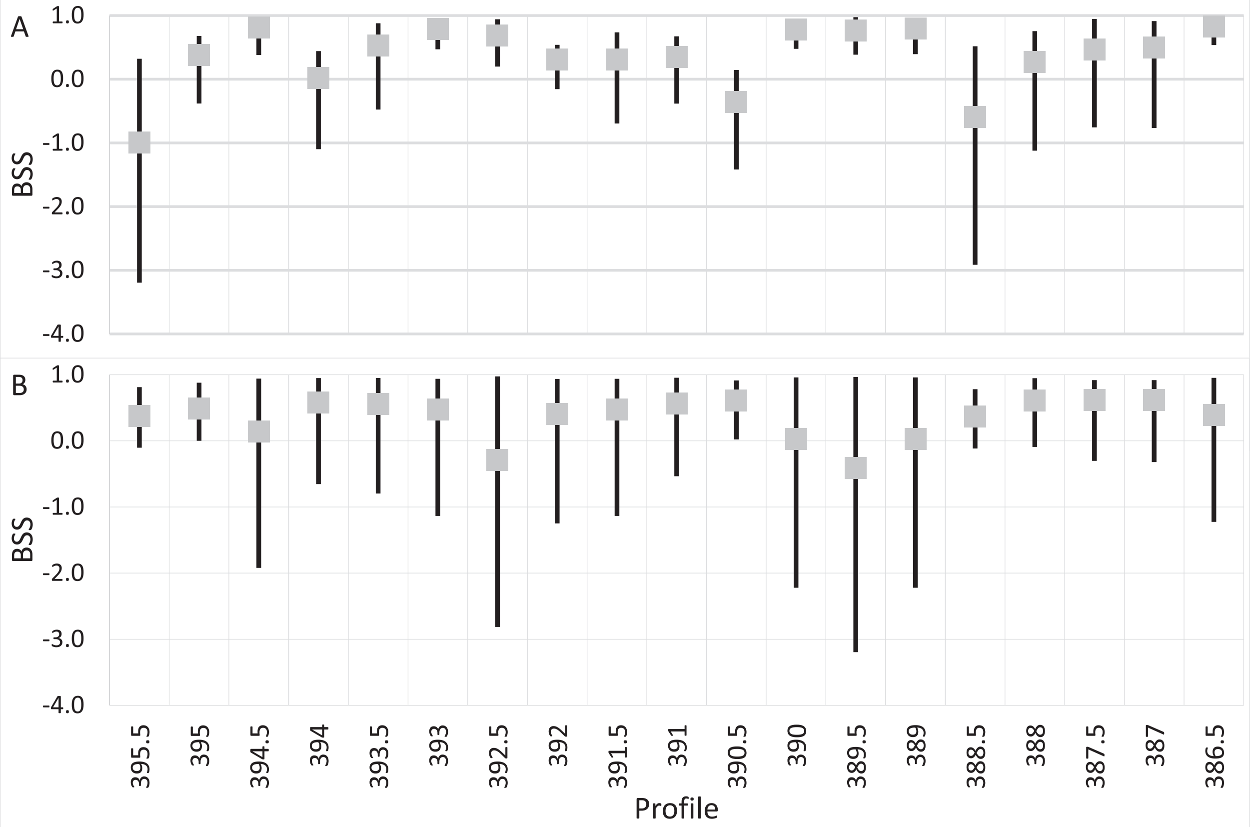

Figure 5 Average, minimum and maximum BSS values for particular profiles with the application of sets of parameters that are optimal for other profiles. A: Profile sensitivity to changes in model parameters. B: Transferability of calibration parameters along the study area.

Moreover, average BSS values for all profiles from a given set of model parameters (profile optimum) were also calculated to find the optimum parameters by site. The average BSS value and its amplitude along the study area is shown in Figure 5B. It can be seen that the five profiles with the smallest average BSS values and their largest span (394.5, 392.5, 390, 389.5 and 389) very strongly affect the simulations of other profiles, while others have a small impact.

Therefore, if we were looking for the answer to the question: what should the representative profile of the examined edge section be characterized by, we could assume that its calibration parameters should have the least impact on the simulations of other profiles and at the same time its sim-

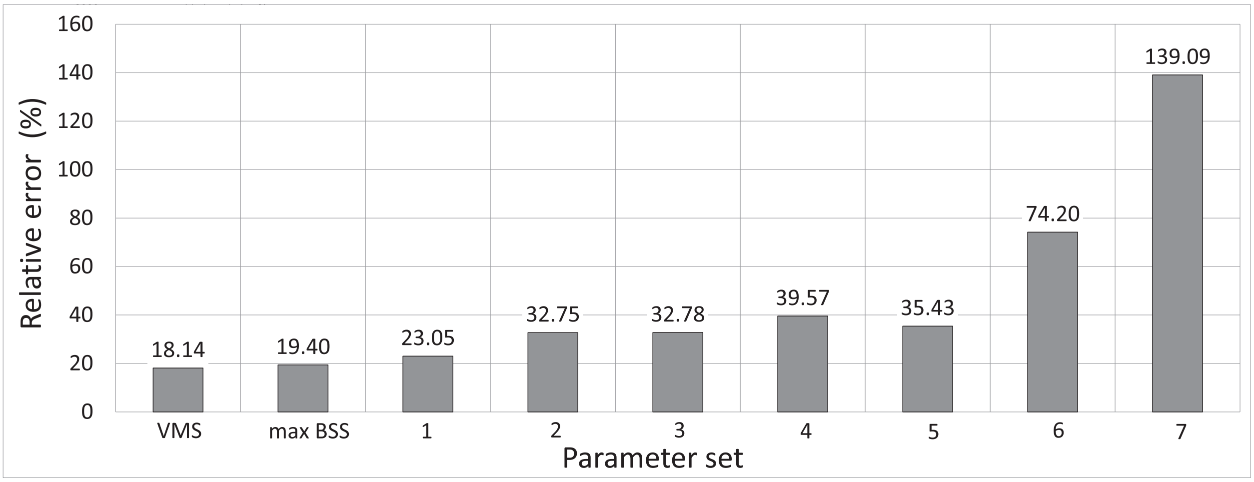

Figure 6 Average value of the relative error for individual parameter sets: no. 1—7 (Table 2); max BSS and VMS (from Figure 4C).

ulations should be the most resistant to changes in parameters. In our case, these are the other profiles: 395, 393.5, 393, 392, 391.5, 391, 387.5, 387 and 386.5. Among the most favorable profiles in this respect, their location does not show special variation. On this basis, it is difficult to clearly define the criterion for choosing a single, representative profile.

The highest average BSS values were 0.62 and 0.61. This means that the application of the optimum parameters presented by profiles 390.5, 388, 387.5 and 387 to all 19 profiles will produce the highest average BSS values. These profiles were used to select the next sets of parameters (no. 2, 3, 4 and 5), for which the *facua* and *wetslp* values are shown in Table 2. Sets no. 2 and 3, which obtained an average BSS = 0.62, are characterized by the following values: *facua* = 0.3 and *wetslp* = 0.55 and *facua* = 0.3 and *wetslp* = 0.6, respectively. Sets no. 4 and 5, with an average BSS value = 0.61, had the values *facua* = 0.32 and *wetslp* = 0.6 and *facua* = 0.31 and *wetslp* = 0.35, respectively (Table 2). For comparison, two more sets were adopted: no. 6 and 7. Set no. 6 contains parameters optimized for profile 389.5. When these values were applied to all profiles, they produced the lowest average BSS values for all profiles (= −0.41). Last, set no. 7 is the model parameters set to their default values.

For each of the 19 profiles located in the research area, 7 simulations characterized by different values of the *facua* and *wetslp* parameters were run. They were run using the particular parameter sets shown in Table 2. Next, the mean values of the relative volumetric errors for each parameter set were calculated and are presented in Figure 6. For comparison, the mean values of the relative volumetric error that were calculated on the basis of the 19 profiles with the max BSS and VMS values are also presented (Figure 4C); these values were 19.4% and 18.14%, respectively.

It seems reasonable to use a set of averaged parameters from all profiles simultaneously (sets no. 1—5) because the relative error rate of these sets varies between 20 and 40%. In nonexperimental conditions, where one randomly located calibration profile is typically used, a relative error of volume changes of at least 40% should be expected; in particularly unfavorable cases, even 75% relative error can occur. At the same time, the use of a noncalibrated model is not recommended because the relative error can reach up to 140% in these cases.

4.3. Influence of the prestorm bathymetry

Morphological data in the form of bathymetric-topographic profiles are usually created as combined profiles, i.e., the final shape is a result of various survey methods used for the underwater part (echosounder) and the subaerial part (geodetic methods, GPS, LIDAR) (see the morphological and hydrodynamic data subsection). Additionally, the data collection times for one profile are not the same, and the bathymetric data are usually shifted in time in relation to the topographic data. This generates errors, especially in the shallow area (up to a depth of 1 meter), where it is necessary to combine topographic and bathymetric data.

This study uses data provided by the Maritime Office in Szczecin in the form of bathymetric profiles that cover depths from −1 m to approx. −15 m from 2006, 2008, 2010 and 2012 for 19 profiles (every 500 m along the coast) and from 2004 for 10 profiles (395.5, 394.5 393.5, 392.5 391.5, 390.5, 389.5, 388.5, 387.5 and 386.5). On this basis, a computational grid was created in accordance with the conditions described in the section on the calibration of the model. As input data for the model, bathymetric data (from approx. −12 m to approx. −1 m) from a given year were linked with prestorm subaerial data from 2009 (from −1 m to the shore and the subaerial part).

Five combinations of prestorm input profiles were created for each of the 19 profiles (10 profiles for 2004). A simulation of the storm event of 2009 was performed using these input profiles and set no. 1 of the model parameters, which was determined as the best set (Table 2). The values and spatial distributions of the relative error (%) for simulations with different input bathymetry data is shown in Figure 7.

The high diversity in the value of the relative error of the volumetric changes depending on the accepted prestorm bathymetry is visible in Figure 7. In the worst case, the error is 70%. However, regardless of the accepted prestorm bathymetry, this error does not exceed 35% in 14 out of 19 profiles and it is lower than 30% in 11 profiles. Comparing these results with values of relative errors associated with

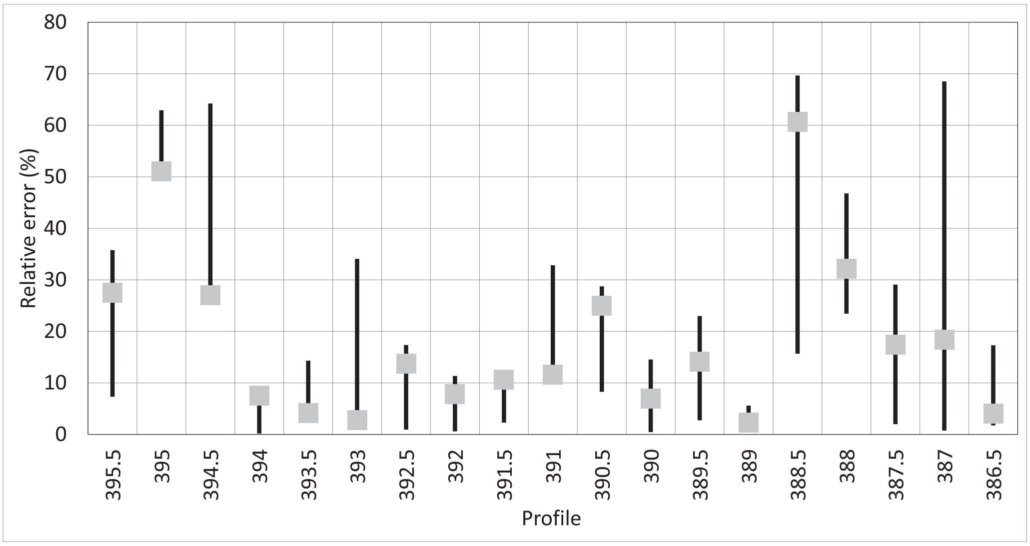

Figure 7 The relative error for the 2009 storm event simulation with different input bathymetry data. Squares depict the 2009 bathymetry, while lines show the error range of the variations in bathymetry.

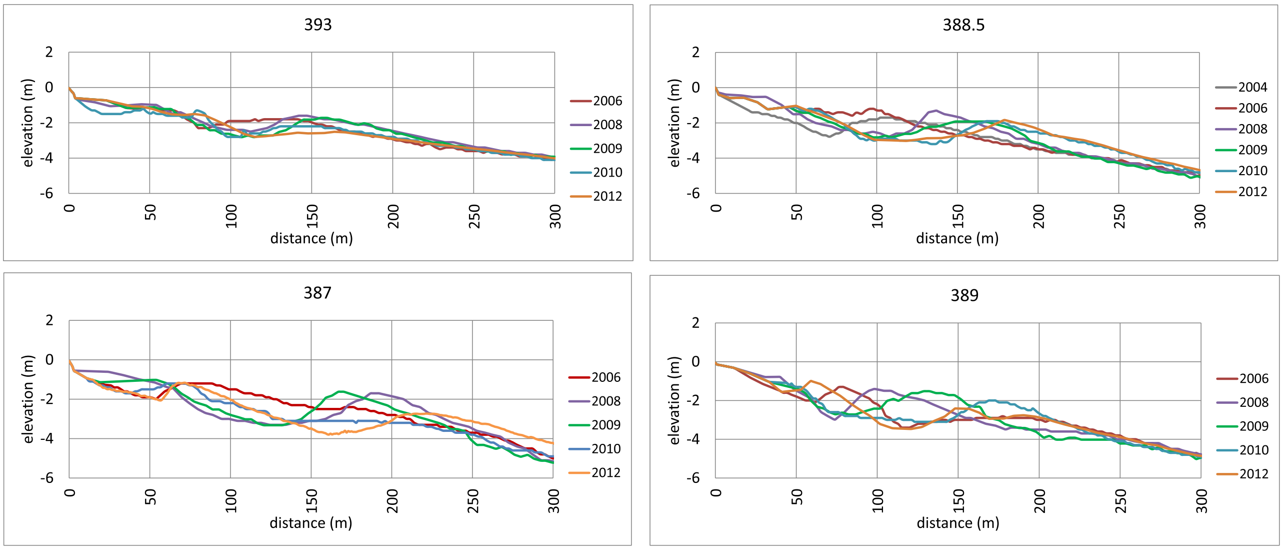

Figure 8 Bathymetric survey in particular years for selected coastal profiles.

the selection of calibration parameters for the model (30—40%), it can be concluded that, except in a few of profiles, up-to-date prestorm bathymetry does not impact accuracy to a greater extent than the proper selection of a set of calibration parameters.

To demonstrate the various shapes and variability of profiles in particular years, 4 profiles (387, 388.5, 389, 393) were chosen and they are illustrated in Figure 8. Analysis of the profile shapes in the nearshore shows that profile 387 features a variety of shapes, which translates to a high amplitude of relative error (ca. 70%; Figure 7), whereas profile 389, in which the shapes from different years are almost the same, reveals a low amplitude of relative error (5%; Figure 7).

In the next steps, an attempt was made to determine the characteristic features of the shore profile that have the greatest impact on the determination of subaerial volumetric changes. Calculations were performed for each profile for each considered year, including the seabed slope and nearshore volume every 10 m from the shoreline (from 0—10 m up to 0—150 m). The difference was calculated consecutively between the values calculated for particular years and the values of the 2009 profile that were used for calibration. Furthermore, the differences between these seabed slopes were correlated with the differences in the subaerial volumetric changes obtained from simulations with prestorm bathymetry from different years in relation to the volumetric changes modeled with the 2009 bathymetry. The results are shown in Figure 9.

The correlation coefficient (R) between the seabed slope and the differences in modeled changes in the nearshore increases from 0.48 to 0.74 in the first 40 m from the shore and then decreases to 0 at 80—100 m offshore. At greater depths, the coefficient is insignificant, as it equals not more than 0.2. In turn, the correlation coefficient between differences in the nearshore volume and differences in the mod-

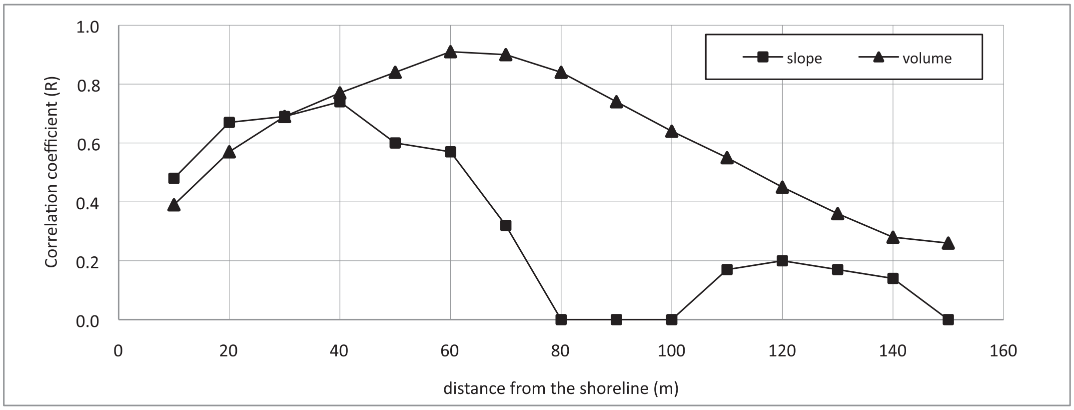

Figure 9 Correlation coefficient (R) of the modeled differences in subaerial volumetric changes with seabed slope changes and nearshore volumetric changes between 2009 and other considered years (see detailed description in the text).

eled changes in the subaerial part rises from 0.39 in the first 10 m to 0.91 at a distance of 60 m from the shoreline. Then, a progressive decrease is observed to about 0.25 at a distance of 150 m from the shoreline.

The conclusion is that changes in the seabed slope up to 40 m off the shoreline and changes in the nearshore volume up to 60 m off the shoreline are the most significant bathymetry-related factors for modeling changes in the subaerial part of the profile. The correlations between these aforementioned differences (for seabed slope at 0—40 m and for nearshore volume at 0—60 m) are shown in Figure 10. An increase in the seabed slope by 2% can result in an increase in the difference in the volume of the subaerial part of up to 8 m^3/m, while a decrease by ca. 1% may decrease that difference to -6 m^3/m (Figure 10A). On the other hand, an increase in the nearshore volume by ca. 20 m^3/m will result in a negative volume in the subaerial part of the profile of -6 m^3/m, while a decrease of 30 m^3/m will decrease the difference to -8 m^3/m (Figure 10B). It is worth mentioning that in the study area, i.e., the Dziwnów Spit, the depth at a distance of 40 m off the shoreline is 1.5 m on average (min. is 0.8 m and max. is 2 m), while at 60 m off the shoreline, the depth is 2 m, on average (min. 1 m, max. 2.5 m).

In summary, the impact of the bathymetry on modeling the subaerial volumetric changes is observed in the first 40 m off the shoreline in terms of the seabed slope and in the first 60 m in terms of the nearshore volume. The greater the slope, the more the nearshore volume decreases. In these situations, the volumetric changes increase, in contrast to the opposite situation — if the slope is gentler, it makes the nearshore volume larger, which will result in smaller changes in the subaerial part.

5. Discussion

In the first stage of this study, an adaptation of the model in profile mode (1D) was carried out for 19 coastal profiles located over the entire length of the study area, 500 m apart (395.5—386.5 km). The calibration was performed for a storm event in 2009 that caused significant changes to the dune and the beach. An evaluation of the correctness of the modeled volumetric changes was performed on the basis of several parameters: Brier skill score (BSS), absolute error of volumetric changes (m^3/m), relative error of volumetric changes (%) and visual match of the profile shape (VMS).

The study of the model calibration involved the following parameters: critical wet slope (*wetslp*), sediment transport parameter for different wave shapes (*facua*), morphological acceleration factor (*morfac*) and Shields coefficient (*smax*). The two latter parameters were set as constant values of 10 and 1, respectively, while the values of the first two ranged from 0 to 1 for *facua* and from 0.3 to 0.6 for *wetslp*, with 0.05 increments. The other calibration parameters remained at their default values. The best calibration results for the 19 coastal profiles were obtained when the value of *facua* was between 0.16 and 0.40 and the value of *wetslp* was between 0.35 and 0.60. These values for *facua* correspond or are slightly higher than those used by Splinter and Palmsten (2012), Vousdoukas et al. (2012) and Elsayed and Oumeraci (2017), where *facua* values varied between 0.1 and 0.3. According to Voukouvalas (2010), *facua* $=$ 0.5 is relevant for moderate wave conditions, while *facua* $=$ 0 or a low value generally corresponds to storms. However, the cited studies referred to tidal areas that feature stronger wave dynamics than their southern Baltic counterparts. For the southern Baltic Sea, in terms of wave action, a storm is understood as a period of time when the significant wave height exceeds 1 m for at least 6 hours (Robakiewicz, 1991). Therefore, accepting slightly higher values of *facua* seems to be appropriate. Furthermore, Elsayed and Oumeraci (2017) correlate the value of *facua* with the mean coastal slope, which in the case of Polish study area characterized by a rather narrow beach compared to tidal coasts, requires the application of slightly higher values of this parameter.

The calibration of the model for particular profiles led to a good coherence between the real and the modeled volumetric changes, as the mean absolute error was ca. 4 m^3/m, and the mean relative error amounted to ca. 20% for a single profile. The worst results were obtained for profiles located near coastal engineering structures. The absolute error there reached as high as 10 m^3/m, while the relative error reached 60%. One disadvantage of 1D model adaptation is the lack of options for taking such structures into consideration, which means that the modification of coastal processes that they induce is overlooked.

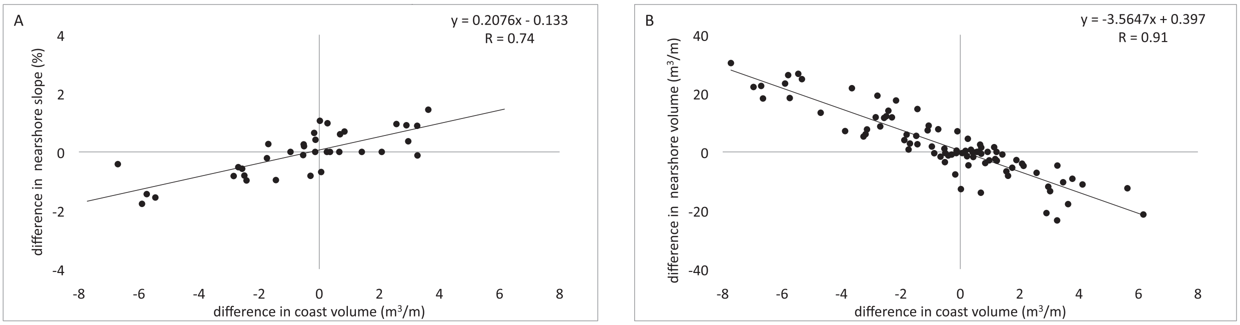

Figure 10 Correlation charts A: differences in seabed slope (40 meters) vs differences in the subaerial part; B: differences in nearshore volume (60 meters) vs differences in the subaerial part.

In the next stage of the study, a verification of whether one set of parameters can be used for all profiles was carried out. This can be very useful if the model is deployed in more sophisticated online tools, such as early warning systems (Haerens et al., 2012). The study revealed that it was possible to apply one set of *facua* and *wetslp* parameters for all profiles at once, previously calibrated for the storm of 2009 within the Dziwnów Spit area. Simmons et al. (2017) noted that optimal parameters for the area of study should be identified after an evaluation of the uniformity of alongshore coastal processes (e.g., the same storm impact regime). In this case, all profiles were identified as a collision regime (when total water level exceeds dune toe and dune erosion occurs) according to the storm impact scale by Sallenger (2000), making the application of one parameter set possible.

However, the increase in the error values for the modeled volumetric changes should be considered. For example, among the tested sets, the lowest mean relative error (25%) was obtained for $facua = 0.27$ and $wetslp = 0.57$; the mean relative error rose to 40% when the parameter values were changed to $facua = 0.32$ and $wetslp = 0.60$. This increase is caused by the construction of a variety of coastal defense structures that modify how natural processes occur. The studies of Simmons et al. (2019) on the changeability and transferability of calibration parameters along shorelines showed that, in cases of missing data for model calibration, the lowest errors were achieved by transferring the parameters from the nearest profiles. However, these studies were conducted on embayment beaches. In the Polish study area, which is fairly straight but includes various coastal defenses, making the system quite complicated, such an approach is somewhat unsatisfactory. The results of this study indicate that the application of an average set of calibration parameters is a reliable alternative.

The last stage of the study of the application of the 1D XBeach model consisted of an investigation of how the bathymetry data recorded before the storm influence the volumetric changes determined by the model. This aspect is crucial due to the substantial difficulty of obtaining data just before and after storm events. In Poland, such data are recorded by the Maritime Offices usually once a year during the summer as a part of the coastal zone monitoring program. Another idea behind this study was to verify whether updating the bathymetric data exported to operational online early warning systems has an impact on the determination of volumetric changes. Therefore, to achieve the goal of this study, all the available bathymetric data were collected, and a simulation of the storm event of 2009 was carried out using the combined data: the prestorm topography recorded prior to that storm event and the bathymetry data from 2004, 2006, 2008, 2010 and 2012.

This study revealed that the impact of the bathymetry on modeling volumetric changes was evident up to 100 m off the shoreline and to a depth of 2 m. A change in the seabed slope of 1—2% within the first 40 m off the shoreline, and hence a change in the nearshore volume of 20—30 m^3/m in the first 60 m, may increase the difference between the real and modeled changes in the volume of the subaerial part in profile by ca. 6—8 m^3/m. The obtained results are in line with those of studies conducted by Splinter et al. (2011). In studies on the possibility of predicting dune erosion induced by a storm event without knowing the prestorm bathymetry, it was revealed that less dune erosion is observed for profiles with gentler seabed slopes, whereas steeper sea bed profiles induce greater erosion in the subaerial part of the profile.

6. Conclusion

The application of the XBeach numerical model to determine the volumetric changes to the southern Baltic dune coast using the example of the Dziwnów Spit allowed us to define:

- the calibration parameters of the 1D model;
- the possibility of using a set of parameters for all profiles at the same time with the determination of related errors; and
- the impact of prestorm bathymetry on the modeled volumetric change.

The morphology of the coast before and after a storm event should be recorded as late as possible and as soon as possible before and after the storm event, respectively. The storm calming period is characterized by the accumulative of coastal and aeolian processes, which the XBeach model does not take into account. These factors affect the volume of the profile and the calibration results. In such cases, the popular BSS indicator should be replaced with the VMS approach. Simulations conducted on the basis of the VMS showed slightly lower absolute and relative error values than those performed on the basis of the best BSS (max BSS).

Good correspondence between the measured and modeled volume changes was obtained. The mean absolute error from all profiles was approximately 4 m^3/m, while the mean relative error was approximately 20%. The poorest results were recorded in the vicinity of coastal engineering structures. In these cases, the absolute error was up to 10 m^3/m, while the relative error was 60%. The disadvantage of the use of this model in 1D mode is its lack of ability to take into account coastal engineering structures and the modification of natural processes that they induce. In this case, the calibration with an extended range of calibration parameters or the application of a 2D model should be applied.

Under the described conditions, it is possible to apply one set of *facua* and *wetslp* parameters for all profiles at the same time; however, the increase in the error values when determining the volumetric change should be expected. It is reasonable to use the averaged parameters from all profiles because in that case, the relative error varies between 20 and 40%. When a single randomly located calibration profile is used, the relative error for the volume changes can be at least 40%, while in particularly unfavorable cases, it may rise to 75%. The use of a noncalibrated model is also not recommended because the relative error can reach up to 140%.

The influence of prestorm bathymetry on modeling volumetric changes is most evident in the area up to approximately 100 m from the shoreline. Changing the seabed slope by 1—2% up to 40 m off the shoreline and changing the nearshore volume by 20—30 m^3/m to 60 m off the shoreline can increase the difference between the measured and the modeled volume change by approximately 6—8 m^3/m. At higher slopes, the nearshore volume decreases. In these situations, the volumetric changes increase; in the opposite situation, when the slope is gentler, the nearshore volume is larger, which results in smaller changes in the subaerial part. Therefore, it seems necessary that the monitoring of the maritime coastal zone in the form of bathymetric and topographic measurements performed only once a year should be extended by measurements performed both before and after the storm.

However, regardless of the prestorm bathymetry used, the relative error of the volumetric changes on the shore is in the range of 30—35%. Comparing these results with the magnitude of the relative errors associated with the selection of model calibration parameters, which were 30—40%, it can be concluded that except in a few profiles, the prestorm bathymetry and the randomness of the selection of the calibration parameters have similar effects on the accuracy of predictions of volumetric changes.

Data availability

The data used for the research described in this article were obtain from the Maritime Office in Szczecin and the Interdisciplinary Centre for Mathematical and Computational Modeling, University of Warsaw. The data supporting the findings of this study are available from the corresponding author N.B. on request.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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