

Modelling beach volume changes caused by moderate and weak hydrodynamic conditions

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Abstract

The goals of this study were the calibration of the XBeach model for moderate and weak hydrodynamic conditions in 2D mode and the determination of the volumetric changes induced by them. 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 (%). An analysis of accuracy in determining volumetric changes in the dune coast, with XBeach applied, provided an average absolute error in determination of volumetric changes of $4.0 \text{ m}^3/\text{m}$ for a significant storm and $1.5 \text{ m}^3/\text{m}$ for moderate and weak hydrodynamic conditions in a 2D model calibration process.

Simulations of morphological changes caused by moderate and weak hydrodynamic conditions for seven timeframes classified into three groups have been run in 2D mode. Within a validation process, the average absolute error in the determination of volumetric changes in the beach was ranging from $0.64 \text{ m}^3/\text{m}$ to $2.42 \text{ m}^3/\text{m}$ depending on the group of hydrodynamic conditions.

A high value of the correlation coefficient (R) between the measured and modelled balance of volumetric changes (m^3/m) for all timeframes – 0.79 and for the ‘strongest’ group no. 3 – 0.91 were revealed. For the remaining groups, i.e., group no. 1 and no. 2 of hydrodynamic conditions, no such correlation was observed. Furthermore, the temporal analysis of the sum of beach volumes proved that a rising trend was observed over 4 months. Thus, moderate and weak hydrodynamic conditions dominated the accumulation within the area of study. XBeach reflected this trend well, producing a difference between the measured and modelled sum of volumes at the end of the timeframe of $7.27 \text{ m}^3/\text{m}$, which is close to the volume determination error by the model.

Keywords

XBeach model; Dune coast; Baltic Sea; Coastal changes; Volume errors

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1. Introduction

The marine coastal zone is a very dynamic area that undergoes continuous changes. Changes in the coast can be investigated on a variety of spatial and temporal scales, and hence different factors and processes will be predominantly affecting the coastal morphology at a given place (Musielak et al., 2017). In the short term, the greatest changes are caused by extreme events (storms) of strong wave action and rapid sea level rise, which can lead to coastal flooding. This is why storm events and their impact on the coast are attracting scientists and researchers related to the topic. Special attention is paid to phenomena that change not only the beach and the nearshore, but also the dune system, which is the natural coastal defence measure. Such storm events are referred to as significant storms by Furmańczyk and Dudzińska-Nowak (2009).

Many researchers observed that storm events, that are not that extreme but occur shortly one after another, can cause greater changes in the marine coastal zone than single catastrophic events (Ferreira, 2005; Furmańczyk and Dudzińska-Nowak, 2009; Coco et al., 2014; Terefenko et al., 2018). Apart from extreme hydrodynamic conditions, the moderate and weak conditions together with calm periods also play a significant role in the functioning of the marine coastal zone. These conditions contribute to changes in the coast and its recovery in-between storm events (Bugajny and Furmańczyk, 2014, 2017). Once a storm ends, coast accumulation starts. Accumulation takes much more time than rapid storm-induced erosion and may last from days (Phillips et al., 2019; Bugajny and Furmańczyk, 2020) through months and years (Phillips et al., 2017; Doddet et al., 2019) to decades (Turner et al., 2016).

Simulations of coastal changes can be carried out us-

ing models. Three different types of models can be applied to predict beach profile changes (Ciavola et al., 2014), i.e. conceptual descriptive models (Sallenger, 2000), models based on the equilibrium profile theory (Brunn, 1962) and process based models (Roelvink and Brøker, 1993). XBeach is one of the most commonly applied process-based models to predict morphological changes in the coastal zone. XBeach was primarily made to simulate processes that cause changes in the coast due to the impact of the storm event (Roelvink et al., 2009). Today, this model is applicable commonly to estimate changes in coastal morphology driven by single extreme storm events (Vousdoukas et al., 2011, 2012; Harley et al., 2011; Splinter et al., 2012; McCall et al., 2010; Bugajny et al., 2013, 2015; Dissanayake et al., 2014; Williams et al., 2015; Harter and Figlus, 2017; Schambach et al., 2018) and storm groups (Splinter et al., 2014; Dissanayake et al., 2015a,b). So far, only a few studies have been published on the application of XBeach to model moderate and weak wave action, focusing on small volumetric changes in the coast and the recovery of the coastal profile (Pender and Karunathna, 2013; Kombiadou et al., 2021; Volpano et al., 2022).

The goal of this study is to utilize XBeach to model volumetric changes in the dune coast caused by moderate and weak hydrodynamic conditions. These conditions do not affect the dune system except in the beach and nearshore areas. For this purpose, the results obtained from a calibration of a 1D model for a storm event were used (Bugajny and Furmańczyk, 2022) and then applied to calibrate the model in 2D for a significant storm. The results of the latter calibration had served as an input simulation for calibration of the 2D model for moderate and weak conditions and then helped in the determination of volumetric changes caused by these conditions. An application of fixed bathymetric and topographic data to all simulations was an additional problem to solve.

Such a flow of actions allowed answering the following questions: To what extent the values of parameters selected for 1D calibration for a significant storm are identical with values derived from 2D calibration? Are the values of parameters selected for 2D calibration for a significant storm optimal for moderate and weak conditions? And finally, does the usage of fixed prestorm bathymetric and topographic data allow determining volumetric changes caused by moderate and weak conditions in a several-month timeframe?

2. Study area and materials

The study area spans the dune coast along 2-km long section of Dziwnów Spit near Międzywodzie (from km 393 to km 395) in the western part of the Polish Baltic coast (Figure 1). The Baltic Sea is a basin with storm wave dominated environments with tides limited to centimetres (Masselink et al., 2011; Sztobryn et al., 2005). Hence, tides are negligible in the processes that shape the coastal zone. The

western Polish coast, which includes the study area, is ranging in 1.96–2.22 m above NN (Normal Null), in relation to storm events between 1811 and 2006 (Musielak et al., 2017). However, the monthly maximum height of the significant wave in the Pomeranian Bay ranged from 2.89 to 4.22 m in 1998–1999 (Paplińska and Reda, 2001).

The study area covers the western part of Dziwnów Spit with its well-developed 12 m tall dunes that create a natural coastal defence. The shore is composed of a wide beach reaching 30–50 m and the nearshore containing 2–3 underwater bars (Dobrcki and Zachowicz, 2005; Musielak et al., 2007). The beach and the bottom sediments consist of fine and medium sand. In terms of coastal dynamics, the area represents alternating accumulation and erosion cells with dominant erosion (Dudzińska-Nowak, 2006a,b; Zawadzka-Kahlau, 1999).

From the east, the study area joins the protected section of Dziwnów Spit. In the vicinity, there are seawall, groins, and Dziwna mouth (km 391.5). To the east of the mouth there is a complex defence system that contains a heavy seawall, a mound seawall, groins, and T-shaped groins as well as beach nourishment (Dudzińska-Nowak, 2015). Currently, Dziwnów Spit is one of a few areas of such a complex coastal defence system, which makes it quite complicated one to study.

2.1 Morphological data

This study uses the morphological data of the coastal zone delivered by the Szczecin Maritime Office in the form of bathymetric profiles that are captured each year as a part of the monitoring programme. These profiles are taken every 500 m along the coast and reach no farther than 2000 m seawards from on-land benchmarks. Bathymetric measurements are carried out from a depth of 1 m to ca. 15 m using an echo sounder. Data from measurements taken in summer 2012 within the area of study, that is, km 397.5–km 391.5 of the Polish coastal chainage (km 0.0 at the Polish-Russian border and km 428 at the Polish-German border), were used. Detailed information on these measurements can be found in Bugajny et al. (2013) and Bugajny and Furmańczyk (2022).

Additionally, airborne laser scanning data (topographic red lidar) derived on September 28, 2012 by means of LMS-Q680i Riegl scanner were applied. These data feature a density of 8 pt/m² as well as vertical and horizontal accuracy x, y and $z \pm 20$ cm (Dudzińska-Nowak and Wężyk, 2014). Similarly to bathymetric profiles, scanning data were also shared by the Maritime Office in Szczecin and taken as part of the annual monitoring programme.

2.2 Remote sensing data

Two sheets of orthophotograph (N-33-66-C-d-3-4 and N-33-66-C-d-4-3) delivered by the Szczecin Maritime Office in 2012 were applied to the study. Aerial photographs were shot by GisPro by means of a DigiCAM60 medium

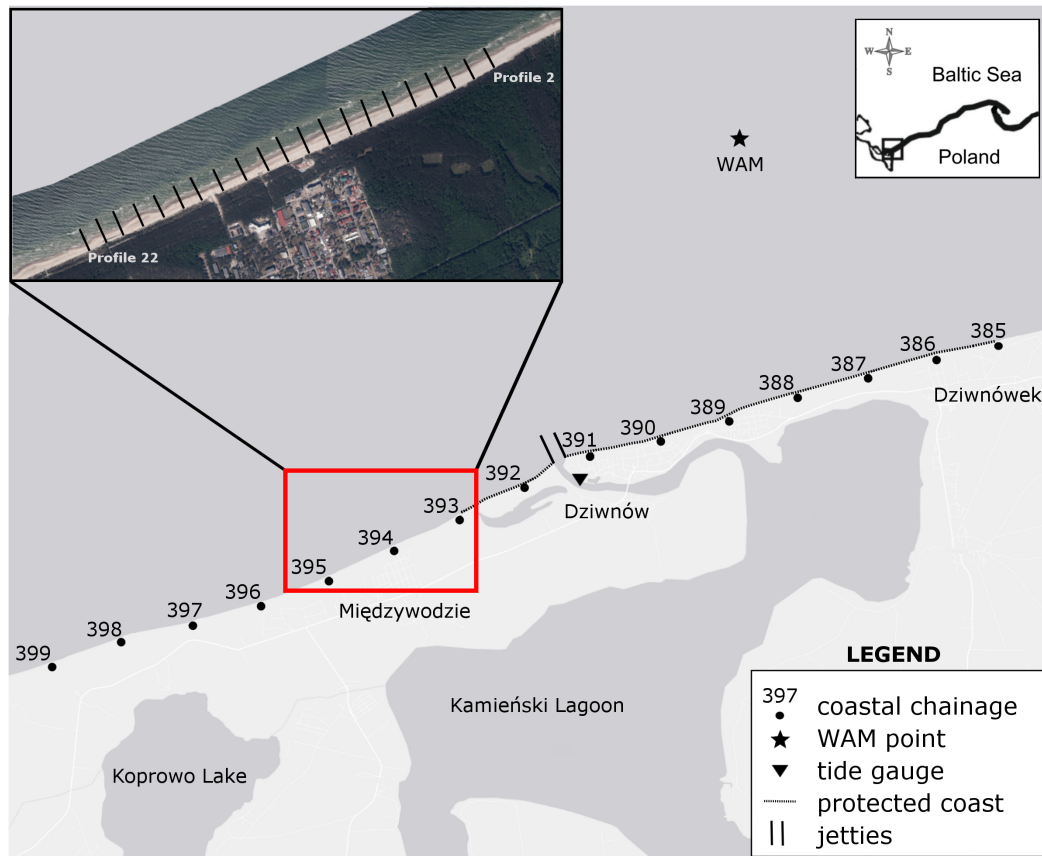


Figure 1. Study area at the Dziwnów Spit with imposed cross-shore profiles used for the XBeach modelling, location of the WAM point and tide gauge from where hydrodynamic data were obtained from.

format digital camera on September 29, 2012. A digitalisation of the orthophotograph was carried out to comply with the PUWG 1922/19 coordinate system. The resulting orthoimages were saved as uncompressed TIFFs, with a pixel size of 0.15 m.

2.3 Hydrodynamic data

2012 water level data are continuous records from a survey station run by the Institute of Meteorology and Water Management National Research Institute. The station is located in the Dziwna mouth (Figure 1). Thanks to telemetry, the data automatically derived from the station are shared as images and the numerical values on the Baltic Information Service website (<http://meteo.imgw.pl/>). The water level data show hourly values as referred to Kronstadt.

Basic wave parameters are derived from the WAM model – Wave prediction Model created by Wave Model Development and Implementation Group (WAMDI Group, 1988). The WAM model was made for global purposes, but it can also be applied locally. It is one of the most common wave models that has been adapted and verified in many water areas around the world, i.a. Black Sea (Valchev et al., 2004; Cherneva et al., 2008), Mediterranean Sea (Ponce de León and Guedes Soares, 2008), and the Baltic Sea (Paplińska,

1999, 2001; Cieślíkiewicz and Herman, 2001, 2002), where verification tests of the WAM model proved very good correlation between modelled and measured wave parameters.

As for analyses, data of 2012 derived from the point of coordinates 54.0625°N, 14.7664°E were applied, that is, placed ca. 3 km north of the city of Dziwnów, at a depth of 10 m (Figure 1).

2.4 Field surveys

The morphological changes were carried out along a 2-km stretch of the coast near the town of Międzywodzie (km 393–395). The study uses the results of surveys taken from September to December 2012 (9 survey campaigns) using GPS RTK. The intervals between campaigns were not the same. On average, a campaign took place every two weeks. An assumption of these campaigns was to record changes in dunes, beach and nearshore in profiles located along the area of study every 100 m. If the hydrodynamic conditions were favourable, these changes were successfully recorded to a depth of 1 m. On other occasions, when conditions were hindering the field work, registration was limited to the area where the measurement could be safely taken (Bugajny and Furmańczyk, 2014, 2017).

The first campaign, which lasted 3 days, consisted of a detailed survey of the beach and the dune to achieve the most accurate condition (morphology) of the area of study. Among the beach, profiles were located 10–15 m from each other, nearshore, every 20 m, whereas on the dune, every 5 m. In consecutive campaigns, 21 profiles were surveyed. Cross-shore profiles were measured from the dune base to a depth of approximately -1 m every 100 m along the coast. During the last three campaigns, due to adverse weather conditions, i.e. low air temperature and short insolation, the changes in the coast morphology were recorded in every other profile from previous campaigns (total of 11 profiles). Before and after each survey, a measurement of at least one control point was taken. The differences in elevation of the control point ranged from $+2.5$ cm to -1.5 cm. An analysis of short-term changes of the coast caused by moderate and weak hydrodynamic conditions included volumetric changes of the beach accepted as per Bugajny and Furmańczyk (2017), while a comparison of measured and modelled volumetric changes was carried out in profiles from those last three campaigns.

3. Methods

3.1 Creation of a bathymetric and topographic map of 2012

Creation of the bathymetric and topographic map that would be used for 2D modelling featured numerous datasets that diverge from each other in terms of form (land elevation measurements, orthophotograph) and accuracy (bathymetric measurements, GPS RTK data, lidar data). The relief of the seabed, the beach, and the dune for a 6-km-long section of the coast (km 397.5–391.5) has been divided into areas as in Figure 2 and drawn up in the following manner:

Area 1

Within this area, bathymetric profiles of 2012, from a depth of ca. 10 m to 2 m along the section of the coast: km 397.5–391.5 were interpolated cross- and longshore every 50 m.

Area 2

Bathymetry within this area was created on the basis of bathymetric profiles of 2012. In addition, a seabed relief was detailed thanks to the orthophotograph of 2012. It allowed one to determine the course of the first (fixed) underwater bar and the trough before it. The elevations of the underwater bar crest were derived from 13 bathymetric profiles (397.5, 397, 396.5, 396, 395.5, 395, 394.5, 394, 393.5, 393, 392.5, 392, 391.5) taken in 2012. Then an interpolation was applied every 1 m along the course of the first underwater bar crest and the trough. The depth of the first underwater bar oscillated between 1.99 and 0.91 m, while the trough could be found from 2.68 m to 1.21 m.

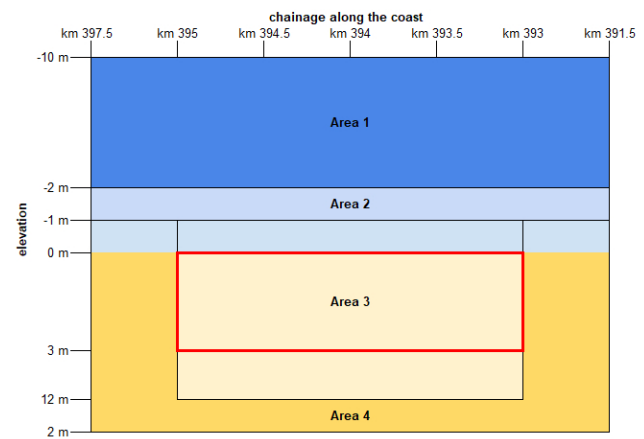


Figure 2. Scheme of datasets used to create a bathymetric and topographic map. *X*-axis – chainage along the coast, *y*-axis – elevation. Limits of the main area of study (domain) for which volumetric changes were calculated is marked in red line.

Area 3

This area spans from the depth of ca. 1 m to a height of 12 m (dune top) and covers the field surveys area. This study uses the survey data collected during the campaign carried out between 17 and 19 September 2012. Surveys enabled a determination of the course of the ephemeral underwater bar and the trough before it, as well as to set out the course of the beach berm and its trough along the shore. Elevation values between the profiles were interpolated every 1 m. Furthermore, survey data on the seafront dune slope from the campaign that took place between 11 and 13 June 2012 were also applied (Bugajny and Furmańczyk, 2014). These data allowed determining the dune base that was later interpolated along the coast every 1 m between profiles. Within a part of the study area (i.e., km 397.5–395 and km 393–391.5), data within the range of 0 and -1 m is missing.

Area 4

The relief of this area was determined on the basis of the data derived from an airborne laser scanning that was performed in September 2012. Within km 395–393, the data were used within the dune system and the hinterland, while within the remaining areas, i.e. km 397.5–395 and km 393–391.5, the seafront limit of the data reached the shoreline defined as an elevation of 0 m in relation to the Kronstadt reference system.

The 2-km long section between km 395 and 393 of the coast is the main area of study where the volumetric changes of the 2D modelling were determined (Figure 2). Due to the oblique angle of wave and creation of shadow zones, which greatly affect the wave parameter values and thus the modelling results, the domain area has been extended by 2 km on both sides. Area to the west of the domain between km 397.5 and 395 and to the east between

km 393 and 391.5 are additional areas and volumetric changes modelled there were not taken into consideration in the analysis.

Next, the prepared input data for the XBeach model were compared with profiles measured during the field campaign between 17 and 19 September. Following the calculated beach volumes, the differences for 21 profiles ranged from $-1.70 \text{ m}^3/\text{m}$ to $1.02 \text{ m}^3/\text{m}$ (average $-0.14 \text{ m}^3/\text{m}$). Despite data sets of different density and accuracy, the so-created computational grid reflects the beach relief and the beach volume very well.

3.2 XBeach setup

3.2.1 Extreme events in 2009

To calibrate XBeach in the area mode (2D), a storm event was applied that had been previously used to calibrate the model in the profile mode (1D) and was described by Bugajny and Furmańczyk (2022). This 2D area approach included oblique waves and longshore transport that had not been considered in the 1D calibration.

To create a domain, prestorm morphological data in the form of bathymetric and topographic profiles taken in 2009 were used. The dissatisfaction of the density of measurement points resulted in longshore interpolation at each 25 m. In turn, the distances between interpolated points in the cross-shore direction were constant – 50 m and spanned over the depth between 10 and 2 m. Moving toward the shore, the grid size was decreasing to 10 m within the area between the ephemeral underwater bar and the dune system.

Due to the consideration of oblique waves and longshore transport, the computational grid has been extended by 2 km on both ends, so it fits between km 397.5 and 391.5. The correctness of the simulation results was verified only in profiles settled in-between km 395–393. Such an extended area was given a computational grid of various mesh sizes that cross-shore spanned from 25 m at the offshore to 3 m onshore, while longshore it was fixed as 25 m. To create an optimal grid, the interpolation deployed a Courant-Friedrichs-Lewy (CFL) convergence condition that was 0.7. An implementation of a variable grid allowed minimising the computing time.

Furthermore, wave boundary conditions were represented by hourly JONSWAP spectra (instat = 41, wave groups generated using a parametric spectrum) oblique to the coast. The sea level at the offshore boundary of the model was accepted as the same as that recorded in the Dziwna mouth.

Two sets of parameters were deployed to a 2D calibration for a significant storm that showed the best Brier Skill Score (BSS) in a 1D calibration carried out by Bugajny and Furmańczyk (2022). The above-mentioned study focused on such parameters as *wetslp* (parameter related to the dune erosion algorithm) and *facua* (parameter for sediment transport related to the wave shape), as well as

morfac (the morphological acceleration factor) and *smax* (parameter related to the Shields coefficient). The latter two accepted the same value as in 1D – 10 and 1, respectively. The values of *facua* and *wetslp* were changing. In the set no. 1 they amounted to 0.27 and 0.57, respectively, while in the set no. 2 – 0.30 and 0.55. Additionally, a set with default values was applied, that is, *facua* = 0.10 and *wetslp* = 0.30. Each next simulation featured different values of *wetslp* and *facua* (next new sets) until satisfying results were received.

3.2.2 Moderate and weak hydrodynamic conditions in 2012

For the area within km 397.5–391.5 a rectilinear computational grid of varying mesh size that in a cross-shore direction ranged from 25 m at the offshore boundary to 2 m on the shore. In the longshore direction, the mesh size spanned 50 m to 10 m. Within the domain area between km 395 and 393, for which volumetric changes have been determined, the size of the longshore mesh was fixed and amounted to 10 m.

Calibration in 2D mode for moderate and weak hydrodynamic conditions used a resultant set from calibration for the significant storm. To find the optimal set of model parameters, several simulations were performed with different values of the *facua* parameter, which ranged from 0.12 to 0.32 at the 0.02 step.

3.3 Morphological evolution

In the study, four measures were used to evaluate model correctness, the same as in Bugajny and Furmańczyk (2022). The first measure of model performance for simulations is quantified with a Brier Skill Score (BSS), which is a commonly used measure within coastal numerical modelling (Sutherland et al., 2004; Roelvink et al., 2009; van Rijn et al., 2003; Williams et al., 2015; Pender and Karunaratna, 2013; Bugajny et al., 2013) and can be divided into five classes: ‘excellent’ (1.0–8), ‘good’ (0.8–0.6), ‘reasonable/fair’ (0.6–0.3), ‘poor’ (0.3–0.0) and ‘bad’ (<0.0) (van Rijn, 2003). In this study, the BSS values were calculated only for the land part of the profile, taking into account the changes of the beach and the dunes. The second measure is proposed by Bugajny and Furmańczyk (2022). It is a visual match of the profile shape (VMS) after the storm with the model result. This measure has been introduced to better evaluate a match between model and poststorm data collected after some time of the storm event. Such data usually includes signs of recovery of the cross-shore profile in a form of visible beach berm or a change in shape of the profile at the dune base, where recovery was induced by aeolian transportation. Such a model match is featured by lower BSS values. The remaining two measures are common: the absolute error of volumetric changes and the relative error of volumetric changes. The first one shows the absolute difference between measured and modelled volumetric changes, while the other is the ratio of the absolute error to the measured volumetric changes, and it is

expressed in percentage.

4. Results

4.1 Model performance and accuracy for significant storm in 2009

Calibration of the model in the 2D mode for the significant storm was performed for about 2-km long section of the coast on the western side of Dziwna mouth. Field data derived from 5 profiles (km 395, 394.5, 394, 393.5 and 393) was compared with results of modelling. In the first run of 2D model calibration, three sets of parameters were used: two sets featured the best BSS for all profiles together that were obtained from the 1D model calibration and one set with default parameters (Bugajny and Furmańczyk, 2022). Set no. 1 (average profile calibration parameters) comprised of the average BSS = 0.7, at *facua* 0.27 and *wetslp* = 0.57. Set no. 2 (the highest average BSS) delivered *facua* = 0.3 and *wetslp* = 0.55, at average BSS = 0.62. The results of the 2009 simulation of the storm event are shown in Figure 3. An analysis of the BSS received for particular profiles (Figure 3A) has shown that an average set of calibration parameters (*facua* = 0.27 and *wetslp* = 0.57) – the set no. 1 – received in the 1D mode calibration is not suitable for the 2D mode. The BSS values ranged here from –0.60 to 0.20. However, three profiles (km 395, 393.5, 393) delivered positive numbers, but their low values could only be classified as ‘poor’ according to van Rijn et al. (2003). Two remaining profiles (km 394.5, 394) provided negative values of BSS which are understood as ‘bad’ matches. Results obtained from the set no. 2 (*facua* = 0.3 and *wetslp* = 0.55) were even worse than those of the set no. 1, since all five profiles delivered negative BSS values ranging from –0.30 to –0.77. Another set – of default values (*facua* = 0.10 and *wetslp* = 0.30) – gave satisfying results: two profiles delivered BSS 0.8, another two in-between 0.6 and 0.8 and the last had value smaller than 0.3. This spread among the profiles resulted in an average BSS = 0.59.

The next simulations used changing values of the two parameters to obtain the best results possible. In case of the best-matching profile shape, the best BSS values were obtained for a set with *facua* = 0.12 and *wetslp* = 0.30. A profile (km 393.5) delivered BSS 0.8, which is a ‘perfect’ match, another two (km 395 and 394.5) between 0.6 and 0.8, what gives a ‘good’ match, while the last two (km 394 and 393) fit in the range of 0.3–0.6, so the match is ‘reasonable’. The average BSS was 0.64 in this set.

Figure 3B shows the distribution of the absolute error of volumetric changes for all sets of parameters. For the simulation with the set no. 1 (from 1D calibration) (Bugajny and Furmańczyk, 2022), this error amounted to values from 24.28 m³/m to 39.80 m³/m, 29.65 m³/m on average. Next simulation with the set no. 2 gave the error ranging from 27.25 to 43.49 m³/m, 32.33 m³/m on average. The set no. 3 with default values of the parameter gave the fol-

lowing error values: max – 8.70 m³/m, min – 1.59 m³/m, average – 5.37 m³/m. Finally, the set no. 4 – VMS (set of parameters that gave the best BSS) delivered the error between 1.10 m³/m and 6.92 m³/m, producing an average of 4.14 m³/m.

Analysis of the relative error along particular profiles (Figure 3C) showed that the simulation with the set no. 1 gave an error of more than 100% with a peak of 128.28%, at an average of 115.43%. Similar error values produced simulation with the set no. 2: 120.55%–145.11%, on an average of 125.97%. The set no. 3 – the default – provided much smaller error values ranging from 4.92% to 41.69%, at an average of 23.36%. The VMS set no. 4 gave slightly better values, ranging from 4.48% to 28.13%. The average error was 17.18%, which is slightly better than the best ones received in 1D calibration, named as max BSS = 19.40% and VMS = 18.14% as mentioned in Bugajny and Furmańczyk (2022).

The greatest discrepancies in volumetric changes induced by a storm for the ‘best fit’ have been located along profile km 395 and 393.5 and reached 7 m³/m. Along profiles km 394.5 and 393 the differences between actual and modelled relief amounted to ca. 2 m³/m. Low value of BSS = 0.31 which has been attributed to the profile km 394 matches with a relative error of over 20% and a difference in volumetric changes of 5 m³/m. However, if a profile shape is being considered, as depicted in Figure 4, then it is clearly visible that the profile run was well recreated by the model. The greatest discrepancies can be observed in the vicinity of the beach berm and the dune base, which has had an impact on the differences in the predicted volume and therefore the relative error. On the other hand, the low BSS value is disturbing. The reason for that can be the fact that only small values of volumetric changes driven by a storm (approx. 20 m³/m) were recorded as well as the ‘nature’ of the BSS alone (Sutherland et al., 2014).

It is interesting that four remaining profiles had high BSS values with quite large differences between the modelled and actual volumetric changes. Analysis of Figure 4 proves that km 393 is underestimated in terms of dune erosion and overestimated in beach erosion, which in sum gives little discrepancy in relation to actual changes. In turn, profile km 393.5, which is characterised by great discrepancies between measured and modelled volumetric changes, appears to be reflected better by the model, because of very well estimated dune erosion and quite well estimated beach erosion. The greatest discrepancies occur at the base of the dune and the beach berm. It may be justified that the model does not recreate the beach berm after a storm and does not take the accumulation of aeolian in the dune base into consideration.

In summary, the results obtained from the model calibration on a significant storm in a 2D mode are satisfactory. The best shape fit for all profiles was received for the following set of parameters: *facua* = 0.12 and *wetslp* = 0.3.

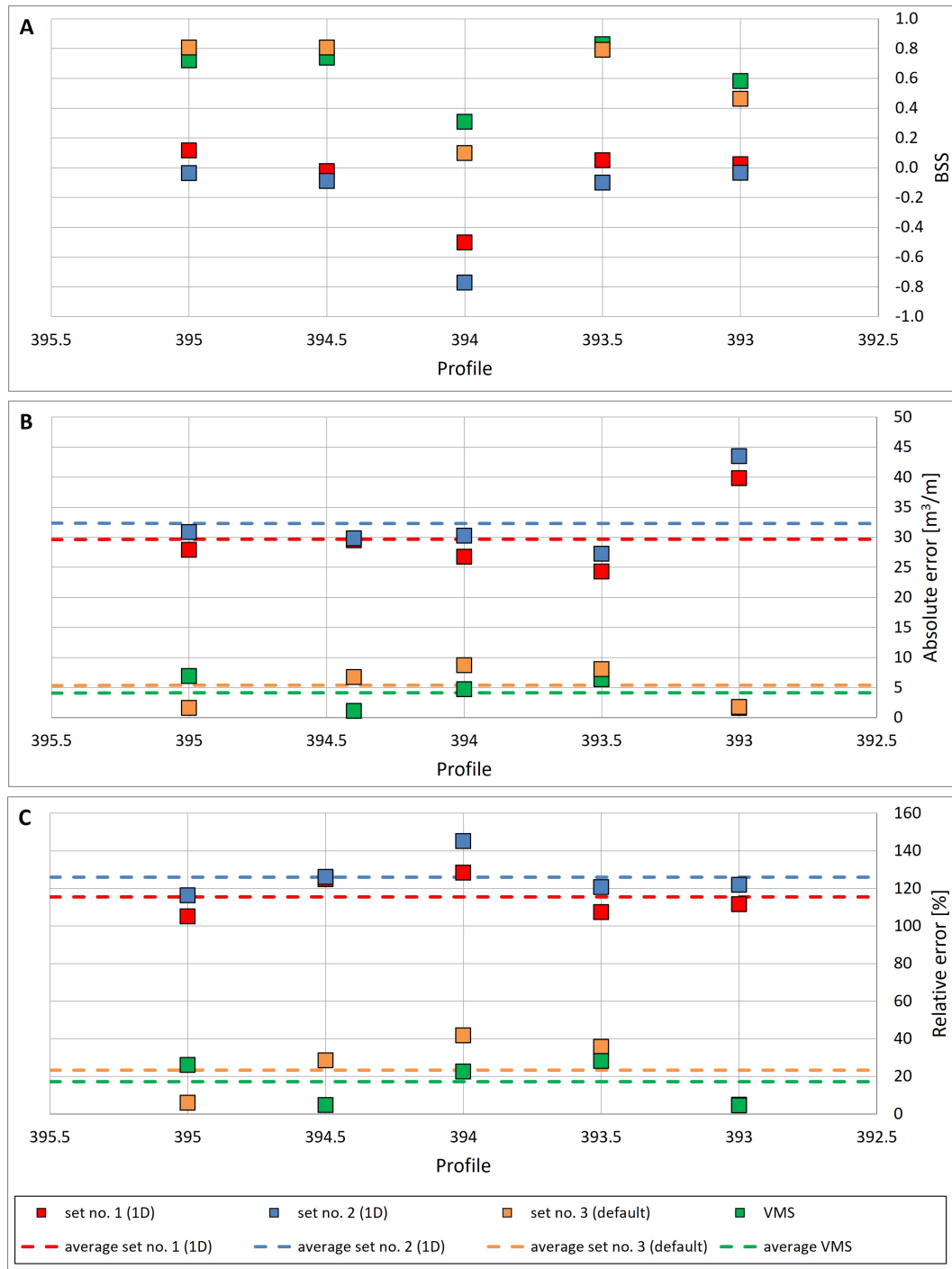


Figure 3. Results of the XBeach 2D model calibration for the storm event of 2009. A: Model match on the basis of the BSS; B: An absolute error of volumetric changes for four sets of parameters; C: A relative error of volumetric changes for four sets of parameters.

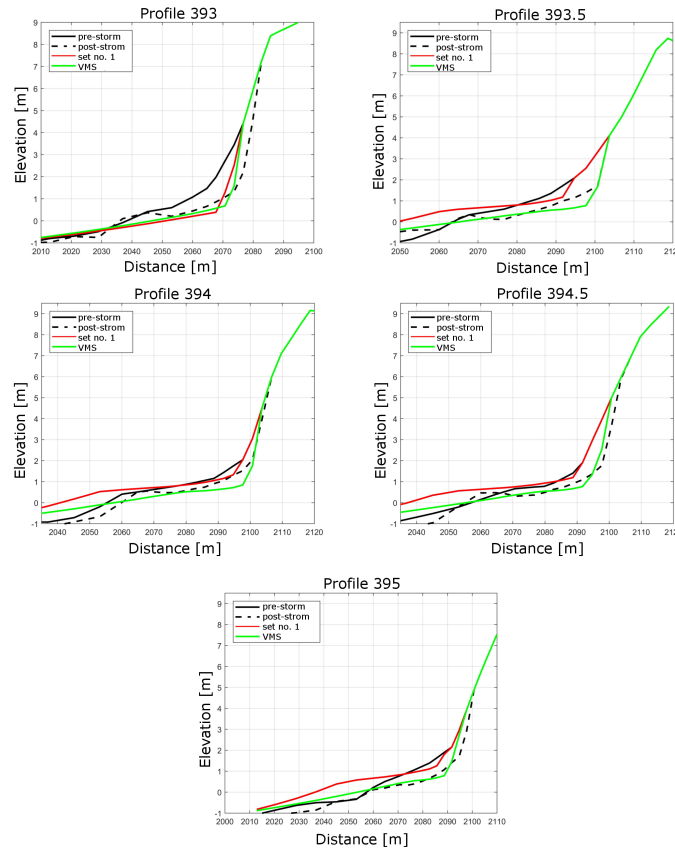


Figure 4. Result of the XBeach 2D simulation for the significant storm of 2009 (red and green lines) compared to the measured pre- and post-storm profiles (solid and dashed lines, respectively).

This set will be used for further work with the model. Furthermore, these results show that even for a not-detailed computational grid, good results of volumetric changes can be achieved, comparable to modelling in a 1D mode.

4.2 Model performance and accuracy for weak and moderate hydrodynamic conditions in 2012

The results of the 2D calibration for the significant storm were imported to the 2D calibration for the moderate and weak hydrodynamic conditions. The timeframe between the first and the second survey campaigns, i.e., 18–29.09.2012, was picked. The wave conditions and the water level oscillation used in the simulation are shown in Figure 5.

Within this period, the water level oscillated between 506 and 562 cm. A significant wave height ranged from 0.13 to 1.54 m and three periods with $H_s > 1$ m were recorded. A classification of timeframes was carried out using hierarchical cluster analysis and applying the Ward's method by Bugajny and Furmańczyk (2014). Five parameters featuring timeframes between campaigns were considered, i.e., maximum significant wave height in a timeframe, trend change coefficient of sea level in a timeframe, time since last storm in a timeframe to the end of this timeframe (in days), last storm duration in a timeframe (in hours), and

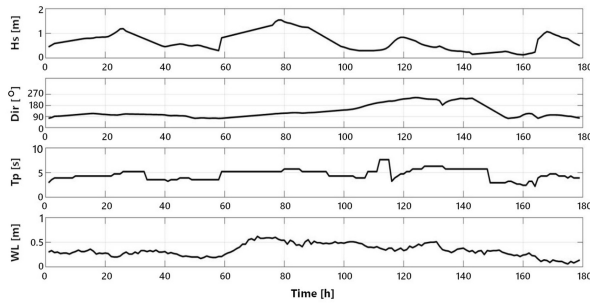
number of storms ($H_s > 1$ m) in a timeframe. As a result of classification, three classes of hydrodynamic conditions were identified. A short description of particular timeframes is shown in Table 1. The first class is represented by 2 timeframes and includes small wave action, where significant wave height did not exceed 1 m. The second class of hydrodynamic conditions is also represented by 2 timeframes with 2–3 periods with significant wave height exceeding 1 m ranging from 1.4 m to 1.9 m. The third class incorporates timeframes with 1–5 periods with significant wave height exceeding 1 m ranging from 1.5 to 2.4 m.

The 18–29.09.2012 timeframe was classified to the third class, the group of the most severe hydrodynamic conditions (Bugajny and Furmańczyk, 2014). The wave data was an incomplete data series that was completed manually. Next, time series of seaward wave propagation were removed as the model is not able to use them in its calculations. Hence, the timeframe, which originally lasted for 12 days, was shortened to almost 8 days, which translates to 180 hours.

The 2D calibration of the model for the moderate and weak hydrodynamic conditions was performed for a ca. 2-km long section of the coast, located on the western side of the Dziwna mouth. A comparative analysis of modelling

Table 1. Characteristics of particular timeframes.

Date	18.09– 29.09. 2012	29.09– 13.10. 2012	13.10– 19.10. 2012	19.10– 03.11. 2012	03.11– 15.11. 2012	15.11– 28.11. 2012	28.11– 04.12. 2012	04.12– 18.12. 2012
Class of hydrodynamic conditions (Bugajny and Furmańczyk, 2014)	3	3	1	3	2	1	3	2
Max Hs (m)	1.54	2.39	0.82	2.34	1.84	0.6	1.62	1.85
Max water level (cm)	562	566	539	548	547	524	558	557
Length of simulation (h)	179	16	246	222	153	82	110	235

**Figure 5.** Characteristics of hydrodynamic conditions (Hs – significant wave height, Dir – average wave direction, Tp – spectral peak period, WL – water level) in 18–29.09.2012.

results and the field data was carried out for all 21 profiles (Figure 5). The first test of the 2D model calibration for moderate and weak hydrodynamic conditions used a set of parameters ($facua = 0.12$ and $wetslp = 0.3$) that was labelled as the best from the 2D model calibration for significant storms. Based on measured and modelled volumetric changes on the beach, an absolute error of volumetric changes (m^3/m) was calculated for each profile. The error values in the profiles are shown in Figure 6A and ranged from $0.57 m^3/m$ to $11.31 m^3/m$, at an average of $3.55 m^3/m$. The highest absolute error values were identified in profile 10 (km 394) which is located in the central part of the simulated area. Furthermore, profiles 18 and 19 placed in the western part together with profiles 5 and 7 of the eastern part proved to have quite significant value of the absolute error from 6 to $8 m^3/m$.

Several simulations were performed to find an optimal set of parameters. For this purpose, the value of the $facua$ parameter was adjusted in the range between 0.12 and 0.32, at a step of 0.2, while the $wetslp$ parameter remained constant at 0.3. Subsequently, differences between measured and modelled volumetric changes of the beach were calculated in particular profiles, along with maximum, minimum, and average of absolute error values (m^3/m) of volumetric changes in particular simulations. The results can be seen in Figure 6B.

The absolute error distribution (m^3/m) as shown in Figure 6B, proved that simulation applied with the set of parameters of the 2D calibration for the significant storm

($facua = 0.12$) had the maximum error value = $11.31 m^3/m$ and decreased as the value of $facua$ rose to 0.28. Here, the error was equal to $3.99 m^3/m$. Further adjustment of $facua$ to 0.32 resulted in an increase in the absolute error value to $6.63 m^3/m$. An average value of the absolute error acted similarly: for $facua = 0.12$ it was $3.55 m^3/m$, then it dropped to 1.52 at $facua = 0.26$, to rise to $2.10 m^3/m$ at $facua = 0.32$. Minimum absolute error ranged from $0.01 m^3/m$ to $0.57 m^3/m$.

Analysis of the maximum, average and minimum values of the absolute and relative errors of volumetric changes in each simulation and upon the visual profile shape fit (VMS) provided with the best results for the following set of parameters $facua = 0.28$, $wetslp = 0.3$, $morfacs = 10$ and $smax = 1$. This set will be used for 2D modelling of volumetric changes in the dune coast. The results of a simulation with this set of parameters were shown in Figure 6C in form of the absolute error value for each profile. It is clearly seen that among 21 profiles, the greatest discrepancies between the measured and modelled volumetric changes amounting to only $4 m^3/m$ were noted in profile 22 in the western part of area of study, profiles 10 and 9 of the central part, and profile 5 in the eastern part. Accepting $facua = 0.28$ meant that the relative error decreased by 50% compared to $facua = 0.12$.

In summary, the set of parameters ($facua = 0.12$; $wetslp = 0.3$) obtained from the 2D calibration for the significant storm proved to be irrelevant for modelling the volumetric changes induced by moderate and weak conditions. An increase in the $facua$ parameter leads to a decrease in the absolute error of volumetric changes in the latter case, with the optimal value of $facua = 0.28$.

4.3 Modelling beach volume changes

The 2D validation of the volumetric changes for the XBeach model was carried out on subsequent timeframes between survey campaigns. An action flow chart is shown in Figure 7.

Simulations of volumetric changes were run for seven timeframes from 29.09.2012 to 18.12.2012. Input data on topography and bathymetry had been the same each time and they became a bathymetric and topographic map created on the basis of surveys and other sources as of 18.09.2012 (see Section 3.1) as measurements were more dense in the aforementioned campaign, that is, beach pro-

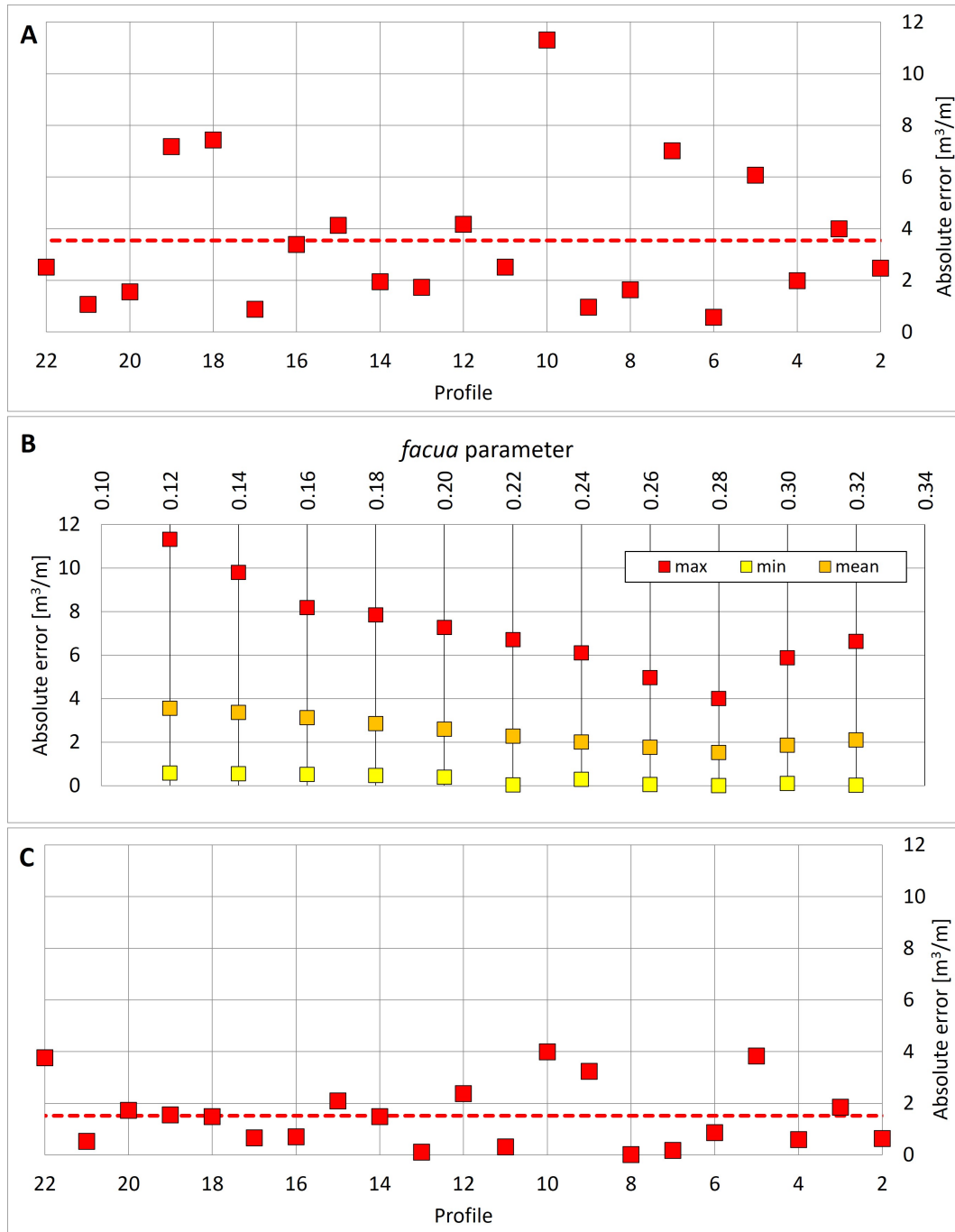


Figure 6. Results of model calibration for moderate and weak hydrodynamic conditions. A: Absolute error of volumetric changes in the beach (m^3/m) along with an average value for a simulation with values of *facua* = 0.12 and *wetslp* = 0.3. B: Absolute error of volumetric changes in the beach (m^3/m) per different value of *facua*. C: Absolute error of volumetric changes in the beach (m^3/m) along with an average value for a simulation with values of *facua* = 0.28 and *wetslp* = 0.3.

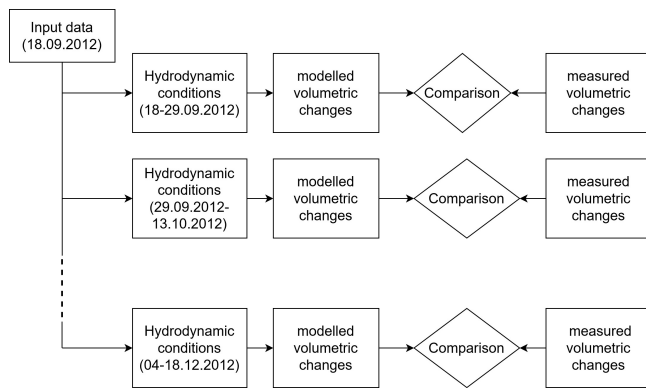


Figure 7. Scheme of modelling of volumetric changes in 2D mode.

files were taken every 10–15 m along the shore and every 20 m in the nearshore. Moreover, all collected source materials enabled a creation of the most accurate bathymetric and topographic map as possible. Next, on the basis of such a map, particular timeframes were simulated – each one with different hydrodynamic conditions. The modelled volumetric changes were then compared with those recorded in the field. Similarly, during model calibration, hydrodynamic data were properly prepared by complementing missing values (if such occurred) through manual interpolation and removal of wave conditions with seaward direction along with corresponding water level values.

A comparison of the modelled and measured volumetric changes was carried out on the basis of the absolute error in volumetric changes (m^3/m). The distribution of the absolute error for 7 timeframes that had been classified into 3 groups of hydrodynamic conditions is shown in Figure 8. A group of the strongest hydrodynamic conditions, the group no. 3, which includes 3 timeframes, proved that average values of the absolute error ranged from 1.92 to $2.89 \text{ m}^3/\text{m}$ depending on the timeframe. The average value of this class was $2.42 \text{ m}^3/\text{m}$. The maximum values of this error for a single profile were $9.60 \text{ m}^3/\text{m}$. The second group of hydrodynamic conditions is referred to as group no. 2 with 2 timeframes inside, featured a maximum value of the absolute error amounting to $7.42 \text{ m}^3/\text{m}$. The average values for two timeframes amounted to $1.57 \text{ m}^3/\text{m}$ and $3.17 \text{ m}^3/\text{m}$, yielding an average value of the class of $2.37 \text{ m}^3/\text{m}$. A group of the weakest hydrodynamic conditions – group no. 1 – composed of 2 timeframes, showed the lowest maximum absolute error values of $1.96 \text{ m}^3/\text{m}$ and the average value of $0.64 \text{ m}^3/\text{m}$ for the entire class.

Hence, the average value of the absolute error of volumetric changes in the beach decreases along with the class number. The weaker the hydrodynamic conditions, the smaller the absolute error. Furthermore, it can be observed that all classes deliver maximum values of absolute errors in the western profiles (19–22), which may be caused by delivering sediments from the eroded cliff coast

located further to the west.

Next, a comparative analysis of the balance of volumetric changes was performed. It referred to all timeframes between 18.09 and 18.12.2012 and each group of hydrodynamic conditions. The balance of the modelled and measured volumetric changes was calculated for 11 profiles located along the study area and the correlation between these changes is shown in Figure 9.

The value of the correlation coefficient (R) between the measured and modelled balance of volumetric changes (m^3/m) for all timeframes accepted a high value of 0.79. The correlation is also very good for group no. 3 with $R = 0.91$. In terms of the other two groups of hydrodynamic conditions, no correlation was found, as R equaled to 0.17 for group no. 2 and 0.06 for group no. 1. This is somewhat justified by the fact that the calibration referred to the group of ‘strongest’ hydrodynamic conditions – group no. 3.

In summary, a comparison of measured and modeled volumetric changes caused by moderate and weak hydrodynamic conditions, which do not erode the dune but affect only the beach and nearshore areas, showed that the XBeach model accurately simulates these changes only for the group with the ‘strongest’ hydrodynamic conditions for which the model was calibrated. In this group, the wave height ranged from 1.5 to 2.4 m and the average value of the absolute error was $2.42 \text{ m}^3/\text{m}$. For other groups, despite the decrease in the absolute error value to $0.5 \text{ m}^3/\text{m}$ in the group with the ‘weakest’ hydrodynamic conditions, the modelled values are too small and the model cannot correctly reflect volumetric changes as recorded.

The spatial distribution of the general balance (for all classes together) of the measured and modelled volumetric changes recorded in the profiles (Figure 10A) showed that XBeach reflects well this spatial balance induced by moderate and weak hydrodynamic conditions. The biggest discrepancies are noticed in three profiles: profile 8 located in the eastern part of the area of study, profile 16 and profile 22 both located in the western part. In each of those profiles, the difference exceeded $10 \text{ m}^3/\text{m}$. In profiles 2, 10, 12 and 20 the difference is between 5 and $10 \text{ m}^3/\text{m}$, while in the remaining profiles, i.e. 4, 6, 14 and 18 – it is less than $5 \text{ m}^3/\text{m}$.

The spatial distribution of the balance of volumetric changes in group no. 3 is similar to the general one for all groups (Figure 10B). The trend was maintained and the biggest discrepancies between the modelled and measured balance of values ranging from 5 to $10 \text{ m}^3/\text{m}$ can be noticed in profiles 10, 12, 16 and 22. Situation in group no. 2 is very different (Figure 10C), as the trend is not maintained. This means that the modelled data revealed dominance of accumulation in the western part and erosion in the eastern part, while the changes observed onshore prove the opposite. The biggest discrepancies in balance ranging from 5 to $10 \text{ m}^3/\text{m}$ were registered for profiles 8, 16, 20

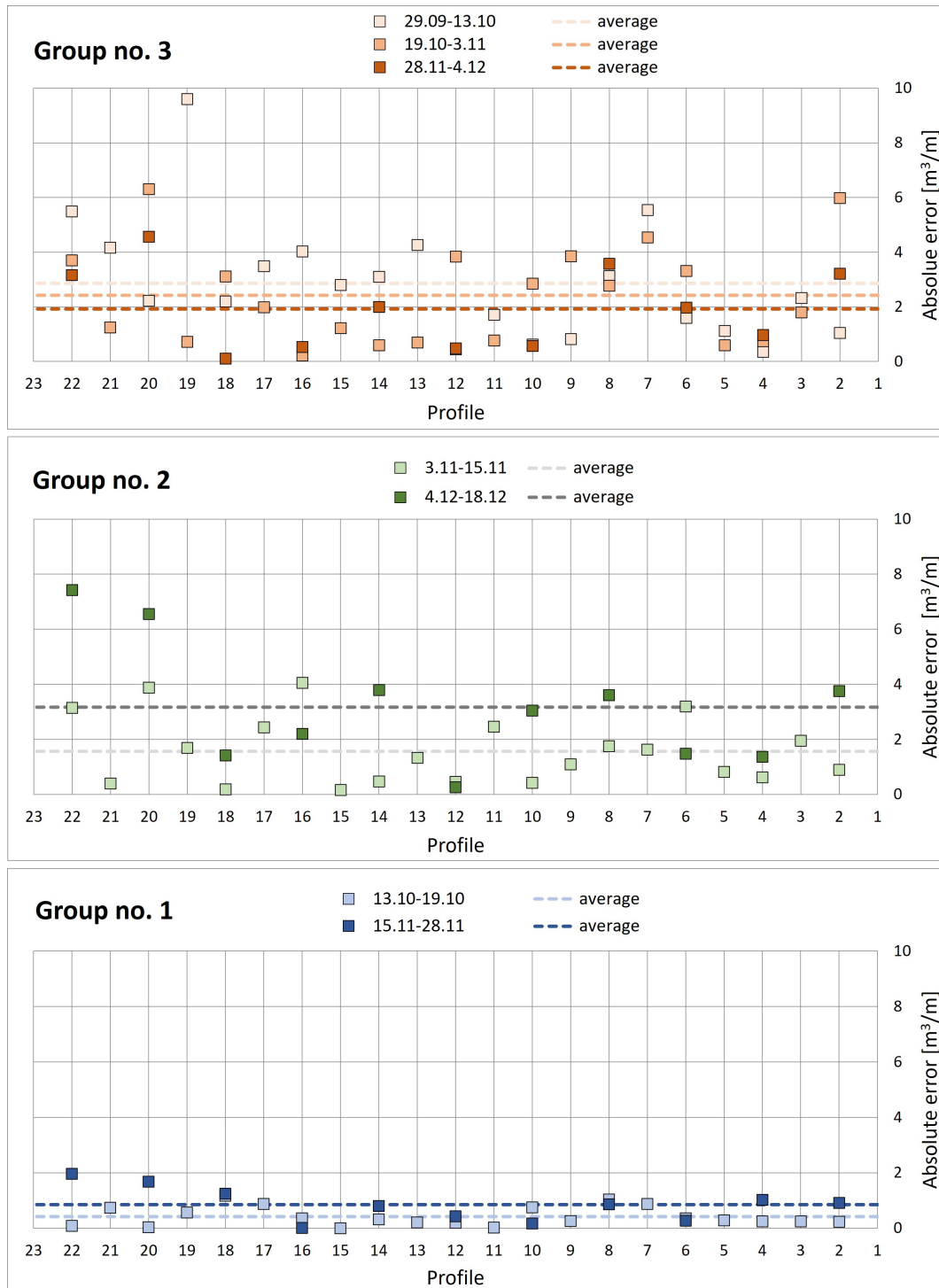


Figure 8. Absolute error of volumetric changes along with an average value for 3 groups of hydrodynamic conditions.

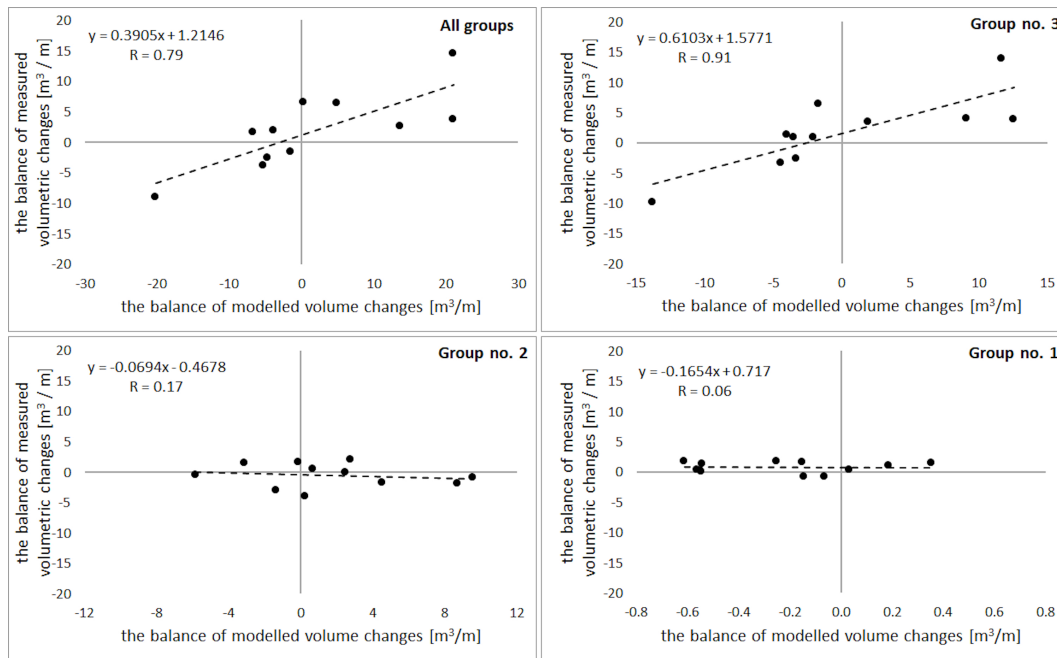


Figure 9. Plots of balance correlation between measured and modelled volume changes for all timeframes between 18.09–18.12.2012 and for particular groups of hydrodynamic conditions.

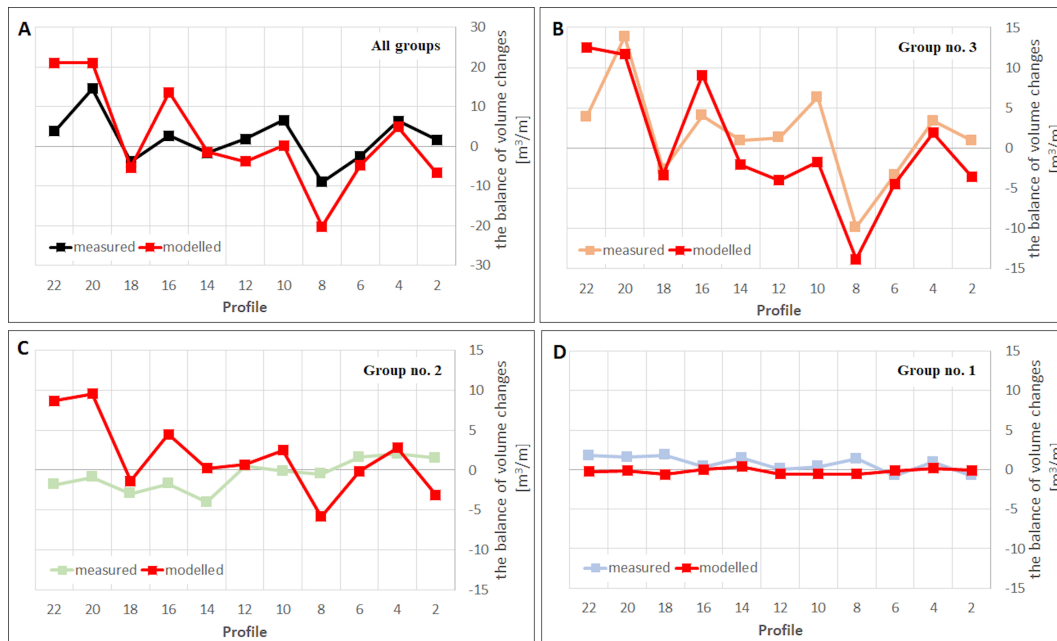


Figure 10. Spatial distribution of the balance of measured and modelled volumetric changes for particular profiles in three groups of hydrodynamic conditions within all timeframes between 18.09–18.12.2012.

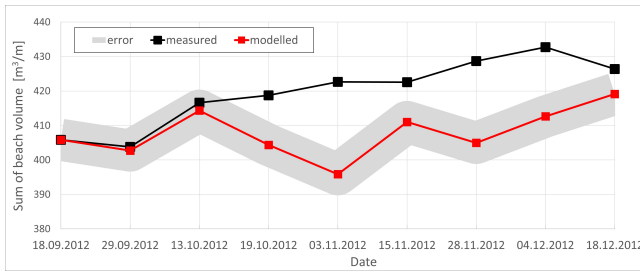


Figure 11. Sum of measured and modelled volume in the period 18.09–18.12.2012 (all timeframes) with an error in determination of the volume by XBeach model.

and 22, so in profiles where the model reveals a significant accumulation. Within the ‘weakest’ group no.1, the declining trend in balance is maintained in the field data when moving from west to east, while the model is quite stable along the entire area and shows only a slight erosion (Figure 10D). The biggest discrepancies in balance reaching $2.5 \text{ m}^3/\text{m}$ were spotted in profiles 18 and 22. In sum, the trend in balance of volumetric changes is calculated for all groups together and for group no. 3 matches with measured values, whereas for group no.2 and no. 1 it does not. Profiles with the biggest discrepancies between measured and modelled changes in the balance that are also valid for at least two classes are: profile 8 in the eastern part and profiles 16, 20 and 22 in the western part.

In sum, as follows from a spatial comparison of balance distribution of modelled and measured volumetric changes, some processes are likely to occur along the profiles that the model cannot reflect. Thus, these profiles should be studied in detail in terms of processes and changes occurring in the coast.

Figure 11 shows a sum of volumes measured and modelled over time. The plot shows that the trend in beach volume sum is increasing in four months, so moderate and weak hydrodynamic conditions triggered accumulation in the area of study. XBeach reflected this trend well and the difference between the measured and modelled sum was $7.27 \text{ m}^3/\text{m}$ at the end of the study period, which is similar to an error in the determination of the volume by the model. The biggest discrepancies in volume sums exceeding $20 \text{ m}^3/\text{m}$ were observed in campaigns of 3.11.2012, 28.11.2012 and 4.12.2012, while ones exceeding $10 \text{ m}^3/\text{m}$ – in campaigns of 19.10.2012 and 15.11.2012.

5. Discussion

There are more than 100 parameters to calibrate in XBeach. Therefore, parameter values that had been derived from 1D calibration were applied to 2D modelling. This time, a rough computational grid was created and a 2009 storm event was simulated that took into consideration a directional wave propagation and a longshore transport. Model results were checked against previously mentioned mea-

sures and referred to five profiles spaced every 500 m within the area of study (km 395–393), as obtained from the Maritime Office. The use of 1D calibration, where no wave direction nor longshore transport was included, borne poor results. The average absolute error amounted to $30 \text{ m}^3/\text{m}$, while the average relative error reached 120%. The next simulations were performed and the best results were received for $facua = 0.12$ and $wetssl = 0.3$. The average absolute error dropped to $5 \text{ m}^3/\text{m}$, while the average relative error lowered to ca. 20%. The chosen values of parameters are considerably lower than in 1D model, especially $facua$. It is connected with including the wave propagation direction in the 2D simulation, where it is being refracted and less wave energy is reaching the shore in comparison to the 1D simulation, where a wave direction was perpendicular to the shore. In the latter situation, the wave was not dissipated and the entire wave energy reached the shore, leading to increased erosion that was compensated by an increase in the parameter responsible for onshore transport.

In the next stage of study, a goal was to determine volumetric changes by means of a 2D XBeach model for timeframes that agree with field work. Past studies (Bugajny and Furmańczyk, 2022) proved that shallow nearshore area is especially important in terms of modelling volumetric changes onshore. Therefore, a more dense computational grid was created and a bathymetric and topographic map was constructed on the basis of all possible data derived from survey profiles, lidar, and remote sensing. An evaluation of relief accuracy was done by a comparison of survey data (GPS RTK) and data interpolated for a numerical grid as an input to the model. As a result of the interpolation of data to the grid, very good results were achieved showing good reflection of beach volume in 21 profiles. The differences in beach volume between the interpolated and measured data ranged from $-1.70 \text{ m}^3/\text{m}$ to $1.02 \text{ m}^3/\text{m}$, on average of $-0.14 \text{ m}^3/\text{m}$.

The first simulation was run with parameters derived from 2D calibration for a significant storm of 2009: $facua = 0.12$ and $wetssl = 0.3$. An average absolute error amounted to $3.55 \text{ m}^3/\text{m}$ in this simulation, while a maximum was $11.31 \text{ m}^3/\text{m}$. Such results forced further calibration, and the best results in the form of the best reflected volumetric changes were received for a set of parameters $facua = 0.28$ and $wetssl = 0.3$. Here, the average absolute error was $1.5 \text{ m}^3/\text{m}$ with a maximum of $4 \text{ m}^3/\text{m}$.

The model validation was further extended for the next survey timeframes, which were classified into three groups with different hydrodynamic conditions. For the group with the ‘strongest’ conditions, XBeach simulated volumetric changes on the beach at average absolute error of $2.42 \text{ m}^3/\text{m}$. For two other groups, the error was even smaller and reached $0.5 \text{ m}^3/\text{m}$ in the ‘weakest’ group, but the model cannot adequately reflect volumetric changes as recorded.

There may be a couple of reasons behind it. First, the selected calibration parameters had a significant impact on volumetric changes. If in the case of changes induced by significant storms and 'strongest' hydrodynamic conditions they turned out to be crucial, then for small changes they did not deliver and the model requires another calibration.

A similar procedure of model calibration and validation was accepted by Pender and Karunaratna (2013). They calibrated XBeach in 1D mode for two hydrodynamic conditions. First, the calibration was run for a storm event, and the other for beach profile recovery. *Facua* was one of the parameters that differed in those calibrations, as its value was higher for weak hydrodynamic conditions. It is then reasonable to conduct a separate calibration for groups no. 1 and 2 of hydrodynamic conditions in the next studies. Furthermore, Volpano et al. (2022), in their studies on nearshore restoration at Lake Michigan, noticed that not only an increase in the value of *facua* (from 0.1 to 0.6) gave better results, but also modelled the nearshore more accurately. The latter was more similar to the surveyed relief; nevertheless, XBeach did not identify the morphological evolution in low-energy environment, disallowing a simulation of beach restoration. Thus, the recommendation is to combine XBeach with other tools that allow for a recreation of that process. On the other hand, van Dam (2019) and Kombiadou et al. (2021) introduced a new parameter in their studies on modelling the shore profile recovery. *Berm slope* is a parameter for the inclination of the beach profile at the shoreline. Exceeding its value means increased transport towards the shore, causing profile restoration in the form of the beach berm (Roelvink and Costas, 2019). The studies of the first author focused on the calibration and validation of the model on a multi-year scale, on the basis of monthly data from the Australian beach of Narrabeen (Turner et al., 2016). A deployment of this parameter considerably improved forecasting the evolution of the shore profile. The studies of Kombiadou et al. (2021) were carried out along three reflective shore profiles in Portugal with 1D calibration of the model for storm and beach recovery. Again, they proved that XBeach not only reflects the volumetric changes induced by storm events well, but it also can simulate changes in the shore profile correctly during its restoration, i.e., creation of the beach berm, within the first 50 days.

Other factors that could have affected the results as obtained are the input hydrodynamic data. In this case, the offshore boundary of the model accepted the values of the water level recorded at the harbourmaster's office in Dziwnów located ca. 1 km inland from the Dziwna mouth, which is armoured with breakwaters. It may be neglected for big volumetric changes caused by significant storms, but for small changes, a difference of 10–20 cm in water level might be a key difference. Furthermore, as there is no gear and equipment, there is no possibility to compare

actual and modelled wave parameters.

Therefore, in the next stage of studies, it seems to be justified to use the latest version of XBeach that enables the deployment of *bermslope* parameter and the data and apply the results of the studies of Bugajny and Furmańczyk (2020) on short-term changes in the beach berm and the beach front during storm calming. Subsequently, XBeach 1D calibration of this process and validation with the use of results of studies carried out by Bugajny and Furmańczyk (2014) together with resulting dependencies should be performed. It would allow modelling long-term coastal changes and include both changes driven by extreme phenomena (Bugajny et al., 2013, 2015, 2022) and by moderate and weak hydrodynamic conditions.

6. Conclusion

Studies on short-term volumetric changes in the coast of southern Baltic caused by various hydrodynamic conditions and modelling of these changes with XBeach, as described here, allowed for drawing the following conclusions:

- moderate and weak hydrodynamic conditions (which do not cause dune erosion in the studied timeframe) cause within the area of study (of tideless sea) a diverse effect on the coast in the form of both accumulation and erosion and their magnitude depends on hydrodynamic conditions and proves of oscillating nature of the shore;
- analysis of accuracy in the determination of volumetric changes in the dune coast at Dziwnów Spit with XBeach for different hydrodynamic conditions proved that:
 - in 1D and 2D calibration, an average absolute error of determination of volumetric changes (caused by the significant storm) by the model is $4 \text{ m}^3/\text{m}$ and an average relative error is 20%;
 - in 2D calibration, the average absolute error of volumetric changes caused by moderate and weak hydrodynamic conditions that do not trigger dune erosion is $1.5 \text{ m}^3/\text{m}$;
 - in a validation process of the 2D model, the average absolute error of determination of volumetric changes caused by moderate and weak hydrodynamic conditions that do not trigger erosion ranges from $0.64 \text{ m}^3/\text{m}$ to $2.42 \text{ m}^3/\text{m}$ depending on the class of hydrodynamic conditions.

The results obtained in the studies appear to be particularly important in terms of the possibility of extension of XBeach application in warning systems and inventory control of effects and hazards in the coastal zone driven

by different hydrodynamic conditions. They can be used, e.g., in the form of a new parameter/indicator associated with volumetric changes in the coast and can be useful in construction of similar coastal zone systems for new sections of the southern Baltic. Moreover, these studies can become an introduction to further studies, resulting in an adjustment of XBeach or creation of a version for tideless seas. However, the work performed revealed a need for continuous monitoring of the coastal zone environment, especially of the relief of the beach, dune and shallow nearshore, which are key elements during calibration and validation of the model for the determination of volumetric changes in the coast.

Further work on the XBeach application should cover issues with a separate calibration for weak hydrodynamic conditions. The problem of acceptance of a water level at the model offshore boundary should also be solved.

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