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A coupled model of wave-driven erosion for the Palanga Beach, Lithuania

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Abstract A model of the coastline dynamics along the Palanga Beach, Lithuania is developed through coupling of the GENESIS software with the external wave model RCPWAVE that accounts for the recent bottom topography. Analysis of the calibration and verification results of the coupled model shows that it reproduces the coastline dynamics reasonably well and can serve as an effective tool for coastal management. The largest discrepancies between the observed and modelled behaviour of the coastline occur near the Rąžė River mouth.

Keywords • *Coastline dynamics • Model calibration • Model verification • GENESIS • RCPWAVE • Palanga Beach • Lithuania*

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INTRODUCTION

Shoreline dynamics is a complex phenomenon that is a result of both natural processes and anthropogenic impacts. In order to understand and predict the coastline dynamics a good understanding of the underlying processes is necessary.

In 2007, the feasibility study the GENESIS software was used for modelling of erosion of the Palanga Beach (Zemlys *et al.* 2007). The lack of the high-resolution bathymetry data was the main reason why it was used a so-called internal wave model that calculates the breaking wave heights and the approach angle of waves at the breaker line using the simplified assumption that the depth contours are parallel to the coastline. This assumption is not always valid in the study area. Breakwaters and a non-diffracting groin (Zemlys et al. 2007) represented the most important single features of bathymetry in the model. This simplification does not account for smaller-scale bottom topography shaping that can be also important for transformation of waves in the near shore and beach erosion.

The goal of this study is to develop a model of the coastline dynamics using an external wave model and high-resolution bathymetry data. Authors also analyse the improvement of the model performance in terms of its ability to replicate changes to the coastline and compare results with the outcome of the Zemlys *et al*. (2007).

MATERIAL AND METHODS

Study area and data

The Lithuanian coast is a part of the southeastern coast of the Baltic Sea (Fig 1). This area represents a generic type of more or less straight, actively developing coasts that (i) contain a relatively large amount of finer, mobile sediments, (ii) are open to predominant wind directions in this water body and (iii) are exposed to wave activity for a wide range of wave approach directions (Žilinskas 2005, Soomere *et al.* 2011).

The Palanga Beach is located in the northern part of the Lithuanian seashore. Fine sand is the most common in the Lithuanian coastal zone. The bathymetric data and the shape of the coastline show that close to Palanga (Promenade) Pier a small submarine bar is formed (Fig. 1 C). This feature has a high influence for coastal processes. In addition, Rąžė River, which flows in the Baltic Sea about 600 m to the North of Palanga Pier, has a local impact for sediment transport along the coast.

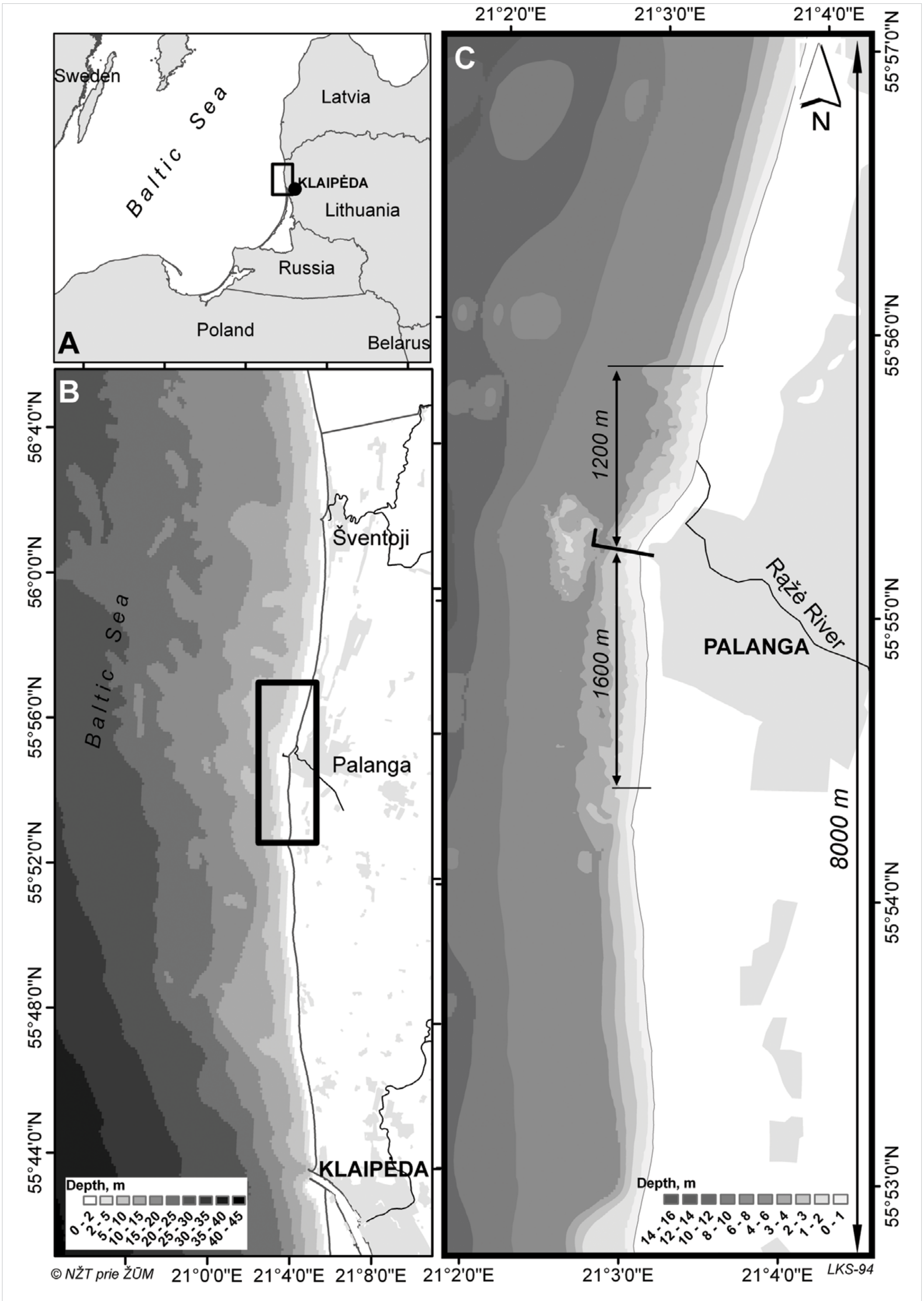

Fig. 1 A. Location map. B. The Lithuanian mainland coast; bottom topography according to L. Ž. Gelumbauskaitė et al. 1999. C. The modelled area; detailed bathymetry according to A. Bitinas et al. 2004, after Hydrography Office of the Lithuanian Maritime Safety Administration, 2008. Compiled by J. Mėžinė, 2013.

The model was developed for the period of 2000–2005 and was driven by the same data as Zemlys *et al.* (2007) in order to ensure comparability of the results with the previous study. Bathymetry data obtained in 2004–2007 with an average spatial resolution of 75 m from Geological atlas of Lithuanian coasts (Bitinas *et al.* 2004), and the Palanga Beach nourishment monitoring (KU CORPI 2008) were used for the external wave model.

Although extensive wave data sets do exist for this area, they are not directly usable for this study. First visually observed wave data for the Lithuanian coast (Kelpšaitė *et al.* 2009; Kelpšaitė *et al.* 2011) reflect wave properties in shallow water in the immediate vicinity of the shoreline and are affected by dissection of the bottom topography. There exist also several long-term simulations of wave time series for the entire Baltic Sea (e.g., Soomere, Räämet 2011), however they are produced with a relatively coarse resolution and also are not internationally available. For the listed reasons wave time series, used as boundary condition for RCPWAVE, were calculated in this study using an external wave model. Authors employed wind speed and direction measured in the Klaipėda Meteorological Station for a period 2000–2005 with a temporal resolution of three hours. The wave heights and periods for a sea area with a depth of 20 m with the same temporal resolution were calculated from the measured wind speed and the fetch length corresponding to the wind direction using the CERC/SPM method (CERC 1984):

$$\frac{g \cdot H}{U^2} = 0{,}283 \cdot \tanh\left[0{,}530 \cdot \left(\frac{g \cdot d}{U^2}\right)^{3/4}\right] \cdot tanh\left(\frac{0{,}00565 \cdot \left(\frac{g \cdot F}{U^2}\right)^{1/2}}{\tanh\left[0{,}530 \cdot \left(\frac{g \cdot d}{U^2}\right)^{3/4}\right]}\right), \quad (1),$$

$$\frac{g \cdot T}{U^2} = 7{,}54 \cdot \tanh\left[0{,}833 \cdot \left(\frac{g \cdot d}{U^2}\right)^{3/8}\right] \cdot tanh\left(\frac{0{,}0379 \cdot \left(\frac{g \cdot F}{U^2}\right)^{1/3}}{\tanh\left[0{,}833 \cdot \left(\frac{g \cdot d}{U^2}\right)^{3/8}\right]}\right), \quad (2),$$

where H is the significant wave height; T is the period, U is the wind speed at the height of 10 m, d is the water depth and F is the fetch length.

Description of the models and setup

Shoreline changes were modelled using the 1–D GENESIS modelling system (Hanson, Kraus 1991; Gravens *et al.* 1991) which is a part of the Beach Processes Module of the Coastal Engineering Design Package, CEDAS (Very-Tech Inc. 2005). The model itself, GENESIS (Generalized Model for Simulating Shoreline Change), is designed for simulations of long-term changes to the shoreline and is applied in various coastal engineering projects.

Depending on the amount and quality of the available data and the level of modelling effort required, GENESIS can be applied in either the scoping mode or the design mode (Hanson, Kraus 1991; Gravens *et al.* 1991). The scoping mode uses minimal data input and might be employed, for example, in a reconnaissance study that better defines the problem and identifies the potential project alternatives. The design mode involves more detailed studies for which a substantial modelling effort is required. In this study, the scoping mode was used.

The changes in the shoreline are calculated in GENESIS using equation obtained from the conservation of the sediment volume (Eq. 3):

$$\frac{\partial y}{\partial t} + \frac{1}{D_B + D_C}\frac{\partial Q}{\partial x} = 0, \quad (3),$$

where Q is the alongshore sand transport rate calculated as a function of the breaking wave height, the approach angle of breaking waves and other wave characteristics (Hanson, Kraus 1991; Gravens *et al.* 1991); D_B is the berm height and D_C is the depth of closure. The x-axis is directed alongshore from the left to the right (for the observer looking to the offshore) and the y-axis is directed offshore. The model state variable is the position of the coastline $y(x,t)$, interpreted as a function of time t and coordinate x.

The alongshore sediment transport is calculated using the following expression, which consists of a sediment transport term and a diffraction term recommended by Coastal Engineering Research Centre (USACE 1984):

$$Q = (H^2 C_g)_b \left(a_1 \sin 2\theta_{bs} - a_2 \cos\theta_{bs}\left(\frac{\delta_H}{\delta_x}\right)\right)_b, \quad (4),$$

where:

$$a_1 = \frac{K_1}{16(\rho_s/\rho - 1)(1-p)1.416^{5/2}} \quad (5),$$

$$a_2 = \frac{K_2}{8(\rho_s/\rho - 1)(1-p)1.416^{7/2}\tan\beta}, \quad (6),$$

where H is the wave height; C_g is the wave group speed given by the linear wave theory; b is a subscript denoting wave breaking condition; Q_{bs} is the approach angle of breaking waves with respect to the local shoreline; K_1, K_2 are empirical coefficients, treated as a calibration parameters (K_1 characterises the magnitude of alongshore sand transport; K_2 is controlling a distribution of sand within calculation area); P_s is the density of sand ($2.65 \cdot 10^3 kg/m^3$); P is the density of water ($1.03 \cdot 10^3 kg/m^3$); p is the porosity of sand on the bed (0.4); *tan* ß is the average bottom slope from the shoreline to the depth of closure.

Waves can be modelled in two different ways in GENESIS: using an internal wave transformation model; or an external (stand-alone) model. We used the external wave model RCPWAVE (Regional Coastal Processes WAVE propagation model). RCPWAVE is a 2D, steady state, short-wave model for simulation of wave propagation over arbitrary bathymetry. The model solves the "mild slope" equation for linear, monochromatic waves. The data needed for RCPWAVE are the properties of deep-water waves (wave height, period and direction as boundary conditions) and bathymetry records. RCPWAVE calculates wave height, period, direction and wave number at each grid location.

The necessary data for the modelling of coastline dynamics are: a) offshore wave properties (height, period, direction, water depth where waves were measured); b) the initial coastline position; c) bathymetry records for the external wave model; d) lateral boundary conditions (the sand flux rates on the left and right borders of the modelling area); e) the effective grain size; f) geometric properties of the nearshore and the beach (berm height, depth of closure); g) the location and characteristics of coastal engineering structures in the model domain (permeability, transmission coefficients); h) the model calibration parameters K_1 and K_2.

It was modelled the shoreline development in an 8000 m long area (from about 4000 m to the South up to about 4000 m to the North of Palanga Pier) (see Fig. 1 C). The boundary points of the study area were chosen in the regions where the coastline was more or less stable. The location of the coastline was assumed stationary at the boundary points.

GENESIS and RCPWAVE use the Cartesian coordinate system with a location-specific orientation. The origin in the RCPWAVE coordinate system is at the landward left-hand side of the study area, the *y*-axis is directed alongshore and *x*-axis to the offshore. The origin in the GENESIS coordinate system (0 m) is at the landward right-hand side of the study area, the *x*-axis is directed alongshore and the *y*-axis to the offshore. In order to match the model arrangements, the (coastline etc.) data commonly presented in the LKS-94 coordinate system were rotated 90 degrees counter clockwise. The respective origin in LKS-94 is (315970, 6197745) for the use of the data with GENESIS and (314300, 6197745) for the use with RCPWAVE. The wave model was run on a rectangular grid with a resolution of 90×30 m. The wave properties were calculated at grid points located at a nearshore reference line. The further propagation and transformation of waves from this line until breaking was calculated within the GENESIS model with a resolution of 15 m and time step of 7.5 minutes.

In order to compare results with the previous study (Zemlys *et al.* 2007), it was used the same value for the median grain size of the sand (average in water and on land) d_{50} = 0.17 mm. The berm height and the depth of closure (to the offshore of which no significant sediment transport occurs) were set to 3 and 7 m (cf. Soomere *et al*. 2011), respectively.

Model calibration and verification

The GENESIS model was calibrated in order to reach reasonably low discrepancies between the modelled and measured accretion and erosion rates and the displacements of the coastline. Similarly to Zemlys *et al.* (2007), the coastline of the year 2005 was used for model calibration (simulation of calibration was for 2000–2005) and the coastline of 2002 for verification (simulation for 2000–2002).

The parameters K_1 and K_2 in Eqs. (4, 5) were adjusted in the calibration process. The parameter K_1 characterises the magnitude of alongshore sand transport and K_2 controls the distribution of sand within the calculation area. Another important parameter is the permeability of the groin near the Palanga Pier, where after removal of the old pier just some stones were left.

RESULTS

The recommended ratio of K_1/K_2 is between 0.5 and 1.0 (Kraus *et al.* 1988). The initial values for the calibration were chosen from Zemlys *et al.* (2007) as K_1=0.7, K_2=0.7. The values obtained via calibration were K_1=0.4 and K_2=0.7. The initial value of the groin permeability was 0.7 (Zemlys *et al.* 2007), after the calibration, the value of 0.85 was chosen.

Figure 2 shows two modelled coastlines before the calibration for 1st of January 2002. This comparison of coastlines was used to check the effect of internal and external wave models. For better visibility we present here the results only for the area between *x*=2400 to *x*=5200 (1600 m to the South and 1200 m to the North of Palanga Pier) where the resolution of measured data was higher. If only the internal wave model was used

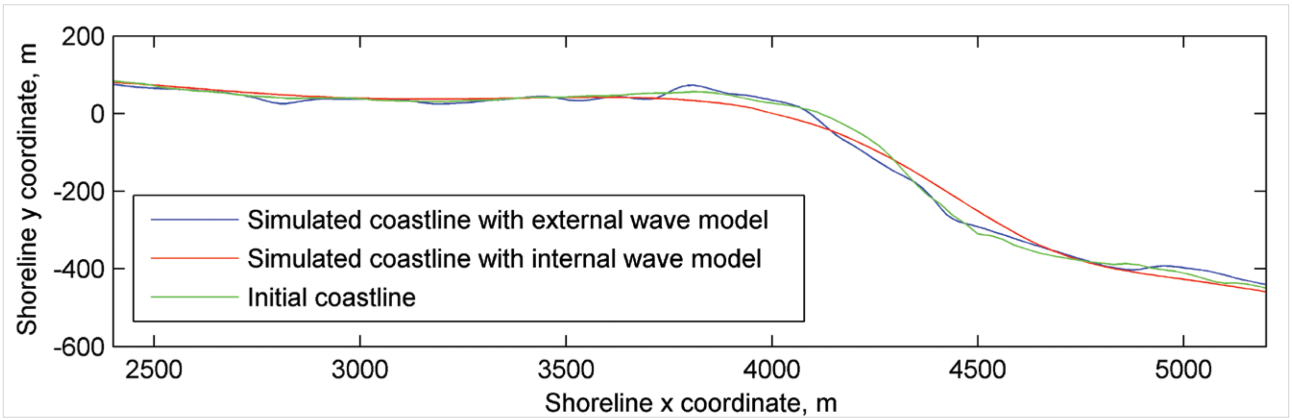

Fig. 2 Coastlines calculated using the internal and external wave models.

(without any additional features of the bathymetry), the obtained coastline is straight, without the small spit that actually exists near Palanga Pier. The simulations that additionally used the external wave model lead to a more realistic coastline shape with an accretion zone on the lee (South) side of the pier and erosion zone to the North. Therefore, the wave data obtained using the RCPWAVE model more realistically represent the impact of local bathymetric features on the wave fields and can be used in further simulations.

The accretion-erosion rates calculated with the calibrated model were compared with the values measured by Žilinskas *et al.* (2005) (Table 1) for the period of 1993–2005. The discrepancies between the two sets of results were the highest in the area to the South of Palanga Pier where the modelled accretion and erosion rates were lower than measured. Generally, the modelled rates match with reality and are satisfactory.

Table 1. Comparison of calculated and modelled accretion–erosion rates

Zone	Distance from the origin of the model (*x* coordinate, m)	Accretion–erosion rate from Žilinskas *et al.* (2005), m/year	Modelled accretion–erosion rates, m/year
Seaside regional park – Auska	500–1000	–1.2	–1.39
Auska sector – Birutė cape	2500–2700	–0.5	–2.19
Birutė cape – Palanga Pier	3000–3400	–13.5	–1.85
	3400–3600	–12.3	–3.6
	3600–4000	–8	–1.4
Palanga Pier – Rąžė River	4000–4200	–6	–10.29
	4300–4700	+6.6	+5.42
Rąžė River – Kuni-giškiai	5000–8000	+1.6	+1.83

The average difference between modelled and measured coastlines for 2005 was ±8.35 m. The biggest discrepancies were found near *x*=4500 m (about 500 m to the North of Palanga Pier). The verification results showed a better agreement between the measured and modelled coastlines than calibration results. The average differences were ±6.21 m. The maximal differences were reached in an area about 1000 m to the North of the pier.

The comparison of the modelled and measured coastlines with those obtained in the previous study (Zemlys *et al.* 2007) in 2002 and 2005 is shown in Fig. 3, 4. The results of both studies for 2002 are close to the measured values: the differences are less than 30 m. The results after calibration (Fig. 4) showed lower discrepancies compared with the results of the previous study (Zemlys *et al.* 2007). A better performance of our model compared with the previous ones becomes evident in an area at *x*>4700 m (about 700 m to the North of Palanga Pier), where our model represents coastal processes more precisely. This difference is also evident as lower RMSE (root mean square error) difference of the modelled and measured coastline: for our simulations, it was 7.67 m (2002) and 10.07 m (2005), while in Zemlys *et al.* (2007) the RMSE was 9.03 m (2002) and 15.44 m (2005).

The highest discrepancies between the measured and modelled coastline reached 29.37 m in Zemlys *et al.* (2007) for the year of 2002. The maximum differences the measured coastline and the coastline modelled in this study were 23.83 m near *x*=5100 m (to the North of Rąžė River). For the year of 2005, the biggest differences between the modelled and measured coastlines reached 36.66 m (Fig. 6), whereas the results of Zemlys *et al*. (2007) deviated from the measured coastline locations by up to –57.07 m. Therefore, our modelling efforts based on the GENESIS model coupled with an external wave model show systematically better results compared to those obtained using simpler models.

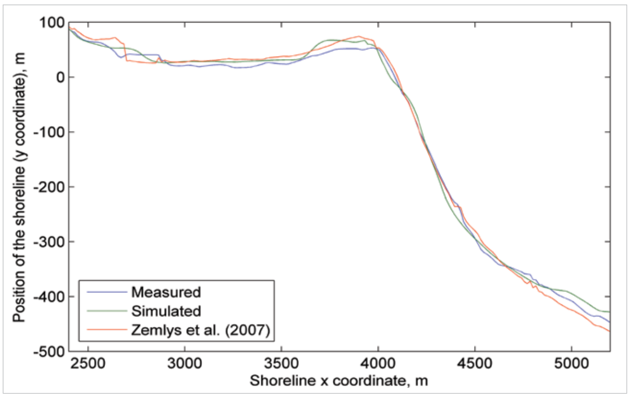

Fig. 3 Verified and measured coastlines for 2002 (verification results).

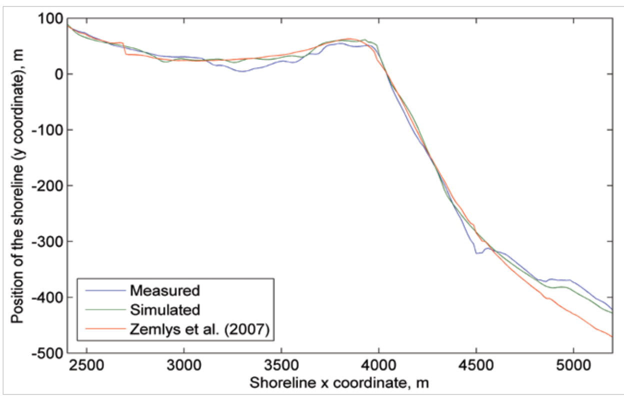

Fig. 4 Calibrated and measured coastlines for 2005 (calibration results).

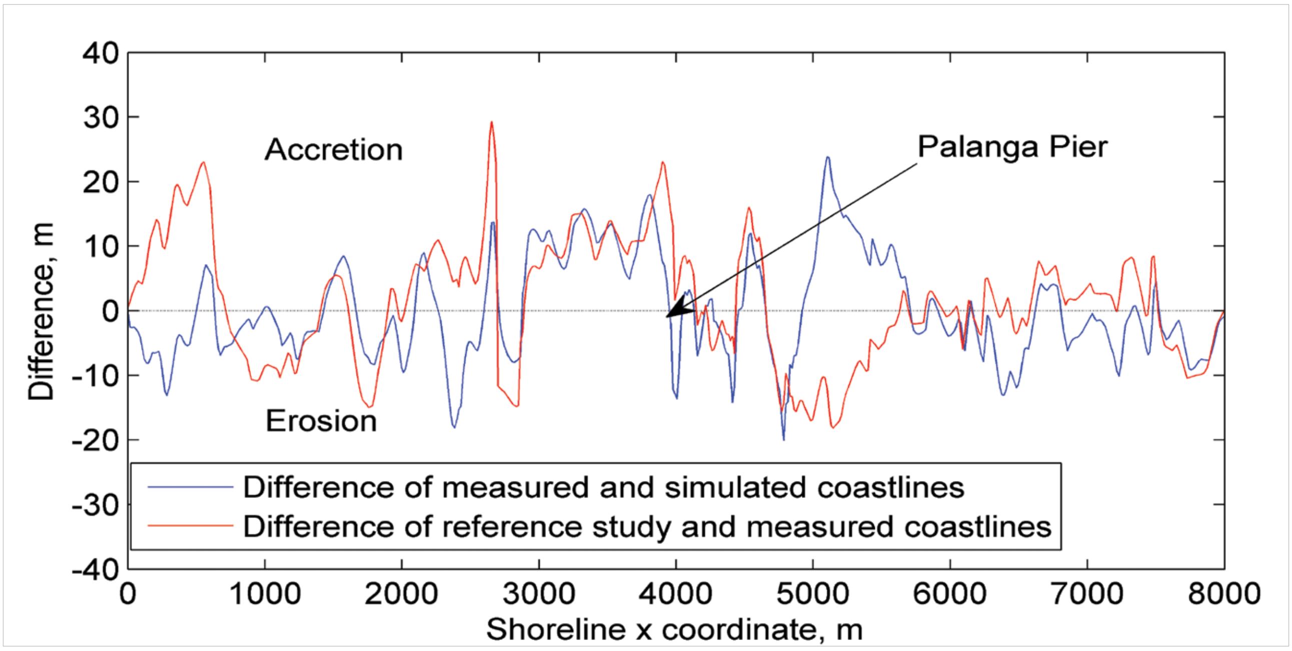

Fig. 5 Difference of measured and simulated coastlines and reference study (Zemlys et al. 2007) and simulated coastlines in 2002.

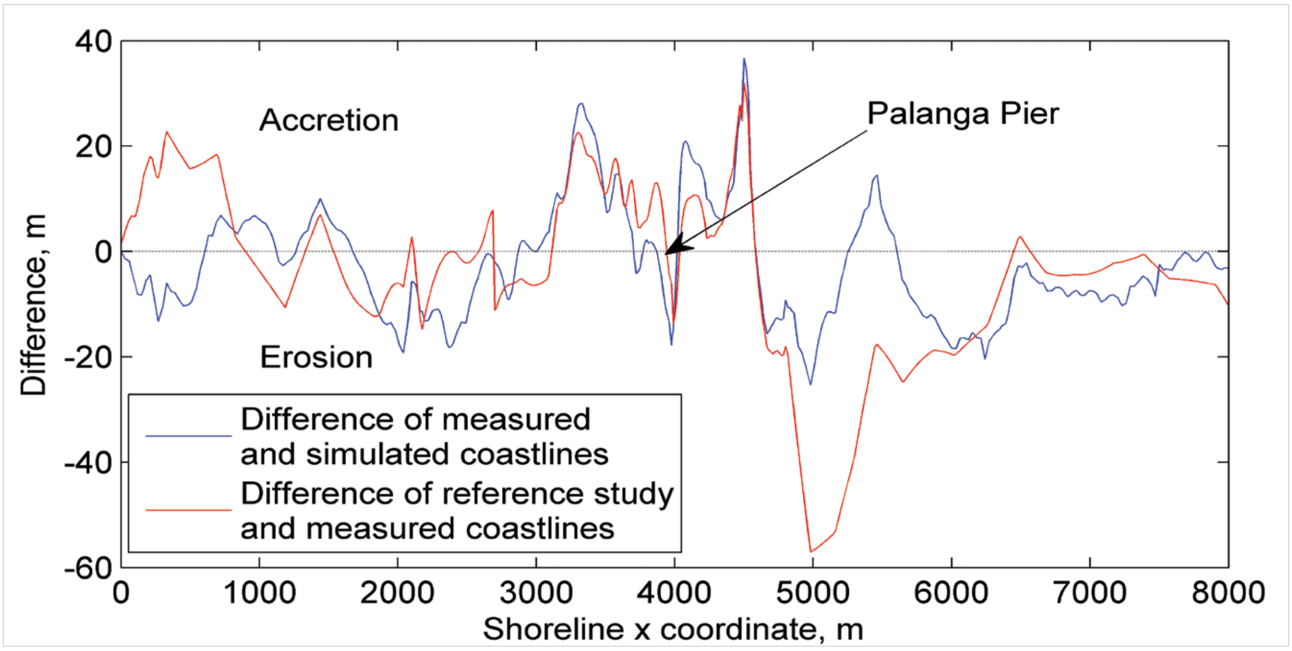

Fig. 6 Difference of measured and simulated coastlines and reference study (Zemlys et al. 2007) and simulated coastlines in 2005.

DISCUSSION

The performance of the described model of coastal processes is generally satisfactory and the model output replicates the main tendencies of the coastal evolution. Still there are some discrepancies between modelled and measured values. A likely reason is that it is not enough to have just erosion-accretion rates for model calibration. The intensity of accretion and erosion can be expressed as the difference of the sand transport rate at two adjacent model grid points, and, therefore, the same accretion-erosion values may correspond to different sand transport rates (Zemlys *et al.* 2007). A deeper discussion of this concept in the Baltic Sea framework can be found in Soomere *et al.* (2013). Net sand transport itself is again equal to the difference of two values bulk transports to the left and to the right (Hanson, Kraus 1991; Gravens *et al.* 1991). In addition, the reason of these differences can be the inaccuracies in the bathymetry data (which were compiled from three different data sets) (Bitinas *et al.* 2004; KU CORPI 2008) and the ignoring of cross-shore sediment transport. It is natural that with the used approach it is not possible to achieve precise calibration results already because measured (for 1993–2005) and simulated (for 2000–2005) accretion-erosion periods do not coincide. Still, the comparison of the measured and modelled accretion-erosion rates shows that our model results are consistent with measured results and describe the main features of coastal processes in the Palanga area.

The biggest discrepancies between the modelled and measured rates occur near x=4500 in an area is influenced by the Rążė River, the impact of which was not taken into account in the model. The model predicted bigger than measured accretion zone on the lee side of Palanga Pier and lower than measured values to the North of the Rążė River mouth. The likely reason for the discrepancies is one of the limitations of the GENESIS model: the CERC model overestimates the bulk and net transport rates in regions with a limited amount of mobile sediments.

Analysis of RMSE values of the coastline relocation indicates that a better agreement between the measured and modelled coastlines is provided by the GENESIS model coupled with an external wave model. The resulting model of coastline changes more adequately reproduces the impact of bathymetric features and describes the changes more realistically than the previous study (Zemlys *et al*. 2007).

Even better results may be expected if more precise bathymetry and measured or modelled wave data would be used. In addition, the use of a higher-resolution RCPWAVE model and accounting for the influence of Rążė River could lead to results that are more precise.

CONCLUSIONS

Authors have modelled the coastline dynamics at the Palanga Beach using a coupled system of the GENESIS model for coastal processes and the external wave model RCPWAVE. This system adequately simulates the wave transformation due to varying bathymetry in the nearshore. During this study, the coastline change model for the Lithuanian coast in Palanga neighbourhood was created and the main features of small-scale bottom topography shape were accounted. The main conclusions are as follows:

- The GENESIS model combined with the external wave model shows satisfactory performance, whereas the root mean square differences between the measured and modelled coastline locations are smaller than in the previous study (Zemlys *et al*. 2007). The developed model of coastline changes can reproduce the impact of bathymetry variations much better and describes situation more realistically than the previous model.
- The discrepancies between the observed and modelled behaviour of the coastline near the Rążė River mouth indicate that the influence of this river (which was not included into the model) is important for sediment transport in the Palanga neighbourhood.

Finally, it should be noted that an increase in the spatial resolution of bathymetry and the use of more representative wave data could further improve the model results. In this study, the wave properties were calculated from wind speed and fetch length using the CERC/SPM wave forecast/hindcast method. This method can be useful just for feasibility study. For future studies, wave data, either produced by more advanced models or measured, should be used.

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