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Morphologic and hydrodynamic conditions of Hel Peninsula's abrasion in the Kuźnica region (southern Baltic)

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Abstract

The purpose of the presented paper is the identification and assessment of causes of intensive abrasion in the open coastline of the Hel Peninsula and the effect of countermeasures. Numerical modeling of nearshore hydrodynamics, topographic analysis and field measurements were carried out. The Baltic Sea hydrodynamic model, a model of wave-induced nearshore circulation and the wave model SWAN were employed. 3D hydrodynamic modeling resulted in the become visible that fields of shear bottom stresses as well as bottom currents depended on atmospheric forcing and depth. A correlation between bottom stresses and topography was obtained. The results of modeling of the nearshore hydrodynamics demonstrated a dominant role for alongshore sediment transport. The magnitude of both cross- and alongshore wave-induced currents strongly depended on wave height gradient, which was significantly greater in storm periods. During storms, sediment transport occurs also in the cross-shore direction.

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INTRODUCTION

The open sea coastline of the Hel Peninsula is subjected to abrasion processes that result from waves and marine currents. These processes do not have a uniform impact along the length of the peninsula, and the most threatened areas are in the segment stretching from Wladyslawowo to Jastarnia. The tip of the peninsula is not affected by any immediate threat of shore abrasion.

In an effort to protect the residents of Kuźnica from the effects of damage during storms, a belt constructed of railroad ties, concrete rubble, and rocks was constructed in 1983 – 1984. Construction was completed in 1996 of a belt of gabions filled with artificially nourished sandy sediments. The dredged output that has been deposited since 1989 on the open sea side of the peninsula has not permanently nourished the rubble zone and has not protected the shoreline from abrasion. With regard to the Hel Peninsula, the effectiveness of the artificial nourishment method does not guarantee that the shoreline will be fully protected.

The undertaken hydro-technical efforts based on previous understanding of abrasion processes in this region did not provide a solution to the problem. Investigation of the reasons for the abrasion intensity was necessary. In the last decade, increasing frequency and intensity of storms have indicated that dynamic parameters play an essential role. Of primary importance is the influence of coastal and bottom currents, which are able to transport eroded material, resuspend sediments and rebuild the bottom topography.

The objective of this paper is to describe the geomorphological and hydrodynamic conditions in the active abrasion region near Kuźnica, located along the shore of the Hel Peninsula. A structure of this presentation contains characteristic of chosen area as the polygon, modeling of bottom currents at offshore waters along the Hel Peninsula and finally coastal currents at the mentioned polygon.

STUDY AREA

An analysis of aerial photographs of a 1:10 000 scale from the 1947 – 1991 period indicated that abrasion processes are the most intense in this region. The segment of shoreline studied was chosen based on an analysis of archival materials and the results of research by Musielak and Furmańczyk on the Hel Peninsula, which described the movement of the rubble zone along the coastline as cellular circulation (Furmańczyk 1994, Furmańczyk and Musielak 1997). The marine waters adjoining the designated shoreline that were included in the study were contained within a polygon (Fig. 1).

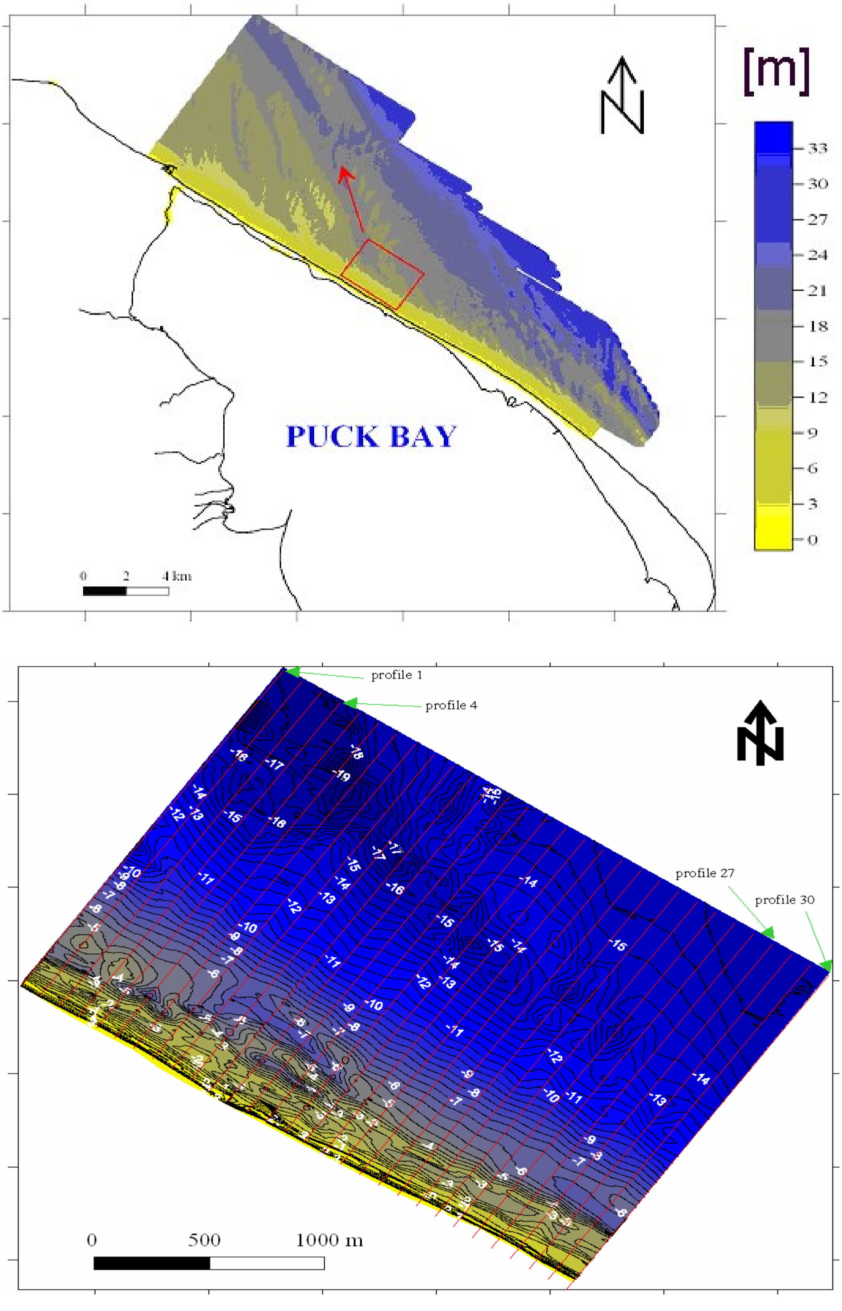


Fig. 1. Location of the research area.

The beginning of this area was situated at km H 9.3 and the end was at km H 12.3. Thirty sampling profiles were located perpendicularly to the shoreline and at a distance of 100 m from each other. The profiles included part of the terrestrial coastal zone from the base of the dunes and the beach to a depth of approximately 17 m, which extended into the nearshore zone. The length of each study profile was 2000 m (Fig. 1, bottom panel). Echo sounding measurements revealed varying bottom topography in the investigated area. A shallow undercoast, down to the 8 m isobath, is characterized by variability in bathmetry and significant sloping.

The bathymetric studies conducted in the nearshore zone indicated that there were two sandbars. The inner sandbar was approximately 100 m from the water line, with its peak occurring at depths ranging from 1.3 to 2.5 m. The average width of the sandbar was ca. 70 m. The inner sandbar was characterized by substantial variation that was moderately dynamic and by weak waviness. The peak was usually parallel to the shoreline, but after storms, during the short quiet phase and especially when waves were oblique to the shoreline, the sandbar could be connected to the shore at one end and repeat regularly along the shoreline (Rudowski 1986).

The peak of the second, outer sandbar occurred at depths of 2.5 – 3.5 m, with the shore side of the trough extending to depths of 3.5 – 4.0 m and the open sea slope reaching depths of 4.5 – 5.0 m. This sandbar was wider than the first, at an average width of 110 – 130 m. The second sandbar was created during intense wave conditions and usually followed a more regular course, running at about 200 – 250 m from the water line. Beyond this area, the bottom morphology became disting and uniform. The slope decreased and isobaths ran parallel to the shoreline. This strip reached a width of 500 – 600 m and was limited by the 14 m isobath offshore. Further towards the open sea a deep undercoast had been separated, which was split into a gently sloped eastern part with no evident form of bottom and western one reminding valley.

One of the particularly interesting elements of the open sea zone of the Hel Peninsula is the elongated depression that is positioned at about a 45° angle to the shoreline of the peninsula. This depression was visible on both bathymetric maps and sonar images of the bottom. The feature was formed in gyttja organic sediments, and in the study grid near Kuźnica occurred at depths of 17 m. The bottom of this depression was about 0.5 - 1.5 m beneath the bottom surface and was filled with fine- and medium-grained sands.

The coastal zone in the vicinity of Kuźnica is comprised mostly of dunes that are destroyed during storm surges. Shore belts, measuring 650 m in length and deployed from km H 11.76 to km H 12.41, were intended to counteract the abrasion process.

MATERIAL AND METHODS

The research methodology was based on experimental studies, modeling and analysis of aerial photographs. Aerial photographs of a scale of 1:10 000 and dating from 1947, 1957, 1963, and 1991 were used to analyze the changes in the elements of the Hel Peninsula shoreline (Fig. 2). One of the permanent shoreline elements visible in the pictures was the dune baseline.

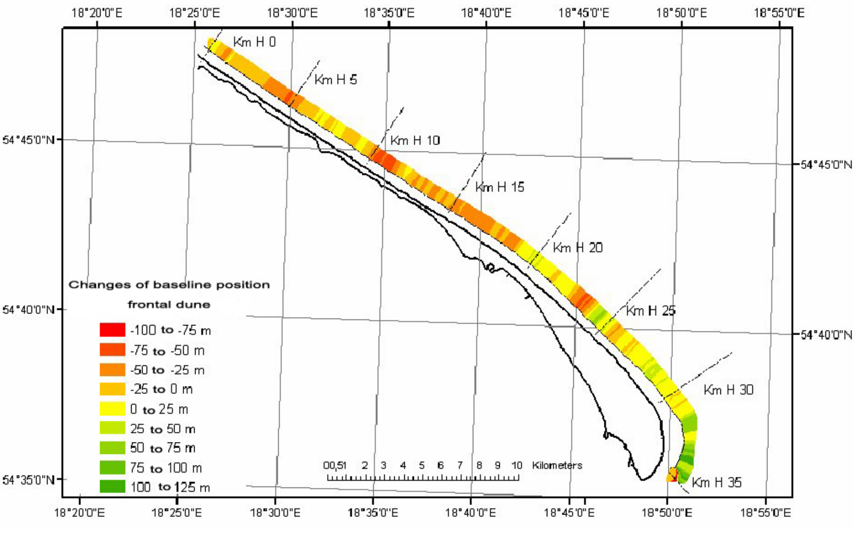


Fig. 2. Classification of changes in the Hel Peninsula coast during the period 1947-1991 (Based on aerial photographs, scale 1:10 000).

Within the scope of the field studies, echo sounder profiles were conducted along selected grid lines and repeated seasonally. Samples of surface sediments were collected along the profiles, and granulometry composition and sediment type were determined. Sonar images of the bottom in the study area were made from hydroacoustic data. Additionally, a multibeam echo sounder was used to study the bottom topography of the shoreface in the open sea zone of the peninsula.

Based on aerial images from the 1947 – 1991 period, a mean rate of recession of the dune baseline was found to be 1.7 m per year (Fig. 2). Similar results for the rate of coastline changes were obtained by Zawadzka - Kahlau (1999) (Fig. 3). Her results were based on the available (at scales of 1:25 000 and higher) cartographical descriptions of the polish coast, as described during 1875 – 1979.

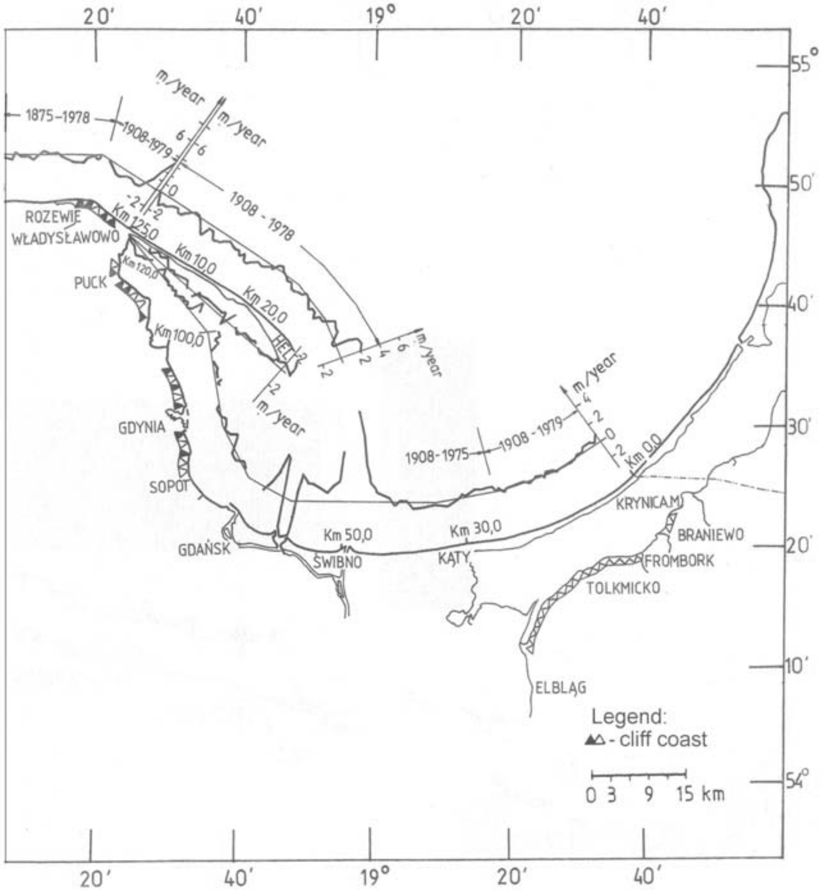


Fig.3. Changes in coastline position (m year^{-1}) between 1875-1979 (modified from Zawadzka – Kahlau E., 1999).

Using maps of the northern shoreline of the Hel Peninsula from 1908 – 1978, the rate of coastal recession in the Kuźnica region was evaluated at nearly 2 m per year. All reliable cartographical information originating from the beginning of the twentieth century and the aerial images taken during the second half of the same century confirmed that abrasian processes in the Kuźnica region were dominating. To counteract this tendency of coastal erosion, artificially nourished sandy sediments have been in use since 1989.

To evaluate bottom stress fields as well as bottom currents the M3D_UG hydrodynamic model based on POM was used (Blumberg and Mellor 1987). The modeled area covered adjacent waters on the north side of the Hel Peninsula down to depths of 100 m, which contained the shallower study polygon (depth to 17 m). This model has been used and validated several times in the southern Baltic area (Jędrasik 1997, Kowalewski 1997, Jędrasik 2005). The present application contains four steps of nested horizontal grids with spatial increments from 5 nm in the Baltic to 50 m in the polygon. Results from the modeling include atmospheric forcing from 2004. The transport capability of rock debris depends significantly on bottom stresses and bottom currents during storms. Selected distributions of the bottom stresses and velocity were taken to illustrate the influence of wind and depth.

The SWAN (*Simulating WAve Nearshore*) wave model was employed to determine the wave field in the region analyzed (Booij et al. 1996). This model has been implemented previously for conditions in the southern Baltic Sea (Cieślikiewicz et al. 2001). Results of the model concur well with measurements. The simulation was conducted in two stages.

In the first stage, the calculation network covered the western part of the Gdansk Basin. The shore conditions employed were deep-water wave motions described based on the so-called wave climate for the southern Baltic.

The second stage of calculations was done in a rectangular area that encompassed the Kuźnica study grid. The shore conditions were the frequency-directional spectrum that resulted from calculations on a larger network. The calculation network was shifted from the east 345° counterclockwise in relation to the bathymetric network in order to obtain results at profiles that were nearly perpendicular to the almost linear shoreline in the studied area. Additionally, in both cases a wind field with constant direction and speed, which means subsequently northerly, easterly and westerly at speeds of 10 m s^{-1}, was assumed.

The results of calculations of the wave model provided the wave parameters that were the input data for the current model (Chlebus et al. 2006). This model permitted estimation of the mean flow velocity in the nearshore zone based on the given wave field (amplitude, period, length, wave propagation angle) and the bottom topography. The factor that describes the generation of flow is the radiation stress gradient, which is directly dependent on the square of the wave amplitude and the propagation angle. These parameters are the primary factors that determine the current field. The model was implemented for the nearshore zone in the vicinity of Lubiatowo (bottom with multiple sandbars, isobaths roughly parallel to the shore). The results obtained from the calculations of the flow field were concurrent with current measurements in the surf zone (Chlebus et al. 2006).

RESULTS

In the shoreface of the study grid, two accretion zones can be identified; one occurred near the sandbar, while the other, dominated by abrasion processes, occurred at greater depths. These zones are visible on the map as bathymetric differences identified in the study grid. Confirmation of the existence of zones in the shoreface was provided by the analysis of selected bathymetric profiles that present the abrasion tendency occurring particularly in the vicinity of the depression (Fig. 4, Tab. 1). This is well documented by the sonar image and the spatial bathymetric map (Fig. 1).

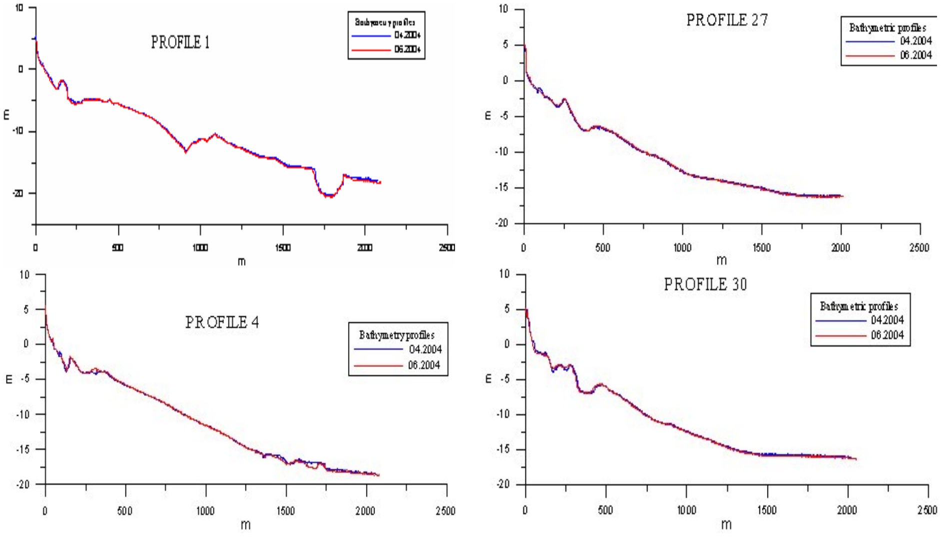


Fig. 4. Examples of bathymetric profiles of the polygon.

By summarizing findings of the morphological studies, it is possible to recreate accurately the process of sediment transfer on the bottom in the vicinity of Kuźnica. During storm surges, the sediment that comprises the dune line and has been supplemented with dredged sand is transported out to sea. This movement reaches as far as the depression located in the northwest of the study grid. During the quiet phase of the storm, when the sandbar system has been recreated, a large part of the volume of the dynamic sandy layer that had been deposited in the depression is carried towards the sea (Fig. 4, Tab. 1).

The values of bottom stresses during the storm on November 23rd, 2004, with wind near 20 m s^{-1} from the NW, reached 0.7 N m^{-2} and even greater than 1 N m^{-2} locally (Fig. 5a). The stress values decreased by one order of magnitude

Table 1

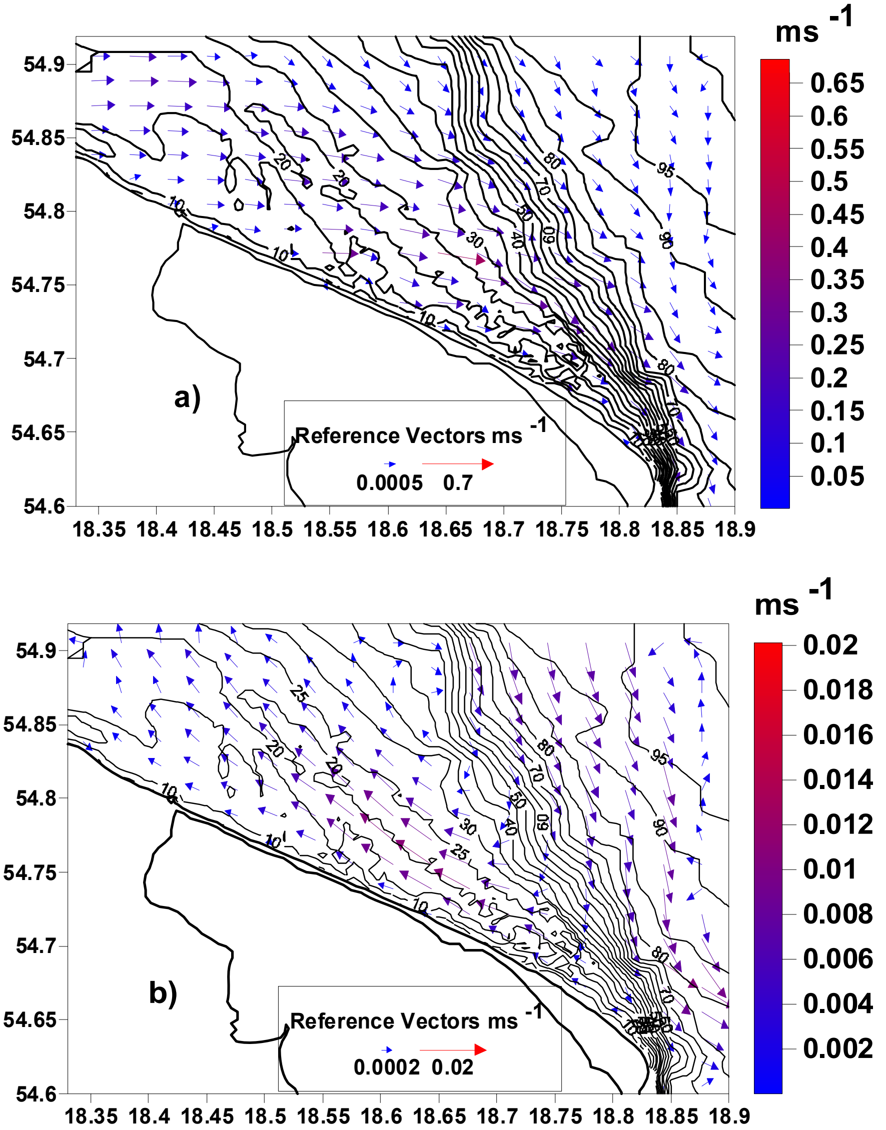
Areas of accumulation and erosion in the selected profiles

The 100 m width of offshore area along profile	The distances from the profiles beginning		
	0-500 m	500-1000 m	1250-1750 m
	Volume of the offshore sediment (th. of m^3) (+ accumulation, - erosion)		
Profile 1	+ 2.5	- 4.5	- 9.5
Profile 4	+ 8.5	- 1.5	- 1.5
Profile 27	- 7.0	+ 3.0	- 7.5
Profile 30	+ 1.5	- 4.0	- 2.0
average	+ 1.375	- 1.75	- 5.125

at the NE part of the study area due to increasing depth. There, a correlation between direction both bottom stresses and isobaths appeared. In the western part of the study area, the vector stresses confirmed intensive flows throughout the entire water column along the Hel Peninsula. High bottom stress values cover the near-bottom area for a ca. 10 km wide strip along the Hel Peninsula (Fig. 5c). The highest values occurred close to the Kuźnica region. Bottom velocity reached values of 0.55 m s^{-1}, which potentially indicates an abrasion area.

The opposite distribution as anticyclone eddy performed at the region of strong gradient of depth during becoming fall silent of storm on 29th of November 2004. On that date the wind was blowing only 3 m s^{-1} from the SW, and the force of the bottom stresses decreased to 0.02 N m^{-2} (Fig. 5b, d). Another important feature of the near-bottom circulation existed following storms, when the shear stresses changed direction and contributed to the outflow of sediments towards the northwest. The stress vectors were parallel to isobaths and local depressions in the bottom (Fig. 5b). During calming down of the storm, modules of the bottom stresses quickly decreased at the shallower part of the study area and maintained higher values in deeper waters (Fig. 5d).

A special sequence of events in the formation of the bottom current fields existed during the development of the storm on November 22nd 2004, when wind velocity increased from 4.6 to 14.7 m s^{-1} (Fig. 6). An anticyclonic eddy of bottom currents at the western, shallower section of the study area was developing, which bordered a cyclonic eddy in the deeper eastern section. Flow divergence appeared at a slope of depth and eastern part of the Peninsula splitting them towards SE and NW with 0.1 m s^{-1} of velocity (Fig. 6). Intensive flows existed in the Kuźnica region offshore of the Hel Peninsula. The bottom currents reached velocities of 0.14 m s^{-1}, which are sufficient to transport sediments. These velocities were evaluated at a depth of 0.2 to 0.8 m above the


a)
Reference Vectors ms -1
0.0005 0.7
ms -1
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
54.9
54.85
54.8
54.75
54.7
54.65
54.6
18.35 18.4 18.45 18.5 18.55 18.6 18.65 18.7 18.75 18.8 18.85 18.9
b)
Reference Vectors ms -1
0.0002 0.02
ms -1
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002

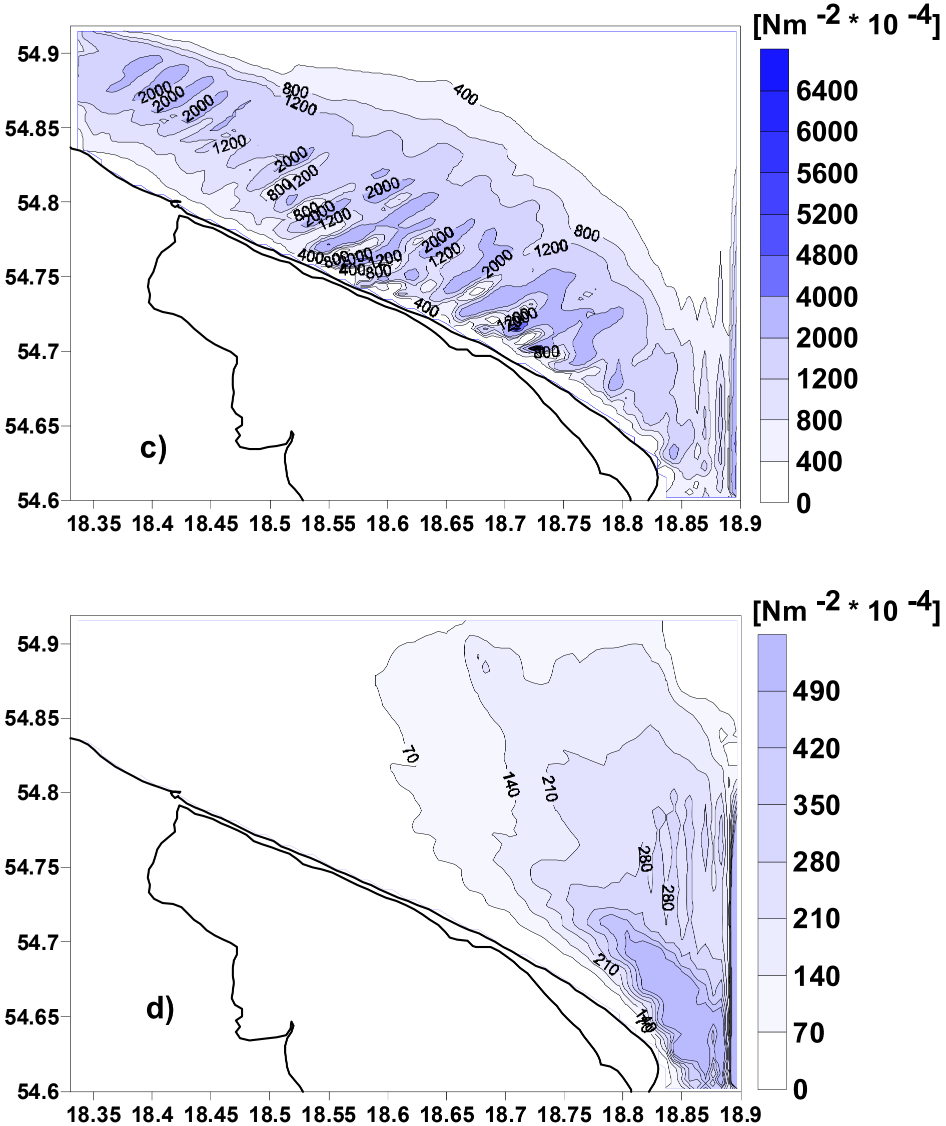
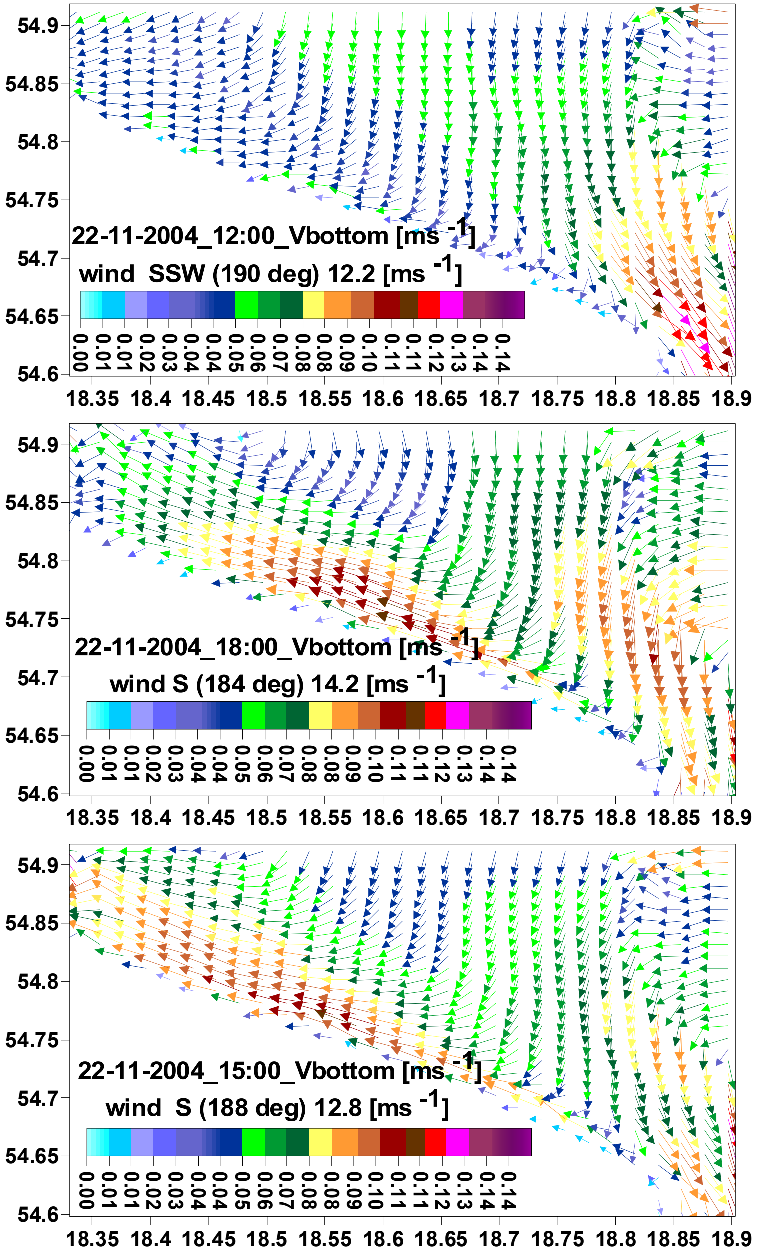


Fig. 5. Vectors of bottom stresses against a background of bathymetry a, b) and modules of bottom stresses (Nm^{-2} 10^{-4}) c, d) north of the Hel Peninsula on 23 Nov 2004 and 29 Nov 2004.


22-11-2004_12:00_Vbottom [ms -1]
wind SSW (190 deg) 12.2 [ms -1]
22-11-2004_18:00_Vbottom [ms -1]
wind S (184 deg) 14.2 [ms -1]
22-11-2004_15:00_Vbottom [ms -1]
wind S (188 deg) 12.8 [ms -1]
54.9 54.85 54.8 54.75 54.7 54.65 54.6
18.35 18.4 18.45 18.5 18.55 18.6 18.65 18.7 18.75 18.8 18.85 18.9
0.00 0.01 0.01 0.02 0.03 0.04 0.04 0.05 0.06 0.07 0.08 0.08 0.09 0.10 0.11 0.11 0.12 0.13 0.14 0.14

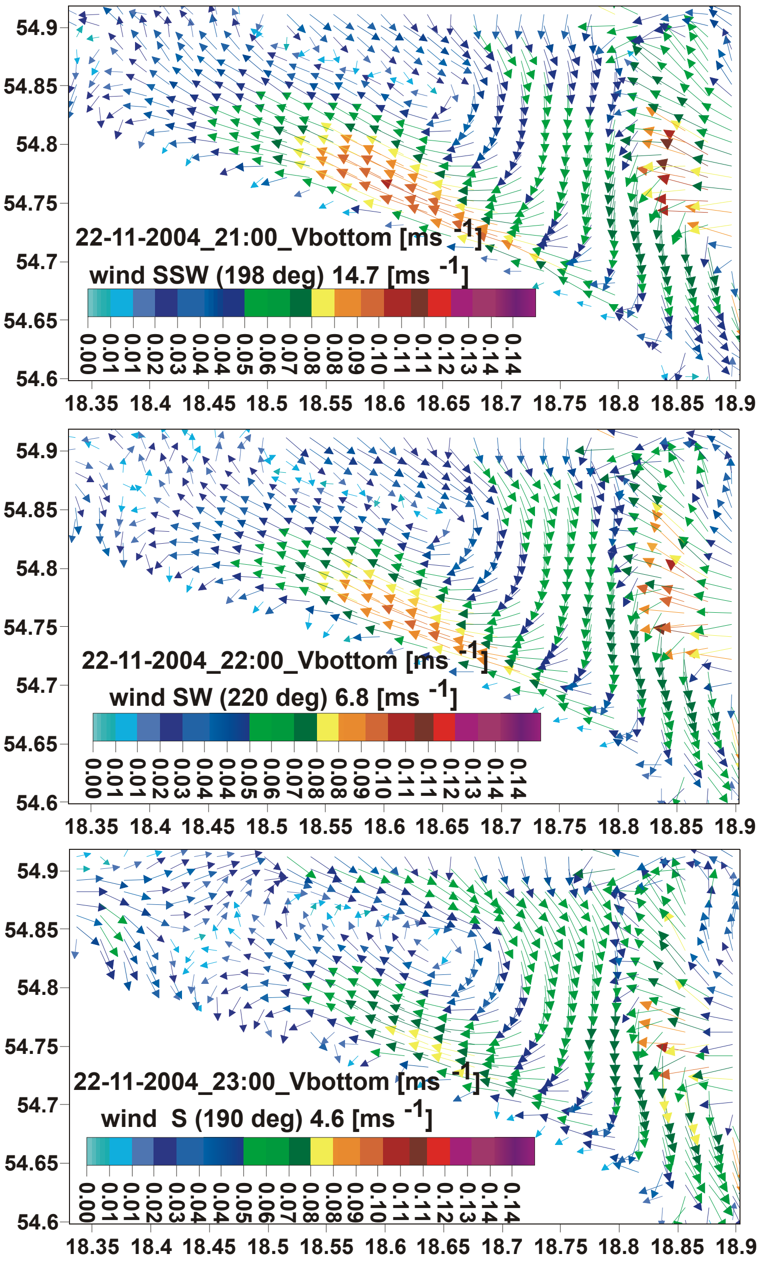


Fig. 6. Evolution of bottom velocity fields north of the Hel Peninsula during 22 Nov. 2004.

bottom. The described velocity fields will be discussed in relation to the sediment granulometric composition in future to outline "patches" of abrasion and accumulation.

The bottom current fields also depend on wind direction (Fig. 7). Flow reversal appeared during eastern winds, particularly from the E and SE. These winds cause a westerly current direction. Under the remaining wind directions, currents flow towards the east or southeast. Little differentiated current fields in the polygon are due to a reduced depth horizon.

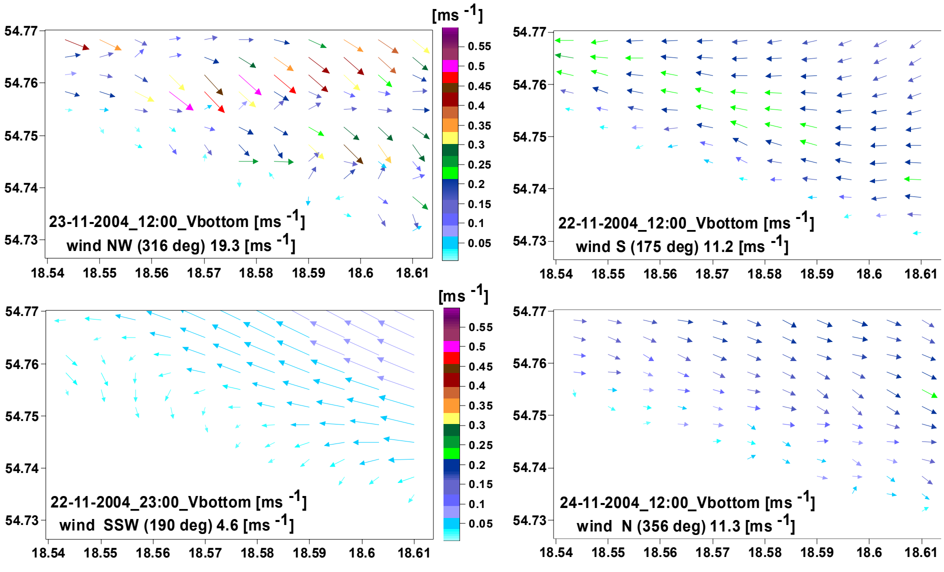


Fig. 7. Changes in bottom velocity fields in the Kuźnica polygon, according to the basic wind directions chosen in 2004.

The initial calculations of the current model for the Kuźnica study grid, based on the results of the SWAN model, indicate that a wave-generated flow concentrated in the direction parallel to the axis of the depression and towards the open sea does exist, especially during periods of strong wave motion and during periods with winds from the E and NE (Figs 8, 9 left). On the

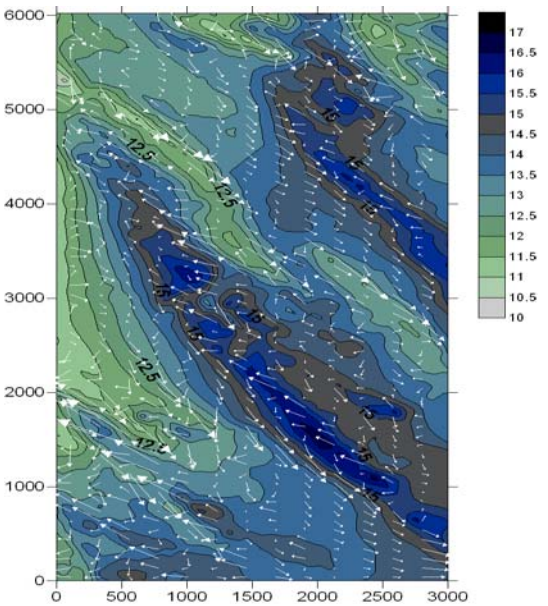


Fig. 8. Vector field of current velocity induced by waves coming from the northeast direction.

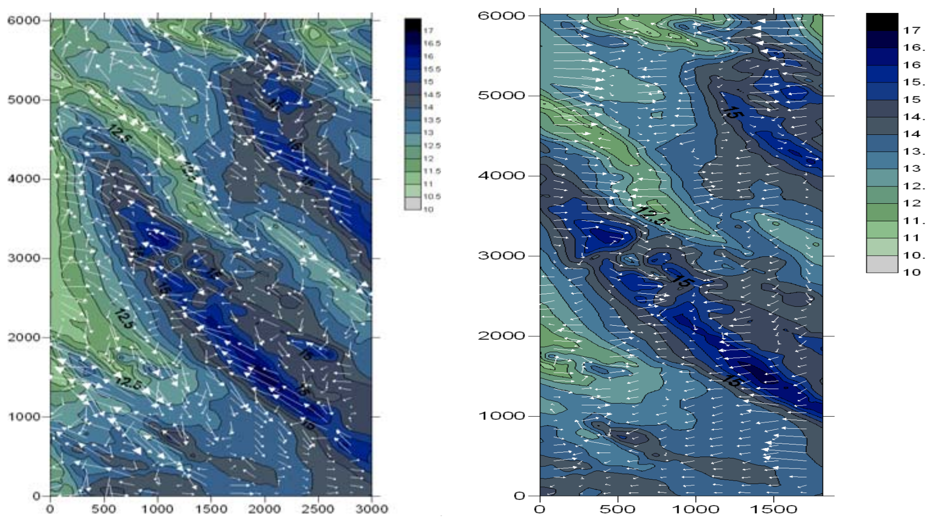


Fig. 9. Vector field of current velocity induced by waves coming from the north (left panel) and northwest direction (right panel).

other hand, during periods with wind from the W and NW direction (Fig. 9 right), this type of flow was not noticeable.

The generation of these wave-induced currents occurs at the edge of the depression in the region where there are significant depth variations, which also produces changes in the wave amplitude and direction of wave propagation. Further calculations of the current model for different wind and wave conditions, including for the Kuźnica study grid as well as for the entire region in question, and the analysis of the identified flows with regard to their ability to transport sediments of specific fractions may provide support for the hypothesis that there is strong flow in the depression that carries rubble out to sea.

SUMMARY

In general, the result of geological analysis shows the existence of areas of strong abrasion and accumulation in the investigated region. In this paper, hydrodynamic numerical models were presented, which are suitable tools for preliminary investigation of sediment transport and morphodymanics of the shoreface of the Hel Peninsula. Evaluation of critical shear stress velocities based on the grain-size of sediments, to be used as erosion thresholds, is needed for mapping sediment dynamics.

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