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The dune coast – the state just prior to the construction of hard engineering protection structures (Ustka-Jarosławiec, the Southern Baltic)

by

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Abstract

The state of a fragment of the southern Baltic Sea shore was assessed on the basis of historical maps, aerial images, the digital elevation model and the data on the geological structure of the nearshore bottom. The alternate erosion and accumulation sections of the coast were observed. They are moving toward the east related to the migration of mega beach cusps. The infrastructure of the military training ground located in the western part of the study area is threatened with abrasion. In 1889-2012, the nearby seashore retreated by an average of 257±11.5 m. The recorded average rate of changes for the period of 1989-2012 was -2.6±0.22 m year^{-1}. In the eastern part of the study area, at the bottom of the nearshore, a thick layer of sand determines the development of new accumulation sections of the coast. The state of the seashore, recognized in this paper, will change due to the construction of four concrete sea-walls. Their operation will disrupt the natural processes described in these studies.

Key words: morphological changes, abrasion, coastal management, GIS, Polish seashore

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Introduction

The study area is the central section of the southern shore of the Baltic Sea between the towns of Jarosławiec and Ustka in Poland (Fig. 1). Dune complexes are located in this area: Lędowskie, Modelskie, Zaleskie and Wickie. According to the Polish Maritime Office's mileage, this section is between 233.6 to 252.0 km.

The analyzes of changes in the position of the water line and the dune base line were based on historical maps from 1889-1989, aerial photographs from 2010-2012, and a digital elevation model based on airborne laser scanning from 2011. The study also used the materials on the geological structure of the bottom of the nearshore zone (Koźbiał 2008, Bilińska et al. 2008).

The aim of the study is to assess the state of the shore, with respect to sea-walls against erosion, as implemented by the Maritime Office in Słupsk.

The southern Baltic coast between Jarosławiec and Ustka is poorly investigated. The authors are not aware of any research on the coastal processes in this area. In the comprehensive studies dealing with the coastal zone of the southern Baltic Sea, this area was either omitted or barely discussed, with often conflicting information (Zawadzka-Kahlau 1999; Pruszak & Zawadzka-Kahlau 2005, 2008; Dubrawski & Zawadzka-Kahlau 2006; Zawadzka-Kahlau 2012; Łabuz 2013, 2014). One of the reasons for this state of knowledge was the prohibited (since the early 1990s) and limited (still now) access to the area, located mostly within the Central Polish Air Force Range in Ustka (Fig. 2), and hence difficulties with fieldwork.

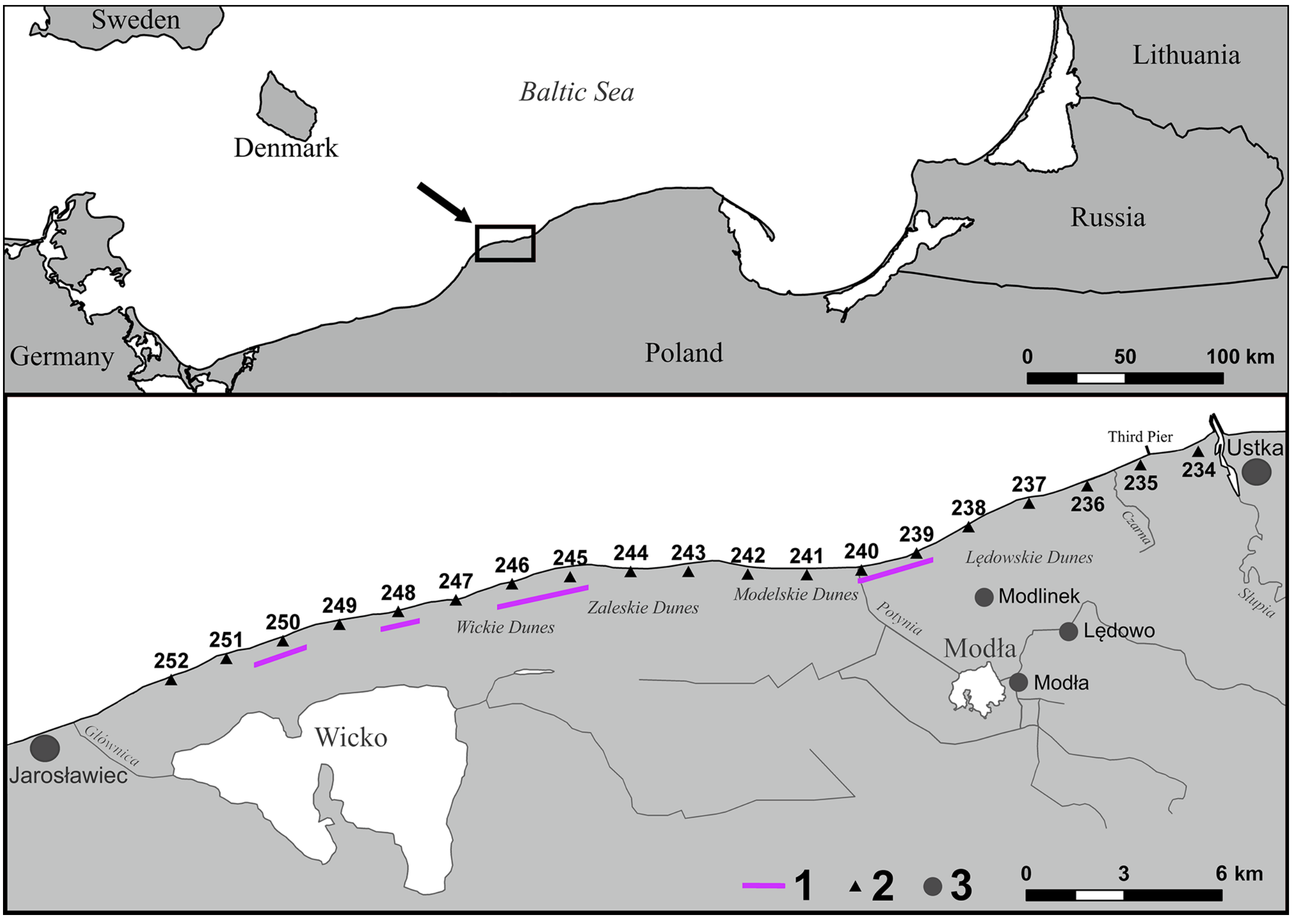

Figure 1

Location of the study area; (1) the structures under construction; (2) km of the study area according to the Maritime Office; (3) selected towns

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Figure 2

Dune coast at 235 km (Photo by P. Domaradzki, 6 June 2013)

The uniqueness of this part of the Polish sea coast consists mainly in the lack of permanent protection structures against abrasion. So far, the study area has not had any concrete protection, but only soft protection in the form of fascine fences, planted vegetation or protective use of tree branches and bushes.

The only hydro-technical structure in this area is the so-called Third Pier, located (234.9 km) about 1 km west of the Ustka Port. The construction of the pier began in 1938, but it was discontinued in 1939 due to the outbreak of World War II. According to the plans, it was meant to be the western breakwater supplementing the existing structures, designed to protect the new, much larger port against storm surges (Barnowski 2011).

Under the current provisions of the program of technical protection of the open seashores in the conditions of the projected sea level rise by 2050, none of the scenarios allowed for the seashore protection in this area (Dubrawski & Zawadzka-Kahlau 2006). However, on 23 January 2012, the Director of the Maritime Office in Słupsk initialed an agreement on financing the project "Protection of seacoast within the Central Polish Air Force Range Wicko Morskie". The project involves the construction of four coastal dykes (Fig. 1) along the low dune coast. The selection of the seashore fragments was based on the results of monitoring conducted by the command of the Central Air Force Range. Beach-walls are planned for the sections of 238.8-240.1, 244.8-246.4, 247.7-248.3 and 249.7-250.7 km (Maritime Office in Słupsk 2013).

According to the Maritime Office in Słupsk (2013), the investment is justified by the coastal erosion processes, which bring economic losses and cause potential danger of flooding of the villages of Modlinek, Modła and Lędowo. In addition, and perhaps most of all, abrasion threatens the valuable infrastructure of the Central Air Force Range (Maritime Office in Słupsk 2013).

Through the construction of hard engineering protection structures, the functioning of the natural processes occurring here today will be disrupted. The state of the seashore and the natural coastal processes, identified in this study, will be modified due to anthropopressure.

Materials and methods

The measurements of the position of the water line and the dune base line have been conducted successfully for many years on the basis of the analysis of maps and aerial photographs (Subotowicz 1973; Leatherman 1983; Furmańczyk 1994, 1995; Moore 2000; Dudzińska-Nowak 2006; Rucińska-Zjadacz & Rudowski 2015). The main paper related to the study area is the work of E. Zawadzka-Kahlau (1999), who analyzed the changes in the position of the water line and the dune/cliff base line for the entire Polish coast for the period of 1875-1983. That paper, however, lacks the information for later years.

The analytic materials for this study were four archival maps (Table 1) from the period of 1889-1989 (Geoportal 2014, Mapster 2014). The location of the water line and the dune base line (*sensu* Zawadzka-Kahlau 1999) were plotted for each map using the ArcGIS Desktop 10.2. Superposition of the obtained

Table 1

Archival maps used in the study

no.	topographic update	name	scale	sheets	estimated measurement error
1.	1889	Meßtischblatt, Topographic Map	1 : 25 000	Saleske, Lanzig	± 8 m
2.	1934	AMS 841	1 : 25 000	Saleske	± 9 m
3.	1975	Topographic Map of Poland	1 : 25 000	Ustka, Duninowo, Postomino	± 9 m
4.	1989	Topographic Map of Poland	1 : 10 000	Wicko Morskie, Modlinek, Ustka Pn, Ustka Pd.	± 1 m

data gave a picture of changes in the coastal zone in the period of 1889-1989.

A possible measurement error was evaluated for each map. This was done according to the following methodology (*cf.* Zawadzka-Kahlau 1999, Dudzińska-Nowak & Furmańczyk 2005). On the basis of the orthophotomap (0.5 m pixel) dated 4 July 2010 from the Centre of Geodetic and Cartographic Documentation in Warsaw (CODGiK) and the Topographic Map of Poland at a scale 1:10 000, the test layer was plotted. The characteristic objects, the location of which has not changed over the past 120 years, were marked on the above map. Then, based on this reference layer, the difference in the position of the selected object with respect to the test layer was measured for each of the embedded archival sheets. The estimated measurement error was half of the total map objects' shift in relation to the reference line and the thickness of the water line on the map scale:

$$E = \frac{|s| + 1}{2}$$

where:
E – estimated measurement error
s – shift of map objects in relation to the reference line
l – thickness of the water line on the map scale

The list of the sheets used with possible, estimated measurement errors is given in Table 1.

The available sheets of map No. 1, topographically valid for 1889, covered 92.4% of the study area, while map No. 2 – 68.5%. Other maps covered the whole analyzed area.

The study also used the materials from the period of 2010-2012. The orthophotomap valid on 4 July 2010, and a digital elevation model (DEM based on ASL, 4 points m^{-2}) of 27 April 2011 were purchased from CODGiK. In addition, six images available online in Google Earth Pro (Google Inc. 2013) were used.

On the basis of the aerial images and the elevation model, the position of the water line (understood as a line in the middle of the uprush and backwash zone) and the dune base line (understood as the upper limit of the beach surface) were plotted. Superposition of all the layers, as well as the sea levels (Institute of Oceanography Gdańsk University 2014) preceding the shooting time, gave the picture of changes in the period from 4 July 2010 to 29 August 2012.

The maps contain the averaged and generalized location of the measured elements, while the aerial images capture the locations at any given time, depending on the sea level and the processes preceding the shooting time. To compare the results obtained on the basis of historical maps and aerial images, based on the available data, in particular four images from 2012 (one taken in May and three in August), the averaged position of the tested elements were plotted for 2012. The difference in the location of the water line at the time was ±4 m, which was taken as the estimated measurement error related to the average water line of 2012. The possible inaccuracy in the assessment of the position of the dune base line in the pictures of 2012 was ±3.5 m, which was accepted as an estimated measurement error taking into account the averaged position of the dune base line for 2012. It should be noted, however, that the calculations are based on a few instantaneous states contained in the maps and pictures, so they do not give a continuous image of the course of the seashore changes in the analyzed time intervals.

Results and discussion

In the period of 1889-2012, along the shore stretching at 233.6-237.2 km, the water line and the dune base line shifted toward the sea. The largest change in their location took place west of the Third Pier in Ustka (km 235). The water line shifted there by 242±12 m, while the dune base line by 211±11.5 m to the north. The average change in the position of the tested elements in this section was 116±12 m.

In the period of 1889-2012, the node point of changes in the position of the water line and the dune base line was between 237.4-237.7 km. West of this position, as far as 240.4 km, the analyzed components shifted inland. The highest rate of changes took place in the middle of the section in question. At 238.8 km, the difference in the position of the water line was -270±12 m, and of the dune base line 257±11.5 m (Fig. 3).

In the period of 1889-2012, the rate of changes in the location of the water line and the dune base line at 241.0-244.4 km was not high, always toward the

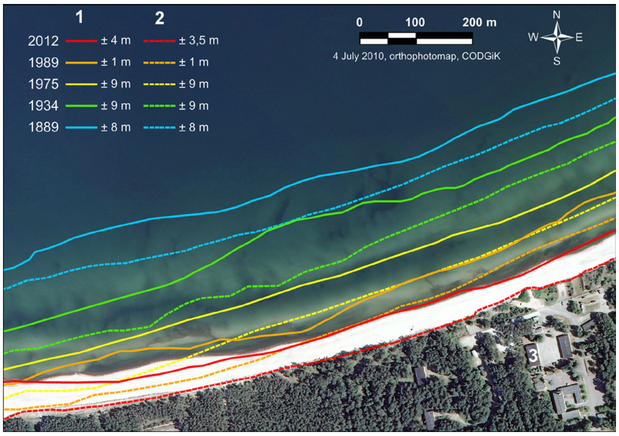

Figure 3

Changes in the position of (1) the water line and (2) the dune base line in the period from 1889 to 2012 at (3) the buildings of the Headquarters of the Central Polish Air Force Range (km 239)

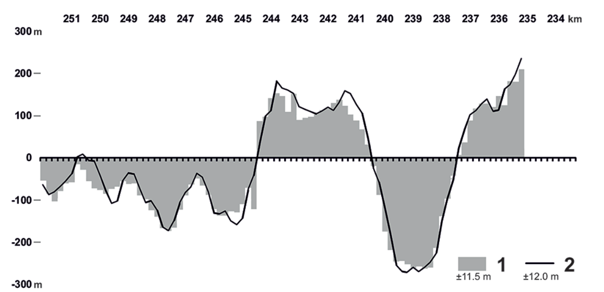

Figure 4

Change in the position of (1) the dune base line and (2) the water line in the period of 1889-2012

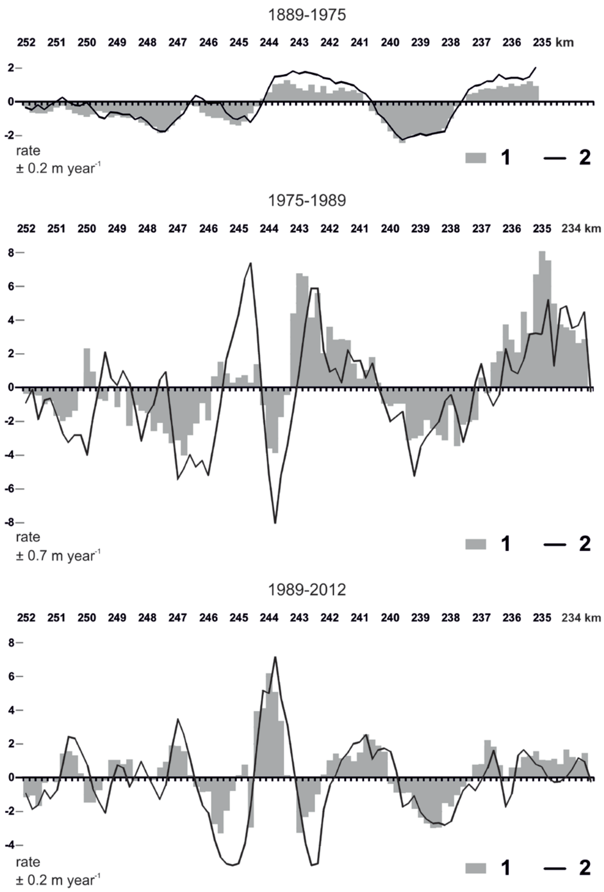

Figure 5

Average annual rate of the change in the position of (1) the dune base line and (2) the water line

sea. The average difference in the location of these elements was 115±12 m.

From 244.4 km to the western end of the study area (252 km), a high rate of change was recorded in 1889-2012. The alternate sections of the positive and negative balance of the position changes shifted their location in all the studied periods. Depending on the considered time interval in the period of 1889-2012, the direction of changes in the position of the water line and the dune base line should be described differently. All the changes that occurred over 123 years shifted the shore line toward the land along the entire section (Fig. 4).

For the period of 1889-2012, the position differences in the water line and the dune base line in 1889-1975, 1975-1989 and 1989-2012 were measured at the points located every 200 m perpendicular to a fixed baseline. The arithmetic mean and the annual rate of changes were calculated. The results are presented in Fig. 5.

There were differences in the results of measurements of the location of the analyzed elements between the period of 1889-1975 and younger periods (Fig. 5 & 6), and a significant difference in the rate of the processes. The average annual rate of changes calculated for the period of 1889-1975 was several times lower across the study area from the average rate of changes in the shoreline for later years. The frequency of storm surges in those years did not change significantly (Kowalska et al. 2012), and the average annual sea level rose in Ustka by about 1-4 mm year^{-1} (Rzeszewski 2011). Therefore, the average change is probably related to changes in the development trends of the fragments of the several kilometers-long seashore stretches within

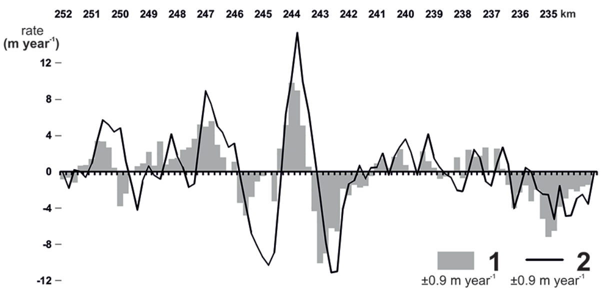

Figure 6

Difference between the average annual rate of the change in the position of (1) the dune base line and (2) the water line in the period of 1989-2012 and 1975-1989

several decades. The effects of intense abrasion on a given stretch over many decades are reduced as a result of accumulation that also occurs there. As a result, the land loss calculated for the 86-year period is lower than for the erosion episode lasting several decades. This is confirmed by the data from map No. 2. In the period of 1889-1934, intense erosion or accumulation were observed in some sections, but the opposite direction of changes in 1934-1975 caused that the values for the period of 1889-1975 were lower than for shorter periods of time.

For instance in 1989-2012, the shore section at 242.2-244.3 km witnessed a reversal of the direction of changes in the position of the water line and the dune base line in relation to the period of 1975-1989. The coastline fragment at 242.2-243.2 km recorded the positive balance of changes in 1975-1989, while in the period of 1989-2012, this section showed the negative balance. The section of 243.2-244.2 km had a negative rate of changes in 1975-1989 and in 1989-2012 the position of the analyzed elements moved toward the sea.

Along the section of 244.2-252.0 km, the shoreline moved landward during the period of 1889-1975. In the period of 1989-2012, three fragments of the section shifted toward the sea as compared to the period of 1975-1989. Along 77% of the section's length, the difference between the rates of changes in the position of the shoreline was positive.

Also the eastward shift of the rate of changes in the position of the water line was observed in relation to the dune base line (Fig. 5). A similar shift is presented in Fig. 6. The data describing the subsequent period show the maximum and minimum values shifted to the east in relation to the corresponding values for the earlier period. Similarly, the extreme changes in the position of the water line are shifted to the east relative to the results for the dune base line.

The determination of accumulation, abrasive and stable sections of the seashore for the periods of 1889-1975, 1975-1989 and 1989-2012, based on the results of the analyses of changes in the position of the water line and the dune base line (Fig. 7), allows to look more generally at the phenomenon described above.

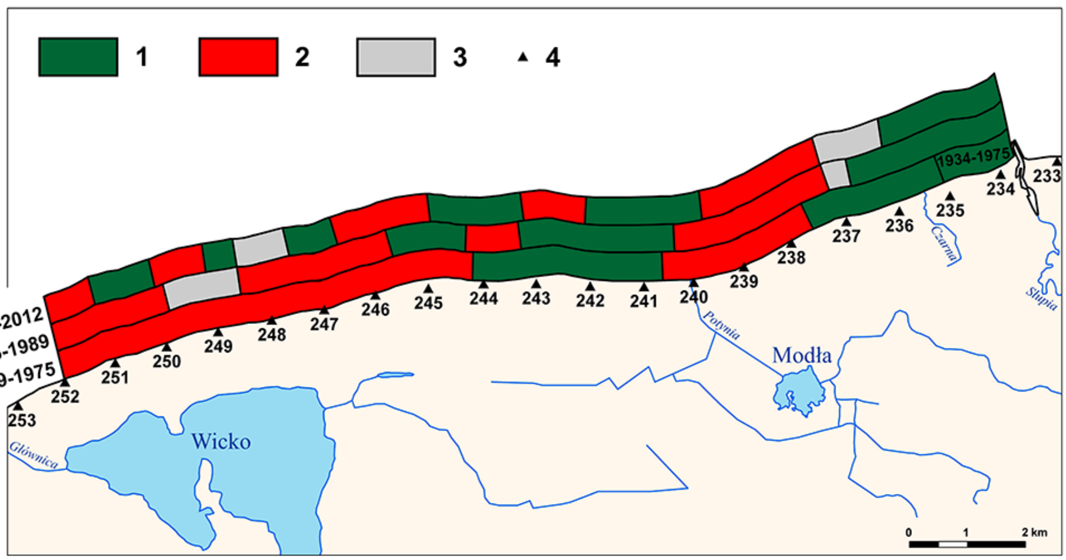

Figure 7

Change in the position of (1) the accumulative, (2) erosive and (3) stable seashore sections in the period of 1889-2012; (4) km of the shore

In the study area, the process of shifting the accumulation and erosion sections eastward is observed, which is consistent with the dominant direction of the longshore transport (Dubrawski & Zawadzka-Kahlau 2006). The nature of 242.2-244.8 km and 233.6-236.4 km stretches changed from accumulation to erosion and *vice versa* not only in 1975-2012, but also as a consequence of eastward migration of the abrasive bay already in 1889-1975.

A similar situation took place in the accumulation sections. The advantage of the material accumulation over erosion occurred in 1889-1975 at 240.7-244.2 km; in 1975-1989, the same process occurred somewhat further to the east (240.4-243.2 km), while in 1989-2012 – at 239.7-242.2 km.

The eastern abrasive bay changed its position. Its western border reached 240.7 km in 1889-1975, 240.3 km in the period 1975-1989 and 239.7 km in 1989-2012.

At 242.0-247.2 km, there are mega beach cusps (*sensu* Rudowski 1964, 1986), understood as bays and headlands, hundreds of meters to several kilometers wide. With time, mega cusps are being shifted toward the east. The comparison of the shoreline in 1975 and 1989 showed a shift of the water line by half the length of the mega cusp (one length of the bay/headland) (Fig. 8). In the areas with a very wide beach in 1975, there was a narrow beach in 1989, and *vice versa*. This phenomenon is visible in the results of the measurements of the position of the water line as significant abrasion or accumulation, but in fact, after a full shift by one mega cusp to the east, the effect of the land area is close to zero.

The process of shifting the sections of accumulation and erosion does not just refer to the easternmost part of the shore (233.6-236.0 km). In contrast to the rest of the research polygon, the natural processes here are significantly modified by anthropogenic factors. In this section, the accumulation stimulated by the breakwater of the Ustka Port can be observed. After the construction of the Third Pier in Ustka in 1939, the intensity of the material accumulation significantly increased. The port breakwater and the Third Pier force the accumulation of sediment on the stretch of about 3 km.

In the remaining, more natural area, with no artificial barriers to sediment and without heavy protection, there are alternate erosion and accumulation sections. Their condition, defined on the basis of the analyses of changes in the position of the water line and the dune base line, is confirmed by the relief of the beach and the surrounding dunes. For example (Fig. 9), at 235.6 km, where the shore shifts toward the sea, the beach is gently inclined, clearly marked by a boundary wall; the sand dunes are young, and there is a slightly sloped dune of 9 m asl at their back. However, in the center of the erosion bay (km 238.6), the dune has an almost vertical north face, undercut by erosion.

The part of the study area located further to the west (km 244.2-252.0) was abraded in 1889-1975 (Fig. 7). In 1975-1989, two short sections of the shore (km 244.3-245.4 and km 248.6-249.8) ceased to retreat. Until 1989, these sections migrated to the east. In 1989-2012, another three areas with predominant accumulation and one stable section appeared at 246.4-251.0 km. In the period 1975-2012, the western part of the study area developed

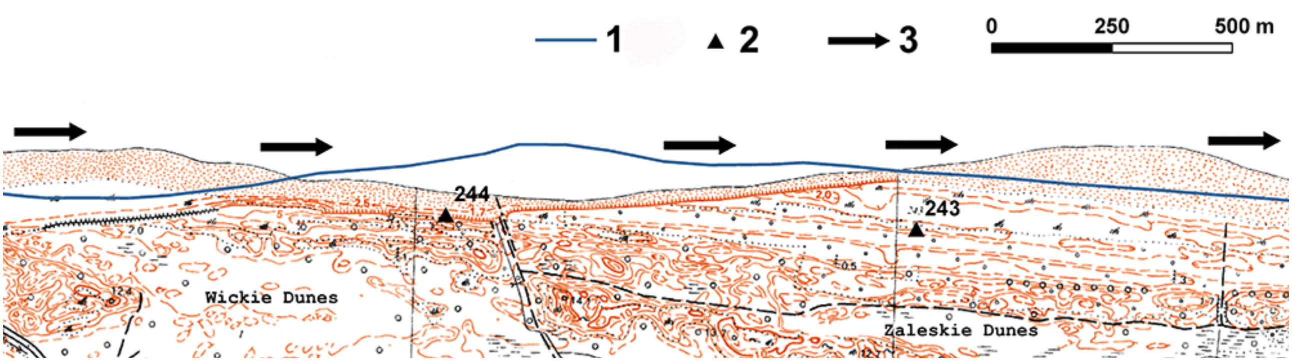

Figure 8

Change in the position of mega beach cusps marked on the map of 1989 (No. 4); (1) water line in 1975; (2) km of the shore; (3) direction of shifting

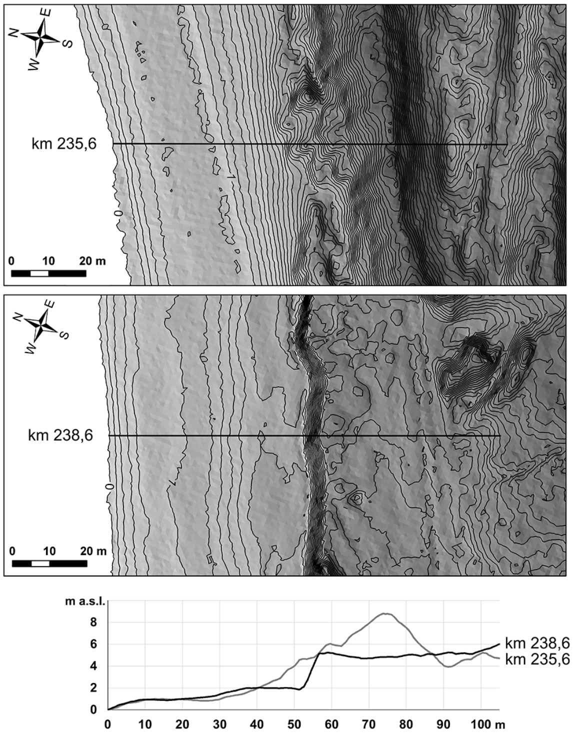

Figure 9

Relief of the beach and its hypsometric cross-sections (as of 27 April 2011, on the basis of the Airborne Laser Scanning of the CODGiK)

from clear erosion into the alternate sections of erosion and accumulation. As evidenced by the examination of the condition and the geological structure of the nearshore seabed (Koźbiał 2008), there is a 4 m thick sand layer at the bottom. There is a system of three bars. The convex profile of the bottom dominates. Therefore, the state of the bottom must be described as clear accumulation (Koźbiał 2008). The supply of the material from the bottom of the nearshore to the shore may explain the development of prograding and stable sections as well as the decline in the rate of erosion.

Forecasts of changes

While trying to predict the risk of abrasion, one should keep in mind the above-described changes in the position of erosion and accumulation shoreline sections. Moreover, the rate of changes in the position of the water line and the dune base line in the part of the analyzed area is so high that it is difficult to make the right quantitative estimate.

After excluding anthropogenic factors, it can be purely hypothetically assumed that if the rate of erosion (-2.6±0.22 m $year^{-1}$ at 238.8 km in 1989-2012) will not change, the dune base line will reach the location of the northernmost buildings of the Central Polish Air Force Range within 15.5-18.2 years. However, compared to the period 1975-1989, in 1989-2012 the abrasive bay (with buildings in the center) moved eastward by about 0.7 km. Thus, the reduction in the rate of the shore erosion should be expected in the future. Theoretically, if the above described processes of natural migration of erosion and accumulation sections do not change, the infrastructure of the Central Polish Air Force Range – being at the risk of erosion at 238.8 km – will be out of the abrasive bay in about 15-25 years and on an accumulation stretch of the coastline in subsequent years.

Given the movement of the erosion and accumulation sections, the decision of the Maritime Office in Słupsk (2014) to locate the hard engineering protection structures between 238.8 km to 240.1 km can be confusing. According to the above findings, the erosion was recorded at 239.6-240.1 km but in the period 1889-1989. In 1989-2012, however, the water line and the dune base line in this section were shifted toward the sea. It is expected that with the shift of the accumulation section (239.6-240.0 km) to the east, the length of the shore endangered with abrasion will be reduced, and at the section of 238.8-239.6 km it will be dominated by accumulation.

Undoubtedly, the construction of the sea-wall will interfere with the natural geomorphological processes; in particular the balance of deposits will change. It can be assumed that the rate of accumulation in the section of 233.6-237.0 km will be reduced. This structure, as a result of the so-called "link side effect", may lead to the development of new erosion sections on both sides (Dudzińska-Nowak 2006).

The storm embankment under construction will protect the low Modelskie Dunes (occurring only along the beach) against erosion, and thus will prevent a possible overflow of the seawaters to their hinterland. To some extent, it can also protect the peat plain, endangered by the sea flood (Dubrawski & Zawadzka-Kahlau 2006), located on average at 0.7 m above sea level. Contrary to the premise of the project "Protection of sea coasts within the Central

Polish Air Force Range Wicko Morskie" (Maritime Office in Słupsk 2014), the villages of Modlinek, Modła and Lędowo do not seem to be threatened by flooding. Their lowermost buildings are located at over 2.5 m asl.

In the western part of the study area, further development of alternate accumulation, erosion and stable sections could be predicted if no sea-wall was built. These sections would move in an easterly direction, similarly to the situation in the other parts of the analyzed area. Accumulative nature of the nearshore (Koźbiał 2008) inhibits the erosion of the shore, which took place in the period of 1889-1975.

The location of the hard engineering protection structures at 244.8-246.4 km corresponds exactly to the location of a deep abrasive bay in 1989-2012. In 1975-1989, this bay was twice as long. Its western boundary shifted 2 km to the east, while the eastern boundary was also shifted to the east, but only at a distance of 0.6 km.

At 247.7-248.3 km, where the third sea-wall is being built, erosion was recorded in 1975-1989. In 1989-2012, however, this section was stable. The accumulation area is located west of the section. It is predicted that the area will migrate eastward. The section will turn into an accumulative section and thus the shore protection will be unnecessary. The concrete structure will interfere with the natural processes and can cause erosion on both sides where at present accumulation of the material predominates. It is possible that the construction of the sea-wall pier will be followed by the encroachment of the sea upon the land along the sections at 248.5-249.0 km and 246.4-247.4 km which are now accumulative.

At 249.7-250.7 km, where the fourth line of the shore embankments is being built, erosion dominated in the period from 1889 to 1989. The highest rate of erosion occurred in 1975-1989 when the position of the water line changed up to -4.0±0.7 m year^{-1}, and the dune base line – -2.0±0.7 m year^{-1}. In 1989-2012, however, the accumulation took place at 250.0-250.8 km. The water line shifted toward the sea at the maximum rate of 2.4±0.2 m year^{-1}, while the dune base line – by 1.6±0.2 m year^{-1}. Therefore, the decision about the location of the hard engineering protection structures at this place is difficult to understand, as they seem unnecessary.

Conclusion

The state of the western part of the Ustka Bay shore is varied. There are alternate accumulative and abrasive sections. The sections change their position while migrating eastward. The Third Pier in Ustka and the breakwater of the Ustka Port to the west force the accumulation of sediments along the stretch of about 3 km.

The shore section at 244.2-252.0 km was abrasive in 1889-1975, while in 1989-2012, it had accumulation or stable sections of a considerable length.

It must be assumed that the construction of shore embankments will disrupt the course of the natural processes. Therefore, migration of the accumulative and abrasive sections toward the east might be interrupted. Due to the operation of the hard engineering protection structures, the accumulative stretches occurring at present can be turned into erosive sections.

The research should be complemented by a precise diagnosis of the bottom of the whole study area: its relief, geological structure and the thickness of the dynamic layer. In a few or a dozen years, after the sea-walls are constructed, the study should be repeated to verify the predictions and compare the state of the shore before the protection and the state after the construction of concrete structures.

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