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HYDROMETEOROLOGICAL CAUSES OF SHORE EROSION ALONG THE POLISH COASTLINE

Abstract

Analysis of hydrometeorological data and of hypsometric measurements of the Hel Peninsula shore from the years 1989-1997 allowed determination of statistical relationships between averaged hydrometeorological parameters and morphological parameters of the shore.

The significant relationship found between mean wind speed and sea level allowed an evaluation of their influence on the Peninsula's shore. It is shown that long-term sealevel changes result in much stronger reaction of the shore than changes of wind speed.

Quantitative relationships between the changes of hydrometeorological factors and the progress of erosion of dune coasts are presented on the example of the Hel Peninsula.

Introduction

During the last 100 years significant intensification of marine erosion of the Southern Baltic coast is observed. It is thought that the probable reason is the increasing activity of hydrometeorological factors, especially strongly marked during the last 30 years. The increasing storminess, and also the predicted sea level rise (between 0.3 and 1.0 metres in 100 years) occurring on the background of a growing defficit of coastal sediments, are the main reasons for the presented attempt at defining the relationships between the hydro- and morphological systems in the aspect of possible development of coastal erosion.

The erosional influence of hydrometeorological factors on the shore (beach and dune/cliff face) was determined for the basal part of the Hel Peninsula. Erosion of this part of the Peninsula is of basic importance to the continuity of this specific morphological form as a whole.

In result of exceptionally disadvantageous hydrometeorological conditions (numerous storms, high mean sea level) during the 1988/89 autumn and winter season, breaking of the Peninsula became a realistic possibility, resulting in high danger to human life and infrastructure, and a risk of significant environmental and biocenotic changes in the unique nature of the Puck Bay. For these reasons self-governmental and state administration, especially the maritime administration, which is strongly involved in coastal management and is responsible for coastal protection, pay special attention to problems of erosion and protection of the Peninsula's coast.

Since 1989, the very strongly eroded base part of the Peninsula is artificially nourished (>800 m^3/m/year). In the period 1989-1997, the effectiveness of the replenishment works was systematically evaluated by the Department of Maritime Hydrotechnics of the Maritime Institute in Gdańsk.

One of the elements of these evaluations was the presented analysis of the variability of the parameters of the nourished beach and dune and of the neighbouring natural stretches, including an attempt at connecting the mean changes of the shore with the hydrometeorological conditions in the period 1989-1997.

Data and method of investigations

The analysis used data from morphometric measurements on reference profiles located along the base part of the Hel Peninsula (km H0.5-9.5). In total, measurements were carried out on 171 profiles presented in scale 1:100 (vertical) and 1:500 (horizontal). The scope of the morphometric measurements is shown in Fig. 1.

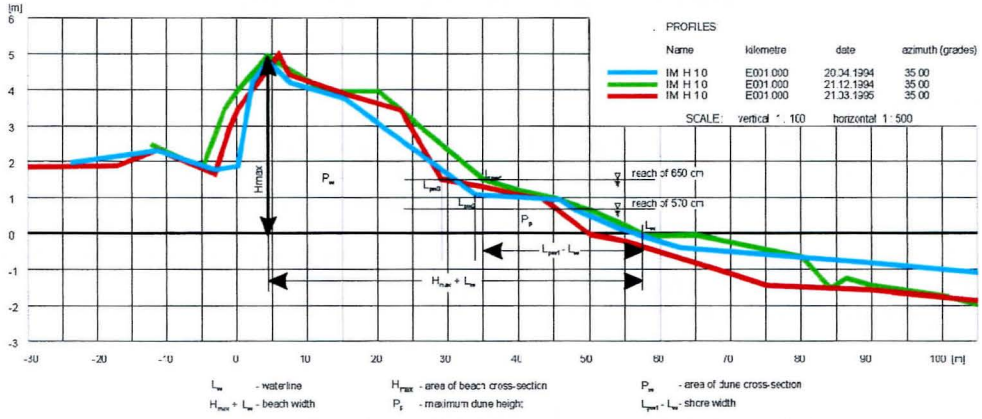

Fig. 1. Diagram of morphometric measurements of the Hel Peninsula shore

The analysis included the seaward part of the dune, i.e. from dune foot to maximum dune height at the crest. This was because the available measurements did not cover the whole width of the dune, reaching to various distances in the dune hinterland.

For the two analysed stretches of the Hel Peninsula coast (km H0.5-4.5 – nourished, and km H5.0-9.5 – not nourished) mean values of all the parameters were calculated for each year in the period 1989-1997 and for the whole period 1989-1997. The means of the morphometric data (measured and calculated) were used to determine the trends and the relationships with changes of hydrometeorological factors.

Also, using statistical methods, the relationships between systems of morphometric parameters were determined using coefficients of regression and correlation. The significance of mean annual changes was determined using the Student's "t" criterion.

Verified and pre-processed sets of hydrometeorological data (sea level, wind direction and speed) allowed a free selection of periods to be analysed. The method and methodology of hipsometric and bathymetric measurements, adopted for the needs of checking the effectiveness of beach nourishment, defined the time boundaries of the evaluation of hydrometeorological and shore changes. Eight (inter-storm surge) periods were distinguished for the assessment of the variability of hydrometeorological parameters.

Since low- and medium-energy wave and current conditions, resulting from long-term meteorological states, are of deciding importance to the shaping of the shore profile, the assessment of variability of the sea level and wind field was carried out on the basis of their average values. The semi-annual mean values of sea level and wind speed, and the determined for these periods shore parameters allowed to define the statistical relationships between them. They also allowed to assess the influence of these factors on the nourished and natural shore of the Hel Peninsula.

State of the nourished and non-nourished shore in the period 1989-1997

In the period 1989-1997, the strongly eroded stretch km H0.5-4.5 of the Hel Peninsula coast was nourished with 3.7 mln m^3 of sand. In result the beach and foredune were rebuilt to parameters ensuring safety of the coast, hinterland and infrastructure. The mean morphometric parameters of the nourished stretch decidedly improved. Nevertheless, in a significant part they still were worse than the parameters of the adjacent stretch of natural coast (km H5.0-9.5).

Changes during 1989-1997 of beach parameters along both stretches (Fig. 2) illustrate the variable activity of hydrometeorological factors and of the connected with them intensity of sediment transport in the coastal zone. In 1989 the width of beaches along both stretches was quite similar (35.1 and 37.3 m). Beaches of both stretches became narrower by March 1990 – markedly on the nourished, strongly eroded stretch, and only slightly on the natural (accumulative) stretch.

In 1991 beach width on both stretches became nearly the same (40.2 and 36.3 m). In the period 1991-1996 the beach width on the nourished stretch slightly narrowed and was always smaller than on the natural stretch, reflecting the longshore displacement of the nourished material at prevailing wind from the west. When wind from this direction became weaker and speed and frequency of wind from the east slightly increased, the beach of the nourished region became wider and the natural beach narrowed.

In 1997, due to increased circulation from the east, the width of the nourished stretch significantly widened and simultaneously the beach on the natural stretch narrowed. It also should be observed that the nourished volume was quickly formed to a shape very similar to the natural shape because the nourished material was finer than the maternal sediments. In effect, the beach of the nourished stretch more strongly reflects direct action of hydrometeorological factors.

Changes of beach height on the nourished stretch were directly connected with changes of sea level. High sea levels in the semi-annual periods resulted in significant narrowing of the nourished beach and in a decrease of its height. The height of the nourished beach changed in the period 1989-1997 between 1.4 and 2.3 m, and on the natural stretch – between 2.1 and 2.5 m.

The slope of the natural beach was slightly smaller than of the nourished beach, and this was accompanied by a smaller reach of water at sea level rise up to the 570 cm level (from 19% to 38% of beach width).

The larger variability of the nourished beach slope was the result of the unfinished process of forming it to the balanced sustainable natural shape, which proceeded in periods of constant supply of material from the artificial dune.

On the nourished stretch the reach of water at sea level rise to the 570 cm level was 28% to 45% of beach width. This confirms that it is less resistant to hydrodynamic factors than the natural beach. The reach of water at sea level rise to the 650 cm level was about the same for both stretches, and did not exceed the mean width of the beaches.

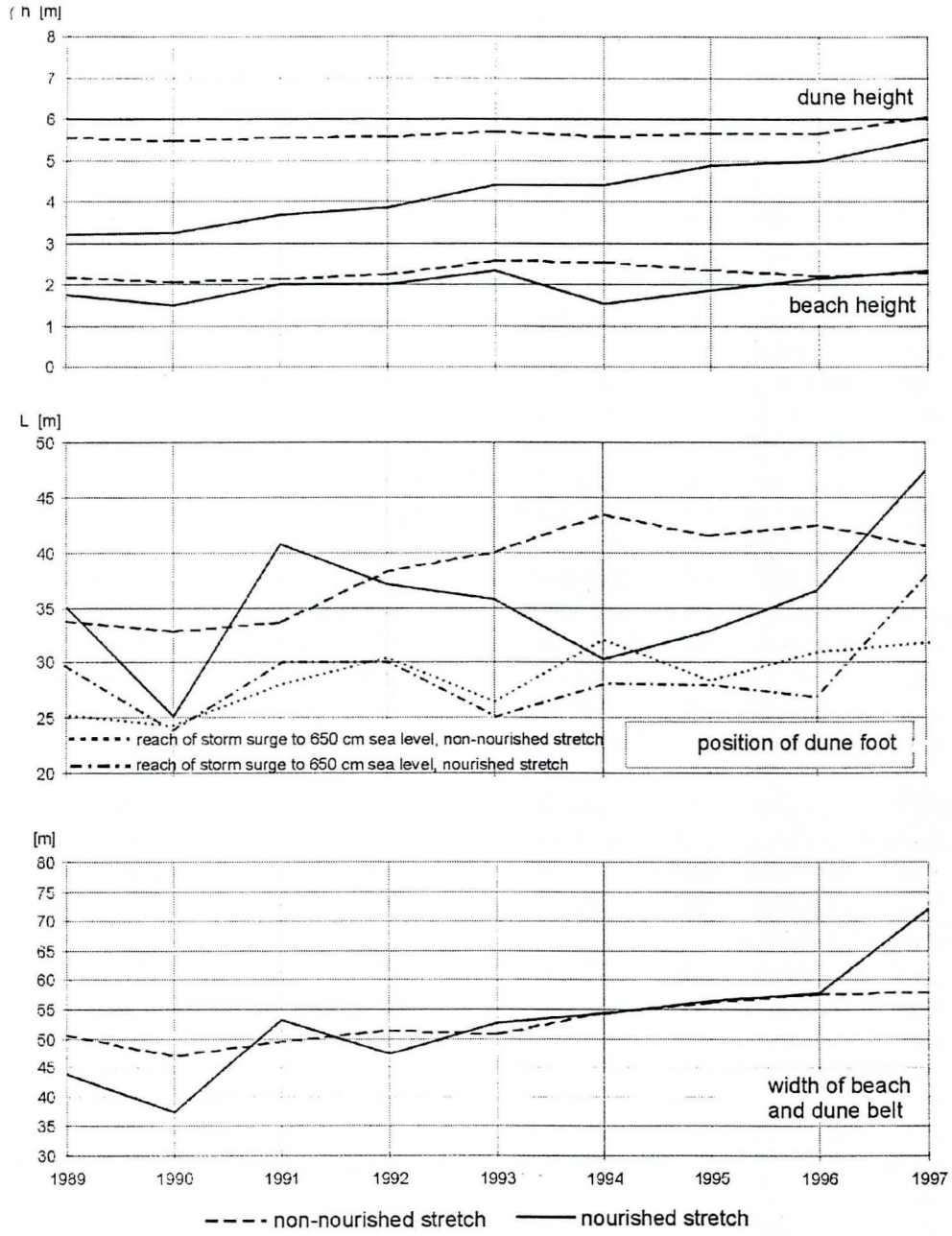

Fig. 2. Morphometry of Hel Peninsula shore on nourished stretch (km H0.5-4.5) and non-nourished strretch (km H5.0-9.5)

The area of the beach cross-section (from the waterline to dune foot) and the filling (amount of material in m^3 per metre of beach width) are closely connected (Figs. 3 and 4). On the nourished stretch these parameters slightly varied in the period 1989-1994 and increased in 1994-1997. On the natural stretch they decreased in 1989-1991, increased in 1991-1995 and decreased again in 1995-1997.

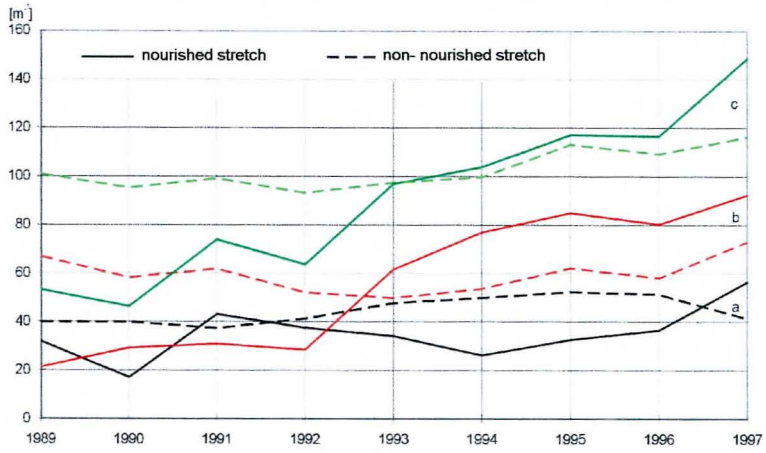

Fig.3. Changes of cross-section area: a – beach (to dune foot), b – dune, c – shore (beach and dune). Hel Peninsula, 1989-1997

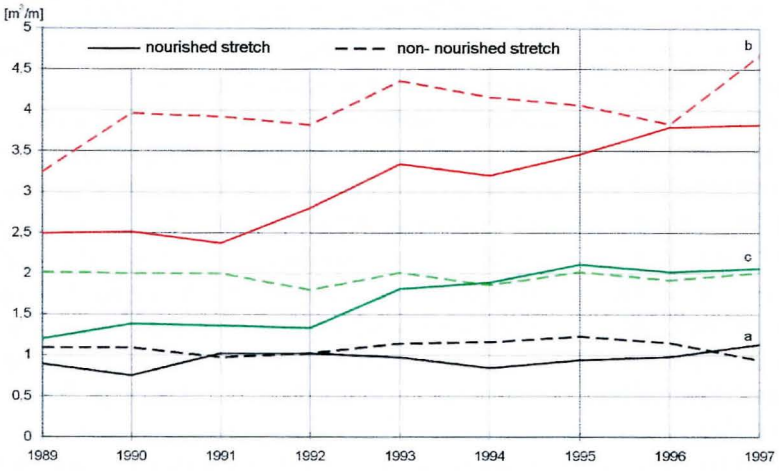

Fig. 4. Changes of filling: a – beach (to dune foot), b – dune, c – shore (beach and dune). Hel Peninsula, 1989-1997

These data confirm that variations of sea level and of wave and current action play a significant role in the loss of sediments from the nourished stretch and in accumulation of a part of them on the natural stretch. When circulation changed from eastward to westward (1996-1997), supply of sediments from the nourished stretch decreased and the beach on the adjacent natural stretch became weaker, as is indicated by the reduction of cross-section area and filling of the beach.

The largest changes took place within the dune on the nourished stretch. In effect of many years of (massive and maintenance) nourishment the dune was rebuilt, its parameters increased significantly (Fig. 2), reaching the design values consistent with the so-called "Hel Standard".

The width of the seaward slope of the dune on the nourished stretch increased from 8.7 m to 25 m, while the width of the same part of the dune on the natural stretch oscillated around 14.5 m (11 to 16 m). However, all the other indicators were better for the natural dune (km H5.0-9.5) than for the artificial one. Parameters of the natural stretch were on the average larger by about 25%, which is a reflection of the weaker erosional trend of this stretch and of the higher resistance of the natural dune to hydrodynamic factors.

The nourishment of the stretch km H0.5-4.5 has visibly strengthened the beach and dune belt of the adjacent natural stretch.

In the period 1989-1997, the width and area of cross-section of the shore along the nourished stretch were about 10% larger than on the natural stretch. However, the lower filling of this belt indicates that there is a permanent sediment deficit in the coastal zone (shore and nearshore) of the nourished stretch. This is a natural characteristic of this part of the Peninsula.

Changes in the cross-section area and filling of the shore depend mainly on lithodynamic processes in the beach belt. Changes in the parameters of dunes, if they are caused by wind only, result in slow transformation of that part of the shore. When the beach becomes destroyed and waves can act directly on the dune foot, dune erosion accelerates significantly, and this is reflected in changes of the morphometric parameters.

The shore height coefficient – the ratio of dune height to beach height – is a good illustration of the dynamics of coastal erosion/accretion processes. When the coefficient is stable there are no significant changes of the shore, or simultaneously proceed processes of dune and beach erosion and accretion. Growth of its value in effect of dune erosion precedes the erosion of the dune. When the height coefficient decreases, strong erosion of the dune is observed often even in spite of a significant widening of the beach. On the nourished stretch the height coefficient markedly increased from 1.86 to 2.66 in result of rebuilding of the dune after the artificial beach attained its limit height. This coefficient facilitates the determination of the resistance of the shore to hydrodynamic action. Its high value indicates low resistance of the beach at high resistance of the dune and the shore as a whole. When the value of the coefficient is low, a wide and flat beach with small area of cross-section and small filling passes into a narrow dune, and the whole shore is not resistant to hydrodynamic factors.

The observed annual differences in the morphometric parameters of the shore allowed to determine the relationships between selected hydrodynamic and morpholithodynamic elements of the region.

Evaluation of the relationships between morphometric parameters of the shore in the period 1989-1997

For the subsets of morphometric data for the nourished shore (km H0.5-4.5) and natural shore (km H5.0-9.5), statistical relationships between the averaged values were calculated.

Table 1. Coefficients of (significant) correlation between selected averaged morphometric parameters of the shore

Morpho-logical element	Analysed system	Nourished stretch (km H0.5-4.5)				Non-nourished stretch (km H5.0-9.5)			
		coeff. of regr.		coeff. of correl.		coeff. of regr.		coeff. of correl.	
		a	b	r_{xy}	p		b	r_{xy}	p
Beach	width – height	0.686	0.034	0.767	0.01	0.884	0.035	0.731	0.02
	width – slope	0.079	-0.0005	-0.559	0.1	-8.651	0.525	0.604	0.05
	width – reach of 570 cm storm surge	7.104	0.178	0.635	0.05	3.354	0.0626	0.689	0.02
	width – reach of 650 cm storm surge	7.780	0.600	0.918	0.001	-9.193	1.345	0.778	0.01
	height – cross-section area	0.113	9.207	0.510	-	-0.134	0.254	0.696	0.02
	height – filling	0.378	0.301	0.871	0.001	0.359	0.319	0.526	0.1
	reach of 570 cm storm surge – reach of 650cm storm surge	2.951	2.023	0.607	0.05	0.188	0.772	0.739	0.01
	cross-section area – filling	0.634	0.009	0.844	0.01	0.473	0.014	0.829	0.01
Dune	width – height	2.096	0.117	0.892	0.001	5.384	0.018	0.214	-
	width – slope	0.219	-0.004	-0.688	0.02	0.433	-0.012	-0.764	0.02
	height – cross-section area	-0.215	4.355	0.987	0.001	0.190	2.830	0.819	0.01
	height - filling	1.725	0.077	0.864	0.001	5.028	-0.072	-0.387	-
	height – cross-section area	-0.796	0.326	0.946	0.001	-0.694	0.228	0.559	0.1
	height – filling	0.330	0.661	0.974	0.001	-4.546	1.514	0.692	0.02
Shore	height – cross-section area	-0.684	3.050	0.937	0.001	0.139	1.713	0.749	0.01
	height – filling	0.335	0.025	0.747	0.1	2.219	-0.005	-0.220	-
	cross-section area – filling	0.775	0.010	0.925	0.001	1.566	0.004	0.386	-

The calculations were performed for 34 morphometric systems (or their derivatives), some of which are shown in Table 1. It was found that along the annually nourished shore proper dimensions of its forms (nearly similar to accumulative dune shores) were maintained in spite of strong erosion, and this corresponded to correlation of over 80% of the parameters. It is worth pointing out that on the nourished stretch there were 14 statistically significant relationships at $p = 0.001$ level.

During the same period, the natural shore was subjected, in spite of low alimentation, to slow erosion, which is reflected by the slight reduction of the forms and correlation of about 40% of the systems. On the natural stretch, there were no relationships at significance level $p = 0.001$. The results of the correlation analysis of dimensions of morphological forms of the Hel Peninsula shore may be used to assess the development of erosion along the whole Southern Baltic coast and to work out a general method of evaluating the resistance of the coastal zone to hydrodynamic action.

The Student "t" tests of the significance of differences in parameters carried out for both stretches between consecutive years from 1989 to 1997 and of differences between parameters of the nourished and natural stretch for the whole period 1989-1997, confirmed that environmental factors strongly influence the changes of morphometric parameters. The influence was especially distinct on the nourished stretch, on which shore parameters were significantly different from the parameters of the natural shore (53% of significant differences). In the period 1989-1997 the average parameters of the beaches differed significantly

in 31 cases (57%), of the dune in 43 cases (80%). This illustrates the influence of artificial nourishment, which to a large extent rebuilt the beach of the eroded stretch, and the parameters of the beach became much more like the parameters of the natural beach. In the period 1989-1992 the parameters of the shore of the nourished stretch approached the levels of the natural stretch.

In the period 1993-1997 morphometric parameters stabilised on both stretches because the volumes of nourishment were reduced to maintenance level and because the influence of hydrodynamic factors became smaller.

The variability of hydrometeorological parameters

Determined from linear and volumetric morphometric data changes of the Hel Peninsula shore illustrate both the macro-scale progress and influence of artificial nourishment and its influence on the shore, and the influence of various hydrodynamic conditions.

The available hydrometeorological data for the period 1989-1997, obtained from measurement stations located along the Peninsula, together with the set of levelling data from this period, allowed to determine the time intervals needed to assess the influence of hydrometeorological factors on the variability of shore parameters.

In the face of the general sediment deficit observed along the Southern Baltic coast (in that along the Hel Peninsula), both the extreme (short-term) and the average conditions (long-term), faciltate continuous erosion of the beach and dune belt on stretches where morphological forms of the bottom and/or geological structure allow generation of a higher energy wave regime. The many years of investigations show that these medium-energy wave and current conditions, resulting from long-term meteorological states are the basic factor, which shapes the litho- and morphodynamic processes in the shore and foreshore zone.

In the search for relationships between the changes of parameters of the shore forms and the changes of sea level and wind direction and speed, their mean values were used. Eight semi-annual sets were distinguished, defined by the dates of levelling measurements, for which statistical distributions, mean values and trends of change of hydrometeorological conditions were presented.

The analysed distributions of sea level at station Hel indicate that the sea level is rising at increasing rates. For five periods the trend was positive for three it was negative (Fig. 5).

The mean sea level at Hel was 507.8 cm in the period 1989-1997 and showed further increase in reference to the multiannual period 1951-1980, on average +5.5 cm.

During the analysed time 1989-1997 the shore was subjected to a series of exceptionally disadvantageous hydrometeorological conditions. The period between winter of 1989/1990 and winter of 1992/1993 was characterised by a particular intensity of storms, occuring at very high mean sea level, culminating in January 1993 (wind speed over 20 m/s, sea level 622 cm).

Also the mean sea level for 1995 was much higher than the multi-annual mean (510 cm). This was due to the high frequency of wind from NW and NE and to significant storms in January and April.

During that period there were 23 storm surges with $H > 569$ cm (Table 2).

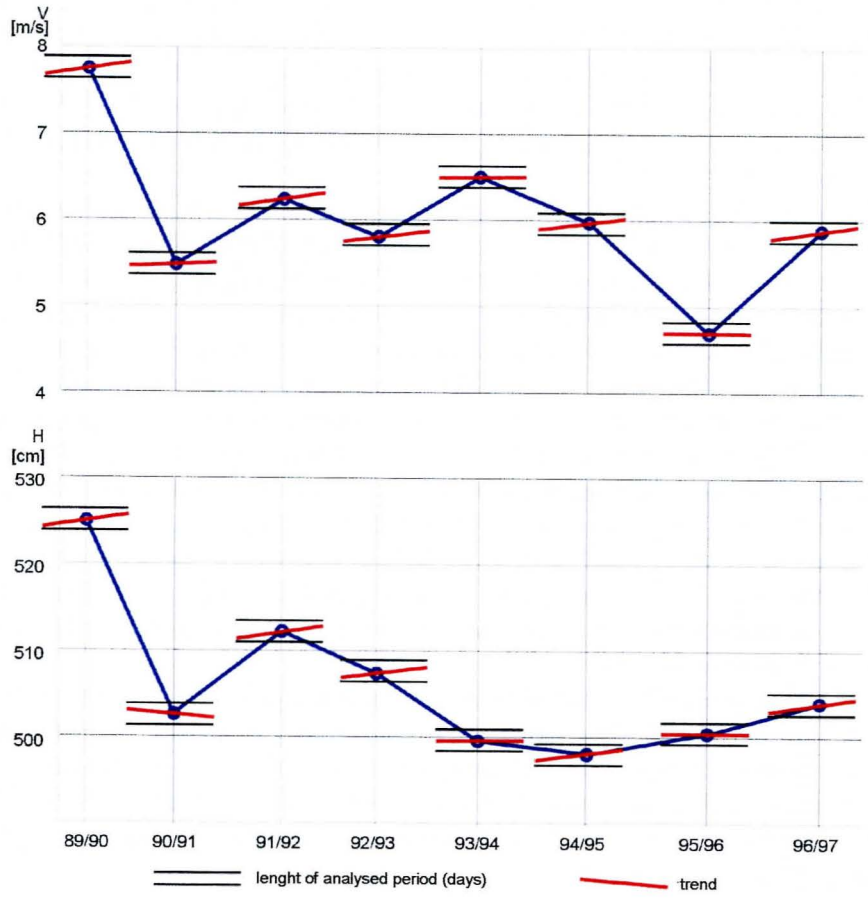

Fig. 5. Lines of wind speed and sea level trend at station Hel for the distinguished periods of measurement

Table 2. Characteristic of storm surges in the period 1988-1997 in the Hel Peninsula region (station Hel)

Year	Number of surges H>569 cm	Duration of surges (hours)	Mean max. sea level (cm)	Range of exceedance Δh (cm)	Mean duration of storm wind (hours)	Date of first storm surge	Date of last storm surge
1988	5	52	584.8	2.5≤Δh≤22.1	34	11.29	12.31
1989	1	11	591.0	Δ h = 10.4	36	12.07	12.07
1990	5	63	579.2	4.0≤Δh≤10.1	35	02.04	03.13
1991	1	8	578.0	Δ h = 3.4	33	12.30	12.31
1992	4	48	586.8	1.4≤Δh≤27.5	36	01.05	01.17
1992	2	8	577.0	4.0≤Δh≤ 5.0	27	09.06	11.26
1993	6	124	595.2	7.6≤Δh≤14.9	43.5	01.14	02.22
1994	-	0	<550	-	-	-	-
1995	2	42	590.5	13.0≤Δh≤13.2	45	01.02	04.09
1995	1	5	576	Δh = 3.8	27	11.04	11.04
1996	-	0	<550	-	-	-	-
1997 (do X)	1	8	590.0	Δh = 8.5	24	04.12	04.12

In the years 1992 and 1993 there were 6 high sea levels. In 1994 and 1996 no such sea levels occurred. The state of the coast and processes of erosion were also influenced by the extreme sea levels at the end of the 80ties (5 storm surges), which forced the starting in 1989 of a massive programme of protection of the Hel Peninsula coast.

The duration of storm surges during the years varied from 0 hours (1994 and 1996) to 124 hours (1993).

During the time of mean maximum sea level (H = 595.2 cm) in 1993, waves reached 15 m into the beach. At sea levels H = 620 cm, along the base and central parts of the Peninsula waves reached to the dune foot and washed away nourished material.

The differences between mean annual sea levels were reflected in the scale of variability of the parameters of the shore. This concerns also the influence of the variability of wind speed and direction, especially the shoreward wind, which generates the most destructive waves.

During the selected semi-annual periods the frequency of these winds varied from 9.2% (October 1989 to March 1990) to 20.0% (March 1995 to August 1996). However, not always high frequency corresponded to high wind speed on these directions, and in effect waves with largest parameters were not generated. For mean elements of the wind field, the highest mean speeds occurred from N and NE and reached 8.0 m/s in the period October 1989 – March 1990 and 6.3 m/s in the period August 1996 – June 1997. Also in these periods were observed significant differences in the analysed morphometric elements, especially in the zone of wave run-up.

The analysed mean wind speed fields in the selected periods clearly indicate that wind speed is growing (Fig. 5). The linear trend is negative only in one case, in the rest the slope of the regression line is growing, indicating a positive trend in mean wind speed.

The observed differences in mean semi-annual sea level and in mean wind speed (Table 3), and the determined changes of the shore, made possible an attempt at determining the relationships between these variables.

Table 3. Changes of mean sea level and mean wind speed for the selected periods

Period of measurements	06.10.89 - 29.03.90	30.03.90 - 29.05.91	30.05.91 - 11.04.92	12.04.92 - 12.03.93	13.03.93 - 20.04.94	21.04.94 - 22.03.95	23.03.95 - 14.08.96	15.08.96 - 19.06.97
$\overline{H}$ (cm)	529.12	502.90	512.57	507.54	498.69	508.82	499.52	503.57
$\pm \Delta H$ (cm)	- 22.22	+ 9.67	- 5.03	- 8.85	+ 10.13	- 9.3	+ 4.05	
$\overline{V}$ (m/s)	7.86	5.41	5.90	5.92	6.38	5.64	4.91	5.72
$\pm \Delta V$ (m/s)	- 2.45	+ 0.49	+ 0.02	+ 0.46	- 0.74	- 0.73	+ 0.81	

Relationships between the hydrometeorological parameters and morphometric changes of the shore

The changes of mean sea level and corresponding mean wind speeds in the so-called semi-annual periods were used for calculating the coefficients of correlation with the changes of mean parameters of the beach, dune and shore of the nourished and natural stretch of Hel Peninsula coast.

It should be pointed out that high statistical values of coefficients of correlation between mean annual values of sea level and wind speed ($r_{xy} = 0.778$ at $p = 0.05$) and their changes ($r_{xy} = 0.645$ at $p = 0.05$) were obtained.

Variations of both the sea level and the wind speed during the analysed periods distinctly shaped the beaches along both stretches (Table 4). This concerned mainly the width, slope and reach of the 650 cm storm surges. Other relationships were only sporadic. Changes of the dune under influence of sea level were less significant than of the beach and concerned the slope and filling parameters. Analysis of the whole shore allows relating the sea level changes only with the width of the shore.

Table 4. Coefficients of correlation between the differences of mean annual parameters of the Hel Peninsula shore (km H0.5-9.5) and the differences of mean sea levels (A), differences of mean wind speed (B) for the period 1989-1997

Investigated parameter	Type of stretch	A		B	
		coefficient		coefficient	
		correlation r_{xy}	significance p	correlation r_{xy}	significance p
BEACH					
Width	nourished (km H0.5-4.5)	0.6017	0.1	0.6528	0.05
	natural (km H5.0-9.5)	0.6970	0.05	0.6625	0.05
Height	z	-0.0016	-	0.6085	0.1
	n	-0.0711	-	0.2695	-
Slope	z	-0.9522	0.001	-0.4286	-
	n	-0.5848	0.1	-0.2417	-
Reach of 570 cm surges	z	0.3214	-	0.6435	0.05
	n	0.1986	-	0.2971	-
Reach of 650 cm surges	z	0.8525	0.01	0.5029	0.1
	n	0.7147	0.05	0.2727	-
Area of cross-section	z	0.5669	0.1	0.5955	0.1
	n	-0.3222	-	0.0529	-
Filling	z	0.4332	-	0.5575	0.1
	n	-0.5167	0.1	-0.2031	-
DUNE					
Width	z	-0.1521	-	-0.3765	-
	n	0.3241	-	0.1309	-
Maximum height	z	-0.1847	-	0.4727	-
	n	0.5793	0.1	0.5825	0.1
Slope	z	0.0590	-	-0.0446	-
	n	-0.5259	0.1	0.1432	-
Area of cross-section	z	-0.2175	-	-0.0746	-
	n	0.4445	-	0.1501	-
Filling	z	-0.3738	-	0.3893	-
	n	-0.7733	0.01	-0.5149	ok. 0.1
SHORE					
Width	z	0.6744	0.05	0.6297	0.05
	n	0.8666	0.01	0.5447	0.1
Area of cross-section	z	0.2699	-	0.4387	-
	n	0.1295	-	0.1121	-
Filling	z	-0.5309	0.1	-0.2066	-
	n	-0.3782	-	0.0235	-
Height ratio	z	0.0205	-	-0.5394	0.1
	n	0.3974	-	0.2392	-
Width ratio	z	-0.1956	-	-0.4896	-
	n	-0.3933	-	-0.3747	-

In general, relationships between the changes of sea level and the changes of shore parameters were found for 14 systems (about 42% of the analysed systems), in that on the nourished stretch for 6 systems and for 8 systems on the natural stretch.

Calculations of correlation between changes of wind speed and changes of the parameters of the shore showed similar relationship for the influence of sea level. Of the 34 analysed systems, statistically significant correlation was found for 12. This concerns mainly relationships with the parameters of the beach (changes of width confirmed for the shore).

The obtained values of correlation allow strict connecting of annual changes of wind speed and sea level with the changes of beach and shore parameters. In cases of extreme action of hydrodynamic factors, occur also correlated relationships with changes of some parameters of the dune. These data are a basis for the methodology of shore measurements for the needs of quick assessment of damages caused by storms and variations (and rise) of sea level.

Summary

In the years 1989-1997 the beach and foredune along the stretch from km H0.5 to km H4.5 of the Hel Peninsula was nourished with about 3.6 mln m^3 of sand, and was constantly remodelled and eroded under the influence of hydrodynamic and wind factors. Also the natural stretch (km H5.0-9.5) was subjected to a slight accumulative rebuilding. For these stretches the relationships between the variability of hydrometeorological parameters and the morphometric changes of the shore were determined.

Morphometric changes of the Hel Peninsula shore obtained from levellings carried out in the years 1989-1997 were presented in the form of mean values of selected parameters. Along the nourished stretch the beach and dune were rebuilt, and the mean morphometric parameters improved, nevertheless in a large part they were worse than on the natural stretch.

Though the width and area of cross-section of the shore on the nourished stretch were about 10% larger than on the natural stretch, the filling was smaller due to higher outflow of sand from that region. It is supposed that the reason for this is in the oblique to the shore trough-like forms located at the base of the Hel Peninsula in larger depths. These forms cause that wave and current energy in that region is higher, increasing coastal erosion in that part of the Peninsula.

The analysed mean changes of morphometric parameters of the nourished and natural stretch in the so-called semi-annual periods allow to observe that there are basic differences in the magnitude of these parameters, which are the derivatives of the spatial variability of energy and material.

The obtained results of correlation analysis of the systems of morphometric parameters of the Hel Peninsula shore may form the basis for assessing the development of erosion of Southern Baltic dune coasts.

Analysis of mean values of sea level and wind speed allowed to state that there is a strong statistical relationship between them, and this allowed an independent evaluation of their influence on the parameters of dunes and beaches of the Peninsula.

Long-term changes of sea level were much more strongly correlated with the changes of the analysed parameters of the shore than the variations of wind speed. This is true both for the influence of sea level changes on the nourished and the natural shore. This result confirms the importance of sea level dynamics as the main (besides waves) agent of erosion of dune coasts of non-tidal seas. Because of that prediction of the trend and the range of variability of sea level is of basic importance for the determination of the rates of coastal erosion. This indicator is increasingly taken into account in the coastal protection programmes of the maritime administration developed for various time scales.

Literature

[1] Boniecka H., Dubrawski R., 1998, *Hydrometeorological conditions for the erosion of Southern Baltic shores*. WW IM No. 5540, Gdańsk (in Polish).

[2] Boniecka H., 1997, *The variability of hydrometeorological conditions in the Hel Peninsula region – period 1980-1996*. WW IM No. 5271, Gdańsk (in Polish).

[3] Boniecka H., 1999, *The reach of storm action on the Southern Baltic shores*. WW IM No. 5598, Gdańsk. (In Polish).

[4] Cieślak A. et al., 1989-1997, *Complex protection of the Hel Peninsula*. WW IM, Gdańsk (in Polish).

[5] Dubrawski R., 1997, *Evaluation of morphodynamic processes in the foreshore of Hel Peninsula in conditions of artificial nourishment, 1989-1996*. WW IM No. 5256, Gdańsk. (In Polish).