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Cliff top recession rate and cliff hazards for the sea coast of Wolin Island (Southern Baltic)

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Abstract The article presents results of studies on the rate of erosion of the Wolin Island cliff-coast (NW Poland) during the last three decades. Trends of geomorphological changes were defined based on multiannual observations (1984–2014). Changes were controlled by secular and extreme processes. Research has shown that the intensity of the processes shaping the Wolin Island cliff-coast were characterized by a clear seasonal variability. Analysis of hydro-meteorological conditions allowed the authors to derive the threshold values of the most important factors initiating cliffs hazard. The destruction of the cliff, differing in range, occurs in the above-threshold conditions. Multiannual research and direct observations of the functioning of the cliff-coast conducted herein provided the basis for proposing the safety shield and information system about the cliff hazard.

Keywords • *cliff coast* • *cliff top recession* • *cliff hazard* • *cliff protection*

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INTRODUCTION

Contemporary processes of cliff formation and development result from the denudation system, and are driven mainly by the climate, which continuously varies over time and is spatially differentiated. The primary factors in the functioning of the denudation system of Wolin Island's cliff-coast are weather conditions, which change according to seasonal, annual and multiyear cycles, geological settings, landform, land cover, and diverse forms of human activity (Trenhaile 1997; Bird 2000; Woodroffe 2003; Pruszak 2004; Valdmann *et al.* 2008; Davidson-Arnott 2010; Žaromskis *et al.* 2010; Bagdanavičiūtė *et al.* 2012).

Cliff-coasts play a crucial role in the contemporary morphosystem of Wolin Island. The Wolin cliffs, 15 km long, constitute a section of a nearly 50-kilometre cliff zone on the Polish seaside (Subotowicz 1982). Systematic fieldwork has been conducted since 1973 to identify and define the morphological variability and developmental tendencies of Wolin's cliff-coast (Kostrzewski, Zwoliński 1995). A verified, thematic database of cliff top recession has been compiled, based on a series of long-term observations at five research sections. It contains the annual rate of Wolin Island's cliff top recession in selected test sections in the years 1984–2014. The database served as a documentation resource for this study. Systematic monitoring of cliff top recession indicated the rate of coastal cliff destruction, which is caused mainly by sea abrasion, mass movements and water erosion. It should be mentioned here that the findings of ongoing studies of individual landform evolution, sets of forms and the types of landforms on the Wolin cliffs, aimed at creating a detailed geomorphological map of the cliff-coast, provide an important supplement to the presented documentation (Kostrzewski, Zwoliński 1986).

The main goal of this work is to use archival materials and current diagnostic studies to present tendencies in the morphodynamic changes on the cliff-coast of Wolin Island, to attempt to classify cliff hazards, and to propose a warning system for the unexpected occurrence of denudation phenomena on the cliff-coast. The presented materials can be used for hydrotechnical purposes on the Polish coastline, as well as in development planning.

STUDY AREA, MATERIAL AND METHODS

In the course of carrying out the proposed research task, comparative studies were conducted of the abrasion processes occurring on Wolin Island in sections with different morpho-lithodynamics. Basic studies took place on the Wolin Island cliff-coast, located in a belt zone between Grodno and Miedzyzdroje. This area was divided into five test sections (Fig. 1), differentiated by the morphology, lithology and exposition of the coast (Table 1).

Research studies on the Wolin Island cliff-coast conducted to date have concentrated mainly on issues concerning geology, geomorphology, hydrology, climate, soil science, biology, tourism and environmental protection (Kostrzewski 1985; Kostrzewski, Zwoliński 1995; Buchwał, Winowski 2009; Hojan 2009; Winowski 2009; Kolander *et al.* 2013; Tylkowski 2013; Hojan, Więcław 2014).

The Wolin terminal moraine, the most important landform in the northern part of the island, is undercut from the sea side with steep cliffs. Detailed studies of the geological structure of this unit were conducted *inter alia* by Krygowski (1959). In their work, the authors confirmed the glaciotectonic character of the Wolin moraine ridge. The Wolin cliffs have also been the subject of detailed lithostratigraphic studies (Borówka *et al.* 1982, 1999; Kostrzewski 1985). In terms of the geological structure of the Wolin cliffs, two series of till can be distinguished. Grey till linked with Warta glaciation occurs in the bottom part of the cliff (Kostrzewski 1985). Its maximum thickness reaches 40 m. The grey till is directly overlain by the Vistulian brown till of lesser thickness, up to a few meters, which can be found only in some sections of the cliff. On the presented moraine till beds there are deposits of fluvioglacial sand as thick as 40 m in many places. Over the top part of the fluvioglacial there are eolian cover sands with a thickness of 2 to 15 m (Borówka *et al.* 1982).

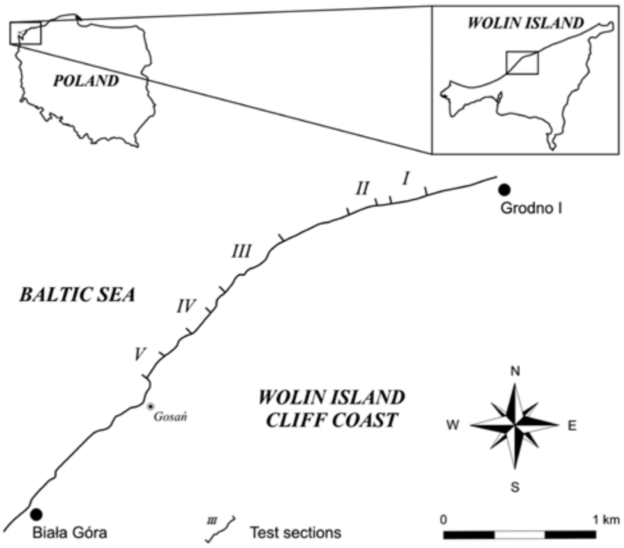

Fig. 1 Location of test sections (I-V) on Wolin Island cliffed coast

Systematic and standardized research on the morphodynamics of the Wolin cliff-coast has been carried out since 1973 on selected test sections of the coast (Fig. 2) east of Międzyzdroje (Kostrzewski, Zwoliński 1986, 1988, 1995). The study consisted of measuring the position of the top of the cliff at one year intervals. For this purpose a method of marked trees was used where the distance between the tree and the top of the cliff along a constant azimuth was measured.

Monitoring results provide a solid basis for a comparative study of the abrasion processes present in the South Baltic Sea cliff-coast. Analyses of the topoclimates and hydrological conditions of the Wolin cliffs have been conducted as part of a comprehensive study of the natural environment of the Wolin National Park. The daily variability of maximal sea levels [cm], the Kronstadt reference system [the water-gauge zero ordinate 508 cm] and daily total precipitation [mm] based on the data provided by the hydrographical and meteorological station in Świnoujście is presented for the sea coast of the Wolin Island. The hydro-meteorological data for the period of 1984–2014 was obtained from the Institute of Meteorology and Water Management in Warsaw.

Table 1 Morphological and lithological features of investigated test sections

Section	Section length [m]	Coast height [m]	Exposition	Lithology
I	250	15	350º	Grey clay / fluvioglacial sands / eolian cover sands
II	210	20	340º	Grey clay, brown clay in parts / fluvioglacial sands
III	400	35-60	323º	Grey and brown clay / fluvioglacial sands / eolian cover sands; the middle part of the section dominated by glaciofluvial deposits
IV	200	50	312º	Fluvioglacial sands / eolian cover sands; at the cliff base two little grey clay outcrops
V	280	30-40	315º	Grey clay / fluvioglacial sands / eolian cover sands; section margins dominated by sand formations.

Fig. 2 Sand-till test section V east of Góra Gosań (95 m above sea level)

Vegetation cover is an important element of the natural environment for retarding the long- and short-term effects of abrasion on the Wolin cliffs. Studies of the flora and of floral habitat on the Wolin cliffs, taking into account previous findings, have been presented by Piotrowska (2003).

RESULTS

Hydro-meteorological determinants of the degradation of cliff coast

The geomorphological transformations of the cliff-coast within the Wolin Island chiefly depend on the dynamics of sea abrasion and slope erosion related to, above all, mass movements and washing-off. The high sea level occurring during storm surges and heavy precipitation have led to the degradation of coastal cliffs manifested, among others, through retreating of its cliff top.

The cliff coast is particularly vulnerable to degradation as a result of sea level rise, especially at high storm-waves. Statistically significant raising trends of the sea level within the Polish coastal area of the Baltic Sea have currently been observed. The analysis of average sea level in Swinoujście for the 2nd half of the 20th century and 1st decade of the 21st century demonstrated a rate of increase of the sea level by 1 mm/year (Tylkowski 2015). The dynamics of transgression within the coastal area of the Pomeranian Bay corresponds with the global average sea level being estimated at 1 mm/year (Harff *et al.* 2007; Hünicke *et al.* 2008; Milne *et al.* 2009; Richter *et al.* 2012). The abrasion of the cliff coast within the Wolin Island occurs at high sea levels which significantly exceed their average level at 503 cm in Świnoujście in the period of 1984–2014. The analysis of the maximal sea level in the period of 1984–2014 did not indicate any statistically significant trends within its variability (Fig. 3). Within the considered period in Świnoujście the highest sea level at 661 cm was recorded on 4 November 1995. These high sea levels and high storm waves occurring at that time constituted a significant factor of abrasion of the cliff coastal within the Wolin Island which was found when the cliff top retreat was measured in summer 1996. The lowest sea level occurred on 27 January 2010 and amounted to 382 cm. The absolute amplitude of the sea level in the period of 1984–2014 amounted to 2.79 m.

The analysis of total precipitation in the period of 1984–2014—similarly to the maximal sea level—did not show any significant statistical directional change (Fig. 4). The average annual precipitation at the Pomeranian Bay was 558.1 mm. The highest level of total precipitation (756.3 mm) was recorded in 2010 and the lowest one (370.6 mm) in 1989. The range of variability of annual precipitation is quite considerable (385.7 mm). Significant irregularities of precipitation are also confirmed by an annual coefficient of precipitation variation reaching 2.0. The area under study is characterised by some sporadic occurrence of high-intensity precipitation. The highest daily total amount of precipitation was found on 28th July 2011 and amounted to 76.6 mm.

The occurrence of extreme hydro-meteorological incidents of high sea levels and daily total precipitation are shown in Table 2. The set extreme thresholds (probability 10%) for precipitation (>60 mm) and sea level (>594 cm) may be treated as hydro-meteorological destructive factors of the cliff coast within the Wolin Island (Tylkowski, Kolander 2014). In the period of 1984–2014 a considerable number of extreme

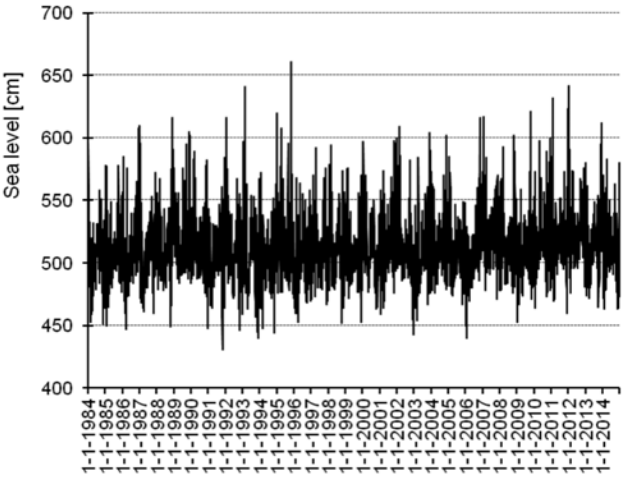

Fig. 3 Daily maximal sea level in Świnoujście within 1984–2014. Compiled by Tylkowski, 2015

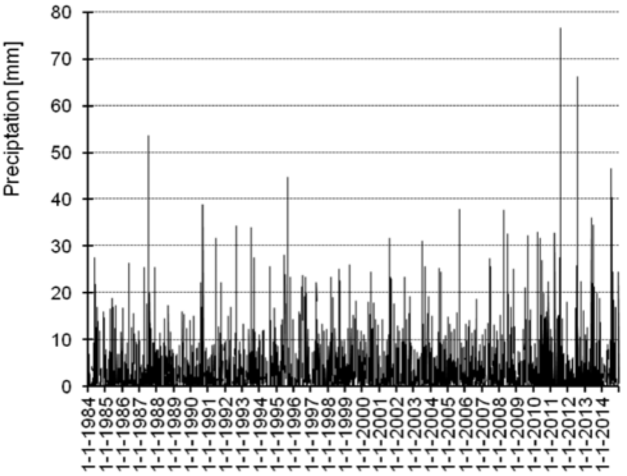

Fig. 4 Daily total precipitation in Świnoujście within 1984–2014. Compiled by Tylkowski, 2015

Table 2 Occurrence of extreme (10% probability) maximal sea level and daily precipitation at the Pomeranian Bay coast in Świnoujście (1984-2014). Compiled by Tylkowski 2015

Hydrometeorological factor	Parameter: Sea level [cm], Precipitation [mm] Date (yyyy-mm-dd)
Maximum daily sea level >594 cm	48 days: 608 (1986-12-19), 597 (1986-12-20), 610 (1987-01-09), 596 (1987-01-12), 609 (1988-11-29), 616 (1988-11-30), 595 (1989-10-03), 605 (1989-11-28), 602 (1989-12-07), 616 (1992-01-17), 597 (1993-01-25), 641 (1993-02-21), 620 (1995-01-03), 608 (1995-04-08), 596 (1995-08-31), 651 (1995-11-03), 661 (1995-11-04), 595 (2000-01-18), 597 (2000-01-21), 598 (2001-11-09), 596 (2001-11-23), 600 (2002-01-02), 609 (2002-02-21), 604 (2003-12-06), 602 (2004-11-23), 616 (2006-11-01), 604 (2006-11-02), 604 (2007-01-22), 597 (2007-01-24), 617 (2007-01-25), 601 (2007-01-27), 602 (2007-01-29), 597 (2007-02-01), 602 (2008-10-30), 613 (2009-10-14), 621 (2009-10-15), 598 (2010-04-30), 600 (2010-12-12), 632 (2011-02-11), 632 (2011-02-12), 623 (2011-12-17), 612 (2012-01-06), 620 (2012-01-13), 642 (2012-01-14), 602 (2012-01-15), 595 (2013-11-24), 605 (2013-12-06), 612 (2013-12-07)
Maximum daily precipitation >60 mm	2 days: 76.6 (2011-07-28), 66.2 (2012-07-29)

incidents of high sea levels were found as potentially destructive factors of the cliff coast within the Wolin Island (Table 2). When the extreme maximal sea level is exceeded, it could generate geomorphological transformations of the cliff coast within the Wolin Island. The specified abrasive sea level threshold >594 cm is close to the alert sea level in Świnoujście ≥580 cm (Wiśniewski, Wolski 2011) and the abrasive threshold (for sand dune abrasion) at the Pomeranian Bay near Dźwinów (Tylkowski 2015). In the period of 1984–2014 abrasive sea level value of >590 cm occurred by 59 days—then they are potentially initialized landslide processes on a cliff coast (Winowski 2014). In the period of 1998–2014 the extreme high sea level for 48 days and extreme high precipitation level for 2 days were found to occur.

The storm surges with extreme high sea level were generated mainly during the occurrence of cyclonic atmospheric circulation (73% cases), especially with the West-North sector (59% cases). During the period of Northwest, North, and West Cyclonic Circulations on sea level rise in the Southern Baltic, in addition to the wind factor, influence infusions marine waters of the North Sea through the Skagerrak and Kattegat. Particularly intense storm surges and abrasion of the Wolin Island cliff occurred during the North Cyclonic Circulation—the most extreme abrasion coast in the period 3–4 November 1995. On the other hand anticyclonic atmospheric circulation generated 23% cases of extreme sea level, but the intensity of the abrasion was then much less intense. For about 4% cases of extreme sea level does not specify the type of atmospheric circulation.

Precipitation with its daily total >30 mm in the period from 1984 to 2014 occurred 24 times. The above regularity can provide evidence on potentially much larger role of storm surges than precipitation in geomorphological transformations of the cliff coast within the Wolin Island.

Taking into considerations annual measurements on the cliff top retreat at the Wolin Island which were performed in summer months (July–August), hydrometeorological determinants were presented in the form of average and maximal sea levels as well as annual and maximal daily total precipitation in Table 3 for the research term of the cliff crown retreat.

Table 3 Hydro-meteorological conditions of the cliff top retreat within the Wolin island in the period of 1985-2014. Compiled by Tylkowski 2015

Research period of cliffs withdrawal	Period of hydrometeorological conditions	Sea level [cm]		Precipitation [mm]	
		Average	Maximum	Total	Maximum daily
1985	1.9.1984 - 31.8.1985	495	578	490.9	18.8
1986	1.9.1985 - 31.8.1986	497	585	534.9	26.5
1987	1.9.1986 - 31.8.1987	502	610	613.7	53.5
1988	1.9.1987 - 31.8.1988	502	572	613.7	53.5
1989	1.9.1988 - 31.8.1989	510	616	382.9	17.3
1990	1.9.1989 - 31.8.1990	509	605	444.5	22.2
1991	1.9.1990 - 31.8.1991	497	582	493.0	38.8
1992	1.9.1991 - 31.8.1992	501	616	489.2	34.4
1993	1.9.1992 - 31.8.1993	500	641	522.5	33.9
1994	1.9.1993 - 31.8.1994	492	572	568.5	34.9
1995	1.9.1994 - 31.8.1995	506	620	640.1	28.2
1996	1.9.1995 - 31.8.1996	493	661	532.6	44.7
1997	1.9.1996 - 31.8.1997	498	592	482.1	23.3
1998	1.9.1997 - 31.8.1998	506	594	555.4	25.0
1999	1.9.1998 - 31.8.1999	502	576	583.6	26.0
2000	1.9.1999 - 31.8.2000	506	597	589.0	24.5
2001	1.9.2000 - 31.8.2001	498	574	525.9	31.6
2002	1.9.2001 - 31.8.2002	512	609	629.0	23.4
2003	1.9.2002 - 31.8.2003	496	584	448.1	31.2
2004	1.9.2003 - 31.8.2004	505	604	590.0	25.6
2005	1.9.2004 - 31.8.2005	506	602	489.5	15.8
2006	1.9.2005 - 31.8.2006	495	549	471.3	37.9
2007	1.9.2006 - 31.8.2007	514	617	634.3	52.9
2008	1.9.2007 - 31.8.2008	507	593	602.4	37.7
2009	1.9.2008 - 31.8.2009	501	602	543.4	25.1
2010	1.9.2009 - 31.8.2010	504	621	729.7	33.1
2011	1.9.2010 - 31.8.2011	508	632	852.7	76.6
2012	1.9.2011 - 31.8.2012	513	642	565.8	66.2
2013	1.9.2012 - 31.8.2013	508	580	608.7	36.1
2014	1.9.2013 - 31.8.2014	505	612	562.3	46.7

Potentially the most favourable conditions for the degradation of the cliff coast within the Wolin Island occurred in the following measurement years: 1996, 2011, and 2012. 1996 was particularly high sea level at 661 cm, while 2011 and 2012—apart from high sea levels (632 cm in 2011, 642 cm in 2012)—was extreme daily precipitation (76.6 mm in 2011; 66.2 mm in 2012).

It should be emphasized that the dynamics of the cliff top retreat does not show any directly proportional dependencies with high sea levels and intense precipitation. It is not always that high storm surges and extreme high precipitation cause significant degradation of the cliff coast. Duration and frequency of inter-rain and inter-storm periods are significant determinants of the Wolin cliffs retreat. In inter-storm periods sediment accumulation takes place within the near-shore area, especially at the foreshore area. The foreshore area having a considerable amount of clustered sediments constitutes the main area of concentration of waving energy and simultaneously reduces abrasion of the coastal cliffs. In addition, it is essential to determine the current state of development of this cliff coastal section (Subotowicz 1982) and local determinants connected with the cliff lithology and exposure.

The cliff top recession rate on Wolin Island

The Wolin cliffs recessed at an average rate of 0.8–1.0 ma^{-1} (meters per year) through the mid-20th century (Subotowicz 1982; Kostrzewski 1984). Measurements of the contemporary cliff recession rate reveal average annual values for cliff top recession rate which fluctuate from 0 to 4.33m (Table 4), with a multiyear average for the entire monitored cliff of 0.24 ma^{-1}. The highest cliff top recession rate (0.35 ma^{-1}) was recorded for sandy section IV (Table 2). Sections II and III are marked by a more than 50% lower value for cliff top recession rate. Till beds appear at their base, and are more resistant to the abrasion processes than sandy deposits. It should be noted that most of the measured values for cliff recession fall within a range of up to 1m, although cases of nearly 10-meter annual cliff top recession rate also occur (Table 5). A particularly interesting situation emerged in November 1995, when an exceptionally strong storm surge (the highest in the 20th c.) brought about radical geomorphologic changes. Consequently, the values measured for the year 1996 were several times higher than those previously recorded (Table 4).

Table 5 presents maximum cliff top recession in single measurement points that occurred in subsequent years of monitoring. Recession values fall in the 0–9.8m range. The average annual values for maximum cliff top recession are 1.5–2 m. Out of 130 measurement points, single values for cliff top recession greater than 2 m were found in only 26 cases. No explicit tendencies towards maximum cliff top recession indicate any considerable randomness in the phenomenon. The abrasion pulse rate is determined by connections between morpho-lithologic and hydro-meteorologic conditions, which fluctuate temporally and spatially.

Table 4 Average annual cliff top recession rate [ma^{-1}]

Year	Sec. I	Sec. II	Sec. III	Sec. IV	Sec. V
1985	-0.24	-0.20	-0.74	-0.24	-0.42
1986	-0.55	-0.35	-0.16	-0.12	-0.13
1987	-0.06	-0.06	-0.11	-0.01	-0.01
1988	-0.01	0.00	-0.01	-0.01	-0.03
1989	-0.09	-0.14	-0.17	-0.04	-0.13
1990	-0.15	-0.14	-0.05	0.00	-0.08
1991	0.00	-0.04	0.00	-0.17	-0.08
1992	-0.02	-0.15	0.00	-0.03	-0.25
1993	-0.16	0.00	-0.02	-0.02	-0.29
1994	-0.03	-0.05	0.00	-0.12	-0.80
1995	-0.03	-0.18	-0.01	-0.22	-0.08
1996	-2.95	-0.66	-0.32	-4.33	-2.34
1997	-0.26	-0.30	-0.13	-0.07	-0.38
1998	-0.14	-0.46	-0.23	-0.26	-0.28
1999	-0.17	-0.38	-0.18	-0.22	-0.15
2000	-0.06	-0.04	-0.07	-0.03	-0.56
2001	-0.05	-0.07	-0.25	-0.43	-0.13
2002	-0.13	-0.10	-0.17	-0.42	-0.11
2003	-0.09	-0.04	-0.17	-0.84	-0.20
2004	-0.01	-0.30	-0.23	-0.34	-0.21
2005	-0.27	-0.10	-0.23	-0.83	-1.27
2006	-0.10	-0.04	0.00	-0.05	-0.07
2007	-0.01	-0.03	-0.02	0.00	-0.01
2008	-0.23	-0.03	-0.11	-0.01	-0.07
2009	-0.03	-0.03	-0.03	-0.04	-0.01
2010	-0.02	-0.06	-0.21	-0.66	-0.29
2011	0.00	-0.17	-0.04	-0.21	-0.13
2012	0.00	-0.69	-0.31	-0.16	-0.28
min	-2.95	-0.69	-0.74	-4.33	-2.34
average	-0.21	-0.17	-0.14	-0.35	-0.31
max	0.00	0.00	0.00	0.00	-0.01
SD	0.55	0.19	0.15	0.81	0.49

SD – standard deviation

Table 5 Maximum cliff top recession [m]

Year	Sec. I	Sec. II	Sec. III	Sec. IV	Sec. V
1985	-0,75	-0,67	-9,65	-1,15	-2,05
1986	-1,1	-1,18	-0,95	-0,4	-1,15
1987	-0,35	-0,3	-1,42	-0,1	-0,05
1988	-0,05	0	-0,1	-0,05	-0,5
1989	-0,38	-0,61	-1,56	-0,29	-0,74
1990	-0,52	-0,39	-0,48	-0,01	-0,56
1991	-0,04	-0,2	-0,1	-0,85	-0,4
1992	-0,1	-0,97	0	-0,3	-4,5
1993	-1,2	0	-0,3	-0,15	-4,1
1994	-0,3	-0,4	-0,1	-0,9	-4,9
1995	-0,15	-0,8	-0,2	-2	-0,5
1996	-5,9	-2,85	-3,45	-7,35	-8,35
1997	-1,6	-1,1	-2,1	-0,45	-4,5
1998	-0,75	-2,45	-1,35	-1	-2,2
1999	-0,6	-1,1	-0,7	-1,2	-1,3
2000	-0,3	-0,3	-1	-0,1	-5,9
2001	-0,3	-0,45	-2	-1,6	-1,1
2002	-1,05	-0,4	-1,2	-3,1	-1,29
2003	-0,6	-0,35	-2,25	-3,5	-2
2004	-0,05	-2,42	-3,28	-3,08	-3,4
2005	-0,97	-0,38	-2,95	-2,87	-9,8
2006	-0,47	-0,1	-0,1	-0,21	-0,5
2007	-0,05	-0,13	-0,18	0	-0,15
2008	-1,4	-0,21	-1,1	-0,05	-0,3
2009	-0,28	-0,25	-0,4	-0,32	-0,11
2010	-0,18	-0,4	-1,3	-3,5	-1,96
2011	0	-1,35	-0,8	-1,45	-1,3
2012	0	-2,6	-2,1	-0,9	-2,6
min	0	0	0	0	-0,05
average	-0,69	-0,8	-1,47	-1,32	-2,36
max	-5,9	-2,85	-9,65	-7,35	-9,8
SD	1,11	0,83	1,89	1,64	2,51

SD – standard deviation

A comparison between average annual rates of cliff top recession and maximum cliff top recession indicates a strong correlation, since the R^2 index of linear correlation fluctuates between 0.71 and 0.93. Therefore, both parameters referring to the process of cliff top recession reflect the observed morphodynamic tendencies.

Geomorphologic changes in the Wolin cliff-coasts

The current geomorphologic changes occurring on the Wolin Island cliff-coast result from the variability of the morphogenetic system of the cliff-coast over time and space. The character and course of these geomorphologic processes are diverse, and are conditioned not only by lithology and land cover, but most of all by seasonal variability in the weather, which determines the rhythm of their functioning throughout the annual cycle. Due to the complexity of the morphogenetic processes that shape cliff-coasts, it is extremely difficult to determine the tendencies of these geomorphologic changes, because although they are similar in different sections of the cliff-coast, the intensity of the changes varies.

However, the analyzed monitoring period (1984–2014) indicated distinct phases of increased activity in the sea cliffs. In 1984, the Wolin cliffs increased their activity considerably as a consequence of a violent storm. Afterwards, the morphogenetic processes stabilized until November 1995, when one of the strongest storms to strike the Polish coast in the 20th century occurred. At that time, the Wolin cliffs were active in all test sections. After this episode, a period of decreased cliff activity was noted. Significantly, diminished activity in the coastal cliffs was observed also in the first half of the 1990s and in the first decade of the 21st century. Variability in the intensity of cliff top recession over time reveals the relatively low intensity of the phenomenon. Only during exceptional and extreme events, especially during intensive storm surges (669 cm in November 1995, 607 cm in 2004; Wiśniewski, Wolski 2011) was a substantial cliff top recession noted in subsequent measuring (in 1996 and 2005).

A general analysis of the linear trend in cliff top recession in the 30-year period studied revealed a weak statistical dependence (Fig. 5). Despite the increased frequency in recent years of uncommon hydro-meteorologic events (storm surges, intensive rainfalls) in the studied test-sections, no intensive cliff abrasion has been observed. A distinctive feature of all sections is the cyclical activity of cliff top recession could be connected with occasionally occurring extreme phenomena. Twenty-year cycles of cliff recession activity were observed with 10–year intervals ±2–3 years between the maximum and minimum of the cycle. During more than 30 years of observations, such situations were found to continue in a period of several years following the highest storm surges, i.e. 1996 (storm surge of 4th November 1995, H=661 cm) and 2005 (storm surges of 23th November 2004, H=602 cm; 24th January 2005, H=585 cm; 15th February 2005, H=572 cm), when a relatively major cliff top recession was documented.

The concept of phasic cliff development introduced by, among others, Subotowicz (1982), Furmańczyk (1994), explains the presented situation. According to this concept, cliff shores undergo various stages of activity during a recession (abrasive stage – active cliff, stabilization stage – inactive cliff). On the basis of monitoring conducted, it should be recognized that in the period examined, the test sections of Wolin Island's cliff-coast were in a stabilization stage twice, in 1989 and 2008, and once in an abrasive stage, around 1998 (Fig. 5).

DISCUSSION

Cliff hazard classification

The destructive impact of sea activity and precipitation has been observed along the entire cliff-coast on Wolin Island (Kostrzewski, Zwoliński 1986, 1988, 1994, 1995). The cliff coast develops mainly as a result of sea abrasion and as a post-effect of intensive subareal processes, predominantly of mass movements and wash downs (Trenhaile 1987; Sunamura 1992; Hampton *et al.* 2004; Epifânio *et al.* 2013). Storm surges undercut and destabilize cliff faces, leading to dynamic disturbance, which manifests itself in activating mass movements, especially in landslides, sandfalls or in rockfalls (Marques 2009; Marques *et al.* 2011). As a consequence of these morphogenetic processes, sand-till walls are exposed, which under favourable weather conditions may in turn come under the influence of precipitation, wind and frost. The temporal and spatial variability of these processes, geomorphologic events, and the meteorological and hydrological phenomena that condition them allows us to propose a classification for the main cliff hazards. A cliff hazard should be understood as a sudden and rapid geomorphologic event that leads to a partial or entire recession or the destruction of a cliff shore, with the potential to have a detrimental effect on human life and activities, as well as on fauna (Hall *et al.* 2002; Hampton *et al.* 2004). The most common cliff hazards include events connected with processes of abrasion, rockfalls and landslides, but also, during favourable weather conditions, with the processes of eolian transportation, washout and wind-fallen tree erosion (Trenhaile 1987; Sunamura 1992).

Each of the above-mentioned hazards is characterized by three elements (Table 6): hazard-promoting factors, their threshold values, and the morphologic effects on the cliff face. The factors promoting cliff

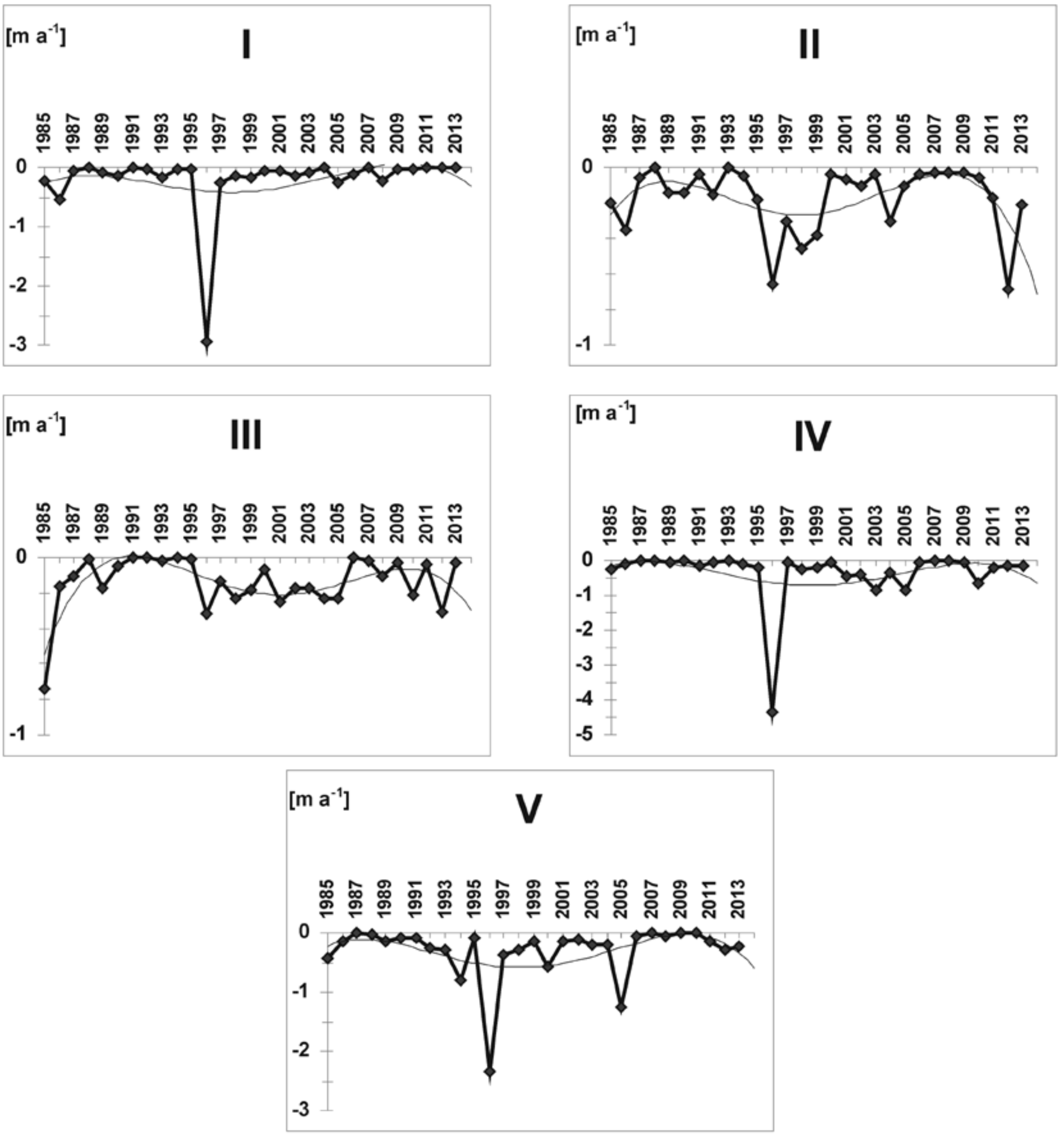

Fig. 5 Cliff top recession rates [ma^{-1}] on Wolin Island and cliff top recession tendency lines on sections I-V in 1984–2014

hazards include storm surges, precipitation, mechanical weathering, snow-melt and wind. On the basis of multiyear self-observations (1984–2014) showed that the beach erosion starts when the sea level exceed 560 cm. Statistically defined extreme sea level (594 cm) is responsible for significant transformation of the foot of the cliff and initiates the mass movements. This value is consistent with empirical research on coastal cliffs abrasion (Winowski 2014). It is worth to note that Karol Rotnicki (pers. comm., 2010[1]) predicts that the highest Holocene sea level since Little Ice Age will be reach in the next 100 years, and is likely to exceed it by a further half a meter up to 2200. In his opinion these fluctuations in sea level affecting inter alia erosion of cliffs (Zwoliński 2011).

Precipitation initiates hazards in the form of landslides, rockfalls and the downfalls of lithologically diversified drifts on cliff shores. The threshold value for landslide processes specified in Table 6 was empirically determined by Winowski (2014) on the basis of cliff slump observations made during the years 2006–2009 and is equal to 40 mm. Shown in Table 2 extreme value of daily rainfall (>60 mm) generates the regular occurrence of mass movements in the area of Wolin Island cliff coast whereas empirical studies of Winowski (2014) have shown that initiation if this process takes place when the daily total rainfall exceed 40 mm.

Irrespective of the assumed precipitation threshold value, an extremely important pre-condition for precipitation to be morphologically effective on the cliff face was the substratum deposits being dampened by a smaller precipitation total several days preceding

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[1] Prof. Karol Rotnicki, Adam Mickiewicz University. Discussion at the conference „Global climate change and their implications for landforms of Poland”. December 1, 2010, Warsaw.

Table 6 Characteristics of cliff hazards on Wolin Island

Cliff hazard	Hazard factors	Factor threshold values	Morphologic effects*
Abrasion	storm surges	sea levels: beach abrasion 560 cm* cliff abrasion 594 cm**	undercuts, kerfs, wave-cut grooves
Landslide	storm surges	abrasive sea level ≥ 590 cm***	landfall, cliff slumps
	precipitation	40 mm*** proceeded by precipitation period	
Rockfall	mechanical and biogenic weathering	fissures and cracks	rock falls, bluffs, heaps
	precipitation	precipitation threshold value inversely proportional to base weathering degree	
Washout	precipitation	long term rainfall causing the loamy ground moisture content to exceed 16%	mudslides and landslides
	snow melt	snow cover over 10 cm thick and air temperature rising from subzero to above-zero daily; average daily temperature ≥ 5°C****	
Eolian transportation	wind	wind velocity > 15 ms^{-1} or wind gusts > 20 ms^{-1}*****	cliff naspas
Windfallen tree erosion	wind	wind velocity > 20 ms^{-1} or wind gusts > 25 ms^{-1}*****	windfallen trees

* Kostrzewski, Zwoliński (1988); ** Tylkowski, Kolander (2014); *** Winowski (2014); **** Zawiślak (2011); ***** RCB (2010)

the landslide hazard. Typically this was a period of up to 14 days. In the case of hazards induced by rockfall processes, in addition to precipitation, other factors include clefts and interstices in the ground, which can appear as a result of mechanical weathering, e.g. frost-weathering or insolation, ground compacting and biogenic activity connected with the fracturing power of tree and shrub roots. Observations have proved that the greater the amount of interstices that increase the loamy drift weathering level, the more easily and extensively slumps of this material are formed. At the same time, substratum drifts are less laden with precipitation, which, in turn, serves as a direct impetus for a rockfall hazard. Another case is connected with precipitation, which increases the danger of a cliff hazard due to washout processes generated by long-term rainfall. Such processes for the loamy faces on Wolin Island are initiated when loamy ground moisture content rises to between 10 and 20%, typically 16%. It should also be noted that washout processes may have a seasonal character, occurring mainly in the springtime, when rapid snow-melt (less often ice-melt) over 10 cm thick occurs on loamy ground at an above-zero daily air temperature and average daily air temperature of $Ts \geq 1.5–5°C$ (Zawiślak 2011).

The two last hazard factors listed in Table 6, i.e. eolian transportation and windfallen tree erosion, share the same initiating factor, namely the wind and its velocity. Eolian transport of sandy fluvioglacial deposits on cliff faces begins at a speed of over 6 ms^{-1} (Hojan 2009). An effective hazard resulting from mass transportation of mineral particles arises at a wind speed of $V>15ms^{-1}$ or when wind gusts reach $V > 20ms^{-1}$. Yet for windfallen tree erosion, stronger winds are required, with a speed exceeding $20ms^{-1}$ or wind gusts of 25 ms^{-1}. The above-mentioned threshold values refer to the wind hazard classification specified by the Institute of Meteorology and Water Management for the Government Center for Security (RCB 2010), for hazard degrees 1 and, 2 respectively.

The cliff hazard classification proposed above is based on threshold values for the meteorological parameters and sea level that induce geomorphologic cliff transformations. The subject of cliff hazards is important from the point of view of both merit and application, and may serve as a basis for formulating a proposal for a warning system against such hazards.

Conducted multiyear observations and verification of adopted threshold values authorizes to use them in determining the risk of destructive processes. Obtained data can therefore provide the basic information in the coastal management.

Application for cliff protection and a cliff hazard warning system

Activities that control the effects of extreme processes along the Polish Baltic Sea shoreline, especially on cliff-coasts, should be based on a precisely defined and operated system of protection and information on possible hazards in the cliff-coast zone. Extensive monitoring of meteorological, hydrological and oceanological conditions, along with well-developed modelling of extreme processes along the cliff shore zone provide the basis for accurate forecasting of potential hazard occurrences in different spatial scales.

A cliff protection and cliff hazard warning system should contain the following elements:

- cliff hazard historical database,
- monitoring of cliff hazard factors: sea level, precipitation totals and intensity, wind speed and direction, air temperature course, snow-cover thickness and density, as well as observations of ground geotechnical transformations, e.g. moisture content, condensation and shearing resistance,
- simulation of probable extreme geomorphologic processes with the use of laboratory tests and field experiments under various geomorphological, hydrogeological, lithological, hydrological and meteorological conditions during different seasons of the year,
- regular short- and long-term cliff hazard forecasts,
- selection of the most probable areas susceptible to a cliff hazard,
- dissemination of potential cliff hazard maps,
- warning announcements for a crisis centre about a predicted exceeding of threshold values for cliff hazard factors.

The key element in a cliff protection and cliff hazard warning system is short-term weather forecasting (few-hour or few-day operational forecasts), which should be made on the basis of direct and indirect observations of environmental conditions carried out by the state service, e.g. the Institute of Meteorology and Water Management–National Research Institute, Polish Geological Institute–National Research Institute, Maritime Offices or environment monitoring field stations. Long-term forecasts, however, should be based also on the findings of geomorphological, geological and hydrological field observations, as well as on experimental study results. Operational and strategic forecasts should comprise not only a qualitative description of potential cliff hazards, but should also provide as precise as possible quantitative forecasts for extreme processes that induce cliff hazards. Therefore, the role of the forecasting system should be two-fold: diagnostic and informative, as well as premonitory, based on the organized monitoring of extreme processes on the South Baltic Sea coast. The cliff protection and cliff hazard warning system thus provides the basis for developing a warning system operated by the civil service, local government units and specialized rescue services, and should be obligatory in order guarantee that it is formalized and brought into effect.

CONCLUSIONS

Long-term studies on the functioning of cliff-coasts (Kostrzewski, Zwoliński 1986, 1988, 1995) under conditions of the increased impact of extreme hydrometeorologic events (Avotniece *et al.* 2010; Jania, Zwoliński 2011) has allowed for time capturing of the most significant geomorphologic changes in the sea cliff structure and for recognition of the tendencies of cliff shore recession. Moreover, a cliff hazard classification as well as a system of protection and information on factor-induced hazards has been proposed.

The cliff top recession rate measured on tested research sections proved that the current development of the Wolin Island cliff-coast is undergoing temporal and spatial diversity of a seasonal nature, depending on the time of year and on the morphological and lithological conditions. In the analyzed 30-year period, one 20-year cycle appeared during which two periods of decreased morphodynamic activity occurred (around the years 1989 and 2008) and one period of increased cliff shore morphodynamics (around the year 1998) manifested by an increased rate of top recession in the Wolin cliffs. The intensity of the morphogenetic processes that shape the cliff coastline also demonstrated a distinct seasonal variability (Kostrzewski, Zwoliński 1986, 1988). The autumn and winter season was dominated by extreme processes which by their activity significantly contributed to cliff modelling. Summer, however, was influenced by processes of an average character which transformed the cliff face to a lesser degree.

This study proposes threshold values for the key cliff hazard inducing factors (mainly marine factors - sea levels, and meteorological factors - precipitation, air temperature or wind) responsible for the transformation of the cliff shores on Wolin Island. Upon further analysis, these factors might be extended to the Polish Baltic coastline along its entire length. It could be stated that crucial cliff hazard-inducing factors include high sea level (594 cm) and precipitation with a daily total exceeding 40 mm a day. Exceeding the proposed threshold values for cliff hazard inducing factors triggers cliff shore destruction of various extents. If the hinterland of the cliff top is used or inhabited by people, these hazards may constitute a direct threat to them and their living and economic conditions, or to recreational facilities. Reliable information on cliff hazards requires standardized hydrometeorological and geomorphological monitoring of the cliff-coasts. Cliff-coast monitoring results should serve as a basis for developing procedures for modelling and forecasting extreme geomorphological events that induce disastrous effects on cliff faces, as well as for alerting the community against direct threats to life and property in the coastline zone.

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REFERENCES

Avotniece, Z., Rodinov, V., Lizuma, L., Briede, A., Kļaviņš, M., 2010. Trends in the frequency of extreme climate events in Latvia. *Baltica 23*, 135–148.

Bagdanavičiūtė, I., Kelpšaitė, L., Daunys, D., 2012. Assessment of shoreline changes along the Lithuanian Baltic Sea coast during the period 1947–2010. *Baltica 25*, 171–184. . http://doi.org/10.5200/baltica.2012.25.17

Bird, E.C.F., 2000. *Coastal Geomorphology: An Introduction.* John Willey & Sons, Chichester, 322 pp.

Borówka, R. K., Gonera, P., Kostrzewski, A., Zwoliński, Zb., 1982. Origin, age and paleogeographic significance of cover sands in the Wolin end moraine area, North-West Poland. *Quaestiones Geographicae 8,* 19–36.

Borówka, R. K., Goslar, T., Pazdur, A., 1999. Wolin End Moraine: age of glacitectonic structures in the light of lithostratigraphic data and radio-carbon dating. *In* R. K. Borówka, Z. Młynarczyk, A. Wojciechowski (eds), *Ewolucja geosystemów nadmorskich południowego Bałtyku.* Bogucki Wydawnictwo Naukowe, Poznań-Szczecin, 43–47. [In Polish].

Buchwał, A., Winowski, M., 2009. Reconstructing temporal patterns of rotational landslides activity using dendrogeomorphological approach (Wolin Island). *Quaestiones Geographicae 28 A/2*, 5–14.

Davidson-Arnott, R., 2010. *Introduction to Coastal Processes and Geomorphology.* Cambridge University Press, 442 pp.

Epifânio, B., Zêzere, J.L., Neves, M., 2013. Identification of hazardous zones combining cliff retreat with landslide susceptibility assessment. *In* D.C. Conley, G. Masselink, P.E. Russell, T.J. O'Hare (eds), Proceedings 12th International Coastal Symposium (Plymouth, England), *Journal of Coastal Research,* Special Issue 65, 1681–1686.

Furmańczyk, K., 1994. *Współczesny rozwój strefy brzegowej morza bezpływowego w świetle badań teledetekcyjnych południowych wybrzeży Bałtyku* [*The modern development of the coastal zone of non-tidal sea with the use of remote sensing research of southern coast of the Baltic Sea*]. Wydawnictwo Naukowe Uniwersytetu Szczecińskiego, Rozprawy i Studia, Vol. 161, 149 pp. [In Polish].

Hall, J.W., Meadowcroft, I.C., Lee, E.M., van Gelder, P.H.A.J.M., 2002. Stochastic simulation of episodic soft coastal cliff recession. *Coastal Engineering 46*, 159–174. http://doi.org/10.1016/S0378-3839(02)00089-3

Hampton, M.A., Griggs, G.B., Edil, T.B., Guy, D.E., Kelley, J.T., Komar, P.D., Mickelson, D.M., Shipman, H.M., 2004. Processes that govern the formation and evolution of coastal cliffs. *In* M.A. Hampton, G.B. Griggs (eds), Formation, Evolution and Stability of Coastal Cliffs: Status and Trends. *U.S. Geological Survey Professional Paper 1693,* 7–38.

Harff, J., Lemke, W., Lampe, R., Lüth, F., Lübke, H., Meyer, M., Tauber, F., Schmölcke, U., 2007. The Baltic Sea coast – A model of interrelations among geosphere, climate, and anthroposphere. *In* J. Harff, W.W. Hay, D.M. Tetzlaff (eds), Coastline Changes: Interrelation of Climate and Geological Processes. *Geological Society of America, Special Paper 426*, 1–10.

Hojan, M., 2009. Aeolian processes on the cliffs of Wolin Island. *Quaestiones Geographicae 28a/2*, 41–46.

Hojan, M., Więcław, M., 2014. Influence of meteorological conditions on aeolian processes along the Polish cliff coast. *Baltica 27*, 63–74. http://doi.org/10.5200/baltica.2014.27.07

Hünicke, B., Luterbacher, J., Pauling, A., Zorita, E., 2008. Regional differences in winter sea-level variations in the Baltic Sea for the past 200 years. *Tellus 60A (2)*, 384–393. http://doi.org/10.1111/j.1600-0870.2007.00298.x

Jania, J., Zwoliński, Zb., 2011. Extreme meteorological, hydrological and geomorphological events in Poland. *Landform Analysis 15*, 51–64.

Kolander, R., Morche, D., Bimböse, M., 2013. Quantification of moraine cliff coast erosion on Wolin Island (Baltic Sea, northwest Poland). *Baltica 26 (1)*, 37–44. http://doi.org/10.5200/baltica.2013.26.04

Kostrzewski, A., 1984. The development of cliff shores in Wolin Island in the light of archival data. *Sprawozdania Poznańskiego Towarzystwa Przyjaciół Nauk No. 100*, Poznań, 129–132.

Kostrzewski, A., 1985. Variation in the particle-size distribution and degree of sand grain abrasion in morainic till of the Wolin Island, NW Poland. *Quaternary Studies in Poland 6*, 83–97.

Kostrzewski, A., Zwoliński, Zb., 1986. Operation and morphologic effects of present-day morphogenetics processes modelling the cliffed coast of Wolin Island, N.W. Poland. *In* V.Gardiner (Ed.), *International Geomorphology 1986*, John Wiley and Sons, Pt 1, 1231–1252.

Kostrzewski, A., Zwoliński, Zb., 1988. Morphodynamics of the cliffed coast, Wolin Island. *Geographia Polonica 55*, 69–81.

Kostrzewski, A., Zwoliński, Zb., 1994. Contemporary morphodynamics of the cliff coasts of Wolin Island. *In* K. Rotnicki (Ed.), *Changes of the Polish Coastal Zone*, Adam Mickiewicz University, 145–155.

Kostrzewski, A., Zwoliński, Zb., 1995. Present-day morphodynamics of the cliff coasts of Wolin Island. *Journal of Coastal Research*, *Special Issue 22*, 293–303.

Krygowski, B., 1959. O związkach rzeźby dzisiejszej powierzchni ze strukturą podłoża na Pomorzu Szczecińskim [About connections of contemporary relief with the base structure of Szczecin Pomerania]. *Zeszyty Naukowe Uniwersytetu im. Adama Mickiewicza, Geografia 2*, 69–86. [In Polish].

Marques, F., 2009. Sea cliff instability hazard prevention and planning: examples of practice in Portugal. *Journal of Coastal Research*, *Special Issue 56*, 856–860.

Marques, F., Matildes, R., Redweik, P., 2011. Statistically based sea cliff instability hazard assessment of Burgau – Lagos coastal section (Algarve, Portugal). *Journal of Coastal Research*, *Special Issue 64*, 927–931.

Milne, G.A., Gehrels, W.R., Hughes, C.W., Tamisiea, M., 2009. Identifying the causes of sea level change. *Nature Geoscience 2*, 471–478. http://doi.org/10.1038/ngeo544

Piotrowska, H., 2003. *Zróżnicowanie i dynamika nadmorskich lasów i zarośli w Polsce* [*Diversity and dynamics of coastal forests and thickets in Poland*]. Bogucki Wydawnictwo Naukowe, Poznań - Gdańsk, 102 pp. [In Polish].

Pruszak, Z., 2004. Polish coast – two cases of human impact. *Baltica* 17, 34–40.

Richter, A., Groh, A., Dietrich, R., 2012. Geodetic observation of sea-level change and crustal deformation in the Baltic Sea region. *Physics and Chemistry of the Earth 53/54*, 43–53. http://doi.org/10.1016/j.pce.2011.04.011

RCB [Rządowe Centrum Bezpieczeństwa], 2010. *Zagrożenia okresowe występujące w Polsce* [*Periodically threats occuring in Poland*]. Wydział Analiz i Prognoz Biura Monitorowania i Analizy Zagrożeń. Warszawa, 39 pp. [In Polish].

Subotowicz, W., 1982. *Litodynamika brzegów klifowych wybrzeża Polski* [*Lithodynamics of Polish cliff-coast*]. Gdańskie Towarzystwo Naukowe, Ossolineum, Wrocław, 150 pp. [In Polish].

Sunamura,T., 1992. *Geomorphology of Rocky Coast*. John Wiley & Sons, 302 pp.

Trenhaile, A. S., 1987. *The Geomorphology of Rocky Coasts*. Clarendon Press, Oxford, 384 pp

Trenhaile, A,S., 1997. *Coastal Dynamics and Landforms*. Clarendon Press, Oxford, 366 pp.

Tylkowski, J., 2013. Temporal and spatial variability of air temperature and precipitation at the Polish coastal zone of southern Baltic Sea. *Baltica 26 (1)*, 83–94. http://doi.org/10.3103/S1068373914090064

Tylkowski, J., 2015. Conditions and rate of extreme dunes abrasion at the Pomeranian Bay. *Landform Analysis 27*, 33–42.

Tylkowski, J., Kolander, R., 2014: Potential hydrometeorological threshold values of the coastal hazard – an example from the Polish Southern Baltic coast. *Russian Meteorology and Hydrology 39 (9)*, 614–619.

Valdmann, A., Käärd, A., Kelpšaitė, L., Kurennoy, D., Soomere, T., 2008. Marine coastal hazards for the eastern coasts of the Baltic Sea. *Baltica* 21, 3–12.

Winowski, M., 2009. Mechanism of the activities of rotational landslides on the cliff coast on the Wolin Island (north-west Poland). *Quaestiones Geographicae 28 A/2*, 101–111.

Winowski, M., 2014: Aktywność osuwisk klifowych pod wpływem ekstremalnych zdarzeń meteorologicznych i hydrologicznych, wyspa Wolin – Bałtyk Południowy [Cliff landslides activity under the influence of extreme meteorological and hydrological conditions, Wolin Island – Southern Balic]. *Landform Analysis 26*, 20–41. [In Polish].

Wiśniewski, B., Wolski, T., 2011. Physical aspects of extreme storm surges and falls on the Polish coast. *Oceanologia 53 (1-TI)*, 373–390. http://doi.org/10.5697/oc.53-1-TI.373

Woodroffe, C.D., 2003. *Coasts: Form Processes and Evolution*. Cambridge University Press, 623 pp.

Zawiślak, T., 2011. *Wyciąg z Instrukcji opracowania depeszy OSTRZEŻENIE Instytutu Meteorologii i Gospodarki Wodnej Państwowego Instytutu Badawczego z dnia 15 maja 2011 roku*. IMGW-PIB, 13 pp. [In Polish]. http://biecz.pl/asp/pliki/td/imigw.pdf

Zwoliński, Zb., 2011. Global climate change and their implications for landforms of Poland. *Landform Analysis 15,* 5–16.

Žaromskis, R., Gulbinskas, S., 2010. Main patterns of coastal zone development of the Curonian Spit, Lithuania. *Baltica 23*, 149–156.