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Quantification of moraine cliff coast erosion on Wolin Island (Baltic Sea, northwest Poland)

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Abstract There are two long-term causes of continuing transgression in the south Baltic Sea – the glacio-isostatic uplift in the Bothnian Bay and the eustatic sea level rise. At a regional scale the cliff sediments and the seasonal climate conditions during the year are significant factors controlling cliff erosion. The erosion of cliffs of glacial sediments has been investigated on Wolin Island, located in the Baltic Sea in northwest Poland. Previous monitoring of morphological processes on Wolin Island provides a baseline for further detailed studies of cliff erosion. In long-term field investigations a mean cliff retreat of 0.14 m a^{-1} was measured during the last 30 years. In this study a high-resolution terrestrial laser scanner was used for monitoring cliff retreat at two test sites. In a four-month interval and an annual interval both sites were scanned and total cliff erosion of 0.090 m a^{-1} and 0.043 m a^{-1} with volume changes of 434.7 m^3 and 888.7 m^3, respectively, was measured. The cliff erosion is significantly higher in the colder and more humid periods. Cliff stabilization occurs in conditions of low and average rainfall and above-average temperatures.

Keywords • *Terrestrial laser scanning* • *Cliff coast erosion* • Polish Baltic Sea coast

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INTRODUCTION

The Wolin Island cliff studies have a long tradition in German and Polish geomorphological research. The research approaches were based mainly on classical field observation and analysis of historical maps and archives. Hartnack (1926) calculated the rate of erosion near Miedzyzdroje (Misdroy), exactly corresponding to the Czubinski Reserve test site (Fig. 1), at 0.8 m·a^{-1} between 1836 and 1889. Heiser (1925) calculated 1.0 m·a^{-1} for a longer observation period (1695-1924). Szopowski (1961) determined it at 0.8 m·a^{-1} on the basis of cartographic data from 1695 to 1886. Several key factors driving the erosion were determined by Kostrzewski, Zwoliński (1986, 1988, 1995 and 2012), who performed measurements directly in the field and described conceptually the geomorphological processes like landslides (rotational and slumps), deflation, slope wash, rill erosion and storm tides. The methodology used so far is based on simple and not precisely stated geodetic measurements (distance changes from selected trees to the edge of the cliff) and included subjective geomorphological mapping at irregular time intervals. All studies are complementary to sediment study and photographic documentation. However, there are also other, more precise contemporary methods that can be used in studies of cliff erosion. Recently a new method of research on this area has been proposed by Buchwał, Winowski (2009). In a dendrogeomorphological investigation they could explain the decadal development of rotational landslides on the Wolin cliff coast. Technical improvement in surveying methods over the last decade/years allows a more precise and three-dimensional study in the cliff coast zone. In the present study our main aim is to present the first application of high resolution spatial surveying using terrestrial laser scanning equipment on the cliff coast of Wolin Island. Here, we determine cliff retreat and cliff erosion volume at two representative test sites on the basis of an interval of one year.

STUDY AREA

The 11.7 km long cliff coast of Wolin Island is located in northwest Poland (Fig. 1). The cliffs are up to 93 m high and are part of a terminal push moraine built by strongly distorted post-glacial sediments (Nord-Rügener-Staffel) covered by aeolian sands (Borówka *et al.* 1982; Kostrzewski 1985). The incorporated Cretaceous marls in the moraine occur very commonly.

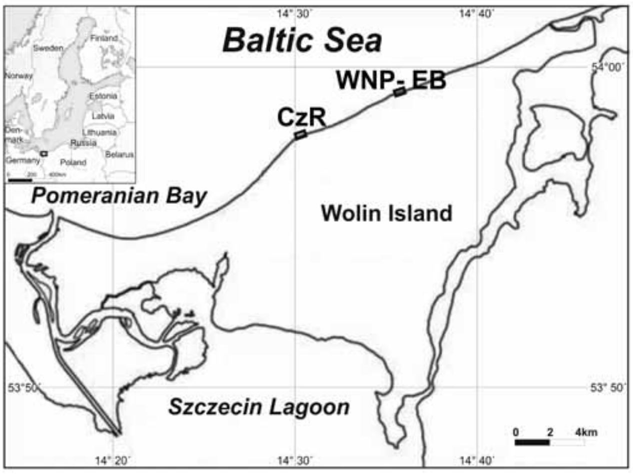

Fig. 1 Location of test site Czubiński Reserve (CzR) and test site Eastern border of Wolinski National Park (WNP-EB) on Wolin Island (NW Poland). Compiled by R. Kolander, 2012.

Climatically, Wolin Island, Poland, belongs to the Western Costal Region (Woś 1999). This region is characterised by the highest number of sunny, warm, and precipitation-free days as well as the lowest number of days with high cloudiness in Poland. Ground frost and frost appear at the lowest frequency in northwest Poland.

Since the 1990s the mean temperature has varied from 6.5°C in 1996 (classified for this area as extremely cold) to 9.8°C in 2007 (very warm). The range of precipitation is from very low (about 450 mm in 2006) to very high (>850 mm in 1998). The year 2011 was warm (9.5°C) and ordinary but had very humid conditions (~750 mm).

For detailed research two representative test sites – Czubinski Reserve (CzR) and the eastern border of Wolinski National Park (WNP-EB) – were selected (Fig. 1). At the CzR test site simple geodetic surveys have been carried out since the 1980s (Kostrzewski, Zwoliński 2012). In contrast, geodetic surveys have not been carried out for the WNP-EB test site until today.

METHODS

A terrestrial laser scanner (Optech, ILRIS-36D) was used for collecting field data in May 2011, September 2011 and May 2012. This long-range scanner can obtain data at a distance of up to 1,500 m, has a range accuracy of 7 mm and angular accuracy of 8 mm at a distance of 100 m. The sampling rate is about 2,500 points per second. A so-called PanTilt provides the ability to generate a 360-degree point cloud from one single position. In this study this optional device was used to scan both locations. All of the scans were made from georeferenced positions. The scans allowed one to observe each smaller mass-movement area in greater detail. For methodological reasons (e.g. the wave length of the laser beam) the research was limited to the cliff zone above water.

DATA ACQUISITION AND PROCESSING

Section WNP-EB is located between 14°35′23.43″ E, 53°59′10.27″ N and 14°35′31.39″ E, 53°59′12.55″ N. At this location 2.427 m^2 were scanned (width of about 160 metres, height of about 15 metres and dominant slope aspect NNW). Section CzR is located between 14°29′56.18″ E, 53°57′46.78″ N and 14°29′58.99″ E, 53°57′48.43″ N. At this location 4.255 m^2 were scanned (width of about 71 metres, height of about 60 metres and dominant slope aspect NW). Both selected locations were scanned twice in 2011 and once in 2012. The observation periods were 125 days from 18th May 2011 to 20th September 2011 and 351 days from 18th May 2011 to 3rd May 2012. All test sites were scanned from two different positions to avoid shadows because of the shape of accumulation and erosion landforms, dead trees or large boulders at the shoreline. A ground resolution of about 40 mm at a mean distance of c. 30-50 m was used to obtain 3D data (see Table 1).

Table 1 Scanning characteristics of test site Czubinski Reserve (CzR) and test site Eastern border of Wolinski National Park (WNP-EB). Compiled by M. Bimböse and R. Kolander, 2012.

Site	Scan	Observed surface [m^2]	TLS points	TLS resolution [mm]	Number of scans
WNP-EB	May 2011	2,427	2,664,117	22	2
	Sept. 2011		2,455,920	39	2
	May 2012		2,511,985	37	2
CzR	May 2011	4,255	4,264,750	33	2
	Sept. 2011		4,481,705	36	4
	May 2012		4,420,107	35	4

In both cases the collected raw data were transformed into the PolyWorks from InnovMetric file format to merge the single point clouds to the final data sets (see Bimböse *et al*. 2011). Every point cloud was georeferenced with up to six GPS points. For detecting changes between the measurement periods an integrated Iterative Closest Point Algorithm function was used to register the point clouds to each other. At both locations a comparison between the point clouds was made to detect changes. The sediment balance of erosion and accumulation was calculated on the basis of cut-and-fill analyses.

RESULTS

In the one-year observation period cliff erosion was spatially different. After processing all data sets the mean retreat rate was calculated (see Table 2). There were losses and accumulations of various volumes.

Table 2 Measured and calculated cliff retreat of test site Czubinski Reserve (CzR) and test site Eastern border of Wolinski National Park (WNP-EB) after 125 and 351 days, and estimated annual result. Compiled by M. Bimböse and R. Kolander, 2012.

Site	Date		Measured mean	Erosion
	Scan 1	Scan 2	erosion [cm]	volume [m³]
WNP-EB	18 May 2011	20 Sept. 2011	5.9	285.0
CzR	18 May 2011	20 Sept. 2011	1.5	310.1
	Scan 1	Scan 3		
WNP-EB	18 May 2011	03 May 2012	9.0 (9.3 yearly)	434.7 (451.4 yearly)
CzR	18 May 2011	03 May 2012	4.3 (4.5 yearly)	888.7 (922.8 yearly)

The cliff retreat at location WNP-EB was about 0.059 m with volume changes of 285.0 m³ between May and September 2011, and 0.090 m with volume changes of 434.7 m³ between May 2011 and May 2012 (Fig. 2). At this 160-m long site the entire area was eroded at a spatially constant rate. Two landslides were recognized where sediment had formed debris cones with thicknesses of 0.349 to 0.701 m. In these cases, erosion intensity is reinforced by falling trees. In the upper, sandy part of the cliff, the root system of falling trees causes losses in cliff sediments. Although trunks of trees on the footslope work briefly like a temporary natural breaker, they are not able to limit the progress of erosion.

In addition to the TLS study, in December 2011 and January 2012 photographic documentation was undertaken. It allowed the observation of cyclic development of the cliff landform. At location WNP-EB in the period from May 2011 to September 2011 there were numerous mature and stable debris cones with an area not greater than 5 m² at the foot of the cliff, containing especially fine-grained sand with an addition of clay (Fig. 3). These observations indicate their origin from the contact zone between the fluvio-glacial sands and boulder clay. Characteristic of this period was a 40-metre wide beach that protected the foot of the cliff against erosion by sea waves. In December 2011, wave energy was so large that it could reach the foot of the cliff. The discharged material was accumulated on the beach and underwater slope. In January 2012 waves reached across the beach and the debris cones were completely eroded. In May 2012 one could again observe a number of small talus cones of up to 5 m².

The retreating rate at location CzR reached 0.015 m with volume changes of 310.1 m³ between May 2011 and September 2011 and 0.043 m with volume changes 888.7 m³ between May 2011 and May 2012 (Fig. 4). At this location two larger erosion areas could be detected in the form of landslides from boulder clay. The larger landslide area had a volume of 225 m³ and an extent of about 20 m². The maximum retreat was 2.581 m at this point and the thickness of the cone amounted to 1.545 m. A second smaller landslide was measured with a maximum retreat of 1.429 m over an area of about 12 m² and the thickness of the cone amounted to 1.029 m. The eroded volume at this point was c. 85 m³.

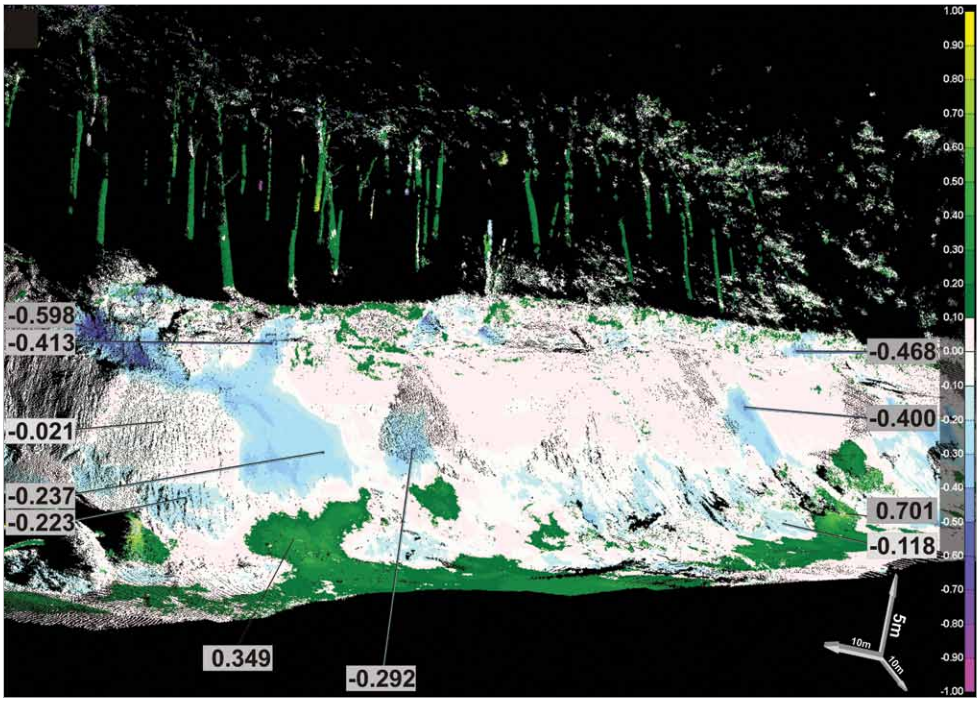

Fig. 2 Sediment balance of erosion and accumulation based on cut-and-fill analyses at test site Eastern border of Wolinski National Park (WNP-EB) from 18th May 2011 to 3rd May 2012. The scale presents erosion/ accumulation points [m]. As shown by the scale bar, the maximum of erosion and accumulation is set at 1 m. The selected points with negative/positive values represent erosion/accumulation [m]. Compiled by M. Bimböse, 2012.

Fig. 3 Test site Eastern border of Wolinski National Park (WNP-EB) during the research periods May 2011 – May 2012. Visible changing the width of the beach and cycle of erosion and accumulation of debris cones. Photos were taken in September 2011, December 2011 and January 2012 from roughly the same point of view. Photos by R. Kolander.

In addition to the typical massive landslides, clayfall (rockfall), slope wash and a system of erosion rills to a depth of 40 cm (Fig. 5) were also observed. In the sandy upper part of the cliff intense aeolian processes were observed that confirm the study by Hojan (2009). In the winter of 2011/2012 erosion of clay debris cones by sea waves produced a beach covered with boulders.

DISCUSSION

The Wolin cliff coastal zone is a place of intense activity of coastal erosion. Apart from the glacio-isostatic uplift in the Bothnian Bay and the eustatic sea-level rise (see Dietrich and Liebsch 2000), important conditions for the cliff coast retreat are also provided by lithology – fine-grained sands lying on glacial till (see Borówka *et al.* 1982, 1986) as well as meteorological factors – precipitation amounts and air temperature (see Woś 1999) and hydrological conditions – sea level and wave energy (see Schwarzer *et al.* 2002). Since 1811 sea-level changes in Świnoujście have demonstrated a constant rising trend of about 0.8 mm a^{-1} (Rotnicki *et al.* 1995; Dziaduszko, Jednorał 1996). But in the last 50 years the rate of rise reached 2 mm a^{-1}, commonly interpreted as a result of global climate change (Pruszak, Zawadzka 2005, 2008). Therefore, marine erosion processes are expected to intensify in the coming years, highlighting the importance of ongoing and long-term research on geomorphic processes reworking cliff sediments.

One of the main reasons for the current moraine cliff erosion on Wolin Island is differences in precipitation. High amounts of precipitation can increase the weight and reduce the stability of sand and especially clay-rich sediments. Precipitation very easily infiltrates into covering sand layers (which can exceed 10 m in thickness) and reaches clay beds. Periodic springs are observed generated at the sand-clay boundary layer. The infiltrated water mobilizes the mass of sediments and changes their consistency into liquid sludge. Increased weight and lower consistency initiate erosion processes. High sea-level and intense wave energy (characteristic of winds from westerly and northwesterly directions) remove old debris cones from the foot of the cliff slope and undercut new cliffs. All these processes reduce the stability of sediments and increase the vulnerability of the cliffs to landslides as observed in the study period.

High sediment moisture, cold or ordinary mean temperature, and cliff height, angle and bearing of

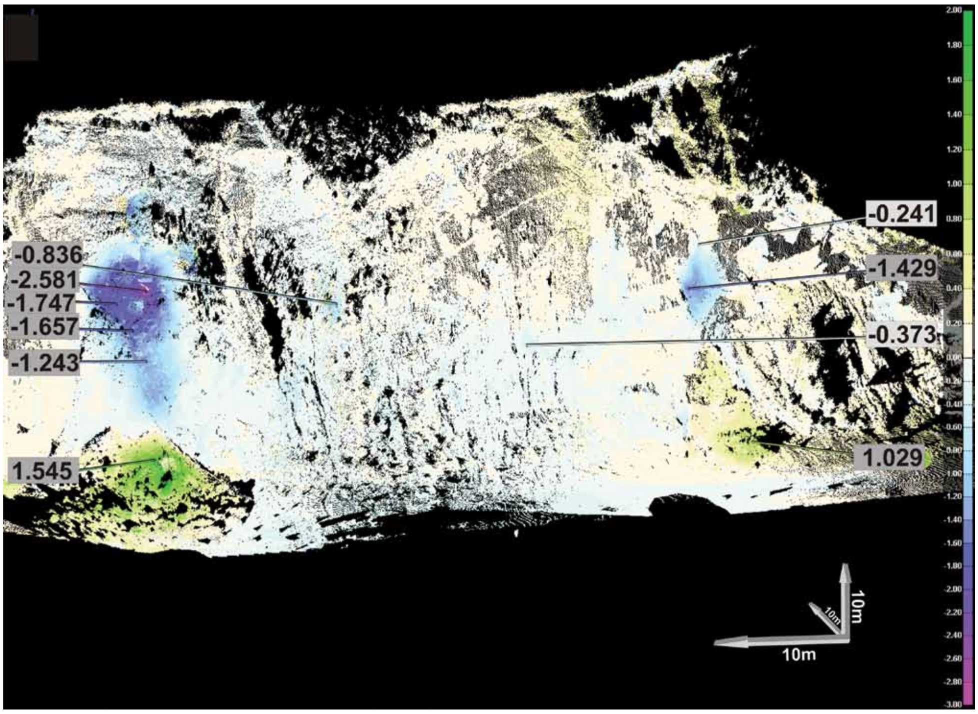

Fig. 4 Sediment balance of erosion and accumulation based on cut-and-fill analyses at Czubiński Reserve (CzR) test site from 18th May 2011 to 3rd May 2012. The scale presents erosion/ accumulation points [m]. As shown by the scale bar, the maximum of erosion is set at 3 m and the maximum of accumulation at 1 m. The selected points with negative/positive values represent erosion/accumulation [m]. Compiled by M. Bimböse, 2012.

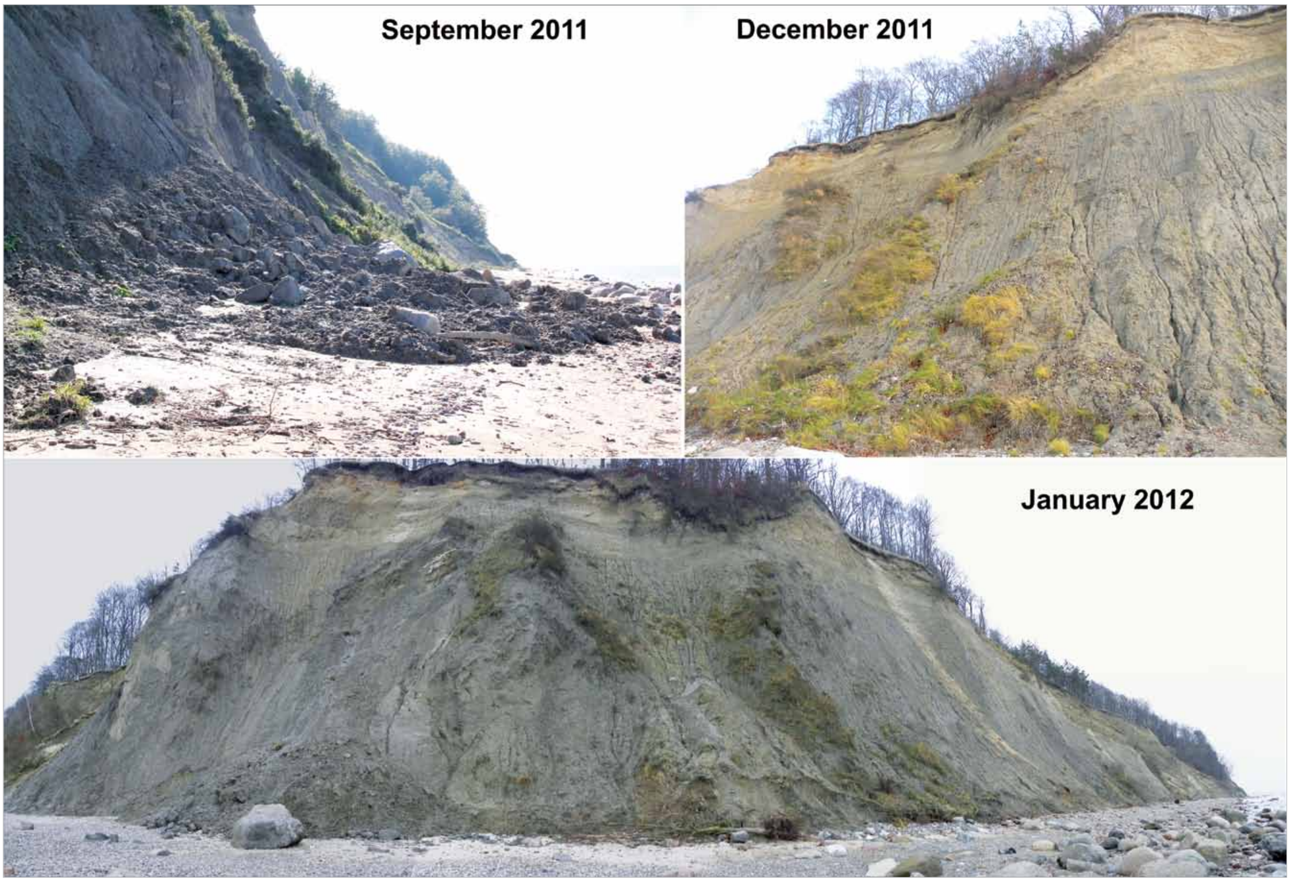

Fig. 5 Czubiński Reserve (CzR) test site during the research periods May 2011 – May 2012. Visible rockfall, slope wash and a system of erosion rills. Photos were taken in December 2011 and January 2012 from roughly the same point of view. Photos by R. Kolander.

maximum fetch indicate a very good situation for cliff erosion on Wolin Island. The cold and humid conditions are reflected in an increase in frost days during the year implying an extension of geomorphological activities. The second half of 2011 and the first half of 2012 belonged to a warm time with average rainfall periods, which are not conducive to intense erosion.

The research to date suggests that, after very low erosion in the years 1991-1995, its intensity increased then significantly (Kostrzewski, Zwoliński 2012). Therefore, higher erosion values were observed in cold to ordinary years with higher precipitation amounts (Fig. 6). Intense erosion in the extremely cold year 1996 was preceded by the very humid year 1995. Freezing water changed its volume in saturated sediments, thereby destabilizing the short-term cliff balance. The high intensity of erosion during 1998 and 2001 is also accounted for by above-average precipitation amounts.

The retreat rates of 0.090 and 0.043 m a^{-1} measured in this study are closest to figures given by Kostrzewski, Zwoliński (2012) as well as other authors. Hartnack (1926), Heiser (1925) and Szopowski

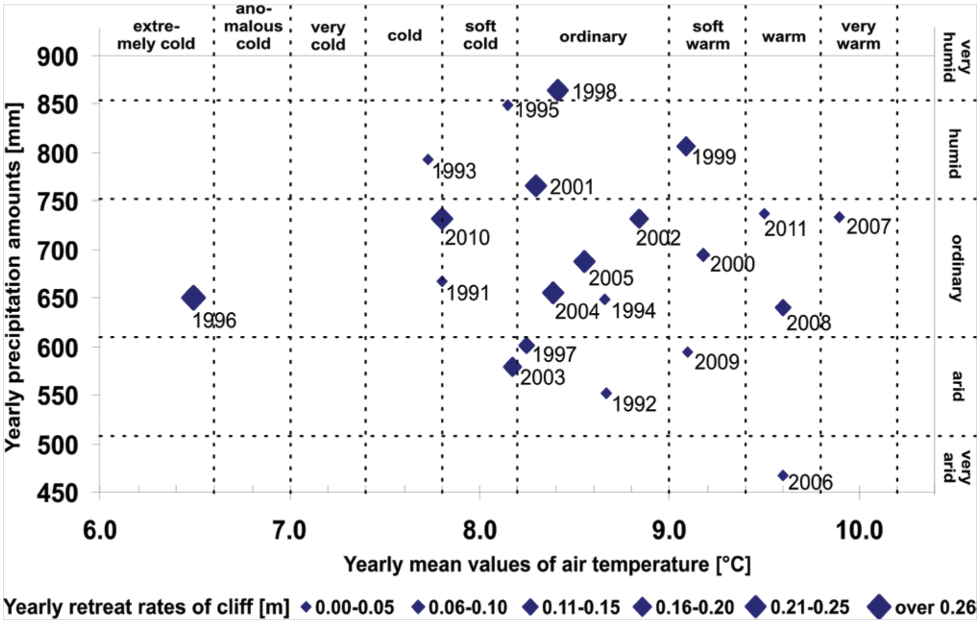

Fig. 6 Classified thermal and precipitation conditions on Wolin Island between 1991 and 2011 according to the classification by Lorenc (1998) and by class of erosion intensity. Compiled by R. Kolander, 2012.

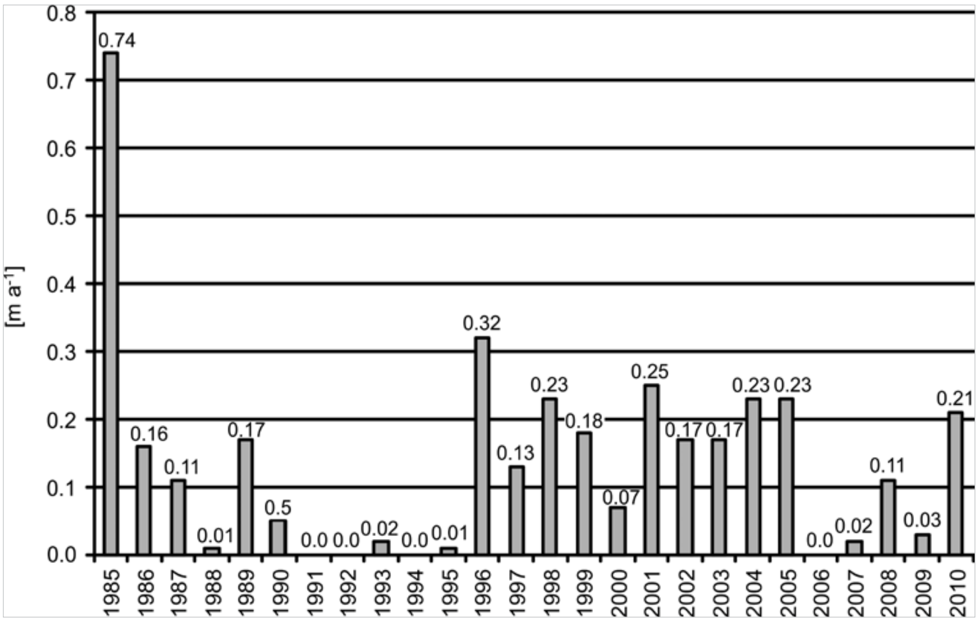

Fig. 7 Cliff retreat at the Czubiński Reserve (CzR) test site in the years between 1985 to 2010 (Kostrzewski, Zwolinski 2012). Cliff retreat rates: minimum 0.00 m a^{-1}, average 0.14 m a^{-1}, maximum 0.74 m a^{-1}, and standard deviation 0.154 m a^{-1}. The years without retreat were 1991, 1992, 1994 and 2006. Compiled by R. Kolander, 2012.

(1961) calculated the rate of erosion at 0.8 to 1.0 m a^{-1}. Pruszak, Zawadzka (2008) estimated Wolin cliff erosion at 0.47 m a^{-1} over the last 100 years, which is nowadays one of the highest values for the Polish Baltic coast. The same authors predict even faster erosion, i.e. 0.66 m a^{-1} by the year 2050. According to the data collected during field measurements by Kostrzewski, Zwoliński (2012), the annual cliff retreat average is not so significant and amounts to 0.14 m a^{-1} (Fig. 7). Starting from 1985, the authors have observed nine years with cliff retreat from 0.00 m a^{-1} to 0.05 m a^{-1}, six years with cliff retreat from 0.06 m a^{-1} to 0.20 m a^{-1}, five years with cliff retreat from 0.21 m a^{-1} to 0.25 m a^{-1}, and only one year (1985) when they measured cliff retreat of 0.74 m a^{-1}.

The results can be compared against those for other shorelines in similar geomorphologic situations, such as that reported by Greenwood and Orford (2007), who obtained a retreat rate from 0.080 to 0.160 m a^{-1} along the Strangford Lough coast in Northern Ireland.

CONCLUSIONS

Meteorological and hydrological properties affect cliff erosion. The use of terrestrial laser scanning is a large improvement in the methodology of cliff erosion measurement being a new and fast method for cliff erosion monitoring. This method provides highly accurate data for quantification and modelling studies. The TLS values measured can be compared directly against earlier cliff retreat data and offer additional information, such as types of erosion and the volume of eroded sediments. To obtain a more precise description of cliff erosion processes in the Wolin Island coastal zone, it is necessary to continue the research with correlations to meteorological and hydrological data.

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