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Assessment of shoreline changes along the Lithuanian Baltic Sea coast during the period 1947–2010

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Abstract Shoreline position measurements at various time instants can be used to derive quantitative estimates of the rate of shoreline change and help to understand the magnitude and timing of erosion or accretion processes. Aerial photographs and topographic maps from 1947 to 2010 have been used to derive instantaneous shoreline positions, from which shoreline change rates have been estimated using statistical parameters: shoreline change envelope (SCE), net shoreline movement (NSM), and end-point rate (EPR). Non-metric multi-dimensional scaling (nMDS) has been applied for shoreline classification into dynamic sectors. This study was carried out along 90.6 km of Lithuanian Baltic Sea coast over the time span 1947 to 2010. The study demonstrated that combined use of cartographic data and statistical methods could be a reliable method for shoreline related studies. Application of such data seems to be trustworthy in qualitative monitoring of shoreline changes, while it is the only available method for long term studies.

Keywords *• Shoreline change • Erosion • Accumulation • Digital shoreline analysis system • Aerial photography • south-eastern Baltic Sea*

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INTRODUCTION

The coastal zone is a dynamic, complex and vulnerable environment, the changes to which have significant economic and social impact on coastal population. In particular, they may threaten human interests by reducing the recreational area and limiting the development of the coastal infrastructure. Erosion and accretion are naturally occurring phenomena which often co-exist in a dynamic equilibrium (Komar 1998; Dean, Dalrymple 2002). However, increasing human activity at the coast has at places disturbed the natural course of the coasts, accelerated erosion processes in one area while causing accretion in others. Consequently, changes to the shoreline position reflect a complex impact of an interaction of climate driven sea level rise, vertical movements of the Earth crust, hydrodynamic and aeolian processes, and human interactions (Jarmalavičius *et al.* 2011).

The shoreline is defined as the physical interface of land and water (Boak, Turner 2005). Its position is one of the most common indicators of environmental change representing the historical rearrangement of beaches (Hapke *et al.* 2010). The methodology used to measure shoreline change is frequently based on delineation of historical shoreline positions from aerial photos, orthophotos, topographic maps and estimation of erosion rates (Smith, Zarillo 1990; Crowell *et al.* 1993; Fletcher *et al.* 2003; Romine *et al.* 2009; Kortekaas *et al.* 2010; Kartau *et al*. 2011). Latest methods for determination shoreline alteration using LIDAR (light detection and ranging) and satellite data incorporate more comprehensive assessments (Maiti, Bhattacharya 2009; Kumar *et al.* 2010; Hapke *et al.* 2009, 2010). Short-term shoreline dynamics is typically monitored using beach profiling techniques (Masselink, Pattiaratchi 2001; Žilinskas, Jarmalavičius 2003, Anthony *et al.*

2006), whereas statistical approaches usually integrate analysis of both short and long-term shoreline change (Maiti, Bhattacharya 2009; Romine *et al.* 2009).

The short-term dynamics of the Lithuanian coastline was comprehensively discussed in a number of studies. Coastal processes and beach characteristics were analysed applying beach profiling technique (Žilinskas, Jarmalavičius 2003; Žilinskas 2005; Jarmalavičius *et al.* 2011) and aerial photos (Dubra 2006; Dubra *et al.* 2011). Morphological features and morphometric characteristics of Lithuanian submarine coast were comprehensively investigated and described (Janukonis 2000; Gelumbauskaitė 2003, 2009; Žilinskas *et al.* 2007; Žaromskis, Gulbinskas 2011). Short-term coastal dynamics was investigated along the short coastal stretches (Žilinskas *et al.* 1994, 2000, 2008) and the entire Lithuanian Baltic sea coast (Kirlys 1990; Žilinskas, Jarmalavičius 1996, 2003; Žilinskas 2005; Jarmalavičius *et al.* 2011) while long-term changes were only briefly described in (Gudelis *et al.* 1990; Žilinskas, Jarmalavičius 2005; Dubra 2006).

The main objective of this study was to evaluate the long-term changes in shoreline position along the Lithuanian Baltic Sea coast using historical cartographic data derived from aerial photographs and topographic maps for the time period 1947–2010, and to apply statistical methods for the identification of sectors of coast with different dynamics.

Study area

The Lithuanian coast is located in the south-eastern part of the Baltic Sea and has the shortest coastline (90.6 km) among the Baltic Sea countries (Žilinskas 1997). The coast is formed of Quaternary deposits and belongs to accumulative-abrasive coastal type supplied by sediments from nearshore bottom and Sambian peninsula (Gudelis 1998; Bitinas *et al.* 2005; Jarmalavičius *et al.* 2011). It is open to predominating (SW, W, NW) wind directions, and exposed to wave activity for a wide range of wave approach directions (Valdmann *et al.* 2008).

The Klaipėda Strait divides this coast into two sections, a 51.03 km long compartment on the Curonian Spit (Kuršių Nerija) and 38.49 km long mainland section (Žilinskas 1997) (Fig. 1). The Klaipėda Strait partially disconnects the sediment drift along the Curonian Spit further to the North. The Curonian Spit is an accumulative structure formed during intensive sand

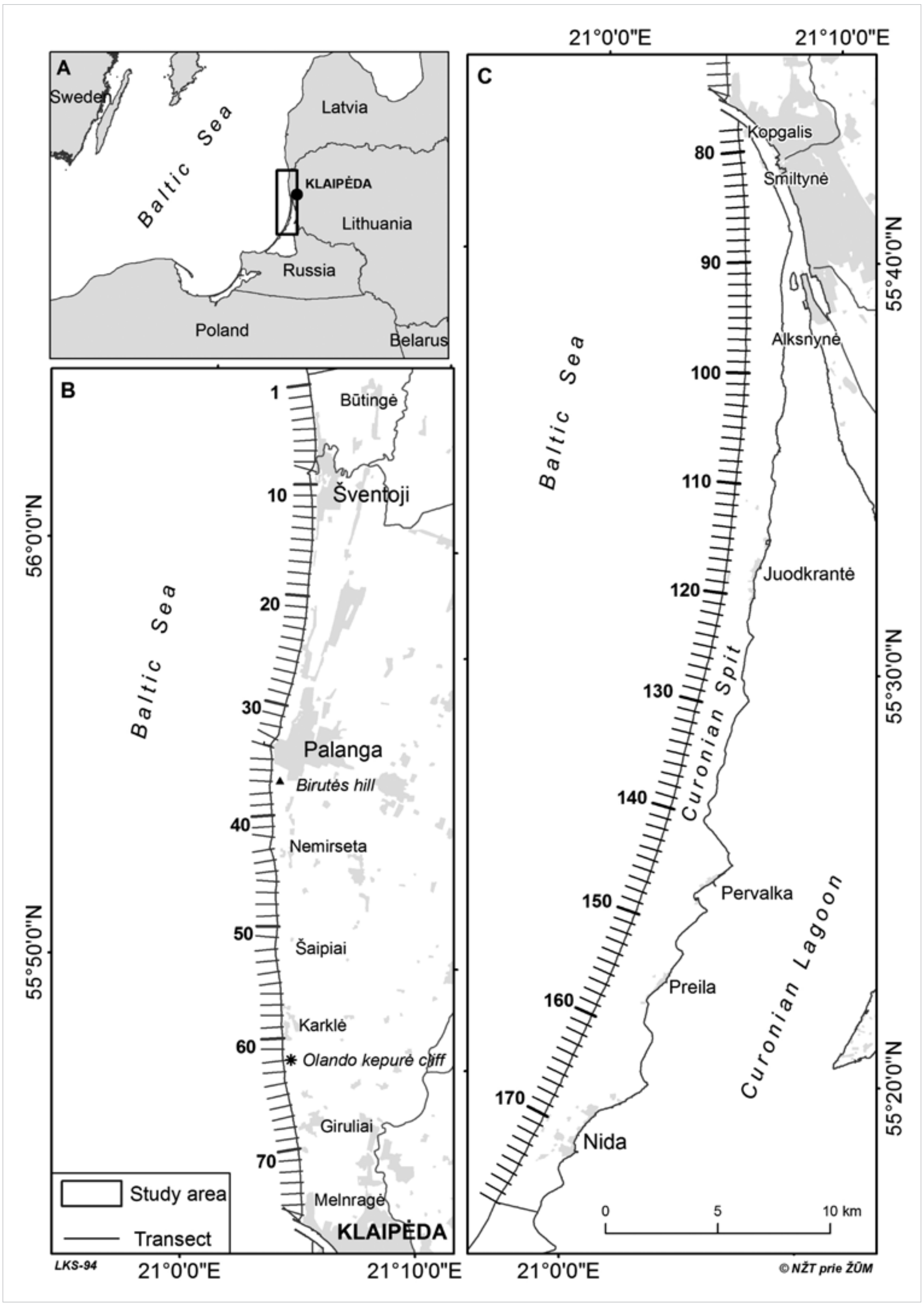

Fig. 1 Location map (A), the Lithuanian mainland coast (B) and the Curonian Spit (C). Compiled by I. Bagdanavičiūtė, 2012.

drift from Sambian peninsula to the North (Gudelis 1998). The upper part of the Quaternary deposits of the Spit is composed of sediment formed in the basins of various Baltic Sea development stages starting from the Baltic Ice Lake and ending with recent marine sediments (Bitinas *et al.* 2005). The coast of this spit has considerable amounts of sediment on shore and in the nearshore. This abundance is expressed as wide beaches, well developed foredunes and the regular presence of 1–4 berms in its underwater slope (Gudelis 1998).The mainland coast suffers from sediment deficit also due to the presence of a morainic plateau in underwater slope and hydrotechnical constructions which intercept nearshore sediment transport. Moreover this coastal sector is highly affected by anthropogenic pressure.

Generally sandy sediments dominate in the composition of the surficial formations of the sea beaches along Lithuanian coast. Fine-grained sand forms the beaches of Šventoji, Palanga, Kopgalis, Smiltynė (Fig. 1). Medium-grained sand forms beaches between Šventoji and Palanga, beaches of Nemirseta, Giruliai and Nida. Coarse-grained sand dominates in the Melnragė and in Juodkrantė. The faces of separate coastal sequences, such as Būtingė, Šaipiai, Pervalka and Preila, are formed by sand with 5–30% gravel. Gravel, cobble and boulders cover up to 70–90% of the beach surface at Karklė and Olando Kepurė (Žilinskas *et al.* 2001; Bitinas *et al.* 2005; Jarmalavičius *et al.* 2011).

MATERIAL AND METHODS

Mapping historical shorelines

In this study the evaluation of long-term coastal changes was performed using cartographic data from the period from 1946 to 2010. Sets of aerial photos of 11 different years (1958, 1971, 1973, 1974, 1975, 1976, 1977, 1979, 1989, 1990, 1991), together with orthophotos (1995, 2005, 2010), and topographic maps (1946, 1947, 1955, 1981, 1984, 1993) were obtained from the National Land Service of Lithuania and Lithuanian Geological Survey (Table 1). Shorelines of different years were derived from collected historical topographic maps and orthorectified aerial photo mosaics in a digital environment. The orthorectification and mosaicking was performed using *ArcGis 9.3* software considering root mean square (RMS) positional error which is based on misfit of the orthorectification model to a master orthorectified image (Romine *et al.* 2009). The processed images of 2010 served as master images for the georeferencing of older aerial photos and topographic maps. Older aerial photos and topographic maps were geo-referenced using polynomial transformation of the first order in *ArcGis 9.3*. The overall accuracy of the transformation, expressed as RMS error for geo-referenced images was less than 4 m (for aerial photos) and less than 1 m (for topographic maps).

Twenty locations of the shoreline in the past (for simplicity called historical shorelines in what follows) were derived from various cartographic sources. These sources had different spatial extent (Table 1). The largest coverage had topographic maps of 1947 and 1984 (the entire mainland coast), 1955 and 1977 (the entire Curonian Spit) and orthophotos of 1995, 2005 and 2010 (the entire Lithuanian Baltic Sea coast).

Shoreline change rates

Calculation of the shoreline position changes over the time was performed for all derived shorelines of 1946–2010. In order to determine the pattern of shift, the relative distance to the historical shorelines was measured from an onshore baseline along 179 shore-perpendicular 1 km long transects spaced 500 m apart. Among them 77 transects were located at the mainland coast and 102 transects at the western coast of the Curonian Spit (see Fig. 1).

The rates of long-term shoreline change at each transect were assessed using the Digital Shoreline Analysis System (DSAS) (ver. 4.2) software (Thieler *et al.* 2009; Fletcher *et al.* 2012). The DSAS is an open source software extension of the ArcGIS that computes rate-of-change statistics from historic shoreline data. Three statistical parameters – shoreline change envelope (SCE), net shoreline movement (NSM), and end-point rate (EPR) – were estimated and analyzed at each transect for mainland in 1947–2010 and western coast of the Curonian Spit in 1955–2010. SCE characterizes the distance between the furthest and the closest (to the baseline) historical shoreline for each transect. This represents the total rearrangement of the shoreline position over the entire period in question:

$$SCE = \Delta(X,Y) \qquad (1)$$

where X, Y are the coordinates of the furthest and the closest shoreline position at each transect.

NSM reports the distance between the oldest and the youngest shoreline features for each transect.

$$NSM = \Delta(X',Y') \qquad (2)$$

where X′,Y′ are the coordinates of the oldest and the youngest shoreline position, respectively.

The EPR is calculated by dividing the distance of shoreline relocation by the time elapsed between the earliest image and the most recent shoreline.

$$EPR = NSM/(year_2 - year_1) \qquad (3)$$

Table 1 Historical data used to study shoreline changes (M – mainland coast, CS – Curonian Spit coast). Compiled by I. Bagdanavičiūtė, 2012.

Year	Type	Scale	Pixel resolution (m)	Spatial extent
1946	Topographic map	1:25 000	2.1	CS (35 km)
1947	Topographic map	1:25 000	2.1	M (39 km)
1955	Topographic map	1:25 000	2.1	CS (45 km)
1959	Aerial photos	1:20 000	1.7	M (31 km)
1971	Aerial photos	1:20 000	3.7	M (19 km)
1973	Aerial photos	1:20 000	1.7	CS (25 km)
1974	Aerial photos	1:20 000	3.5	M (21 km)
1975	Aerial photos	1:20 000	2.0	M (23 km)
1976	Aerial photos	1:18 000	1.0	M (31 km), CS (25 km)
1977	Aerial photos	1:23 000	3.5	CS (39 km)
1979	Aerial photos	1:25 000	2.2	M (34 km), CS (13 km)
1981	Topographic map	1:10 000	0.5	M (24 km)
1984	Topographic map	1:25 000	2.1	M (38 km), CS (25 km)
1989	Aerial photos	1:20 000	2.3	CS (21 km)
1990	Aerial photos	1:20 000	1.7	M (29 km), CS (12 km)
1991	Aerial photos	1:18 000	2.0	CS (35 km)
1993	Topographic map	1:10 000	0.5	M (22 km)
1995	Orthophotos	1:10 000	0.5	M (39 km), CS (50 km)
2005	Orthophotos	1:10 000	0.5	M (39 km), CS (51 km)
2010	Orthophotos	1:10 000	0.5	M (39 km), CS (45 km)

Uncertainty and error

The shoreline position is highly variable in short time scales due to heavy storms, wave and wind set-up, when extreme natural fluctuations induce significant temporary shoreline retreatment (Stive *et al.* 2002; Janukonis 1994). Mapping the historical shorelines introduce additional uncertainties. Three positional and four measurement errors were recently described (Fletcher *et al.* 2003, 2012; Genz *et al.* 2007; Romine *et al.* 2009; Hapke *et al.* 2010) for the historical shoreline positions digitized from aerial photographs and topographic maps. The impact of tides on the shoreline location is negligible in this part of the Baltic Sea where the tidal range is a few cm (Leppäranta, Myrberg 2009). The level of the topographic sheet plotting error (a component of the measurement error) is ignored in this study.

The largest positional error is usually connected with the match of coordinates and mutual location of fixed objects in historical and contemporary maps. The coastal regions of Lithuania, however, contain a number of clearly identifiable objects or structures that can be used for adequate matching of maps from different decades. The location of such objects in different maps usually differs no more than by a few meters, and it can be assumed that the related error in the shoreline location is of the same magnitude. The impact of potential (seasonal or short-time) sea level fluctuations is normally negligible for topographic maps that have been adjusted to the long-term mean water level. This impact could be much larger for ortophotos that usually cannot be related to an exact time instant and/or water level. For this reason we consider in detail one positional (sea level fluctuation) and three measurement (rectification, digitizing and pixel) errors (Table 2).

Sea level fluctuation error (E_{sl}) expresses the horizontal movement of the shoreline position due to water level fluctuations. This error may be substantial in the area in question as the sea level exhibits considerable seasonal course and quite large short-term variability along the entire Lithuanian coast. For the above reasons it was considered only for aerial photographs since they were obtained without regard to sea level fluctuation, which can influence the position of the digitized shoreline. Such photos, however, are normally taken under good weather conditions when the overall sea level is close to its long-term average or slightly below it and the changes in the shoreline position occur in the region of the steepest descent of the beach profile at the landward end of the surf zone.

Georeferencing error (E_g) is calculated from the georeferencing and rectifying process. It characterises the alignment of a rectified aerial image to an earth based coordinate system, in this case LKS-94. The georeferencing error is expressed as its RMS value, calculated by the ArcGIS software as a measure of the offset between points on an aerial photo and established ground control points (GCPs, about 35 points along the entire coastline). Digitizing error (E_d) is a mean of the differences between repeated digitalization of the same image. Pixel error (E_p) characterises the pixel size of an

Table 2 Average errors and total uncertainty in position of historical shoreline for study area. E_{sl} – sea level fluctuation error (m), E_g – georeferencing error (m), E_d – digitizing error (m); E_p – pixel error (m); U_T – total shoreline position uncertainty (m). Compiled by I. Bagdanavičiūtė, 2012.

Cartographic data/Errors (m)	E_g	E_d	E_p	E_{sl}	U_T
Topographic map (1947, 1955, 1984)	±1	±6.3	±2.1	–	±6.7
Aerial photos (1977)	±4	±7	±3.5	±0.8	±8.8
Orthophotos (1995, 2005, 2010)	±0.5	±5	±0.5	±2	±5.4

image. For orthorectified images (1995, 2005, 2010) it is 0.5 m, which means that any feature smaller than 0.5 m cannot be resolved. The pixel size in aerial photos varies from 1 to 3.7 m, in topographic maps from 0.5 to 2.1 m (Tables 1 and 2).

For the shoreline position derived from the topographic maps for the period between 1947 and 1984, the total uncertainty (U_T) can be expressed via the individual errors (Hapke *et al.* 2010):

$$U_T = \pm\sqrt{E_g^2 + E_d^2 + E_p^2} \quad (4)$$

The uncertainty for the aerial photos and orthophotos is (Hapke *et al.* 2010):

$$U_T = \pm\sqrt{E_g^2 + E_d^2 + E_p^2 + E_{sl}^2} \quad (5)$$

For topographic maps, E_{sl} is omitted and U_T is calculated for each year, for which the shoreline was derived (Table 2). The uncertainty of an end-point shoreline change rate (U_R) is a quadrature addition of the uncertainties for each year's shoreline position, divided by the number of years between the shoreline surveys (Hapke *et al.* 2010):

$$U_R = \pm\frac{\sqrt{U_{T1}^2 + U_{T2}^2}}{year_2 - year_1} \quad (6)$$

where U_T^1 is the shoreline position uncertainty of the first year ($year_1$) and U_T^2 of the second year ($year_2$), which can be calculated by Eq. (1) or (2) accordingly. The uncertainty of shoreline change rate was ±0.14 m/year for the mainland coast (period of 1947–2010) and ±0.16 m/year for the Curonian Spit (period of 1955–2010).

Grouping of transects

Grouping of transects according to the shoreline position change over time was performed by non-metric multi-dimensional scaling (nMDS) (Shepard 1962; Zuur *et al.* 2007) on non-transformed data of four time periods of the mainland coast (1947–1984, 1984–1995, 1995–2005, 2005–2010) and the Curonian Spit (1946–1977, 1977–1995, 1995–2005, 2005–2010). In order to simplify the classification procedure, grouping of transects from the mainland coast and from the Curonian Spit was carried out separately. The *Primer 5* software (Plymouth Marine Lab) was employed for analysis and Euclidean distance was used as association measure. Stress values were calculated to check consistency between numerical estimates of association and their distance based on representation in the ordination plot. Stress values below 0.1 generally indicate good ordination with no real prospects of a misleading interpretation.

RESULTS

Mainland coast

Shoreline position change was calculated at each transect based on 14 digitised shorelines representing different years. Since these shorelines had different spatial coverage, five shorelines with the largest overlap (1947, 1984, 1995, 2005, 2010) were included into the assessment and four time periods were analyzed (Fig. 2).

The most considerable estimated changes in shoreline position occurred in 1947–1984. The largest shoreline advance was detected at Šventoji (179 m; transect 10) and Palanga (66 m; transect 33) respectively. The most significant retreat of shoreline was observed at Kunigiškiai (transect 25; -39 m), Nemirseta (transect 43; -42 m), Šaipiai (transect 52; -47 m) and Melnragė (transect 75; -36 m). The period of 1984–1995 revealed significant retreat of shoreline in the northernmost stretch between the Latvian border and Šventoji (transect 5; -75 m) and at Palanga (transect 34; -45 m). An intense retreat by 36 m was also observed at Palanga in 1995–2005.

Average shoreline change (EPR) was estimated for the entire 1947–2010 period. The highest positive EPR value was estimated for Šventoji (3.4 m/year at transect 10) and the highest negative for Būtingė (retreat by 1 m/year at transect 5). Negative EPR values (less than -0.5 m/year) were established at several sectors: Palanga (transect 34; -0.7 m/year) and Melnragė (transect 76; -0.7 m/year).

MDS ordination of shoreline position changes along the mainland coast in 77 transects over four time periods (1947–1984, 1984–1995, 1995–2005, 2005–2010) resulted in clear grouping which reflected well Euclidean distances between pairs of transects (stress value 0.06). Three major groups of transects were derived after analysis (Fig. 3).

Transects of the first group located at a coastal section with a total length of 8.0 km (transects 8 to 14 and 33). This section is characterized by accretion during the whole study period of 1947–2010. The ave-

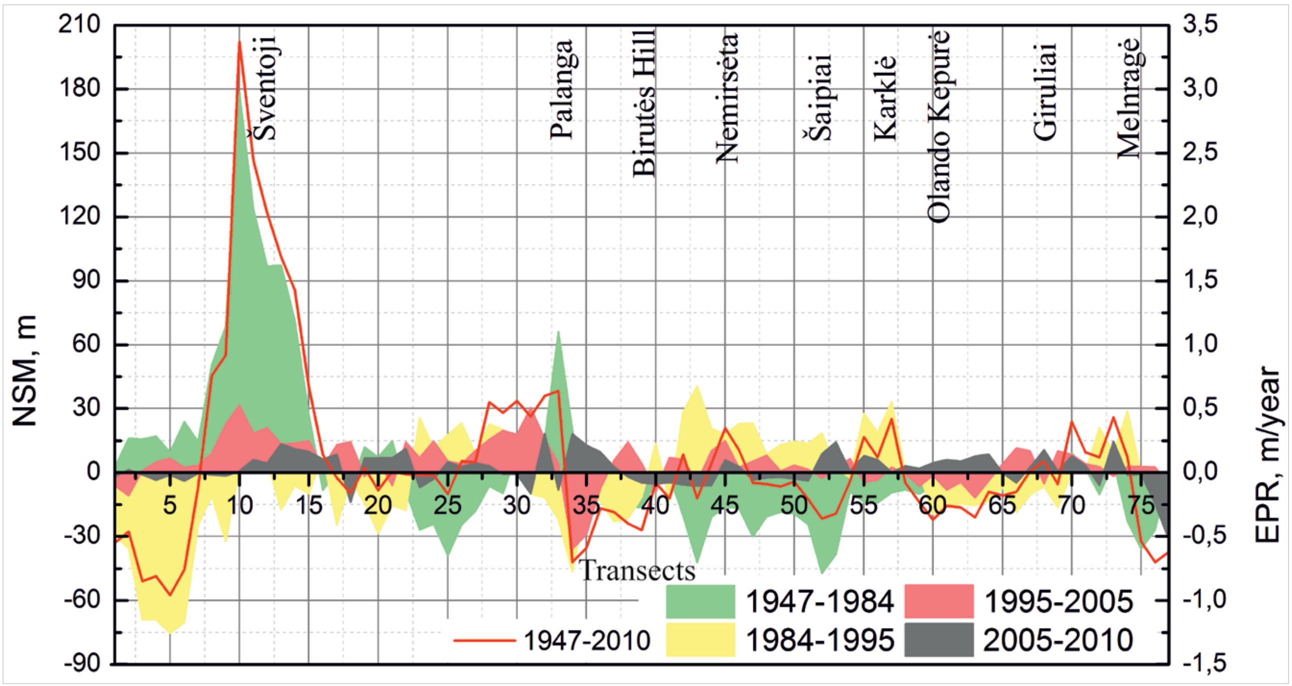

Fig. 2 Net shoreline movement (NSM) for 1947–1984, 1984–1995, 1995–2005, 2005–2010 time periods, and End point rate (EPR) for 1947–2010. Compiled by I. Bagdanavičiūtė and L. Kelpšaitė, 2012.

rage EPR was +1.66 m/year and the shoreline moved seawards by 104 m on average (Table 3). Considerable shoreline advance (by 94 m in average) was observed in 1947–1984.

The second group comprised of five transects defined as erosive with the shoreline retreat in the periods 1984–1995 and 1995–2005 (by 66 m and 4 m, respectively, Table 3). Although accretion was observed till 1984, in long-term content the shoreline moved landwards by -0.82 m/year on average with the overall shoreline retreat of 51 m on average. During four major periods the similarity of shoreline changes at five erosion-dominated transects (group 2) was much higher than that observed at eight accumulation-dominated ones (group 1) (Fig. 3).

Major part of the transects (64 research sites) were defined as quasi stable with no clear long-term pattern of accretion or erosion (group 3 in Fig. 3). Somewhat surprisingly, highly opposite trends in shoreline development were characteristic for the most of transects of this group (Fig. 4). For this group, significant negative correlations between changes of shoreline position

Table 3 Statistical summary of shoreline changes in the mainland coast. Compiled by I. Bagdanavičiūtė, 2012.

Shoreline statistics		Group 1	Group 2	Group 3	Total
Number of transects		8	5	64	77
Shoreline stretch (km)		4	2.5	32	38.5
1947–2010	Mean EPR (m/year)	1.66±0.14	-0.82±0.14	-0.05±0.14	0.08±0.14
	Min-max EPR (m/year)	0.64–3.37	-0.96–-0.7	-0.7–0.67	-0.96–3.37
	Mean NSM (m)	104	-51	-3	5
	Min-max NSM (m)	40–212	-60–-44	-44–42	-60–212
	Mean SCE (m)	109	74	28	39
	Min-max SCE (m)	51–212	69–82	8–50	8–212
1947–1984	Mean NSM (m)	94	17	-9	4
	Min–max NSM (m)	51–179	9–24	-47–27	-47–179
1984–1995	Mean NSM (m)	-10	-66	1	-5
	Min–max NSM (m)	-32–5	-75–-47	-36–41	-75–41
1995–2005	Mean NSM (m)	17	-4	4	4
	Min–max NSM (m)	4–32	-36–7	-29–30	-36–32
2005–2010	Mean NSM (m)	3	2	1	2
	Min–max NSM (m)	-8–13	-4–18	-31–18	-31–18

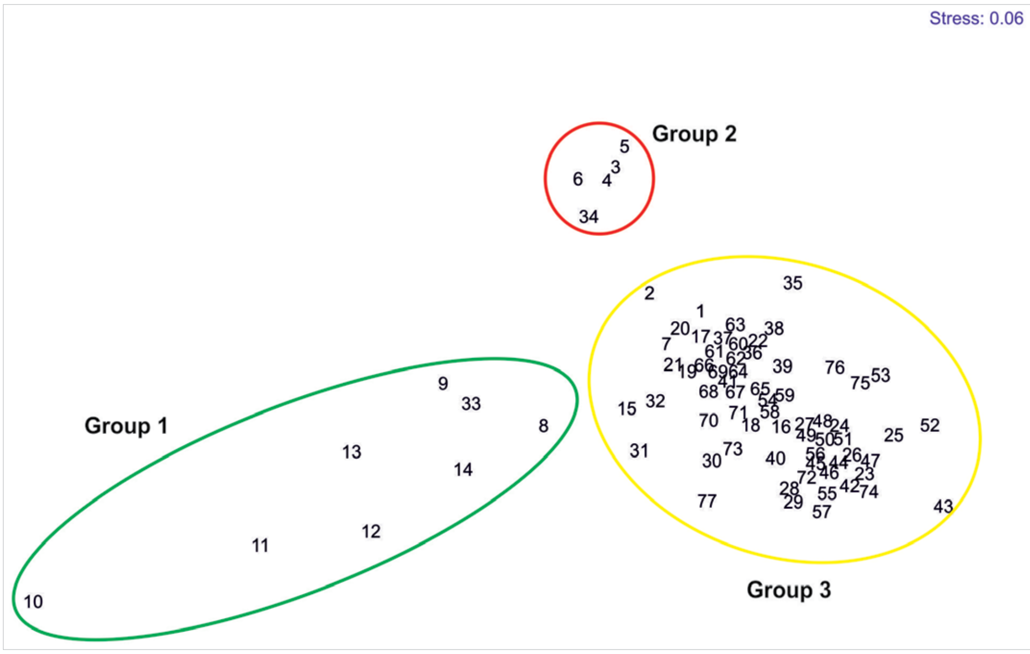

Fig. 3 MDS grouping plot of 77 transects according to shorelines movement during four periods of 1947–1984, 1984–1995, 1995–2005 and 2005–2010. Compiled by D. Daunys, 2012.

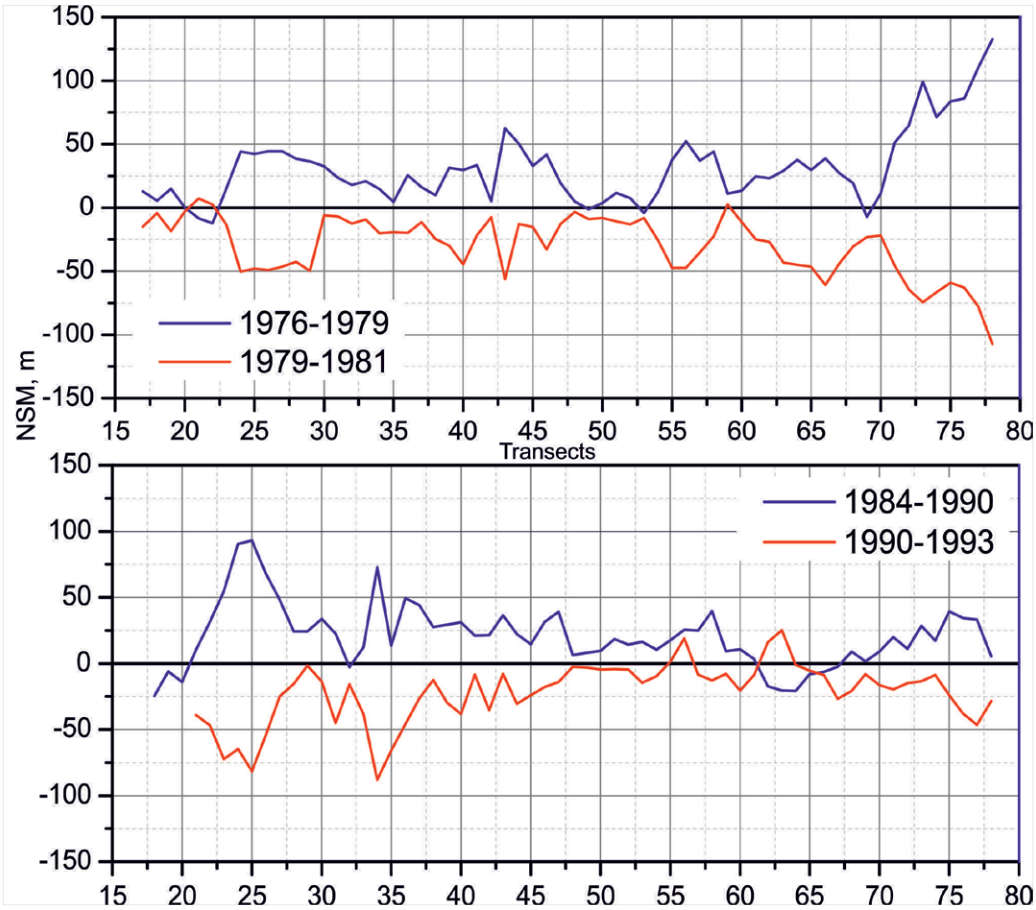

Fig. 4 Short–term trends in shoreline development at transects of group 3 (see text for clarifications) during four consecutive periods. Compiled by D. Daunys and L. Kelpšaitė, 2012.

became evident for consecutive short-term periods (r= -0.88, p<0.001, n=62 for the periods of 1976–1979 and 1979–1981; r= -0.70, p<0.001, n=52; for the periods of 1984–1990 and 1990–1993). Therefore, periods of seemingly intense accretion were often followed by equally strong erosion. The average EPR rate and NSM for this group were -0.05 m/year, and -2.9 m, respectively (Table 3).

The entire mainland coast has experienced negligible accretion in 1947–2010 when the shoreline advanced by 5 m with EPR 0.08 m/year (uncertainty range ±0.14 m/year) (Table 3). Accumulation trends of 1.6 to 4.4 m were estimated over the analyzed time periods for the entire shoreline with the only erosion dominated period (NSM =-5 m) apparently occurred in 1984–1995.

Curonian Spit

Shoreline position changes were calculated at each transect along 13 shoreline images in 1946–2010. Since derived shorelines had different spatial extent due to lack of cartographic data for certain years, five data sets (1955, 1977, 1995, 2005, 2010) were included into the assessment and four time periods were analyzed (Fig. 5).

Accumulative trends were dominant at the Curonian Spit. The most considerable shoreline changes took place in 1955–1977 (Fig. 5). During this period the largest shoreline advance of 60 m was observed at Alksnynė (transect 95), whereas the most significant shoreline retreat of 50 m was observed at Preila (transect 154). Although spatially more frequent but less pronounced retreat of the shoreline was observed subsequently (1977–1995), when 22 to 25 m of shoreline retreat was observed at Pervalka (transect 141), Juodkrantė (transects 109 and 112) and Alksnynė (transect 95). At the same time the most significant shoreline advance of 38 m was observed south of Preila (transect 159). The change of the shoreline retreat into advancement was observed along the entire coast during the following decade 1995–2005. Positive EPR values were dominant along the entire coast. The highest EPR (1.3 m/year) was observed for the stretch at Alksnynė (transect 94). A very few sectors were characterized by a negative EPR of -0.4 and -0.3 m/year at Nida and south of Alksnynė, respectively, while the lowest EPR -0.8 m/year was observed at Preila (transect 154).

MDS ordination of 76 transects (out of 102 possible along the Curonian Spit) over four time periods resulted in relatively noisy grouping, which still reflected well Euclidean distances between pairs of transects (stress value 0.09). Three relatively distinct groups defined as accumulative (group 1), erosive (group 2) and quasi-stable (group 3) were derived after evaluating coincidence between MDS grouping and EPR values of corresponding transects (Fig. 6).

A group (1) of nine transects dominated by accumulation processes (except for 1977–1995 period with prevailing erosion) is characterized by average EPR values exceeding 1 m/year and shoreline seawards movement of 60 m (max. +71, min. +42 m) in average (Table 4). Erosive transects (group 2) were determined by average shoreline retreat of 36 m during 1955–1977 period (Table 4). The shoreline moved landwards by approx. 23 m in average (min. -42 m and max. -5 m,

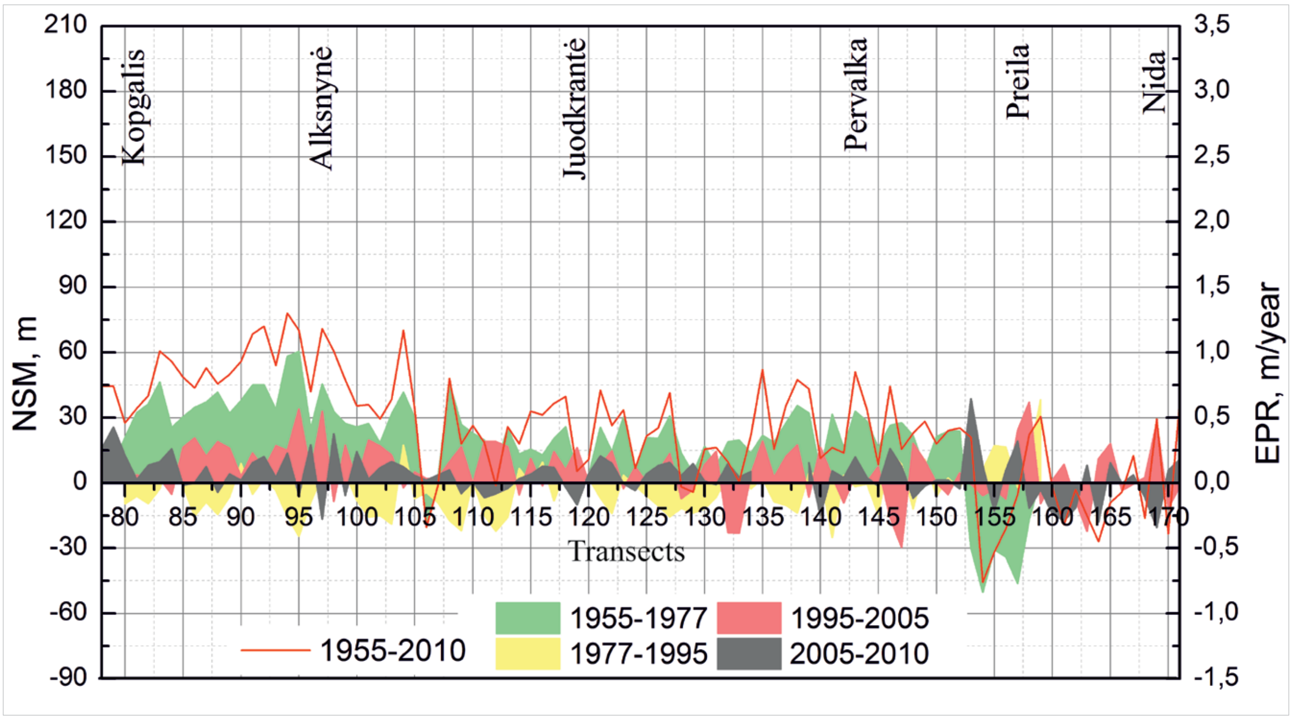

Fig. 5 Net shoreline movement (NSM) for 1955–1977, 1977–1995, 1995–2005, 2005–2010 time periods, and End point rate (EPR) for 1955–2010. Compiled by I. Bagdanavičiūtė and L. Kelpšaitė, 2012.

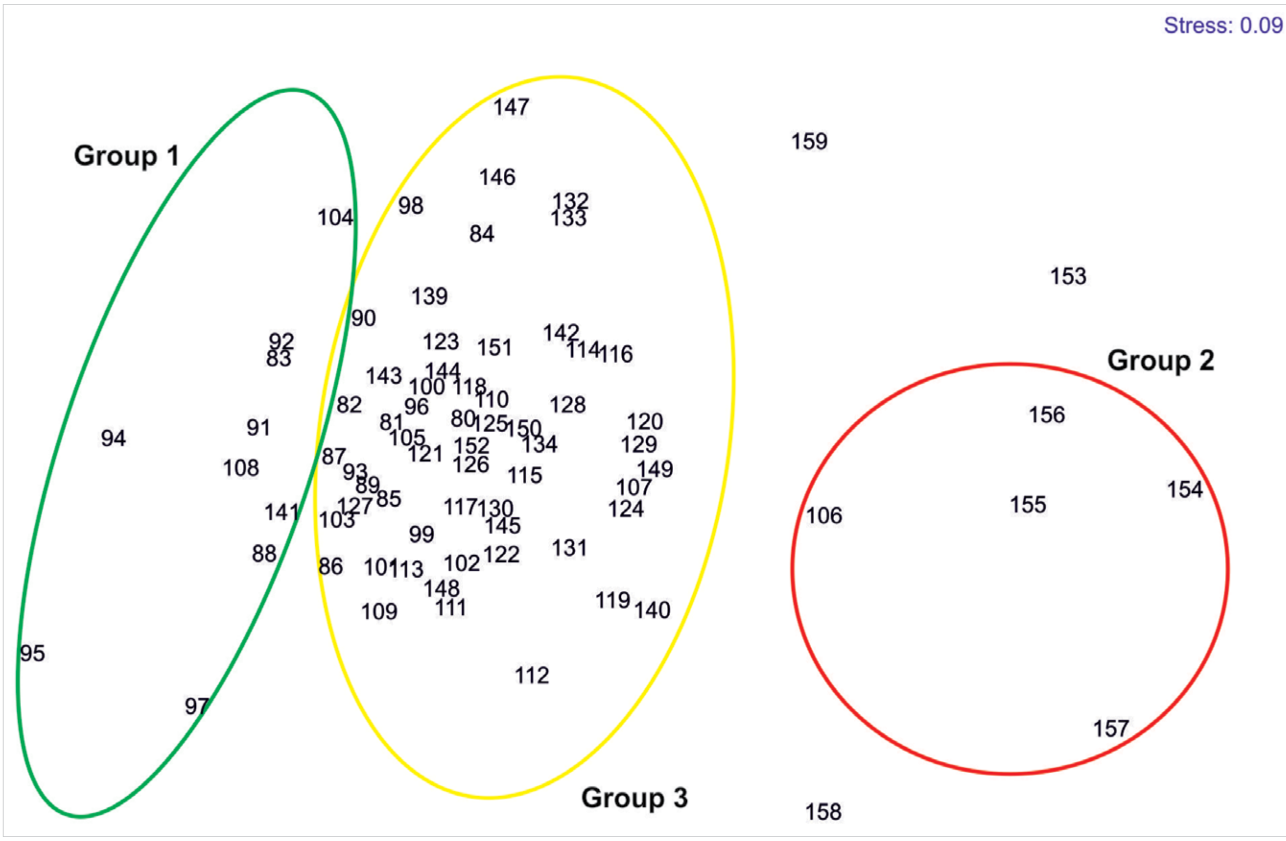

Fig. 6 MDS grouping plot of 76 transects according to shorelines movement during four periods of 1955–1977, 1977–1995, 1995–2005 and 2005–2010. Compiled by D. Daunys, 2012.

Table 4 Statistical summary of shoreline changes in the Curonian Spit coast. Compiled by I. Bagdanavičiūtė, 2012.

Shoreline statistics		Group 1	Group 2	Group 3	Total
Number of transects		9	5	62	102
Shoreline stretch (km)		4.5	2.5	31	51
1955–2010	Mean EPR (m/year)	1.08±0.16	-0.41±0.16	0.47±0.16	0.48±0.16
	Min–max EPR (m/year)	0.76–1.3	-0.76–-0.09	-0.07–1.01	-0.76–1.3
	Mean NSM (m)	59	-23	26	26
	Min–max NSM (m)	42–71	-42–-5	-4–55	-42–71
	Mean SCE (m)	63	37	31	35
	Min–max SCE (m)	46–82	22–50	9–55	9–82
1955–1977	Mean NSM (m)	48	-36	20	20
	Min–max NSM (m)	42–60	-50–-18	-30–38	-50–61
1977–1995	Mean NSM (m)	-6	7	-3	-3
	Min–max NSM (m)	-25–17	-4–17	-25–38	-25–38
1995–2005	Mean NSM (m)	14	2	5	6
	Min–max NSM (m)	2–34	-7–24	-30–37	-30–37
2005–2010	Mean NSM (m)	3	4	4	4
	Min–max NSM (m)	-5–14	-13–19	-15–39	-17–39

in the individual transects) with the average rate of -0.41 m/year.

The rest of 62 transects (group 3) had no clear long-term pattern of accumulation or erosion. Many coastal stretches that exhibit highly similar accumulation rates during one year (1976–1977) and six-year (1984–1990) periods may reveal equally strong erosion during consecutive periods (1990–1995) (Fig. 7). Although variable-sign short-term behavior was observed at places, the average NSM of 55 year period (1955–2010) was +26 m (min. -4 m, max. +55 m) with the average EPR rate of +0.47 m/year. These figures are consistent with the average Curonian Spit NSM and EPR characteristics (26 m and 0.48 m/year, respectively). Such quite a small accumulation trends were interrupted by a single erosion period during 1977–1995 (-3 m).

DISCUSSION

Long-term shoreline changes driven by major trends in climate do not necessarily coincide with the short-term coastline variability caused by heavy storm impacts

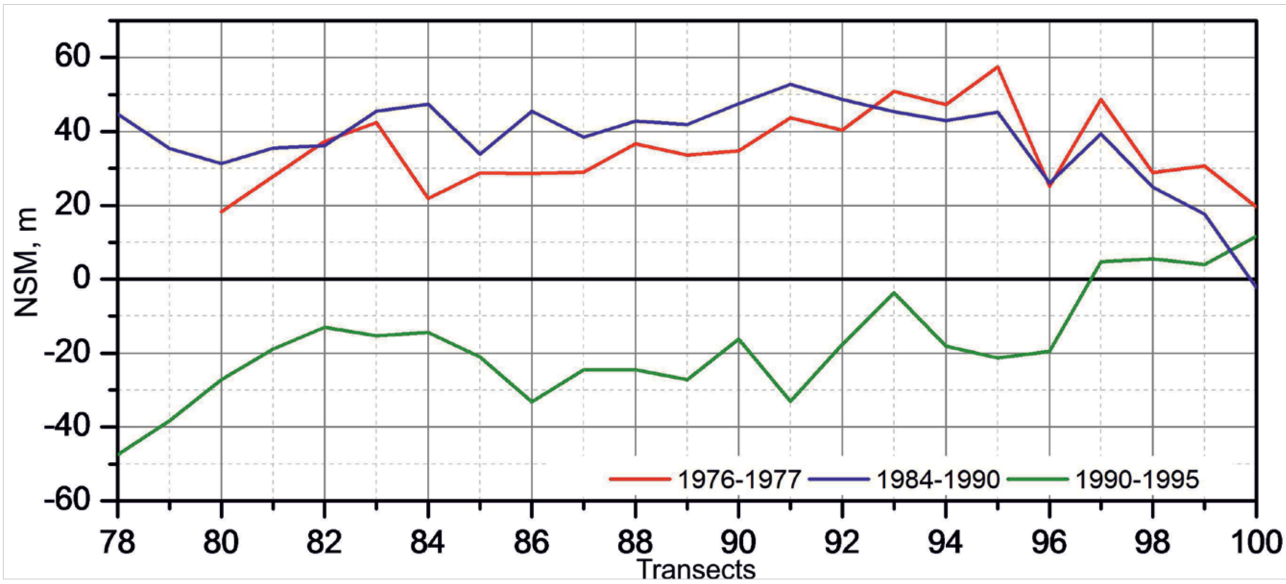

Fig. 7 Short–term shoreline changes in the Curonian Spit during three periods. Compiled by D. Daunys and L. Kelpšaitė, 2012.

and seasonal variations in the hydrodynamic activity (IPCC, 2007). According to MDS grouping of long-term changes during four periods in 179 transects, approx. 5.5% of the shoreline is characterized by predominance of erosion processes. Two thirds of the relevant sectors are clustered in 2 km long stretches at Preila and Būtingė (transects 154–157 and 3–6, respectively), the rest are at Palanga (transect 34) and north of Juodkrantė (transect 106). Accumulation was identified as being dominant to approximately similar extent (7.8% of the total shoreline). The clusters of transects that exhibited accretion also covered only 2–4 km long stretches (transects 8 to 14 in Šventoji area and transects 91–92, 94–95 and 97 in Smiltynė–Juodkrantė) (Fig. 8). The maximum accumulation and erosion rates were found to be significantly lower at the Curonian Spit than on the mainland coast (1.3 m/year versus 3.3 m/year and -0.76 m/year versus -0.96 m/year) (see Figs 2, 4). However, several vulnerable coastal stretches such as Kopgalis and Nida surroundings were not included into long-term analysis and grouping due to lack of comparable data.

Different authors divide the Lithuanian mainland coast into different accumulative/erosive stretches. According to 20 years coastal change study held in 1970–1990 (Gudelis *et al.* 1990), Latvian border–Šventoji and Nemirseta–Giruliai sectors were referred as either passive or active erosion zones. These results are consistent with our assessment for 1974–1990, which shows that both coastal stretches suffered from erosion (Table 5). Long-term (1947–2010) data analysis of this stretch shows, however, that the erosive sector was shortened from 9 to 4 km. At the same time the Nemirseta–Giruliai sector was quasi-stable on the long-term run with an average EPR value of -0.1 ±0.14 m/year (Fig. 8).

The Giruliai–Klaipėda sector, referred by Gudelis (1990) as accumulation zone, was determined as quasi-stable with signs of slight accumulation (Table 5). Our long-term assessment of this sector indicates quasi-stable situation at Giruliai–Melnragė and erosive area at Melnragė–Klaipėda (Fig. 8). The coasts at Šventoji–Nemirseta and Juodkrantė–Russian border were referred by Gudelis (1990) as quasi-stable transitional zone, while our data shows 25% and 46% of erosive sectors respectively in these two areas during 1974–1990 (Table 5). In 1947–2010 period both these stretches remained quasi-stable with short sectors of accumulation (transects 28–33) and erosion (transects 35–41, 154–157) (Figs 8, 9).

Coastal studies during period between 1993 and 2007 (Žilinskas 2008) indicate the most intensively eroded sectors at Šventoji–Latvian border, Palanga, Nemirseta–Olando Kepurė cliff, Melnragė, Klaipėda port, Juodkrantė, Preila, and to the north of Nida. Our study for a comparable time span between 1995 and 2010 also revealed erosive stretches at Latvian border–Būtingė (transects 1–3; mean EPR -0.39 m/year), Palanga (transects 33–35; mean EPR -0.84 m/year), Nemirseta (transect 43; EPR -0.73 m/year), Olando Kepurė cliff zone (transects 59–63; mean EPR -0.10 m/year) and Melnragė (transects 76–77; mean EPR -1.64 m/year) (Fig. 9). Considerable erosive trends were observed at Preila-Nida stretch (max EPR -1.31 m/year).

It is worth to note that during the last 100 years, the water level in Klaipėda Strait has risen by about 15 cm (Dailidienė *et al.* 2004, 2006). A rough estimate of the shoreline retreat for sandy beach owing to the water level rise can be obtained using the Bruun rule (Dean, Dalrymple 2002). As the average slope of the active beach profile (till the 20 m isobath) is about 1:120 (Gudelis 1998), this would mean the shoreline retreat by about 15–20 m on average in natural conditions. This

Table 5 Comparison of shoreline changes from cartographic (period of 1974–1990, this study) and reference data (period of 1970–1990, after Gudelis *et al.* 1990). Compiled by I. Bagdanavičiūtė, 2012.

Dynamic stretches for the period 1970–1990 (after Gudelis *et al.* 1990)		Data for the period 1974–1990			
		Transects	EPR, m/year		
			mean	max	min
Latvian border – Šventoji	Erosive	1–13	-1.59	-0.37	-4.47
Šventoji – Nemirseta	Quasi stable	16–4	1.06	4.59	-1.58
Nemirseta – Giruliai	Erosive	45–66	-0.37	0.75	-1.93
Giruliai – Klaipeda	Accumulative	67–77	0.60	1.39	0.05
Kopgalis – Juodkrante	Accumulative	78–120	1.76	4.42	-1.92
Juodkrantė – Russian border	Quasi stable	121–164	0.21	6.18	-1.20

has definitely not happened. Apart from the stabilising impact of various coastal engineering structures and attempts of coastal protection, this mismatch suggests that there still is significant sediment flow into the Lithuanian nearshore from adjacent parts of the Baltic Sea coast.

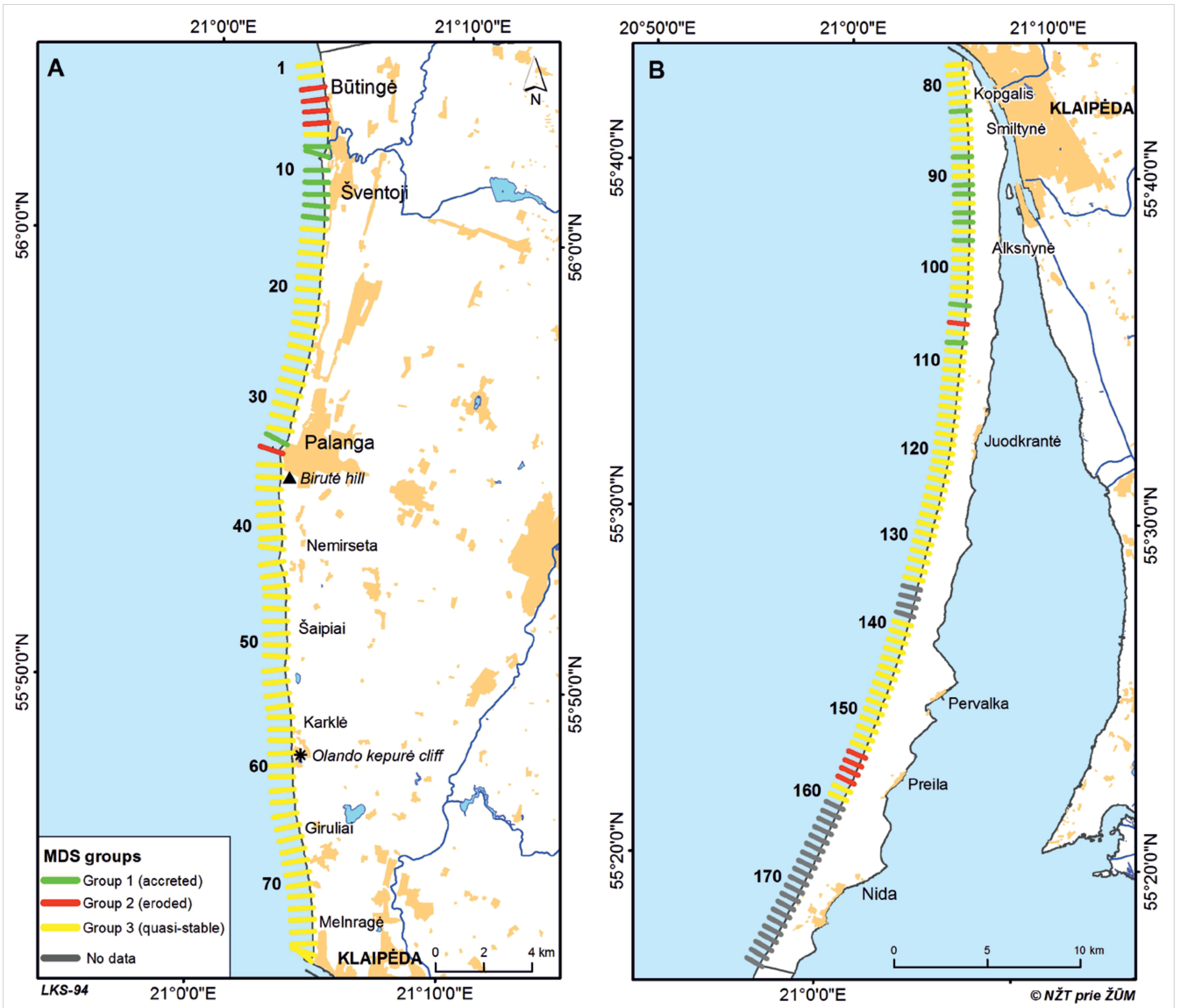

Fig. 8 Division of the Lithuanian coasts according to MDS grouping of transects: A – mainland coast, B – Curonian Spit coast. Compiled by I. Bagdanavičiūtė, 2012.

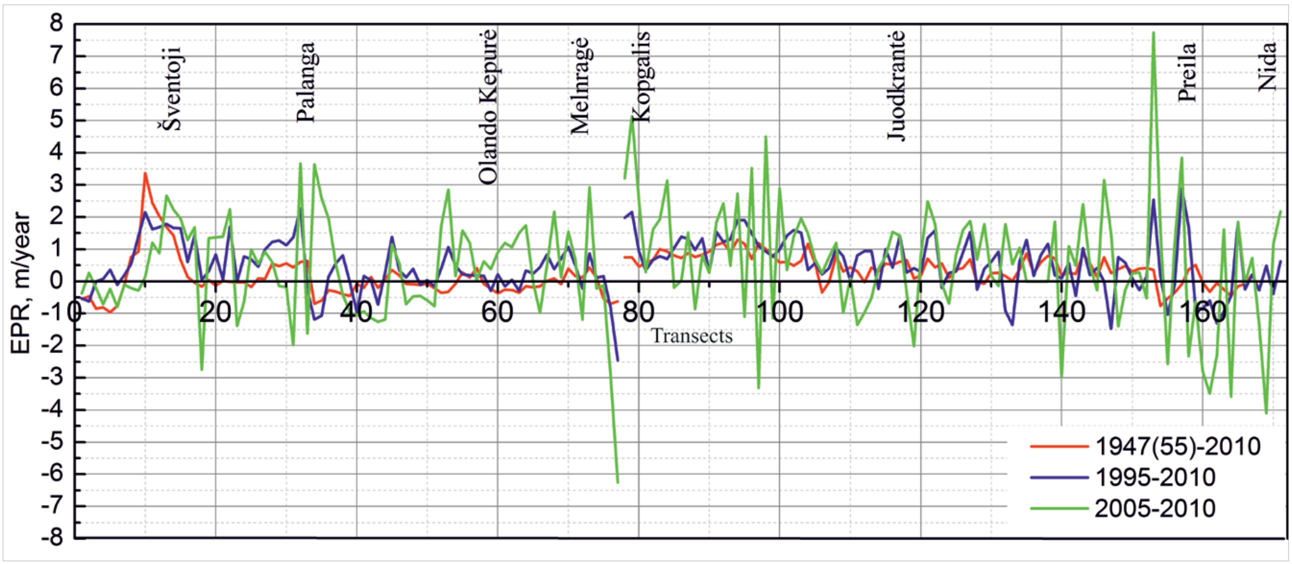

Fig. 9 EPR rate for the Lithuanian coast: medium term (mainland coast 1947–2010, Curonian Spit 1955–2010), medium scale (1995–2010), short term (2005–2010). Compiled by I. Bagdanavičiūtė and L. Kelpšaitė, 2012.

CONCLUSIONS

Short term (time scale of 5–15 years) shoreline changes usually represent coastline vulnerability to extreme hydrometeorological events and/or effects of anthropogenic interventions (Schernewski *et al.* 2011). Our analysis suggests that this is exactly the case along the Lithuanian coast (both mainland coast and the Curonian Spit) where substantial variations in the accumulation or erosion rate (and even frequent switch from accumulation to erosion or *vice versa*) occurred during subsequent relatively short (below 20 years) time periods. The extent of shoreline shifts is often >20 m and reaches over 60 m during such periods at selected locations. These hot spots of coastal evolution may need additional intervention in order to prevent the problems to expand to adjacent sectors.

Somewhat counter-intuitively, the analysis revealed almost no secular tendency of the loss of land over larger coastal sectors. A few areas that exhibit very rapid rate of accumulation or erosion (adjacent to the Šventoji and Klaipėda harbours or the Palanga pier) are clearly connected with the presence large-scale coastal engineering structures. The analysis still makes it possible to identify several areas with long-term shoreline changes possibly driven by natural factors. These areas form about 10–15% of the entire Lithuanian coastline whereas the accumulation and erosion areas have a comparable length. Apart from the above-mentioned hot spots and these areas of long-term changes, our analysis suggests that the rest of the Lithuanian coastline exhibits a generally stable nature and even the already occurred water level rise in the last decades has not overridden this stable evolution.

Finally it should be underlined that present result, present assessment are basically consistent with several studies (Gudelis *et al.* 1990; Žilinskas 2008) that rely on *in situ* beach profiling techniques. Although the accuracy of our assessments of shoreline changes to some extent suffers from several uncertainties, the qualitative patterns of erosion and accretion from in situ studies match well the accumulation/erosion trends derived from historical cartographic data. Even when the quantitative characteristics extracted from historical data are not perfect, application of such data seems to be highly reliable in qualitative monitoring of shoreline changes, while it is the only available method for the long term studies. Therefore, further integration of historical datasets on shoreline position with litho-morphodynamic "ground truth" could provide important supplementary information for better understanding of coastal changes.\

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