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Observation on the interplay of sea level rise and the coastal dynamics of the Curonian Spit, Lithuania

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Long-term sea level rise is commonly considered to enhance coastal erosion, the rate of which is often evaluated using the Bruun Rule. We make an attempt to assess the recent coastal dynamics of the Curonian Spit in terms of the shoreline displacement rate on the basis of a comparison of maps from different years and coastal monitoring data. The obtained results are compared with those calculated according to the Bruun Rule. It was found that only individual-year average changes over the entire spit are linked to sea level variations, whereas long-term trends of shoreline dynamics are uncorrelated with the sea level increase. Although the sea level has increased in the study area, coastal recession has been observed since 1910 in the southern part of the Lithuanian sector of the Curonian Spit and accretion in the northern part, while the central part has been stable.

Key words: sea level rise, beach recession, Bruun Rule, Curonian Spit

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INTRODUCTION

Global climate change and sea level rise are often related to increasing coastal erosion and associated socio-economic transformations in coastal regions (Nicholls et al., 2008; Torresan et al., 2008). An important component of the adaptation strategy is an assessment of the vulnerability of the coast to sea level rise (Barth, Titus, 1984; Nicholls et al., 1995; Rotnicki et al., 1995; Zeidler, 1992, 1995; Žilinskas, Jarmalavičius, 1996; Pruszak, Zawadzka, 2005; Nageswara Rao et al., 2008; Abuodha, Woodroffe, 2010; Yin et al., 2012). Coastal recession driven by sea level rise is often roughly evaluated by employing the so-called Bruun Rule (Bruun, 1962, 1988; Bruun, Schwartz, 1985). Although this model was later upgraded (Dubois, 1977; Dean, Maurmeyer, 1983; Leatherman, 1990), its basic principles have remained unchanged till now (FitzGerald et al., 2008). Its applicability has been verified by both laboratory wave tank experiments (Schwartz, 1965) and by field investigations in various coastal regions (Schwartz, 1967; Rosen, 1978; Dean, Maurmeyer, 1983; Zhang et al., 2004; Kaplin, Selivanov, 1995; Corbella, Stretch, 2012). However, according to other authors (Cooper, Pilkey, 2004; Davidson-Arnott, 2005; List et al., 1997; Schuisky, 1999; SCOR Working Group 89, 1991; Paskoff, 2004; Saye, Pye, 2007) this model does not fully reflect natural processes, because of the following reasons:

– Its underlying assumptions (no alongshore transport, all the eroded sand remains within the coastal zone to the depth of closure, sand transport into and over the foredune is ignored) rarely occur in nature (Pilkey et al., 1993);

– Parameters used in the model (in particular the depth of closure and the slope of the equilibrium profile) are not precisely defined (Pilkey et al., 1993; Thieler et al., 2000; SCOR Working Group 89, 1991);

– Uncertainties related to time needed for the beach to readjust to a new position (Healy, 1991);

– Uncertainties related to other natural factors (Cowell et al., 2006).

Due to these disadvantages, Cooper and Pilkey (2004) rejected the Bruun Rule because it was, according to their opinion, incompatible with its purpose. However, they did not offer any reasonable substitute and at present there exist no other universally accepted model for shoreline changes. It is not appropriate to apply a passive flooding model to sandy shores that are subject to substantial wave loads because coastal processes and recession are obviously affected by sea level rise in a more complex manner (Urbanski, 2001; Brunel, Sabatier, 2009). An inundation model can be meaningful only for very gently sloping coasts, for example, salt marches. The ability of probabilistic models to replicate coastal recession due to sea level rise (Cowell et al., 2006; Ranasinghe, Callaghan, 2011) is still under discussion (Pilkey, Cooper, 2006; Cooper, Pilkey, 2007). For the listed reasons, coastal recession has been often evaluated by applying the Bruun Rule and adjusting it to local conditions (Nicholls et al., 1995; Kaplin, Selivanov, 1995; Kont et al., 2003; Snoussi et al., 2009; Kask et al., 2009; Kartau et al., 2011).

Such a broad spectrum of opinions concerning the usability of the Bruun Rule for assessments of coastal evolution shows that the natural development of coasts in response to the sea level rise substantially depends on local conditions. As this model is based on a simple balance equation of sediment volumes, it has a clear relevance in many occasions; however, its potential is limited and it is thus appropriate to apply it with some care, accounting for particular local conditions, and to verify it against data (SCOR Working Group 89, 1991). According to Thieler et al. (2000), there is no universal model for coastal evolution and the most viable alternative is an empirical approach based on local experience.

In this paper, we make an attempt to establish the basic trends of the evolution of the coastline of the Curonian Spit on the basis of coastal monitoring data and cartographic material from the past (starting from 1910), and to assess the adequacy of the Bruun Rule to characterize coastal development in this area under moderate sea level rise.

STUDY AREA AND METHODS

The 51 km long Lithuanian section of the Curonian Spit stretches from the border of the Russian Federation to the southern jetty of the Port of Klaipėda (Fig. 1). This section is characterized by a variety of morphometric and lithological features. Its northern part between Smiltynė and Alksnynė has up to 70 m wide beaches and up to 12 m high foredunes. The average nearshore slope (*tan*θ, where θ is the average sloping angle of the seabed) is about 0.008. The width of the nearshore zone (from the coastline to the seaward border of the breaker zone) is approximately 430 meters. It continues down to a depth of 4.5 m and usually contains 3–4 sand bars. The beach sediments are composed of fine-grained sand (a mean grain diameter (*d*) – 0.18–0.20 mm). To the south of the Klaipėda Strait the width of the beach and the height of foredunes gradually diminish but the nearshore zone becomes wider, and the grain size of bottom sediments increases. At Juodkrantė (Fig. 1), the beach width is 30–50 m, the foredune elevation is 3–5 m, the nearshore zone extends to approximately 500 m (to the 6 m isobath) and its average slope *tan*θ reaches 0.010. Although the nearshore contains only 2–3 sand bars, they are larger than those at Smiltynė. On the beach, coarse-grained sand occurs with a mean grain diameter up to 0.40–0.60 mm. Further to the south, from Juodkrantė to Nida, the beach width increases to 40–60 m and the foredune elevation increases up to 5–7 m. The nearshore zone widens up to 670 m, extends to a depth of 7 m and is marked by 23 distinct bars. The beach is mainly composed of medium-grained sand (*d* in the range of 0.25–0.35 mm) (Žilinskas et al., 2001; Žilinskas, Jarmalavičius, 2007).

We assessed both long and short-term rates of shoreline recession. The analysis of long-term changes covers the period 1910–2010, the changes over which were determined on the basis of carthometric analysis (Pupienis et al., 2012). We used maps from 1910, 1947 (1 : 25 000) and orthophotos from 1990, 1997, 2005 and 2010 (1 : 10 000). The analysis focused on linear trends of the shoreline

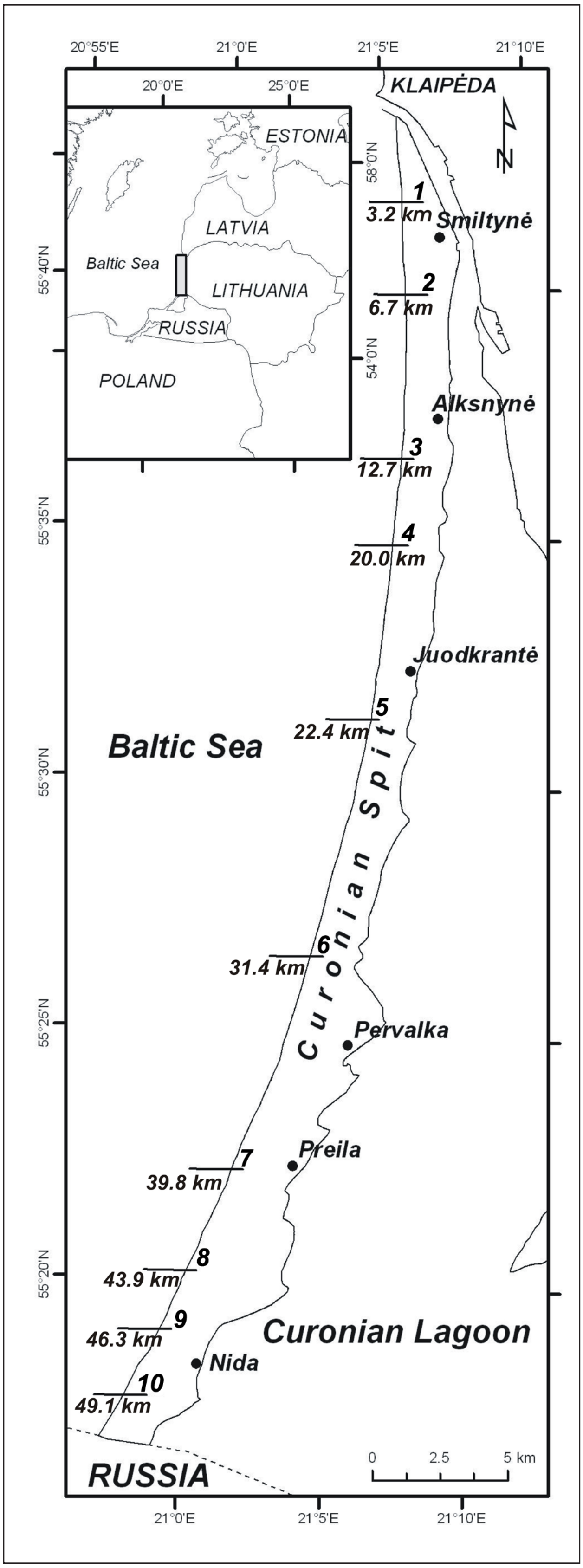

Fig. 1. Location map. *1–10* – measurement sites. Distance (km) from Klaipėda port jetties

1 pav. Tyrimų rajonas. *1–10* – matavimų vietos. Atstumas (km) nuo Klaipėdos uosto molo

displacement (extracted using DSAS software) (Crowell et al., 1997; Douglas, Crowell, 2000; Bagdonavičiūtė et al., 2012). The intersection point of the beach profile and the mean sea level were interpreted as the location of the shoreline.

Short-term changes to the shoreline position were analysed on the basis of coastal monitoring data that have been carried out since 1995. The observations are made once a year, in June, when relatively calm weather is predominant and the sea level is close to the long-term average level. For investigation, 10 coastal profiles were selected (Fig. 1).

In the paper, sea level data of the Klaipėda Tide Gauge Station selected from the archive of the Department of Marine Research were used (Dailidienė et al., 2006). For the evaluation of long-term changes, annual average (over calendar years) sea level data was used. For short-term changes we used monthly average sea level values. As short-term (one-year) coastal changes covered the period from June to May of the subsequent year, the mean annual sea level for the same period was calculated based on the average monthly values.

Bruun (1962) presented the following equation for assessing the coastal possible recession depending on the sea level rise:

$$R = -Hw/h + B,$$

where R is the change in the shoreline location; H is the change in the water level; h is the depth at which waves keep a universal shape of the profile (closure depth); B is the beach elevation near the foredune base and w is the width of the active profile (distance from the shoreline to the seaward limit of sediment motion).

As later modifications of this equation (Dubois, 1977; Dean, Maurmeyer, 1983) do not essentially change the obtained results, its original version (Bruun, 1962) is used in this paper. We associated the parameter B with the beach elevation at the foredune toe, as in 1995–2011 erosion processes mainly took place seaward of the foredune (on the beach). Much greater uncertainties are associated with the determination of the depth of closure (Pilkey et al., 1993; Thieler et al., 2000; SCOR Working Group 89, 1991). According to Bruun and Schwartz (1985), Bruun (1988), based on the maximum wave height, the depth of closure should be about 8 m. However, on the basis of significant wave height (Hallermeier, 1981; Houston, 1996), it was found that the depth of closure should be smaller, in the range of 4.4–6.1 meters. On the basis of coastal sand granulometric composition and morphometric characteristics (Jarmalavičius, Žilinskas, 2006; Žilinskas, Jarmalavičius, 2007) it was concluded that the main sediment movement zone extends to a depth of about 4.1–7.3 m. These depths are smaller than the depths recommended by Bruun (1988), and are close to those calculated according to Houston (1996) and Soomere et al. (2013).

LONG-TERM COASTAL CHANGES

Long-term shoreline displacements varied significantly in individual coastal sectors of the Curonian Spit (Fig. 2). In its northern part, at Smiltynė and Alksnynė, accretion prevailed and the shoreline moved up to 40 m seawards. In the central part of the spit, at Juodkrantė, the shoreline remained nearly unchanged (Profile 5), while in the southern part, at Nida the shoreline has receded by up to 26 m. On average, the observed shoreline accretion over the entire spit was 4 m per 100 years.

At the Tide Gauge Station in the Klaipėda Strait, the mean sea level rose by 0.017 m per 100 years, in 1910–2010. The results of calculations based on the Bruun Rule for this time period are not consistent with the above trends. They indicate that the shoreline should have receded more or less uniformly, about 10 m on average, from 8 m (Profile 5) to 12 m (Profile 9) along the entire spit per 100 years.

A similar pattern of shoreline displacement tendencies existed in 1947–2010. The shoreline moved by up to +39 m (Profile 2) seawards in the northern part of the spit while erosion (retreat by up to 23 m at Profile 8) was evident in the southern part of the spit. During this time period the mean sea level rose by 0.18 m. In this case the Bruun Rule predicts that the coast should have retreated from 9 m to 12 m (11 m on average). This prediction does not correspond to the real shoreline displacement: the shoreline instead advanced by 8 m on average.

The changes to the shoreline are very different in different sections (Fig. 3) and not necessarily

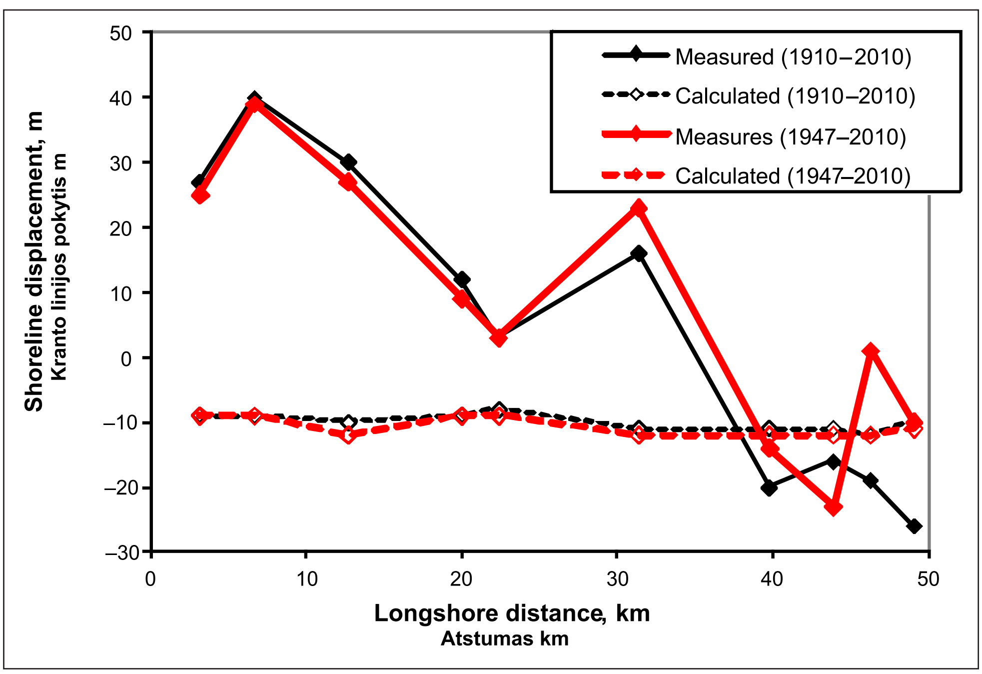

Fig. 2. Measured and calculated according to the Bruun shoreline displacement in 1910–2010 and 1947–2010 in different coast places of the spit. Distance from Klaipėda port jetties

2 pav. Išmatuota ir pagal Bruun formulę apskaičiuota kranto linijos kaita 1910–2010 m. ir 1947–2010 m. skirtingose Kuršių nerijos vietose. Atstumas nuo Klaipėdos uosto molo

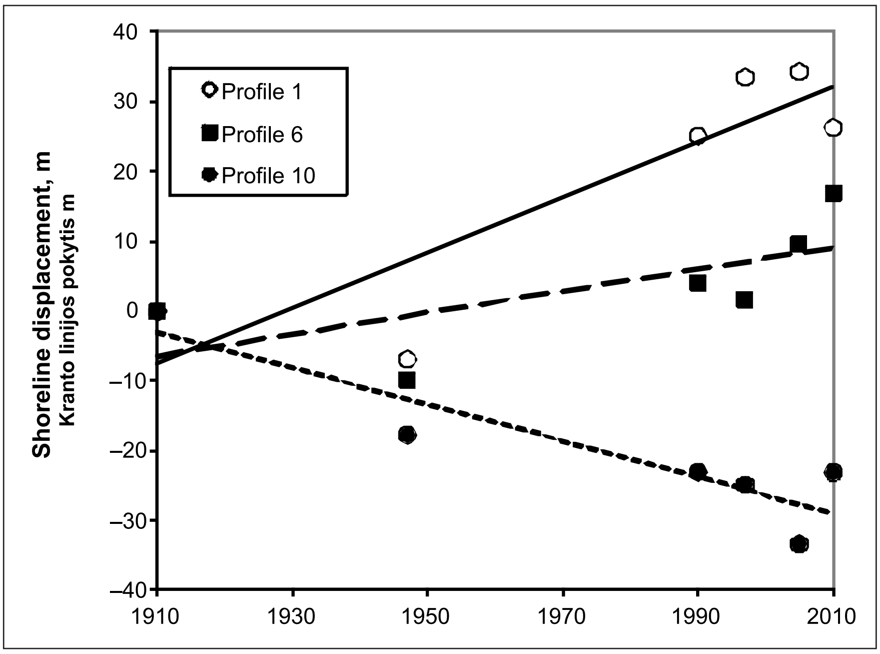

Fig. 3. Shoreline displacements in 1910–2010 and their trends. The locations of profiles are shown in Fig. 1

3 pav. Kranto linijos padėties kaita 1910–2010 m. ir jos linijiniai trendai. Profilių vietos nurodytos 1 pav.

match the variations in the sea level. For example, the shoreline considerably retreated at Profiles 1 and 6 in 1910–1947 when the sea level decreased a little (Fig. 4). However, from 1947 shoreline transgression at Profiles 1 and 6 (but recession at Profile 10) occurred together with a rapid sea level rise (Fig. 4). Unlike the prediction of the Bruun Rule, accretion is recorded together with sea level

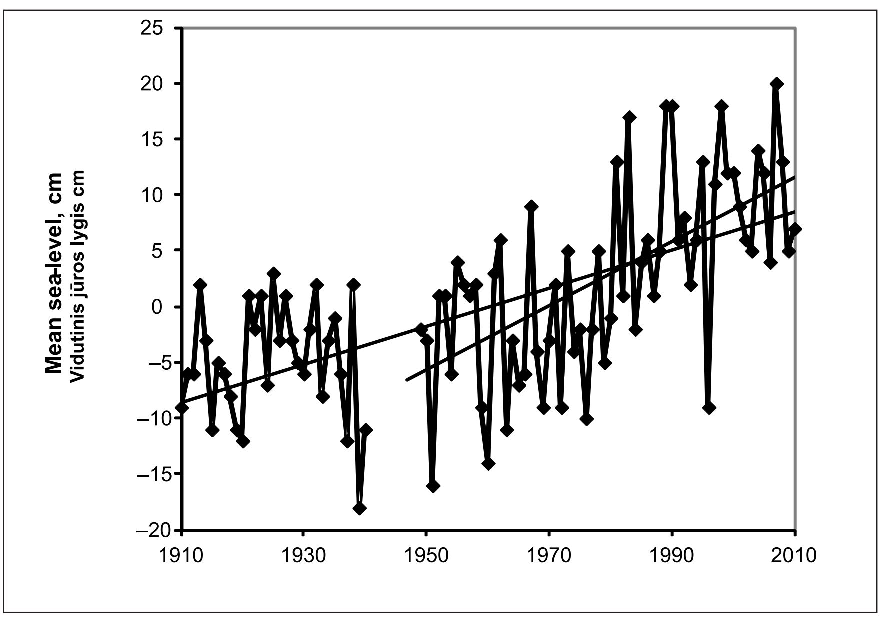

Fig. 4. Mean sea-level fluctuation in 1910–2010 and linear trends from 1910 and from 1947

4 pav. Jūros lygio kaita 1910–2010 m. ir jos linijiniai trendai nuo 1910 m. ir 1947 m.

rise at these sites. Moreover, sea level fall is at places associated with shoreline recession.

It should be noted that because of extensive inner-annual variability of the sea level and the shoreline position it is often not possible to precisely determine trends of shoreline displacements. The described big discrepancies between measured and calculated changes show that the classical Bruun Rule is not an adequate model to predict shoreline changes along the Curonian Spit. Even more, there is no reliable correlation between the sea level and shoreline displacements.

OBSERVATIONS IN 1995–2012

Rates of short-term shoreline dynamics and certain coastal morphometric characteristics were estimated from direct measurements over 17 years (1995–2012, Table). The sea level rise, calculated using linear regression, was 0.04 m during these 17 years. Still, accumulation dominated in the northern part of the spit even in the presence of this sea level rise. The shoreline advanced from 2.9 to 38.9 m. Only in the central part of the spit the shoreline position remained nearly unchanged and in the southern part of the study area the shoreline receded by up to 7.8 m.

The Bruun Rule predicts that the shoreline should have withdrawn by 0.2–1.5 m on average (Fig. 5). In fact, Fig. 6 shows that the shoreline position, averaged over the entire spit, exhibits accumulation and has advanced by 12.3 m per 17 years despite the sea level rise. Still, changes to the sea level and shoreline dynamics for individual years are obviously correlated: large values of the sea level correspond to the recession of the coastline (Fig. 6).

The presented analysis of changes at 10 separate profiles in the last 8 years thus reveals relatively significant differences between measured and calculated values of shoreline changes. The variations of the measured values cover a much wider range than those calculated on the basis of the Bruun Rule. Also, there is no homogeneous tendency in shoreline change for all profiles.

However, considerable differences of the behaviour of the shoreline are evident as short-term fluctuations of the location of the waterline in individual sectors. These differences are somewhat smaller when the trends in the shoreline behaviour are removed. Though they still remain significant, they are smaller than those determined for longer (1910–2010; 1947–2010; 1990–2010) periods for which general tendencies are perceptible (Figs. 7, 8).

Table. **Coastal morphometric characteristics and shoreline displacement over 17 years (1995–2012) determined from measurements and calculated using the Bruun Rule. Positive changes reflect accretion, negative ones reflect erosion**

Lentelė. **Kranto morfometrinės charakteristikos ir kranto linijos kaita per 17 metų (1995–2012), išmatuotos ir apskaičiuotos pagal Bruun formulę. Teigiamos reikšmės – akumuliacija, neigiamos – erozija**

Profile Profilis	**Beach elevation near the foredune toe, m (*B*) Paplūdimio aukštis m (*B*)**	**Active profile width, m (*w*) Aktyvaus profilio plotis m (*w*)**	**Depth of closure, m (*h*) Aktyvaus profilio gylis m (*h*)**	**Shoreline displacement, m (measured) Kranto linijos pokytis m (išmatuotas)**	**Shoreline displacement, m (after Bruun) Kranto linijos pokytis m (apskaičiuotas pagal Bruun)**
1	4	400	4.1	+5.3	–0.3
2	3	360	4.0	+3.4	–1.0
3	2.8	490	5.0	+19.4	–1.5
4	3.2	450	5.8	+21.6	–0.2
5	3.6	430	5.8	+3.6	–0.3
6	3.3	600	6.1	–0.9	–1.0
7	3.1	660	7.6	+38.9	–0.7
8	3.4	630	6.6	+36.9	–0.8
9	3.4	670	6.6	+2.9	–1.1
10	3.1	610	7.3	–7.8	–0.6
Mean	3.3	530	5.9	+12.3	–0.8

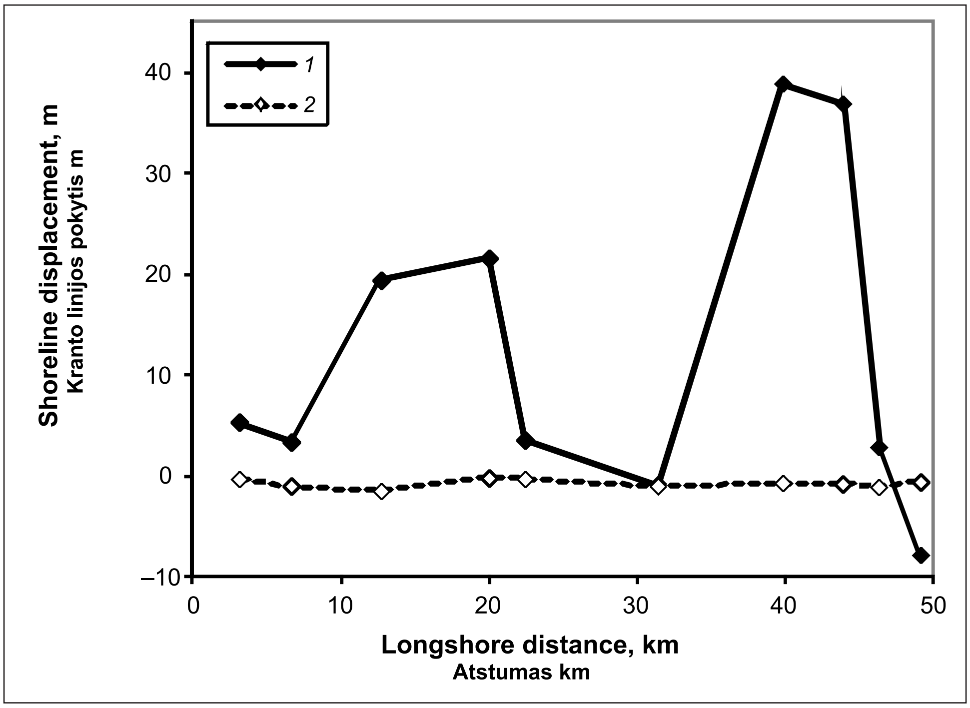

Fig. 5. Shoreline displacement (m) in 1995–2011 in different places of the spit coast. Distance from Klaipėda port jetties. *1* – measured, *2* – calculated according to Bruun

5 pav. Kranto linijos padėties kaita (m) 1995–2011 m. skirtingose Kuršių nerijos vietose. Atstumas nuo Klaipėdos uosto molo. *1* – išmatuota, *2* – apskaičiuota pagal Bruun formulę

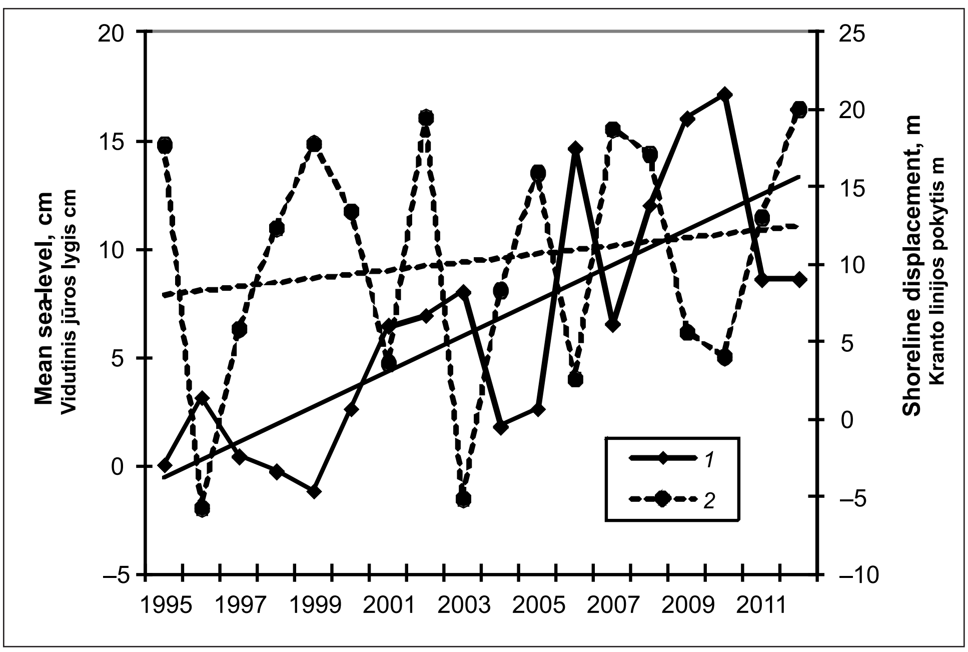

Fig. 6. Fluctuations of the spatially averaged shoreline to the whole spit (*1*) and mean sea-level (*2*) between 1995 and 2011. Position of the shoreline change calculated from the first observation (1995 year) taking it for "0"

6 pav. Vidutinė visos Kuršių nerijos kranto linijos padėties (*1*) ir jūros lygio (*2*) kaita 1995–2011 m. Kranto linijos pokyčiai matuoti nuo pirmo stebėjimo (1995) suteikiant jiems „0" reikšmę

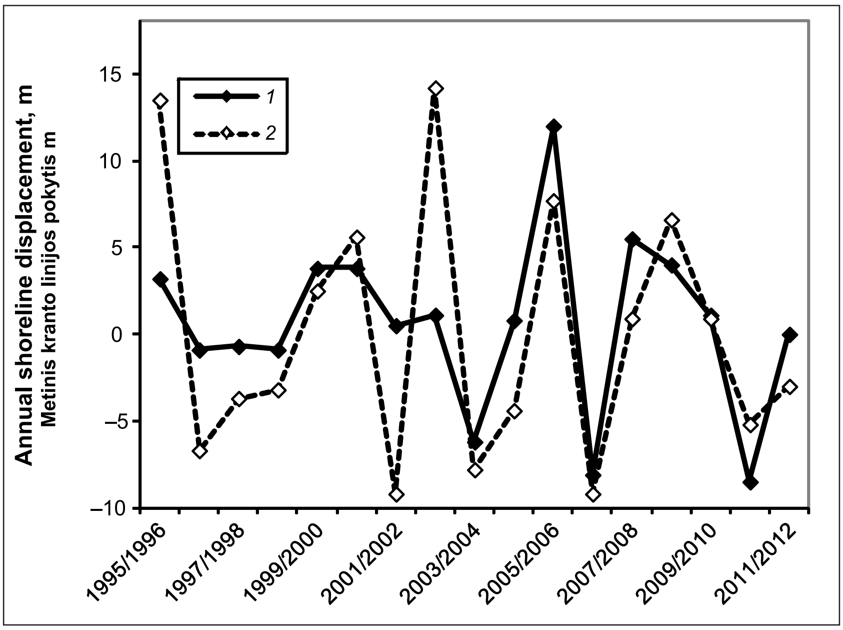

Fig. 7. Yearly coastal changes in 1995–2011. *1* – measured, *2* – calculated on the basis of Bruun

7 pav. Metiniai kranto linijos pokyčiai 1995–2011 m.: *1* – išmatuoti, *2* – apskaičiuoti pagal Bruun formulę

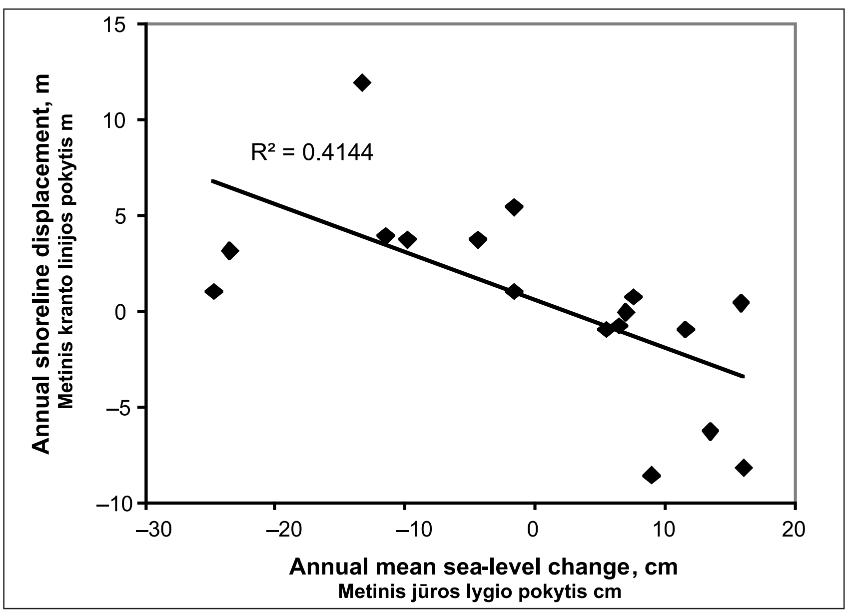

Fig. 8. Relationship between the yearly sea-level change (cm) and the yearly shoreline change (m) in 1995–2011

8 pav. Priklausomybė tarp jūros lygio (cm) ir kranto linijos padėties (m) metinės kaitos 1995–2011 m.

DISCUSSION AND CONCLUSIONS

The presented material signifies that no drastic evolution of the shoreline occurred in 1910–2010 along the considered part of the Curonian Spit coast despite a certain rise in the sea level. The northern part of the spit had predominantly accumulation, in the southern part erosion was observed and the central part remained relatively stable. This shows that a slight sea level rise does not affect coastal dynamics significantly in the study area where much important factors are sand availability (Carter et al., 1987; Hoffmann and Lampe, 2007; Thom, 1983; Selivanov, 1996; Storms et al., 2002), waves and alongshore sediment transport (Dubois, 1992; Shuisky, 1999). It may be therefore concluded that the observed sea level change has played a secondary role in the coastal dynamics of the study area. Furthermore, the coasts often develop not only to reach the equilibrium profile, but also striving for the equilibrium shoreline planform (Jackson, Cooper, 2010). In this case even minor sea level fluctuations eventually have little influence on the shoreline planform configuration.

For the formation of a beach profile, a certain amount of unconsolidated deposits is required. They may originate from the adjacent eroded coastal section. It can be illustrated by the example of alongshore movement of sand waves determined in the Gulf of Finland at the Baltic Sea (Ryabchuk et al., 2012). Therefore, even if the sea level rises, local evolution of a single coastal section and longer stretches can exhibit extensive accretion provided a sufficient amount of sediments is transported from adjacent coastal sections in favourable conditions. The situation along the Curonian Spit is similar, for example, to the southern coasts of Australia (Thom, 1984) where despite rising sea level, in some sections the coasts were eroded, while in other domains accumulation took place. Several other authors (Dolotov, 1992; Shuisky, 1999) also mention that sea level rise does not always lead to shore recession. Aagaard et al. (2007), investigating limiting factors in coastal dunes natural development, also indicated that the period of dunes growth coincides with the period of intense sea level rise. Such processes have probably occurred also in the past evolution of the Curonian Spit. As a result of intensive Sambian (Samland) Peninsula erosion during the Littorina Transgression (about 7.0 ka BP), a large amount of sand was carried to the northeast and gave rise to the formation of the Curonian Spit (Gudelis, 1998). Afterwards, together with the sea level stabilization, the spit formation rates decelerated. Thus, the spit growth can be related to coastal erosion in adjacent coastal segments. Hoffmann and Lampe (2007) described a similar process on the Southwest Baltic Sea coast, when the Holocene coastal barriers system evolution coincided with a sea level rise.

The presented evidence suggests that it is not always appropriate to link the potential coastal recession directly to global warming and associated rapid sea level rise. The rising sea level may under certain conditions accelerate erosion in certain coastal sections. Wave-, wind- and current-driven transport may increase the amount of unconsolidated material (that inevitably has to be somewhere accumulated) in other coastal sections. Also, a decrease in the amount of sediments in the coastal zone may result in beach erosion. Therefore, it is not acceptable to assess possible coastal recession rates for the future by means of considering only coastal morphometric characteristics, which are known to contain extensive uncertainties (Pilkey et al., 1993; Thieler et al., 2000; Cooper, Pilkey, 2004).

Importantly, the presented data show that the influence of sea level fluctuations is clearly reflected in short-term (one-year) changes in the location of the shoreline. An individual profile is very volatile because of nonstationarity of rhythmic shoreline topography; therefore the impact of sea level rise can be assessed only for comparatively long coastal sectors. The above analysis showed that beach profiles fairly quickly adjusted to changes in the sea level. According to Alison et al. (1982) the time of beach adjustment to sea level rise is proportional to the square of the amplitude of sea level change. A beach profile can respond to a sea level rise by 0.5 m in a few hours. Thus, despite the uncertainty of the readjustment time (Healy, 1991), it may be ignored considering the annual period.

The main outcome of the study is that the sediment budget and recession or advancement of the coastline of the Curonian Spit are largely governed by alongshore and cross-shore sediment transport and sea level changes play a secondary role. This is consistent with the understanding that response to the sea level change should be evaluated based on local characteristics of particular coastal sections and, ideally, should be based on observations (SCOR Working Group 89, 1991).

There are several reasons why a long-term sea level rising trend is not reflected in the coastal dynamics of the Curonian Spit. Firstly, the coast of the Curonian Spit is a complex system with non-linear interactions between the coastal system and its driving factors. As the natural development of the spit is determined by a number of mutually-interacting factors, the impact of long-term sea level rise is not necessarily reflected in the long-term shoreline displacement. Secondly, as the sea level trend is small (0.017 m/100 yr), other factors (waves, alongshore sediment transport) evidently have a greater effect on coast development. Still, short-term (annual-scale) sea level changes, with much larger amplitudes (dozens of cm), are clearly reflected in the coastal dynamics.

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JŪROS LYGIO KILIMO POVEIKIS KURŠIŲ NERIJOS KRANTO KAITAI

Santrauka

Manoma, kad kylantis pasaulinio vandenyno lygis skatina krantų eroziją. Krantų recesijos tempui įvertinti dažnai naudojama Bruun formulė. Pastarosios verifikavimui, remiantis Lietuvos Kuršių nerijos dalies krantų kaitos duomenimis, ir skirtas šis straipsnis. Pagal įvairių metų žemėlapių palyginimo bei kranto monitoringo duomenis buvo nustatytas Kuršių nerijos kranto kaitos tempas. Gauti rezultatai buvo palyginti su apskaičiuotais pagal Bruun formulę. Nustatyta, kad tik atskirais metais vidutiniai visos tiriamos kranto atkarpos linijos pokyčiai siejasi su vandens lygio pokyčiais, o daugiametės kranto linijos kaitos tendencijos nesisieja su vandens lygio kilimo trendu. Nepriklausomai nuo kylančio vandens lygio Lietuvai priklausančioje Kuršių nerijos pietinėje dalyje nuo 1910 m. stebima kranto recesija, šiaurinėje – akumuliacija (*accretion*), o vidurinė dalis išlieka santykinai stabili.

Raktažodžiai: jūros lygio kilimas, kranto arda, Bruun formulė, Kuršių nerija