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Coastal sediment balance in the eastern part of the Gulf of Riga (2005–2016)

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Abstract A hurricane known as Ervin or Gudrun travelled over Latvia in 8–9 January, 2005. As a result of severe SW and W winds, as well as lack of sea ice, clearly pronounced changes in the distribution of coastal sediment has been induced. Cross-shore profile leveling at various time instants was used to obtain quantitative estimates of the amount of accumulated sediments. The total volume of sediments eroded from the subaerial part of coastal slope reached 0.8 million m^3. This paper represents assessment of consequent changes and coastal slope "rebuilding" success after this storm event. The data indicates lack of significant overall net loss of subaerial sediment volume along the most part of the eastern coast of the Gulf of Riga. Significant primary dune growth and beach accumulation is mostly limited to southernmost part of assessed coastal stretch. Total volume of fine sediments in beach and primary dunes still is 5 % lower than before erosion event of 2005. Erosion vulnerability and total length of coastal sections that are expected to be a subject to future coastal retreat is increasing.

Keywords • *Gulf of Riga • coastal processes • storms • sediment balance • beach • retreat*

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INTRODUCTION

Human intervention in the particularly complex naturally occurring phenomena – coastal evolution, may, to some extent, disturb existing quasi-equilibrium, causing accelerated erosion in some sections and accretion in others (Pranzini, Williams 2013). Gulf of Riga coastal zone is area of particular economic and social vulnerability to erosion due to its relatively high extent of development (Eberhards 2003). Coastal erosion and retreat may represent management challenges and obstacles that are difficult to overcome for use of affected coastal areas.

The first published scientific information concerning coastal processes in Gulf of Riga date from the 1930's and 1940's (Sleinis 1937). One of the most comprehensive look at coastal origin, morphology, and recent coastal processes was the monograph by V. Ulsts (1957). Other publications by V. Ulsts *et al* (1967) contain findings in the patterns and differentiation of the transport of sediments in the lithodynamic zone. During the second half of the 20th century coastal research continued in fields of modern coastal processes and lithodynamics (Veinbergs *et al.* 1982; Venska 1990). From 1987 to 1994 coastal monitoring network was created, covering most of the coastline of Latvia (Eberhards, Saltupe 1999). Based on the data obtained from coastal monitoring network (Eberhards *et al.* 2009), several assessments dedicated to the coastal erosion and damage done by the hurricane of 2005 was published (Eberhards, Saltupe. 2006, Eberhards *et al*. 2006).

STUDY AREA

Eastern part of Gulf of Riga in Latvia (from mouth of Gauja River to the border with Estonia) is approximately 87 km long. It stretches mostly in submeridional (N-S) direction and thus exposed to dominant southwesterly (SW) and westerly (W) winds, as well as rare, but impactful NW storms. The coastal features are formed mostly of Quaternary deposits. For the most part coastline is straightened by erosion-accumulation (Ulsts 1998). The range of coastal environments includes moderate energy, sediment rich to sediment deficient sections. Beaches are consisting mostly of sandy material. Significant part of coastal area is undeveloped and has only several localized spots of anthropogenic impact on sediment balance (Ulsts 1998; Eberhards, Lapinskis 2008).

The coastline of study area can be conditionally divided into sections that differ according to coastal morphology and dominant morphodynamic processes: the southern part (Gauja River – Inčupe River), the central part (Inčupe River – Vitrupe River), and the northern part up to the border with Estonia (Eberhards 2003) (Fig. 1). Coastal area within central and northern part of the study area is characterized by relatively pronounced deficit of fine grained sediments. Due to that, dominant beach width rarely exceeds 30 m, and development of primary dunes also is rare. In contrast – southernmost part of study area is supplied by coastal sediment drift and thus contains large amounts of sand both in nearshore and in well developed ridge of primary dunes (Eberhards 2003).

In central part of study area soft cliffs formed in various Quaternary deposits, as well as hard cliffs in Devonian terrigenous clastic sedimentary rock are occurring. According to previous publications, rate of bluff/cliff retreat in this section during the last 70–100 years was around 0.05–0.5 m/year (Eberhards, Lapinskis 2008). Significant part of this coastal section is characterized by densely borne boulders covering upper part of underwater slope and beach. These are remnants of glacigenic deposits and are acting as a barrier, limiting the wave action and impact on the coastal morphology. Area around the mouth of the Lilaste River is a convergence zone of local longshore sediment flow (Ulsts 1998), and thus is represented by most notable foredune ridges reaching more than 5 m in height. Coastal area in northern part of study area is particularly gently sloping and sediment deficient, thus – typical features of subaerial coastal slope (beach and primary dunes) usually are very underdeveloped.

With few short exceptions, the beach is present in all of the study area. It has a very important role in the coastal system. During storms, it is the location of large-scale longshore transport and, together with the primary dunes, acts to ensure the long-term stability of the system, accumulating sediments in calm conditions, and supplying it under extreme conditions to sediment-deficient zones of the coastal slope, simultaneously dissipating and dispersing incoming wave energy (Rijn 1998; Komar 1998; Lapinskis 2010).

EROSION CAUSED BY STORM OF 2005

During the hurricane of 2005, eastern part of the Gulf of Riga was subjected to severe conditions due

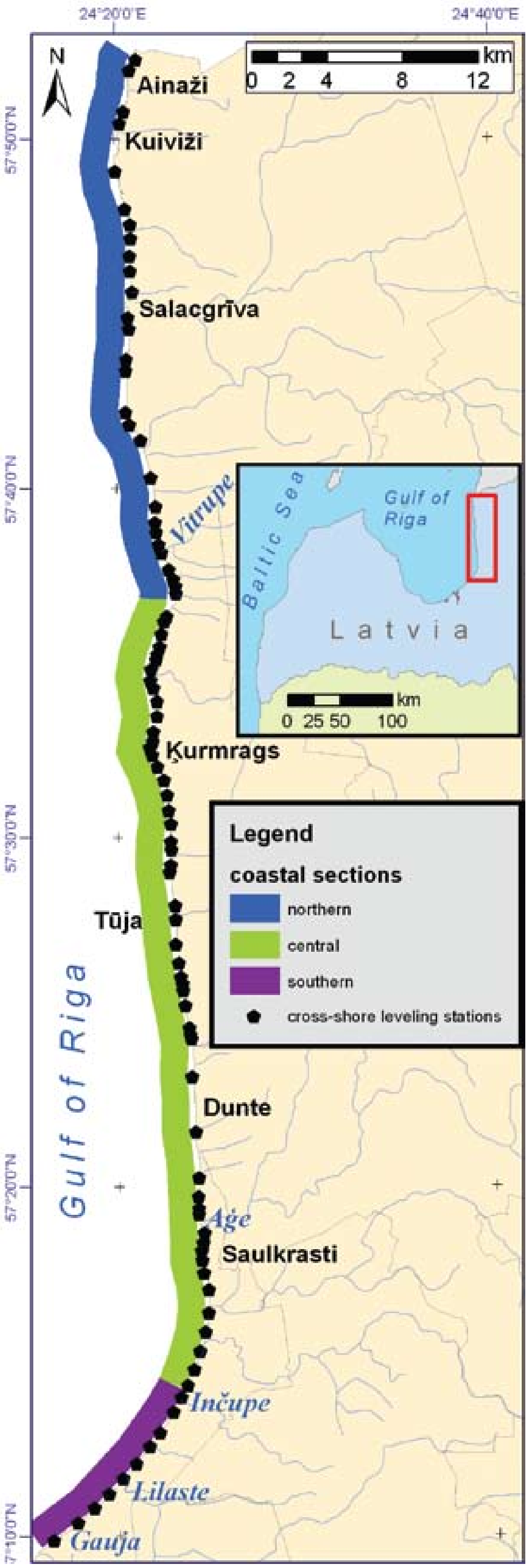

Fig. 1 The study area, location of leveling transects and the division in three coastal sections according to differences in coastal morphology and morphodynamics. All figures in the article compiled by J. Lapinskis.

to particularly high surge level that persisted for more than 24 hours. According to calculations, erosion rate reached maximum in proximity of the mouth of the Gauja River, where, 20–40 m^3/m of fine grained sand was removed from beach, primary dunes and older forested dunes. Retreat of the sandy bluff face in Saulkrasti reached 10–15 m (Eberhards *et al.* 2006; Eberhards *et al.* 2009).

It has been suggested, that the impact of severe storms and their lasting effect on the coastal zone are magnitudes higher that that of "typical" storms (Rijn, 1998). The changes in coastal sediment distribution and slope parameters generated by such rare events can persist for decades and create new coastal retreat risk areas in long-term.

The objectives of this study are:

- to describe the coastal changes on eastern part of Gulf of Riga, Latvia, that has occurred since hurricane Ervin on January 9, 2005;
- to obtain conclusions about the coastal sediment balance on the basis of the observed post-storm slope "rebuilding" success.

MATERIALS AND METHODS

Coastal geological processes monitoring network in study area consists of 90 cross-shore leveling stations that are perpendicular to the coastline and are covering subaerial part of the coastal slope. The measurements have been conducted on the yearly basis in late summer and early autumn. Using local fixed benchmarks of known elevation during leveling data analysis, adjustments are made, to take into account deviation of sea level from the mean sea level datum. The placement of each profile has been chosen corresponding to the specific properties of the general coastal parameters in the area, so that it would be possible to obtain information about all varieties in terms of sediment balance. Leveling profiles are placed more densely in those coastal sections where earlier publications have already shown the balance of sediments to be far from neutral (Eberhards, Saltupe 1995; Ulsts 1998). The data are available in the database of the Laboratory of coastal processes at the Faculty of Geography and Earth Sciences of the University of Latvia.

Analysis of changes (dynamics) in the volume of sediment, was undertaken separately for the beach and the active aeolian relief (primary dunes, if present) employing a least squares technique. For the purpose of this study, assumption was made, that the upper limit of the beach is the foot of the primary dune or bluff/cliff. Accordingly, the upper limit of primary dune was taken as the point where vertical changes resulting from aeolian processes do not exceed 0.02 m in one year.

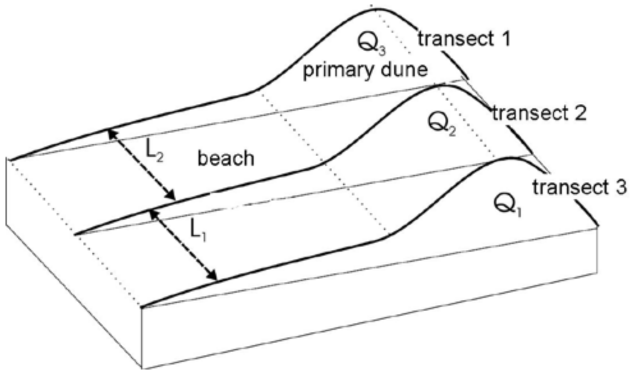

Fig. 2 Parameters used for beach and primary dune deposits volume calculation.

The amount of beach and primary dune forming sediments were processed by using the formula (Lapinskis 2010):

$$V = \sum_i \frac{(Q_i + Q_{i+1}) \cdot L_i}{2}, \text{ where (Fig. 2):}$$

V – volume of sediments in a particular coastal area (m^3);
i = 1, 2, ...n.;
Q – area of coastal slope cross-section (m^2);
L – distance between coastal slope cross-sections (m).

Application of this approach is based on the assumption that two neighboring coastal transects are representing simple average sediment volume of coastal stretch between those transects. Limitations of this approach are associated with decrease in reliability of the obtained data as the distance between transects increases. The calculated data from each section are arranged in 2-D graph, where X is the year of survey, and Y is the eroded/accreted sediment volume relative to the summer of 2004. This permits the determination of annual changes in sediment balance. Coastal changes in sections between measurement sites are interpolated.

After an analysis of the data obtained from the on-site cross-shore leveling stations, a map of the predominant coastal processes of study area was made, maximum coastal changes (sediment balance in beach and primary dunes) were determined, and in coastal sections subjected to – the long-term rate of coastal erosion was calculated $m^3/m/year$.

RESULTS AND DISCUSSION

Long-term changes within coastal system that are driven by major climatic trends do not necessarily coincide with the localized, short-term coastline variability that can be caused by particularly heavy storm impacts and seasonal variations in the hydrodynamic activity of the sea (Pachauri, Reisinger 2007). A consecutive measurement time series of at least ten years regarding the volume of material forming the beach and the primary dune (if present) allows each coastal section to be assigned to a certain type of dynamic change, and permits determination of its long-term sediment budget (Lapinskis 2010). Long-term monitoring data should be applicable to projection preparation as to the reaction of this coastal section to extreme future meteorological phenomena.

The parameters of all shore slope types tend to adapt to the prevailing wave conditions and the amount of available sediment. The typical profile of the shore slope formed in fine-grained sediments is very poorly adapted for storm conditions, when wave energy considerably exceeds the mean level, and water level rises due to storm surge. Generally, it rapidly obtains a gentler slope, which is possible at the expense of eroded material from the upper part of the slope. After the storm event, under low-energy wave conditions, the slope should regain its previous parameters. This happens much more slowly, with a gradual landward movement of sediment, thus making the profile as such steeper and in better equilibrium with the hydrodynamics of low-energy wave action (Rijn 1998; Lapinskis 2010).

According to total sediment volume changes calculated, three coastal evolution trends can be distinguished within study area (Figs. 3, 4). For the purpose of this study, certain thresholds of sediment budget changes have been adopted – coastal section has been considered as being dominated by erosion or accumulation respectively if average sediment volume change is more than 0.5 m^3/m/year. Approximately 24 % (20.4 km) of study area is dominated by erosion, 46 % (39.0 km) is dominated by accumulation and 30 % (27.6 km) does not show significant long-term changes. It must be noted, that only 20 % of accumulation dominated coastal sections exceeds rate of accumulation greater than 1m^3/m/year, but more than 75 % of erosion dominated sections exceeds rate of erosion greater than 1 m^3/m/year.

Loss of sediments caused by storm of January 2005 has been relatively similar within all study area, reaching volumes around 10 m^3/m with some short exceptions, where eroded volume was as high as 40 m^3/m. For the majority of study area, during the years without severe storm events (2008–2016), the volume of beach and primary dune sediments has fluctuated from year to year by less than 3.0 m^3/m, and this applies to all morphodynamic coastal types (Figs. 3, 4). Contrary to that, during the first year after the 2005 and 2007 storm events, volume of beach and foredune forming material has in many places been increased by 4–8 m^3/m, which in some sections corresponds to more than 40 percent of total sediment volume respectively. In short, the so-called intensive post-storm recovery phenomena can be observed in

Fig. 3 Morphodynamics of subaerial part of coastal slope during the study period. Southern part of study area. Note that the division of study area in two parts (Figs. 3, 4, and 7–10) is made solely for the purposes of figure management convenience.

all coastal types during the first year after erosion episode (Figs. 5, 6). More pronounced accumulation takes place as well in coastal sections where previous erosion was insignificant.

As the relatively calm conditions persist, sediment accumulation intensity decreases, however pre-storm sediment volume has been achieved in all accumulation dominated coastal sections. The situation differs significantly in coastal sections with chronic sediment deficiency – pre-storm volumes are never reached and several years after storm event gradual decrease in total sediment amount can be observed. As a result, the total sediment volume and volume maximums in 2016 was slightly lower, but in several sections between Vitrupe River and Salacgrīva even lower by as much as 50–60% compared with year 2004 (Fig. 6).

Fig. 4 Morphodynamics of subaerial part of coastal slope during the study period. Northern part of study area.

In the central and northern part of the study area, the cumulative fluctuations in sediment volume during study period are insignificant. This indicates much lower cross-shore and longshore transport intensity due to lower energy wave conditions, and the chronically sediment deficient conditions in these sections (Figs. 7–10).

Southern coastal section stands out from the rest of the study area – the sediment volume of the primary dunes within southern coastal section has been gradually increasing during the whole period of observation and formation of new dune ridge in certain areas has occurred. In the first three years after the storm of 2005, beach face, back beach and primary dune regained all of the lost sediment volume. Contrary to that, in the central part of study area a considerable amount of beach and bluff/cliff material has been eroded in years after the 2005 storm event. In certain coastal stretches, coastal retreat rate persists within range of 0.2–0.6 m/year, formation of primary dunes does not take place at all, and volume of beach sediment remain very low (Figs. 7–10).

In the Skulte River – Vitrupe River section, where 8.5 km of low and underdeveloped fore-dune stretches where present before 2005, recovery of the primary aeolian relief is occurring at a particularly slow rate, and 12 years after the storm only approximately 3.8 km of embryonic dune can be seen.

During hurricane Ervin a considerable amount of sandy material has been mobilized and consequently transported to previously typical accretional sections of the study area, as well to the coastal sections affected by harbour hydrotechnical constructions. Transport of sediment further down the underwater slope, than would ordinarily be the case, during hurricane can be considered as another probable explanation for exceptionally weak post-storm accumulation in coastal sections previously characterized by long-term stability or slow retreat.

Given the lack of severe storm events after 2007, it can be assumed that the observed coastal evolution patterns in central coastal section are possible due to the increasing fine-grained sediment deficit in the coastal zone, negatively reinforced by existing anthropogenic interference – hydrotechnical and anti-

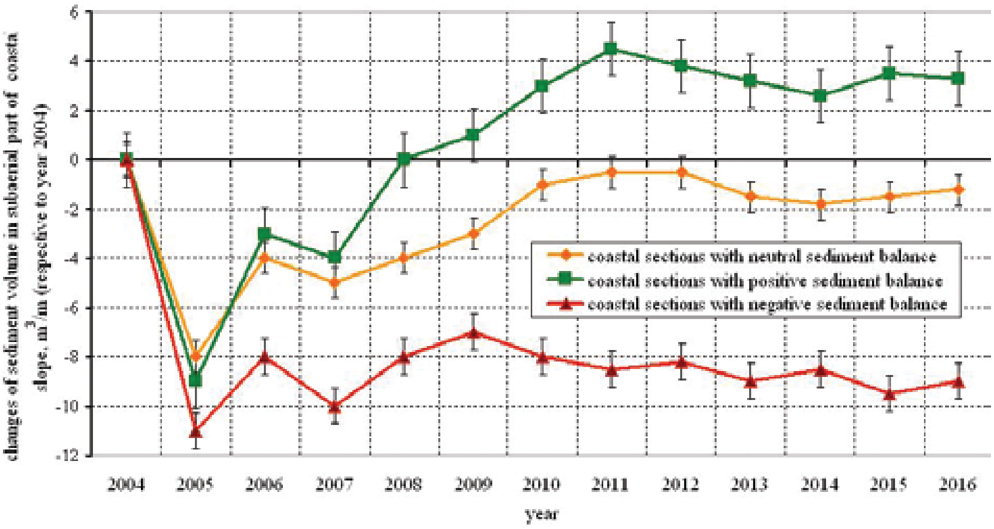

Fig. 5 The simple arithmetic average sediment volume of the subaerial part of coastal slope (beach and primary dune) within coastal sections with different evolution tendencies (in m^3 per meter of coastline), compared to the pre-storm conditions (year 2004).

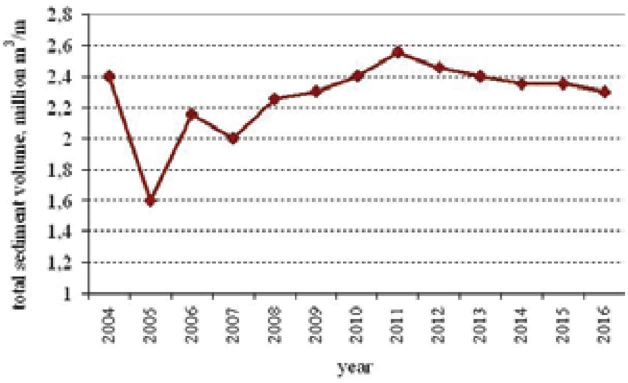

Fig. 6 The total sediment volume of the subaerial part of coastal slope (beach and primary dune) in the in the study area, compared to the pre-storm conditions (year 2004).

erosion structures, as well as gradually increasing recreational load.

The presented results are consistent with theoretical analysis of alongshore sediment transport parameters within study area (Vi ka, Soomere 2013). The coastal sections with alongshore sediment transport divergence and convergence conditions are corresponding with those where the erosion or accumulation on the coastal subaerial part is most pronounced.

In previous publications different authors have been dividing the Gulf of Riga coast into sections according to the dominant tendencies in morphodynamics. According to studies conducted during late 20-th century (Ulsts 1998), prevalence of coastal stretches prone to accumulation was slightly lover. It should be particularly noted, that there are significant changes in spatial distribution of erosion and accumulation dominated localities if compared to situation during 1980-ties. In accordance with Eberhards (2003), study area is consisting of many short stretches with varying and different degree of erosion intensity, interspersed with stable and stagnant coastal sections. Evaluation of storm of 2005 impact retention (Eberhards *et al.* 2006; Eberhards, Saltupe 2006), notes that the lasting negative consequences and significant increase of future erosion rate are not to be expected.

CONCLUSIONS

The analysis of field data revealed several distinct tendencies of coastal evolution within study area. Considering the study period, witch probably was to some extent uncommon – extremely severe storm event in 2005 followed by 12 years with little or no storm activity, resulting overall net loss of subaerial sediment volume was insignificant. Several new coastal erosion sections have appeared in expense of previously stable coast. Nevertheless, accumulation intensity within typical accumulative coastal sections are somewhat compensating for land loss in cliffed, sediment deficient coastal sections. Beach and primary dune sediment volume within most of the analyzed transects remains fairly stable in the long-term, still there are exceptions – approximately 20 km (24% of study area coastline) are considered erosion dominated with 3–25 m^3/m sediments lost since 2004. Without direct linkage to the total sediment balance in each coastal stretch, activity of accumulation becomes significantly more pronounced during the first year after storm event.

It is possible to identify coastal sections with long-term sediment volume changes possibly driven by artificial factors. These stretches form approximately 8% of the study area where sediment volume changes within these sections are occurring at higher rate and more pronounced tendency than in similar sections without anthropogenic impact.

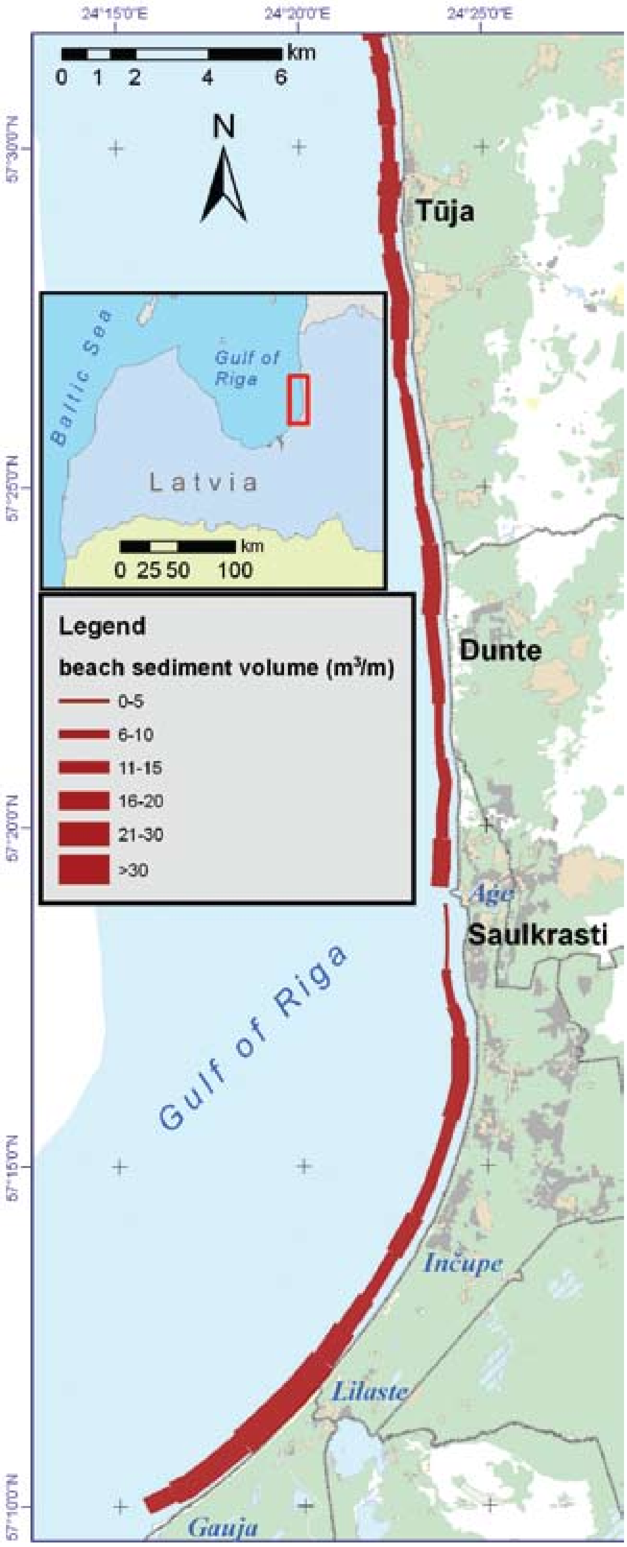

Fig. 7 Total beach sediment volume during the summer of 2016. Southern part of study area.

Fig. 8 Total beach sediment volume during the summer of 2016. Northern part of study area.

In general, it can be assumed that previously published erosion assessments and coastal classification attempts are rather consistent with our results, but observed inconsistencies suggest some acceleration of coastal change during past decades.

Partly as a result of severe erosion during hurricane of January 2005, "guerilla" coastal protection actions in the most erosion prone areas have been intensified. While until now the possible negative consequences of such actions are not unambiguously identifiable, probability of erosion section "migration" and overall erosion intensification is very real.

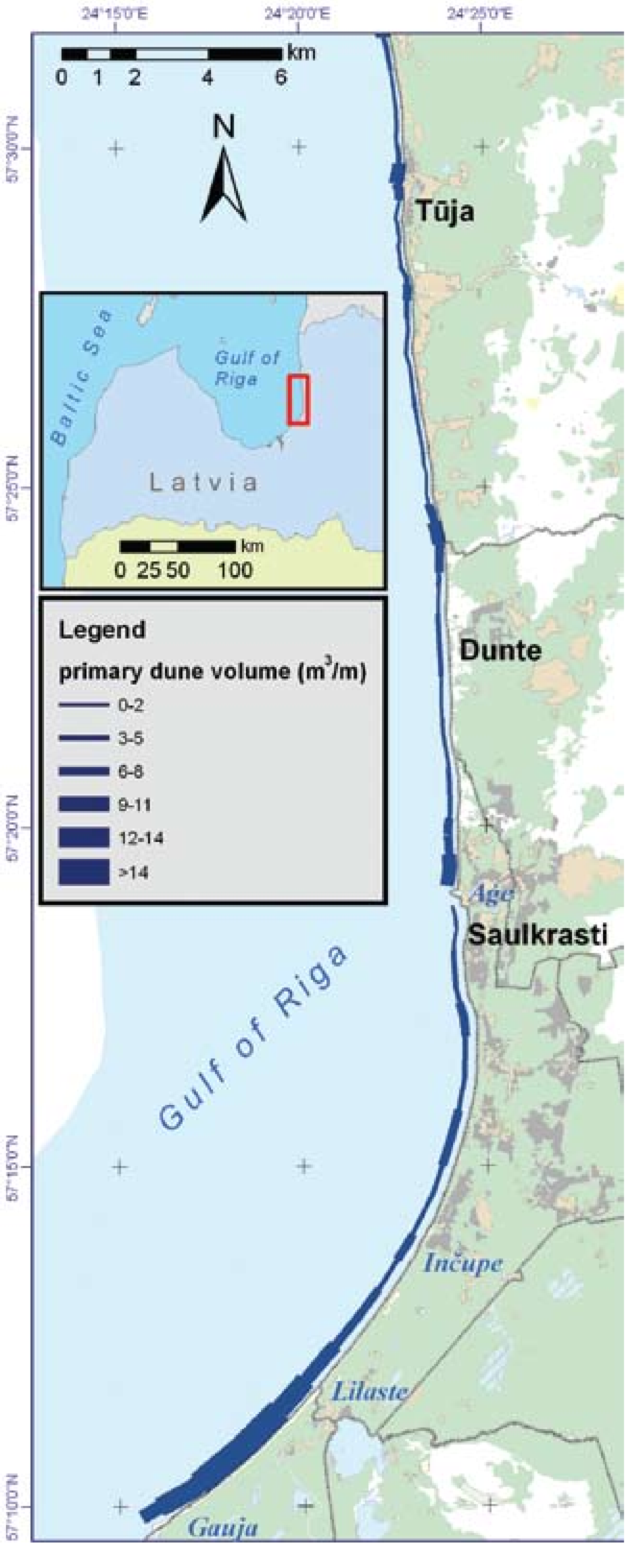

Fig. 9 Total primary dune sediment volume during the summer of 2016. Southern part of study area.

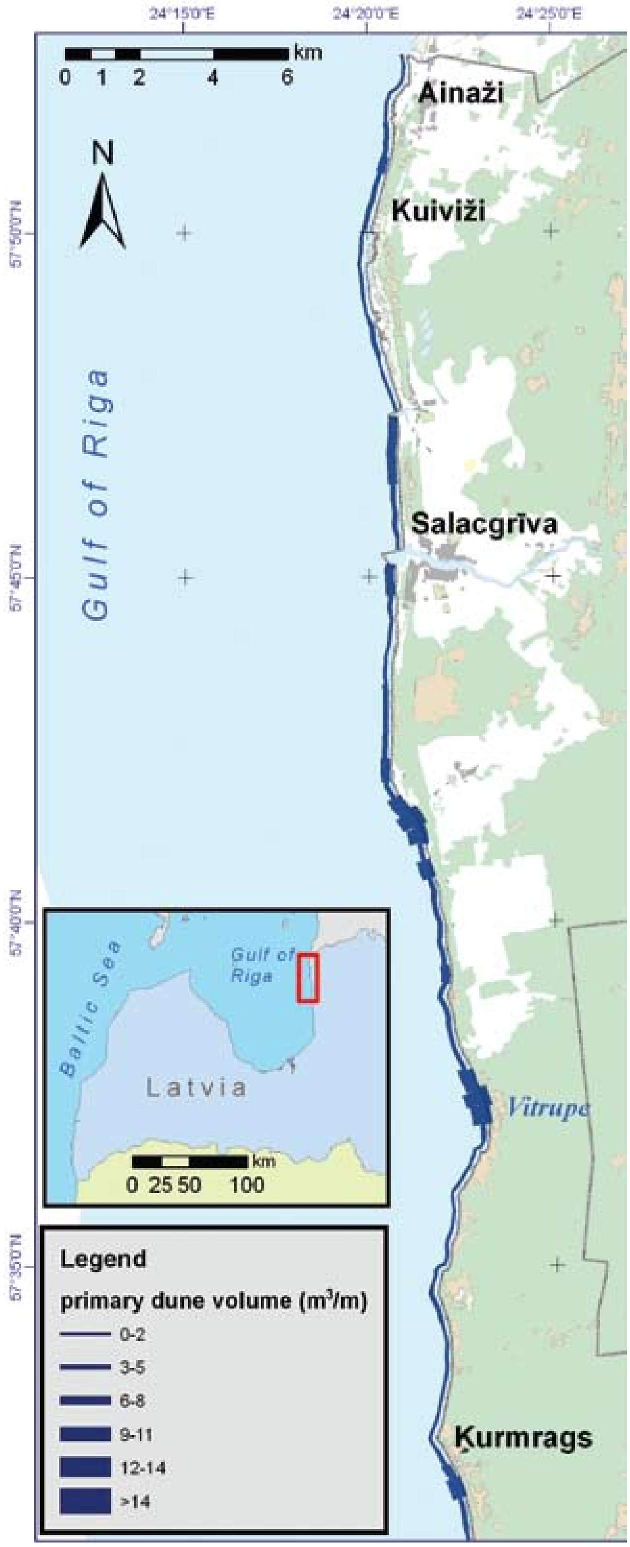

Fig. 10 Total primary dune sediment volume during the summer of 2016. Northern part of study area.

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