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# Simulated wave-driven sediment transport along the eastern coast of the Baltic Sea

Tarmo Soomere<sup>a,b</sup>, Maija Viška<sup>a,\*</sup>

<sup>a</sup> Institute of Cybernetics at Tallinn University of Technology, Akadeemia tee 21, 12618 Tallinn, Estonia

<sup>b</sup> Estonian Academy of Sciences, Kohtu 6, 10130 Tallinn, Estonia

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## ABSTRACT

Alongshore variations in sediment transport along the eastern Baltic Sea coast from the Sambian (Samland) Peninsula up to Pärnu Bay in the Gulf of Riga are analysed using long-term (1970–2007) simulations of the nearshore wave climate and the Coastal Engineering Research Centre (CERC) wave energy flux model applied to about 5.5 km long beach sectors. The local rate of bulk transport is the largest along a short section of the Sambian Peninsula and along the north-western part of the Latvian coast. The net transport has an overall counter-clockwise nature but contains a number of local temporary reversals. The alongshore sediment flux has several divergence and convergence points. One of the divergence points at the Akmenrags Cape divides the sedimentary system of the eastern coast of the Baltic Proper into two almost completely separated compartments in the simulated wave climate. Cyclic relocation of a highly persistent convergence point over the entire Curonian Spit suggests that this landform is in almost perfect dynamical equilibrium in the simulated approximation of the contemporary wave climate.

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## 1. Introduction

The coasts of the Baltic Sea can be divided into two large categories. Bedrock-based, frequently skären type predominates along its northern coast, starting from the vicinity of Saint Petersburg and extending over the entire Bothnian Sea and the Gulf of Bothnia down to the south-eastern (SE) part of Sweden. Sedimentary coasts predominate along the southern and eastern coasts of this water body, from the southern tip of Sweden over Denmark, Germany, Poland and the Baltic states. Most of the coasts of Estonia are heavily fragmented by numerous islands, peninsulas and bays deeply cut into the mainland. This fragmentation confines alongshore sediment transport into relatively small almost disconnected compartments (Soomere and Healy, 2011).

The longest connected domain of sedimentary coasts of the Baltic Sea, the focus of the current study, stretches from the Sambian Peninsula to the east and north-east (NE), and extends up to the eastern coast of the Gulf of Riga (Fig. 1). This section is generally thought to represent a large, more or less continuous sedimentary system (Žaromskis and Gulbinskas, 2010). An idealised view is that sediment is mostly transported counter-clockwise along both the SE coast of the Baltic Proper (Gudelis et al., 1977; Knaps, 1966) and the southern and eastern coast of the Gulf of Riga, with a discontinuity and/or partial discharge at the Kolka Cape (Žaromskis and Gulbinskas, 2010). As typical for the Baltic Sea, sediment transport along this section is not necessarily continuous (Knaps, 1982). While the Curonian Spit is a sandy landform, large parts

of underwater slope in Latvia are covered with boulders, pebbles and coarse sand washed out of till. Only a few parts of the Latvian nearshore host large amounts of fine sediment, for example, coasts of Irbe Strait, southern part of the Gulf of Riga and a short coastal section to the SE of Kolka Cape (Ulsts, 1998).

During the existence of the Baltic Sea in its contemporary shape, this coastal domain has undergone remarkable changes. The sediment volume eroded from the Sambian Peninsula has been partially transported to the east and NE, and created the Curonian Spit (Žaromskis and Gulbinskas, 2010). The Lithuanian and Latvian coasts further to the north of the Curonian Spit have been markedly straightened by prolonged marine erosion and deposition (Eberhards, 2003; Eberhards et al., 2006; Gudelis, 1967; Knaps, 1966; Ulsts, 1998). The changes are less marked in the Gulf of Riga but still substantial even in relatively sheltered areas such as Pärnu Bay (Kartau et al., 2011). As a result, most of the domain in question consists of two main types of coasts: cliffed abrasional parts, with more or less clearly defined scarp or bluff in usually relatively soft cliffs, and gently sloping, generally advancing depositional coasts (Eberhards, 2003; Eberhards et al., 2006; Gudelis, 1967).

Almost all these coasts develop under overall sediment deficit (Eberhards and Lapinskis, 2008; Kartau et al., 2011; Žaromskis and Gulbinskas, 2010) and weak uplift of the crust superimposed with climatically controlled sea level rise (Harff and Meyer, 2011). They are thus very sensitive to changes in the hydrodynamic loads (Eberhards et al., 2006) and especially to the sea level rise. Even sections that usually show accumulation features such as the Curonian Spit may be heavily damaged in certain storms (Žaromskis and Gulbinskas, 2010). Large parts of the Latvian coast are estimated in terms of risk of erosion as either “very vulnerable” or “vulnerable”. Such risk of erosion is most common

\* Corresponding author. Tel.: +372 6204178; fax: +372 6204151.

E-mail address: [majja@ioc.ee](mailto:majja@ioc.ee) (M. Viška).

along both the Baltic Proper coast (69%) and the coast of the Gulf of Riga (66%) (Eberhards, 2003; Eberhards et al., 2006).

The major factor shaping the coasts in the almost tideless Baltic Sea (Leppäranta and Myrberg, 2009) is the wave activity. Although currents do play a role in the transport of fine material in the offshore, in this paper we focus on sediment transport processes in the surf and swash zone governed by wave activity. In this light it is natural that rapid erosion events at certain locations in the recent past (Eberhards et al., 2006; Orviku et al., 2003) are associated with a combination of changes to the wave climate and with a decrease in the length of the ice season (Orviku et al., 2003; Ryabchuk et al., 2011; Tõnisson et al., 2011). Although there may exist extensive interannual and considerable decadal-scale variations in the (annual mean) wave height at certain locations (Soomere and Räämet, 2011), no long-term changes to the spatially averaged annual mean wave height have been identified in the entire Baltic Sea (Broman et al., 2006; Soomere et al., 2012; Zaitseva-Pärnaste et al., 2011). A specific feature of the Baltic Sea is that changes in the nearshore wave climate are not necessarily associated with an alteration of the wave height. For example, owing to a relatively small size of the basin, a systematic change in the trajectories of cyclones crossing the sea (Sepp et al., 2005) may become evident as a change in the wave approach direction. The latter change may substantially impact not only the magnitude but even the direction of the wave-driven littoral flow. Moreover, the wind climate of the northern Baltic Proper has a two-peak directional structure. The most frequent are south-western (SW) winds whereas somewhat less frequent north-northwestern (NNW) winds may be even stronger (Soomere and Keevallik, 2001). The distribution of wave approach directions matches this pattern (Räämet et al., 2010). Owing to the specific orientation of a part of the coastline in question, even a relatively minor change in the proportion of these two peaks may substantially change the resulting net littoral flow.

There exist very few theoretical estimates of the direction of wave- and current-driven littoral flow in this area. To a certain extent, the predominant direction of littoral flow can be estimated based on the similar direction of local wind-driven nearshore currents. The strongest currents among these near the Latvian coast are created by northerly and westerly winds (Eberhards, 2003). The data from a hydrometeorological station near Ventspils shows that in 1980–2000 the predominant winds were from the SW, west and south. These winds produce alongshore water movement to the north. The associated wave fields apparently create littoral flow in the same direction (Eberhards, 2003).

Recent studies have established the basic properties of the Baltic Sea wave climate for the open sea and for selected coastal sites using instrumental measurements (Broman et al., 2006; Soomere et al., 2012), historical wave observations (Zaitseva-Pärnaste et al., 2009, 2011) and numerical simulations (Soomere and Räämet, 2011; Suursaar, 2010; Suursaar et al., 2008). These studies have been linked with the potential changes to the coastal processes for limited coastal sections (Hanson and Larson, 2009; Kelpšaitė et al., 2009, 2011; Tõnisson et al., 2011). An attempt to link the alongshore changes to the overall wave intensity with the major erosion and accumulation regions is described in (Soomere et al., 2011). Several efforts made towards predicting the long-term impact of wave-driven coastal processes on the evolution of coastal morphology are presented in (Zhang et al., 2010) for a neighbouring section of the southern Baltic Sea.

There have also been attempts to use different mathematical methods (incl. the Coastal Engineering Research Council (CERC) method employed in this paper) for estimates of sediment transport along the eastern Baltic Sea coast. Calculations for a few locations along the coast suggest that this transport is mostly to the north or NE but may be reversed near Pape (close to the Lithuanian–Latvian border) where that net sediment flow seems to be mostly directed to the south (Ulsts, 1998). Observations, however, clearly signify that the appearance of sand ridges at this location have features

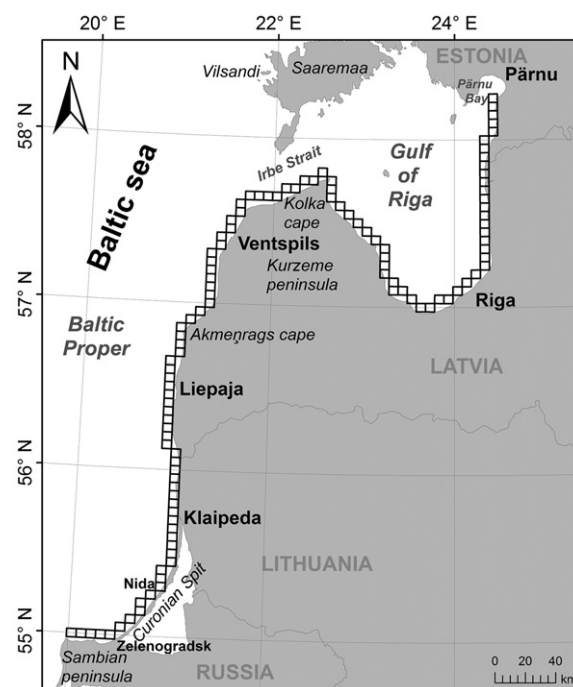


Fig. 1. Study area and the location of calculation points of the wave model on the eastern coast of the Baltic Sea.

characteristic to sediment transport to the north (Ulsts, 1998). Another set of calculations for about 25 points from the Sambian Peninsula to the Kolka Cape (Eberhards, 2003) shows a more realistic pattern of alongshore variations in the littoral flow but still has too low resolution for making definite conclusions about its details. Several more detailed modelling attempts have been undertaken for limited coastal sections (e.g. the vicinity of Palanga, Lithuania) (Zemlys et al., 2007).

In this paper, we make an attempt to systematically analyse the alongshore variations in the wave-driven sediment transport and the associated net littoral flow. The focus is on decadal changes to these quantities along the eastern Baltic Sea coast from the Sambian (Samland) Peninsula up to Pärnu Bay in the Gulf of Riga (Fig. 1). The main goal is to identify sections in which the net transport systematically increases or decreases along the direction of the littoral flow. These areas can be associated with major erosion and accumulation domains, respectively. To a first approximation, we ignore both cross-shore and alongshore variations in the sediment properties and concentrate exclusively on potential erosion and accumulation patterns created by alongshore changes in the wave properties. This approach is justified in a longer perspective: it opens a way for predictions of changes to such areas in the future wind climate irrespectively of short-term and/or local changes to the sediment properties. This goal also makes it possible to use a generic energy flux model for the calculation of the alongshore transport: in this context the exact transport rate is immaterial and the necessary information is extracted from its alongshore variations.

We start with a short overview of the numerically simulated wave data, a description of the method for the calculation of the alongshore sediment transport and a justification of the analysis of alongshore variations in this quantity in Section 2. Results of calculations of alongshore variations in the bulk transport (equivalently, variations in areas with potentially high activity of coastal processes) and net transport are discussed in Sections 3 and 4, respectively. Section 5 focuses on the analysis of divergence and convergence regions of the net littoral flow, with a goal to identify potential areas of fastest accumulation and erosion. The basic messages are formulated in Section 6.

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