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Baltica

BALTICA Volume 26 Number 2 December 2013 : 145–156
doi:10.5200/baltica.2013.26.15

Simulated and observed reversals of wave-driven alongshore sediment transport at the eastern Baltic Sea coast

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Viška, M., Soomere, T. 2013. Simulated and observed reversals of wave-driven alongshore sediment transport at the eastern Baltic Sea coast. *Baltica, 26 (2), 145–156.* Vilnius. ISSN 0067-3064.

Manuscript submitted 21 August 2013 / Accepted 21 November 2013 / Published online 11 December 2013

Abstract This paper aims to analyse the sensitivity of patterns of numerically simulated potential sediment transport along the eastern Baltic Sea coast. The study area extends from the Sambian (Samland) Peninsula to Pärnu Bay in the Gulf of Riga. The magnitudes of net and bulk transport depend largely on how the shoaling and refraction of the waves are resolved. The qualitative patterns of net and bulk sediment transport are almost insensitive with respect to the details of wave transformation in the nearshore and with respect to grain size. The overall counter-clockwise transport along the study area contains two persistent reversals along the coast of the Baltic Sea proper and two frequently recurring reversals along the eastern margin of the Gulf of Riga. Individual years with normal levels of wind speed may host completely different patterns of sediment transport. The location of the most persistent convergence and divergence areas of the net transport acceptably matches the granulometric composition of the nearshore seabed up to a few km from the shoreline.

Keywords • *Alongshore sediment transport* • *Coastal processes* • *CERC model* • *Geological composition of the nearshore* • *Baltic Sea* • *Gulf of Riga*

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INTRODUCTION

The study area – the eastern coast of the Baltic Sea, from the Sambian (Samland) Peninsula in Kaliningrad District, Russia, to Pärnu Bay in Estonia – is an example of a sequence of partially connected sedimentary compartments (Knaps 1966; Eberhards 2003). Single sediment grains may be, theoretically, transported to distance of about 700 km along this stretch. It is usually described in a generalized manner as a more or less continuous sedimentary system (Žaromskis, Gulbinskas 2010) in which the sediment is transported counter-clockwise (Knaps 1966; Gudelis *et al*. 1977; Eberhards *et al*. 2009) and where the basic process is the straightening of the coastline (Knaps 1966; Gudelis 1967; Ulsts 1998; Eberhards 2003).

Early estimates of the magnitude and direction of the wave-driven alongshore sediment flux in the eastern Baltic Sea were obtained using an improved Munch-Petersen formula (Munch-Petersen 1936; Knaps 1938, 1965) and upgraded in later years (Ulsts 1998; Lapinskis 2010). The results commonly match the historical observations of sediment transport. The simulated long-term net sediment transport is generally counter-clockwise, from the south to the north along the Lithuanian and Latvian coasts until the Kolka Cape and further counter-clockwise in the Gulf of Riga.

In a closer view, however, this picture has a number of interesting and nontrivial features. Both the nature and typical grain size of sediments change considerably over this stretch (Ulsts 1998; Kalnina et al. 2000; Saks et al. 2007). The Curonian Spit is entirely sandy. The western Courland (Kurzeme) coasts often consist of gravel with pebbles and boulders, or of sand and gravel with some pebbles. In the contrary, the coasts of the Gulf of Riga mostly consist of mixed sediments and have much finer-grained sand.

The intensity of erosion and accumulation along the study area addressed in many studies, in particular, based on the analysis of shoreline changes (Gudelis *et al*. 1977; Eberhards, Lapinskis 2008; Eberhards *et al*. 2009; Kartau *et al*. 2011, among others). The sediment transport, coastal processes in general and erosion in particular are usually more intense along the open Baltic Sea coast than in the Gulf of Riga. The local deviations of the littoral flow from the above-described general pattern have been analysed using both observational (Gilbert 2008; Eberhards *et al*. 2009; Zhamoida *et al*. 2009) and numerically simulated data sets (Ulsts 1998; Zemlys *et al*. 2007; Viška, Soomere 2012; Soomere, Viška 2013). The alongshore transport is the most intense along the north-eastern coast of the Courland Peninsula and in the western part of the Sambian Peninsula.

Several eminent headlands like the Akmenrags Cape (Stone Cape in some sources), Ovisrags Cape or Kolka Cape may serve as natural barriers for the alongshore sediment flow (Eberhards 2003). A part of sediment brought into motion by waves may be transported away from the coast at these capes and headlands (Eberhards 2003). The direction of the alongshore net transport, however, may be variable, at least within single years. Numerical simulations signal the presence of an end station of the transport at the Kolka Cape, a major divergence area of net transport in the vicinity of the Akmenrags Cape and a pair of convergence and divergence areas near Klaipėda (Soomere, Viška 2013; U. Bethers, pers. comm. 2013). This means that several segments may host clockwise net transport (called reversals below) on both the coasts of the Baltic Proper and the eastern Gulf of Riga, and that the sedimentary systems along the Baltic Proper may be only partially connected. The situation is different along the Curonian Spit. It hosts a highly mobile convergence area that literally "feeds" with sand different parts of the spit in different years and keeps the entire landform in an almost perfect equilibrium (Viška, Soomere 2012).

It is natural to expect that the described features of the simulated alongshore transport become evident in the composition of the nearshore and coastal sediments. The relevant comparisons have only been performed near large harbours where the coastal engineering structures have stopped the littoral flow or where extensive dredging has been necessary to maintain the required depth of the fairway and harbour basins (Eberhards 2003; Eberhards *et al*. 2009). Such comparisons are not straightforward as the seabed in the nearshore may consist of sand masses formed in the past or may reflect morphological structures (tombolo, salient) formed owing to certain local features. Moreover, the comparisons have to cover a long enough time interval in order to eliminate the impact of local features such as the formation and gradual relocation of sand bars. Their dynamics often resembles interspersed periods of erosion (during the formation of a sand bar) and accumulation (when a sand bar approaches the waterline) (Ulsts 1998). Also, the availability of mobile sediments is limited in many sections of the coast.

It is thus not surprising that numerical estimates of the potential alongshore transport (e.g., Viška, Soomere 2012) by several times exceed the observed transport intensity. An obvious reason for this mismatch is the use of the significant wave height to characterise the energy flux of beaching waves in the version of the CERC (Coastal Engineering Research Centre) model that was tuned for the root mean square wave height (Soomere, Viška 2013). While designed to compensate for a systematic under-estimation of the modelled wave heights (Räämet, Soomere 2010), doing so led to severe over-prediction of the alongshore transport rate.

The implications of the inability of numerical wave models to properly represent the directional structure of approaching waves (cf. Räämet *et al*. 2010) and the use of simplified approximations for wave refraction and shoaling on the simulated transport rate are less clear. As the details of the nearshore bathymetry are usually poorly known, they are commonly ignored (e.g., Zemlys *et al*. 2007) and the isobaths of the shallow-water region are assumed to be parallel to the coast. It is also customary to assume that the incidence angle of open-ocean waves at the breaker line is small and that the joint impact of refraction and shoaling can be evaluated using an implicit expression (Dean, Dalrymple 1991). The study area, however, hosts a substantial amount of wave fields that propagate almost along the coast. Their refraction is accompanied by a considerable decrease in the wave height. This feature motivated to employ a simplified scheme for the shoaling-driven changes and to resolve the refraction process in detail (Viška, Soomere 2012; Soomere, Viška 2013). For larger incidence angles this scheme may overestimate both the breaking-wave height and the approach angle at the breaker line.

It is likely that the described reasons of the mismatch between the simulated and observed sediment transport rates do not substantially modify the qualitative features of transport. In particular, they apparently do not affect the pattern of convergence and divergence areas of sediment flux. In this paper, authors address the problem of stability of various qualitative features of numerically simulated potential sediment transport along the eastern Baltic Sea coast using the CERC approach. The focus is on the impact of above-discussed aspects that were either ignored in the previous research or only approximately accounted for. First of all, the joint impact of refraction and shoaling of waves along their propagation from the grid cells of the wave model until the breaker line is accurately resolved based on the linear wave theory. Doing so makes it possible to adequately represent the impact of waves that approach the study area under large incidence angles. Further, the calculations are repeated with several values of the typical grain size and using different specifications of the modelled wave height.

These efforts demonstrate that the qualitative patterns of the alongshore sediment transport are stable with respect to changes in the model and its input data. It is thus likely that these patterns become evident in the composition of nearshore sediments. The coastline of most of the study area has considerably advanced towards the sea since the Litorina Sea (Eberhards *et al.* 2009), therefore, the composition of nearshore (at least down to the closure depth and to some extent offshore) is largely governed by the wave-driven sediment relocation. The seabed sediments should thus mirror not only the overall intensity of coastal processes (Soomere *et al.* 2013*b*) but also the general pattern of sediment motions. For example, the vicinity of the major divergence areas of sediment flux the seabed should be almost void of finer sediment whereas frequent convergence areas are eventually characterized by abundance of sand and silt. In other words, the geological composition of the nearshore may provide an implicit means to evaluate the adequacy of numerical simulations. The final part of the paper focuses on the comparison of the established pattern of alongshore transport and the geological composition of seabed.

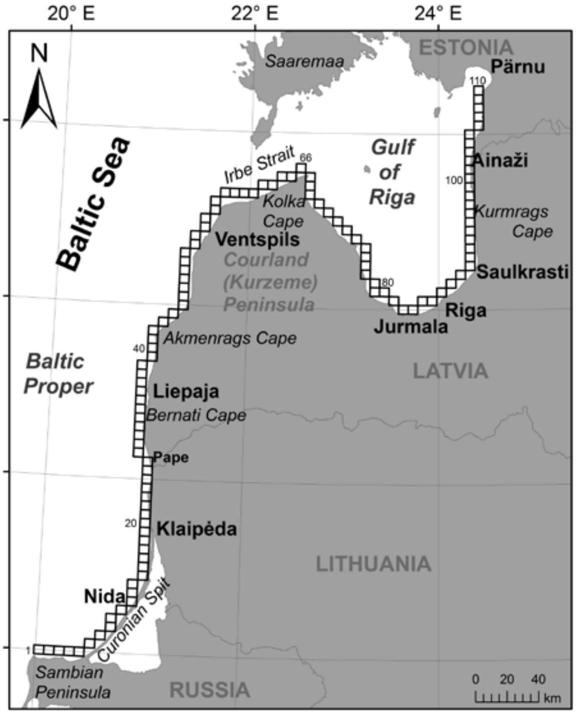

Fig. 1 Scheme of calculation points of the wave model and corresponding coastal sections along the study area. Compiled by M. Viška.

MATERIAL AND METHODS

Similarly to (Viška, Soomere 2012; Soomere, Viška 2013), the calculations rely on the hourly time series of wave properties evaluated using the third-generation spectral wave model WAM (Komen *et al.* 1994) and adjusted geostrophic winds. The wave model was run for the entire Baltic Sea with a spatial resolution of about three nautical miles for 1970–2007 (Räämet, Soomere 2010). The presence of ice was ignored. Doing so is generally acceptable for the southern part of the study area but may substantially overestimate the impact of waves in the Gulf of Riga. The long-term average significant wave height is underestimated by about 15% by Räämet, Soomere (2010). The reader is referred to (Soomere, Räämet 2011) for a more detailed discussion of the existing simulations of the Baltic Sea wave climate.

The study area is divided into 110 about 5.5–7 km long sections (Fig. 1) that match the locations of grid cells of the wave model. The alongshore transport is calculated using the CERC approach from the wave height and approach direction at the breaker line. These quantities are evaluated from the modelled time series of significant wave height, peak period and mean direction. The joint impact of shoaling and refraction on the wave height and direction from the grid cell until the breaker line is evaluated using standard assumptions of the linear wave theory. The numerically reconstructed wave field is assumed to be monochromatic, the wave height h_0 at a grid cell equal to the modelled significant wave height h_{S0} or root mean square wave height h_{rms0}, the period T equal to the modelled peak period, and the wave direction matching the modelled mean direction. We also assume that the depth isolines are straight and parallel to the average orientation of the coastline within each coastal section. Wave reflection, whitecapping, interactions with seabed and nonlinear interactions within the wave field are ignored. Under these assumptions the wave height h_b at the breaker line is (Dean, Dalrymple 1991)

$$h_b = h_0 \left(\frac{c_{g0}}{c_{gb}} \frac{\cos\theta_0}{\cos\theta_b} \right)^{1/2} \qquad (1),$$

where c_g is the group speed and θ is the approach angle of waves and subscripts 0 and b represent wave properties at a model grid cell and at the breaker line, respectively.

The changes to the wave direction follow Snell's law $\sin\theta / c_f = const$ and thus $\sin\theta_b = \sin\theta_0 c_{fb} c_{f0}^{-1}$, where c_f is the phase speed (celerity) and the meaning of subscripts has been explained above. The phase and group speed at a model grid cell are found from the finite-depth dispersion relation $\omega = \sqrt{gk_0 \tanh k_0 d_0}$ where $\omega = 2\pi / T$ is the angular frequency, $g = 9.81$ m s^{-2} is the acceleration due to gravity, k_0 is the wave number and d_0 is the water depth at the wave model cell.

The calculation of the breaking-wave height h_b relies on the concept of breaking index $\gamma_b = h_b / d_b$, where d_b is the water depth at the breaker line. There is no consensus about the common value of the breaking index. For monochromatic waves approaching strongly reflecting beaches it may reach values ~1.5 whereas for almost horizontal bed it is 0.55–0.6 (Nelson 1994; Massel 1996). For irregular waves in the surf zone the ratio h_b/d_b may be much smaller, even in the range of 0.2–0.5 (Lentz, Raubenheimer 1999). The coasts in the study area are mostly sedimentary, with gently sloping profiles resembling Dean's equilibrium profile. As we are interested in the location of the seaward border of the surf zone, the use of a constant value $\gamma_b = 0.8$ is justified (USACE 2002; Dean, Dalrymple 1991, 2002).

As breaking waves are long waves, their group speed c_{gb} and phase speed c_{fb} are equal: $c_{gb} = \sqrt{gd_b} = \sqrt{gh_b/\gamma_b}$. Substituting these expressions into Eq. (1) leads to the following algebraic equation of 6[th] order for the breaking-wave height h_b (Soomere *et al.* 2013*a*):

$$F(h_b) = h_b^6 \frac{g^2 \sin^2 \theta_0}{\gamma_b^2 c_{f0}^2} - h_b^5 \frac{g}{\gamma_b} + h_0^4 c_{g0}^2 \left(1 - \sin^2 \theta_0\right) = 0. \quad (2)$$

The leading term of Eq. (2) vanishes for incident waves with $\theta_0 = 0$. Such waves only experience shoaling under the described set of assumptions and their breaking height is $h_b = \left(h_0^4 c_{g0}^2 \gamma_b / g\right)^{1/5}$ (Komar, Gaughan 1972; Dean, Dalrymple 1991). This expression is often used for almost incident waves for which $\cos\theta_b \approx 1$ and $\sin^2\theta_b \approx 0$ (Dalrymple *et al.* 1977; Dean, Dalrymple 1991, p. 115).

As the Baltic Sea waves often approach the coast under quite large angles (Viška, Soomere 2012), we solve the full equation (2). It has only three non-zero coefficients. Its leading term and the constant term have the same sign whereas the coefficient at h_b^5 has the opposite sign. Therefore, the polynomial $F(h_b)$ has exactly one minimum at $\tilde{h} = 5\gamma_b c_{f0}^2 / 6g \sin^2 \theta_0$. Consequently, Eq. (2) has two different real solutions if this minimum corresponds to a negative value of $F(\tilde{h})$, a double real solution if $F(\tilde{h}) = 0$ and no real solutions if $F(\tilde{h}) > 0$. The latter case probably means that the modelled waves are already breaking (cf. Soomere *et al.* 2013*a*).

The solution that represents the breaking-wave height can be identified by considering the case $\theta_0 \to 90°$. For such angles, the constant term of Eq. (2) is very small, the smaller real solution tends to zero and the larger real solution approaches a constant value $\hat{h} = \gamma_b c_{f0}^2 / g$. For typical Baltic Sea wave fields, this value substantially exceeds the possible wave heights and the smaller real solution represents the breaking-wave height.

The intensity of wave-driven alongshore sediment transport is estimated in terms of the potential immersed weight transport rate (called simply transport rate below) $I_t = (\rho_s - \rho) g (1 - p) Q_t$ (USACE 2002). We use $\rho_s = 2650$ kg m^{-3} and $\rho = 1015$ kg m^{-3} for the densities of sediment (sand) particles and sea water, respectively, and $p = 0.4$ for the porosity coefficient. According to the CERC method $I_t = KP_t$, where $P_t = Ec_{gb} \sin\theta_b \cos\theta_b$ is the rate of beaching of the alongshore component of wave energy flux Ec_g at the breaker line and E is the wave energy. Following (USACE, 2002), we use the expression $K = 0.05 + 2.6 \sin^2 2\theta_b + 0.007 u_{mb} w_f$ for the coefficient K designed for the use of the root mean square wave height (USACE 2002, III-2). Here $u_{mb} = (h_b/2)\sqrt{g/d_b} = \sqrt{g\gamma_b h_b}/2$ is the maximum orbital velocity according to the linear wave theory and $w_f = 1.6\sqrt{g d_{50} (\rho_s - \rho)/\rho}$. An appreciable approximation for the typical grain size of sand in the study area is $d_{50} = 0.17$ mm (Zemlys *et al.* 2007; Zhamoida *et al.* 2009; Kartau *et al.* 2011). The resulting hourly transport rates are used to evaluate annual means of the bulk and net (positive for counter-clockwise drift) transport for each coastal section (cf. Viška, Soomere 2012; Soomere, Viška 2013).

SIMULATED SEDIMENT TRANSPORT

The significant wave height of a monochromatic wave train coincides with the root mean square height of such a train and thus is applicable for the CERC formula in case of regular swells. This approach is obviously incorrect for wind seas. The contemporary definition of significant wave height is $h_S = 4\sigma$, where σ is the standard deviation of the water surface elevation. The energy of a wind sea equals to the energy of a sinusoidal wave train with the root mean square wave height $h_{rms} = 2\sqrt{2}\sigma = h_S/\sqrt{2}$ of the wind sea; equivalently, $E = (1/8)\rho g h_{rms}^2 = (1/16)\rho g h_S^2$.

There is no consensus on how to quantify the breaker line for a wind sea as waves of different heights start to break at different depths. A conservative estimate for the water depth at the breaker line is $d_b = h_{rmsb}/\gamma_b$, where h_{rmsb} is the root mean square wave height at breaking.

For almost incident waves it is acceptable to ignore the leading term in Eq. (2) (Dalrymple *et al.* 1977; Dean, Dalrymple 1991). The coefficient K only weakly depends on the (particular specification of the) wave height. Therefore, to a first approximation, a change in the specification of the height of such waves reduces to an introduction of a linear coefficient in the CERC formula. For example a replacement of the root mean square wave height by the significant wave height results an increase in the sediment transport by $2\sqrt{2} \approx 2.83$ times. This property is reflected by the difference in the (constant) coefficient $K_c = 0.39$ for the significant wave height and $K_c = 0.92$ for the root mean square wave height in the earlier research (USACE 2002, III-2). Importantly, in spite of a substantial change to the magnitude of the transport rate, such a replacement affects neither the direction of the transport nor the qualitative pattern of its alongshore variations. Consequently, the pattern of divergence and convergence areas of net transport driven by almost incident waves is invariant with respect to the choice of the wave height in the CERC formula.

This feature is not necessarily valid for waves with larger incidence angles, for which refraction additionally modifies the transport rate. The use of h_{rms} instead of h_S means that the constant term in Eq. (2) decreases and the graph of the polynomial F is shifted downwards in (h, F)-coordinates. Therefore, for any incidence angle $0 < \theta_0 < 90^{\circ}$ we have $h_{rmsb} < h_{Sb}$. The relative weight of the constant term and the difference between h_{rmsb} and h_{Sb} decrease with the increase in θ_0.

Recalculation of the net and bulk transport rates using the exact solution of Eq. (2) leads to a certain decrease in the long-term average of both these quantities (Fig. 2, 3, Table 1). A closer inspection (not shown) reveals that the transport driven by waves approaching the coast under large angles ($\theta_0 > 30^{\circ}$) was considerably overestimated in (Soomere, Viška 2013). The transport by waves with $\theta_0 < 30^{\circ}$ was usually slightly underestimated as shoaling often led to a considerable increase in the wave height.

The qualitative patterns of annual average net and bulk transport (Fig. 3) calculated using Eq. (2) almost exactly coincide with those evaluated by Soomere, Viška (2013) using a simplified approach for shoaling. The open coast of Baltic Sea hosts much higher bulk transport than the Gulf of Riga. The most intense transport takes place along the Sambian Peninsula and in the north-western Courland Peninsula (that host almost 50% of the entire net transport in the study area). The biggest spatial variability in the calculated transport rates is also on the north-western coast of Latvia. The match of the areas of larger and smaller transport is almost perfect for the bulk transport except for a short segment of the western part of the Curonian Spit. Interestingly, local variations in the transport along the study area are generally smaller for the calculations based on Eq. (2) than in (Soomere, Viška, 2013). This feature evidently reflects more adequate estimates of the impact of waves approaching under large angles by Eq. (2) and signals that such waves provided extremely large (and often overestimated) contributions to both net and bulk transport in (Soomere, Viška 2013).

The use of solutions of Eq. (2) instead of the simplified approach of Soomere, Viška (2013) generally leads to a certain decrease (by a few per cent along the coast of the Baltic Proper and about 10% in the Gulf of Riga) in the annual and long-term average bulk

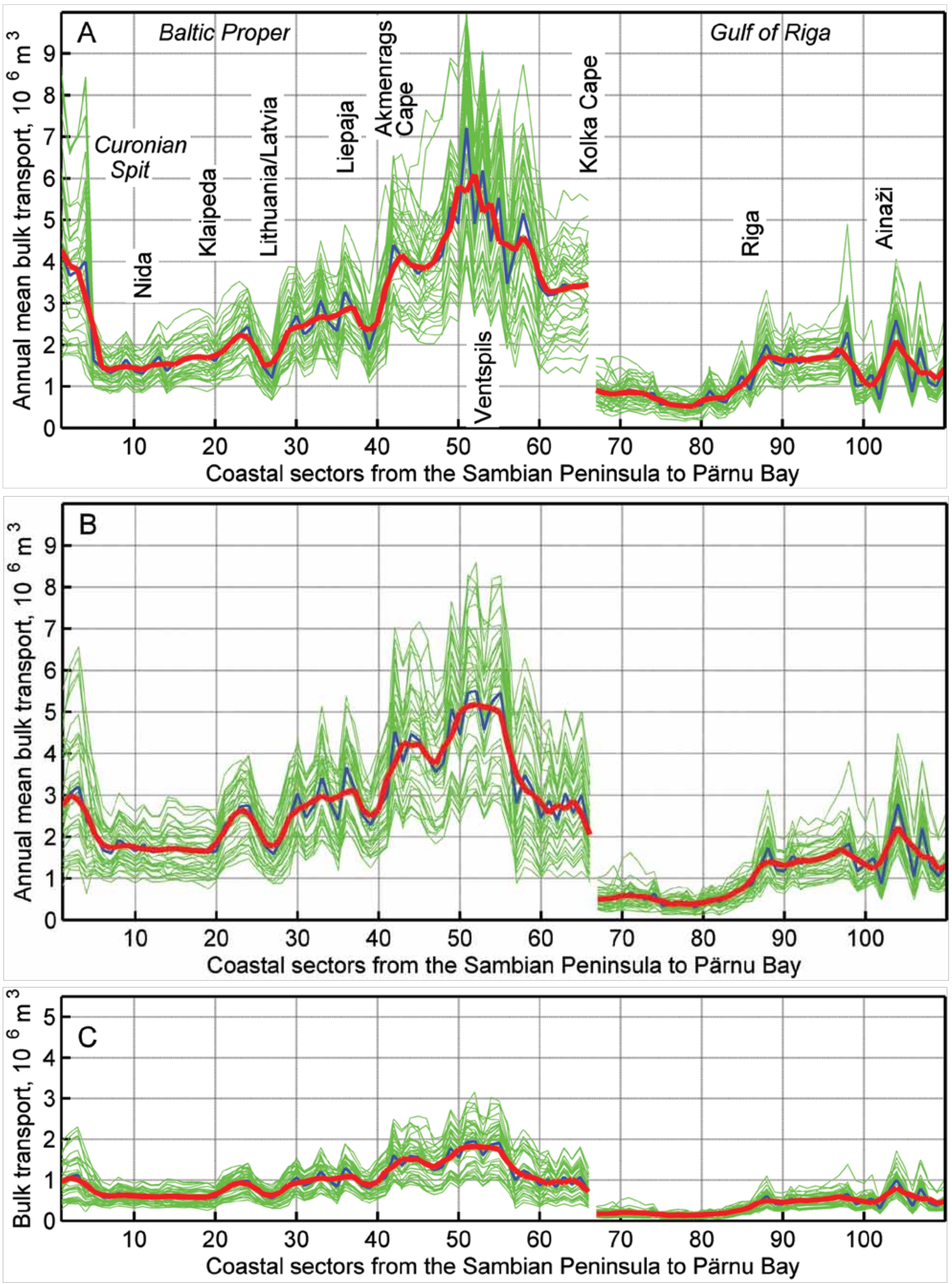

Fig. 2 **A.** Simulated potential bulk transport in the study area for $d_{50} = 0.17$ mm, using significant wave height as input for the CERC formula and a simplified representation of shoaling (Soomere, Viška 2013). Green: single years, blue: average for 1970–2007; red: moving average of the blue line over three subsequent coastal sections. **B.** The same as panel A but using the full solution of Eq. (2). **C.** The same as panel B but using root mean square wave height as input for the CERC formula. Compiled by T. Soomere.

transport. The changes are the largest in the sections hosting the most intense transport. These sections evidently have the largest proportion of waves approaching under large incidence angles. Some parts of the study area, for example, the western part of the Curonian Spit, reveal an increase in the bulk transport when the solutions to Eq. (2) are employed. The decrease in the net transport is more systematic, about 10% on average.

The match of the rates of net transport calculated in (Soomere, Viška 2013) and using Eq. (2) is less exact (Fig. 3). The segments of its large and small absolute values fully coincide but its alongshore variations calculated using Eq. (2) exhibit less frequent zero-crossings (divergence and convergence areas). For example, the reversal Ventspils (Soomere, Viška 2013) is present only in a few years in the calculations employing Eq. (2). Another similar reversal to the north of the border between Latvia and Lithuania is also present less frequently. Both short segments of southwards transport on the eastern coast of the Gulf of Riga also become evident in selected years and are not present in the long-term mean.

The changes associated with the variations in the typical grain size are even smaller, about 6–8% for both the bulk and net transport (Table 1). Importantly, no qualitative changes are found in the patterns of the net and bulk transport for different grain sizes (Fig. 3).

The magnitude of the simulated transport is extremely sensitive with respect to the input wave data. The use of root mean square wave height as the input for the CERC formula (incl. the expression for the group speed) leads, similarly to the case of almost-incident waves, to a radical decrease in the wave-driven transport by about 2.8 times (Fig. 2, 3, Table 1). The potential net transport becomes considerably (by about 30–40%, Fig. 4) smaller in this case than the transport estimated from the field data. For example, the simulated net transport along the north-western coast of the Courland Peninsula ($500–700\times10^3$ m^3 a^{-1}) is about 70% of the estimate $750–1000\times10^3$ m^3 a^{-1} by Eberhards (2003).

A large part of this difference may stem from the interpretation of the location of the breaker line. For regular swells (that are common for the open ocean coast) it is natural to interpret the breaker line as the location where most of the crests start to break and to associate it with the breaking depth h_{rmsb} for the root mean square wave height. The largest waves in a typical wind sea (that is common for the Baltic Sea) are better described by the significant wave height. Their breaking (and the associated intense motion of bottom sediments) starts at deeper locations characterized by the breaking depth for the waves with the significant wave height h_{Sb}. As the CERC formula expresses the sediment transport in the entire surf zone, it is natural to assume that it relies on the energy flux supplied at the line where relatively large waves often break,

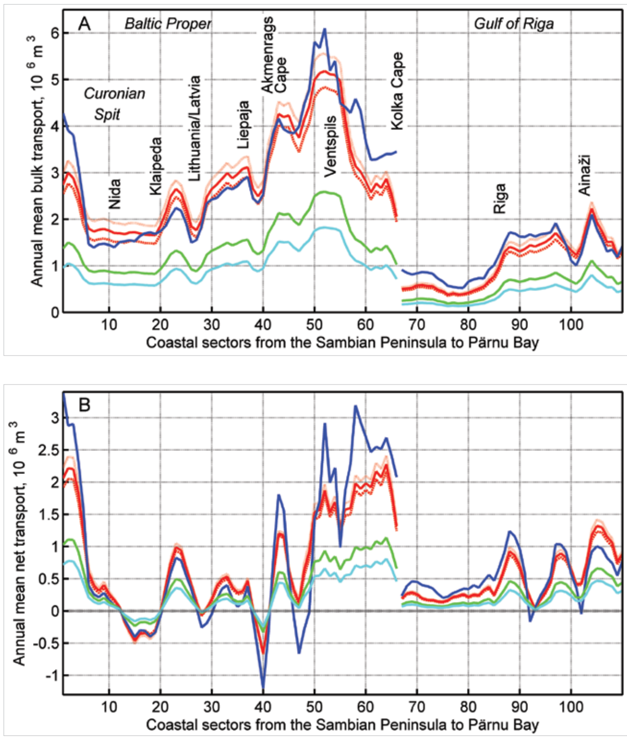

Fig. 3 Simulated potential bulk transport **(A)** and net transport **(B).** All lines indicate the moving average over three subsequent coastal sections, calculated as an average over all years 1970–2007. Blue: $d_{50} = 0.17$ mm, simplified representation of shoaling, significant wave height as input for the CERC formula (Soomere, Viška 2013). Other colours correspond to the use of solutions of Eq. (2). Red lines: significant wave height as input for the CERC formula; dotted line (upper): $d_{50} = 0.063$ mm, solid line (middle): $d_{50} = 0.17$ mm, dashed line (lower): $d_{50} = 1.0$ mm. Green: $d_{50} = 0.17$ mm; root mean square wave height as input for the wave energy but group velocity at the breaker line estimated based on the significant wave height. Cyan: $d_{50} = 0.17$ mm, root mean square wave height as input for the CERC formula. Compiled by T. Soomere.

that is, at the depth of h_{Sb}/γ_b. Calculations using the “mixed” specification of the wave height (h_{Sb} for the wave energy and h_{rmsb} for the group speed at the breaking line) led to a reasonable match of the simulated and observed transport rates (Fig. 4).

SENSITIVITY OF THE CONVERGENCE AND DIVERGENCE AREAS

The entire pattern of the simulated net transport reflects the well-known overall counter-clockwise sediment flux. Differently from the earlier research, it contains two short but relatively persistent reversals (Fig. 4). These reversals can be characterized using the associated areas of divergence and convergence of the transport (Soomere, Viška 2013). Four such areas (divergence near Klaipėda and at the Akmenrags Cape, convergence at the Curonian Spit and to the north of Liepaja) appear at the same locations in all calculations (Fig. 4). Several less persistent divergence and convergence areas (Soomere, Viška 2013) are represented in Fig. 4 as segments that have almost

Table 1 Annual average bulk and net transport (in 10^3 m^3, both annual mean of net transport and the mean of its absolute values) along the eastern coast of the Baltic Proper and in the Gulf of Riga for different variations of the calculation scheme and interpretation of the input wave height in the CERC formula. The case $d_{50} = 0.17$ and accounting for only refraction corresponds to the data presented in Soomere and Viška (2013).

Properties of the run			Net, Baltic Proper		Net, Gulf of Riga		Bulk	
d_{50}, mm	Use of Eq. (2)	Wave height	mean	Abs (mean)	mean	Abs (mean)	Baltic Proper	Gulf of Riga
0.063	yes	h_S	840	1020	528	542	3102	1144
0.17	no	h_S	864	1167	555	565	2983	1198
0.17	yes	h_S	783	955	496	509	2870	1064
1.0	yes	h_S	730	895	467	478	2658	991
0.17	yes	h_{rms}	277	338	175	180	1011	375

zero long-term net transport. Between such areas occasionally short-term reversals may occur. While some of such short-term reversals correspond to local minima of the bulk transport, one reversal to the north of Riga hosts intense bulk transport.

One persistent reversal area is located in the northern part of the Curonian Spit between Nida and Klaipėda. Its borders vary considerably in different years (Fig. 5) whereas in single years it may be replaced by a northwards sediment flux. Its northern border (a divergence area next to Klaipėda) thus probably does not serve as a robust barrier for the sediment motion to the north. Such an 'intermittent' transport regime seems to be an intrinsic part of the dynamical equilibrium of the spit (Viška, Soomere, 2012). The overall appearance of the reversal indicates that in the long-term perspective the divergence area around Klaipėda suffers from sediment deficit.

A relatively short but persistent reversal of sediment transport is located between Liepaja and the Akmen-

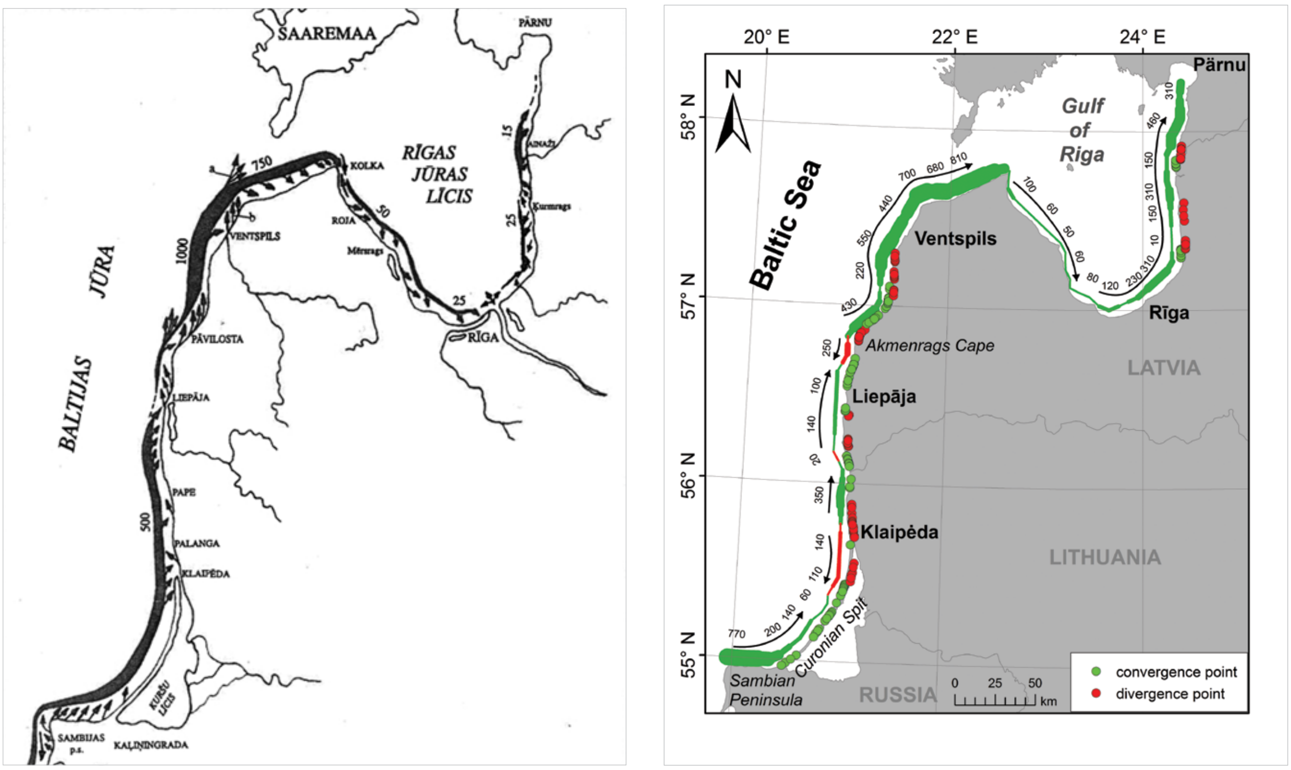

Fig. 4 Direction (arrows) and magnitude (numbers at arrows, in 1000 m^3) of net sediment transport: left – original scheme by R. Knaps, amended by V. Ulsts (1998); right – simulated potential net sediment transport using $d_{50} = 0.17$ mm, Eq. (2) and root mean square wave height as the input to the CERC formula. Compiled by M. Viška.

rags Cape. Its length considerably varies in time, from about 15 up to 50 km. The convergence area at its southern border substantially moves in different years (Fig. 5). The most interesting feature is the highly persistent divergence area at the Akmenrags Cape. Its location varies only by about ±5 km from its average position. It is evident during all the simulated years except for the quite unusual year 1984 (Soomere, Viška 2013).

The divergence and convergence areas and the related reversals are much less persistent in the Gulf of Riga. No such areas seem to exist at its western coast except possibly in a few single years. The long-term sediment flux almost vanishes or is reversed at two locations at the eastern coast of the gulf – near Saulkrasti and at the border between Latvia and Estonia (Fig. 3). The simulated net sediment transport shows quite frequently occurring short reversals at both sites. In selected years, the reversal near Saulkrasti may extend to several tens of km. This matches the results of Knaps (1965) where this reversal covers more than 30 km. It occasionally starts from the Kurmrags Cape and extends approximately to almost Saulkrasti. The vicinity of this cape suffers from erosion: a seamark that was originally located on the top of a coastal sandstone scarp is now at the waterline.

Another area of divergence is often (during about a half of years) located near Ainaži. The associated reversal is quite short, normally <15 km. Knaps (1965) identified here no reversal and concluded that the long-term average sediment flow is to the north. Eberhards (2003) discussed the situation at this site in the light of silting of the nearshore. A set of underwater sandbars are visible to the south of Ainaži on orthophotos made in 1982. Their position and appearance signals the alongshore sediment flux to the south. A similar pattern can be seen also in orthophotos taken in 2007. Therefore, the simulated data for this region for 1970–2007 likely reflect the correct average direction of sediment flow to the south, despite the fact that some of previous calculations and observations showed an uninterrupted average flux to the north.

Although the described pattern of net transport (incl. its reversals) seems to be stable, it may undergo substantial changes in single years. For example, in 1984 the annual average transport was directed to the north. While such a pattern was only slightly unusual for the coast of the Baltic Proper, it was exceptional in the Gulf of Riga: the simulated sediment transport along its western coast was entirely to the north (Soomere, Viška 2013). This hindcast matches the observational evidence that large sediment volumes were transported to the north this year. Ulsts (1998) found a significant sediment movement to the north between Roja Harbour (on the western coast of the Gulf of Riga) and the Kolka Cape. Together with intense sediment supply along the western coast of the Courland Peninsula, this process resulted in the formation of a temporary spit to the east of the Kolka Cape.

THE COMPOSITION OF THE NEARSHORE SEABED

The presented results confirm that the overall counter-clockwise pattern of net sediment transport along the eastern Baltic Sea coast and in the Gulf of Riga is modulated by several persistent reversals. The four most persistent divergence and convergence areas are almost insensitive with respect to the variations in the sediment transport model, the typical grain size and even with respect to the interpretation of the wave height. This invariance suggests that they have been present for a long time and, most probably, have exerted a certain impact on the sediment structure in the adjacent nearshore. We use for comparisons of this pattern and the geological composition of the study area a composite map of nearshore bottom sediments (Fig. 6). It is compiled using data from (Bottom… 1996; Ulsts, Bulgakova 1998; Bitinas *et al.* 2004) using three different systems to denote various sediment classes that do not fully overlap.

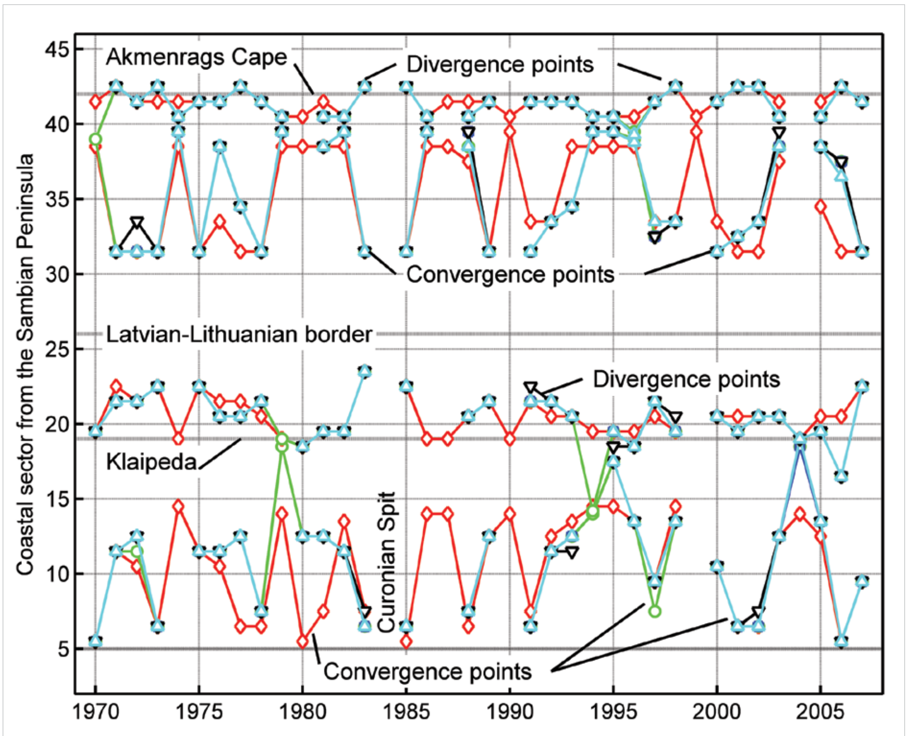

Fig. 5 Location of persistent divergence and convergence areas on the eastern Baltic Proper coast. Red: $d_{50} = 0.17$ mm, simplified representation of shoaling (Soomere, Viška 2013). Other colours correspond to the use of solutions of Eq. (2). Green: $d_{50} = 1.0$ mm, blue $d_{50} = 0.17$ mm, black $d_{50} = 0.063$ mm, all using significant wave height as the input to the CERC formula; cyan: $d_{50} = 0.17$ mm, root mean square wave height as the input for the CERC formula. Compiled by M. Viška and T. Soomere.

The Curonian Spit entirely consists of fine sand. It is thus natural that its nearshore is sandy whereas finer sand is found further offshore. A very narrow fine-grained sediment strip is mostly present in the vicinity of the waterline along the Courland coast starting from the Latvian–Lithuanian border and extends until the Irbe Strait. This strip simply reflects the tendency for some sand to gather around the waterline even if there is a general deficit of finer sediment. Thus, its presence cannot be associated with the locations of divergence or convergence areas. For this reason, we focus on the geological composition of a somewhat wider underwater area.

To the north of Klaipėda only the immediate nearshore contains a sandy strip. In more offshore locations till interspersed with some sand predominates until Palanga. The area where till predominates almost exactly matches the region in which divergence of the sediment flux may occur. The sandy strip widens to the north of Palanga, approximately in the area where a relatively persistent convergence area is frequently located (Fig. 4). It drastically diminishes at the border between Latvia and Lithuania where the net sediment transport is often reversed. In this segment gravel with pebbles and boulders covers the nearshore and extends almost to the waterline. A frequent divergence area is, however, located somewhat to the north of the section where gravel with pebbles and boulders predominate until the waterline (Fig. 4). Therefore, there is no perfect match of this divergence area with the geological composition of the nearshore although the sandy strip is relatively wide in this area.

A divergence area frequently occurs at and to the south of the Bernati Cape. This area is mostly characterized by a low sedimentary coast that was inactive before the middle of the 20th century. It started to suffer from erosion in 1954. The length of the eroding section reached about 3–4 km in 1993. The average coastline retreat was 13 m in years 1991–1993 (Ulsts 1998). Particularly strong erosion has occurred at this cape during the last quarter of the 20th century, possibly because of the changes in the main wave approach direction and hence an increase in the sediment transport rate (Eberhards 2003). This conjecture matches a major change in the air-flow direction since 1988 in the northern Baltic Sea (Soomere, Räämet 2013).

A larger coastal segment that often hosts a convergence area is located in the vicinity of Liepaja (Fig. 4). Consistently with this observation, there is an area of fine-grained sand at Liepaja. The sandy area is, however, narrow and occasionally discontinuous to the north of this city. This mismatch evidently reflects the impact of Liepaja Harbour. Its constructions disrupt the natural sediment transport and cause a deficit of sediments to the north of Liepaja where mostly gravel with pebbles and boulders occur on the seabed.

Consistently with the appearance of a persistent divergence area (Fig. 4), the nearshore of the Akmenrags Cape contains almost no fine sediments (Fig. 6) although the beach itself is sandy and occasionally contains growing foredunes. A sandy or silty strip of appreciable width reappears at a distance of a few km to the north of this cape (Fig. 6). It extends over the entire segment where the simulations indicate a frequent convergence area (Fig. 4). A headland between this segment and Ventspils contains much less sand and at places consists of gravel, pebbles and boulders, again consistently with an occasional presence of a divergence area (Fig. 4).

The simulations suggest that almost unidirectional (on the annual average) sediment transport to the north-east occurs from Ventspils to the Kolka Cape. No clearly distinguishable convergence or divergence areas exist along this stretch. The upper layer of the seabed is mostly sandy or silty, signalling intense transport in this section. Starting from the Irbe Strait a fine-grained sand strip in the nearshore becomes wider and reaches a maximum width near the Kolka Cape (Fig. 6). The intense sediment transport along the western coast of the Courland Peninsula to the entrance of the Gulf of Riga has caused an extensive growth of the Kolka Cape to the north-east and deposition of large volumes of sand in its vicinity in the past (Ulsts 1998; Eberhards 2003). A part of this sand is transported further into the interior of the Gulf of Riga. The flux of sand to the south-east of the Kolka Cape is relatively weak (because of a limited fetch for waves approaching from the north-west) but almost unidirectional (except for the unusual year 1984 as discussed above). Its intensity generally increases along the coast until Jurmala. Near this city, the coastline turns and the sediment is further driven by waves excited by south-western winds. Interestingly, no persistent convergence area exists near the River Daugava mouth, possibly because of the joint impact of waves excited by south-western and north-north-western winds (Ulsts 1998). These two wave systems together cause intense transport back and forth between Jurmala and Saulkrasti.

The sandy strip in the nearshore becomes narrower to the north-east of Riga but is continuous until Saulkrasti where an appreciably persistent convergence area exists (Fig. 4). Its interplay with an often occurring divergence area (located just to the north of Saulkrasti) may be the reason why the nearshore of Saulkrasti is sandy but boulders and rock predominate to the north of this city until Tuja. Another pair of divergence and convergence areas is located at Ainaži. Although they appear only in selected years (Soomere, Viška, 2013), it is still characteristic that a relatively wide spot of nearshore sand is located exactly where Fig. 4 shows a small convergence area.

The presented comparison confirms that all major simulated convergence areas (Fig. 4) have an appreciable match with relatively wide nearshore areas covered with silt or sand (Fig. 6). The match of the nearshore sediment composition with divergence areas is less evident but is it still typical that such areas mostly contain coarse sediment – gravel, pebbles, boulders or even pre-quaternary rock.

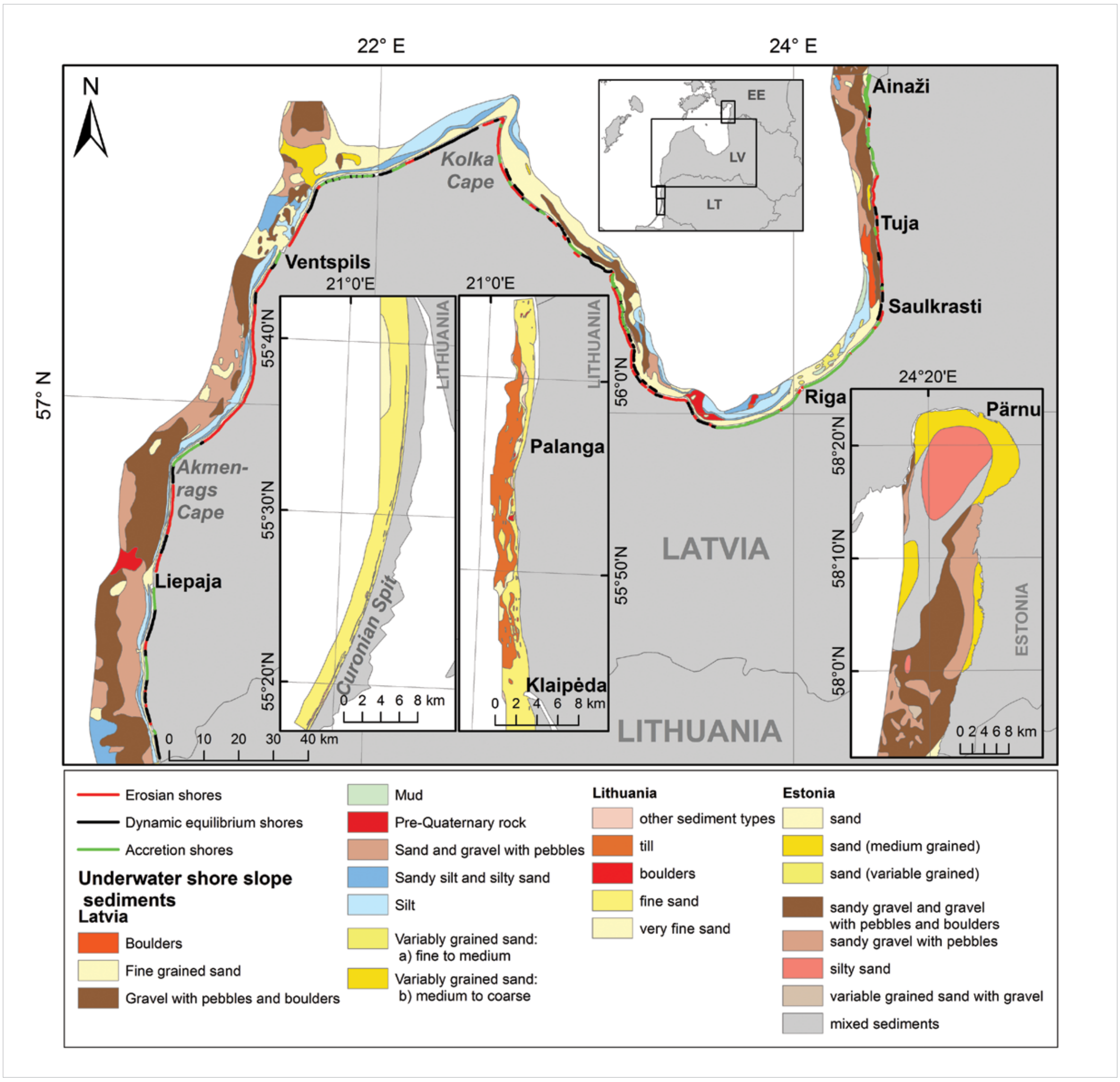

Fig. 6 Geological composition of the nearshore of the study area. Note that different countries use different specifications of sediment types. Compiled by M. Viška.

DISCUSSION

The results of numerical simulations confirm the existence of the well-known generally counter-clockwise pattern of net sediment transport along the study area. This pattern involves an end station at the Kolka Cape, two persistent reversals along the coast of the Baltic Proper and two frequently occurring reversals on the eastern coast of the Gulf of Riga. As expected, its qualitative appearance is stable with respect to the details of the calculation scheme of the alongshore transport and input conditions such as the typical grain size and the particular interpretation of the wave height.

It is well known that the use of the CERC formula is associated with relatively large uncertainties in the resulting magnitude of sediment transport (USACE 2002). The results presented above call for a re-evaluation of its certain parts for the specific conditions of the Baltic Sea. Low levels of remote swells in this water body have been shown to impact the validity of commonly used expressions for the closure depth. The formulas designed for the open ocean coasts work properly in semi-enclosed bayheads where the proportion of remote swells is comparable to that on the open ocean coasts (Soomere *et al*. 2013*b*). Our results suggest that it may be reasonable to apply in the CERC formula the group speed of breaking waves using the significant wave height at the Baltic Sea coasts (where the wind seas predominate).

An important task of this research was to identify observational support to the presence of reversals of the net transport. It is natural to associate persistent convergence areas with abundance and/or accumulation of sand. In the contrary, divergence areas may be associated with a deficit of sand and erosion regions.

As the location of such areas may substantially vary in different years, their match with the composition of the coast and the nearshore is not necessarily straightforward. In addition, their impact not necessarily becomes evident in segments affected by other processes, for example, intense dynamics of sand bars that serve as a buffer for changes in the nearshore (Weishar *et al*. 1991). Their cyclic relocation may easily override the impact of, for example, a divergence area for many years. The presented comparison suggests that there is an acceptable match between the location of major convergence and divergence areas and the geological structure of the seabed to a distance of a few km from the waterline. The match is less evident for divergence areas but it is still typical that such areas contain coarse sediments.

The presented analysis suggests that long-term changes in the study area may be substantially modulated by decadal variability in the wind and wave climate. The situation at the Bernati Cape (where erosion started from the mid-1950s and was relatively intensive in the 1990s) or near Ainaži (where the analysis of processes during different time intervals may give controversial results) vividly exemplifies the importance of the long-term view. An important message, albeit not new in the coastal science, is that a long interval, at least several tens of years of observations or simulations, is often necessary in order to obtain an adequate representation of the nature of processes. Given the extensive natural variability of the processes in the study area, it is not surprising that the analyses based on different averaging periods may lead to substantially different conclusions and seeming discrepancies between the results of different authors.

Finally, the simulations also revealed that the long-term transport patterns may show radically different nature during single years with quite usual wind speeds and wave heights but with unusual wave approach directions. Namely, truly exceptional years (such as 1984) in terms of a completely different pattern of sediment transport may occur in the study area in the existing wave climate. This feature calls for further studies into these properties of the climate of semi-enclosed seas that substantially affect wave-driven sediment transport patterns such as changing wind directions (Jaagus, Kull 2011), combinations of high water level and wave storms (Orviku *et al*. 2003) or changes to the ice cover (Ryabchuk *et al*. 2011).

CONCLUSIONS

The overall counter-clockwise pattern of net sediment transport along the eastern Baltic Sea coast and in the Gulf of Riga contains two persistent reversals on the coast of the Baltic Proper and two frequently occurring reversals on the eastern coast of the Gulf of Riga. This pattern is stable with respect to the particular modelling scheme of the alongshore transport, the typical grain size and even with respect of the interpretation of the wave height.

The established pattern may show radically different nature during single years with unusual direction of wave storms. An acceptable match exists between the location of major convergence and divergence areas of sediment flux and the geological structure of the nearshore seabed.

Acknowledgements

Authors highly appreciate supportive comments of Dr. Loreta Kelpšaitė (Klaipėda) and Prof. Vitalijs Zelčs (Riga) on the original submission. The study was a part of the project "Science-based forecast and quantification of risks to properly and timely react to hazards impacting Estonian mainland, air space, water bodies and coasts" (TERIKVANT), supported by the European Regional Development Fund (ERDF) within the framework of the Environmental Technology R&D Programme KESTA. The research was supported by the Estonian Ministry of Education and Research (targeted financing No. SF0140007s11), Estonian Science Foundation (grant No. 9125) and European Union (via a support to the Estonian Centre of Excellence CENS from the ERDF and by the DoRa international PhD studentship for M. Viška).

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