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Vessel-wave induced potential longshore sediment transport at Aegna Island, Tallinn Bay

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Abstract. The potential impact of high-speed vessel wakes on the longshore drift of semi-sheltered, medium-energy beaches is evaluated based on recent studies in almost tideless Tallinn Bay, the Baltic Sea. Energy flux and wave propagation direction of vessel wakes is estimated based on high-resolution water surface profiling in summer 2008. The wind-wave time series in 1981–2008 is modelled on the basis of a simplified scheme for a long-term wave hindcast with the use of a triple-nested version of the WAM model. Longshore drift, created by wind waves and by vessel wakes, is estimated by the energy flux model, also known as the Coastal Engineering Research Centre (CERC) model. Vessel wakes cause longshore drift that in 2007–2008, as compared to the drift produced by wind waves on the SW coast of the Aegna Island at the entrance to Tallinn Bay, had a magnitude about 75% less and the opposite direction.

Key words: wind waves, ship wakes, littoral drift, wave modelling, Baltic Sea, Tallinn Bay.

1. INTRODUCTION

An accurate knowledge of the wave climate, acting on a specific area, is an important component for the understanding of the behaviour of the coastal system. Waves are the major driving force for the littoral processes on both high-energy shorelines [1] and on low-energy shores of sheltered sea coasts or lakes [2]. Usually waves are produced by natural phenomena such as wind, earthquakes and tides. In the recent past, however, waves produced by various moving vessels have become an important component of the overall wave activity on many sections of the coast. This has led to the situation, where the impact of anthropogenic waves is no longer negligible [2,3]. It is well known that heavy ship traffic has the potential to cause environmental damage in the vicinity of vulnerable areas such as wetlands or low-energy coasts where vessel waves can cause extensive shoreline erosion and resuspension of bottom sediments, trigger ecological disturbance, or harm the aquatic wildlife [3–5].

The sea area between Tallinn and Helsinki in the Gulf of Finland, the Baltic Sea (Fig. 1), hosts one of the most intense ship traffic regions in the world with about 65 000 ship crossings annually. During the high (summer) season, the number of passenger ferries and hydrofoils traversing Tallinn Bay has reached up to 70 times per day [6]. Large, high-speed vessels with service speed in the range of 25–40 knots comprise the majority of these vessels since about the year 2000, along with some conventional passenger ferries or cargo ships [6,7]. Tallinn Bay is one of the few places in the world where such high-speed vessels continue to operate at their service speeds in relatively shallow water close to the shoreline [7]. These vessels are known to produce long and high waves, with the energy flux being up to 35% of the total wave energy flux on some sections of the coast in Tallinn Bay [6,7]. Although there have been considerable changes in the high-speed vessel fleet, the vessel-induced wave energy and energy flux has not changed significantly since 2000 [7]. On some shorelines, the waves approach from a substantially different direction compared to wind waves. Their short-term impact has been observed in the form of rapid loss of beach sediment accompanied by equally rapid changes of the beach profile under certain conditions [8].

The main aim of this study is to quantify the role of vessel waves on the longshore sediment transport on a section of the coast of Tallinn Bay where the approach angle of vessel wakes differs from that of wind waves. We focus on an almost straight section of the SW coast of the Aegna Island (Fig. 2), at the entrance of Tallinn Bay. This section – a site used to study the properties of vessel wakes in 2008 [7] – has been suffering from severe erosion over recent years [9].

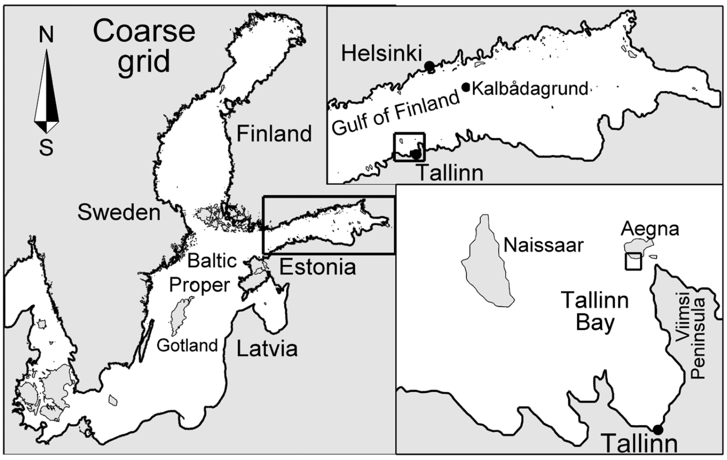

Fig. 1. The Baltic Sea and Tallinn Bay, and the nesting of the wave model.

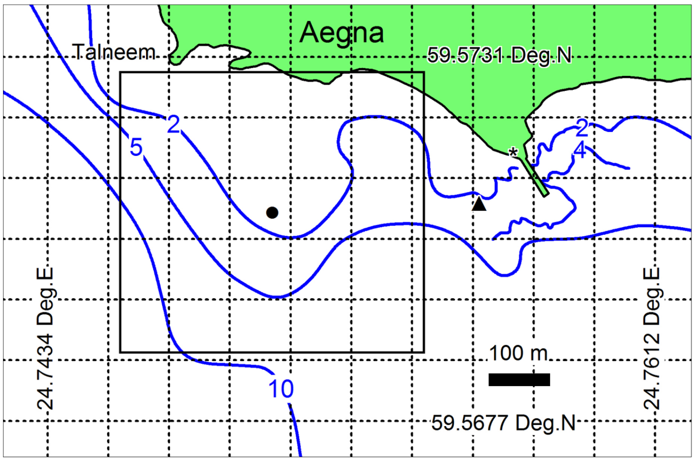

Fig. 2. The study site on the SW coast of Aegna. The small filled triangle shows the wave measurement site and the circle – the centre of the grid cell of the wave model with the mean depth of 2 m [7].

We are specifically interested in the relative magnitude of the longshore sediment transport in the surf zone caused by wind waves and vessel wakes. The relevant potential transport rates are estimated numerically by means of the CERC (Coastal Engineering Research Centre) sediment transport model [10] forced by the results of multi-nested wind wave modelling [11] and *in situ* measured properties of vessel wakes.

2. STUDY AREA

Tallinn Bay is a semi-sheltered bay, approximately 10 × 20 km in size, on the southern coast of the Gulf of Finland in the almost tideless Baltic Sea (Fig. 1). The overall hydrodynamic activity is fairly limited: the significant wave height in the open part of the gulf rarely exceeds 5 m during the most extreme storms, and the speed of the surface and coastal currents usually remain well below 1 m/s [12]. The largest water level variations are driven primarily by weather systems, with a maximum recorded range of 2.47 m [7]. Typical water level variations are within a few tens of centimetres. Very high (more than 1 m above the mean sea level) water level events are rare. Thus, the wind wave impact is concentrated into a relatively narrow range of the coastal zone.

The northern part of the western coast of the Viimsi Peninsula (Fig. 1) and a large part of the SW and western coast of Aegna are protected by (i) very shallow waters, (ii) a pavement composed of cobbles and pebbles in the vicinity of the shoreline, and occasionally (iii) a belt of boulders from the shoreline down to a water depth of about 1 m [7,9]. The protected sections of the coastline are not directly vulnerable to ship waves [9] although long ship waves may affect some parts of the coastal slope [6]. No such protection exists for a coastal section adjacent to a jetty on the SW coast of Aegna [7]. A small, mixed sand and gravel beach next to the jetty is actively shaped by both wind waves and ship wakes [8].

Aegna is separated from the Viimsi Peninsula by a shallow-water (typical depth 1–1.5 m) channel with two small islands. The islands and the geometry of the channel effectively block waves approaching from the east. The SW coast of Aegna (Fig. 2) therefore receives almost no wave energy from the east. Also, south and SSW storms produce no large waves at this site because of the short fetch (<15 km) in this direction. Moreover, these waves approach the shore almost perpendicularly and result in negligible longshore sediment transport. The most significant waves along this section come from the west, entering Tallinn Bay between the mainland and the Naissaar Island. Significant wave energy also enters Tallinn Bay from the north and NW. These waves impact the coast in a similar way to waves approaching from the west or from the SW. They all contribute to littoral drift from the east. This direction of sediment transport matches the local geomorphic features. Along the shoreline to the west of Aegna jetty there is an evident sediment deficit and coastal erosion [9]. Long-term accretion occurs only in a short section immediately to the west of the jetty, which serves as a groyne, stopping the littoral flow.

The coastal section studied is fully open to the south and receives a large amount of energy from wakes produced by ships sailing from Tallinn to Helsinki. Its coastline and the isobaths in its vicinity are predominantly (albeit not perfectly) oriented perpendicularly to the corresponding ship wave rays. The properties of ship waves in this area have been measured over many years [6,9,13]. In the following, we use high-resolution measurements of the time series of the water surface from a recent study [7], which allow adequate calculation of the ship-induced wave energy flux. The coast is somewhat sheltered from waves, approaching from the NW by a shallow area near cape Talneem. This is the reason why the waves from ships sailing to Tallinn are negligible in this area [7].

The sea bottom in the study area is relatively gently sloping and with no steep slopes. In the vicinity of the jetty, there is an area of relatively deep water, where depths increase over a short distance to approximately 2 m [7]. Further seaward there is a more or less linear slope down to depths of 6–8 m and a gently sloping terrace 0.5–1 km wide to about 15 m water depth. This variability causes some differences to the properties of ship wakes reaching different parts of the SW shore of Aegna. These differences, as well as local small-scale variations of wind wave fields, are not accounted for in our simulations that have a spatial resolution of about 470 m.

Finer sediments have been mostly carried away from the coastal zone, where a pebble and boulder pavement has formed in places down to a depth of about 2–3 m. Although in some places sand and gravel are found between larger sediments in the nearshore, the pavement protects the floor from further erosion. As there is very little fine-grained sediment available in the surf zone and on the coastal slope, the estimates of the magnitude of the wave-induced longshore transport are only indicative. More sand and gravel, interspersed in the pavement, is found at water depths of 6–10 m. At a depth of 10–12 m, coarse sand is found sporadically, with ripples on the surface indicating that wave activity occasionally affects the sea floor even at these depths.

3. WIND WAVE PROPERTIES AND VESSEL WAVE DATA

The wind wave properties in the nearshore of the study site are estimated on the basis of a simplified scheme for long-term wave hindcast with the use of a triple-nested version of the WAM model [14]. The implementation of the model is described in detail in [15] and the improvements, leading to a more adequate representation of short-wave properties in Tallinn Bay (such as an extended frequency range), in [11]. All the submodels calculate the two-dimensional wave spectrum for 24 evenly spaced directions, representing wave propagation, and for 42 frequency bins for wave periods covering the range from 0.042 to 2.08 Hz with an increment of 10% between the neighbouring bins. The grid step of the innermost model (that covers Tallinn Bay and its vicinity, Fig. 1) is about 1/4 nautical miles. This resolution allows an adequate representation of the wave growth in weak wind and short fetch conditions and an acceptable description of wave properties in the coastal zone, up to a depth of about 5 m and as close as 200–300 m to the coast [11,15].

The method of speeding up the wave computations [15] consists of reducing the long-term calculations of the time series of wave properties to an analysis of a set of pre-computed maps of wave fields. The calculations are split into a number of short independent sections under the assumption that, to the first approximation, an instant wave field in Tallinn Bay is a function of a short section of wind dynamics. This assumption matches reality well if wave fields rapidly become saturated and have a relatively short memory of wind history. It is also assumed that wave properties in Tallinn Bay are mostly defined by wind conditions in the Gulf of Finland. These assumptions are correct in Tallinn Bay for about 99.5% of the cases [15].

The model is forced with one-point wind data from Kalbådagrund (59°59′N, 25°36′E, Fig. 1) for the years of 1981–2008. This is the only measurement site in the Gulf of Finland that correctly represents marine wind conditions. The presence of ice is ignored. Doing so leads to some bias of the results, because the mean number of ice days is from 70 to 80 annually [16] and, statistically, the ice cover damps wind waves either partially or totally during the most windy winter season. Therefore, the computed annual mean parameters of wind waves are somewhat overestimated and represent average wave properties during the years with no extensive ice cover. The model produced time series of wave properties for each 3-hour time slice at the centre of a grid cell with dimensions of 0.5’ × 0.25’ (about 463 × 470 m, Fig. 2) located beyond the surf zone for typical wave conditions. These properties of the wave field and the associated potential sediment transport were assumed to be constant within these time slices.

Ship wakes were measured by tracking sea-surface elevation with a resolution of 5 Hz using an ultrasonic water level gauge [7]. The device was mounted about 100 m from the southern coast of Aegna, about 60 m from the southern end of Aegna jetty (59°34.259′N, 24°45.363′E) in around 2.7 m water depth (Fig. 2). Single waves and their properties for each vessel wake were extracted from the time series of the water level with the use of both zero-upcrossing and zero-downcrossing methods. The energy of each ship wake was found by summing the energy of single waves, separated from a manually selected section of the demeaned and detrended water surface record, based on the zero-upcrossing method [17] or, alternatively, from the long-wave energy spectrum of the wake [7]. The energy flux (wave power, equal to the product of wave energy and group velocity) was calculated for each wake by means of summing the energy flux, carried by each wave for the given water depth and over the period of the wave [17]. The properties of the ships, producing the most energetic wakes, and the basic parameters of the wakes are presented in Table 1.

Although the orientation of the ship track was almost constant, the propagation direction of the leading, largest vessel waves varies for different wakes depending on the exact location of the sailing line and the Froude number [18]. This variation is generally a few degrees [18] and diminishes owing to the nearshore refraction when ship waves approach the coast. As the resulting variation of the approach angle of ship waves was a small fraction of the angular resolution (15°) of the spectral representation of the wind wave model, we assume that the vessel waves approached from a fixed direction. This direction was defined with the use of several examples of straight-crested waves that reached the coast with very limited breaking (Fig. 3). The orientation of the crests was estimated from several photos and video recordings taken during the experiment [7], based on their orientation with respect to a line connecting two big rocks visible on the sea surface and identifiable on 'Google Earth' images. This procedure gave for the propagation direction of the largest and longest vessel waves the value of 10°. The directions are counted clockwise from the direction to the north. Figure 3 confirms that such waves cause littoral transport to the west.

Table 1. High-speed ships operating the Tallinn-Helsinki ferry route in summer 2008 [7] and average properties of their wakes (integrated over the duration of the wakes [17]) on days with comparatively low wind wave background (28–30 June, 1–9, 12, 13 and 20 July 2008)

Vessel	Departures per day	Energy, 10^4 J·s/m^2	Energy flux, 10^4 W·s/m
SuperSeaCat	6	5.4	27.4
Nordic Jet, Baltic Jet	6	2.8	13.6
Star	5	5.0	24.0
SuperStar		6.6	30.7
Viking XPRS	2	2.0	8.9
Superfast	1	3.3	14.8

Fig. 3. A straight-crested vessel wave at a beach adjacent to Aegna jetty.

4. LONGSHORE TRANSPORT

The potential longshore sediment transport rate Q_l per unit time is most commonly assumed to be proportional to the longshore component of the wave energy flux [10]:

$$Q_l = K \frac{Ec_g \sin\alpha_b \cos\alpha_b}{(\rho_s - \rho) g (1-p)}, \tag{1}$$

where K is the non-dimensional (CERC) coefficient, Ec_g is the wave energy flux, E is wave energy, c_g is the group velocity of waves, α_b is the wave approach angle relative to the shoreline, ρ_s and ρ are the densities of sediment particles and seawater, respectively, g is the acceleration due to gravity, and p is the porosity coefficient. The sign of the potential transport rate is usually chosen so that the motion from the left to the right of the person looking to the sea is positive. The sign and the value of the integral of the transport rate show the dominant direction and the magnitude of net transport, respectively. The ratio of the net and bulk (the integral of the modulus of the transport rate) potential transport characterizes the intensity of the transport of sediments through the section in question compared to the oscillatory motions. As we are only interested in the transport in the surf zone, no specific bottom boundary layer model (cf. [19]) is employed.

Importantly, the calculated sediment transport is not reached for the coast in question because of the lack of available finer material. For this reason we only use the ratio of the potential transport rates for different wave systems. This measure gives an estimate of the relative role of each wave system.

We use the following empirically derived relationship for the coefficient K, showing its dependence on the properties of the wave field and sediments [10,11]:

$$K = 0.05 + 2.6\sin^2 2\alpha_b - 0.007 u_{mb}/w_f, \tag{2}$$

where

$$u_{mb} = \frac{\kappa}{2}\sqrt{gh_b} \tag{3}$$

is the maximum orbital velocity in breaking waves from the linear wave theory. Here $\kappa = H_b/h_b$ is the breaking index, H_b is the wave height at breaking, h_b is the breaking depth, d_{50} is the mean grain size and

$$w_f = 1.6\sqrt{gd_{50}\frac{\rho_s - \rho}{\rho}} \tag{4}$$

is the approximation of fall velocity in the surf zone [10,11].

As mentioned above, the properties of the wind wave field (significant wave height, peak period, and mean propagation direction) were calculated for each 3-hour time slice [15] and were assumed to be constant within such time slices. The modifications of the wave properties owing to wind wave propagation up to the surf zone were estimated, based on the linear wave theory and the assumption that the wave energy is concentrated in monochromatic waves with the period equal to the peak period and the direction of propagation equal to the mean propagation direction. Given the uncertainties in wind data and wave hindcast, a more exact calculation of transport properties, based on the full wave spectrum, is not reasonable. For the same reason, the estimate of shoaling of waves, propagating from the centre of the computational grid cell (Fig. 2) to the surf zone, was approximated indirectly by choosing the breaking index $\kappa = 1$ as suggested in [11]. In this approximation $h_b = H_b$, that is, the breaking wave height is simply equal to the modelled wave height at the centre of the nearshore cell.

5. RESULTS

Waves affecting the coasts of Tallinn Bay and Aegna are primarily generated in remote sea areas of the Gulf of Finland. Westerly winds may bring to this area wave components, which are excited in the northern sector of the Baltic Proper. The wind regime in the Gulf of Finland, and the entire Baltic Sea is strongly anisotropic [20,21]. The most probable wind and storm direction is SW whereas NNW winds are less frequent but, statistically, the strongest in the northern Baltic Proper. During some seasons, strong easterly winds may blow along the axis of the Gulf [21]. As the study site is fully sheltered from waves excited by easterly winds and the fetch length for SSW winds is very small at about 15 km, only SW, W and NNW winds can bring substantial amounts of wave energy to the SW coast of Aegna. These wave systems approach the study area so that the resulting littoral drift is directed to the east [8].

A plot of the frequency of occurrence of modelled wind wave conditions with different wave propagation directions and heights H_S along the SW coast of Aegna in 1981–2008 (Fig. 4) confirms this hypothesis. The orientation of the coastline and isobaths at the seaward border of the surf zone for waves approaching the coast is from WNW to ESE. Although some isobaths have a slightly larger angle, up to 45°, to the parallels, the general appearance of the shoreline and the nearshore leads to an orientation of the coastline of 22.5° with respect to parallels being adopted. This assumption matches the directional resolution (1°) of the output of the WAM model for the wave propagation direction. Sediment transport is positive (to the west) when waves propagate in the range of directions between 293°–22°, and negative (to the east) for waves propagating in the directions between 23°–112°. It is assumed that the rest of the waves (propagating in the range of directions from 113° to 292°) do not cause any sediment transport. Here the angle is counted clockwise from the north.

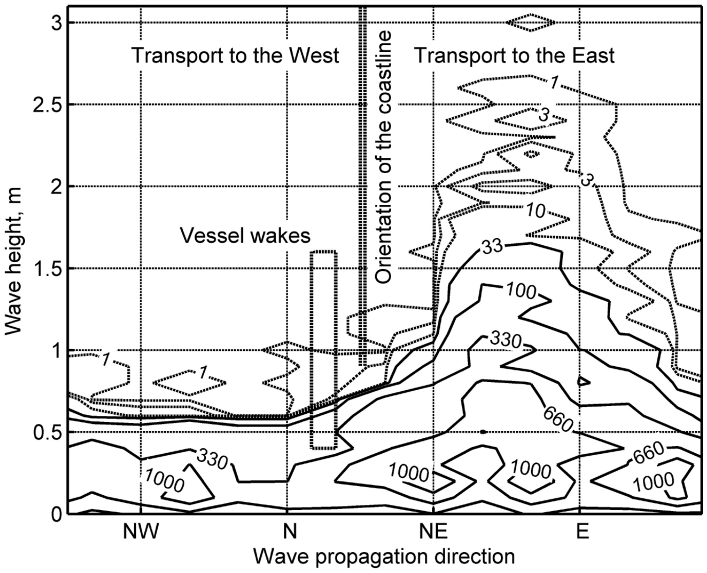

Fig. 4. Scatter diagram of the number of occurrence of different modelled significant wave heights and propagation directions in the nearshore of the SW coast of Aegna. The wave height step is 0.1 and the direction step is 15° as in the wave model.

Large wind-waves that may cause effective longshore transport exclusively approach the coast from a relatively narrow range of directions from the SW to W. This distribution is in accordance with the above discussion of the potential approach directions of the largest storm waves. Waves higher than 1 m normally propagate in an even narrower range of directions, 50°–80° from the north, that is, to the ENE. The majority of relatively intense wave conditions (including almost all events with the wave height of >0.6 m) therefore cause longshore sediment transport to the east. Note that there is a relatively low probability of high waves approaching from the south, which is the direction from which the largest ship waves usually approach.

As mentioned above, the typical propagation direction of large, long vessel-induced wakes (that mostly travel almost to the north) is close to 10°. Such waves cause longshore sediment transport to the west, that is, opposite to the transport induced by wind waves.

This qualitative picture is confirmed by the results of numerical modelling of the potential rate Q_l of the annual and monthly sediment transport, based on wave conditions from 1981 to 2008. The time series of the potential transport rates caused by wind waves were calculated from Eqs. (1)–(4), based on their numerically estimated time series of significant height, peak period and propagation direction. These quantities, estimated once every three hours, were assumed to represent the average properties of the wave field within the corresponding three-hour intervals. The resulting time series was then used to estimate the annual mean potential transport and the potential transport in July 2008.

The analogous values for the ship-induced potential transport were calculated first for single ship wakes, based on the measured ship wave energy flux and the assumption that all ship waves approaching the coast propagate in the direction of 10°. This was done for days with comparatively low wind wave background (28–30 June, 1–9, 12, 13, and 20 July 2008 [7]) during which ship-induced waves were clearly identifiable (Table 1). Longshore transport, caused by the ship wakes, was then calculated for each day using the average values for the energy flux, produced by each type of high-speed vessels (Table 1), and the timetable of departures, from which the number of operated ships was established. The contribution from wakes from other ships is quite small (a few percent of that of high-speed vessel wakes) and was ignored in the calculations.

Doing so adequately accounts for double wakes, the total energy and energy flux of which are approximately equal to the sum of the relevant parameters of wakes of single ships [7,17]. The largest uncertainty stems from the limited number of observed ship wakes (between 20 and 60 for different ships). The variability of the energy flux and the periods of the largest waves for the wakes in question is, however, fairly limited [17] and there is no reason to expect that there are larger variations during other seasons.

The results are presented in Table 2 for the mean grain size value of $d_{50} = 5$ mm, which is the approximate mean grain size on the SW coast of Aegna. The ratio of the potential transport caused by ship and wind waves is

Table 2. Numerically simulated values of the potential longshore sediment transport rate on the SW coast of Aegna

	Wind waves		Vessel wakes	
	1000 m^3/year	1000 m^3/month	1000 m^3/year	1000 m^3/month
Bulk	879	55	222	19
Net	−736	−51	222	19
Directional transport, %	−84	−93	100	100

Monthly values are given for July 2008 and the annual values for the ship traffic from August 2007 to July 2008. The bottom row shows the percentage of the westward (positive) or eastward (negative) net transport compared with the bulk transport.

almost the same for other grain sizes used in the calculations (0.063, 0.1, 0.2, 1, 2, and 5 mm). The annual potential sediment transport rate, generated by vessel wakes, forms approximately 25% of the similar rate caused by wind waves and is directed opposite to the natural longshore drift. This result indicates that vessel wakes, although their impact does not control the sediment transport pattern in the study area, do cause a substantial component of the overall sediment motion on the SW coast of Aegna and that their role cannot be neglected. Their actual role, however, may be even bigger, because the longest and highest ship waves may initiate offshore sediment transport [8].

6. DISCUSSION

The Coastal Engineering Research Centre formula used for the calculation of the potential sediment fluxes along selected coastal sections has many shortcomings because of deficiencies in the underlying physics [22] and uncertainties in the representation of the general appearance of the nearshore in the model. As, at the study site, finer sediments exist only in places, the potential transport rates are probably by several orders of magnitude larger than the actual transport rates. The complex geometry of the nearshore affects both the refraction properties of the approaching waves and their energy loss due to damping and reflection. In general, it is a difficult task to precisely determine the breaking angle between the wave crest and the isobaths. Therefore, the magnitudes of the calculated sediment fluxes are probably overestimated. However, this approach is suitable for describing the net direction of sediment fluxes and the ratio of the bulk and net sediment transport [11].

This analysis demonstrates that waves, created by the high-speed vessels, may cause significant changes to coastal processes even on medium-energy coasts. A major component of the impact stems from the fact that wind waves and ship wakes may systematically approach from different directions and initiate sediment fluxes in opposite directions. This feature has been demonstrated to result in unexpected changes on the coasts, impacted by ship wakes [8]. For example, during the absence of ship traffic, an approximately 30 cm high berm (consisting mostly of the same grain size as the rest of the beach material) usually developed over night on the beach next to Aegna jetty during an experiment in 2008. In the morning, however, it was found that the first ship wakes completely washed the berm away. This process of smoothing the coastal profile may reflect the oppositely directed sediment flux.

Previous studies have shown that that vessel wakes may contribute considerably to the energy budget of shorelines during relatively calm periods [6,23]. Although this contribution is relatively small (about 10%) in terms of the energy [6], it may be much more substantial in terms of the highest waves [7] and, especially, in terms of the energy flux. This measure also accounts for the wave periods and to a large extent defines the impact of the waves on coastal processes. The magnitude of this impact also depends on the direction of the wave approach. In the analysed case, the approach angle of vessel wakes was considerably smaller than that of the largest wind waves and thus the relative impact of ship wakes is comparatively small. The situation may be different on other beaches, in particular, where the majority of wind waves approach the beach almost perpendicularly to the shoreline. In such cases, ship wave activity may play an important role in the stability of many types of soft coastal engineering structures (such as beach renourishment) or artificial islands.

The described potential changes in the sediment transport suggest that frequent presence of high vessel generated waves (the equivalent of which occur under natural conditions very infrequently in semi-sheltered sea areas) and their unusually high runup [24] generally needs response in impacted areas. These aspects should be addressed in the analysis of the impact of ship traffic in vulnerable areas either in terms of coastal protection or warnings for the users of the nearshore or the beach [25], or at a more general level, for example, through the interpretation of the excess hydrodynamic activity in coastal areas affected by high vessel wakes as a specific type of pollution [26].

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Laevalainete poolt põhjustatud potentsiaalne pikiranda settetransport Aegna edelarannikul

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On hinnatud kiirlaevalainete potentsiaalset mõju settetranspordile keskmise loodusliku lainekoormusega randades Aegna saare edelaranniku näitel. Laevalainete levikusuund ja energiavoog on leitud 2008. aastal teostatud lainemõõtmistest. Tuulelainete energiavoog on arvutatud lainemudeli WAM kõrglahutusega versiooniga Kalbådagrundil mõõdetud tuuleandmete alusel aastaiks 1981–2008 kolmetunniste lõikude kaupa leitud lainekõrguse, -perioodi ja levikusuuna kaudu. Lainete poolt põhjustatud potentsiaalset pikiranda settetransporti on hinnatud nn CERC-i mudeliga. On näidatud, et aastail 2007–2008 käigus olnud kiirlaevade lained põhjustavad Aegna edelarannikul setete edasikande, mille intensiivsus on ligikaudu 25% tuulelainete poolt tekitatust ja mis on vastupidises suunas loodusliku transpordi suhtes.