THE RELATIVE IMPORTANCE OF WIND-WAVES AND SHIP-WAKES ON LONGSHORE DRIFT IN TALLINN BAY, THE BALTIC SEA

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Surface waves and their interactions with sediments and benthic organisms are the main hydrodynamic process affecting littoral ecosystems of small natural and artificial islands. The role of high-speed ferry wakes on the wave energy budget and their impact on longshore drift of semi-sheltered beaches of small islands has been evaluated based on recent studies in almost tideless Tallinn Bay, the Baltic Sea. High resolution water surface time-series containing signals of > 600 ship wakes were collected almost continuously for 30 days at a depth of~2.7 m**.** The wind-wave climate (1981–2008) in the vicinity of the study site is estimated 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 [9]. Longshore drift created by wind waves and by Ferry Wakes was estimated by the energy flux model, also known as CERC model [4]

Взаимодействие поверхностных волн с донными отложениями является одним из основных гидродинамических процессов прибрежной зоны, влияющих на прибрежные экосистемы. В данной работе исследуется вклад судовых (в частности, волн от быстроходных паромов) в энергетический спектр волн и перенос донных отложений в полузакрытых бухтах таких, как Таллиннский залив в бесприливном Балтийском море. Анализ основан на 30-дневной записи волн, сделанной в 100 м от берега на глубине ~ 2.7 м и содержащей сигналы > 600 быстроходных паромов. Статистика ветровых волн (1981-2008 гг.) в исследуемом районе рассчитана с использованием модели WAM по упрощенной схеме долгосрочного прогноза [9] (Komen и др., 1994). С помощью модели CERC, использующий поток волновой энергии, сделаны оценки переноса донных отложений в прибрежной зоне [4].

Introduction

Vessel-wake effects on the aquatic ecosystem and the coastal environment have received considerable attention in the literature [13, 15, 22]. There has been less attention given to their role as a coastal hazard for natural and artificial islands or as a form of environmental pollution [21]. The first adequately documented case of ship-induced coastal hazards in the open sea, which led lead to loss of life, seems almost unbelievable. In 1912 in the Gulf of Finland, the Baltic Sea, a boy was washed from a wharf and drowned [12]. The wharf was 2.7 m above water level and was located at a distance of about 10 km from the sailing line of the warship *Novik*. The nonlinear wave height amplification combined with extensive shoaling of the long waves in shallow water is the probable reason of this event. There have been more recent similar events [7, 6] resulting from the breaking of waves generated by fast ships.

It is now widely accepted that heavy ship traffic has the potential to cause environmental damage in the vicinity of vulnerable areas such as low-energy coasts or wetlands where wake-waves can cause extensive shoreline erosion or rapid changes to the coastal profile near the waterline [17, 25], resuspend and transport bottom sediments, trigger ecological disturbance, and harm the aquatic wildlife [19, 1, 15, 14].

The continuing evolution of ships with more, faster and larger ships on important routes has led to the situation in which ship wakes may form a key component of the hydrodynamic activity on some medium- and high-energy coasts [21, 17]. Early measurements of ship wave heights typically agree that the wave heights do not substantially exceed 1 m at the depths of 3–5 m [16]. These results have been obtained based on a limited number of observations and contain relatively large uncertainties. The major effects of the presence of high, solitonic, vessel wakes are intense wave breaking and runup. Reports of such ship wave events stress that holidaymakers have been forced to "flee for their lives when enormous waves erupted from a millpond-smooth sea", or that waves look like "the white cliffs of Dover" [6].

The most significant effects and hazards associated with the increased hydrodynamic activity caused by ship waves occur when the leading ship waves are much longer than the typical wind waves [21]. This feature may become decisive in planning of artificial islands in otherwise semi-sheltered areas, but in the vicinity of ship lanes hosting intense fast ferry traffic. Even a small increase in hydrodynamic loads may lead to a significant increase in sediment transport when the bed stress due to local factors is near a critical threshold for erosion or deposition [29]. Also, relatively small levels of long-period wave energy can cause greater beach response than an equal amount of energy in the wind-wave frequencies [3].

In this paper, we concentrate on changes in the relative role of ship waves and wind waves for longshore sediment drift at Aegna Island. We focus on Tallinn Bay, the Baltic Sea (Figure 1), an area characterized by an overall mild, but largely intermittent, wind wave regime [21]. While the annual mean significant wave height is well below 0.5 m, wave heights exceeding 4 m occasionally occur in the bay [20]. According to studies performed in the early 2000s, the daily highest ship waves (with a typical height of slightly >1 m) were equivalent to the annual highest 1–5% of wind-generated waves. Vessel wakes contributed, at least, 5–8% of the total wave energy, and about 18–35% of the energy flux (the rate of transport of the wave energy – the product of the wave energy density and the group speed), even in those coastal areas of Tallinn Bay that were exposed to the dominant winds [21].

There have been significant changes in the types of vessels operating in this area. The vessels that produced the highest and longest waves in the early 2000s [24] have been taken out of service. A new generation of large ferries with service speeds 25–30 knots has replaced the older ferries that sailed at 15–20 knots. Also, small hydrofoils have been replaced by much larger ships [17]. The sailing lines have remained unchanged and no limitations have been imposed on vessel speed. With these changes, the number of large vessels that are able to travel at near-critical speeds [22], when the largest waves are generated, has almost doubled since about the year 2000.

There have also been significant variations in the overall wave intensity in the northern Baltic Sea basin [2, 26]. The sea was comparatively calm at the end of the 1970s. A rapid increase in the annual mean wave height occurred from the mid-1980s until the mid-1990s (Fig. 2). This change lasted for about 15 years and has been reversed with a significant decrease in the mean wave height since 1997. By the year 2005, the annual mean wave height had decreased almost by a factor of three in the northern Baltic Sea from its peak [26]. The Gulf of Finland is open to the Baltic Proper and to waves excited by dominant westerly winds (Figure 1), and thus changes to the wave climate in the Gulf should mirror those that happen in the Baltic Proper.

Earlier estimates of the relative role of the ship waves [21] were based on calculations for the years 1981–2002 when there was unusually high wind wave activity in the Baltic Proper [26]. The substantial changes to the natural wave regime in recent years combined with the changes to the structure of the fleet suggest that there is a clear need to update estimates of the relative importance of wind and ship waves for coastal change and for coastal hazards.

This paper discusses the role of vessel wakes in the overall wave activity for a section of medium-energy coast based on an experiment undertaken in June–July 2008 [17]. We consider the major quantities characterizing both explicit and implicit wave-induced litho dynamical process driving mechanisms, such as the daily maximum wave height (compared to extreme natural waves in this area) and the contribution of ship-generated potential rate of annual and monthly sediment transport to total wave generated sediment transport.

STUDY SITE AND METHODS

The study site was located on the SW coast of Aegna, immediately west of the jetty (Figure 3, 59°34′50″N, 24°45′28″E). The island, is about 1.5×2 km in size and located at the northern entrance of Tallinn Bay, Estonia. The most significant waves at the site are generated by the dominant W–SW winds and come from a western direction.

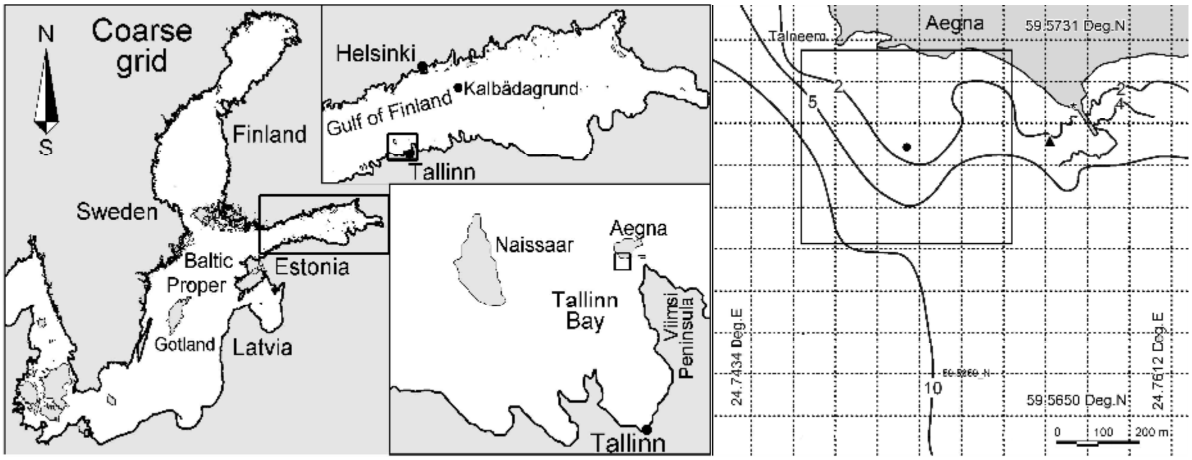

Fig. 1. The Baltic Sea and Tallinn Bay; the nesting of the wave model (left and middle panels); the study site on the SW coast of Aegna (right). The triangle shows the wave measurement site and the circle – the centroid of the grid cell of the wave model with the mean depth of 2 m.

Significant wave energy may also enter Tallinn Bay from the N and NW but the study site is somewhat sheltered from these waves by the Talneem Cape, the WSW end of Aegna. The site is also fully open to the wakes from ships sailing from Tallinn towards the Gulf of Finland [17] but it is quite well sheltered from the wakes of ships sailing to Tallinn.

The properties of the waves were established from a high resolution (5 Hz; ±1 mm) time series of water surface elevations collected using an ultrasonic echo-sounder (General Acoustics LOG_aLevel$^{®}$) mounted in about 2.7 m water depth, ~100 m offshore. The site was ~2700 m from the sailing line, at the closest point. The data were collected almost continuously over 30 days (21 June – 20 July 2008). The record contains more that 650 vessel wakes, about 400 of which can be separated from the wind wave background [17].

The wave climate in the vicinity of the study site is estimated with the use of a triple-nested version (Fig. 1) of the WAM model [9]. The innermost model (grid step of about 1/4 nautical miles) has as an extended frequency range and allows adequate description of nearshore wave properties, up to a depth of about 5 m and as close to the coast about 200–300 m [20]. The wave calculations are split into a number of short independent sections. To the first approximation, it is assumed that an instant wave field in Tallinn Bay is a function of a short section of wind dynamics. This is justified provided wave fields rapidly become saturated and have a relatively short memory of wind history. It is implicitly assumed that remote wind conditions insignificantly contribute to the local wave field. These assumptions are correct in Tallinn Bay for about 99.5% cases [20]. The model is forced with data from Kalbådagrund (59º59′N, 25º36′E, Figure 1), the only measurement site in the Gulf of Finland that correctly represents marine wind conditions. The model produced time series of wave conditions (significant wave height, peak and mean period, propagation direction etc.) for all 3-hour periods from 1981–2008. The presence of ice is ignored. As the mean number of ice days is 70–80 annually and, statistically, the ice cover usually is present during the windiest season, the computed mean parameters of wind waves are somewhat overestimated and represent average wave properties during the years with no extensive ice cover.

Single waves and their properties in each vessel wake were extracted with the use of both zero-upcrossing and zero-downcrossing methods. The maximum wave height, defined as the maximum of wave heights obtained by these two methods, almost always coincides with the maximum variation of the water surface within a 30 s interval [17]. The daily highest ship waves are compared with the calculated significant wave heights within the 3-hour sections. In many cases waves from two vessels arrived simultaneously. Such combined wave systems frequently resulted in the highest waves of the day.

The energy of each ship wake is found by summing the energy of single waves separated from a manually selected section of the de-meaned and de-trended water surface record based on the zero-upcrossing method [11] or, alternatively, from the long-wave energy spectrum of the wake [17].

While solely energy-based comparisons of waves of different origin are equivalent to a comparison of the squared wave heights, the energy flux implicitly accounts for the wave periods since longer waves have larger group velocities. It is assumed that the wind-wave energy propagates with the group velocity of the wave corresponding to the spectral maximum. Unlike the approach in [24], the energy flux for ship wakes is calculated by summing results from single waves [17].

The longshore sediment transport rate can be calculated by different models. One of the most extensively used is the so-called CERC model [4, 8]. The main idea of this model is that the potential longshore sediment transport rate (which of course depends on the available quantity of littoral material) is driven by the longshore component of wave energy flux [4]. The longshore sediment transport rate is commonly expressed as the volume transport rate Q_l (expressed here in cubic meters per time unit):

$$Q_l = \frac{I_l}{(\rho_l - \rho) g (1 - p)}. \qquad (1)$$

Here ρ_s and ρ are the densities of sediment particles and seawater respectively, g=9.81 m/s^2 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 hand 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 transit of sediments through the section in question compared to the back-and-forth motions.

The CERC model assumes that the quantity I_l in Eq. (1) is proportional to the wave energy flux P_l:

$$I_l = K P_l = K (E_b C_g) \sin\alpha_b \cos\alpha_b . \qquad (2)$$

Here E_b is the wave energy and C_b wave group velocity at the breaker line, α_b is the wave breaker angle relative to the shoreline, and K is a nondimensional coefficient. We employ the following empirical dependence of the coefficient K on properties of the wave field and sediments [4]:

$$K = 0.05 + 2.6 \sin^2 2\alpha_b 0.007 u_{mb} / w_f , \qquad (3)$$

where α_b is also the angle between wave crests and the isobaths,

$$u_{mb} = \frac{\kappa}{2}\sqrt{g d_b} \qquad (4)$$

is the maximum orbital velocity in breaking waves within the linear wave theory, $\kappa = H_b / d_b$ is the breaking index, H_b is the wave height at breaking and d_b is the breaking depth [4],

$$w_f = 1.6\sqrt{g d_{50} \frac{\rho_s - \rho}{\rho}} \qquad (5)$$

is the approximation of fall velocity in the surf zone [4] and d_{50} is the mean grain size of sediments.

The properties of the wave field (significant wave height, peak period, and propagation direction) were calculated for each 3-hour time slice at the centroid of the grid cell, closest to the study site (Fig. 1) and located beyond the surf zone for typical wave conditions [20]. These properties and the potential sediment transport were assumed to be constant within such time slices. The modifications of the wave properties owing to wave propagation up to the surf zone were estimated based upon linear wave theory and the assumption that the wave energy is concentrated in monochromatic plane 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, 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 centroids to the surf zone was not calculated but was approximated indirectly, by choosing the breaking index $\kappa = 1$. In this approximation, $d_b = H_b$ and the breaking wave height is simply equal to the modeled wave height at the centre of each sector [27].

Longshore transport for the ship wakes were calculated using the average energy value for each type of the vessels. Based on the information about how many times each type of vessels sailed during each day [17], we estimate the average longshore transport initiated by ship-wakes during the day and during the year.

RESULTS

Waves affecting Tallinn Bay and Aegna Island 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 as well as the entire Baltic Sea is strongly anisotropic [23]. The most probable wind and storm direction is SW. NNW winds are less frequent but, statistically, the strongest in the northern Baltic proper. During certain seasons, strong easterly winds may blow along the axis of the Gulf [23].

Figure 2 displays the probability density plot of the occurrence of wave conditions with a given wave propagation direction and the significant wave height H_s based on modeled wave parameters at the SW part of Aegna Island in 1982–2008. Wind-waves propagate to the shore at an angle between 315°–135°. This angle is counted clockwise from the north (Fig. 2). These angles correspond to NNW–W, SW–S, and SSE wave directions. A relatively frequent occurrence of high waves approaching the SW coast of Aegna Island from the direction of about 40° corresponds to waves excited by SW storms which are the most frequent in the area in question.

This feature suggests that sediment transport induced by ship waves (the propagation direction of which is close to 10°) is generally directed oppositely to the transport induced by wind waves.

The orientation of the coastline and isobaths at the seaward border of the surf zone for waves approaching the coast is from NW to SE. Waves traveling in the direction of 45° from the north, that is, perpendicularly to the coast, do not initiate longshore sediment transport. Sediment transport is positive (to the West) when waves propagate in the range of directions between 335°–45°, and negative) to the East) for waves propagating in the directions between 45°–135°.

The majority of wave conditions (including almost all events with the wave height of >0.75 m) therefore cause eastwards sediment transport. The highest wind waves have a narrow directional range. Waves higher than 1 m normally propagate in the range of directions 25°-85° from the north. These waves, therefore, mainly cause eastwards longshore sediment transport. In other words, sediment transport driven by wind waves is predominantly to the west. Note the relatively low probability of high waves approaching from the South – the direction from which the largest ship waves usually approach. Therefore, ship wakes apparently cause sediment transport to an opposite direction of the wind-wave-induce transport.

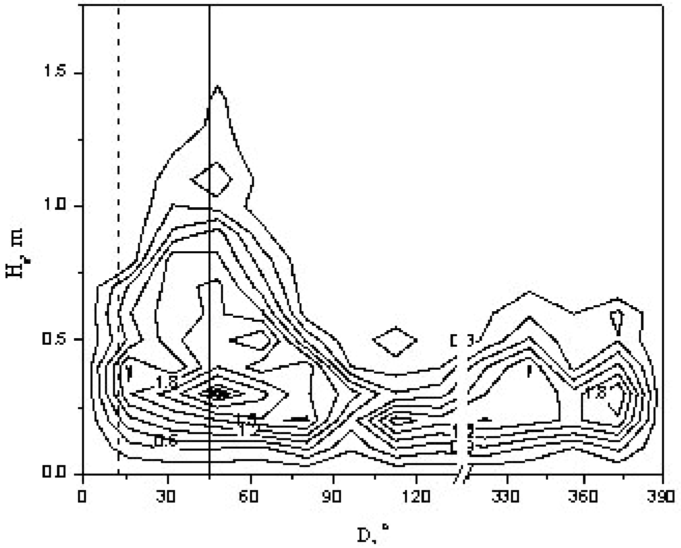

Fig. 2. Scatter plot of the occurrence of wave conditions with different wave height and approach angle. The dotted vertical line corresponds to the typical approach angle of the largest ship-wakes. Solid line corresponds to the direction perpendicular to the coastline

This hypothesis is confirmed by the numerically modelled potential rate Q_l of annual and monthly sediment transport based on wave conditions in 1982–2008. The results are presented in Table 1 for the mean grain size value of 5 cm, which is the dominant grain size at the study area – a mostly gravel beach.

Table 1

Potential transport rate along Aegna Island for the various sectors.

	Potential transport rate for wind-waves		Potential transport rate for ship-wakes	
	1000 m^3/year	1000 m^3/month (2008 07)	1000 m^3/year	1000 m^3/ month (2008 07)
Bulk	879	55	222	19
Net	-736	-51	222	19
%	-84	-93	100	100

Table 1 shows that the sediment transport rate generated by ship wakes is approximately 4 times smaller than the sediment transport rate created by wind waves. This result indicates that ship wakes create a substantial part of the overall sediment motion on the SW coast of Aegna and their role cannot be neglected. Their factual role, however, may be even bigger, because the longest and highest ship waves sometimes are propagating almost perpendicularly to the coast and may initiate essential sediment transport offshore [25].

DISCUSSION

The CERC formula for calculation of different sediment fluxes along selected coastal sections has many uncertainties because of uncertainties in the general appearance of the nearshore and the availability of finer sediments in the region in question. For example, at the study site finer sediments exist only at places. 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. One should, therefore, interpret the magnitude of the calculated sediment fluxes as largely overestimated. However, this model is suitable to use for describing (i) the net direction of sediment fluxes and (ii) the ratio of the bulk and net sediment transport.

The basic message from the performed analysis is that waves created by the high-speed vessels may create unexpectedly high impact on coastal processes even in medium-energy coasts of a small island. A part of this large impact stems from the fact that wind and ship wakes may systematically approach from different directions and initiate sediment fluxes in the opposite directions, a feature which may result in unexpected phenomena at the coast [25]. This was observed during the Aegna experiment at night time where during the absence of ship traffic approximately 30 cm berm developed over night. In the morning, however, it was found that the first ship wakes completely washed the berm away.

It was also found that vessel wakes contribute significantly to the energy budget of shorelines during relatively calm periods [10, 24]. Although this contribution is relatively small (~10%) in terms of the energy budget, it is substantial in terms of the highest waves and the energy flux. The 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 [5] generally needs response in impacted areas, either in terms of coastal protection or warnings for the users of the nearshore or the beach [18].

The continuing high level of ship wave activity in Tallinn Bay and in similar sea areas shows that there remains concern about the potential impact of ship wakes on vulnerable coasts. In the light of the United Nations Convention on the Law of the Sea (UNCLOS), the excess hydrodynamic activity in coastal areas affected by high vessel wakes should be interpreted as a specific type of pollution along with releasing certain substances or noise into the environment [28]. This feature may play an important role in the stability of artificial islands, and, in general, it should be addressed in the analysis of the impact of harbors and associated ship traffic in the neighborhood of vulnerable areas.

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