Journal of Coastal Research	SI 56	812 - 816	ICS2009 (Proceedings)	Portugal	ISSN 0749-0258

Energy pollution: the relative influence of wind-wave and vessel-wake energy in Tallinn Bay, the Baltic Sea

L. Kelpšaite†, K.E. Parnell†‡, and T. Soomere†

†Institute of Cybernetics
at Tallinn University of Technology,
Tallinn 12618, Estonia
loreta@cs.ioc.ee
soomere@cs.ioc.ee

‡ School of Earth and Environmental Sciences,
James Cook University
Townsville, Queensland 4811, Australia
kevin.parnell@jcu.edu.au

ABSTRACT

KELPŠAITE, L., PARNELL, K., and SOOMERE, T., 2009. Energy pollution: the relative importance of wind-wave and vessel-wake energy in Tallinn Bay, the Baltic Sea. Journal of Coastal Research, SI 56 (Proceedings of the 10th International Coastal Symposium), 812 – 816. Lisbon, Portugal, ISSN 0749-0258.

The role of frequent vessel wakes on the wave energy budget of semi-sheltered beaches has been re-evaluated for the almost tideless Tallinn Bay, the Baltic Sea. High-resolution water surface time series containing signals of >650 ship wakes collected over 30 days at a depth of ~2.7 m shows that (i) the daily maximum heights of vessel wakes have increased considerably since the beginning of the decade while (ii) the leading wave periods (10–13 s) and integral properties of vessel wakes such as the total wave energy and its flux have remained largely unchanged. The typical daily largest ship waves (1.2–1.4 m) are equivalent to the annual highest 0.8–1.8% of wind waves and the highest ship waves (1.7 m) to the highest 0.25% of wind waves. Unlike the Baltic Proper, the overall wind wave intensity has varied insignificantly over the last three decades in Tallinn Bay where vessel wakes contribute about 10% in terms of wave energy and 25% in terms of energy flux. Substantial seasonal variation of wave intensity with markedly low wind waves in the biologically most active season suggests that vessel wakes may play a decisive role during some seasons even in areas with overall high wind wave activity.

ADDITIONAL INDEX WORDS: *wave climate, coastal management, vessel wakes, energy pollution*

INTRODUCTION

Vessel-wake effects on the aquatic ecosystem and the coastal environment have received considerable attention in the literature (MADEKIVI, 1993; PARNELL and KOFOED-HANSEN, 2001; SOOMERE, 2007). There has been less attention given to their role as a coastal hazard or as a form of environmental pollution (SOOMERE, 2005b). 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 (KRYLOV, 2003). 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 (KOFOED-HANSEN and MIKKELSEN, 1997; HAMER, 1999) 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 wetlands or low-energy coasts where wake-waves can cause extensive shoreline erosion or rapid changes to the coastal profile near the waterline (PARNELL *et al.*, 2007, SOOMERE *et al.*, 2009), resuspend and transport bottom sediments, trigger ecological disturbance, and harm the aquatic wildlife (SCHOELLHAMER, 1996; BOURNE, 2000; PARNELL and KOFOED-HANSEN, 2001; OSBORNE *et al.*, 2007, among others).

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 hydrodynamic activity on some medium- and high-energy coasts (SOOMERE, 2005b; PARNELL *et al.*, 2008). 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 (PARNELL and KOFOED-HANSEN, 2001). 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” (HAMER, 1999).

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 (SOOMERE, 2005b). 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 (TALKE and STACEY, 2003). 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 (COATES and HAWKES, 1999).

In this paper, we concentrate on changes in the relative role of ship waves and wind waves for coastal hazards and on coastal processes. We focus on Tallinn Bay, the Baltic Sea (Figure 1), an area that is characterized by an overall mild, but largely intermittent, wind wave regime (SOOMERE, 2005b). While the annual mean significant wave height is well below 0.5 m, wave heights exceeding 4 m occasionally occur in the bay (SOOMERE, 2005a). According to studies performed in the early 2000s, the

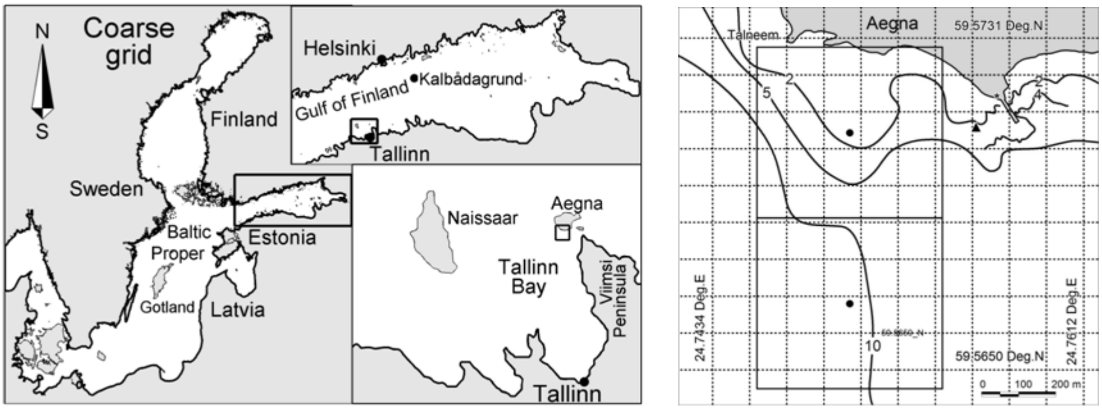

Figure 1. The Baltic Sea and Tallinn Bay; the nesting of the wave model (left and middle panels); the study site on the SW coast of Aegna (right). The triangle shows the wave measurement site and the circles – the centroids of the grid cells of the wave model with the mean depth of 2 m and 7 m (referenced as the 2 m site and 7 m site).

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 (SOOMERE, 2005b).

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 (SOOMERE and RANNAT, 2003) 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 (PARNELL *et al*., 2008). 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 (SOOMERE, 2007), 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 (BROMAN *et al*., 2006; (SOOMERE and ZAITSEVA, 2007). 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 (Figure 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 (SOOMERE and ZAITSEVA, 2007). 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 (SOOMERE, 2005b) were based on calculations for the years 1981–2002 when there was unusually high wind wave activity in the Baltic Proper. 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 (PARNELL *et al*., 2008). We consider the major quantities characterizing both explicit and implicit wave-induced coastal hazards and process driving mechanisms, such as the daily maximum wave height (compared to extreme natural waves in this area) and the contribution of ship-generated wave energy and flux to total wave energy and its flux.

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, about 1.5×2 km in size, is located at the northern entrance of Tallinn Bay. The most significant waves at the site are

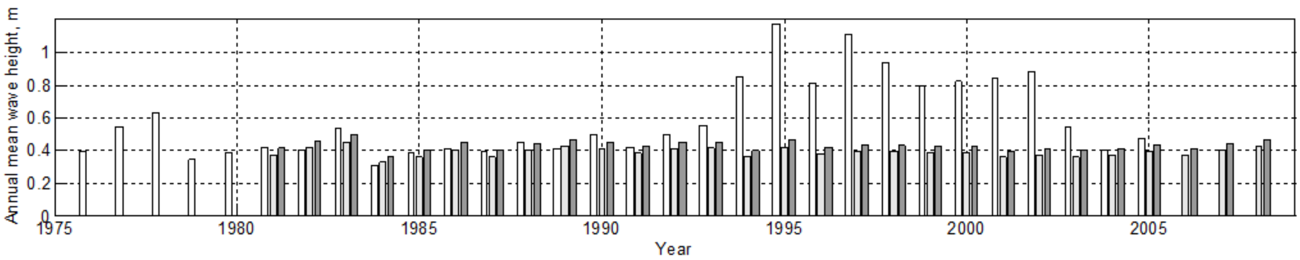

Figure 2. Annual mean visually observed wave heights at Vilsandi (1976–2005, white bars, SOOMERE and ZAITSEVA, 2007) and modeled wave height at Aegna (1981–2008, light grey bars: 2 m site; dark grey bars: 7 m site).

generated by the dominant W–SW winds and come from the W. 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 WSW end of Aegna. The site is also fully open to the wakes from ships sailing from Tallinn towards the Gulf of Finland (Parnell *et al.*, 2008) but is quite well sheltered from 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 echosounder (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 (Parnell *et al.*, 2008).

The wave climate in the vicinity of the study site is estimated with the use of a triple-nested version (Figure 1) of the WAM model (Komen *et al.*, 1994). 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 depth of about 5 m and as close to the coast as about 200–300 m (Soomere, 2005a). 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 (Soomere, 2005a). 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 (Parnell *et al.*, 2008). 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 (Kurennoy *et al.*, 2009) or, alternatively, from the long-wave energy spectrum of the wake (Parnell *et al.*, 2008).

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 Soomere and Rannat (2003), the energy flux for ship wakes is calculated by summing results from single waves (Parnell *et al.*, 2008).

RESULTS

Unlike the situation in the Baltic Proper, interannual variations in the annual mean significant wind-wave height are fairly minor at the study site (Figure 2). While some variations of the annual mean wave height (for example, low wave heights in 1984, 1987, and 1991) are similar in Tallinn Bay and in the Baltic Proper, there is no evidence of increased wave heights in the late 1990s in Tallinn Bay. The variations are perfectly correlated for the 7 m and 2 m sites. This property allows direct comparison of estimates obtained in Soomere and Rannat (2003) for a 6.7 m deep measurement site with the results of the current study.

The annual mean wave height ranges between 36–50 cm at the 7 m site where the overall mean wave height is 43 cm. Interannual variations of the mean wind-wave energy density and its flux are somewhat larger. They range between 80–230 J/m^2 (97–270 J/m^2) at the 7 m (2 m) site, and 300–800 W/m at the 2 m site. The overall mean energy density at the 2 m and 7 m sites is 143 and 169 J/m^2, respectively. The comparable ranges of variations of the energy and its flux suggest that larger wind waves do not necessarily have longer periods.

The wave regime in Tallinn Bay is not sensitive to changes to winds blowing from directions for which the wave field is strictly fetch-limited, that is, for winds from the E, S, and SW. As the bay is largely open to the W and NNW winds, these winds will have undergone no substantial changes between 1981–2008. Easterly winds are generally weak and infrequent in the entire Baltic Sea basin. Thus, the substantial changes in the wave regime in the Baltic Proper have been caused exclusively by changes to the properties of SW winds, from which Tallinn Bay is sheltered.

The wave regimes of the Baltic Sea and its sub-basins have pronounced seasonal variability (Soomere, 2005a; Soomere and Zaitseva, 2007). The monthly mean wave height varies up to three times in the Baltic Proper and typically by a factor of two in the coastal areas (Figure 3). The corresponding variations of wave energy and flux are much larger. Therefore, the contribution of ship waves is the most important during the relatively calm period (April–August) which is also the biologically most active time and the spawning time of several fishes.

During strong NW-NNW and W storms, relatively high waves may penetrate into Tallinn Bay. The maximum significant wave height in the central part of this basin may reach 4.5 m in extreme storms (Soomere, 2005a). The model shows that the largest waves (H_S = 3.02 m) occurred at the study site on 19 November 1998 during westerly storm with wind speed over 21 m/s over several hours. High waves, however, occur infrequently in this area:

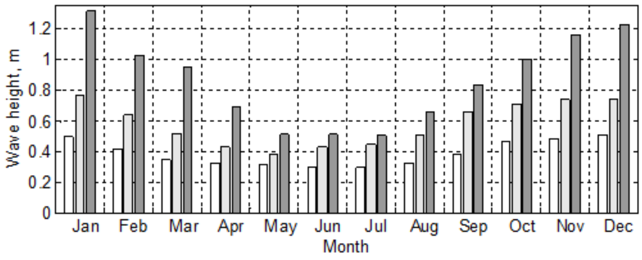

Figure 3. Monthly mean wave height at Aegna (1981–2008, white bars), Vilsandi (1954–2005, light grey bars, Soomere and Zaitseva, 2007), and Almagrundet (1978–2003, dark grey bars, Broman *et al.*, 2006).

$H_S > 1$ m occurs with a probability of <2% and $H_S > 2$ m with a probability of ~0.1% (Figure 4).

The daily maxima of ship wave heights (i) occurred exclusively for relatively long waves with periods of ~10 s or larger, (ii) exceeded 1 m and were typically approximately 1.2 m, even in completely calm conditions (Figure 5). The largest ship wave heights in generally calm conditions were 1.5 m. The combined ship and wind wave heights reached 1.7 m on a few days, with the significant height of the background about 0.3–0.4 m (Parnell *et al.*, 2008). The lowest daily maxima correspond to weekends (Sunday, 6 July, and a weekend 19–20 July) when the number of ships is somewhat smaller, and the loadings are likely to be less.

The highest waves measured in this study are significantly higher than waves previously reported for Tallinn Bay (Soomere and Rannat, 2003). Assuming no loss or spreading of wave energy, a 1.08 m high wave with a period of 11 s, detected at Aegna in 2002 with the use of a pressure sensor at the depth of 6.7 m, would evolve to about a 1.3 m high wave at the location of the echosounder (Figure 1), at a depth of about 2.7 m. In this light, several recorded wave heights close to 1.4 m suggest that the maximum ship wave heights have increased since 2002. Combined, wind and vessel generated waves, with heights of >1.7 m, add significantly to the total wave energy on this section of the shoreline (Figure 5).

Parnell *et al.* (2008) demonstrate that the average mean vessel-wake energy density over the entire measurement cycle in 2008 is about 16 J/m^2. Comparison with the above values for the annual mean wind-wave energy density at the 2 m site shows that the contribution of vessel wakes is about 10% in terms of the annual mean wave energy but up to 20% during relatively calm years. The semi-sheltered study site only receives substantial wake energy from ships sailing towards the open Gulf of Finland. The typical energy of wakes of ships sailing in the opposite direction is about 10 times smaller (Kurennoy *et al.*, 2009). A large part of this energy was recorded in the earlier (Soomere and Rannat, 2003) experiments. Therefore, the overall amount of ship wave energy received by the coast of NE Tallinn Bay has not decreased since 2002 when the annual mean energy was 15.8 J/m^2 (Soomere and Rannat, 2003), although the ships that produced the largest and longest waves in the past are no longer in service.

The average vessel-wake energy flux was estimated to be about 70 W/m at the study site over all the measurement cycle in 2008 (Parnell *et al.*, 2008). This estimate is smaller than the 110 W/m derived in 2002–2003 for a neighboring site at a depth of 7 m (Soomere and Rannat, 2003). The difference may partially result from the changes to the fleet, with new ships tending to generate shorter waves, and thus contributing less to the energy flux. The more probable reason, however, lies in the difference of the calculation methods. Earlier estimates assumed that the vessel wakes propagated with the group velocity of the wave with a weighted mean period of the wake. This assumption generally underestimates the role of the longest waves. Additionally, wave energy loss due to interaction with the bottom and spreading due to refraction accompanying wave propagation from the measurement site used in 2002 to the current measurement site combined with a partial sheltering of the site in 2008 from a part of wakes can easily explain the difference.

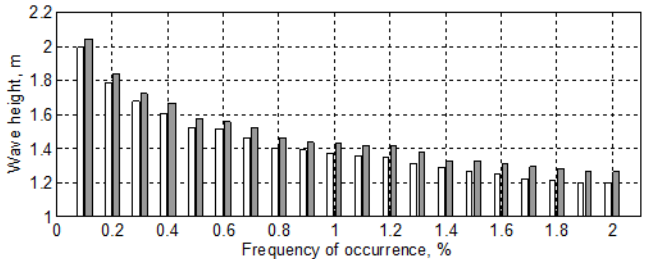

Figure 4. Probabilities of occurrence of large significant wave heights near SW Aegna for 2 m water depth (white bars) and 7 m water depth (grey bars) sites shown in Figure 1.

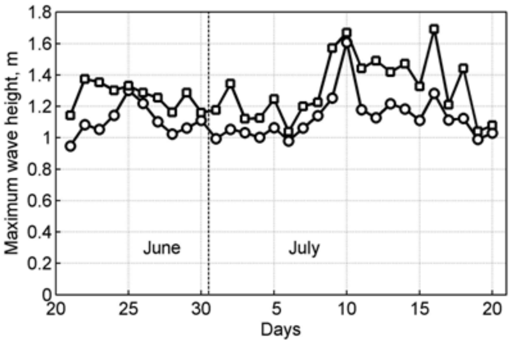

Figure 5. Daily maximum ship wave heights. Squares reflect unfiltered data and circles – data filtered using a low-pass filter with a cut-off frequency at 0.4 Hz. Reproduced from (Parnell *et al.*, 2008), with permission from Estonian Academy Publishers.

The average value of numerically simulated wind-wave energy flux over 1981–2008 at a depth of 2.7 m was 480 W/m. At this site, the vessel wakes contribute about 15% of the total energy flux and ~25% in relatively calm years. During the calm season, the energy flux due to vessel wakes is about 1/3 of the wind-wave energy flux (Figure 6). As the intensity of many beach processes (such as sediment transport in the surf zone) are determined by the energy flux, the impact of vessel wakes may become decisive on some sections of coast.

DISCUSSION

The continuous recording of ship wake properties over almost a month allowed the derivation of reliable estimates of the contribution of vessel wakes to the overall wave activity at the study site. The daily maximum heights of vessel wakes have increased considerably since the beginning of the decade. Although the ships that produced the largest and longest waves in the past are no longer in service, the leading wave periods (10–13 s) and integral properties of vessel wakes such as the total wave energy and its flux have remained largely unchanged.

An intriguing result of the wind wave modeling shows that there has been no substantial change to the overall wind wave intensity in Tallinn Bay despite very significant changes occurring in the Baltic Proper. This feature shows that (i) there have been no large changes to the properties of the W and NW-NNW winds in the surrounding sea areas and (ii) the properties of wind wave fields excited by other wind directions are strictly fetch-limited in Tallinn Bay and thus are almost entirely defined by the local wind speed. In particular, the increase in storminess does not compensate the impact of the new, anthropogenic component of local hydrodynamic activity.

The vessel wakes contribute significantly to the energy budget of shorelines during relatively calm periods. Although this contribution is relatively small (~10%) in terms of the energy budget, it is substantial in terms of the highest waves and energy flux. The frequent presence of high vessel generated waves (the equivalent of which occur under natural conditions very

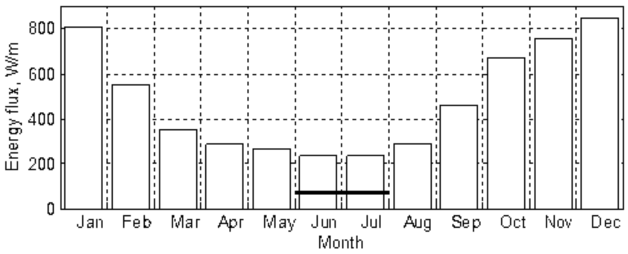

Figure 6. Average density of wind-wave energy flux at Aegna (1981–2008). The horizontal line shows the average density of vessel-wave energy flux (70 W/m) in summer 2008.

infrequently) and their unusually high runup (DIDENKULOVA *et al.*, 2009) generally needs response in impacted areas, either in terms of coastal protection or warnings for the users of the nearshore or the beach (PIANC, 2003). The role of ship traffic may even be decisive in terms of geomorphic changes on some sections of the beach (SOOMERE *et al.*, 2009).

The continuing high level of ship wave activity in Tallinn Bay and in similar sea areas means there remains a 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 (STUMBO *et al.*, 1999). This feature should be addressed in the analysis of the impact of harbors and associated ship traffic in the neighborhood of vulnerable areas.

ACKNOWLEDGEMENTS

This research is supported by Estonian Science Foundation (Grant 7413) Marie Curie scheme (TK project CENS-CMA, MC-TK-013909, and RTN project SEAMOCS, MRTN-CT-2005-019374), and by James Cook University, Australia, who provided the opportunity for Kevin Parnell to be involved in this study. The authors are grateful to the Finnish Meteorological Institute for providing the Kalbådagrund wind data.

LITERATURE CITED

BOURNE, J., 2000, Louisiana's Vanishing Wetlands: Going, Going... *Science*, 289 (5486), 1860–1863.

BROMAN, B.; HAMMARKLINT T.; RANNAT K.; SOOMERE T., and VALDMANN, A., 2006. Trends and extremes of wave fields in the north–eastern part of the Baltic Proper. *Oceanologia*, 48 (S), 165–184.

COATES, T.T. and HAWKES, P.J., 1999. Beach recharge design and bi-modal wave spectra. In: EDGE, B.L. (ed.), Proceedings of the 26th international conference Coastal Engineering 1998 (22–26 June 1998, Falconer Hotel, Copenhagen), ASCE, 3, 3036–3045.

DIDENKULOVA, I.; PARNELL, K.E.; SOOMERE, T., and PELINOVSKY, E., 2009. Shoaling and runup of long waves induced by high-speed ferries in Tallinn Bay. *Journal of Coastal Research*, Special Issue No 56,

HAMER, M., 1999. Solitary Killers. *New Scientist*, 163 (2201), 18–19.

KOFOED-HANSEN, H. and MIKKELSEN, A.C., 1997. Wake wash from fast ferries in Denmark. In *Proceedings of the 4th International Conference on Fast Sea Transportation*, Sydney, Australia. Baird Publications, pp. 471–478.

KOMEN, G.J.; CAVALERI, L.; DONELAN, M.; HASSELMANN, K.; HASSELMANN, S., and JANSSEN, P.A.E.M., 1994. *Dynamics and modelling of ocean waves*. Cambridge University Press.

KURENNOY, D.; SOOMERE, T., and PARNELL, K.E., 2009. Variability of properties of wakes from high-speed ferries. *Journal of Coastal Research*, Special Issue No 56,

KRYLOV, A.N., 2003. On the Wave Resistance and Large Ship Waves. *My Memoirs*, Politechnika, Sankt-Peterburg, pp. 364–368 (in Russian).

MADEKIVI, O. (ed.), 1993. *The environmental effects of ship-induced waves and currents*. Vesi ja Ympäristöhallinnon Julk. Sarja A, 166, 113 pp. (in Finnish).

OSBORNE, P.D.; MACDONALD, N.J., and PARKINSON, S., 2007. Sediment transport in response to wave groups generated by high-speed vessels. In: *Proceedings of the International Conference "Coastal Sediments 07*" (May 13–17, New Orleans, Lousiana, USA), ASCE, pp. 110–123.

PARNELL, K.E. and KOFOED-HANSEN, H., 2001. Wakes from large high-speed ferries in confined coastal waters: Management approaches with examples from New Zealand and Denmark, *Coastal Management*, 29 (3), 217–237.

PARNELL, K.E.; MCDONALD, S.C., and BURKE, A.E., 2007. Shoreline effects of vessel wakes, Marlborough Sounds, New Zealand. *Journal of Coastal Research* SI 50, 502–506.

PARNELL, K.E.; DELPECHE, N.; DIDENKULOVA, I.; DOLPHIN, T.; ERM, A.; KASK, A.; KELPŠAITE, L.; KURENNOY, D.; QUAK, E.; RÄÄMET, A.; SOOMERE, T.; TERENTJEVA, A.; TORSVIK, T., and ZAITSEVA-PÄRNASTE, I., 2008. Far-field vessel wakes in Tallinn Bay. *Estonian Journal of Engineering*, 14 (4), 273–302.

PIANC, 2003, *Guidelines for managing wake wash from high-speed vessels*. Report of the Working Group 41 of the Maritime Navigation Commission, International Navigation Association, Brussels, 32 pp.

SCHOELLHAMER, D.H., 1996, Anthropogenic sediment resuspension mechanisms in a shallow microtidal estuary. *Estuarine, Coastal and Shelf Science*, 43 (5), 533–548.

SOOMERE, T., 2005a. Wind wave statistics in Tallinn Bay. *Boreal Environment Research*, 10 (2), 103–118.

SOOMERE, T., 2005b. Fast ferry traffic as a qualitatively new forcing factor of environmental processes in non-tidal sea areas: a case study in Tallinn Bay, Baltic Sea. *Environmental Fluid Mechanics*, 5 (4), 293–323.

SOOMERE, T., 2007. Nonlinear components of ship wake waves. *Applied Mechanics Reviews*, 60 (3), 120–138.

SOOMERE, T., and RANNAT, K., 2003. An experimental study of wind waves and ship wakes in Tallinn Bay. *Proceedings of the Estonian Academy of Science. Engineering*, 9 (3), 157–184.

SOOMERE, T.; PARNELL, K., and DIDENKULOVA, I., 2009. Implications of fast ferry wakes for semi-sheltered beaches, Aegna Island, Baltic Sea, *Journal of Coastal Research*, Special Issue No 56,

SOOMERE, T. and ZAITSEVA, I., 2007. Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi. *Proceedings of the Estonian Academy of Sciences, Engineering*, 13 (1), 48–64.

STUMBO, S., FOX, K., DVORAK, F., and ELLIOT, L., 1999. The prediction, measurement, and analysis of wake wash from marine vessels. *Marine Technology and SNAME News*, 36 (4), 248–260.

TALKE, S.A. and STACEY, M.T., 2003. The influence of oceanic swell on flows over an estuarine intertidal mudflat in San Francisco Bay. *Estuarine, Coastal and Shelf Science*, 58 (3), 541–554.