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Implications of Fast-Ferry Wakes for Semi-Sheltered Beaches: A Case Study at Aegna Island, Baltic Sea

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ABSTRACT

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The almost-tideless Tallinn Bay, the Baltic Sea, is one of the few places in the world where high-speed ferries frequently operate close to the shoreline and where wake-waves may have a significant effect on the morphology and the sediment dynamics on medium-energy beaches, in particular, because of the difference of the wake propagation direction from that of dominant wind waves. The properties of ship waves were measured continuously during four weeks in summer 2008 offshore from a semi-sheltered beach located ~2700 m from the sailing line. Beach profiles were measured up to several times a day for more than 20 days. An adjacent jetty restricts sediment transport from the east. Overnight and during high-energy wave conditions, wind generated waves build the beach adjacent to the jetty. During calm periods the beach is not replenished and significant loss of sediment across the beach profile is evident due to ship wakes. The beach, therefore, never reaches an equilibrium shape, as might normally be expected on the up-drift side of a groin. Instead, the area offshore adjacent to the jetty serves as a sink for the beach sediments.

ADITIONAL INDEX WORDS: *Beach processes, ship wakes, sediment transport, beach equilibrium*

INTRODUCTION

Over the last two decades, increasing traffic consisting of larger and faster ships has led to the situation in which ship wakes may form a key component of hydrodynamic activity on some sections of the coast (PARNELL and KOFOED-HANSEN, 2001; SOOMERE, 2005). Potential effects, depending on the natural wave climate, of the ship-wake induced water movements and intense wave breaking and runup are increased resuspension and transport of bottom sediments in deeper areas of the affected water body (SCHOELLHAMER, 1996; OSBORNE *et al*., 2007) and rapid changes of the nearshore and beach coastal profile (PARNELL *et al*., 2007).

There is contradictory evidence about the magnitude of the related processes and about the potential threats. It is intuitively clear that even a small input of vessel-induced waves may lead to a significant increase in sediment transport, in particular, when the bed stress due to local factors is near a critical threshold for erosion or deposition (TALKE and STACEY, 2003). While it may be assumed that the extra hydrodynamic activity is the most dangerous in inland waterways and estuaries (SCHOELLHAMER, 1996; BOURNE, 2000) where large vessel waves can bring into motion massive amounts of sediment (OSBORNE and BOAK, 1999) and create suspended sediment concentrations as large as 10–100 g/l in rivers, BAUER *et al*. (2002) found that vessel waves have a tendency to maintain the existing shore profile rather than causing net sediment loss at the particular location studied.

The most significant effects caused by the addition of new hydrodynamic activity occur in cases where the properties of ship waves are different from those of the natural waves, particularly in areas with overall low natural wave activity where an increase in wave height may lead to substantial changes to beach processes (BOURNE, 2000; PARNELL *et al*., 2007). The effect of these waves on a beach and on dune erosion may be related to the incident wave angle and wave period (KOBAYASHI *et al*., 2009).

The detection of effects related to changes to other properties of approaching waves is complicated. The specific contribution of long ship-waves to the wave climate in sheltered areas is frequently equivalent to an increase to the typical wave lengths in the affected area (SOOMERE and RANNAT, 2003). Conceptually, such a change in the local wave regime is similar to a case where open ocean swell reaches coastlines not previously affected and can be interpreted as a model case of a major shift of the wave climate towards longer periods. The consequences may be unexpectedly large because the reaction of the beach depends not only on the wave height, but also on the width of the nearshore in which sediment is brought into motion. In particular, groups of long, transient waves (that create high orbital velocities in relatively deep areas and frequently exhibit larger runup heights than wind waves of the same height) affect bottom sediments over a much wider nearshore strip. Therefore, it is not unexpected that relatively small levels of long-period energy in combination with wind waves can cause greater beach response than an equal amount of energy which exists only at higher local wind-wave frequencies (COATES and HAWKES, 1999). The presence of vessel-generated long and high waves (which occur very infrequently under natural conditions in semi-enclosed microtidal basins (SOOMERE, 2005)) may cause an extensive resuspension of fine bottom sediments in the deeper part of the nearshore, which is not normally affected by wind waves (SOOMERE and KASK, 2003).

Changes to wave direction of approach may have considerable impact on the local beach processes. The related effects, caused by ship waves, have received little attention in the scientific literature, mostly in the context of potential hazards connected with non-linear interaction and overtopping of ship wakes approaching coastal engineering structures from unexpected directions (see Soomere, 2007 and references therein).

The most significant effect, however, may be connected with potential changes to the magnitude (and even direction) of littoral flow. Where there is heavy fast-ferry traffic, there may be frequent ship-induced waves approaching the coast from a narrow range of directions, and depending on the typical approach angle of dominant wind waves, ship waves may create substantial littoral "counterflow." Importantly, except in a few circumstances, the shoreline effects of waves generated by ships travelling the same route but in opposite directions, will be quite different, depending on a range of local factors.

This paper presents some results of an experiment undertaken in June and July 2008 on Aegna Island (located at the entrance of Tallinn Bay, the Baltic Sea, Figure 1). Tallinn Bay is one of the few places in the world where high-speed ferries continue to operate at or close to service speeds close to the shoreline, with up to 50 sailings per day servicing the Tallinn–Helsinki route. High-speed (fast) ferries are interpreted here as the vessels, the regular sailing regime of which, contains extensive sections in which the depth Froude number (the ratio of the ship's speed and the maximum phase speed of linear water waves for the given depth) exceeds 0.6. When this threshold is exceeded, long and long-crested waves carry a large part of the energy of the ship wake (Soomere, 2007). The influence of increased energy caused by ship traffic on shoreline geomorphology will vary significantly depending on a range of factors. This study aimed to quantify the short term effects of ship wakes on local beach processes, and consider the longer term implications of combined natural and vessel induced waves approaching consistently from different directions on beach morphology.

STUDY SITE AND METHODS

A range of vessel types have serviced the Tallinn–Helsinki route (Figure 2) since about the year 2000 including high-speed monohull, twin hull and hydrofoils (operating speeds ~60 km/h), conventional ferries (~30 km/h) and hydrofoils (Soomere and Rannat, 2003). A new class of large 'conventional' ships operating at ~50 km/h has been introduced in recent years (Parnell *et al*., 2008). Significant effects of vessel wakes in the Tallinn Bay area have been reported (Soomere, 2005; Erm and Soomere, 2006). A partial reason for the relatively large impact is that Tallinn Bay has almost no tide and experiences water level variations driven primarily by weather systems. Although the full historical range of such variations is 2.47 m (from –0.95 m to 1.52 m with respect to the long-term mean), over the summer months when ship traffic is most intense, the sea level variations are fairly small (usually within 20–30 cm) and thus the hydrodynamic impact of wind waves is confined to a narrow belt along the coast.

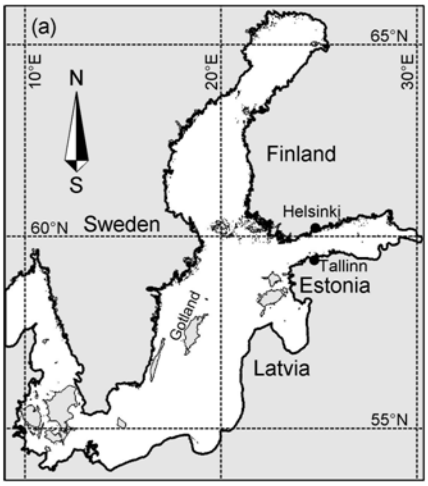

Figure 1. The Baltic Sea, and the location of Tallinn Bay.

The measurement site was located on the SW coast of Aegna, at a small mixed gravel-sand beach immediately west of the jetty (Figure 3, 59°34′50″N, 24°45′28″E). The island is separated from the Viimsi Peninsula by a shallow-water (typical depth 1–1.5 m) channel with two small islands. Effectively, no wave energy enters Tallinn Bay from the east. The site is fully open to the ship wakes and the average slope in the immediate vicinity of the shoreline and beachface is approximately linear.

The experiment site is fully open to the south. Although the majority of storms blow from the SW, they produce no large waves because of short fetch (~10 km) in this direction. Moreover, these waves approach the shore perpendicularly and result in negligible longshore sediment transport. Owing to their small lengths, they only affect sediments at the coastline and in very shallow water.

The most significant waves at the study site (Figure 3) and along the adjacent shore to the West, come from the West, entering Tallinn Bay between the mainland and the island of Naissaar. Significant wave energy enters Tallinn Bay from the north and NW but the study site is sheltered from these waves by the WSW end of Aegna and shallow water about 300 m to the West and even if they reach the SW coast owing to refraction, they impact the coast in a similar way to waves approaching from the West.

The littoral drift, therefore, is from West to East (Figure 3a). Along the shoreline to the west of the study site there is an evident sediment deficit and coastal erosion (Kask *et al*., 2003). Long-term accretion occurs only in a short section immediately adjacent to the jetty where the beach is much wider (up to 25 m, Figure 3b)

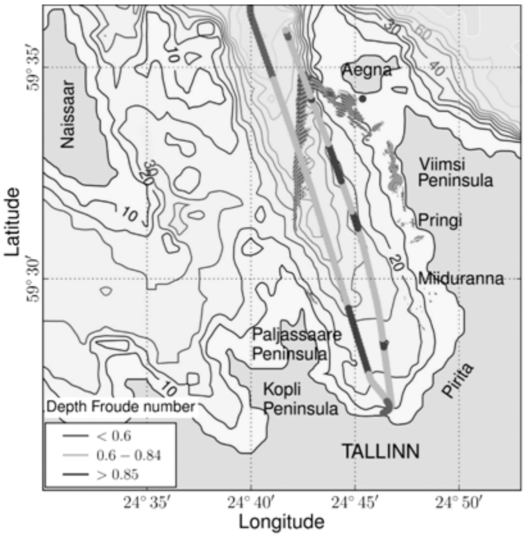

Figure 2. Sailing line from Tallinn towards Helsinki (eastern track) and the "fan" of vessel wakes at a point in time for a ship travelling to the west of Aegna Island. Image by T. Torsvik. Reproduced from (Parnell *et al*., 2008), with permission from Estonian Academy Publishers.

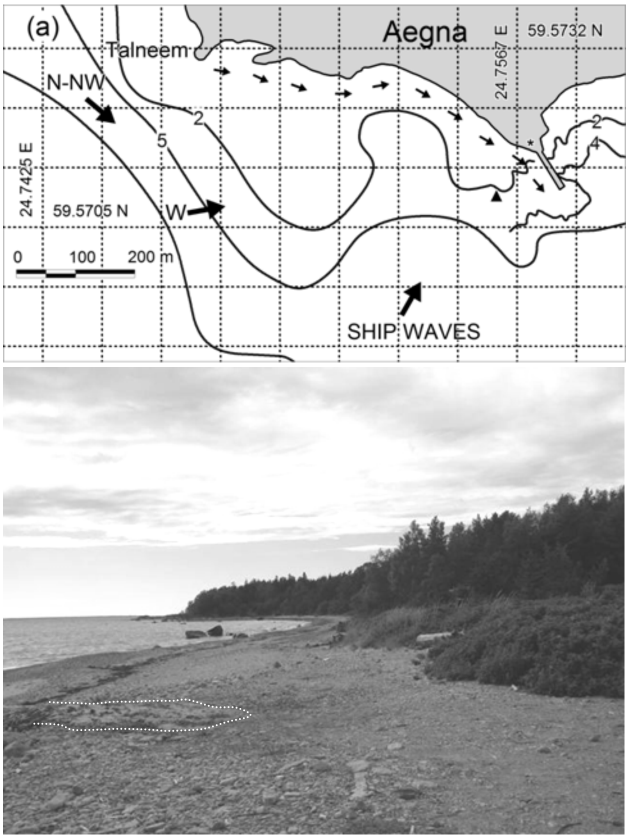

Figure 3. (a) The study site on the western side of the Aegna Jetty. Large arrows show predominant wave propagation direction for wind waves during N-NW and W storms, and for ship waves. The sequence of small arrows indicates the direction of sediment transport. Image by A. Kask; (b) the coast at the study site. An overwash deposit is indicated by a dotted line.

than along the rest of the SW coast. This deposit consists of a relatively thin coating of finer sediment, with cobbles and boulders (~20–50 cm in diameter) permanently visible, indicating that the beach adjacent to the jetty is not currently accreting. The largest and longest vessel waves approached the beach from a narrow range of directions, from vessels sailing from Tallinn to Helsinki (Figure 3a).

The properties of the incoming waves were established from a time series of water surface elevations collected in about 2.7 m water depth, ~100 m offshore from the study site. The site was ~2.7 km from the sailing line of outgoing vessels, at the closest point. Wakes experienced at the shoreline were generated ~3–4 km from the site. Video and manual recordings of wave runup were made, and beach profiles were measured up to several times a day. When possible, vessel track and speed were calculated using data from a laser rangefinder. A detailed overview of the measurement procedure is presented in (PARNELL *et al*., 2008).

RESULTS

During calm conditions, incoming vessel generated waves of up to 1.5 m, with periods of ~10–13 s were measured (PARNELL *et al*., 2008). Combined, wind and vessel generated waves resulted in waves of over 1.7 m (Figure 4). Such vessel generated waves add significantly to the total wave energy experienced on this section

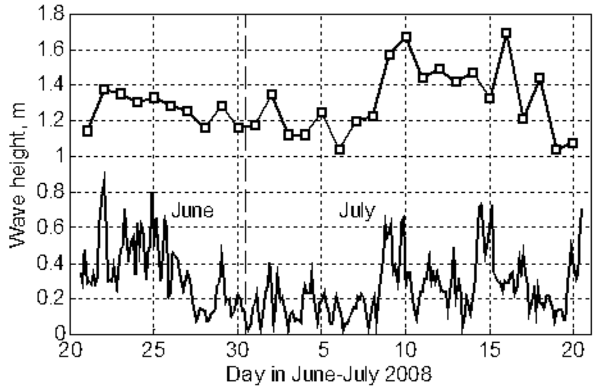

Figure 4. Daily highest ship waves (squares, from PARNELL *et al*., 2008) and modeled significant wave height at the measurement site.

of the Aegna Island shoreline, where the annual mean significant wave height is about 0.43 m and where >1.2 m wind waves occur with a probability of less than 2% (KELPŠAITE *et al*., 2009).

Wake events have a clearly discernible impact on the shoreline. An attempt to quantify this impact was made through recording of the runup of ship-induced waves on the beach face (PARNELL *et al*., 2008). While wind waves with the height of <0.5 m produced runup events up to 20–30 cm above still water level, the largest ship waves produced substantial runup heights that commonly exceeded the height of measured waves. The highest and longest ship waves from the first group reached over 1 m above still water level with several examples going over the berm crest, over 1.5 m above still water level (DIDENKULOVA *et al*., 2009; TORSVIK *et al*., 2009). On a few days there was evidence of overwash deposits at heights about 2 m above water level (Figure 3b).

The beach profiles demonstrate considerable variability over relatively short periods of time, with levels varying by over 0.5 m (Figures 5 and 6). Higher beach levels are associated with periods of high wind wave energy, with the beach losing sediment during periods of low wind waves. Figure 7 shows a period of considerable beach accretion between 25 and 27 June (Julian Days 177 to 179), which corresponded to a period of high wave energy on June 25–26 (Figure 4), during which time the surveyors were unable to survey the lower beach due to the high energy and water level conditions. The rapid accretion is illustrated in Figures 8 and 9, with the beach profile reaching its highest levels and the beach achieving its highest volume (15.1 m^3/m), on 27 June, an increase of approximately 2.5 m^3/m over pre-storm volumes. Following the high wave-energy period, the beach profile returned to pre-storm conditions by 29 June.

The beach was in an eroded state on 9 July (Julian Day 191)

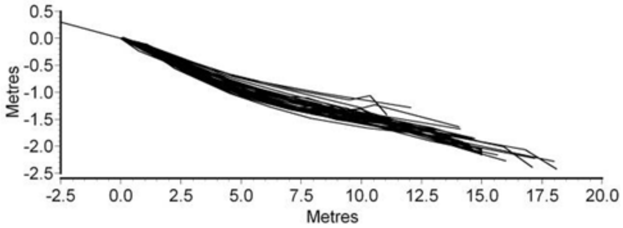

Figure 5. Beach profiles measured between 23 June and 19 July 2008.

Figure 6. The same section of beach in an accreted (left) and in an eroded (right) state.

when some profile measurements were made (Figures 7 and 9). This followed a period of low wind-waves during the first 9 days of July when significant wave height was mostly below 20 cm and even below 10 cm on some days. Beach volume on 9 July was approximately 11 m^3/m, 4 m^3/m less than the maximum volumes achieved under high energy conditions. After more 'normal' wind energy conditions returned, the beach recovered with volumes on 18 July being similar to those measured at the beginning of the experiment.

Rapid beach response to vessel wakes was frequently observed. Following the high energy period on 25–27 June, sediment loss due to vessel wakes was evident. Before vessel traffic commenced for the day, at 07:30 on 28 June, the beach volume was 14.4 m^3/m (Figure 8, Julian Day 180.31). By 10:00 (Figure 8, Julian Day 180.42), the beach volume had reduced by 0.75 m^3/m to 13.7 m^3/m, after the early morning vessel traffic had passed. With vessel traffic and lower wave-energy conditions, the beach volume had further reduced to 12.8 m^3/m by 07:35 the following morning (Figure 8, Julian Day 181.36).

Vessel generated waves therefore have a significant effect on the morphology and sediment budget of the Aegna shoreline. At the experiment site, there is no sediment transport from the East, due to the presence of the adjacent jetty and the sheltering effect of the Viimsi Peninsula. As demonstrated above, under moderate to high wind wave conditions the beach to the west of the jetty is accreted with sand and gravel transported from the west. Typically, overnight, when vessel traffic was minimal, a small mixed sand and gravel berm of 15–30 cm height, equivalent to a high-water berm, formed as a result of wind wave generated sediment transport. This berm was completely removed by the first set of vessel wake-waves each morning, with sediment being transported offshore. When there is high wave energy, the beach builds substantially. On calm days when vessel-generated waves dominate, there is very rapid loss of sediment. The approach angle of vessel-induced waves to the study site is such that ship-induced water motions (and the resulting sediment transport) are predominantly perpendicular to the coast, with a small westward-directed component. Numerical simulations (Figure 2, see TORSVIK and SOOMERE, 2008; TORSVIK *et al.*, 2009) indicate that waves excited by ships sailing at Froude numbers below ~0.8 are expected to result in eastwards transport. Only in a few cases when ships are sailing at speeds close to critical, is the approach angle of the largest waves able to result in westwards transport.

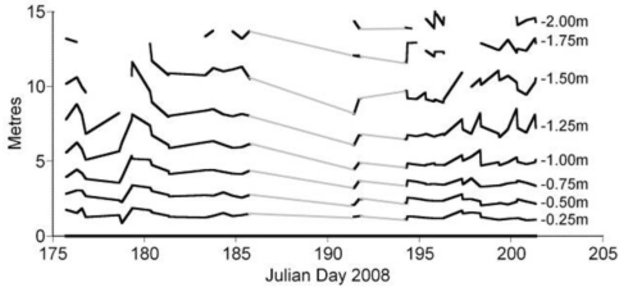

Figure 7. Excursion distances from the upper beach profile closure point (0 in Figure 5), at 0.25 m contour intervals between 23 June and 19 July. Grey lines represent significant periods of time during which no profiles were measured. Increasing values on the *y*-axis indicate the beach is building seaward. Converging lines show the beach getting steeper.

The western side of the jetty is protected by energy-absorbing tetrapods and wave reflection from it is fairly small. Sediment eroded (sometimes over very short time periods) from the beach is therefore transported offshore, adjacent to the jetty (except for a small fraction of material in overwash fans, as mentioned above). The area offshore adjacent to the jetty serves as a sink for the beach sediments.

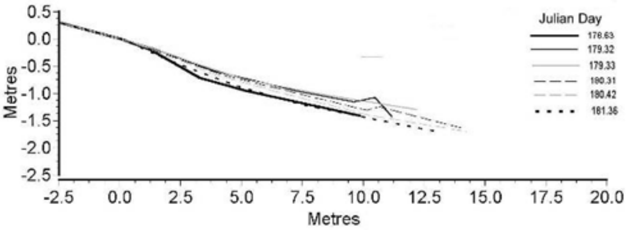

Figure 8: A selection of profiles between Julian Days 178 to 182.

The "life cycle" of the beach reflects an interesting response to the joint effect of wind waves and vessel-generated waves. During calm periods, when there is no wind-wave generated sediment transport, the beach is not replenished and significant loss of sediment across the beach profile is evident (due to the effects of the vessel-generated waves). The beach again builds when wind waves return. The beach, therefore, never reaches an equilibrium shape, as might normally be expected on the updrift side of a groin with a unidirectional sediment transport system.

In the longer-term, in the absence of vessel-generated waves, the beach on the updrift side of the jetty would be expected to accrete to a point of equilibrium where the beach shape would provide some protection to the coast to the west, thereby reducing shoreline erosion and also protecting the jetty. Currently, wind waves bring sediment from the sediment-depleted beach to the west, and vessel-generated waves take those sediments offshore into deeper water adjacent to the jetty, and the shoreline to the west of the jetty remains unprotected.

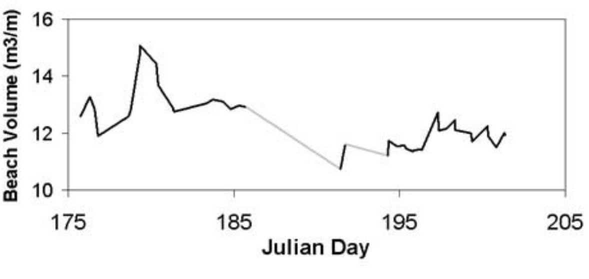

Figure 9: Beach volume calculated between 0 m and 12 m (distance axis), and 0 m and –2 m (height axis). Grey lines represent significant periods of time during which no profiles were measured.

DISCUSSION

The wake-waves generated, particularly by fast ferries and high-speed conventional vessels, can contribute significantly to the energy budget of shorelines along vessel routes and significantly change the sediment budget dynamics of adjacent beaches. The role of ship traffic may be decisive in terms of geomorphic changes on certain sections of the coast even when the share of ship wave energy is only a few percent of the total wave energy. The longer length and/or different propagation direction of ship wakes may be the decisive factor, and may lead to substantial changes to the nature of the local erosion-accretion system. In the case of Aegna, vessel wakes result in an offshore sediment transport of large quantities of quite coarse sediment.

The potential changes to the direction of the littoral drift and/or the balance between local erosion and accretion is most likely in cases where beach sections are affected by large wake-waves approaching from a narrow range of directions. This situation is most common when the wake effects are not reversed for ships travelling in opposite directions, such as when the incoming and outgoing shipping lanes are separated (which is the typical case near large harbors), when the incoming and outgoing ships are using different speeds (Torsvik *et al*., 2006), or when the shipping lane is not relatively parallel to the adjacent shoreline.

The continuing high level of ship wave activity in many parts of the world means there remains a concern about the potential impact of ship wakes on vulnerable coasts. On some sea coasts the presence of high and long ship-induced waves, which are accompanied by significant beach runup, is believed to be an additional agent of coastal erosion even if they have periods of only about 7 s and occur only a small number of times a day (Velegrakis *et al*., 2007).

LITERATURE CITED

Bauer, B.O.; Lorang, M.S., and Sherman, D.J., 2002. Estimating boat-wake-induced levee erosion using sediment suspension measurements. *Journal of Waterway, Port, Coastal and Ocean Engineering,* 128 (4), 152–162.

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

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, vol. 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,

Erm, A. and Soomere, T., 2006. The impact of fast ferry traffic on underwater optics and sediment resuspension. *Oceanologia*, 48 (S), 283–301.

Kask, J.; Talpas, A.; Kask, A., and Schwartzer, K., 2003. Geological setting of areas endangered by waves generated by fast ferries in Tallinn Bay. *Proceedings of the Estonian Academy of Sciences. Engineering*, 9 (3), 185–208.

Kelpšaite, L.; Parnell, K., and Soomere, T., 2009. Energy pollution: the relative importance of wind-wave and ship-wake energy in Tallinn Bay, the Baltic Sea. *Journal of Coastal Research*, Special Issue No 56, .

Kobayashi, N.; Buck, M.; Payo, A., and Johnson, B., 2009. Berm and dune erosion during a storm. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 135 (1), 1–10.

Osborne, P.D. and Boak, E.H., 1999. Sediment suspension and morphological response under vessel-generated wave groups: Torpedo Bay, Auckland, New Zealand. *Journal of Coastal Research*, 15 (2), 388–398.

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*" (13–17 May 2007, 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*, Special Issue 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), 272–302.

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

Soomere, T., 2005. 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 Kask, J., 2003, A specific impact of waves of fast ferries on sediment transport processes of Tallinn Bay, *Proceedings of the Estonian Academy of Sciences. Biology. Ecology*, 52 (3), 319–331.

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.

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.

Torsvik, T. and Soomere, T., 2008. Simulation of patterns of wakes from high-speed ferries in Tallinn Bay, *Estonian Journal of Engineering*, 14 (3), 232–254.

Torsvik, T., Dysthe, K., and Pedersen, G., 2006. Influence of variable froude number on waves generated by ships in shallow water. *Physics of Fluids*, 18, Paper 062101.

Torsvik, T.; Didenkulova, I.; Soomere, T., and Parnell, K., 2009. Variability in spatial patterns of long nonlinear waves from fast ferries. *Nonlinear Processes in Geophysics*, accepted.

Velegrakis, A.F.; Vousdoukas, M.I.; Vagenas, A.M.; Karambas, Th.; Dimou, K., and Zarkadas, Th. 2007. Field observations of waves generated by passing ships: A note. *Coastal Engineering*, 54 (4), 369–375.

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