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Monitoring wave-induced sediment resuspension

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Abstract. The objective of this paper is to quantify resuspension and bed load transport of bottom sediments, induced by fast ferry wakes and wind waves near Aegna jetty, Tallinn Bay, using *in situ* measurements of waves, resuspension and optical properties of sea water. A new autonomous experimental set of two PAR-sensors, anchored into the sea bed, was used to measure the underwater irradiation. Wakes usually caused a rapid increase of the optical density of sea water by up to 50% from its background value. The total impact of fast ferry waves in terms of resuspended sediment concentration has not been substantially reduced compared to measurements in the past. However, wind waves apparently are the main driving force for both sediment resuspension and transport in 3 m deep water.

Key words: Tallinn Bay, ship wakes, wind waves, sediments, resuspension, underwater irradiation.

1. INTRODUCTION

During the last decade, wakes from fast ferries in the vicinity of ship lanes have become a problem of growing concern in many countries [1–4] including Estonia, and particularly in Tallinn Bay. Large, high-speed catamarans were operating the Tallinn–Helsinki route between 1999 and 2008. Systematic investigations of the wakes produced by these vessels and their impact upon coasts and traffic of smaller craft on the bay started in 2001 [5–7]. Wake parameters in Tallinn Bay are thoroughly analysed in [8–12]. Intense traffic of even larger and faster ships has led to a situation where ship wakes may form a key component of the hydrodynamic activity on some sections of the coast. The ship-wake-induced resuspension of sediments and the impact of breaking waves may cause increased transport of bottom sediments in deeper areas of the nearshore and an alteration of the beach profile. Understanding these processes is very important in order to protect the coasts, along with the planning and sustainable management of harbours, wind farms and other constructions in the sea.

On the Tallinn–Helsinki line, large ships with speeds up to 50 km/h are sailing close to the shore about 20 times per day (Table 1). Although some smaller vessels have been taken out of service, the new generation of large, highly powered ferries (for example, Tallink *Star*) that cross the Gulf of Finland in two hours (compared to classical high-speed catamarans that take 1¾ h), have entered into service since 2007 and made 13 crossings daily in 2008. These ferries are almost 200 m long with a space for up to 2000 line metres for vehicles. The vessels operating during this time were *Star*, *SuperStar* and *SuperFast* (Tallink), and *Viking XPRS*. Also, several smaller but faster ferries of monohull (*SuperSeaCat*) or catamaran (*Nordic Jet* and *Baltic Jet*) type were operating in 2008.

The reaction of the seabed to the ferry wakes can be established and roughly estimated using optical measurements [13–15]. In Tallinn Bay, systematic optical studies, accompanied with wave measurements, laboratory analysis of water samples and sampling of resuspended sediments, started in 2003 near the coast of Aegna Island [13], in an area most susceptible to ship wakes (Fig. 1). Vessels sailing to Helsinki pass by the coast of Aegna at a distance of only two kilometres.

The objective of this study is to quantify the resuspension and bed load transport of bottom sediments, induced by fast ferry wakes and wind waves near Aegna jetty using an autonomous experimental optical sonde and experimental sets of sediment traps.

Table 1. Time schedule of passenger ships, travelling from Tallinn to Helsinki on 23 July 2008. Ferries that produce optically detectable wakes are shown in bold

Ferry	Dep. time	Ferry	Dep. time	Ferry	Dep. time
Star*/*SuperStar	**07:30**	*Galaxy***	13:30	***Nordic*/*Baltic Jet***	**17:25**
SuperSeaCat	**07:45**	***SuperSeaCat***	**14:00**	***Viking XPRS***	**18:00**
Viking XPRS	**08:00**	***Star*/*SuperStar***	**14:00**	***Star*/*SuperStar***	**18:30**
Nordic*/*Baltic Jet	**08:00**	***Nordic*/*Baltic Jet***	**15:00**	***Nordic*/*Baltic Jet***	**19:30**
Jaanika/*Merilin**	10:00	***SuperFast 1*/*2***	**15:30**	***SuperSeaCat***	**19:30**
Nordic*/*Baltic Jet	**10:15**	*Jaanika/Merilin**	16:00	*Jaanika/Merilin**	20:00
SuperSeaCat	**10:30**	***SuperSeaCat***	**16:15**	***Star*/*SuperStar***	**21:00**
Star*/*SuperStar	**11:00**	*Nordlandia***	17:00	***SuperSeaCat***	**21:40**
Nordic*/*Baltic Jet	**12:55**				

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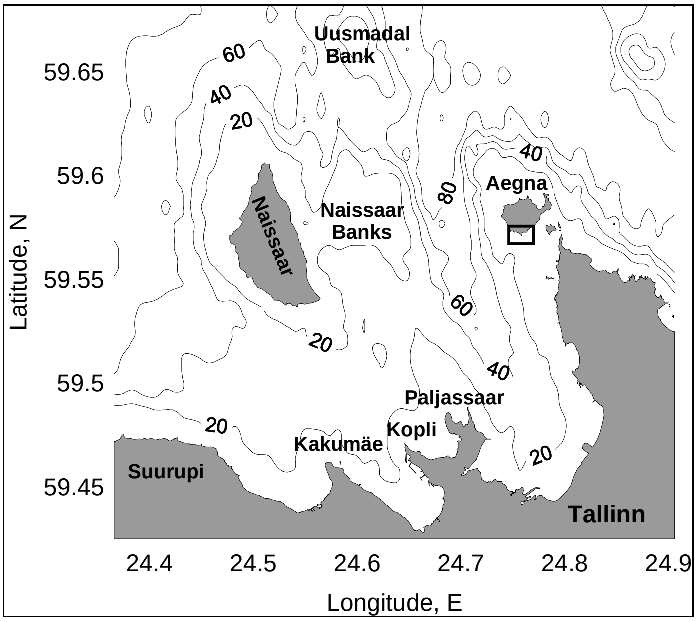
* Hydrofoils.

** Classical low speed ferries.

(a)



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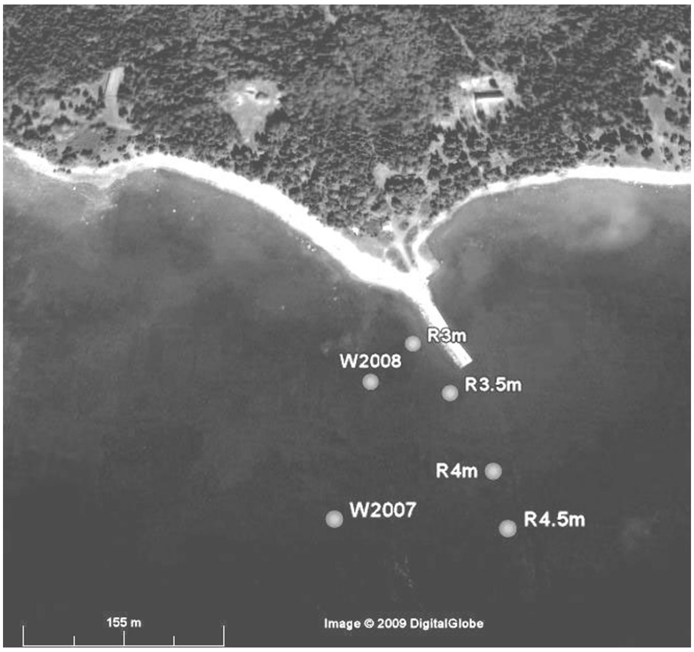

Fig. 1. (a) Bathymetry of Tallinn Bay and the location of Aegna Island; (b) the study area with the wave measurement site in 2007 (W2007) and 2008 (W2008), and sediment flux measurement sites at water depth of 3, 3.5, 4 and 4.5 m (R3m, R3.5m, R4m and R4.5m).

2. MEASUREMENT METHODS AND DATA

2.1. Optical measurements and quantification of wake impact

The measurement site was located near the SW coast of Aegna, about 100 m offshore from a small mixed gravel-sand beach and about 60 m west of the jetty (Fig. 1b, 59°34.259′N, 24°45.363′E). The water depth ranged from 3 to 4.5 m and the bottom was covered with sand, gravel and bigger stones (Fig. 2).

The properties of wind waves and ship wakes were measured synchronously with the underwater irradiation. The transport of suspended matter was studied with the use of two types of sediment traps to quantify the horizontal (both shoreward and seaward) resuspended and bedload sediment fluxes.

During the period 24–29 July 2008, an autonomous optical sonde, consisting of two planar PAR (400–700 nm) sensors Li 192SA (Fig. 2a), were anchored to the sea bottom to measure irradiance data from the lower sensor $E_d(z_l)$ and upper sensor $E_d(z_u)$. The data (mean values over the 5 min periods with the sampling frequency 1 Hz) were recorded by a data logger (Li 1400).

The theoretical basis of the light measurements is thoroughly discussed in [16–18]. The optical parameter, best used to describe the worsening of light conditions due to sediment resuspension, is the diffuse attenuation coefficient K_d (PAR), calculated from the underwater irradiation data as

$$K_d = -\frac{1}{z_l - z_u} \ln \frac{E_d(z_l)}{E_d(z_u)}, \tag{1}$$

where $E_d(z)$ is downwelling plane irradiance and z_l and z_u are the depths of the lower and upper underwater sensors, respectively.

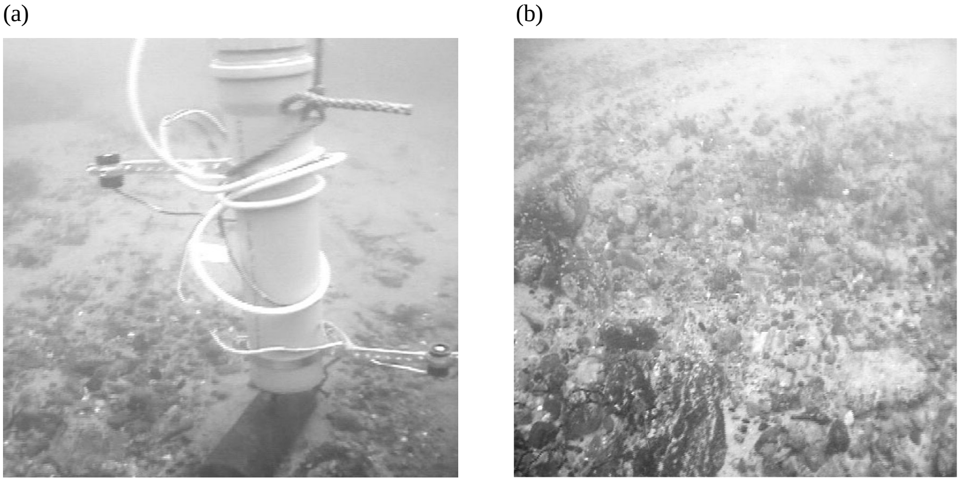

Fig. 2. (a) Optical measurements on the sea bottom; (b) sand-gravel bottom at the measurement site. Underwater photos by Madis Listak.

To estimate the impact of wakes, a method developed in [19,20] was used. The method is based on the fact that K_d depends on the concentrations of optically active substances in the water:

$$K_d = K'_{d,S} C_S + K'_{d,chl} C_{chl} + K'_{d,y,e} C_{y,e} + K_{d,w}, \tag{2}$$

where C_S, C_{chl} and $C_{y,e}$ are the concentrations, and $K'_{d,S}$, $K'_{d,chl}$ and $K'_{d,y,e}$ are the empirical attenuation cross-sections [21] of suspended matter, chlorophyll and yellow substance, respectively. It can be assumed that the concentrations of chlorophyll and yellow substance are not influenced by ship wakes. Assuming that they were approximately constant during the measurement period, Eq. (2) can be rewritten as

$$C_S = \frac{1}{K'_{d,S}} (K_d - K), \tag{3}$$

where K is a constant, describing all attenuation components except suspended matter.

We use here an empirical value of $K'_{d,S} = 0.05$ m^2/g, calculated from the data for Muuga Bay and Tallinn Bay [13] and used in previous wake studies [13–15,19,20]. Approximately the same value (0.066 ± 0.017 m^2/g) was obtained for four north Estonian lakes in [22].

The impact of wakes can be quantitatively described as [14]

$$M_W = \frac{1}{K'_S} \int_{t_1}^{t_2} [K_d(t) - K_{d0}(t)] \mathrm{d}t, \tag{4}$$

where M_W [g·s/m^3] characterizes the "total" impact of wakes over the time period $[t_1, t_2]$, K_{d0} is a background value of the diffuse attenuation coefficient and $K_d(t)$ describes the time-dependence of K_d.

2.2. Wave measurements

Wave data sets were collected with a subsurface pressure transducer (wave gauge) Wave Recorder LM2 (PTR Group Ltd., www.ptr.ee, Estonia, sampling frequency 4 Hz continuously). In the first case, the gauge was mounted at a height of 3 m and in the second case at 1 m from the bottom at water depths of 4.5 m and 3 m, respectively.

In order to monitor the waves, excited by *Star*, measurements were carried out in September–October 2007 (case 1, W2007 in Fig. 1b). In summer 2008, optical measurements were conducted at the same location (case 2, W2008 in Fig. 1b). The deployment in 2008 lasted from 23 June until the end of September with some gaps.

2.3. Measurement of sediment resuspension and bed-load transport

The seabed composition was analysed in 2007 in an area a short distance NW of the measurement site [23]. The results showed that 14.2% of sediments were gravel (typical diameter $D > 2$ mm), 84.5% sand ($0.063 < D < 2$ mm) and only 1.3% silt ($D < 0.063$ mm). About 76.7% of the sand was very fine ($0.063 < D < 0.2$ mm).

The intensity of sediment resuspension was quantified using two types of the experimental sediment trap in the summer of 2008. The first was used to estimate the horizontal flux of sediments at two different heights (20 and 60 cm above the sea bed) and directions (shoreward and seaward). The second set was used to catch the sediments, transported as bedload onto two plates with slopes of 15° and 25°. The horizontal flux of suspended matter was measured on 2, 22 and 30 July and also on 11 and 12 September at locations marked with “R” in Fig. 1b. The bed load transport was measured on the same days, with the exception of 2 July. The amount of sediments was determined by the dry weight of the samples.

3. RESULTS AND DISCUSSION

3.1. Waves and optics

The measurement of wakes from *Star* in the autumn of 2007 showed that the typical maximum wave height was 0.9 m and the period about 8 s. The maximum measured wave height was 1.6 m and maximum periods reached 13 s (Fig. 3). These values are similar to or even higher than those recorded previously for waves excited by monohulls and catamarans [9].

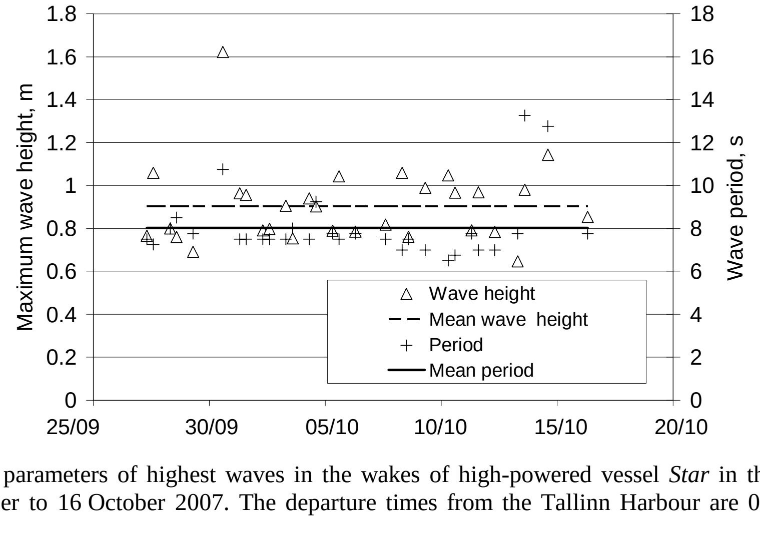

Fig. 3. The parameters of highest waves in the wakes of high-powered vessel *Star* in the period 27 September to 16 October 2007. The departure times from the Tallinn Harbour are 07:00 and 14:00.

The average spectral energy density of ship wakes over 25–29 July 2008 had a similar nature to that described in [12]. While in [12] the largest spectral peak was at 9.2 s, our data showed a peak of 10.3 s with somewhat lower peaks at 12.3, 7.8 and 6.6 s (Fig. 4).

The longest continuous measurements of underwater irradiation took place from 24 to 29 July 2008 (Fig. 5a). The measured underwater irradiance at both levels ($E_d(z_l)$ and $E_d(z_u)$) and K_d, calculated from these values, are plotted in Fig. 5a. As the Sun was the light source, only daytime (from 06:00 to 22:00) data are reliable. The levels of irradiation suggest that clear skies dominated during the measuring period.

The wind wave background was small on 24–29 July 2008, with wind wave heights less than 20 cm on 24 July and below 10 cm on other days (Fig. 5b). The maximum heights (from the trough bottom to the top of the wave crest) of ship waves reached 1.4 m, but mostly they were below 1 m.

A good match between the amplitude of the wakes and the attenuation coefficient is evident on some days. For example, the peaks of K_d at 08:10, 10:25, 10:55, 11:25, 16:30, 16:50, 17:55, 18:10, 19:15, 19:25, and 20:05 on 27 July (Fig. 6) coincide well with the timetable of ships (Table 1). The match was, however, lower on some other days. For the sake of compendious presentation of all measured data, the mean values of the wave amplitude and K_d were calculated for each time instant over all days of measurements. The resulting average daily variations of the quantities in question are plotted in Fig. 7. These aggregated graphs show more or less the same peaks as in Fig. 6. The “still time periods”, when no ferries were passing for an hour or more, are marked by filled

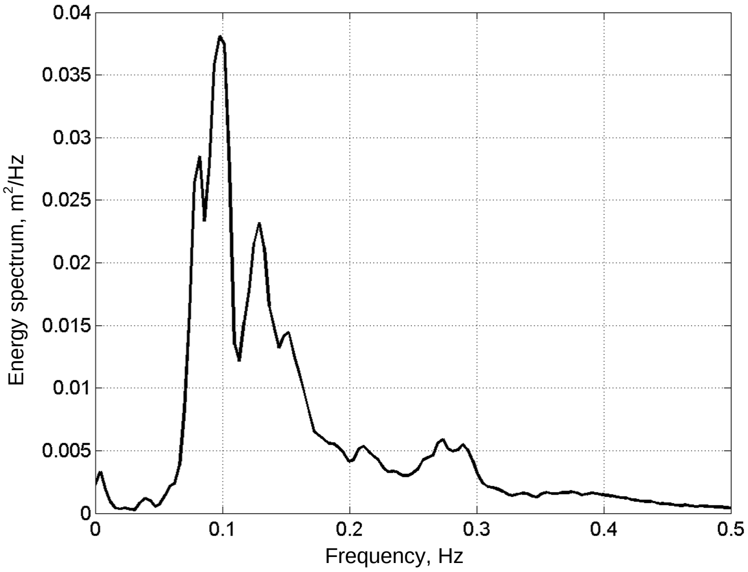

Fig. 4. Mean energy density of fast-ferry wakes averaged over time period 25–29 July 2008. The wind wave background is small (less than 10 cm).

circles. The peaks of K_d in Fig. 7 are in good qualitative correlation with the mean maximum wave heights and reflect the schedule of ferries (Table 1).

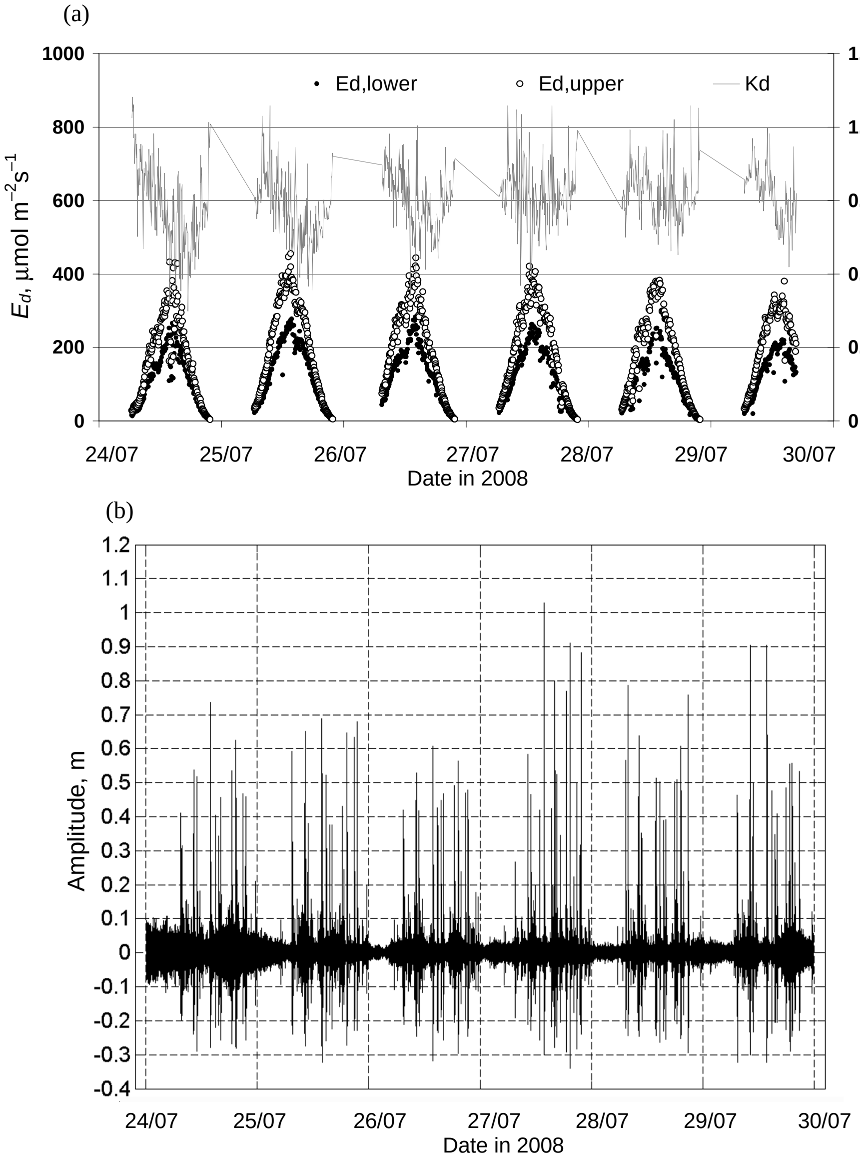

Fig. 5. (a) Underwater irradiace $E_d(z_l)$, $E_d(z_u)$ and diffuse attenuation coefficient K_d; (b) wave amplitude, measured synchronously with light field.

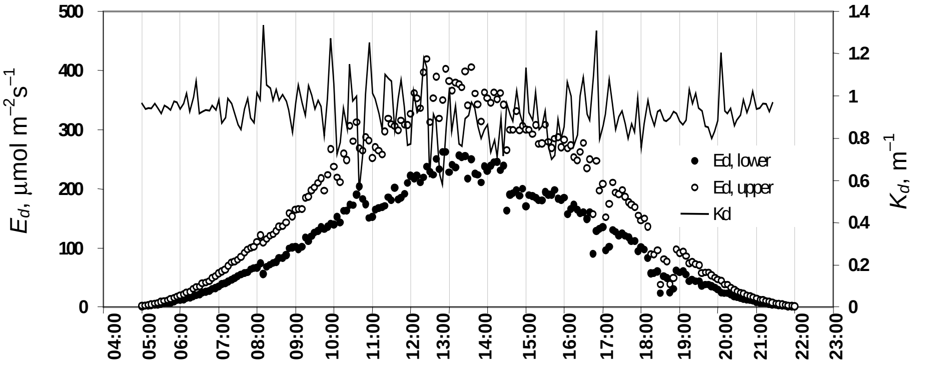

Fig. 6. The underwater light field $E_d(z_l)$, $E_d(z_u)$ and diffuse attenuation coefficient K_d on 27 July 2009.

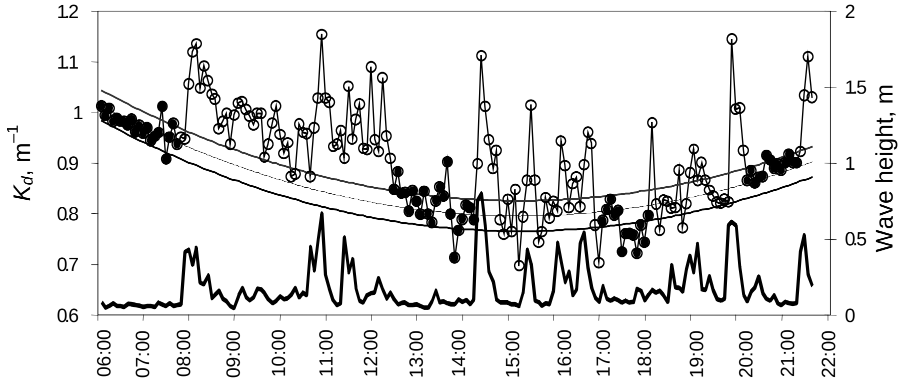

Fig. 7. Maximum wave heights (lower bold line), K_d (circles, black line), empirical background value of K_d and its standard deviation limits (thin lines) on 24–29 July 2008. The values used for calculating the background value are indicated by filled circles.

In previous papers we used the value for K_d immediately before the wake [13,14] or the mean value $K_{d,\mathrm{mean}}$ [19,20] as the background value of K_{d0} in Eq. (4). Using the mean value is, generally speaking, not always adequate because the background changes during the day. The reasons for that could be inherent (such as changing water properties) as well as apparent (for example, a variation of measured K_d) values depending on the incoming light conditions. The data set in question did not allow us to specify the exact reason for such changes. We do not exclude the possibility that the properties of the sea water can change during the day due to advection of the water masses under the impact of wind waves and currents, or primary production. The changes may also be driven by the ferry wakes. It is, however, not very likely that these changes occurred synchronously every day. It is more plausible to adopt the view that the changes are basically caused by varying light conditions that depend primarily on the spectral distribution and solar zenith angle. Dependence $K_d(t)$ on a clear day (Kirk's curve) must go through a minimum at the maximum altitude of the Sun [24–26], but our dataset has a principal difference from the Kirk's curve in that the minimum values of the "still period" points were registered between 14:00 and 17:00 (Fig. 7), while the sun time noon in Tallinn was at 13:27 (http://www.aai.ee/?page=oopaev), local summer time.

Thus, another approximation must be used for K_{d0}. A high correlation $(R^2 = 0.83)$ with the values at "still periods" was achieved using a second order polynomial (thin line in Fig. 7). We used this curve for $K_{d0}(t)$ as the background attenuation level in Eq. (4). The standard deviation $\delta_{K_{d0}} = \pm 0.03$ 1/m for $K_{d0}(t)$ was calculated using the values of the above-mentioned "still periods".

The next step was to calculate the daily impact of ferry wakes. It seems that no large "ventilation" event (that is, rising of sediments above both sensors) took place during measurements. Therefore the condition $K_d(t) - K_{d0}(t) - |\delta_{K_{d0}}| > 0$ was always satisfied and one can perform the integration only over values above the background value. A value $M_W = 14\ 430$ g·s/m^3 was obtained for the daily total impact. The mean concentration of (re)suspended sediments can be calculated for a navigation day from Eq. (4) as

$$C_{S,m} = \frac{M_W}{t_2 - t_1} = \frac{14\ 430}{14 \cdot 3\ 600} \cong 0.3\ \text{g/m}^3. \tag{5}$$

In previous studies, the impact was calculated for an approximately 5h interval either by means of summarizing the impacts of several ferries [14] ($M_W = 14\ 000$ g·s/m^3 for 2003–2004) or integrating $\Delta K_d(t)$ both above and below the initial value of K_d [20] ($M_W = 13\ 000$ g·s/m^3). In this work we found an almost equal value for the impact over a whole navigation day. Therefore the impact of ship wakes in terms of resuspension of finer bottom sediments in 2008 was about three times lower than estimated earlier. Owing to different integration methods in these studies, the earlier data are apparently overestimated.

3.2. Transport and resuspension of sediments

The rates of horizontal sediment fluxes (Table 2) are highly variable ranging from 0.3 to 740 g/(m^2·h) and depending on the elevation from the sea bed, the direction of the flux (shoreward or seaward), time in the day and the water depth. As expected, resuspension is generally greater in the lower layer than in the upper one. While in the lower layer in most cases the seaward sediment fluxes are larger (up to 2.5 times, with a mean of 1.6 times), in the upper layer the mean shoreward and seaward fluxes are the same (Table 2). Daytime fluxes are many times greater than night-time fluxes (Table 3), and this can be interpreted as the effect of fast ferry wakes, but not exclusively.

Table 2. Measured horizontal fluxes and relations between seaward and shoreward fluxes of sediments. Four traps (94 × 94 mm^2) on the same frame were used to trap the sediments

Date, 2008	Depth, m	Time		Level, cm	Flux, g/(m^2·h)		Seawards flux/ shorewards flux
		From	To		Seawards	Shorewards	
02 July	4	15:00	22:40	20	63.7	42.4	1.5
		15:00	22:40	60		28.3	
		22:50	07:40	20	6.0	6.0	1.0
		22:50	07:40	60	6.0		
		07:50	15:56	20	8.0	6.7	1.2
		07:50	15:56	60	4.0	4.0	1.0
22 July	3	07:30	15:05	20	71.5	28.6	2.5
		07:30	15:05	60	6.4	14.3	0.4
		17:35	20:49	20	741.9	292.7	2.5
		17:35	20:49	60	33.6	50.3	0.7
23 July	3	20:58	08:00	20	220.1	156.1	1.4
		20:58	08:00	60	0.9	0.9	1.0
30 July	3.5	09:57	15:10	20		2.1	
		09:57	15:10	60	2.6	1.9	1.4
		20:25	09:48	20	3.1	5.4	0.6
		20:25	09:48	60	2.1	2.1	1.0
11 September	4.5	19:45	10:45	20	1.1	0.5	2.2
		19:45	10:45	60	0.4	0.3	1.3
12 September	4.5	10:55	18:35	20	1.4	1.0	1.4
		10:55	18:35	60	1.4	0.8	1.7
Average				20	124	54	1.6
				60	26	24	1.1

Table 3. Mean horizontal seaward and shoreward fluxes of sediments and their average day/night ratios

	Mean sediment flux, g/(m^2·h)			Relation day/night of mean fluxes		
	All	Seaward	Shoreward	All	Seaward	Shoreward
All	49	65	34	6.5	6.1	6.9
20 cm	87	124	54	3.5	4.1	2.9
60 cm	8.9	6.4	11.4	11.6	9.5	13.7
Day	54	85	36			
Night	27	30	24			

A WSW-SW wind with a speed up to 10 m/s occurred on 22 July. During that day, three measurements of resuspension were undertaken at a water depth of 3 m. It seems that at such small depths, not only the ferry wakes but also moderate wind waves cause significant resuspension of bottom sediments. The significant height of wind waves was 0.3–0.5 m during the morning, with wave periods of 2.8–3 s. In the daytime, the significant wave height was about 0.5 m and the wave period 3–3.2 s. In the evening of 22 July and on the night of 23 July the significant wave height varied between 0.3–0.5 m with periods of 2.6–3.1 s. Under these conditions, the near-bottom shear velocity exceeded the resuspension value by almost twice. The greatest bed load transport, with over 25 g/(m^2·h), was recorded on 22 July (Table 4).

On 30 July, wind waves were below 10 cm during the day, and the induced resuspension was negligible. Between 9:57 and 15:10, the total flux of resuspended sediments was 2.1 g/(m^2·h) at a height of 20 cm and 1.9 g/(m^2·h) at a height of 60 cm above the bottom. This is hundreds of times less than the resuspension induced by wind waves at a depth of 3 m.

On 12 September, sediment resuspension was measured all day. However, the natural wind wave background had a height of 0.3 m and a period of 2.25 s, and only 13 fast ferry wakes were measured. The shear velocities at a water depth of 4.5 m did not exceed the critical limit with respect to the above-mentioned parameters. The maximum flux was only 1.4 g/(m^2·h) (Table 2). The maximum bed load transport was only 0.3 g/(m^2·h) (Table 4).

The spectrum of wind waves for 22 July and the spectrum of fast ferry wakes for 30 July are plotted in Fig. 8. It is evident that wind waves were tens of times more powerful than the fast ferry waves at these low depths and, therefore, induced greater resuspension. To more clearly capture the resuspension, induced by fast ferries, the effect of wind waves must be eliminated. Further measurements, therefore, should be undertaken in deeper water, preferably at depths of 10–20 m. At a 20 m depth, for example, a wind wave with a period of 6 s has to be more than 1.7 m high in order to resuspend fine sand. In the study area, the probability of occurrence of such waves is less than 1% [27]. On the other hand, an only 0.8 m high fast ferry wave with a 10 s period will resuspend sand at this depth, and as shown by this and previous studies, ferry wakes are frequently higher than 0.8 m.

Table 4. Measured shoreward fluxes of bedload sediments. A frame consisting of two plates (with slopes of 15° and 25°) with the traps in them (196 mm of diameter) was used to trap the sediments

Date, 2008	Depth, m	Time		Flux, g/(m^2·h)	
		From	To	15°	25°
22 July	3	23:10	07:50	10.9	1.7
		15:00	22:55	4.2	25.1
23 July	3	08:00	15:56	2.0	4.2
30 July	3.4	20:28	09:40	0.8	4.9
		09:45	15:10	3.9	2.4
11 September	4.5	19:45	10:30	0.3	0.1
12 September	4.5	10:35	18:25	0.1	0.3

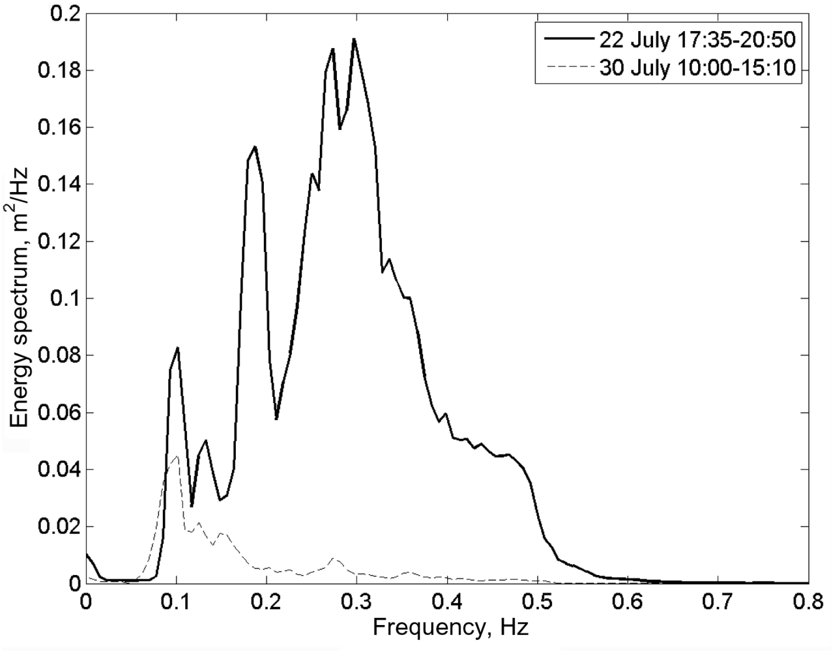

Fig. 8. Energy density of wind waves and fast ferry wakes on 22 and 30 July.

The dataset of bedload sediment fluxes (Table 4) is quite limited. However, the above experiments have given us some guidance for further studies. First, contrary to projections, no systematic dependence of the magnitude of the bedload flux on the slope of the rolling plane was registered during the experiments. Second, no significant bedload transport was recorded at a depth of 4.5 m. This is somewhat unexpected, because the long-period ferry wakes should bring a substantial amount of energy to near-bottom motions at these depths.

4. CONCLUSIONS

A new autonomous experimental device for underwater optical measurements was tested over a week to monitor the impact of ship wakes. Measurements on 24–29 July 2008 showed that the average daily impact of ship wakes in terms of resuspension of bottom sediment near the coast of Aegna in Tallinn Bay is 14 400 g·s/m^3, which is approximately three times lower than estimated previously. Moreover, ship traffic in Tallinn Bay causes a daily increase in the suspended matter concentration of about 0.3 g/m^3 in the near-bottom coastal waters.

Measurement of wakes from a big fast ferry (Tallink *Star*) in autumn 2007 showed that the typical height of the largest wake waves is 0.9 m and their period is 8 s. These values are comparable to earlier measurements of wakes from classical high-speed monohulls and catamarans. The average spectral energy density of ship wakes on 25–29 July shows the largest spectral peak at 10.3 s and somewhat lower peaks at 12.3, 7.8 and 6.6 s.

At water depths less than 3 m, even relatively small wind waves (about 0.5 m in height and period about 3 s) induce much more intense resuspension than the fast ferry waves.

Two types of sediment traps were used for pilot studies to directly measure resuspended and bedload sediment fluxes. The seaward flux of sediments at a height of 20 cm above the bottom was in most cases much greater than the shoreward flux. At a height of 60 cm above the bottom, the seaward flux is, on average, the same as the shoreward flux. The data, concerning the magnitude of resuspension and bedload transport, are indicative and call for further research.

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Lainete põhjustatud setete resuspensiooni seire

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Töö sisuks on määrata laeva- ja tuulelainete põhjustatud põhjasetete resuspensiooni ning edasikande intensiivsust reaalajas lainetuse, vee optiliste parameetrite ja settevoogude mõõtmiste alusel. Mõõtmised toimusid Tallinna lahes Aegna kai lähistel. Vee optilise tiheduse mõõtmine toimus kahel PAR-anduril põhineva eksperimentaalse autonoomse sondi abil. Määrati ka suurte kiirpraamide tekitatud lainete põhiparameetrid. Kiirlaevalained põhjustavad vee optilise tiheduse järsu, kuni 1,5-kordse tõusu 5–20 minutiks. Laevaliikluse summaarne mõju põhjasetete resuspensioonile oli kiirlaevaliikluse intensiivsuse vähenemise tõttu 2008. aastal väiksem, kuid seoses suuremate laevade kasutuselevõtuga on jäänud eelnevate aastatega samasse suurusjärku. Lainete ja settevoogude mõõtmised näitavad, et madalatel sügavustel (~3 m) ning mõõduka lainetusega (>0,5 m) domineerivad tuulelainete tekitatud settevood.