

# Quantifying sediment resuspension and internal phosphorus loading in shallow near-shore areas in the Gulf of Finland

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Sediment resuspension was quantified in shallow, sheltered and semi-exposed coastal areas in the Gulf of Finland. Cylindrical sedimentation traps were placed at six locations including emergent aquatic vegetation stands (*Phragmites australis*), submerged vegetation stands (*Myriophyllum spicatum*, *Potamogeton pectinatus* and *Potamogeton perfoliatus*) and unvegetated shallow (1–1.5 m) areas. During the study period (19 May–29 September 2009, sampling interval of two weeks), there was a seasonal development of macrophyte stands, as well as variation in suspended matter and sediment resuspension. The resuspension-inhibiting effect of macrophytes was found as decreasing resuspension values in concordance with the increasing macrophyte density during the growing season. However, measured phosphorus resuspension was highest among emergent macrophytes due to high concentration of phosphorus in sediments. A linear regression model for resuspension in shallow coastal areas was developed with which sediment resuspension rate may be predicted.

## Introduction

In shallow areas, sediment–water interaction is an intensive ongoing process due to water movement caused by wave action (Carper and Bachmann 1984, Floderus and Håkanson 1989, Floderus and Pihl 1990, Bengtsson and Hellström 1992). This interaction transfers particles and nutrients from sediment to water (Simon 1989), thus affecting the primary production of coastal areas (Middelburg and Soetaert 2005). Sediment–water processes also relocate fine sediments to deeper areas (Håkanson and Jansson 1983, Gabrielson and Lukatelich 1985, Petticrew and Kalff 1991, Christiansen *et al.* 2002, Ziervogel and Bohling 2003) thus affecting the sediment quality distribution of shallow areas.

Main factors that control sediment resuspension in shallow areas are wind-induced waves and currents, fetch size, sediment quality and bottom topography (Evans 1994). Wind-induced resuspension depends on speed, duration and direction of the wind (Håkanson 1977, Ward 1985) together with shore topography that can be described by fetch calculation (Anon. 1984, Ekebom *et al.* 2003). Resuspension occurs when bottom shear stress exceeds a critical shear stress value for the sediment bed in question (Evans 1994), and hence the potential for sediment to resuspend depends on the sediment quality (Bengtsson *et al.* 1990, Ziervogel and Bohling 2003). Shear stress can be described by bottom-sediment water content and grain size (Håkanson and Jansson 1983). In non-cohesive sediments, it

can be generalized that the smaller the grain size, the lower critical stress is needed for resuspension to occur (Shields 1936). However, in the case of cohesive sediments such as mud blankets or organic detritus, the relationship between critical shear stress and particle size is less clear (Partheniades 1993, Lau and Droppo 2000). Water depth is also a prominent factor by setting the limit for the wave height reaching bottom sediment (Carper and Bachmann 1984).

Shallow and sheltered coastal areas are commonly colonized by aquatic macrophytes, which have been observed to attenuate water movement (Fonseca *et al.* 1982, Machata-Wenninger and Janauer 1991) thus inhibiting sediment resuspension (Dieter 1990, Hamilton and Mitchell 1996, Horppila and Nurminen 2001). As reviewed by Madsen *et al.* (2001), the relationship between water movement and aquatic vegetation is bidirectional: macrophyte stands may affect sediment quality due to enhanced sedimentation rates (James and Barko 1990, Petticrew and Kalff 1992), and wave energy can regulate macrophyte distribution (Koch 2001) and cause damage to macrophytes (Stewart *et al.* 1997). As sediment quality is an important factor in resuspension-born nutrient loading, the development and area of macrophyte stands may have an effect on the amount of nutrients released from the sediment (Søndergaard *et al.* 1992, Barko and James 1998, Horppila and Nurminen 2001, Horppila and Nurminen 2003).

Coastal eutrophication is a threat to marine ecosystems of the archipelago areas typical to the northern part of the Baltic Sea (Bonsdorff *et al.* 1997). As resuspension can constitute a substantial proportion of the internal nutrient loading in shallow water areas (Simon 1989, Kristensen *et al.* 1992, Søndergaard *et al.* 1992, Niemistö and Horppila 2007) and increase productivity (Fanning *et al.* 1982, Hellström 1991, Wallin and Håkanson 1992), studies on sediment resuspension can produce new information on nutrient dynamics and eutrophication in coastal areas of the Baltic Sea. The importance of sediment resuspension to nutrient recycling and the trophic level of coastal areas in the Baltic Sea was presented by Wallin and Håkanson (1992), and the significance of oxidized organic-rich sediments as phosphorus source in the Gulf of Finland discussed by

Lehtoranta (2003). The aims of this study were: (1) to quantify sediment resuspension in shallow and sheltered coastal areas in the brackish Gulf of Finland, (2) to quantify factors affecting sediment resuspension and create a simple empirical linear model to depict factors affecting sediment resuspension and to predict resuspension in areas similar to the study area, and (3) to estimate the level of total phosphorus loading to water column caused by resuspended matter in shallow near-shore areas.

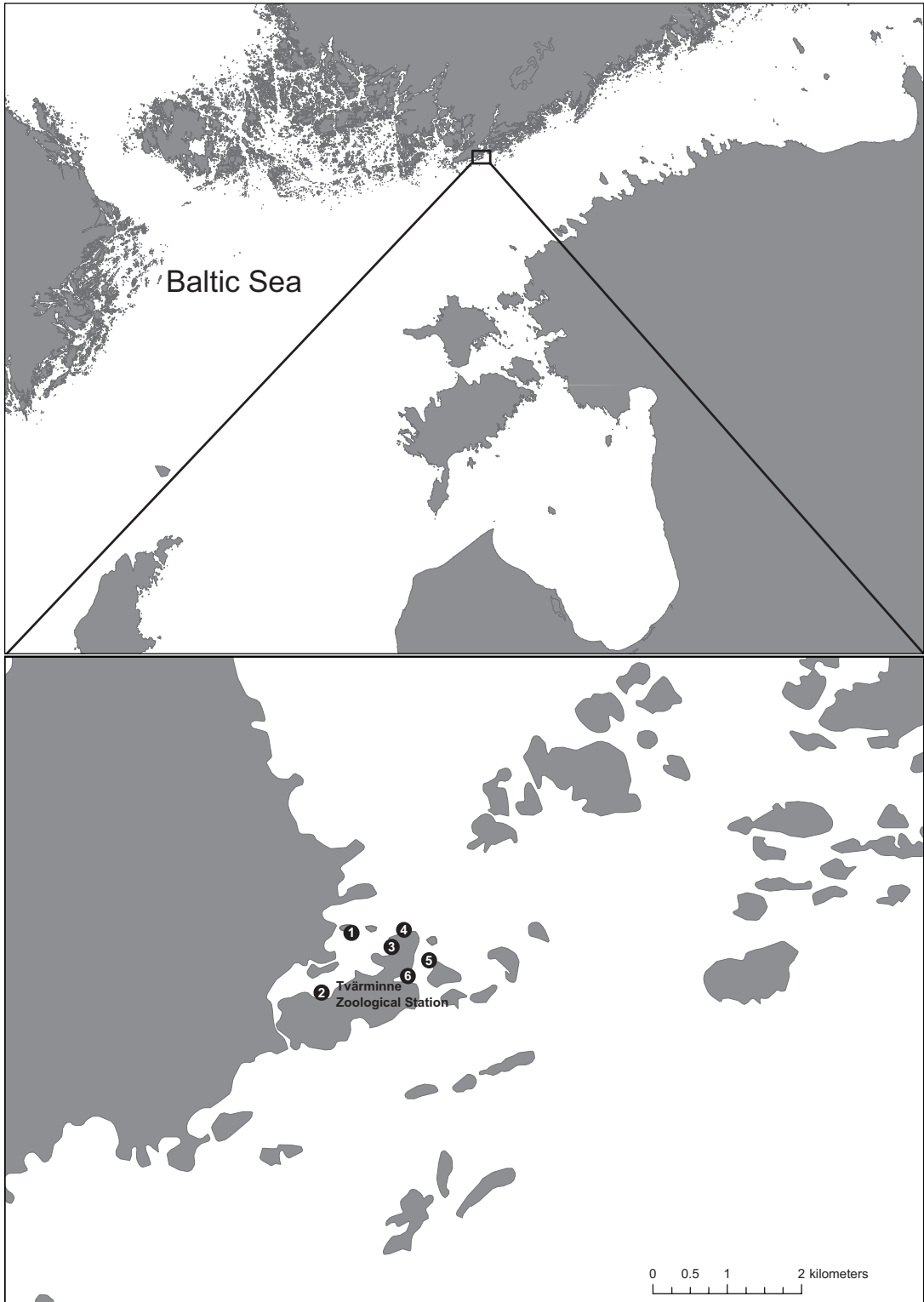
## Material and methods

### Study area

The study was carried out in the vicinity of the Tvärminne Zoological Station in the coastal areas of the western Gulf of Finland, Baltic Sea (59°50'N, 23°18'E) during 19 May–29 September 2009 (Fig. 1). Sampling stations (6 locations, 10 sampling stations in total) were selected to represent sheltered and semi-exposed locations based on average fetch calculation by Suominen *et al.* (2007). The range of average fetch at the locations was 90–524 m, which is characteristic to clay, sandy and till shores (Tolvanen and Suominen 2005). The locations were also selected to include areas with emergent and submerged macrophyte stands and areas with no vegetation. Water depth at the sampling locations was 1.0–1.4 m.

### Data collection

At each sampling station, three replicate sedimentation traps were placed inside emergent vegetation stands (Stations EM, 10 m from shoreline), adjacent open water containing submerged macrophytes (Stations SM, 10 m from shoreline or emergent stand if present) or unvegetated areas (Station OP, 10 m from shoreline or emergent stand if present). There were a total of 4 emergent macrophyte stations (1-EM, 2-EM, 3-EM, 6-EM), 4 submerged macrophyte stations (1-SM, 2-SM, 4-SM, 5-SM) and 2 unvegetated areas stations (3-OP, 6-OP). Sediment and seston sampling as well as emptying of sediment traps



**Fig. 1.** Map of the study area showing the sampling stations. Shoreline® 2010 National Land Survey of Finland, License 49/MML/10.

were conducted in total of 9 times during the study at 14-d intervals, excluding the last period (21 d). The traps were consisted of plastic tubes with the inner diameter of 54 mm and length/width ratio of 6, which is best suited for relatively calm flow conditions (Bloesch and Burns 1980). The traps were placed on the bottom. The upper part of the tube was fitted with an external buoyant-foam plastic ring placed 5 cm from the top in order to keep the tube vertically aligned. The top of the tube collecting the suspending matter was 40 cm above the sediment surface.

Vegetation density was measured as number of stems per area (stems m<sup>-2</sup>) for emergent macrophytes (*Phragmites australis*, stations 1-EM, 2-EM, 3-EM, 6-EM), and as a percentage of volume infested (PVI) for submerged macrophytes (*Potamogeton perfoliatus*, 1-SM, 2-SM, 4-SM, 5-SM, *Myriophyllum spicatum*, 2-SM, and *Potamogeton pectinatus*, 1-SM, 2-SM). The sediment resuspension rate at each location was calculated using the method by Gasith (1975), which can be applied to shallow areas. This method is based on the assumption that the content of organic matter in the bottom sediment differs from that of suspended seston. The method uses the following equation:

$$R = S(C_S - C_T)/(C_{SS} - C_T) \quad (1)$$

where  $R$  is the sediment resuspension rate (g DW m<sup>-2</sup> d<sup>-1</sup>),  $S$  is the entrapped settling flux (g DW m<sup>-2</sup> d<sup>-1</sup>),  $C_S$  is the organic fraction of gross sedimentation (%),  $C_{SS}$  is the organic fraction of surface sediment (%),  $C_T$  is the organic fraction of suspended matter in water column (%).

The dry weight of suspended matter equivalent to water volume of sediment trap was subtracted from the gross sedimentation (Gasith 1975, Bloesch 1994) by siphoning the trap and transporting material to a dish. The organic-matter content of the trap material was measured by loss on ignition (LOI): samples were ignited for 2 h at 550 °C as commonly used in resuspension studies (Weyhenmeyer 1997). Trapped material was analyzed for total phosphorus (Murphy and Riley 1962). Seston samples (three replicates from each station) were taken from the water column with a tube sampler, filtered through a Whatman GF/C filter and analysed for suspended solids and LOI.

Filtered and unfiltered water was analyzed for total phosphorus. Surface sediment samples were taken with an Ekman sampler (a corer was used in station 6-EM due to high organic-matter content) at each station every time the traps were sampled (three replicates, 0–1 cm layer) and analysed for LOI. Total phosphorus was analyzed from sediment in accordance with methods used for trapped material. Total phosphorus flux from resuspension was obtained by multiplying the resuspension rate by total phosphorus content of the surface sediment. Weather data were collected with the Gavis GroWeather station maintained by the Tvärminne Zoological Station. Wind speed and direction was measured in 30-minute intervals throughout the study period. Water level data recorded at the Hanko station (59°77'N, 22°95'E) were obtained from the Finnish Meteorological Institute (FMI). Fetch length data originated from the UTU Marine Shore Fetch Data 2007 database provided by Suominen *et al.* (2007). The data contain fetch direction (in meters) calculated for 48 directions, average fetch (Ekeboom *et al.* 2003) and maximum effective fetch (Håkanson and Jansson 1983, Anon. 1984) for points located in 10-meter intervals on the shoreline. Wave length and period was determined from the wind and fetch data (Anon. 1984). A theoretical shear stress model by Hamilton and Mitchell (1996) was used to determine shear stress for point locations.

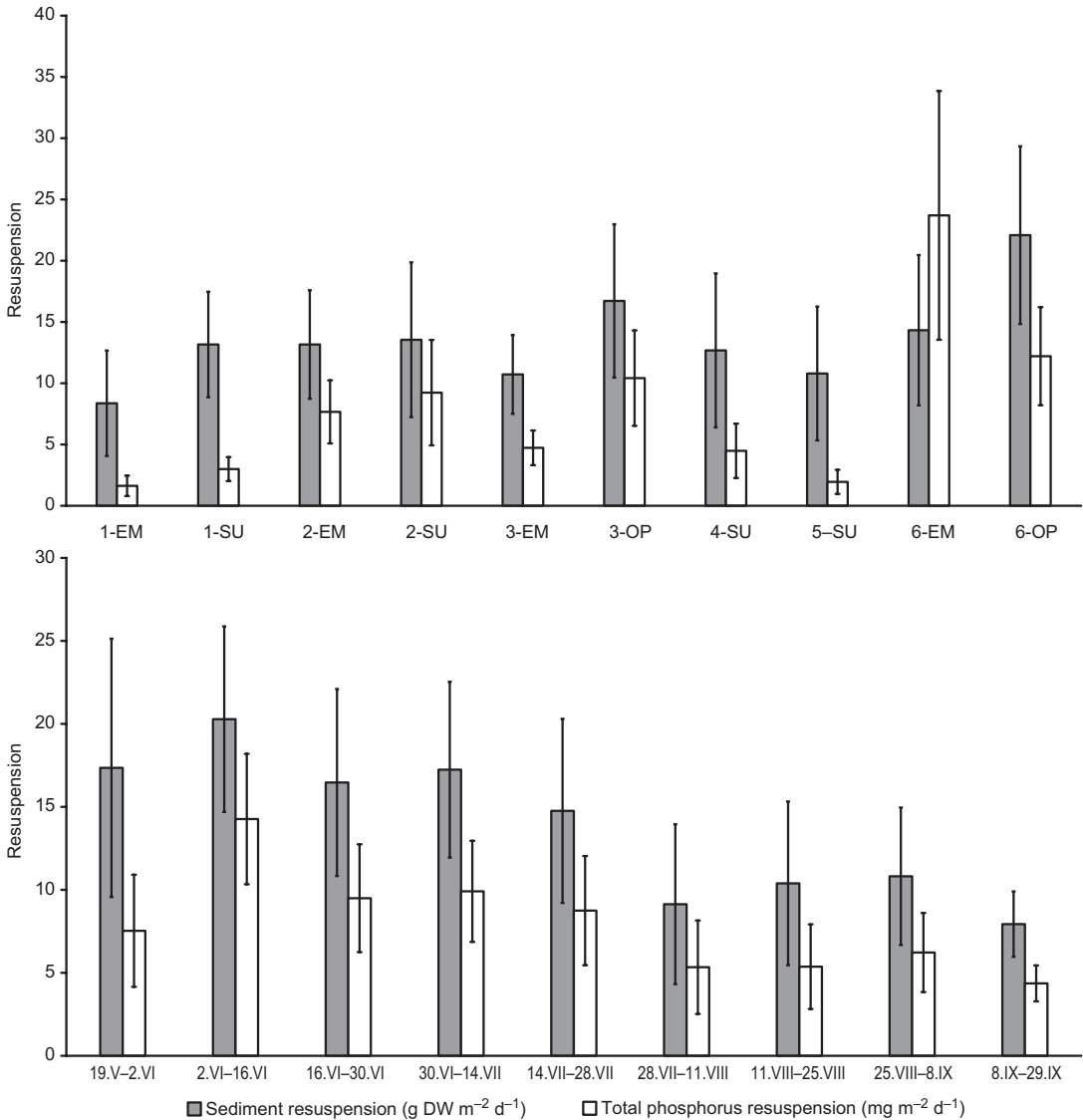
## Statistical analysis

Sediment resuspension was predicted with a stepwise linear regression model using the pooled field data. Spearman's correlation was used to the test model performance by analysing correlation between model results and measured values not used in the regression model parameterization. Correlation and regression analyses were carried out with SPSS Statistics software ver. 15.0.

## Results

### Sediment resuspension

Mean resuspension during the entire study period



**Fig. 2.** Mean ( $\pm$  SD) daily rates of sediment resuspension ( $\text{g DW m}^{-2} \text{d}^{-1}$ ) and total phosphorus resuspension ( $\text{mg m}^{-2} \text{d}^{-1}$ ) during the study at each sampling station (top) and during different periods (bottom).

(133 d) at all stations was (mean  $\pm$  SD)  $14 \pm 6 \text{ g DW m}^{-2} \text{d}^{-1}$ , which results in a total resuspension of  $1.8 \pm 0.8 \text{ kg DW m}^{-2}$  in 133 d and an annual average of  $4.9 \pm 2.4 \text{ kg DW m}^{-2}$ . Average gross sedimentation was  $20 \pm 8 \text{ g DW m}^{-2} \text{d}^{-1}$ , indicating that on average 70% of the gross sedimentation originated from resuspension. Based on the average resuspension rate and the average total phosphorus concentration in the surface sediment ( $0.5 \text{ mg g}^{-1} \text{DW}$ ) in the study area, resuspension-born phosphorus loading was  $7 \text{ mg m}^{-2} \text{d}^{-1}$ . The

average resuspension rate during the entire study period was the lowest ( $8.4 \pm 4.3 \text{ g DW m}^{-2} \text{d}^{-1}$ ) at emergent macrophyte station 1-EM and the highest at open water station 6-OP ( $22.1 \pm 7.3 \text{ g DW m}^{-2} \text{d}^{-1}$ ) (Fig. 2). The maximum resuspension rate during a single measurement period was  $29.2 \pm 0.8 \text{ g DW m}^{-2} \text{d}^{-1}$  recorded at open-water station 3-OP during the first period (Table 1). Variation in resuspension of phosphorus among stations was over 10-fold. Contrary to the resuspension rate of dry matter, the highest rate of average

phosphorus resuspension during the entire study period ( $23.7 \pm 10.2 \text{ mg P m}^{-2} \text{ d}^{-1}$ ) was found among emergent macrophytes at station 6-EM. During the study period, average phosphorus concentration in the surface sediment samples ( $0.5 \pm 0.4 \mu\text{g mg}^{-1}$ ) was lower than in sedimented matter ( $1.3 \pm 0.4 \mu\text{g mg}^{-1}$ ). During the study period, the lowest rate of average phosphorus resuspension ( $1.6 \pm 0.8 \text{ mg m}^{-2} \text{ d}^{-1}$ ) was found at station 1-EM. The rates of seston and phosphorus

resuspension were the highest during the second period (2 June–16 June) and the lowest during the last period (8 September–29 September). The resuspension rate decreased towards the end of the study (Fig. 2).

The concentration of suspended solids in the water column varied between  $1.5 \text{ mg l}^{-1}$  and  $11.0 \text{ mg l}^{-1}$  with the lowest value measured at station 1-EM and the highest at station 2-SM. At all stations, the mean concentration of suspended

**Table 1.** Sediment resuspension rate ( $R$ , mean  $\pm$  SD,  $\text{g DW m}^{-2} \text{ d}^{-1}$ ), phosphorus resuspension ( $R_p$ , mean  $\pm$  SD,  $\text{mg m}^{-2} \text{ d}^{-1}$ ) and total phosphorus concentration in sediment ( $P_s$ ,  $\text{mg g}^{-1}$ ) at the sampling stations during the study period (station locations 1–6, EM = emergent macrophyte stand, SM = submerged macrophyte stand, OP = open water).

	2 June	16 June	30 June	14 July	28 July	11 Aug.	25 Aug.	8 Sep.	29 Sep.
1-EM									
$R$	$6.5 \pm 1.8$	$17.0 \pm 1.0$	$6.3 \pm 0.1$	9.4	$12.4 \pm 2.3$	$4.3 \pm 0.3$	$6.1 \pm 0.6$	$7.3 \pm 1.3$	$4.8 \pm 1.6$
$R_p$	$1.3 \pm 0.4$	$3.4 \pm 0.2$	$1.3 \pm 0.0$	2.5	$3.1 \pm 0.7$	$0.8 \pm 0.1$	$0.9 \pm 0.1$	$2.3 \pm 0.4$	$1.0 \pm 0.3$
$P_s$	0.2	0.2	0.2	0.3	0.3	0.2	0.1	0.3	0.2
1-SM									
$R$	$24.6 \pm 2.9$	$21.1 \pm 1.5$	$16.0 \pm 2.1$	18.0	$13.2 \pm 3.0$	$5.2 \pm 0.5$	$7.6 \pm 0.3$	$8.7 \pm 1.0$	$7.4 \pm 1.4$
$R_p$	$5.6 \pm 0.6$	$4.7 \pm 0.8$	$4.0 \pm 0.6$	3.9	$2.9 \pm 0.6$	$0.5 \pm 0.1$	$1.9 \pm 0.1$	$2.8 \pm 0.3$	$0.7 \pm 0.1$
$P_s$	0.2	0.2	0.3	0.2	0.2	0.1	0.2	0.3	0.1
2-EM									
$R$	$17.5 \pm 1.7$	$18.8 \pm 3.8$	$18.0 \pm 3.2$	$15.4 \pm 4.1$	$12.0 \pm 2.2$	$10.5 \pm 1.1$	$11.0 \pm 1.2$	$9.9 \pm 0.6$	$7.1 \pm 0.3$
$R_p$	$8.1 \pm 0.9$	$12.9 \pm 2.7$	$7.9 \pm 1.3$	$8.2 \pm 2.0$	$8.4 \pm 1.5$	$6.2 \pm 0.6$	$7.3 \pm 0.8$	$6.4 \pm 0.4$	$3.6 \pm 0.2$
$P_s$	0.5	0.7	0.4	0.5	0.7	0.6	0.7	0.6	0.5
2-SM									
$R$	$19.7 \pm 2.6$		24.6	$25.0 \pm 4.5$	$13.8 \pm 2.2$	$9.3 \pm 1.1$	$10.3 \pm 4.2$	$9.4 \pm 1.3$	$7.3 \pm 0.8$
$R_p$	$9.5 \pm 1.3$		17.1	$14.9 \pm 2.7$	$9.7 \pm 1.5$	$5.6 \pm 0.6$	$8.9 \pm 3.8$	$3.6 \pm 0.5$	$4.6 \pm 0.5$
$P_s$	0.5	0.7	0.7	0.6	0.7	0.6	0.9	0.4	0.6
3-EM									
$R$	$7.4 \pm 2.0$	$12.6 \pm 2.2$	$14.7 \pm 1.0$	$14.2 \pm 1.5$	$13.1 \pm 2.8$	$9.7 \pm 0.6$	$9.5 \pm 1.6$	$8.4 \pm 1.8$	$6.9 \pm 1.2$
$R_p$	$3.2 \pm 0.8$	$9.9 \pm 1.8$	$4.5 \pm 0.3$	$6.0 \pm 0.6$	$3.0 \pm 0.6$	$6.5 \pm 0.4$	$5.2 \pm 1.0$	$1.5 \pm 0.9$	$2.6 \pm 0.3$
$P_s$	0.4	0.8	0.3	0.4	0.2	0.7	0.6	0.2	0.4
3-OP									
$R$	$29.2 \pm 0.8$	$21.0 \pm 4.5$	$22.0 \pm 1.7$	17.3	$17.9 \pm 0.2$	$16.0 \pm 0.4$	$9.9 \pm 1.2$	$12.0 \pm 2.2$	$10.0 \pm 1.8$
$R_p$	$17.2 \pm 0.5$	$12.5 \pm 2.7$	$15.9 \pm 1.2$	10.8	$12.0 \pm 0.2$	$4.7 \pm 0.1$	$4.9 \pm 0.6$	$8.3 \pm 1.5$	$7.4 \pm 1.3$
$P_s$	0.6	0.6	0.7	0.6	0.7	0.3	0.5	0.7	0.7
4-SM									
$R$	$17.0 \pm 5.2$	$18.3 \pm 4.1$	$22.3 \pm 2.1$	$16.9 \pm 2.3$	$9.0 \pm 1.6$	$4.1 \pm 0.9$	$8.2 \pm 0.6$		$8.8 \pm 0.7$
$R_p$	$7.8 \pm 2.6$	$4.8 \pm 1.2$	$8.8 \pm 0.8$	$5.8 \pm 0.8$	$2.8 \pm 0.5$	$0.8 \pm 0.2$	$2.2 \pm 0.2$		$2.8 \pm 0.2$
$P_s$	0.5	0.3	0.4	0.3	0.3	0.2	0.3	0.2	0.3
5-SM									
$R$		21.5	$19.3 \pm 0.5$	$10.5 \pm 3.1$	$11.4 \pm 1.6$	$5.7 \pm 0.3$	$8.9 \pm 0.9$	$9.3 \pm 1.0$	$6.2 \pm 1.8$
$R_p$		3.0	$3.2 \pm 0.3$	$2.2 \pm 0.6$	$3.0 \pm 0.5$	$0.6 \pm 0.0$	$1.4 \pm 0.2$	$1.3 \pm 0.1$	$1.0 \pm 0.4$
$P_s$	0.2	0.1	0.2	0.2	0.3	0.1	0.2	0.1	0.2
6-EM									
$R$		$25.5 \pm 1.3$	$12.4 \pm 2.7$	$19.3 \pm 2.2$	$18.3 \pm 1.7$	$8.3 \pm 2.2$	$8.8 \pm 1.3$	$13.6 \pm 1.1$	$9.4 \pm 1.3$
$R_p$		$45.0 \pm 2.3$	$22.7 \pm 4.9$	$29.4 \pm 3.3$	$27.7 \pm 2.6$	$15.0 \pm 4.0$	$12.9 \pm 2.0$	$20.2 \pm 1.7$	$16.8 \pm 2.3$
$P_s$	1.6	1.8	1.8	1.5	1.5	1.8	1.5	1.5	1.8
6-OP									
$R$		29.1		$25.4 \pm 0.8$	$26.5 \pm 7.2$	$18.2 \pm 3.7$	$23.5 \pm 3.5$	$22.6 \pm 3.3$	$10.5 \pm 1.0$
$R_p$		21.2		$15.4 \pm 0.5$	$14.9 \pm 4.3$	$12.8 \pm 2.6$	$8.3 \pm 1.4$	$9.6 \pm 1.3$	$3.3 \pm 0.3$
$P_s$	0.5	0.7	0.3	0.6	0.6	0.7	0.4	0.4	0.3

solids decreased towards the end of the study period. The organic fraction of suspended solids was lower during early summer and higher in mid-summer and autumn (Table 2).

## Factors affecting sediment resuspension

### Macrophytes

At the start of the study period, submerged macrophytes were absent from all stations (Table 2). Development of submerged vegetation stands was first observed at the beginning of June. The stands reached their maximum (35 PVI at 2-SM) at the beginning of September.

There were no emergent macrophyte stands at the start of study period; only withered stems from previous growing season were found and taken into account when calculating vegetation density. At all emergent macrophyte stations, vegetation growth started at the beginning of June and the maximum density was reached at the beginning of September. The highest stem density (68 stems  $m^{-2}$ ) was measured at station 6-EM in August. No macrophytes were present at open-water stations 3-OP and 6-OP.

### Wind and openness

The average wind speed during the study period was  $5.4 m s^{-1}$ , and the most frequent direction was from W-SW (Fig. 3). The maximum wind speed recorded within a measurement period during varied between  $8.0 m s^{-1}$  (28 July–11 August) and  $20.1 m s^{-1}$  (2–16 June). Due to changes in wind speed, wind direction and air pressure, the water level varied between the minimum of  $-20 cm$  recorded at the beginning of the study period and the maximum of  $+35 cm$  recorded at the end of the study period. The mean fetch at all stations was 208 m (max. 524 m at station 4 and min. 90 m at station 3).

### Sediment properties

The organic-matter content of the surface sediment varied between 0.5% and 22.4%, with a

mean  $\pm$  SD for all the stations being  $4.3\% \pm 5.8\%$ . The lowest values were measured for the sandy bottoms of stations 1-SM and 5-SM (Table 2), and the highest value was recorded for the muddy sediment at station 6-EM. There was a strong correlation between the organic fraction of surface sediment and the total phosphorus concentration ( $r_s = 0.87$ ,  $p < 0.01$ ,  $n = 88$ ). The total phosphorus concentrations in the sediments ranged from 0.2 to  $1.5 mg g^{-1}$  and were the lowest at stations 1-EM, 1-SM and 5-SM and the highest at station 6-EM (Table 1).

## Resuspension model

A multivariate linear regression model was created with a stepwise method to predict the mass of resuspended matter and to test the environment variables affecting sediment resuspension. The variables used in the regression analysis in order of significance were density of emergent macrophytes, density of submerged macrophytes, maximum wind speed from the open directions and organic fraction of sediment. The maximum wind speed from a direction where fetch  $> 100 m$  recorded during the study period turned out to be the best variable in predicting sediment resuspension in the linear regression with the standardized coefficient  $\beta = 0.36$ , and was included in the model to represent wind-induced forcing on sediment resuspension. Wind-induced forcing on resuspension was also described as calculated theoretical shear-stress values according to Hamilton and Mitchell (1996), but was excluded from the regression model due to lack of predictive power. Also, wind speed or fetch alone did not improve predictions. In addition to wind-fetch calculation, wave energy estimation was carried out based on theoretical wave lengths using equations by Carper and Bachmann (1984), but with no success in improving the model prediction. The use of water level as an explanatory variable was also not successful in improving model performance.

Resuspension is thus predicted by the linear equation:

$$R = a + \beta_1 D_E + \beta_2 D_S + \beta_3 W_M + \beta_4 \times C_{SS}, \quad (2)$$

where  $R$  is the resuspension rate ( $g DW m^{-2} d^{-1}$ ),



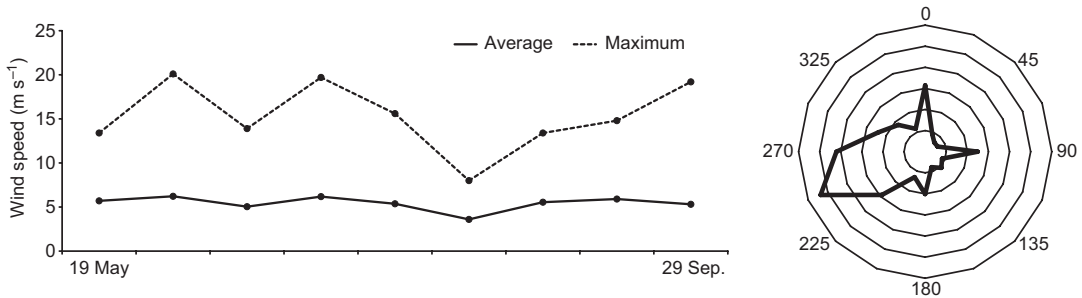
$D_E$  is the density of emergent macrophytes ( $m^{-2}$ ),  $D_S$  is the density of submerged macrophytes (PVI, %),  $W_M$  is the maximum wind speed from a direction where fetch > 100 m ( $m s^{-1}$ ).

The regression model was parameterized based on the field data ( $n = 233$ ) using randomly selected 133 measurements and validated by plotting 100 model results against residual 100

**Table 2.** Emergent macrophyte density ( $D_E$ , mean  $\pm$  SD, stems  $m^{-2}$ ), submerged macrophyte density ( $D_S$ , mean  $\pm$  SD, PVI), organic fraction of gross sedimentation ( $C_S$ , mean  $\pm$  SD, %), organic fraction of surface sediment ( $C_{SS}$ , %) and organic fraction of seston suspended in the water ( $C_T$ , mean  $\pm$  SD, %) in sampling stations (station locations 1–6, EM = emergent macrophyte stand, SM = submerged macrophyte stand, OP = open water).

	2 June	16 June	30 June	14 July	28 July	11 Aug.	25 Aug.	8 Sep.	29 Sep.
<b>1-EM</b>									
$D_E$	15.3 $\pm$ 5.0	20.3 $\pm$ 8.4	33.6 $\pm$ 6.5	30.8 $\pm$ 4.6	42.0 $\pm$ 7.0	60.0 $\pm$ 8.7	61.3 $\pm$ 6.1	59.3 $\pm$ 3.1	52.3 $\pm$ 7.5
$C_S$	20.7 $\pm$ 0.6	24.5 $\pm$ 1.0	25.4 $\pm$ 2.8	24.6 $\pm$ 4.4	25.8 $\pm$ 1.0	20.4 $\pm$ 1.1	25.4 $\pm$ 1.4	24.3 $\pm$ 1.2	21.3 $\pm$ 2.5
$C_{SS}$	0.8		1.2	0.9	1.0	1.1	1.2	1.4	1.5
$C_T$	56.1 $\pm$ 2.0	67.5 $\pm$ 2.0	59.5 $\pm$ 2.0	74.0 $\pm$ 2.9	71.0 $\pm$ 1.9	64.3 $\pm$ 3.7	72.8 $\pm$ 3.9	70.2 $\pm$ 4.7	80.6 $\pm$ 2.8
<b>1-SM</b>									
$D_S$	0	8.0 $\pm$ 2.0	10.7 $\pm$ 3.1	19.0 $\pm$ 3.6	22.7 $\pm$ 3.1	24.0 $\pm$ 5.3	25.0 $\pm$ 5.0	25.0 $\pm$ 5.0	23.7 $\pm$ 4.0
$C_S$	15.0 $\pm$ 1.7	19.2 $\pm$ 0.1	15.7 $\pm$ 0.6	18.8 $\pm$ 0.8	23.7 $\pm$ 0.7	22.0 $\pm$ 0.6	21.7 $\pm$ 1.6	23.6 $\pm$ 0.5	20.3 $\pm$ 1.7
$C_{SS}$	0.8	0.7	0.9	0.6	1	0.8	1.0	0.9	0.5
$C_T$	51.7 $\pm$ 4.4	56.5 $\pm$ 5.2	64.4 $\pm$ 5.6	72.0 $\pm$ 0.5	62.5 $\pm$ 2.9	64.9 $\pm$ 1.1	69.6 $\pm$ 1.6	57.8 $\pm$ 1.4	60.7 $\pm$ 2.1
<b>2-EM</b>									
$D_E$	5.3 $\pm$ 5.0	17.7 $\pm$ 4.7	24.3 $\pm$ 4.0	26.3 $\pm$ 2.1	39.3 $\pm$ 7.5	44.3 $\pm$ 10.0	41.7 $\pm$ 10.4	40.7 $\pm$ 11.0	34.7 $\pm$ 11.4
$C_S$	19.3 $\pm$ 1.5	20.5 $\pm$ 1.7	15.9 $\pm$ 2.9	23.9 $\pm$ 5.3	26.8 $\pm$ 5.8	21.1 $\pm$ 1.3	19.8 $\pm$ 1.1	20.8 $\pm$ 0.8	19.7 $\pm$ 1.2
$C_{SS}$	2.9	3.7	2.3	2.7	2.2	3.1	3.4	3.6	3.3
$C_T$	37.6 $\pm$ 0.5	55.2 $\pm$ 3.7	55.8 $\pm$ 2.5	53.6 $\pm$ 3.9	60.5 $\pm$ 6.3	68.9 $\pm$ 5.0	59.9 $\pm$ 2.0	56.6 $\pm$ 0.7	61.3 $\pm$ 0.8
<b>2-SM</b>									
$D_S$	0	0	10.0 $\pm$ 2.0	15.3 $\pm$ 5.0	20.0 $\pm$ 3.5	26.0 $\pm$ 1.7	30.0 $\pm$ 0.0	35.0 $\pm$ 0.0	31.3 $\pm$ 1.2
$C_S$	18.3 $\pm$ 0.6	14.3 $\pm$ 7.5	16.9 $\pm$ 2.5	16.9 $\pm$ 3.3	22.3 $\pm$ 0.5	19.4 $\pm$ 0.8	19.5 $\pm$ 2.5	19.5 $\pm$ 0.7	19.7 $\pm$ 0.5
$C_{SS}$	2.0	4.2	3.5	3.5	4.8	2.9	6.5	5.0	4.3
$C_T$	36.8 $\pm$ 0.7	48.8 $\pm$ 1.8	53.4 $\pm$ 1.6	53.4 $\pm$ 7.3	69.9 $\pm$ 3.1	52.0 $\pm$ 3.2	65.1 $\pm$ 4.4	66.7 $\pm$ 1.2	66.9 $\pm$ 1.2
<b>3-EM</b>									
$D_E$	8.0 $\pm$ 2.0	21.3 $\pm$ 3.1	27.7 $\pm$ 9.3	36.3 $\pm$ 3.8	43.7 $\pm$ 5.5	46.0 $\pm$ 7.0	45.3 $\pm$ 9.5	42.0 $\pm$ 11.1	29.3 $\pm$ 14.5
$C_S$	28.7 $\pm$ 2.1	25.8 $\pm$ 2.6	24.6 $\pm$ 2.7	24.0 $\pm$ 0.7	23.8 $\pm$ 0.4	22.1 $\pm$ 0.8	23.1 $\pm$ 0.8	20.9 $\pm$ 0.7	22.2 $\pm$ 1.5
$C_{SS}$	3.9	5.7	3.6	4.5	1.7	0.5	7.5	0.8	2.9
$C_T$	35.2 $\pm$ 2.6	47.4 $\pm$ 1.3	53.1 $\pm$ 4.1	63.6 $\pm$ 3.6	63.6 $\pm$ 2.7	63.1 $\pm$ 13.2	65.1 $\pm$ 3.0	70.3 $\pm$ 2.3	59.2 $\pm$ 2.9
<b>3-OP</b>									
$C_S$	12.3 $\pm$ 6.4	17.5 $\pm$ 0.8	15.6 $\pm$ 0.8	16.4 $\pm$ 3.0	19.7 $\pm$ 0.2	18.2 $\pm$ 1.1	18.0 $\pm$ 2.6	21.1 $\pm$ 2.1	17.8 $\pm$ 1.8
$C_{SS}$	2.5	4.4	5.0	4.3	3.9	4.0	2.7	6.0	5.3
$C_T$	36.6 $\pm$ 2.3	43.8 $\pm$ 0.5	59.3 $\pm$ 5.2	59.8 $\pm$ 3.9	63.6 $\pm$ 1.7	60.1 $\pm$ 1.8	60.3 $\pm$ 3.4	55.3 $\pm$ 1.1	56.6 $\pm$ 0.2
<b>4-SM</b>									
$D_S$	0	0	0	3.3 $\pm$ 2.9	8.3 $\pm$ 2.9	13.3 $\pm$ 2.9	19.3 $\pm$ 1.2	20.0 $\pm$ 0.0	20.0 $\pm$ 0.0
$C_S$	15.3 $\pm$ 2.1	17.2 $\pm$ 3.7	12.4 $\pm$ 3.0	22.5 $\pm$ 0.5	24.3 $\pm$ 0.8	26.2 $\pm$ 2.6	28.9 $\pm$ 0.5	23.8 $\pm$ 3.2	26.2 $\pm$ 0.4
$C_{SS}$	0.6	0.5	0.7	0.6	1.1	0.7	0.7	0.9	2.0
$C_T$	52.0 $\pm$ 1.8	66.5 $\pm$ 2.7	65.0 $\pm$ 3.3	72.0 $\pm$ 2.4	65.7 $\pm$ 2.0	80.7 $\pm$ 2.2	62.1 $\pm$ 3.2	75.1 $\pm$ 2.3	55.8 $\pm$ 1.9
<b>5-SM</b>									
$D_S$	0	0	1.7 $\pm$ 2.9	8.7 $\pm$ 1.2	13.3 $\pm$ 3.1	19.7 $\pm$ 4.5	28.3 $\pm$ 2.9	26.7 $\pm$ 2.9	20.7 $\pm$ 3.1
$C_S$	12.7 $\pm$ 0.6	13.5 $\pm$ 5.1	7.2 $\pm$ 1.6	19.3 $\pm$ 1.0	20.2 $\pm$ 1.4	22.4 $\pm$ 0.6	20.4 $\pm$ 1.4	20.2 $\pm$ 0.9	20.6 $\pm$ 1.9
$C_{SS}$	0.8	0.6	0.8	0.4	1.2	0.8	0.9	0.8	0.7
$C_T$	43.6 $\pm$ 0.9	57.1 $\pm$ 3.3	60.7 $\pm$ 0.9	64.0 $\pm$ 2.5	56.8 $\pm$ 1.5	67.0 $\pm$ 1.3	68.9 $\pm$ 4.7	72.0 $\pm$ 3.8	54.9 $\pm$ 4.4
<b>6-EM</b>									
$D_E$	16.7 $\pm$ 2.9	27.7 $\pm$ 1.2	45.7 $\pm$ 8.5	45.0 $\pm$ 9.2	58.0 $\pm$ 5.3	67.7 $\pm$ 2.5	63.7 $\pm$ 5.1	52.7 $\pm$ 3.1	39.0 $\pm$ 3.6
$C_S$	34.5 $\pm$ 10.6	25.2 $\pm$ 2.3	29.0 $\pm$ 5.6	31.4 $\pm$ 1.2	23.3 $\pm$ 0.7	26.8 $\pm$ 3.1	26.1 $\pm$ 2.0	25.0 $\pm$ 0.8	20.3 $\pm$ 1.9
$C_{SS}$	21.7	22.4	21.0	18.4	20.6	21.0	21.0	22.6	17.0
$C_T$	46.6 $\pm$ 2.9	51.1 $\pm$ 7.3	67.4 $\pm$ 3.2	67.4 $\pm$ 2.5	63.8 $\pm$ 1.6	56.7 $\pm$ 2.7	58.1 $\pm$ 2.6	74.8 $\pm$ 4.3	66.0 $\pm$ 0.9
<b>6-OP</b>									
$C_S$	14.7 $\pm$ 0.6	17.4 $\pm$ 0.9	20.0 $\pm$ 4.8	20.0 $\pm$ 4.8	18.1 $\pm$ 1.4	18.1 $\pm$ 1.4	15.8 $\pm$ 1.2	18.9 $\pm$ 0.7	18.0 $\pm$ 0.8
$C_{SS}$		4.1	4.6	4.6	2.5	5.0	1.7	1.5	1.7
$C_T$	45.7 $\pm$ 2.6	49.4 $\pm$ 0.6	62.1 $\pm$ 6.2	62.1 $\pm$ 7.2	65.2 $\pm$ 5.7	49.6 $\pm$ 0.8	54.2 $\pm$ 1.8	70.5 $\pm$ 1.6	64.9 $\pm$ 0.2





**Fig. 3.** Wind speed during measuring periods (left), and cumulative wind direction rose (right) for the study period.

observations not used in the model parameterization (Table 3). With the use of four explanatory variables the  $r^2$  value of the regression was 0.54, and 0.49 when three variables were used (excluding sediment organic fraction). All four variables were statistically significant ( $p < 0.01$ , see Table 3). When the model was tested by using the data ( $n = 100$ ) that were not used for model parameterization, the Spearman correlation between observed and predicted values was 0.67.

## Discussion

### Sediment resuspension in shallow coastal areas

The average sediment resuspension rate ( $14 \pm 6$  g DW  $m^{-2} d^{-1}$ ) was lower and less variable as compared with fluxes of sediment measured in a more open areas in the Gulf of Finland ( $0.7\text{--}170$  g  $m^{-2} h^{-1}$ ) (Erm *et al.* 2011). The reason for lower variability is fetch of the study area and the absence of ship-generated waves. Sediment resuspension varied among sampling station and measurement periods, which was an expected result for the time series of sediment fluxes (Erm *et al.* 2011). The highest resuspension rate was 2.5 times greater than the lowest one. Large spatial differences were caused by fragmented and complex shoreline patterns creating several sheltered sediment accumulation areas even at shallow depths.

Sediment resuspension was higher at the beginning of the study. The high amount of sedimented matter during early summer can be caused by sedimentation of the vernal bloom (Blomqvist and Larsson 1994, Heiskanen and

Leppänen 1995, Heiskanen *et al.* 1998). This newly formed unconsolidated organic material is frequently resuspended at near-shore locations (Bengtsson *et al.* 1990, Christiansen *et al.* 2002). Decreases in sedimentation and resuspension during the study period can be caused by relocation of this autoctonous matter to deeper areas (Christiansen *et al.* 2002). However, at the beginning of the study period, the organic fraction of suspended solids was lower indicating that a larger part of the suspended matter was of inorganic origin. Also the sedimentation of vernal bloom was likely to have occurred before the start of the study period.

### The effect of aquatic vegetation on resuspension

Sediment resuspension was higher at the start of the macrophyte growing season and declined as macrophytes reached peak biomass supporting the hypothesis that developed macrophyte

**Table 3.** Regression analysis results and parameters to predict sediment resuspension (g DW  $m^{-2} d^{-1}$ ):  $a$  is the constant value and  $\beta_1\text{--}\beta_4$  values are coefficients for explanatory variables (density of emergent macrophytes (stems  $m^{-2}$ ), density of submerged macrophytes (PVI), maximum wind speed from directions where fetch  $> 100$  m ( $m s^{-1}$ ) and organic fraction of surface sediment (%), respectively).

Variables	$a$	$\beta_1$	$\beta_2$	$\beta_3$	$\beta_4$	$r^2$
Parameter	11.71	-0.20	-0.30	0.86	0.26	0.54
$p <$		0.01	0.01	0.01	0.01	
Standardized coefficient		-0.64	-0.44	0.36	0.29	

stands inhibit sediment resuspension (Barko and James 1998). Average resuspension among macrophyte stands was also lower than at the open-water stations. This pattern was in concordance with earlier resuspension studies carried out in littoral areas (e.g. Dieter 1990, Horppila and Nurminen 2001, Horppila and Nurminen 2003), emphasizing resuspension inhibition caused by aquatic vegetation. Based on our results, sediment resuspension among macrophyte stands was life-form- and density-dependent. Among the tested resuspension model variables, the density of emergent macrophytes produced the highest standardized coefficient value (Table 3), indicating it to be the best predictive variable for sediment resuspension in the study area. Wave dampening effect of submerged macrophytes has also been previously found to be the highest in dense vegetation (Koch 2001), and resuspension reduction by macrophytes has been connected to high vegetation biomass (James *et al.* 2004). Life-form dependency of sediment resuspension in vegetation stands has previously been studied by Horppila and Nurminen (2005), who found that the effect of emergent and submerged vegetation was of similar magnitude but differed from the effect of floating-leaved vegetation (Nurminen and Horppila 2009). In this study, based on the standardized coefficient beta values of the regression analysis (Eq. 2 and Table 3) the resuspension-inhibiting effect of emergent macrophytes was higher than that of submerged macrophytes. The reason for this may be the differences in the density and species of emergent macrophytes studied. *Phragmites australis* may form dense colonies: the highest density measured in this study was 68 stems  $m^{-2}$ . Horppila and Nurminen (2005) reported that *Typha angustifolia* reached a maximum of 22 stems  $m^{-2}$ . The maximum densities (PVI) of submerged macrophytes were 35% and 30%, in Horppila and Nurminen (2005) and in this study, respectively.

The phosphorus concentration in sediments among vegetation stands can be higher (Chambers and Prepas 1994) or lower than in the open-water area (Sand-Jensen 1998). In this study, the results were not uniform. Given the density dependency of the resuspension-inhibition effect of macrophytes (Koch 2001, James *et al.* 2004), here the difference may be caused by differences

in densities of the stands. At station 6, higher stem density (up to 68 stems  $m^{-2}$ ) could reduce water momentum more efficiently than at station 3 (density up to stems 46  $m^{-2}$ ), which resulted in an increased sedimentation rate.

The organic-matter content in sediments at station 3 was the same in the emergent macrophyte stand and in the adjacent unvegetated area, and so was the total phosphorus content. This can be caused by the sheltered location, which promotes accumulation of organic matter in the sediments also in unvegetated areas.

### The effect of wind speed and fetch on resuspension

In shallow waters, resuspension is mainly a wind-driven process (Carper and Bachmann 1984, Gabrielson and Lukatelich 1985, Bengtsson and Hellström 1992), which was also corroborated by this study. The highest resuspension rate (average of all stations) and the maximum wind speed were recorded during the same period (2–16 June). Linearity assumption in wind–resuspension relation is debatable because of the observed threshold nature of critical shear stress (Miller *et al.* 1977). Nonlinear methods have been used in models (Simons 1986, Lou *et al.* 2000), however de Jonge and van Beusekom (1995) and Kelderman *et al.* (2012) found that resuspension of muddy sediments can be described by a linear function of effective wind speed since surface area of resuspended sediment grows linearly with increasing wind speed. Gabrielson and Lukatelich (1985) found a combination of fetch and duration of wind exceeding a certain value to be the best predictor for sediment resuspension. In this study, duration of wind exceeding calculated shear stress values (Hamilton and Mitchell 1996) for each location did not show better predictive power than maximum wind speed. As Teeter *et al.* (2001) noted, some resuspension models have successfully used wind alone without calculation of wave characteristics directly. Thus, this was the conclusion also in our study with the difference that maximum wind a direction where fetch > 100 m was used. Also the calculation of theoretical critical shear stresses did not improve model

performance. For example, Hamilton and Mitchell (1996) achieved better predictions based on calculated shear stresses as compared with that based on wind speed and wave characteristic. The reason behind differing conclusions can be that Hamilton and Mitchell (1996) modeled suspended solid concentrations in the water column with a measuring interval of 2–3 weeks, and in this study, resuspension was a cumulative sum of sedimented material collected in a period of 2–3 weeks. As James *et al.* (2004) stated, calculated critical shear stress does not include the impacts of aquatic vegetation, which can also explain why it showed low predictive power in this study, where collected data consisted of resuspension measurements conducted mainly in emergent or submerged vegetation stands.

The calculation of exposure indexes together with wind data is a straightforward way to describe potential water movements at a certain point which showed predictive power in the empirical statistical model. Exposure indexes are most applicable for areas with nearly straight and smoothed shorelines. A value based on one single point does not necessarily represent the true *in situ* exposure conditions in fragmented archipelago areas as discussed by Ruuskanen *et al.* (1999). This is most evident at the more sheltered sides of small islands in the outer archipelago (Kiirikki 1996).

Based on regional climate simulations, strengthening of wind extremes is expected to occur in the Baltic Sea region (Nikulin *et al.* 2010). Considering the apparent wind-dependency of resuspension in shallow areas found also in this study, it can be concluded that according to predictive models, the occurrence of sediment resuspension in coastal areas of the Baltic Sea will increase. In addition, possible shortening of the ice-cover period in northern Europe (Meier 2006) could result in a increased sediment resuspension (Niemistö and Horppila 2007).

### **The effect of macrophytes on sediment quality**

The highest organic-matter content was measured at station EM-6, emergent macrophyte stand with the highest macrophyte density and

low fetch. Based on the lake bottom classification by Håkanson and Jansson (1983), this sediment would be classified as an accumulation bottom. The sediment total-phosphorus content varied between 0.2 and 1.5 mg g<sup>-1</sup>, which is generally low as compared with sediments from deeper areas (Carman and Jonsson 1991, Conley *et al.* 1997, Lehtoranta 2003). Sediments with lower organic-matter (0.9%–1.1%) and phosphorus contents (0.2 mg g<sup>-1</sup>) were found on open sandy bottoms common around Hanko Peninsula. Low nutrient concentrations in these less sheltered sediments is explained by organic sediment transport to deeper areas by wave energy (Jönsson *et al.* 2005).

High organic-matter content of surface sediment among emergent vegetation indicates that dense reed stands in sheltered locations can act as a trap for fine material. In this study, the highest phosphorus resuspension was measured in a dense, emergent macrophyte stand due to high phosphorus concentration in the surface sediment. Differences in the organic-matter content and phosphorus concentration in surface sediments found in this study indicate the spatial heterogeneity of sediments in the archipelago areas of the Gulf of Finland (Emelyanov 1988), and therefore also the high spatial differences in resuspension-based phosphorus loading. Contrary to the results reported by Lehtoranta *et al.* (1997) who found a negative correlation between the organic-matter content and phosphorus concentration in the sediment, in this study we found this correlation to be positive. This difference may be caused by the fact that we used surface (0–1 cm) sediments, which are likely to be deposited very recently, whereas Lehtoranta *et al.* (1997) used 0–10 cm profile data.

Organic matter of surface sediments is incorporated into a mobile fluff layer on the sediment surface (Stolzenbach *et al.* 1992, Emeis *et al.* 2002, Ziervogel and Bohling 2003), which can act as a phosphorus reservoir for pelagic primary production (Laima *et al.* 2001). This mobile fluff layer comprises unconsolidated material composed of aggregated biogenic and inorganic particles, which accumulate on the seafloor during calm weather conditions and are easily resuspended (Emeis *et al.* 2002) as well are characterized by low shear stress values (Ziervogel and

Bohling 2003). Resuspension of sediment with high organic-matter content in shallow areas found in this study may have similar effect on primary production as the described fluffy layer, despite probable different origin (decomposing epiphytic algae and macrophytes, detritus).

### Resuspension and nutrient loading in the Gulf of Finland

In this study, resuspension contributed the major part (60%–89%) of the gross sedimentation, which is often the case in shallow areas (Gabrielson and Lukatelich 1985, Wallin and Håkanson 1992, Blomqvist and Larsson 1994). Based on the resuspension and sediment sampling carried out by us, phosphorus resuspension in shallow coastal areas was  $7 \text{ mg m}^{-2} \text{ d}^{-1}$ . Using this estimate, regional projections of resuspension-based internal phosphorus loading can be made. From the shore openness data of Suominen *et al.* (2007), it can be estimated that a total of 30 km<sup>2</sup> of littoral areas similar to the study area are located in the Gulf of Finland. Assuming constant resuspension to be of similar magnitude along the entire coastline, the total annual resuspension in these areas would be 153 000 tonnes dry weight, and the total annual phosphorus resuspension 77 tonnes. As compared with the riverine nutrient input in 2006 (HELCOM 2009), nutrient resuspension in the littoral areas would be as little as 1.5% of the external loading. Although internal phosphorus release is small as compared with the external loading, it originates from a small area (0.1% of total surface area), and therefore could have local importance for nutrient cycling. Extrapolation of the results from a small study area to a larger area — in this case northern coast of the Gulf of Finland — includes several uncertainties, spatial variation of sediment types (Emelyanov 1988) being one of the most obvious uncertainty. Temporal variation of sediment properties is discussed in the study of Christiansen *et al.* (2002), who concluded that sediment nutrient concentration in shallow waters shows no seasonal variation because of frequent resuspension.

The regression model with four explanatory variables derived from the empirical data was

to some extent ( $r^2 = 0.54$ ) able to predict resuspension in the study area. When attempting to test the model fit against field the measurement data not used in the model parameterisation, the Spearman correlation of 0.67 was obtained which indicates that the model can be used for rough quantitative estimation of resuspension in coastal areas similar to the study area. Major sources of error and lowering of the predictive power of the model are stochastic processes that cause resuspension that were not included in the model as parameters, for example sediment resuspension caused by feeding of benthivorous fish (Breukelaar *et al.* 1994). Currents can bring resuspended matter that originated far away. In such situations, a sediment sample taken within close range of the trap does not necessarily represent a correct type of resuspended sediment, which can result in over- or underestimation of resuspension when using the Gasith (1975) method for defining the resuspended proportion of sedimented matter. As indicated in this study, the resuspension rate in coastal areas varies highly spatially and temporally. In the resuspension model, the effect of currents and wind-induced water movement was modeled by using the maximum wind speed from directions where fetch is over 100 m as a proxy to describe the amount of water movement at the measurement site during the measurement period. Better description of water movement causing sediment resuspension could be achieved by *in situ* measurements of water movement and turbulence near the bottom sediment. Including this as a parameter in the model would likely increase its predictive power. In addition to the fetch value for the sampling site, spatial variation of sediment resuspension potential was attempted to be included in the model by using the sediment characteristics (LOI, %) of the sampling site as a model parameter. Errors in sampling and analytical procedures such as displacement of sedimented material from the traps during the sample collection and siphoning may reduce the amount of sedimented matter and thus the calculated resuspension value. The resuspension model is derived from the field data thus all errors related to the sampling lower its predictive power which can partly explain the relatively low  $r^2$  value of the regression. However, accord-

ing to the regression analysis, all the explanatory variables used were statistically significant.

## Conclusions

Sediment resuspension in shallow areas is a continuous process controlled by several variables. In this study, sediment resuspension in sheltered and semi-exposed shallow coastal areas was quantified. Based on the collected data, the most important factor in regulating resuspension in shallow areas was the presence of aquatic macrophytes. Emergent macrophytes seem to dampen water movement more efficiently than submerged macrophytes, which results in lower resuspension. Wind-induced waves and currents create water movement causing sediment to resuspend, and resuspension potential of the sediment depends on sediment properties, e.g. organic fraction of sediment.

This study indicates that the amount of nutrients recycled from the sediment in shallow areas can be a remarkable addition to the nutrient concentrations in the water column and thus need to be integrated into nutrient budget models. Next step in quantifying nutrient loading from coastal areas would be to study sediment resuspension in deeper and more open transitional bottoms of archipelago areas and bays. Mapping of sediment quality and resuspension potential in these areas would shed light on internal nutrient loading of oxygenated bottoms in coastal areas of the Baltic Sea.

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