BOREAL ENVIRONMENT RESEARCH 16 (suppl. A): 42–48
ISSN 1239-6095 (print) ISSN 1797-2469 (online)

Helsinki 31 March 2011

Monitoring the concentration, distribution, origin and size of suspended particles in the water column during harbour dredging in Pakri Bay, the Gulf of Finland

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Received 19 Nov. 2009, accepted 30 Aug. 2010 (Editor in charge of this article: Kai Myrberg)

Sipelgas, L. 2011: Monitoring the concentration, distribution, origin and size of suspended particles in the water column during harbour dredging in Pakri Bay, the Gulf of Finland. *Boreal Env. Res.* 16 (suppl. A): 42–48.

Dredging activities can influence ecological balance in the vicinity of developing ports. In the current study, monitoring of suspended matter load in the water column during dredging operations was performed using WetLabs AC-spectra instrument which allows for direct measurements of absorption and attenuation coefficients. The corresponding spectral scattering coefficients were calculated and used for the description of the concentration and composition of suspended matter. Also, concentrations of suspended matter (SPM) and chlorophyll *a* (Chl *a*) were determined from the water samples. The analysis showed that the particles were mainly of mineral origin in the south-eastern part of the bay near the harbour dredging area and mainly of organic origin in the central and open part of the bay. The current study also showed that the calculation of the Chl-*a* concentration from the absorption coefficient using the empirical regression method can sometimes produce questionable results.

Introduction

One of the main challenges identified by the European Sea Ports Organisation (ESPO) in its environmental code (ESPO 2003) is the sustainable development of sea ports. According to the document, environmental impacts caused by port-related activities should be reduced (Trozzi and Vaccaro 2000). The first step is to properly manage environmental issues, which requires continuous environmental monitoring. Remote and continuous monitoring is a key factor for improving the understanding of marine environmental conditions in the vicinity of harbours — the development of these methods is therefore encouraged.

Each year thousands of tonnes of material are dredged in harbour areas in Estonia. Dredging operations in coastal waters affect water quality by increasing suspended matter concentrations. A release of suspended matter into the water column usually takes place over a very limited area, while a local hydrodynamic regime causes the spreading and dispersion of particulate matter over a much larger sea area (Sipelgas *et al*. 2006). If dredging operations are performed within a sea area with an intensive hydrodynamical regime and close to biologically sensitive areas, monitoring of suspended matter distribution with high temporal and spatial resolution is required. Higher turbidity decreases water transparency and less light penetrates to marine biota, resulting in a lower photosynthetic activity in the euphotic zone. In the Baltic Sea, higher turbidity can be caused by several natural factors of which

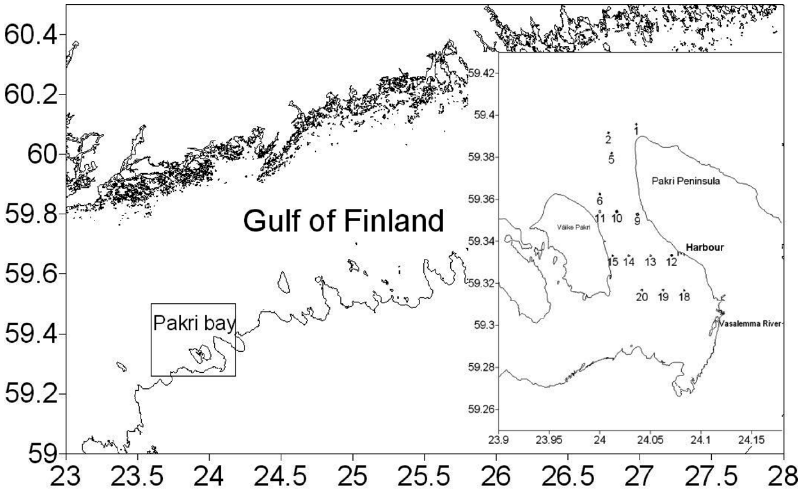

Fig. 1. Study site and sampling stations.

the most frequent are: resuspension of bottom sediments and phytoplankton blooms, especially surface accumulations of cyanobacterial blooms that frequently occur in July and August.

An adequate knowledge of the distribution of suspended matter is essential for assessing the environmental impact of dredging operations and for taking preventive measures against any possible reduction in water quality below acceptable levels. The use of remote sensing and point sampling for monitoring suspended matter concentrations during dredging works have been discussed in our previous study (Sipelgas *et al*. 2006). Recent advancements in ocean optical instrumentation (Wetlabs AC-9 and AC-spectra) allow for direct measurements of the absorption and attenuation coefficients with high spectral and temporal resolutions. Previous studies have shown that inherent optical properties (attenuation, absorption and scattering coefficients) can be used for describing the composition of suspended particles in the water column (Babin *et al*. 2003, Binding *et al*. 2008, Oubelkheir *et al*. 2005, 2007, 2008). High-resolution spectral data about absorption, attenuation and scattering coefficients open new possibilities for monitoring suspended matter load in the water column during dredging.

The goal of the current study was to investigate the possibilities of distinguishing the turbidity caused by dredged sediments from the turbidity caused by “natural” suspended matter using *in situ* measurements of inherent optical properties.

Methods

In July 2008, dredging operations started in the Paldiski South Harbour, Pakri Bay, the Gulf of Finland, the Baltic Sea. During July cyanobacterial blooms were detected on the water surface on several occasions. Field measurements of inherent optical properties and water sampling were performed on 25 July 2008. Low (1–2 m s^{-1}) north-easterly wind was measured at the weather station on the Pakri Peninsula at the time of sampling (Fig. 1). The profiles of attenuation (c) and absorption (a) coefficient were measured by a Wetlabs AC-spectra instrument and the data was processed using the WetView software. The corresponding scattering coefficient (b) for the spectral range from (λ) 402 to 730 nm was calculated from the measurement data as follows:

$$b(\lambda) = c(\lambda) - a(\lambda) \qquad (1)$$

Chl-a concentrations (mg m^{-3}) were determined by filtering the water samples through Whatman GF/C glass microfibre filters (pore size 1.2 μm, diameter 47 mm, Whatman International Ltd., Maidstone, England), extracting the pigments with hot ethanol (90%, 75 °C) and measuring the absorption at the wavelengths of 665 nm and 750 nm. The concentrations were calculated using the Lorenzen (1967) formula.

In order to determine suspended matter concentrations (SPM, mg l^{-1}) in water, the samples were filtered through pre-weighted Millipore

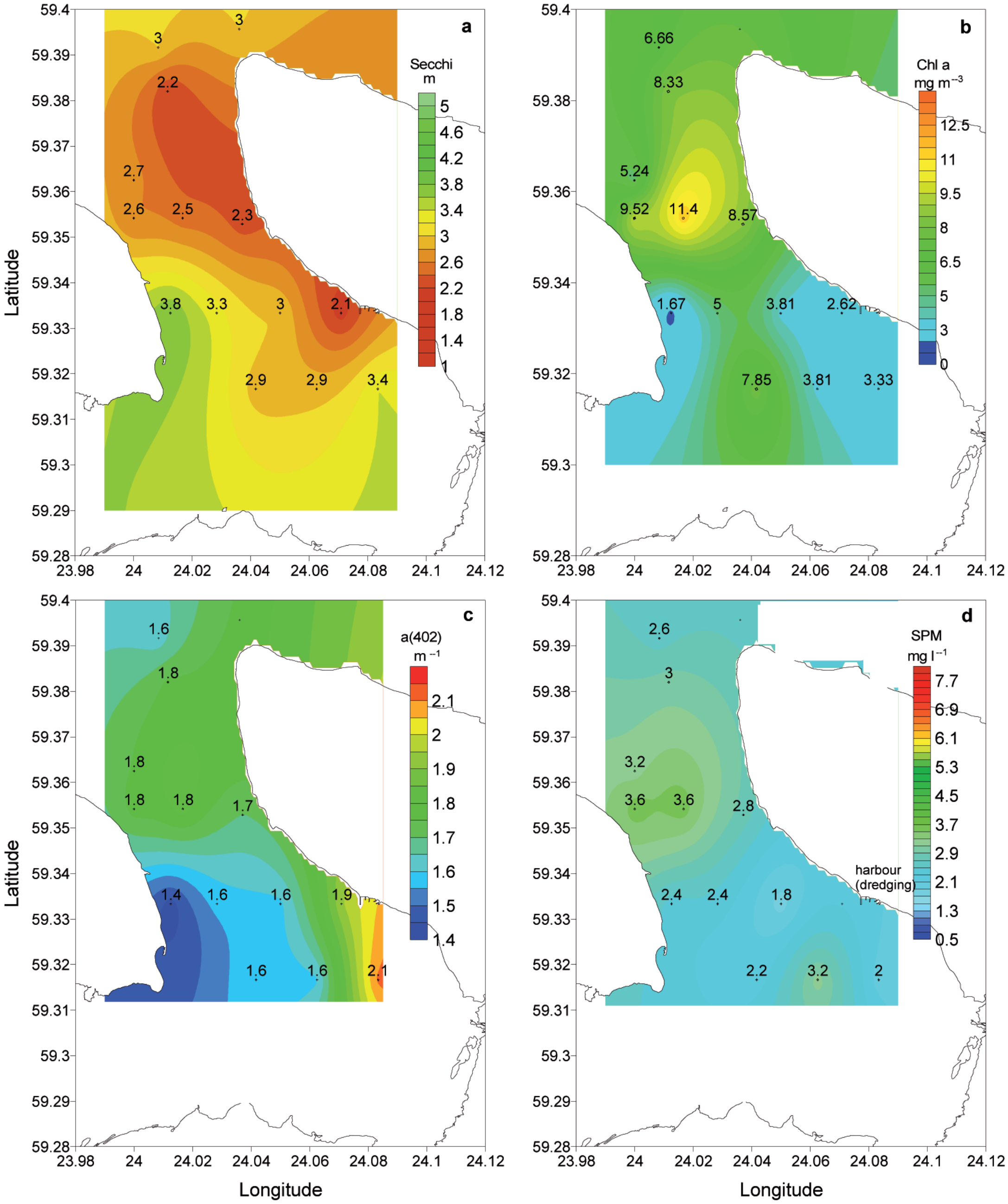

Fig. 2. (**a**) Secchi disk depth (m), (**b**) Chl *a* (mg m^{-3}) concentration in surface water samples, (**c**) absorption at 402 nm (m^{-1}) determined from surface water, and (**d**) SPM concentration (mg l^{-1}) determined from surface water samples.

membrane filters (pore size 0.45 μm, diameter 47 mm, Millipore Corporation, Bedford, MA) and the filters were dried to a constant weight at a fixed temperature (103–105 °C). Filter weight increase is indicative of suspended matter concentration in the water sample.

Results and discussion

Water transparency (Secchi depth) in Pakri Bay on 25 July 2008 varied between 2.1 and 3.8 m (Fig. 2a). The Chl-*a* content varied from 2 to 11 mg m^{-3} (Fig. 2b). Patches of surface accumulations of cyanobacteria were observed in the open part of the bay. The stations with a higher Chl-*a* concentration were the ones where cyanobacterial scum was visible on the surface. Suspended matter concentration determined from the surface water varied from 1.8 to 3.6 mg l^{-1} (Fig. 2d). Higher values of SPM in surface water corresponded to higher/increased values of Chl *a*.

In the open part of the bay, colored dissolved organic matter (CDOM) content corresponded to the Chl-*a* concentration (Fig. 2c). The coeficient of determination (r^2) of the correlation between these two parameters in the open part of the bay (stations 1–11) was 0.57 indicating that the higher values of CDOM resulted from degradation of phytoplankton. At southeastern stations, higher values of CDOM were caused by CDOM discharge from the Vasalemma River. At the dredging site, the SPM and Chl-*a* concentrations were at their background level, meaning that a higher concentration of SPM due to dredging was not detected in the surface water.

On the basis of AC-spectra data we calculated the vertical profiles of the SPM and Chl-*a* concentrations using a common empirical method (Melin *et al.* 2007). Regressions between suspended matter concentration *vs.* scattering coefficient and Chl-*a* concentration *vs.* absorption coefficient were established. The complete AC-spectra data (between 402 and 734 nm) were used to find the best correlation for our regression model (Fig. 3). The results revealed that SPM correlated well with the scattering coefficient at any wavelength between 402 and 734 nm (Fig. 3), while Chl *a* correlated with absorption coefficient at wavelengths over 550 nm (Fig. 3). We chose the wavelength 580 nm for calculating the vertical profiles of SPM concentration and 678 nm for calculating the vertical profiles of Chl *a* concentration. The corresponding regression formulas are the following:

$$\mathrm{SPM} = 1.9194b_{(580)} - 0.1424, \qquad (2)$$

$$\mathrm{Chl}\ a = 29.842a_{(678)} - 4.6343. \qquad (3)$$

The SPM distribution at the depth of 4 m is relatively uniform all over the bay, but at the depth of 9 m close to the dredging works there is a distinct maximum of SPM which exceeds the general background level of SPM (0.5–4 mg l^{-1}) in Pakri Bay (Fig. 4). The Chl-*a* distribution at the depth of 4 m was similar to that in the surface water, having higher values in the central part of the bay (Fig. 4). The Chl-*a* concentrations calculated with Eq. 3 for the depth of 9 m in the central part of the bay, are smaller than 7 mg m^{-3}, which is realistic as the light intensity at the depth of 9 m was less than 1% of that at the surface. However, Chl-*a* maxima calculated with Eq. 3 for the depth of 9 m occur near the harbour which does not seem realistic (Fig. 4). The maxima are probably caused by the absorption of resuspended particles, not by phytoplankton. By analyzing the origin of particles in the next section we try to reveal the origin of highly absorbing particles at the dredging site.

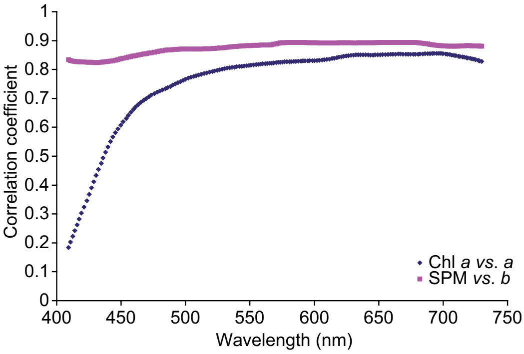

Fig. 3. The correlation coefficient (*r*) between the Chl-*a* concentration and the absorption coefficient (*a*) and between the SPM concentration and the scattering coefficient (*b*).

Scattering coefficient spectra were used to describe the origin of the particles at different depths. As shown in different studies (e.g., Morel 1978, Babin *et al.* 2003), the scattering spectra of phytoplankton have minima around 450 nm and 660 nm. These minima are related to phytoplankton pigment absorption. We found two distinct types of spectra (Fig. 5) from our surface data — one spectrum with two minima and the second spectrum with almost exponential shape. The former corresponds to SPM containing mostly phytoplankton particles and the latter to SPM containing mostly mineral particles according to our laboratory measurements (Fig. 2). We used the power function (Babin *et al.* 2003) to describe the scattering coefficient spectra (Fig. 5).

$$b(\lambda) = A(\lambda)^{-\gamma} \qquad (4)$$

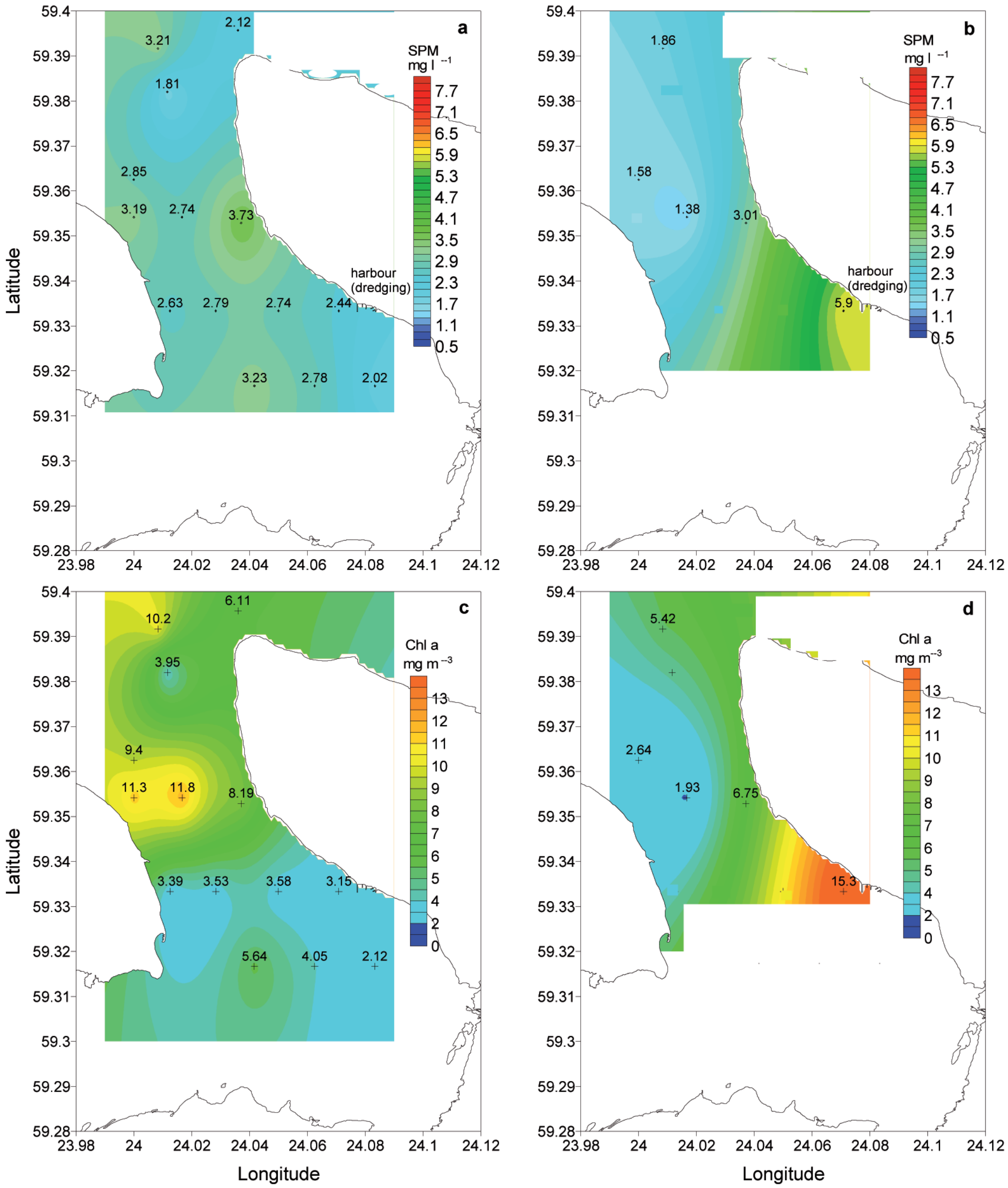

Fig. 4. Distributions of SPM (mg l^{-1}) at the depths of (**a**) 4 m and (**b**) 9 m; as well as distributions of Chl *a* (mg m^{-3}) at the depths of (**c**) 4 m, and (**d**) 9 m.

If $r^2 > 0.8$, we considered that the particles were mostly of mineral origin and if the $r^2 < 0.8$ the particles were considered to be mostly of plankton origin. The threshold value was set based on our laboratory measurements — at the stations where the $r^2 < 0.8$, the Chl-*a* concentration was more than 5 mg m^{-3}, indicating a high amount of phytoplankton particles in water. Mineral particles were in the southern part of the bay, while in the open and central parts there were mostly plankton particles (Fig. 6). So, the spectral analysis revealed that the high absorption that caused the Chl-*a* maximum at the harbour station at the depth of 9 m (Fig. 4d) was related to the high absorption by mineral particles and not by phytoplankton particles. This analysis shows that the empirical method for calculation of the Chl-*a* concentration from the *in situ* absorption coefficient is not always valid.

The analysis of the particle size distribution was performed based on the slope of the scattering spectra which is related to the Junge exponent and can be used to describe the particle size: the greater the slope, the smaller the particles (Fig. 7). In the open part of the bay, plankton particles are larger than the mineral particles. In addition, with depth the particles become larger in size as the slope becomes smaller.

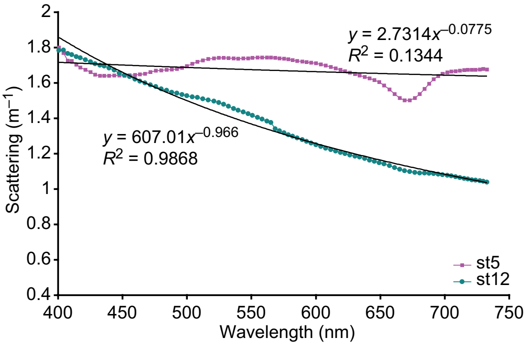

Fig. 5. Surface water scattering coefficient spectra for stations 5 and 12.

At the dredging site in the south-eastern corner of the bay the particles were mostly of mineral origin and with depth the particle size increased slightly. The SPM concentration increased with depth and reached the maximum 15 mg l^{-1} near bottom at the depth of 9 m. An

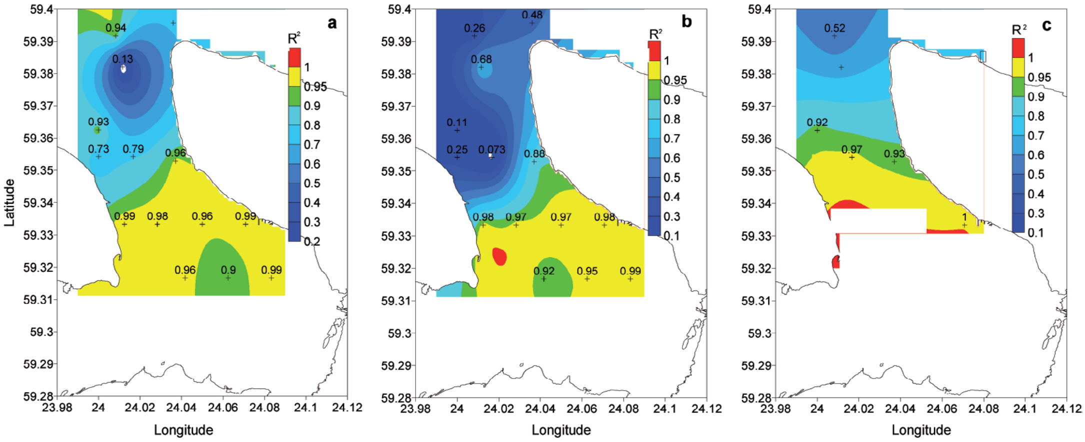

Fig. 6. Coefficients of determination (r^2) of scattering spectra at the depths of 0, 4 and 9 m.

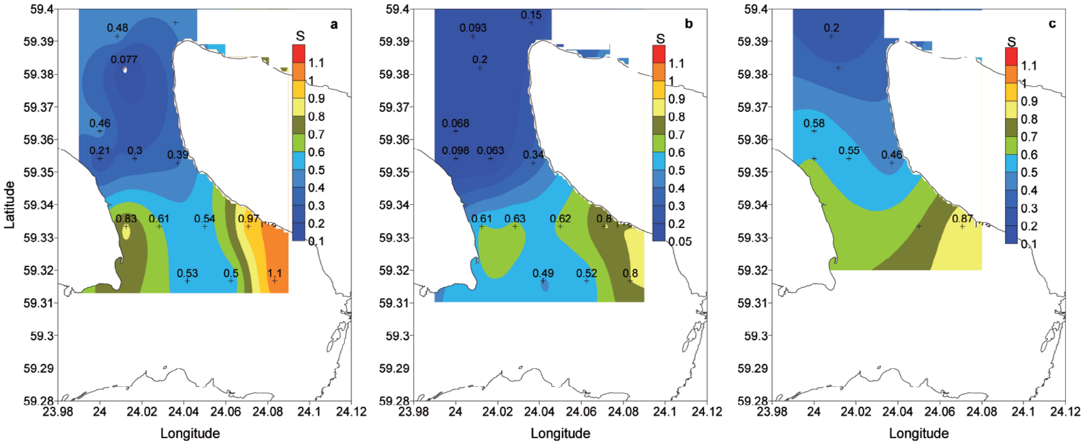

Fig. 7. Slopes of the scattering spectra at the depths of 0, 4 and 9 m.

increased number of small mineral particles near the harbour also resulted in high absorption, around 600–700 nm, causing errors in the calculation of the Chl-*a* concentration at the depth of 9 m from the absorption spectrum.

Conclusions

The measurements of inherent optical properties were used to describe the horizontal and vertical distribution of particles during the harbour dredging in Pakri Bay. Vertical profiles of the Chl-*a* and SPM concentrations were determined from the *in situ* measured absorption and scattering spectra using the empirical correlation method. The obtained vertical profiles of Chl *a* and SPM showed a strong increase in concentrations at the depth of 9 m at the station closest to the harbour dredging site. The scattering coefficient spectra were used to describe the origin and size of particles during the dredging works in the Paldiski South Harbour. The spectra were described with the power function and the corresponding coefficient of determination revealed the origin of the particles. The coefficient of determination over 0.8 indicated that the scattering coefficient spectra had almost exponential shape which corresponds to the mineral particles in water. Mineral particles were in the water column near the harbour and in the southeastern part of the bay. The SPM concentration exceeded the background level of Pakri Bay at the depth of more than 5 meters only at station 12 that was the closest to the dredging works. In the central and open parts of the bay $r^2 < 0.8$, hence the particles in the water column were mostly plankton. The slope of the scattering spectra was used to describe the distribution of particle size. Based on our data, the particles were larger in the open and central parts of the bay and smaller near the harbour. With depth the particles became larger. An increased number of small mineral particles near the harbour also resulted in high absorption, around 600–700 nm, that caused errors in calculation of the Chl-*a* concentration at the depth of 9 m from the absorption spectrum. The analysis of scattering coefficient spectra enabled us to distinguish the turbidity caused by dredged sediments from the turbidity caused by phytoplankton bloom.

Acknowledgments: This work was partially supported by the Estonian Science Foundation (grant 7633). The author would like to express her gratitude to Urmas Raudsepp, Rivo Uiboupin and Miisu for their help in this study.

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