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RESEARCH ARTICLE

Sediment characteristics and wind-induced sediment dynamics in shallow Lake Markermeer, the Netherlands

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Abstract In 2007/08, a study was undertaken on the sediment dynamics in shallow Lake Markermeer (the Netherlands). Firstly, sediment characteristics were determined at 49 sites in the lake. Parameters such as median grain size and loss on ignition showed a spatial as well as water depth related pattern, indicating wind-induced sediment transport. Highly significant correlations were found between all sediment parameters. Lake Markermeer sediment dynamics were investigated in a sediment trap field survey at two permanent stations in the lake. Sediment yields, virtually all coming from sediment resuspension, were significantly correlated with average wind speeds, though periods of extreme winds also played a role. Sediment resuspension rates for Lake Markermeer were high, viz. on average ca. 1,000 g m^{-2} day^{-1}. The highly dynamic nature of Lake Markermeer sediments must be due to the overall shallowness of the lake, together with its large surface area (dynamic ratio = [$\sqrt{}$(area)]/[average depth] = 7.5); wind-induced waves and currents will impact most of the lake's sediment bed. Indeed, near-bed currents can easily reach values >10 cm/s. Measurements of the thickness of the settled "mud" layer, as well as ^{137}Cs dating, showed that long-term deposition only takes place in the deeper SE area of the lake. Finally, lake sediment dynamics were investigated in preliminary laboratory experiments in a small "micro-flume", applying increasing water currents onto five Lake Markermeer sediments. Sediment resuspension started off at 0.5–0.7 cm/s and showed a strongly exponential behaviour with respect to these currents.

Keywords ADCP · Lake · Micro-flume · Resuspension · Sediment characteristics · Sediment traps

Introduction

Sediments are an integral part of water courses and originate in river basins through land and channel erosion processes; sediments are transported from river systems into lakes and oceans as the final sinks. In shallow lakes, sedimentation and resuspension of bottom materials are mainly driven by wind-induced currents and wave actions. Here, sediment characteristics, water depth and fetch (i.e. the length of free water over which winds can blow) are main determinants for sediment distribution patterns (Håkanson and Jansson 1983; Kelderman et al. 1984; Lick et al. 1994; Azza 2006). For a better insight into the above items, knowledge of sediment distribution patterns and dynamics are essential. Necessary tools can be e.g. surveys on sediment characteristics

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(Håkanson and Jansson 1983; Kelderman et al. 1984; Cheng et al. 2004; Azza 2006), field sediment trap studies (Bloesch 1995; Kelderman et al. 1998; Huang and Liu 2009), and lab/field resuspension/sedimentation experiments (Bailey and Hamilton 1997; Schaaff et al. 2006; Kleeberg et al. 2008; Egemose et al. 2009).

Lake Markermeer is a large, shallow lake in the central part of the Netherlands (see Fig. 1a). Over the last decades, measures have been taken to control point and non-point sources of pollution. Despite this, the water quality of the lake is still sub-optimal with frequent eutrophication events (mainly green-algae such as *Scenedesmus* spp.) and, especially, high turbidity and low light transparency (Van Duin 1992; Vijverberg et al. 2010). This must be due to continuous erosion and resuspension of bottom material, driven by the shallowness of the lake and its relatively large open water areas.

The present study aimed at getting better insight into the processes playing a role in sediment resuspension, sedimentation and (re-)distribution in Lake Markermeer. Understanding these processes is of major importance for predicting and assessing the effects of potential mitigation measures to improve water quality in the lake. The research took place over 4 months in 2007/08 and comprised an inventory of major sediment characteristics, a sediment trap field survey at two permanent stations, and additional field and laboratory investigations on the impact of physical factors such as wave height and near-bed currents, on Lake Markermeer sediment resuspension and redistribution behaviour.

Materials and methods

Lake Markermeer was formed in 1976 by the construction of the "Houtribdijk" (dike), separating it from Lake IJsselmeer (see Fig. 1a). The latter was formed in 1932 by the construction of a separation dam between the North Sea/Wadden Sea and the former estuary ("Zuiderzee"). Due to inputs from rain and the IJssel River, a tributary of the River Rhine (see Fig. 1a), the originally marine water has turned into a freshwater system (Cl^- generally <200 mg/L; Waterbase 2010[1]).

Lake Markermeer is a large (680 km^2), shallow lake (average depth 3.6 m). Water depths range from <0.5 m, mainly on the western shores to >5 m, especially in the South-East (see Fig. 1b). About 90% of the lake is between 2 and 5 m deep (Van Duin 1992). Maximum depths up to 30 m can be found in a narrow, dredged navigation channel near Amsterdam (see Fig. 1b). Water exchange takes place especially with Lake IJsselmeer, and the hydraulic residence time in Lake Markermeer amounts to 1–1.5 years (Van Duin 1992; Vijverberg et al. 2010). Water temperatures are between near-zero in winter to >23°C in July/August. Dominant wind directions are West to South-West, especially for the higher wind speeds (KNMI 2010). Suspended solid (SS) concentrations are often >50 mg/L and can reach values as high as 300 mg/L. Secchi depth visibilities are usually between 0.2 and 0.8 m (Van Duin 1992; Waterbase 2010).

The original sediment bed of Lake Markermeer was formed in the Holocene, and consists mainly of clay and loam (Van Duin 1992). This is overlain, especially in the South-East, by a fine silt layer originated from e.g. eroded shore material and from supply via the IJssel River. In the North, close to the Houtribdijk, a shallow, sandy area can be found.

Related with sediment resuspension/redistribution phenomena in Lake Markermeer, the following investigations were carried out over the period November 2007–March 2008:

Sediment characteristics

During five cruises from 21 to 27 November 2007, sediment samples of the upper 2–3 cm were taken at 50 stations[2] in Lake Markermeer (see Fig. 2a). For this, a 1 L stainless steel Ekman grab sampler was used. The exact geographical positions of the stations were tracked with a Garmin GPS meter. At four selected stations (see Fig. 2a), local sediment heterogeneity ("sediment patchiness") was investigated by analyzing separately 3–4 sediment samples taken within ca. 15 × 15 meters. Finally, ca. 60 cm core samples (diameter = 10 cm) were taken with a Beeker sampler (Eijkelkamp, Delft) at stations 14 and 15 (see Fig. 2a), for radioactive dating with ^{137}Cs isotopes,[3] to determine sedimentation history at these two locations (for details, see Vijverberg et al. 2010).

Immediately after Ekman grab sampling, sediment description was made on sediment colour and texture, and the pH was measured with a WTW pH 340i meter. The samples were put in 1L closable polythene bags that were temporarily stored outside in the shade (air temperature 5–10°C) for a maximum of 3 days. The sediment samples were then transported to the UNESCO-IHE laboratory, followed by storage in the dark at 5°C until later analysis, generally within 1 week. Further sediment processing took place after careful homogenization of the samples. Analyses, unless stated

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[1] Data base of water quality data in the Netherlands, from the Ministry of Infrastructure and the Environment.

[2] Of which one sample was lost; however this station, in the North-East, remained part of the data base since it was one of the stations for the sediment resuspension experiments (see Fig. 2a).

[3] Related with the 1986 Chernobyl accident.

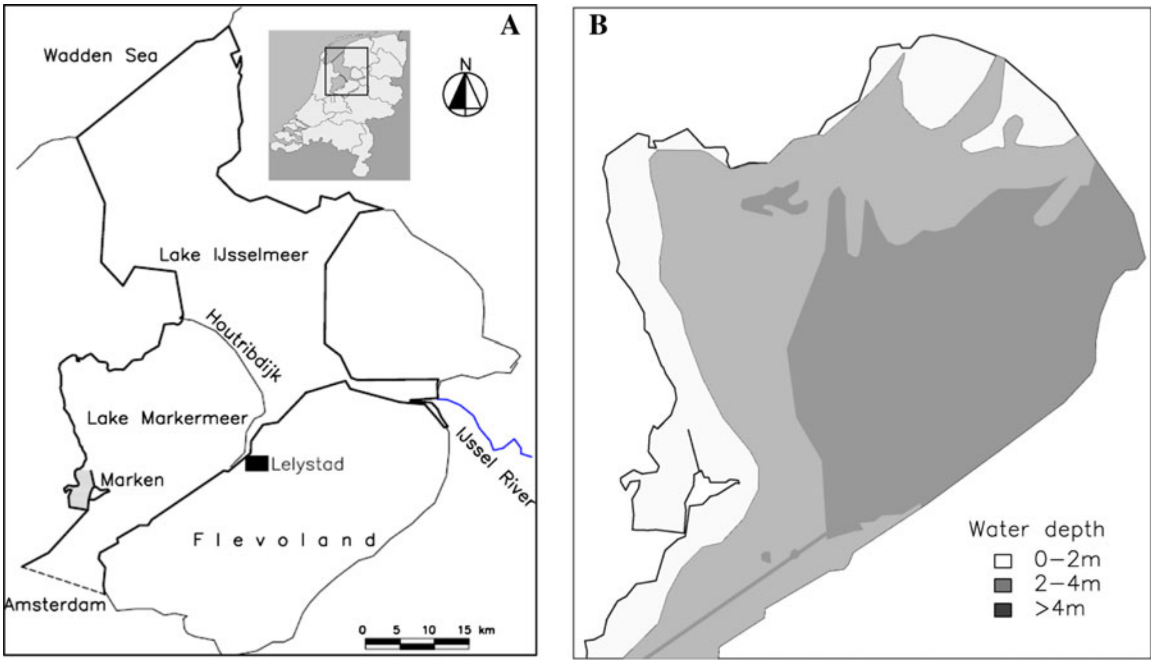


Fig. 1 **a** Lake Markermeer and Lake IJsselmeer (the former "Zuiderzee" estuary) in central Netherlands. The *grey shaded* area west of the Marken penisula ("Gouwzee"; cf. Fig. 1b) is not part of the lake. **b** Water depths distribution in Lake Markermeer (after Vijverberg et al. 2010)

otherwise, followed certified NEN procedures of the Dutch Normalization Institute. NEN procedures are much in line with "Standard Methods" (APHA/AWWA/WEF 2005); for details, see Ang'weya (2008):

- Water content (W.C., %, as the fraction water weight to total wet weight) by drying 50 g sediment at 70°C till constant weight.
- Grain size analysis: after adding demineralised water to 50–100 g sediment samples, these were wet-sieved over Endecotts or Fritsch stainless steel sieves with consecutive mesh sizes: 2.0; 1.0; 0.5; 0.25; 0.125; 0.063 and 0.045 mm + collecting pan. The fraction >2 mm was not included in the eventual grain size calculations (Håkanson and Jansson 1983). The different sediment fractions were then dried at 70°C till constant weight. The fractions were used for estimation of grain sizes, expressed in phi units ($\phi = -^{2}\log(\mathrm{d})$, with d = diameter (mm)). Thus $\mathrm{d} = 1\ \mathrm{mm} = 2^{\circ}$ is equivalent with $\phi = 0$; $\mathrm{d} = 0.125\ \mathrm{mm} = 2^{-2}$ with $\phi = 2.0$, etc. The cumulative weight fractions according to increasing phi-values were plotted on probability paper (Buller and McManus 1979; Håkanson and Jansson 1983). Here, generally linear behaviours were observed, indicating near-normal distribution of the phi-sizes. The following parameters were then calculated:

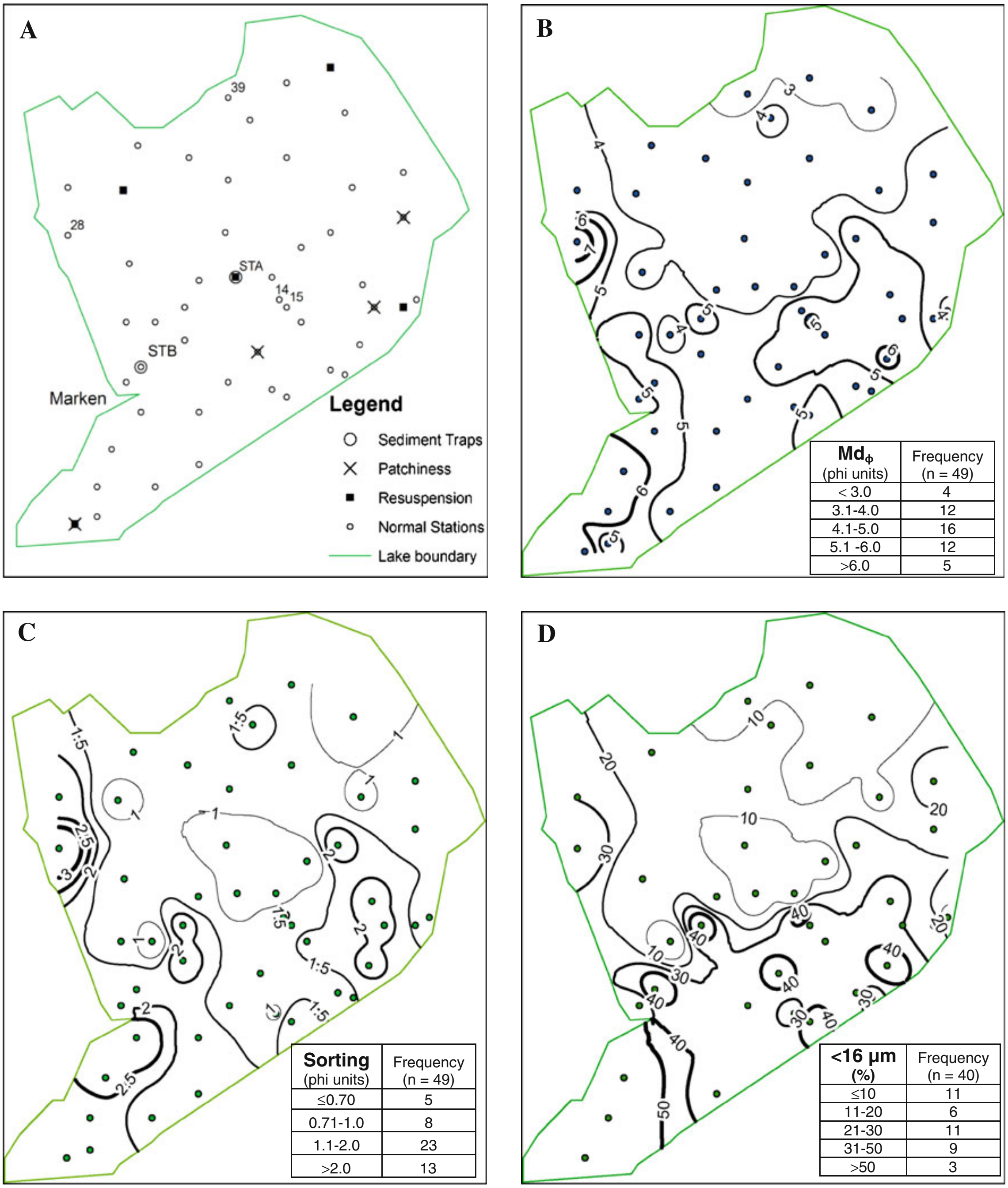
  - Median grain size Md_{ϕ} (50% >; 50% < Md_{ϕ}).
  - Sorting coefficient S (equivalent to "standard deviation"; Håkanson and Jansson (1983)): S = ½ ($\phi_{84} - \phi_{16}$) indicates the phi size for which 84 and 16%, respectively, is smaller than that phi size.

Size fractions <0.045 mm were further analyzed—in an external certified laboratory—with a Malvern laser diffraction apparatus. The data were used to estimate the <16 μm grain size fraction (cf. Day 1973).

About 50 g of dried sediment was carefully crushed with a mortar and underwent the following analyses:

- Loss on ignition (LOI, %) was determined by igniting 5–10 g dried sediment in a muffle furnace at 550 ± 10°C for 2 h and determining weight loss (APHA/AWWA/WEF 2005).
- For the analysis of total phosphorus (t-P, mg/g), 0.5–1 g of the dried sediment was first digested with concentrated salicylic acid + H_2SO_4 + Se (Houba et al. 1995). After this, t-P was analyzed colorimetrically as soluble reactive phosphorus, using a standard ascorbic acid/methylene blue method (APHA/AWWA/WEF 2005) on a Perkin Elmer UV–VIS Lambda 20 spectrophotometer at 880 nm wavelength;
- Total nitrogen (t-N; mg/g), as NH_4^{+}–N, after digestion using the macro-Kjeldahl method, followed by analysis on above instrument at 655 nm wavelength (APHA/AWWA/WEF 2005).

The results for above sediment parameters were plotted on the map of Lake Markermeer using contour diagrams. For this, ArcGIS 9 with linear interpolation ("inverse distance weighted"; power 3) was used.



Md$_\phi$ (phi units)	Frequency (n = 49)
< 3.0	4
3.1-4.0	12
4.1-5.0	16
5.1 -6.0	12
>6.0	5

Sorting (phi units)	Frequency (n = 49)
≤0.70	5
0.71-1.0	8
1.1-2.0	23
>2.0	13

<16 µm (%)	Frequency (n = 40)
≤10	11
11-20	6
21-30	11
31-50	9
>50	3

Fig. 2 **a** Locations of the monitoring stations in the Lake Markermeer research: the 50 stations for sediment characteristics, and of these: two sediment trap stations STA and STB; four stations for sediment heterogeneity ("patchiness"); five stations for preliminary laboratory resuspension experiments. For numbered stations, see text. **b–h** Contour diagrams for the different sediment characteristics in Lake Markermeer; 2B: Median grain size (phi units); **c** Sorting (phi units); **d** grain size <16 µm (%); **e** Water content (%); **f** Loss on Ignition (%); **g** Total-N content (mg/g); **h** Total-P content (mg/g)

Sediment trap field survey

Sediment traps were installed at two permanent lake stations, viz. at STA, in the centre, and at STB, close to the Marken peninsula (see Figs. 1, 2a). Monitoring took place in the autumn/winter season, from end of November 2007 to February 2008; see Table 1 (for details, see De Rozari 2008, 2009). The water depths at STA and STB were 4.2 and 3.2 m, respectively. The opaque, cylindrical Plexiglas sediment traps had an aspect ratio L/D of 11

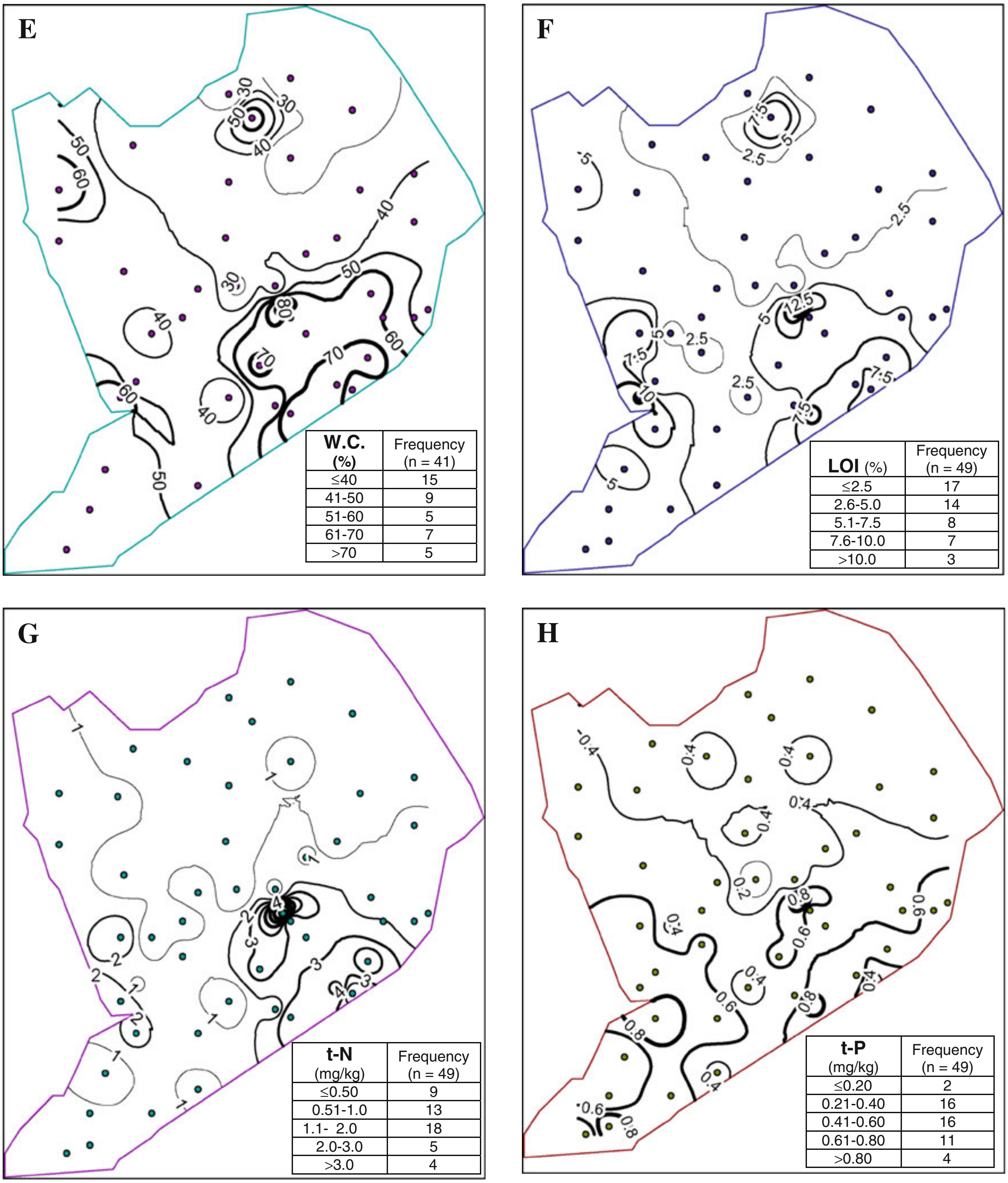


Fig. 2 continued

(L, length: 50 cm; D, internal diameter: 4.5 cm) and thus complied with a minimal requirement of 3 (Bloesch and Burns 1980). Each trap tier consisted of two vertically positioned cylinders as duplicates at 180° at two water depths: (a) opening 0.5 m above the bottom ("bottom traps") and (b) opening at half the water depth at the sites ("half-depth traps"). The traps were clamped onto a long stainless steel rod that had been driven vertically into the sediment and was fixed to the station's platform. The bottom and half-depth traps were always positioned perpendicular to each other to avoid possible interferences between them. The two stations were visited in 2-week intervals (see Table 1); longer intervals may lead to partial degradation of the collected material (Håkanson and Jansson 1983).

The material in the sediment traps was collected and quantitatively transferred to pre-dried (520°C) Al-foil cups, which were transported to the UNESCO-IHE laboratory and stored in the dark at 5°C until analysis, in general within 3 days. The following analyses were carried out:

- Sediment yield (g dry material m^{-2} day^{-1}), after drying at 70°C, as described before;
- LOI (%), t-N and t-P (mg/g), as described before.

Data on average wind speeds and directions during the measuring period were taken from a climate station near Lelystad (see Fig. 1a) owned by the Royal Dutch Meteorological Institute (KNMI 2010).

Physical and other field measurements

Parallel to above field programme, an additional measurement campaign was carried out in November–December 2007. This was focused on water and sediment dynamics near the lake bed. Only the measurements of relevance here will be highlighted (for details, see Vijverberg et al. (2010). Continuous monitoring of water levels and wave heights were carried out at permanent station STA, using a remote sensing water level gauge. Water current velocities over the vertical were also measured at this station with an Acoustic Doppler Current Profiler (ADCP). Vertical and near-bed suspended solids concentrations were monitored both using an Optical Backscatter (OBS) sensor and an Argus Surface meter (ASM). The measuring period for all these parameters (10 min time intervals) was from 4 to 18 December 2007. From 22 to 27 November, we measured the thickness of the "muddy layer", settled on top of the original sea bed (before 1932) at 71 stations across the lake, using dual-frequency echo sounding (operating at 33 and 210 kHz).

Quality control

For sediment characteristics except for sediment grain size, averages were determined of duplicate analyses on the homogenized sediment samples. Of the duplicates, 75–90% was within 15% (Ang'weya 2008). For the sediment trap field survey, duplicates were used for each depth. All glassware in the laboratory analyses had been cleaned thoroughly before use, if necessary with dilute HCl. Chemicals used were all of analytical grade and blanks and standard solutions were prepared for every batch of samples. Milli-Q water was used in all analyses.

Results and discussion

Sediment characteristics

Detailed results at the 49 stations (see Fig. 2b–h) have nearly all been presented in Ang'weya (2008). Sediment always had a light brown top layer, indicating oxidized conditions (Berner 1980), and pH ranged from 6.6 to 8.0. Overall, the different sediment characteristics in Lake Markermeer showed quite consistent patterns. Median grain size (Fig. 2b) ranged from $Md_\phi = 2.5$ ("medium sand") at N.E. station 39–7.2 phi units ("medium silt") at N.W. station 28. Lowest Md_ϕ values (coarsest grain sizes) were found in the shallow N.E. zone near the Houtribdijk, whereas high Md_ϕ values, up to >6.0 phi units were generally present in the deeper (>3–4 m) east zone of the lake. On the other hand, some stations in the shallow 0–2 m western zone had relatively high Md_ϕ values, whereas low-medium phi sizes were also observed at the deeper east areas. Overall, no significant correlation ($p > 0.05$; *t* test; cf. Ott and Longnecker 2001) was found between medium grain size and water depth. This must be due to the overall shallowness of the lake (>70% has water depth <4 m), which makes the whole lake susceptible to current and wave actions, causing frequent sediment resuspension and transport. Other factors such as dominant wind direction and fetch may be equally important for sediment grain size distribution (Håkanson and Jansson 1983; Lick et al. 1994; Azza 2006). To investigate effects of local water depths variations, two stations close together (about 500 m) were compared (see Fig. 2a). One station (14) was located in a small, deep pit (water depth 5.5 m.). The other station (15), with water depth 4.0 m, was just outside this pit. A relatively small difference was observed here, with fine grained sediment ($Md_\phi = 6.0$) at station 14, and intermediate characteristics ($Md_\phi = 4.9$) at station 15. Much clearer differences were observed for the sediment parameters W.C, LOI and t-N (see hereafter).

For Sediment Sorting S (Fig. 2c), only moderately sorted to very poorly sorted sediments were found (S = 0.70–3.40; cf. Håkanson and Jansson 1983). This indicates a heterogeneous sediment composition, consistent with the dynamic nature of Lake Markermeer sediments (Håkanson and Jansson 1983; Azza 2006; Chang et al. 2007). Remarkably, the poorest sediment sorting was observed in the shallow west zone of the lake, with a maximum S = 3.40 phi units found at the earlier mentioned station 28. The best sorted sediments were found in the shallow, sandy N.E. zone.

The grain size fraction <16 μm of the Lake Markermeer sediments (Fig. 2d) is high, viz. 30–40% over most of the lake area and extremes up to 57% in the S.W. zone. Especially, these small-sized sediments are highly susceptible to resuspension. In agreement with the earlier reported Md_ϕ results, minimum <16 μm contents were found in the shallow N.E. zone.

Water Content (W.C.) (Fig. 2e) of the sediments ranged from 22 to 83%, with the highest value in deep pit station 14. It may be expected that for muddy sediment, the "fluffy" extreme top layer will have water contents >90% (Håkanson and Jansson 1983; Azza 2006). Related especially to grain size and sediment packing, coarser sediments will have relatively low water contents, whereas muddy sediments have higher. Indeed, a positive, significant correlation ($p < 0.001$) was found between W.C. and Md_{ϕ} ($R^2 = 0.47$; $n = 41$).

The other sediment characteristics generally showed a similar behaviour as median grain size. Loss on Ignition (Fig. 2f) ranged from <0.5%, mainly in the N.E. part of the lake, to 12.6% at station 14. High LOI contents will especially be found for fine-grained sediments. LOI is roughly equivalent with organic carbon (OC) content, with a ratio LOI: OC of ca. 2 (Håkanson and Jansson 1983).

T-N contents in Lake Markermeer (Fig. 2g) followed the above LOI trend well, with values ranging from around 0.1 mg/g, again in the N.E. stations, to 8.1 mg/g at station 14. T-P contents (Fig. 2h) were between <0.1 and 0.95 mg/g at station 14. In general, the spatial variations for this parameter were less consistent than for LOI and t-N, with higher values especially in the southern part of the lake.

The above trends have been assessed quantitatively using linear correlation analysis (Ott and Longnecker 2001). Results indicate that all sediment parameters are mutually correlated highly significantly ($p < 0.001$; $n = 40–49$), with R^2 between 0.35 and 0.69. Md_{ϕ} correlations had the lowest R^2 values, viz. 0.25–0.36 and showed non-linear behaviour. Assuming an exponential relationship, the R^2 for the LOI–Md_{ϕ} correlation increased from 0.36 to 0.53 (see Fig. 3). An exponential relationship can indeed be expected in view of the negative logarithmic scale for phi sediment grain sizes on the one hand, and an expected inverse linear relationship between sediment grain size/surface area and sediment LOI, N and P contents, on the other (Berner 1980; Håkanson and Jansson 1983). Highest R^2, viz. 0.69 was found for the correlation between LOI and t-N. This indicates that organic material is the strongly dominant source of particulate nitrogen in Lake Markermeer sediments (Berner 1980; Håkanson and Jansson 1983). Correlations for t-P were less significant, with $R^2 = 0.43–0.45$. Here, physico-chemical P bonds, with Ca, Al and Fe, will also play an important role (Berner 1980).

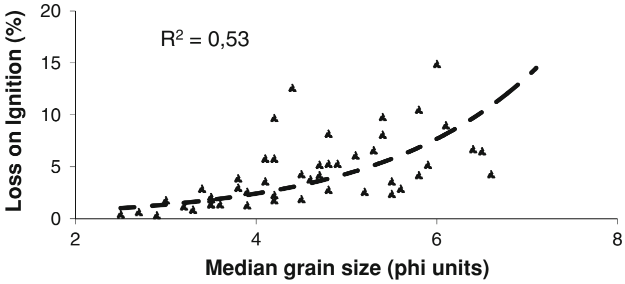


Fig. 3 Correlation between Median grain size and LOI for 49 stations in Lake Markermeer. The *hatched line* indicates the exponential trend line through the data points ($R^2 = 0.53$)

Finally, the "sediment patchiness" at four sites in Lake Markermeer was expressed with the coefficients of variation, CV = (standard deviation/average)*100%, for 3–4 samples taken within ca. 15 × 15 m. CV values ranged from 0.8 to 11% for W.C., 7.0–22% for LOI, 12–45% for t-N and 13–22% for t-P. This indicates moderately homogeneous sediment conditions at the four sites. Kelderman et al. (1984) reported CV values from about 1% for sediment grain size to 20–30% for LOI contents.

Sediment trap field survey

Sediment yields (g m^{-2} day^{-1}) for the sediment traps

Stations STA and STB, together, were assumed to be representative for whole Lake Markermeer. To our experience, setting up of additional, temporary stations would probably have been unsuccessful due to the large chance of obstructions, e.g. by inquisitive tourists and vandalism. Sediment yields (Table 1) show generally small differences between duplicate traps, viz. on average 8.4%. This is in line with expected differences <10% (Bloesch and Burns 1980). However, the upper range of our observations, 25–40% difference (see Table 1) certainly warrants the use of duplicates here. The patterns of sediment yields at the two stations were markedly similar. Yields at station STB were significantly higher than at STA, both for the bottom and half-depth traps (sign test (Ott and Longnecker 2001); $p < 0.001$; $n = 14$). Over the 3-month monitoring period, the average sediment yield in the bottom traps at STA amounted to 1,194 and 2,557 g m^{-2} day^{-1} at STB. This seems unexpected since STB lies rather close to the shore (Marken peninsula; see Fig. 1a). Under the dominant S.W. wind direction, the effective fetch at this station will thus be substantially lower than at STA. This would lead to lower wave heights and thus lower resulting bottom currents at STB (Håkanson and Jansson 1983; Lick et al. 1994; Azza 2006; De Vicente et al. 2010). To our idea, two mechanisms are responsible for the higher yields at STB: (1) its lower water depth (3.2 vs. 4.2 m), and thus higher susceptibility to wind-induced sediment resuspension, and (2) its finer sediment type, with higher Md_{ϕ} and <16 μm content (see Fig. 2b, d).

In Table 1, periods with relatively higher versus lower sediment yields can be seen in conjunction with average wind speeds over the seven monitoring periods. Assuming that the trapped material consists virtually only of resuspended sediment (see below), an exponential relationship may be expected between wind speed W (m/s) and sediment yield Y (g m^{-2} day^{-1}), especially for higher wind

Table 1 Sediment trap yields (g m^{-2} day^{-1}) for bottom and half-depth sediment traps at stations STA and STB, during the seven monitoring periods, end 2007/beginning 2008

Period	Date	Yield at STA (g m^{-2} day^{-1})		Yield at STB (g m^{-2} day^{-1})		Average yield (g m^{-2} day^{-1})		Average wind speed (m/s)	Days with wind ≥8.0 m/s (Bf 5) and ≥10.0 m/s (≈Bf 6)	
		Bottom	Half-depth	Bottom	Half-depth	Bottom	Half-depth		Bf 5	≈Bf 6
I	22/11–4/12 (12 days)	1,400 (0.36%)	940 (16%)	2,690 (0.22%)	1,380 (4.1%)	2,045	1160	5.8	2	1
II	4/12–18/12 (14 days)	1,290 (–)	800 (21%)	3,580 (40%)	1,190 (–)	2,435	995	5.0	2	2
III	18/12–2/1 (15 days)	470 (–)	320 (25%)	840 (13%)	440 (–)	655	380	4.3	2	0
IV	2/1–16/1 (14 days)	1,370 (17%)	1,040 (6.5%)	3,580 (0.61%)	1,680 (5.7%)	2,475	1,360	6.9	3	1
V	16/1–29/1 (13 days)	1,630 (0.92%)	940 (2.6%)	2,740 (3.5%)	1,470 (3.6%)	2,185	1,205	6.9	5	0
VI	29/1–12/2 (14 days)	1,650 (3.8%)	1,035 (3.4%)	3560 (12%)	1490 (–)	2,605	1260	5.4	3	2
VII	12/2–26/2 (14 days)	550 (6.5%)	300 (4.1%)	910 (1.6%)	410 (4.2%)	730	350	4.1	1	0
AVERAGE		1,194	768	2,557	1,151	1,876	959	5.5		

Between brackets are indicated the differences between duplicates; (–) = no duplicate. Also indicated are the averages over STA and STB, as well as average wind speeds over the seven monitoring periods, and days of extreme wind conditions

speeds (Lick et al. 1994; Malmaeus and Håkanson 2003; Cózar et al. 2005): Y α W^x, with x $\approx$ 2. Indeed the sediment yields at stations STA and STB could be expressed in the following (weakly) significant exponential relationships ($R^2 = 0.58$–0.68; $p < 0.05$ for $n = 7$); see Fig. 4:

$$\text{For STA}: Y = 32.4 * W^{2.1} \quad (1)$$

$$\text{For STB}: Y = 14.8 * W^{2.3} \quad (2)$$

The above argumentation will be a simplification, since not only average wind speed, but also wind direction and (often short) periods of extreme winds may be equally or even more important (Håkanson and Jansson 1983; Lick et al. 1994; Schaaff et al. 2006). Average daily wind speeds over the measurement campaign are presented in Fig. 5. In our case, substantially higher sediment trap yields were found in period VI (average wind speed 5.4 m/s) as compared to period V (6.9 m/s). This must be due to a two-times occurrence of wind speeds ≥10 m/s during period VI, and none in period V. A similar pattern was found for periods II/V. No effects of wind *direction* could be observed since 100% of all winds ≥8 m/s had come from a direction between West and South (KNMI, 2010).

Significantly (sign test; $p < 0.001$; $n = 14$) lower sediment yields were obtained for the half-depth traps compared to the bottom traps (see Table 1), viz. for STA on average 36%; for STB 55% lower yields. Similar results were reported by Kelderman (1983), Bloesch (1995), Weyhenmeyer et al. (1995) and De Vicente et al. (2010). This clearly points to a re-settling of resuspended sediment between the two water depths. The larger difference found for STB can partly be ascribed to its higher water depth and thus larger vertical difference between bottom and half-depth traps, and may also be due to different water currents and directions at the two stations (Van Duin 1992; Mukhopadhyay 2008).

Composition of the trapped material

Differences between duplicate traps were relatively small, viz. <10% (De Rozari 2008, 2009). In contrast to sediment yields, no significant differences in material composition were found between the monitoring periods ($p > 0.05$; $n = 7$). The LOI content (as surrogate for organic matter) of the trapped material ranged from 11.1 to 16.8% (average 14.0 ± 0.7; $n = 22$) for STA and 7.1–12.6% (average 9.7 ± 0.6%; $n = 25$) for STB (95% Confidence intervals will be used throughout this paper; cf. Ott and Longnecker 2001). The above differences between STA and STB must be due to differences in LOI composition of the extreme sediment top layer ("fluffy layer"; Vijverberg et al. 2010) at the two sites. In this respect, the higher LOI content found at STB (see Fig. 4f) does not contradict this, since in

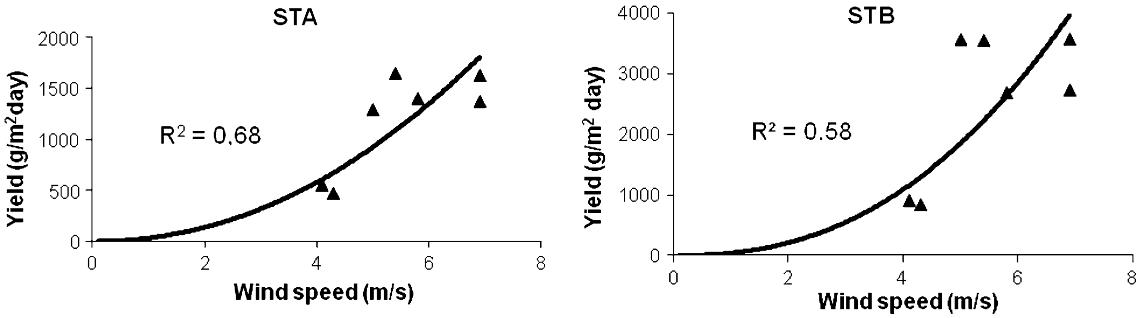


Fig. 4 Regression lines between wind speed and sediment trap yield for stations STA (see Eq. 1) and STB (see Eq. 2), from end of November 2007 to February 2008

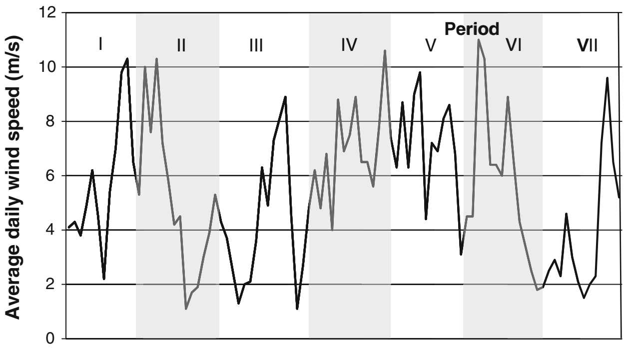


Fig. 5 Average daily wind speeds (m/s) over the seven sediment trap monitoring periods from end of November 2007 to February 2008 (see Table 1)

Fig. 4f, the LOI content of the upper 2–3 cm sediment is reflected, rather than that of the top mm or so. Overall, LOI content of the trapped material (mainly resuspended sediment) is well comparable with the maximum LOI value found for Lake Markermeer sediment, viz. 12.6% at the earlier mentioned “deep pit” station 14 (Fig. 4f). Similarly, t-N was between 4.8 and 9.4 mg/g (average 6.0 ± 0.5; n = 26) for STA and 1.7–6.0 mg/g (average 3.5 ± 0.4 mg/g; n = 26) at STB. For t-P, these values amounted to 0.87–1.3 mg/g (average 1.0 ± 0.04 mg/g; n = 26) and 0.64–1.1 mg/g (average 0.86 ± 0.06 mg/g; n = 26), for STA and STB, respectively (De Rozari 2008, 2009). Similar values had been found at station 14, viz. 8.1 mg/g t-N and 0.95 mg/g t-P).

Extrapolation to whole-year sediment resuspension rates for Lake Markermeer

Due to time and budget limitations, our sediment trap survey could only take place over a period of 3 months, end of November 2007–February 2008. To make a reliable estimation of the annual sediment resuspension rates in Lake Markermeer, two extra steps were made:

1. Converting sediment yields into estimated resuspension rates in the lake;
2. Extrapolating the results of the three winter months to whole-year data.

For item 1, it will be clear that the trapped material will always be a mixture of resuspended sediment and directly settling biotic matter. Their relative proportions can often be derived using differences in LOI, N or P contents between these two sources (Gasith 1976; Kelderman 1983; Bloesch 1995; Weyhenmeyer et al. 1995; Huang and Liu 2009). As mentioned above, the LOI content of the trapped material was always close to that of the extreme sediment top layer (taken as that of station 14). Also, LOI contents in the half-depth traps were not found to be higher than in the bottom traps; this would indeed have been a clear indication for settling biotic material (Kelderman 1983; Bloesch 1995). Major deviations can only be expected for longer (>1–2 weeks) periods of extremely calm weather conditions, with wind speeds <1–2 m/s (see Fig. 5) (cf. Kelderman 1983). Therefore, it may be assumed that virtually all (>95%) of the trapped material will indeed have consisted of resuspended sediment material.

With respect to item 2, large seasonal differences may be expected for sediment yields, especially due to wind speed variations. For the period March–November 2008, average monthly wind speeds were between 3.8 and 6.1 m/s (average 4.4 m/s; KNMI 2010), substantially lower than during the measuring period, end November 2007–February 2008 (4.1–6.9 m/s; average 5.5 m/s; see Table 1). In the above 9-months period, only two occasions of wind speeds $\geq$10 m/s were found, in contrast to six events during the 3 months measuring period. Monthly averaged wind speeds from March to November 2008 were substituted into the earlier presented Eqs. (1) and (2) to arrive at corresponding estimated bottom sediment trap yields over this period March–November: 732 and 666 g m^{-2} day^{-1} for STA and STB, respectively. This leads to the following sediment trap yields (and thus, virtually, sediment resuspension rates) on an annual basis: 850 g m^{-2} day^{-1} for STA and

1,140 g m^{-2} day^{-1} for STB; on average 995 g m^{-2} day^{-1} for Lake Markermeer.

Our observed sediment trap yields are very high and clearly indicate the overall turbulent character of Lake Markermeer sediments. Above estimated sediment resuspension rates may even be a slight underestimation of the "average" behaviour, comparing the 2007/08 wind conditions with those over 1981–2010 (KNMI 2010) (average wind speeds: 4.7 vs. 4.8 m/s; number of days with winds $\geq$10 m/s: 8 vs. 18). For earlier sediment trap studies in Lake Markermeer, Van Duin (1992) reported sediment yields (bottom traps) of 320 g m^{-2} day^{-1} for STA and of 545 g m^{-2} day^{-1} for STB, from April to October/November in 1988 and 1989. These values are comparable with above estimated March- November data (STA: 732; STB: 666 g m^{-2} day^{-1}). Above author presented no details on the exact monitoring periods, nor on the individual 1-week monitoring results. Also, accurate wind data for the climate station "Lelystad" are only available from 1990 onwards (KNMI 2010).

In similar studies, widely different sediment trap yields were found, ranging from <5 to >2,500 g m^{-2} day^{-1} (Kelderman 1983; Kristensen et al. 1992; Weyhenmeyer et al. 1995; Weyhenmeyer and Bloesch 2001; Li et al. 2008; Huang and Liu 2009). Important here is the value of the so-called dynamic ratio (DR), the square root of the lake area A (km^2) divided by the mean water depth D (m) of the lake (Håkanson and Jansson 1983; Håkanson 2006). For DR > ca. 4, virtually 100% of the lake sediment area will be affected by resuspension. Lake Markermeer (A = 680 km^2; D = 3.6 m) has DR = 7.5, falling in the latter category. As a consequence, the lake has continuously high suspended solids contents, viz. on average 45 ± 18 mg SS/L (Waterbase 2010). This is comparable with lakes with equally high DR values such as Lake IJsselmeer, the Netherlands (40 mg SS/L) and Lake Balaton, Hungary (20–30 mg SS/L) (Håkanson 2006), as well as Lake Taihu, China (40 mg SS/L) (Huang and Liu 2009). In contrast, lakes with low DR values will show much lower SS contents, generally <5 mg SS/L (Håkanson 2006).

It should be noted that, rather than "lake surface", the "fetch" i.e. the open water lengths over which winds can blow, is even more important (Håkanson and Jansson 1983; Cózar et al. 2005). Typical fetch values for Lake Markermeer are 10–20 km (cf. Håkanson and Jansson 1983). Following the SS modelling approach of Cózar et al. (2005), based on the general wave theory, the wave length L_w directly determines the water depth region (<$D_{crit.}$) under influence of waves (and thus susceptible to resuspension): $L_w = 2\ D_{crit.}$. As mentioned before, 70% of Lake Markermeer has a water depth <4.0 m. Taking this as $D_{crit.}$, thus $L_w = 8.0$ m, the necessary wind speed to reach this L_w (assuming average fetch = 15 km) will be: $\geq$ca. 5 m/s. For Lake Markermeer, this situation occurs during ca. 55% of the year (KNMI 2010). Alternatively, for the shallow water zone <2.0 m (ca. 15% of the lake area; see Fig. 1b), sediments will be resuspended during >80% of the time (cf. Cózar et al. 2005; KNMI 2010). Above is a simplification since there may be other factors involved such as wind duration ("building up" of waves), and wind fluctuations (e.g. day/night) (Cózar et al. 2005).

For Lake Markermeer, a "semi permanent" situation will exist of high SS contents due to wave-induced resuspension. This will especially hold for the extreme sediment top layer ("fluffy layer"). Vijverberg et al. (2010) investigated the dynamic sediment behaviour under influence of wave-induced near-bed currents, at station STA (see Fig. 2a). In their time series for December 2007 (see Fig. 6), the water turbidity (NTU) at 0.5 m above the sediment bed follows the same pattern as the near-bed current u (m/s) and wave height H_{mo} (m) (cf. Håkanson 2006). Vijverberg et al. (2010) further derived that sediment dynamics in Lake Markermeer can best be described by means of a two-fraction representation, *viz.* for a fluffy top layer, with a settling rate $v_s = 0.025$ mm/s, and an underlying, more coarse sediment fraction with $v_s = 0.8$ mm/s. Application of a SS model based on the "Delft 3-D model" (Mukhopadhyay 2008; Vijverberg et al. 2010) then predicted successfully the dynamic behaviour of sediment resuspension, and especially vertical SS gradients, in Lake Markermeer. The fluffy layer will be in resuspension for wind speeds W > 1–2 m/s, whereas the more coarse sediment fraction will only be resuspended for W > ca. 10 m/s (Bf 6), leading ultimately to SS contents, homogeneously over the vertical, of 150–200 mg/L for stormy conditions (W > ca. 15 m/s). Vertical SS gradients will be present for intermediate wind conditions, with near-bed SS values reaching 2–3 times the average contents (Vijverberg et al. 2010).

After the enclosure of the former "Zuiderzee" in 1932, a muddy layer of settling particulate organic matter (such as phytoplankton) as well as eroded shore and resuspended sediment material gradually covered the original marine sediment bed. In November 2007, the thickness of this "muddy" layer was measured at 71 lake stations, using dual-frequency echo sounding (Vijverberg et al. 2010). Remarkably thin layers (<10 cm, indicating a settling rate of 0.5–1 mm/year) were found over the whole lake area except for the deeper SE stations, where thicknesses up to >20 cm were observed. These stations cover a major part of the >4 m water depth zone (see Fig. 1b). Apparently, the deeper parts of Lake Markermeer serve as "sedimentation basins" of resuspended particulate matter. Vijverberg et al. (2010) also used radioactive ^{137}Cs dating for finding out the "sedimentation history" at the "deep pit" station #14 and just outside this pit (#15) (see Fig. 2a). The vertical profile

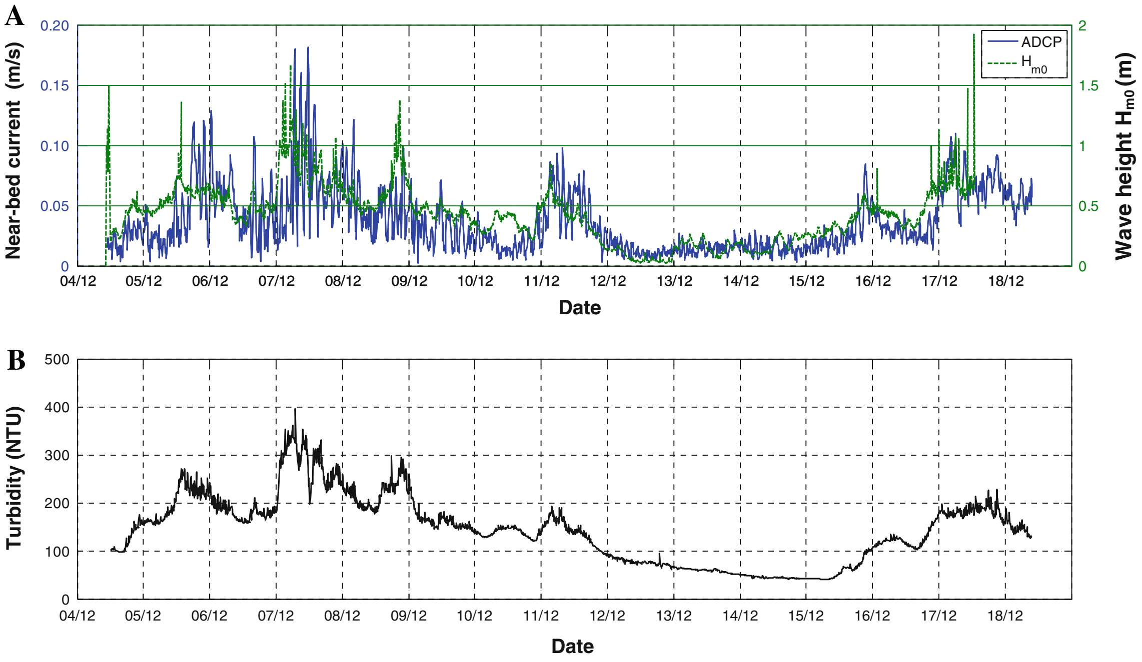


Fig. 6 *Upper* diagram: time series of near-bed currents u (m/s) measured with ADCP together with wave height H_{mo} (m) at station STA. The *lower* diagram shows the time series of the turbidity (NTU) measured about 0.5 m above the sediment bed with an Optical Backscatter (OBS) sensor (after Vijverberg et al. 2010)

at station 14 showed 5–10 times higher ^{137}Cs contents than at site 15, a clear indication of final accumulation of "old", earlier resuspended sediments in the deeper areas of Lake Markermeer. These findings are thus a clear support for the previously discussed sediment trap results.

Sediment resuspension as a function of near-bed currents

The earlier mentioned time series (4–18 December 2007) of near-bed currents u at station STA (see Fig. 6) show an average u = 3.6 cm/s and peak values of 10–15 cm/s (for details, see Vijverberg et al. 2010). A significant correlation ($p < 0.05$) was found between near-bed currents and wind speeds during the measuring campaign. We also carried out some preliminary laboratory experiments in a small rectangular "micro-flume" (Kansiime and Nalubega 1999), in which we investigated resuspension for sediments collected, end of November 2007, at five stations in Lake Markermeer (see Fig. 2a) (De Rozari 2008). The micro-flume (L = 6.0 cm; W = 14.5 cm) was filled with a ca. 3 cm thick sediment layer, over which tap water was led. Starting from zero and slowly increasing the water current u, sediment resuspension started off at 0.5–0.7 cm/s. For higher u values, an exponential increase in suspended solids contents could then be observed for the five sediments, with values of 500–3,500 mg SS/L for u = 1.3 cm/s (De Rozari 2008). Taking averages over the five stations, the following exponential relationship was found between the SS content (mg/L) and u (cm/s):

$$\mathrm{SS} = 27 * e^{3.4u} (R^2 = 0.96) \qquad (3)$$

Taking the measured u values at station STA in December 2007 (see Fig. 6), and correcting for average annual wind speeds (KNMI 2010), we arrived at an annually averaged near-bed current in Lake Markermeer of 1.5 cm/s. Using Eq. 3, this would result into an annual SS content of 4,430 mg SS/L in the micro-flume, and, accordingly, ca. 100 mg/L for Lake Markermeer (average water depth = 3.6 m vs. 8 cm in the micro-flume). This is substantially higher than the earlier mentioned actual 45 mg SS/L found for Lake Markermeer. However, as mentioned before, vertical SS gradients will often occur, with strongly increased near-bed SS values (Vijverberg et al. 2010).

The above preliminary laboratory experiments can only give an indication of the actual Lake Markermeer sediment resuspension behaviour as a function of near-bed currents. Our sampling procedure at the five stations made use of mixed Ekman grab samples and will certainly have disrupted the original sediment stratification, and in particular the integrity of the "fluffy layer". A major improvement would be the use of "undisturbed" sediment cores. In that case, excellent agreements between laboratory and field conditions can be reached, especially if certain precautions are kept in mind with respect to irreversible changes such as compaction (Schaaff et al. 2006; Kleeberg et al. 2008). However, even for these "undisturbed" cores, large differences between laboratory and field results have been reported (Bailey and Hamilton 1997; Malmaeus and Håkanson 2003; Kleeberg et al. 2008; Egemose et al. 2009). In this respect, the preservation of the original "fluffy layer", together with avoiding general sediment compaction will be essential, otherwise laboratory experiments may largely (typically 3–50x) underestimate actual sediment resuspension rates in the field (Bailey and Hamilton 1996; Kleeberg et al. 2008). An equally important factor is the natural "aging" of settled sediment particles under field conditions, where these particles, e.g. through digestion/excretion by benthic organisms, may gradually be covered with a thin biofilm, having a "glueing" effect, thus largely decreasing sediment resuspension rates (Malmaeus and Håkanson 2003; Håkanson 2006; Egemose et al. 2009). On the other hand, for Lake Markermeer with its highly dynamic sediment behaviour, sediment ageing seems to be of less importance. Currently, laboratory resuspension experiments using "undisturbed" Lake Markermeer sediment cores are taking place at the Deltares Institute, Delft.

For the abatement of the high turbidity values in Lake Markermeer, one feasible option would be to reduce the large wind fetches in the lake by creating artificial islands. In that case, wave heights and, consequently, near-bed currents would much be reduced (http://www.delftcluster.nl/website/nl/page831.asp.; website in Dutch; accessed 30 September 2010). Thus, by reducing the average fetch by a factor 2 (from the present ca. 15 km to ca. 8 km), near-bed currents in Lake Markermeer would be reduced by 30–50% (Håkanson and Jansson 1983; Lick et al. 1994); i.e. from the present average 1.5–0.9 cm/s. In view of an expected exponential relationship between SS contents and near-bed currents (cf. Eq. 3), this may potentially lead to a >80% reduction in the SS contents in Lake Markermeer. Other possible measures for SS reduction would be the construction of long, half open dams, or of large deep pits in the lake serving as "final sedimentation basins" for resuspended sediment material. These options are currently being studied, amongst others by using Delft 3-D based-models for sediment dynamics in Lake Markermeer (Mukhopadhyay 2008; Vijverberg et al. 2010; Kelderman et al. 2011).

Conclusions

The following conclusions can be drawn from this study on Lake Markermeer sediment dynamics:

- Sediment characteristics indicate a spatial as well as depth-related pattern, with muddy, organic-rich sediments mainly concentrated in the S.W. and S.E. parts of the lake, and coarse-grained, organic-poor sediments in the N.E. area. Significant correlations were found between virtually all sediment parameters.
- Except for some deep areas, Lake Markermeer sediments are highly susceptible to wind-induced resuspension, due to the shallowness of the lake, its large effective fetches, and the muddy character of most of the sediment. With the help of sediment traps in the field, an annual sediment resuspension rate of ca. 1,000 g m^{-2} day^{-1} could be estimated. This rate is strongly dependent on average wind speeds as well as incidents of extreme winds. Additional field surveys, amongst others using ^{137}Cs, indicated that permanent sedimentation in Lake Markermeer only takes place in the deep S.E. part of the lake.
- Preliminary laboratory experiments on five Lake Markermeer sediments showed a strongly exponential relationship between resuspension rates and near-bed currents. Reducing the effective fetches in the lake—e.g. by creating artificial wetlands- would lead to at least equally large reductions in the SS contents of the lake water.

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