Hydrobiologia **241**: 163–172, 1992.

Wind-induced resuspension in a small shallow lake

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Received 28 June 1991; in revised form 21 November 1991; accepted 14 January 1992

Key words: suspended matter, surficial film, cohesive sediments, erosion, settling sediment traps, bottom shear stress

Abstract

Resuspension of inorganic sediments in a very shallow Swedish lake is studied using settling sediment traps and measurements of suspended matter. Theoretical aspects of resuspension dynamics is discussed emphasizing special shallow lake aspects. Bottom shear stress distribution is computed for different wind conditions.

Introduction

In shallow lakes, a large portion of the wind energy reaches the bottom after energy transformation to waves, currents and turbulent fluctuations and causes erosion of bottom material. Resuspension may take place from the entire lake bottom. The surficial sediment layer is frequently in suspension. When resuspended, the material may have different physical and chemical characteristics than when it was brought into the lake. The process of sediment-water interaction and dispersion of sediments in a lake has significant implications for many environmental problems. Beach erosion and sand transport in coastal waters have been addressed by many researchers, but not much work has considered lakes and especially not cohesive sediments. In a recent paper Mehta *et al.* (1989) gave a state of the art report and described the physical processes of cohesive sediment transport in estuarine waters. Concerning resuspension dynamics of small lakes very little can be found in the literature. Great efforts have been devoted to study the movement of sediment in Lake Balaton, Hungary, e.g. Felföldy *et al.* (1969) and Somlyody (1981), but Lake Balaton although shallow is a large lake. Aalderink *et al.* (1984) studied the resuspension process in a very small lake and compared how well the resuspension rate was estimated with different formulas proposed in the literature. Field studies have been made in North American prairie lakes, e.g. Carper *et al.* (1984), Nolen *et al.* (1985), and in Danish lakes, e.g. Sondergaard (1986). Lick and coworkers, Shen & Lick (1979), Lick (1982, 1986) described the full resuspension dynamics including resuspension, redeposition, circulation and compaction of fresh bottom material.

In the present paper, theoretical aspects of the dynamics of resuspension are given emphasizing the importance of the characteristics of the very loose sediments for the resuspension potential. Special shallow lake conditions are discussed. Observations are reported from the very shallow Lake Tämnaren in Sweden, which is 1–2 m deep. Measured depositions and concentrations are related to bottom shear stress computed from wind data.

Resuspension dynamics

When the bottom shear exerted by waves and currents exceeds the critical shear stress for initiation of motion of the sediments, the bottom is scoured. For cohesive material the critical shear stress depends on the degree of compaction. The very top fresh material has a lower critical value than material further down in the bed. Resuspended material is distributed over the lake by currents. As long as a storm lasts, particles are continuously deposited on shallow areas and brought back into suspension, while in deep areas particles may deposit permanently even during storms. When the wind fails, particles settle all over the lake.

In a small shallow lake the suspended solid concentration is almost evenly distributed in the lake water. The deposition of suspended material is determined by the settling velocity, the water depth and the concentration of suspended matter. The deposition rate is proportional to the concentration and an apparent settling velocity, which is different for different particle sizes and may depend on the concentration. From laboratory experiments and evaluations of field measurements, apparent settling velocities of about 0.05 mm s^{-1} have been reported for flocculated fresh sediment particles, Sheng & Lick (1979), Aalderink *et al.* (1984), Bengtsson *et al.* (1990). Cohesive material flocculates. While Stokes velocity decreases with individual particle size, aggregate settling velocity retains the same order of magnitude since the floc diameter increases with decreasing particle size.

The ratio between the effective or apparent settling velocity and the terminal fall velocity in quiescent water depends on the probability that a particle reaching the bed will stay there. When the time mean value of the bed shear stress tends to zero, the effective settling velocity approaches the terminal fall velocity. When the bed shear stress is higher than the critical shear stress for deposition, there is no net deposition and the effective settling velocity is nil. For sediments which contain material ranging from coarse silt to clay, the critical shear stress for deposition ranges over one order of magnitude as found in laboratory tests by Mehta & Partheniades (1975).

The resuspension potential of estuarine cohesive sediment beds has been discussed by Mehta *et al.* (1982). They distinguished between the settled bed, where the fine sediment is consolidated, the consolidating bed with freshly deposited material, and the stationary suspension bed, which exists only when strong currents or high waves are present and where deposited material immediately is brought into suspension. Erosion from the settled and from the consolidating bed is called resuspension, but Mehta *et al.* call the process of bringing redeposited material back from the suspension bed to the water, while a storm or a strong current still prevails, redispersion.

Assuming that a single apparent settling velocity value can represent all sediments except those very fine particles that hardly ever settle, but are represented by a background concentration, c_b, of suspended matter, and that the erosion rate is representative for the part of the bottom which is eroded, the change of suspended matter in the lake water is determined as

$$h \frac{\delta c}{\delta t} = a_e E - w(c - c_b)\,, \qquad (1)$$

where h = mean water depth, c = concentration of suspended matter, t = time, E = erosion rate, w = apparent settling velocity, which may depend on c, a_e = fraction of bottom area which is eroded.

During a prolonged storm c remains almost constant. By measuring the deposition in traps during the storm and the concentration of suspended matter in the water, cw and c are known and w can be calculated. When c is constant E can be determined if it is known from which parts of the bottom erosion takes place. After the storm has ceased $E = 0$. From the recession of the concentration of suspended matter a settling velocity can be determined.

Equation (1) with $a_e = 1.0$ was used by Aalderink *et al.* (1984) when comparing different resuspension rate formulas, although they introduced the background concentration to account for the concentration of organic material.

Erosion

The rate at which sediments erode depends on the shear stress exerted on the bottom and on the critical shear stress at which erosion is initiated. The character of the bottom material may be such that once the critical stress is exceeded the erosion is very fast, either because armouring particles have been moved away so that the fine material easily can be released, or because the sediment behaves as a Bingham fluid, i.e. when the shear stress is in excess of a particular value the sediment bed will flow as a fluid with an increased viscosity corresponding to its sediment concentration. The bed erodes to a level at which the applied shear stress approaches the critical shear stress. Some days after deposition of bottom material, the resuspension rate can be described by

$$E = C_e (\tau/\tau_c - 1)^n , \qquad (2)$$

where E = resuspension rate, C_e = entrainment coefficient, τ = bottom shear stress, τ_c = critical bottom shear stress for initiation of motion and n = exponent = 1, Mehta *et al.* (1982). The equation has been extensively utilized for estimating fine sediment transport. The value of the erosion coefficient in the erosion rate formula (2) depends on the sediment characteristics. Sheng & Lick (1979) chose a coefficient corresponding to 0.02 kg m^{-2}, h when the critical shear velocity was 0.7 cm s^{-1} and the exerted stress corresponded to a shear velocity less than 1.4 cm s^{-1}. For very fresh deposits, the erosion rate increases more than linear with increased excess shear, and thus the exponent in Eq. (2) exceeds unity.

In a lake the availability of erodible material is usually limited as was pointed out by Lick (1986). The erodible material is brought in suspension within a few hours or less. Thus, once the critical shear stress is exceeded all material that can be stirred up by a particular wind, the resuspension potential, is rapidly resuspended.

Critical shear stress

For non-cohesive material and unidirected flow, the critical shear stress is well determined from the Shield's diagram. Komar & Miller (1974) found that the diagram is approximately valid also for turbulent rough oscillatory flow down to a grain size of 0.1 mm. For particles of 0.1 mm the shear velocity is about 1 cm s^{-1}. From laboratory experiments it has been found that also for newly deposited fine lake sediments the critical shear velocity is about or somewhat lower than 1 cm s^{-1}. For three different Lake Eire sediments Sheng & Lick (1979) and Sheng (1980) measured critical shear velocities in the range 0.7–1 cm s^{-1}. Einstein & Krone (1962) determined the critical shear velocity for unconsolidated (newly deposited) material of different sediment concentration (thus different water content), and found the critical shear velocity to be 1.0 cm s^{-1} for sediment concentration 17 kg m^{-3} (density 1.011 relative to water) and 1.7 cm s^{-1} for concentration 59 kg m^{-3} (density 1.051). Freshly deposited material may have a relative density of up to 1.02, while surface deposits not subjected to erosion may have densities of 1.1–1.2 relative to the density of water.

For very low sediment concentrations, Migniot (1968, 1977) suggested that the critical shear velocity should increase almost linearly with sediment concentration, being about 1 cm s^{-1} when the sediment concentration is 300 kg m^{-3}. These values are low compared with what was reported by Sheng, Lick, Einstein and Krone. The sediment concentration is less than 300 kg m^{-3} at the water–sediment interface in a shallow lake, but increases with depth into the sediments. The change of sediment concentration within the sediments has been investigated in Lake Balaton, Rakoczi (1986). Just after a major storm, the material of the top 15 mm was very loose. A few days after the storm event the top 5 mm was still very loose, but the material below had consolidated to a sediment concentration of almost 300 kg m^{-3}, which was constant down to 35 mm. At 80 mm the sediment concentration was 500 kg m^{-3}. If the relation between critical shear velocity and sediment concentration suggested by Migniot is valid, the loose material of the top 5 mm, which amounts to almost 1 kg m^{-2} and is the surface sediment concentration of the top 5 mm, should be the resuspension potential when the bottom shear stress corresponds to a shear velocity of 1 cm s^{-1}. Shear velocity as used throughout the paper is defined as the square root of the shear stress divided by the density of water, cf. Eq. (3) in the next section.

The Balaton study showed that the very surficial sediments remained very loose. Experiments by Mehta *et al.* (1982) have shown that the critical shear stress at the mud-water interface does not alter after deposition. Below a top loose film the critical shear stress increases with time due to consolidation. There is an increase with depth of the critical shear for initiation of motion. Disregarding the top mm:s the resuspension potential decreases significantly with increasing age of the sediments.

Special shallow lake conditions

In a lake where there are deep areas, which are not affected by wave action, material accumulates on these bottom areas. The combination of resuspension of fine material from shallow bottoms and sedimentation on deep bottoms acts as a sorting process. The particle size of the bottom material on near-shore shallow bottoms is restricted within a narrow range. In a very shallow lake wave action is effective over almost the entire lake bottom. There are not areas where fine material can accumulate permanently. Consequently the particle size of the bottom material is distributed over a wide particle size range.

The wave height and the wave period in a not very large lake are determined by the fetch, the wind speed, and the depth where the waves are generated, but not by the wind duration unless the storm is of very short duration. A widely used procedure for predicting wave parameters is the semi-empirical method developed by Sverdrup & Munk (1947) and Bretschneider (1958), the SMB method. The method is used in this study to determine wave characteristics from meteorological data.

When waves are approaching land they are affected by the bottom. Knowing the bottom contours and the wave characteristics, it is possible to trace a wave as it is progressing towards land. As long as the wave does not break the transported energy per unit time remains constant. Since the waves in Lake Tämnaren are small, Airy wave theory was used to compute the changing wave height and the particle velocity near the bottom.

The shear stress can be determined using the traditional velocity squared relation,

$$\tau/\rho_w = f u^2/2 = u_*^2 , \qquad (3)$$

where τ = shear stress at the bottom, ρ_w = density of water, u = bottom velocity, f = friction factor for oscillatory movement and u_* = friction velocity. The friction factor is related to the particle velocity, the wave period and the bottom roughness. Relations for smooth and rough turbulent conditions are given in the work of Jonsson (1966).

Except for the top mm surficial layer the bottom sediments consolidate with time. In a lake, which is deep over a large part over its area, only a fraction of the bottom is eroded during a storm, and it may be different parts of the bottom which is eroded for different storms. Longer periods pass between erosion occasions at a particular site in a deep lake than in a shallow lake. Therefore, the critical shear stress for initiation of erosion may be lower in a very shallow lake than for the erodible bottoms of a deep lake. For a shallow lake, 1 m, Aalderink *et al.* (1984) found the critical particle velocity above which resuspension occurred to be very low, 1 cm s^{-1}. Bottom velocity is related to shear velocity through a friction factor which in turn is a function of particle diameter and wave characteristics. Using Airy wave theory a bottom velocity of 1 cm s^{-1} can be computed to generate a shear stress corresponding to a shear velocity of about 0.1 cm s^{-1}, which is much lower than what is reported from most laboratory experiments but in the range of the values suggested by Migniot.

In a severe storm a large part of the lake bottom of a shallow lake is eroded. As discussed in relation to Eq. (2) all freshly deposited material which is available for resuspension under the action of a given shear velocity is fast brought in suspension. As was shown in for example the flume experiments of Einstein & Krone (1962), the critical shear stress for deposition of clay is considerably lower than that for initiation of motion. The critical shear stress for deposition is exceeded over almost the entire shallow lake bottom. Therefore, until the storm ceases there is no place where resuspended material can accumulate. As the wave action on the bottom proceeds during a storm of long duration, the bottom is softened and also bottom material not being eroded in the early phase of the storm is brought is suspension. However, not much non-fresh sediment is exposed to wave action, and therefore is not loosened and not eroded. In a very shallow lake redispersion and redeposition is almost in equilibrium during a storm.

The suspended matter in the lake water is determined by the amount of material that is available for resuspension for a particular wind. The resuspension potential for certain wind conditions can be quantified at a point per unit area in g m^{-2} or for a whole lake in kg, which in the latter form can be related to an increase in suspended matter, g m^{-3}. The concentration of suspended matter in the lake water is related to wind conditions through the availability of very loose bottom material for different winds taking into account not only the actual wind situation but also storm situations over the previous weeks or months. During a storm the concentration of suspended matter in the water is almost constant. When all erodible material is resuspended from the bottom areas where erosion takes place, the concentration of suspended matter, c, is

$$c = c_b + a_e \, \mathrm{mp}/h \, , \tag{4}$$

where c_b = initial background concentration, a_e = fraction of bottom which is eroded, mp = mean areal resuspension potential, h = mean depth.

If the resuspension potential for a particular wind is very high, the concentration of suspended matter may be limited by the limited capacity of the turbulent fluctuations to hold particles in suspension during the storm. Such conditions do not exist in the studied Lake Tämnaren.

In shallow lakes, the currents may be quite strong. Still, since the velocity for which erosion is initiated for unidirectional flow exceeds 0.3–0.4 m s^{-1} for all grain sizes, it is only in very extreme situations that currents alone give rise to resuspension. Particle velocities in a wave are usually higher than in bottom currents, and also the friction factor is higher. Erosion may occur even when the maximum particle bottom velocity is less than 0.1 m s^{-1}. The important effect of the currents in the resuspension process is to transport suspended material over the lake. Also, as was found by Bengtsson *et al.* (1990), the combined energy input to the bottom from currents and waves results in increased erosion rate and increased extension of bottom areas over which erosion takes place as compared with the effect of waves alone.

In summary, in a very shallow lake there are no bottom areas where suspended material can accumulate. The entire lake bottom is frequently eroded. The time between erosion occasions at a site is rather short, which means that the time for consolidation is also short. Critical shear stress for initiation of motion is lower than that for erodible bottoms in deep lakes.

Observations in Lake Tämnaren

Different methods can be used to evaluate resuspension in lakes. The softness of the bottom sediments can be examined to determine where there are accumulation bottoms, which of course is of no meaning when resuspension occurs from the entire lake bottom. Sediment traps can be used to collect settling material, e.g. Hargrave & Burns (1979), Rosa (1985). At least in shallow lakes it is not clear what the settling sediment trap deposition represents. During a storm material may be recycled between the bottom and the lake water many times, so that the traps catch much more material than what represents the resuspended material. Instead a measure of the redispersion as defined by Mehta *et al.* (1982) is obtained. It appears that the best way of quantifying resuspension in shallow lakes is to measure the suspended solids concentration in the lake water, e.g. Kenney (1985), Aalderink *et al.* (1984). In the present study suspended matter concentration and settling sediment traps deposition were used to relate resuspension to wind conditions.

Lake Tämnaren is situated near Uppsala. The depth is 1.5 m over almost the whole lake. The lake is 35 km^2 with a fetch of 8 km for southwesterly and northeasterly winds and 4 km for northwesterly and southeasterly winds. The bottom material is not sorted. The grain size distribution is d_{20} 0.0002 mm, d_{50} 0.002 mm, d_{80} 0.02 mm and d_{95} 0.33 mm. The bed is soft down to several meters. Axelsson, as reported by Rakoczi (1986), has taken core samples and has found that the dry bulk density (sediment concentration) of the top surface sediment is 80 kg m^{-3}.

Resuspension studies were carried out in the summer of 1985, and in the late autumns of 1986 and 1987. The concentration of suspended matter was measured by taking water samples, which were analyzed in the laboratory. Settling sediment traps were placed 0.4 m from the bottom along two lines 50, 100, 200 and 300 m from and perpendicular to the eastern shore and at two positions in the middle of the lake. The traps were plastic tubes of 12 cm diameter and 40 cm height. The lake water samples as well as the sediment trap deposits were analyzed for dry mass and organic content. The sediment deposits and the concentrations of suspended matter did not deviate much from one position to another in the lake. The winds were observed at Uppsala 40 km from the lake and, for a few control periods, at the lake. The daily means of the Uppsala wind records and the local data at the lake closely agreed.

In the summer the organic content of the suspended matter in the lake water was rather constant about 5 g m^{-3}, but the percentage of organic content varied, decreasing with increasing concentration of suspended matter. In the autumn the organic matter in suspension was less, below 1 g m^{-3}.

When the wind ceases to low speeds and material in suspension settles, it is possible to estimate a sedimentation time scale. If a certain background concentration, c_b, corresponds to a steady state concentration for the low wind speed, the time dependent solution of Eq. (1) is

$$c = c_0 \, e^{-t/T_s} + c_b \left(1 - e^{-t/T_s}\right), \qquad (5)$$

where c_0 is the initial concentration when the wind declines, and T_s is the sedimentation time scale defined as

$$T_s = h/w, \qquad (6)$$

h being the mean lake water depth defined as lake volume divided by surface area.

At nine occasions when the wind speed decreased rather suddenly from about 5–6 to 1–2 m s^{-1}, the decrease in the concentration of suspended solids was observed and the sedimentation time scale was estimated to be in the range 0.4–0.8 days. Since the mean depth is 1.5 m, the time scale, letting it be representative for all particle fractions, corresponds to an apparent settling velocity of 0.02–0.04 mm s^{-1}. Although it is known that large particles settle out faster than small particles, different settling velocities cannot be determined from Eqs (5) and (6), since the concentration of suspended solids is not separated on different particle fractions.

Bengtsson *et al.* (1990) found that in the autumn of 1986 the concentration of suspended solids in Lake Tämnaren increased considerably when the wind speed exceeded 7–8 m s^{-1}. As long as the wind speed did not exceed this value, the deposition in the settling sediment traps was 20–40 g m^{-2}, d. Having information about for how long the winds prevailed at speeds exceeding 8 m s^{-1}, it is possible to estimate the resuspension rate or rather the redispersion rate at high winds. If the deposition rate at low wind speeds is dep_0, and assuming that the redeposition in the settling tubes continues at the same rate, *r*, throughout the duration of the high wind speed occasions, t_d, then

$$\text{trap deposition} = \text{dep}_0\,(t - t_d) + r\,t_d\,, \qquad (7)$$

where t = length of observation period.

Only during three periods in the autumn of 1986 did the wind speed exceed 8 m s^{-1}. In late September for a period of 0.5 days, for two full days in early October and at three occasions corresponding to a duration of 2.5 days during an extended period of two weeks in November. The traps were emptied only every week, so there were not enough data to relate trap deposition of individual days to wind speed. The redeposition rate for the storm occasions of the three periods was, using Eq. (7), estimated to 1000, 500 and 700 g m^{-2}, d. The measured data and the computed redeposition rates are given in Table 1. Since the lake is very shallow, the redeposition rate equals the continuous resuspension during a storm, i.e. the redispersion rate ($r = E$).

The intention of having sediment traps placed in Lake Tämnaren in 1987 was to obtain a mean value of the concentration of suspended solids for individual days and to obtain a measure of the redispersion rate during storms. When there were no storms the daily deposition was 30–40 g m^{-2}. In the autumn of 1987 the settling sediment traps were emptied daily. The deposition was compared with the concentration of suspended matter in the lake water and related to wind conditions. Since there were situations of high winds during the investigation period, the relation between wind and resuspension can be explained much better from the 1987 data than from the observations of the two previous years.

Table 1. Calm weather deposition and storm redeposition rates in 1986 estimated from settling sediment trap deposition in Lake Tämnaren.

Period	Dep g m^2	Days W > 8 m s^{-1}	Calm dep g m^2, d	Storm dep g m^2, d
19–26 Sept	700	0.5	30	1000
27 Sept–3 Oct	1100	2	30	500
7–20 Nov	2100	2.5	30	700

Trap deposition should be proportional to the concentration of suspended solids times an effective settling velocity integrated over the study period, t,

$$\text{dep} = \int cw\,\mathrm{d}t = \overline{cw}\,t\,. \qquad (8)$$

A trap catches falling particles, even if away from the trap those particles would have moved up and down in the currents. Thus, it is not clear what the trap deposition represents. Still, the daily trap deposition in Lake Tämnaren was plotted versus the daily mean suspended matter concentration, Fig. 1. The trap deposition increases with increasing concentration. When the concentration exceeds 50 g m^{-3}, the ratio between daily trap deposition and concentration is about 30 m d^{-1} (0.30 mm s^{-1}), which thus would be a representative redispersion velocity. This velocity is a measure of the vertical movement of particles, but does not describe how particles settle on the bottom. The high redispersion (settling) velocity at high concentrations, which occur at high wind speeds, is probably a direct effect of intense turbulent fluctuations in waves bringing and keeping sediment in suspension.

Previously the apparent settling velocity representative for bed deposition was estimated to 0.02–0.04 mm s^{-1}. The settling velocity representative for deposition in settling traps during

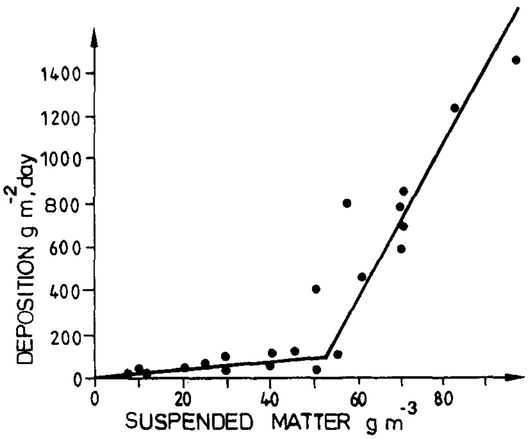

Fig. 1. Daily trap deposition in Lake Tämnaren, Sept–Oct 1987, versus inorganic suspended matter in the lake water.

storms is about 10 times higher. The trap deposition related settling velocity is a measure of the continuous movement of suspended particles and related to the redispersion rate. The 1987 data reveal that when the wind speed exceeds 8 m s^{-1}, the daily sediment trap deposition is 500–1500 g m^{-2}, which is consistent with the estimated redispersion rate from 1986, 500–1000 g m^{-2}.

For Lake Balaton, Somlyody (1981) found a linear relation between steady state concentration of suspended matter and wind speed. When the suspended matter concentration measured in Lake Tämnaren is plotted against wind speed, there is an approximative linear relation if the excess wind speed above a threshold speed of about 6 m s^{-1} is considered. The observed relations between suspended solids in the water and wind speed are given in Fig. 2. Rain storms cause land erosion. Material may be flushed into the lake water by overland flow on the lake banks or by the increased river inflow to the lake. During the entire investigation period of 1987 there were only very minor rain storms, 2 mm or less, except at one occasion, when 9 mm fell. This rainfall might have influenced the suspended solids, cf. Fig. 2.

Wave theory was used to compute the wave height and the bottom shear stress distribution in Lake Tämnaren caused by different winds. As an example, the bottom shear velocity distribution for a southeasterly wind of 10 m s^{-1} is shown in Fig. 3. The bottom shear velocity distribution for eight actual situations were computed. The fraction of bottom which was eroded assuming a critical shear velocity of 0.5 cm s^{-1} is given in Table 2. Measured concentration of suspended matter before and during the storms are given. It is seen from Table 2 that there is an almost linear relation between the observed increase of suspended matter and the fraction of eroded area. Therefore, the resuspension rate is approximately the same from all the part of the bottom which is eroded. The resuspension rate is not dependent on the bottom shear once the critical value is exceeded. Most of the suspended matter emanates from a thin loose surficial sediment layer. The proportionality factor between suspended matter and fraction of erodible area is about 80 g m^{-3} corresponding to a resuspension potential per unit eroded area of 150 g m^{-2}, cf. Eq. (4). The increase of the concentration is plotted versus eroded area in Fig. 4.

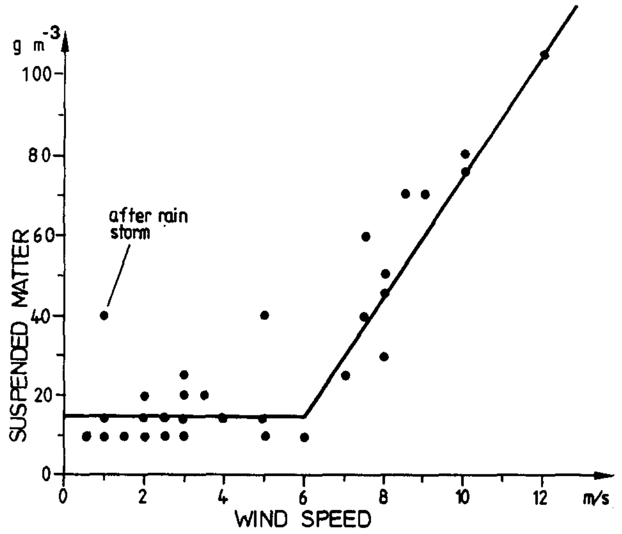

Fig. 2. Concentration of suspended matter in Lake Tämnaren versus mean wind speed over the preceeding 18 h.

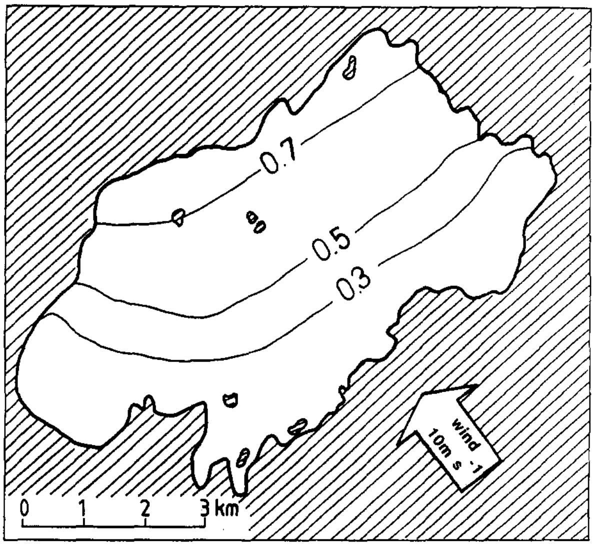

Fig. 3. Computed shear velocity distribution (cm s^{-1}) at the bottom of Lake Tämnaren for wind SW 10 m^{-1}.

Table 2. Observed concentration of suspended matter before (ss_0) and during storm (ss), area fraction from which resuspension occurred, Lake Tämnaren, autumn 1987.

	Wind m s^{-1}	Fraction eroded area	ss–ss_0 g m^{-3}	ss_0 g m^{-3}	ss g m^{-3}
NW	7	0.10	10	15	25
NW	7.5	0.10	20	20	40
NE	7.5	0.50	50	10	60
S	8	0.35	30	10	45
NE	9	0.65	60	10	70
S	10	0.50	60	20	80
SE	10	0.50	55	20	75
SE	12	0.80	90	20	110

Conclusions

In a very shallow lake there is no place where deposited material can accumulate on the bottom. Therefore, the bottom material is not sorted. The bottom is frequently eroded. In Lake Tämnaren the critical shear stress for initiation of loose surface sediment motion corresponds to a shear velocity of 0.5 cm s^{-1}. Most of the resuspended material is from a thin surficial film of newly deposited material. The concentration of inorganic suspended matter in the lake water can be related to the fraction of bottom area from which the thin surficial loose sediment layer is eroded. The apparent settling velocity of particles that reach the bottom is 0.02–0.04 mm s^{-1}. A redispersion velocity representative of deposition in settling tubes is 0.3 mm s^{-1}. It represents the short term recycling of material during storms. The daily deposition is 30–40 g m^{-2}, but during storms the redispersion rate may be 1000 g m^{-2}, d.

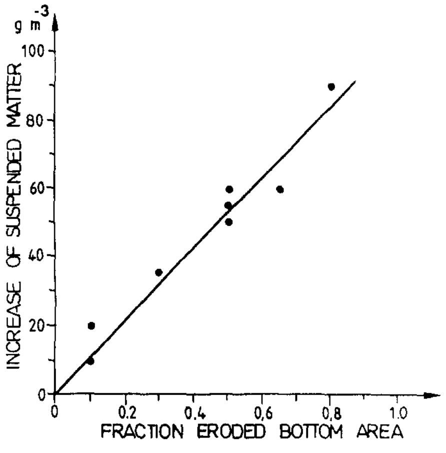

Fig. 4. Concentration of suspended matter versus fraction of eroded bottom area, Lake Tämnaren 1987.

Acknowledgement

Dr Laszlo Rakoczi from Vituki, Budapest, introduced us to the problem of resuspension in shallow lakes and shared his experience from the Lake Balaton study with us.

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Notation

The following symbols are used in this paper:

a_e = fraction of lake bottom which is eroded
C_e = entrainment coefficient
c = concentration of suspended matter or solids
c_0 = concentration before the wind declines
c_b = background concentration during calm weather
dep_0 = trap deposition rate at low wind speed
E = erosion rate
f = friction factor
h = average lake water depth
mp = resuspension potential per unit area
r = redeposition rate during storm
T_s = sedimentation time scale
t = time
t_d = storm duration
u = water particle velocity
u_* = shear velocity
ρ_w = density of water
τ = bottom shear stress
τ_c = critical shear stress for initiation of sediment motion