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J. Bloesch (ed.), Sediment Resuspension.

A review of methods used to measure sediment resuspension

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Abstract

Resuspension of bottom sediments is an important lake-internal process with regard to particle cycling and sedimentation. Current methods to measure sediment resuspension are reviewed, such as optical and acoustical instruments, instantaneous multiple point water samplers, sediment traps, sediment cores and grabs, radiotracers such as Pb^{210}, Cs^{137} and Be^{7}, mass balance calculations, various modelling approaches, statistical methods (correlation analysis), and laboratory experiments.

For the quantification of resuspension, the combined use of sediment traps, sediment cores, near bottom current meters, and turbidity meters to measure suspended and settling particulate matter in the hypolimnion of lakes is recommended; in addition, wind stress, seiches, slumping and sliding, and riverine input may be monitored to elucidate the mechanisms behind the process.

Introduction

Sediment resuspension, which is known to affect nutrient cycling and deposition of sediments, has long been recognized as an important lake-internal process in large lakes, such as Neusiedlersee (Löffler, 1974), Lake Kinneret (Serruya, 1977) and Lake Erie (Charlton & Lean, 1987). In the shallow basins of these lakes, wind driven resuspension is evident by the elevated turbidity that can be measured throughout the water column. These periods of high turbidity may be observed even during summer stratification with less turbulent hypolimnia, and where particulate matter input into the lake via large tributaries is not significant. Recently, resuspension phenomena, though minor when compared to the large resuspension events, were observed in deep and small lake basins, and where the driving wind force was not apparent (Bloesch & Uehlinger, 1986; Bloesch & Sturm, 1986; Lemmin & Imboden, 1987).

Evans (1994) has dealt with the theory of resuspension, the relevant variables such as lake depth and wind stress, and the importance (quantification) of the process to various water systems. The basic processes and driving forces of resuspension and sediment transportation in lakes have been described in detail, e.g., by Hakanson & Jansson (1983), Hilton *et al.* (1986) and Bengtsson *et al.* (1990). Lam & Jaquet (1976) suggested that threshold current velocities of 2–3 cm s^{-1} were sufficient to resuspend clay and silt particles, whereas sand would resuspend with 20 cm s^{-1}, respectively. In these calculations, the drag coefficient is assumed to be dependent on flow conditions, particle size and bottom roughness; *i.e.* strong currents ($\sim$20 cm s^{-1}) create ripple structures changing the acting forces (skin friction) on particles at the sediment surface. The ecological significance of resuspension includes impact on cycling of nutrients and contaminants (Rosa *et al.*, 1983; Allan, 1986; Nishri, 1993; Wisniewski, 1993).

The aim of this paper is to introduce and review the methods available to measure sediment resuspension, and to suggest procedures for future research.

Review of methods and results, and discussion

The concentration of resuspended bottom sediments in the water can be directly and quantitatively measured by optical and acoustical methods. Several types of instruments are available, such as beam transmissometers and nephelometers (Gibbs, 1974; Pierson & Weyhenmeyer, 1994), time-laps or video-cameras (Davies, 1985), infra-red sensors (Erlingsson, 1991), and high-frequency echosounders (Wright *et al.*, 1986; Bedford *et al.*, 1986; Thomas, 1986; Bokuniewicz *et al.*, 1991). These instruments are either mounted on or close above the bottom sediments, or deployed from moving ships or platforms.

The optical instruments, basically, measure the light absorption (attenuation) or scattering in the lake water, and hence the temporal or spatial change in particle concentrations. Layers in the upper hypolimnion usually carry fewer particles than near bottom layers. Hence, the occurrence of turbidity and the decrease of particulate matter concentration with the distance above bottom sediments provide a good measure for the intensity of resuspension. The infra-red sensor developed by Erlingsson (1991) measures the relative elevation of the lake bottom and hence the erosion of sediments from which the amount of resuspended material can be calculated; unfortunately, infra-red light is absorbed very quickly in water, and this method can only be used in the littoral zone or shallow waters of a few meters depth.

The acoustic instruments make resuspended particles visible through echo sounding; by backscattering the signals from the particles they provide the parameters for a water column mass conservation equation, with which resuspension can be quantified (Bedford *et al.*, 1986). A modern approach is to digitalize the signals in data loggers (Pearson & Thomas, 1991).

Unless these instruments are deployed at the sediment surface for an appreciable time period, the optical and acoustic methods measure the instantaneous particle concentration only, thus particular resuspension events may not be observed. When measuring from a moving ship, horizontal differences of resuspended particle concentration can be monitored.

An instantaneous multiple point water sampler, designed to collect undisturbed water samples at multiple heights between 20 cm and 1.8 m above the sediment-water interface has been used in the Laurentian Great Lakes by Rosa *et al.* (1983). Samples are taken using horizontally operated stainless steel, and PVC piston-type bottles, driven by pneumatic cylinders, and operated by an electronic timer, controlling a solenoid valve. The supporting structure with sampler is lowered to the lake bottom, and sufficient time is allowed to elapse before beginning the sampling, as sediments are artificially resuspended by this activity.

Another method of estimating resuspension is the collection of sediments by a vertical series of sediment traps exposed close to the lake bottom (Rosa *et al.*, 1983; Rosa, 1985; Hakanson *et al.*, 1989; Rosa *et al.*, 1991) or by comparing traps exposed just below the thermocline with near bottom traps (Bloesch & Uehlinger, 1986; Charlton & Lean, 1987). By using sequencing interval traps short term resuspension events can be detected (Bloesch & Sturm, 1986). By applying traps, a time interval of some days (usually 1–14 days) is integrated, thus all resuspension events that occurred during trap deployment are measured. As with the instantaneous measurements, the decrease in flux with distance from lake bottom provides quantitative information on sediment resuspension. However, the problem is to find the appropriate reference level, where resuspension is thought to have no effect on suspended particulate matter concentration in the water column above the traps. Chambers & Eadie (1981) have shown that in large lakes a nepheloid layer, similar to that in the oceans (Sheldon *et al.*, 1972; Biscaye & Eittreim, 1974; Brewer *et al.*, 1976), is fed by resuspended material and can develop to a considerable thickness.

The proposal of Gasith (1975) to correct the trap settling flux for resuspension can be used to estimate resuspension, which is the difference between uncorrected and corrected settling flux, *i.e.* gross (secondary matter) sedimentation minus net (primary matter) sedimentation (see eq. (1) given in Fig. 1). This method is referred to as the 'label approach' by Floderus (1989) and has been modified by several authors (Charlton & Lean, 1987; Hakanson *et al.*, 1989; Blomqvist & Larsson, 1992). In addition to the sediment traps, sediment cores taken by gravity corers and the sampling of suspended particulate matter above or in the vicinity of the traps are needed for this calculation. The organic content of resuspended bottom sediments, vertically settling tripton (primary flux) and entrapped sediments (secondary flux) are then used to calculate resuspension (see eqs 2 and 3 in Fig. 1). It can generally be assumed that the organic matter content in resuspended bottom sediments is lower than in fresh material. Instead of organic content of particulate matter (or POC = particulate organic carbon, or PON = particulate organic nitrogen) allochthonous titanium, aluminum, and apatite content may be used as conservative elements to calculate resuspension (Blomqvist & Larsson, 1992). The general assumption is that refractory particulate matter content in bottom sediments is higher than in fresh material. Floderus (1989) pointed out that during periods of rapid primary sedimentation (e.g. during the spring phytoplankton bloom, often correlated with biogenic calcite precipitation), the label approach will overestimate primary flux or underestimate resuspension. This is due to the fact that both materials have the same chemical composition (referred to as rebound particles, *i.e.* those particles that have settled through the water column but have not become incorporated into the sediments; Walsh *et al.*, 1988; Hicks *et al.*, 1994).

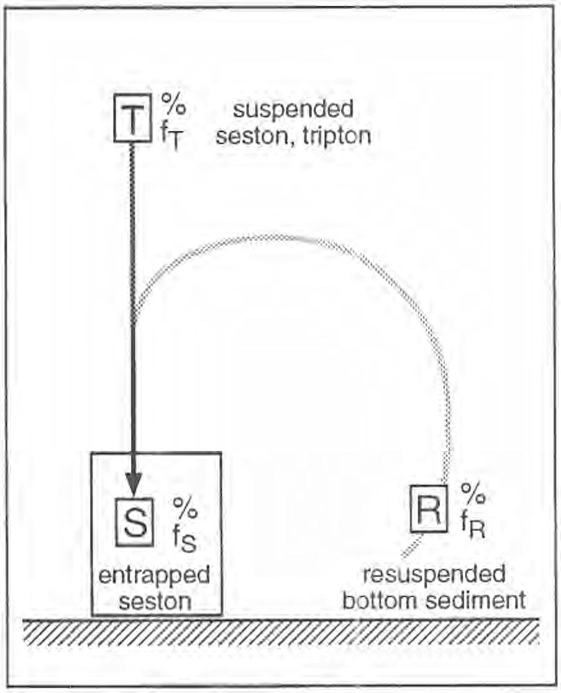

Fig. 1. Schematic view of bottom sediment resuspension measured by sediment traps exposed close to the lake bottom. (Modified from Gasith, 1975). T = suspended tripton [mg dry weight]; f_T = organic fraction of T [%]; R = resuspended bottom sediment [mg dry weight]; f_R = organic fraction of R [%]; S = entrapped settling flux [mg dry weight]; f_S = organic fraction of S [%].

(1) $R = S - T$ (2) $R \cdot f_R = S \cdot f_S - T \cdot f_T$

(3) $R = S \cdot \frac{(f_S - f_T)}{(f_R - f_T)}$

A most interesting methodological approach to quantify resuspension using sediment traps has been proposed by Flower (1991). He compared traps having high aspect ratio (recommended height:diameter > 5; Bloesch & Burns, 1980) with traps having lower aspect ratio. Whereas the former traps measured primary and secondary flux, the latter traps yielded settling flux similar as that found in the bottom deposits (calculated from radiometric data), *i.e.* the 'real' settling flux.

Occasionally, entrapped benthic and littoral organisms (Lastein, 1976) or pollen grains (Davis,

1973) can be found in near bottom traps. Chironomid larvae in traps may indicate resuspension, however, cannot be used to quantify this flux; they may also be supplied from individuals migrating upwards from the sediments for emergence.

Another way to compare trap catches and sediment cores is by using the differences between sediment accumulation rates (Pb^{210} and Cs^{137} dating; natural markers; varve counting) and trap settling flux (Bloesch & Evans, 1982). Resuspension is indicated, when accumulation rates are considerably lower than trap catches. However, geochemical processes, focusing, compaction of sediments, and methodological errors of both the trap method and the dating techniques have to be taken into account. For an updated and comprehensive review of the trap and coring methods, see: Rosa *et al.* (1991) and Blomqvist (1992), respectively.

Long-lived and short-lived radionuclides, e.g. Cs^{137} (half life 30 years) and Be^{7} (half live 50.3 days), may be used for measuring resuspension (Cornett *et al.*, 1994). In general, Cs^{137} is accumulated in the bottom sediments (Santschi *et al.*, 1990) and fresh material has lower activity. Thus, increased Cs^{137}-activity in suspended matter can indicate resuspension, e.g. during fall and winter turnover (Müller *et al.*, 1991). On the other hand, Be^{7} is removed quickly by natural decay in the bottom sediments, whereas its activity is higher in fresh material. Hence, resuspended particles are characterized by low Be^{7} concentration (Cornett *et al.*, 1994).

Studying bottom sediment resuspension by synoptic grab sampling has been proposed by Floderus (1989). On T-bottoms (zones of sediment transportation [Hakanson & Jansson, 1983]), the resuspended fine matter is found deposited as ephemeral mud blankets on top of the winnowed sediment surface between two resuspension events; measuring the thickness of this layer allows quantification of resuspension.

A comparison of trap catches with a mass balance determination of particulate matter (input-outflow) allows for a quantification of resuspension, when measured settling flux of particulates exceeds the calculated retention (Dillon *et al.*, 1990). As Evans (1994) pointed out, this approach assesses the whole lake resuspension process rather than the measurement of single episodic resuspension events.

The most sophisticated way to determine sediment resuspension is to develop models based on theoretical assumptions or a mass balance of suspended solids (Emery, 1978; Mehta *et al.*, 1982; Lick, 1982; Aalderink *et al.*, 1984; Kozerski, 1986; Evans & Hakanson, 1992). The flux of resuspension can be calculated using the concept of wind stress affecting waves and currents, or the flow induced shear stress (Aalderink *et al.*, 1984). In this respect, the characterization of sediments in cohesive and non-cohesive fractions is necessary. Kozerski (1986) developed a simple mathematical model to calculate resuspension, based on the composition differences of tripton, bottom sediments and entrapped sediments as shown by the modified approach of Gasith (1975). Statistical methods (correlation analysis) to compare various catchment data and field observations such as wind, lake morphometry and turbidity may also be used to calculate resuspension (Evans & Hakanson, 1992; Hakanson, 1994).

All these modelling approaches suffer from various fundamental assumptions, which are not fully met in-situ, such as no or uniform horizontal transport, homogeneous resedimentation, uniform wind direction and duration, uniform sediment features, etc. However, these simplified models provide a good measure for estimating relative quantities of resuspended bottom sediments.

A final methodological approach considered in this review is the investigation of resuspension phenomena in laboratory tests under controlled conditions. For example, the shear stress is induced through water oscillation in flumes or chambers (Mehta *et al.*, 1982; Lick, 1982; Tsai & Lick, 1986; Brassard *et al.*, 1994). However, the basic problem is to relate results obtained from lab tests to the extremely variable in-situ conditions. In situ-flumes (Young, 1977) may overcome some of these problems.

Conclusions

Resuspension (and subsequent sediment transportation and resedimentation) is a phenomenon that occurs not only in large, shallow and turbulent water bodies, but also in the hypolimnion of deeper smaller lakes. The impact of bottom resuspension on lake metabolism, such as nutrient release from resuspended particles, is still not yet fully understood. Depending on the methodological approach and technology, resuspension can be directly quantified either by measuring bottom erosion and sediment redeposition, or by measuring the increase or composition in particulate matter suspension above lake bottoms. Indirect calculation of resuspension include modelling with physical parameters such as currents, waves, seiches (Gloor *et al.*, 1994) and subsequent shear stress, or mass balance studies. Experiments in flumes and chambers can elucidate the process of resuspension.

The methods reviewed above used to quantify resuspension suggest that for in-situ studies, a combination of sediment traps, sediment cores, near bottom current meters, and turbidity meters need to be employed to best measure suspended particulate matter in the hypolimnion of lakes. Instrumented platforms combining different measurements at the same location may facilitate to investigate the causes of resuspension (Pearson & Thomas, 1991). In addition, it is recommended to monitor wind stress, seiches, slumping and sliding, and riverine input to elucidate the mechanisms behind the process.

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