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Significance of Sediment Resuspension and Particle Settling

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ABSTRACT Seasonal particle characteristics and sediment-trap-measured resuspension rates are examined for the Laurentian Great Lakes and compared with other large, deep lakes. Results are used to estimate the influence of particle-related processes on the current chemical composition of these lakes. Even in deep systems, such as the Laurentian Great Lakes, particle settling times are relatively short and compounds with a high affinity for particulate matter are efficiently scavenged and removed to the sediments. After reaching the bottom, the settled materials are mixed by the feeding activities of bottom-dwelling organisms into an homogenized pool representing years-to-decades of recent sedimentation. It is apparent from the relatively slow decline of the concentrations of these particle-associated constituents in water and biota that sediments are a leaky sink; small concentrations persist for decades because of processes that can remobilize materials from the bottom.

10.1 Introduction

The annual cycle of particle production and transport plays a major role in the seasonal and long-term behavior of nutrients and contaminants in lakes. Compounds entering the lakes are removed to the sediments at a rate proportional to their affinity for settling particles (Eadie and Robbins, 1987). Particle residence times in the water column are relatively short. Even in deep systems, such as the Laurentian Great Lakes, particle settling times are less than one year (Wahlgren et al., 1980). Constituents such as fallout Sr-90 and chloride have built up over time in the water because they have a low affinity for particulate matter and thus are very inefficiently transferred to sediments. In contrast, particle-associated contaminants—such as plutonium isotopes, Cs-137, and hydrophobic organic compounds—have been efficiently scavenged and removed to the sediments. After reaching the bottom, the settled materials are mixed by the feeding activities of bottom-dwelling organisms into an homogenized pool representing years to decades of recent sedimentation (Robbins, 1982).

Concern with the long removal times of recently controlled trace contaminants and nutrients (e.g., PCB, DDT, and phosphorus) in lakes and an increasing interest in restoration have led to a closer examination of the processes involved in the exchange of these and other materials between the water and the large inventory stored in the lakes' sediments. It is apparent from the relatively slow decline in the concentrations of particle-associated constituents in water and biota that sediments are a leaky sink; small concentrations persist in the water for decades because of processes that can remobilize materials from the bottom.

Four processes responsible for redistributing sediments in small lakes have been identified (Hilton, 1985): slumping, intermittent complete (lake) mixing, peripheral wave action (in the littoral zone), and random (shallow water wave) redistribution. In large lakes, surface wave and littoral zone processes are less important, while intermittent mixing (especially seasonal overturns) and internal waves (Mortimer, 1971; Chambers and Eadie, 1981) are the dominant processes. Current speeds of up to 13 $cm{\cdot}s^{-1}$ have been reported at 1 m above the bottom for the 100-m-deep Lake Michigan station (Figure 10.1) during the summer (Saylor and Miller, 1988) and winter currents of over 25 $cm{\cdot}s^{-1}$ were observed during the unstratified period (Saylor, personal communication). These currents have sufficient energy to remobilize the unconsolidated floc from the sediment-water interface.

In this chapter, we will examine the seasonal particle characteristics and resuspension rates (as measured by sediment traps) at a 100-m-deep station in Lake Michigan and compare them with a more limited data set recently

Figure 10.1 Sediment trap deployment sites in Lakes Superior, Huron, and Michigan. The station in Lake Ontario is from Rosa (1985) and those in Lake Erie are from Charlton and Lean (1987).

collected for stations of similar depth in Lakes Huron and Superior and with other data reported for large, deep lakes. We will then use these results to estimate the influence of particle-related processes on the current chemical composition of these lakes.

Sediment trap and water samples were collected at the stations shown in Figure 10.1. The traps used were 10.2-cm-diameter cylinders with a 5:1 aspect ratio above the top of a funnel. The samples were collected in $CHCl_3$-poisoned 500-ml bottles located below the funnel (see Chambers and Eadie, 1981, and Eadie et al., 1984 for details of collection, preservation, and analysis). Water samples were collected in 5-L Niskin bottles. Total suspended matter (TSM) was measured by filtering 4 L through preweighed glass fiber filters.

The Laurentian Great Lakes are seasonally stratified, carbonate-buffered systems with mean depths ranging from 19 (Erie) to 149 m (Superior) and hydraulic residence times ranging from 3 to 180 years. Contaminants entering the lakes become intimately involved in the seasonal cycle of particle production and transport as illustrated in sediment-trap-measured mass flux isopleths for the 100-m-deep Lake Michigan station (Figure 10.2). During the winter, when the lakes are isothermal or weakly stratified, materials from underlying sediments are nearly uniformly distributed throughout the water column. Stratification begins in the late spring (May–June) and is accompanied by a succession of plankton blooms (from diatoms to greens) that appear to benefit from nutrients resupplied earlier from the bottom by vigorous vertical mixing. With the completion of stratification, the epilimnion is effectively isolated from un-

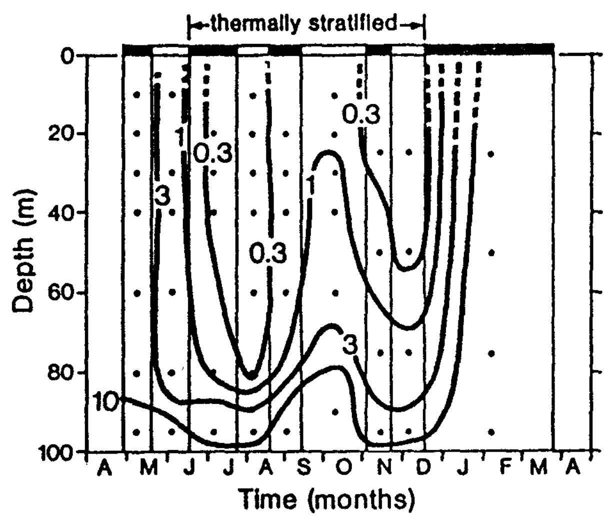

Figure 10.2 Isolines of total mass flux for the 100-m-deep Lake Michigan trap station. The alternating black and white bands at the top and the vertical lines delimit the periods of collection. Solid black circles indicate locations of traps. The first and last deployment captured extensive resuspended sediment. Soon after stratification, the water column clears as particles rapidly settle out. $CaCO_3$ precipiation dominates the increased mass flux during August and September.

derlying waters. Key nutrients are depleted and the water column is cleared as detritus sinks through the epilimnion. Beginning in August, calcium carbonate begins to precipitate in the warm surface waters of three of these lakes (Ontario, Michigan, and Huron), producing a new population of rapidly settling particles (Strong and Eadie, 1978). This process is usually complete by the end of September, although the signal persists in the hypolimnion as these particles settle out. The aftermath of this annual "whiting" event is well-scavenged epilimnetic water possessing the minimum amount of suspended matter. The low concentration and flux of particulate matter in early fall is partially the consequence of the formation of (high-density) calcite in the size range efficiently grazed by zooplankton (Vanderploeg et al., 1987). Zooplankton biomass is high during late summer and these animals ingest a significant fraction (~0.1 d^{-1}) of the TSM. The calcite is indiscriminately ingested along with very slowly settling detritus and repackaged into rapidly settling fecal pellets. In the late fall, when the lake overturns, resuspended sediment materials begin to reappear in near-surface waters.

10.2 Particle Characteristics and Size Distribution

The distribution of particle sizes and their chemical composition mediate processes such as the settling and transport of particle-associated constituents. Particles enter the lake via long-range atmospheric transport, terrestrial runoff from the basin watershed, and in-situ production processes, such as primary productivity and $CaCO_3$ precipitation. In an examination of 26 Canadian lakes of varying eutrophy, Sprules et al. (1983) reported a bimodal particle-size distribution—with peaks at 8–16 μm and approximately 500 μm—which is similar to nearshore and to temperate-to-polar offshore marine environments.

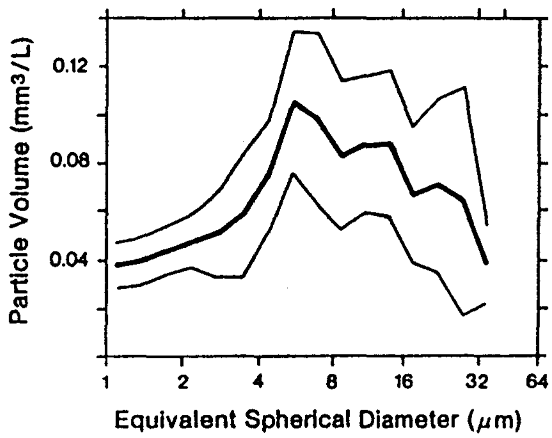

Figure 10.3 Mean (± one standard deviation) particle-size distribution for 35 Lake Michigan surface water samples at the station located approximately 10 km inshore from the sediment trap station. Samples were analyzed by Coulter counter.

A similar size distribution (Figure 10.3) for particles less than 80 μm has been measured for 35 samples collected from a depth of 4 m near the Lake Michigan trap station over the period from 1977–1985 (see Vanderploeg, 1981a, and b for details of the Coulter counting procedure and individual sample spectra). Since seasonal data were very consistent from year to year, they were combined and 10-day blocks were averaged. Throughout the year, particles with a nominal diameter of less than 16 μm constituted the major fraction of the TSM volume. The peak at 8 μm is a result both of calcite abundance during late summer and of non-calcareous seston in this size category throughout the year (Vanderploeg et al., 1987).

The seasonal total of particle volumes (Figure 10.4*a*) has a large pulse in the 4- to 32-μm-size range in July, when the seston was dominated by small, low-specific-gravity (ca. 1.2 $g \cdot cm^3$) diatoms and flagellates (Vanderploeg, 1981a; Scavia and Fahnenstiel, 1987), resulting in the maximum particle volume for the year and relatively low mass. During late August to September, $CaCO_3$ particles (specific gravity = 2.7 $g \cdot cm^3$) increase in the 2- to 16-μm-size categories and constitute a significant fraction of the total TSM mass. In a series of experiments using a mild-acid-addition technique to distinguish between calcite and other seston, Vanderploeg et al. (1987) examined the size spectra of the $CaCO_3$ during this whiting period. The $CaCO_3$-size-distribution

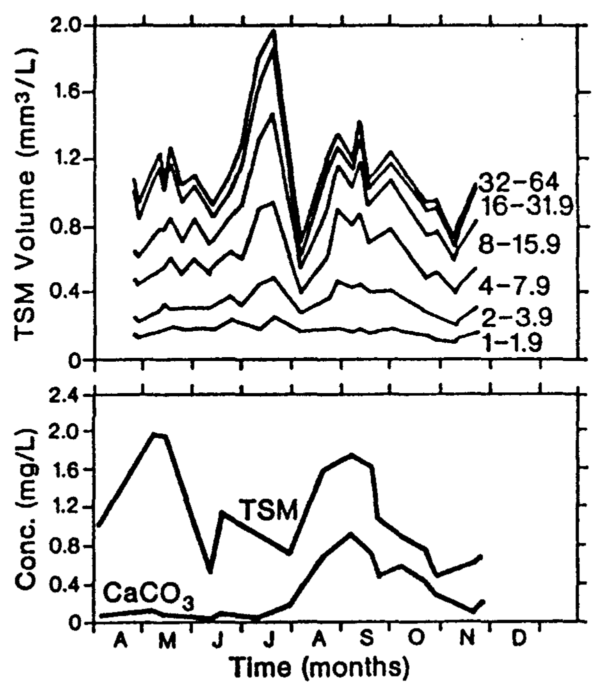

Figure 10.4 (*a*) Seasonal measurements of particle volumes in the identified nominal size ranges at a station approximately 10 km inshore from the Lake Michigan trap station. The curves represent cumulative particle volumes. (*b*) Seasonal concentration of surface-water total suspended matter (TSM) at the same site. The lower curve represents the fraction of the TSM analyzed as $CaCO_3$.

peaked at 7 μm. The concentration of near-surface TSM was systematically measured at the Lake Michigan trap station. TSM mass peaked in the thermally unstratified early spring (see Figure 10.4*b*) during the period of intense resuspension and again during the late summer due to precipitation of $CaCO_3$ (Strong and Eadie, 1978).

10.3 Particle Setting Velocities

There is an important distinction between the particulate matter in the lake collected as the total suspended matter (TSM) associated with a water sample and that collected as settling matter in a sediment trap. The former represents an instantaneous estimate of the population of particles in the water (if the sample is large enough to capture the rare, large particles), while the latter is a time-integrated sample of settling particles that, because of their size and/or density, have sufficiently high settling velocities to be captured.

Although imperfect, because of the different sampling time scales, a mean settling velocity for the ensemble of particles can be estimated by dividing trap-measured mass flux by the average concentration of TSM collected at the trap location at the times of deployment and retrieval. Attempts have been made to improve this estimate by using a depth-weighted mean TSM for the interval above the trap (Bloesch and Sturm, 1986). In the Laurentian Great Lakes, there is little (less than two-fold) difference in TSM concentration throughout the vertical profile until the benthic nepheloid layer (BNL) is reached. In this near-bottom layer, the sources of TSM and trapped material are primarily from local resuspension and horizontal transport (Eadie et al., 1984); a depth-weighted TSM would therefore result in an erroneously high value for settling velocity.

Using TSM values from trap locations, settling velocities have been calculated for the three open-lake stations (Figure 10.5). During the stratifed period, the settling velocities in the upper 35 m of the water column are similar for the three lakes (mean = 0.52 ± 0.16 $m \cdot d^{-1}$), not significantly different from the value of 0.76 $m \cdot d^{-1}$ reported by Rosa (1985) for epliminetic settling of particulate matter in offshore Lake Ontario, nor from the 0.55 $m \cdot d^{-1}$ calculated for two offshore stations (7 and 10) in Lake Erie (Charlton and Lean, 1987). The higher settling velocities (2 to 3 $m \cdot d^{-1}$) in the BNL of our three lakes are again similar to that estimated for Lake Erie (1.6 $m \cdot d^{-1}$). Using the same approach, similar values (epilimnion = 0.66 and BNL = 1.87 $m \cdot d^{-1}$) were reported for the Swiss lake, Lake Zug (Bloesch and Sturm, 1986), and can be estimated (epilimnion = 0.75 and BNL = 4.0 $m.d^{-1}$) for the Greifensee (Lee et al., 1987). These calculated epilimnetic-ensemble particle-settling velocities fall within the range measured with in-situ settling chambers (−0.32 to 1.68 $m.d^{-1}$) during stratified conditions in Lake Erie (Burns and Pashley, 1974). This surprising uniformity may be due to the biological repackaging of the wide spectrum of particulate matter into a less-diverse array of fecal material.

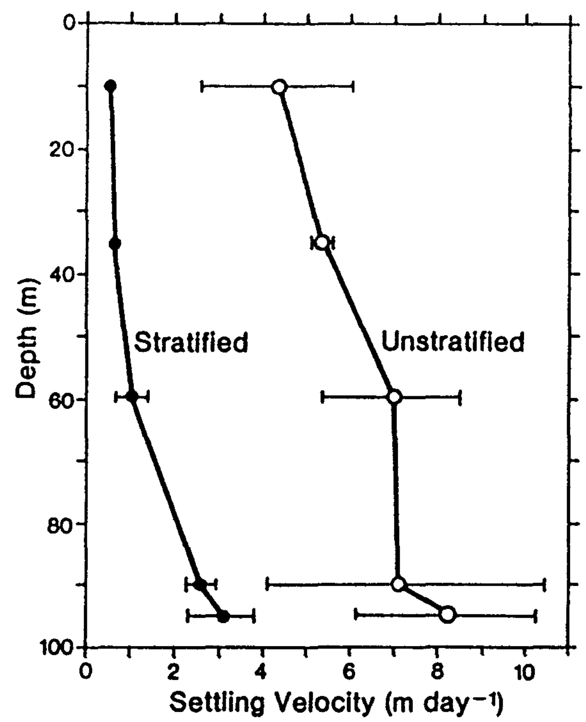

Figure 10.5 Particle-settling velocity averages for the stations in Lakes Michigan, Huron, and Superior (see Figure 10.1). Those calculated for the stratified period are similar to other reported values. The high rates throughout the water column during the unstratified period and for the BNL during the period of stratification indicate extensive recycling of particulate matter.

During the unstratified period, settling velocities in the upper water column are approximately 5 m·day^{-1}, an order of magnitude higher than during stratification. At this rate, the particle residence time in the water column is only 20 days. Within the (ca. 20-m-thick) BNL, the particle residence time is only a few days during the unstratified period and about a week during thermal statification. These rates imply that a large recharging of the particle pool, either via horizontal transport or local sediment resuspension, occurs throughout the year. Contributions from these two sources have not yet been discriminated.

10.4 Particle Fluxes

Seasonal particle fluxes reported for Lakes Michigan (Eadie et al., 1984; Eadie and Robbins, 1987), Ontario (Rosa, 1985), and Erie (Bloesch, 1982 and Charlton and Lean, 1987) exhibit pronounced seasonal differences. During the stratified period, the mass fluxes are low ($<$ 1g.m^2·d^{-1}) near the surface and increase exponentially near the bottom. When thermal stratification breaks down, the mass flux increases dramatically.

An example for offshore Lake Michigan (see Figure 10.2) is used to illustrate the seasonal cycle of particle flux in some detail. Fluxes near the surface show a seasonal pattern that is in general agreement with the TSM measurements (see Figure 10.4*b*). The maximum fluxes correspond to the TSM maxima in April to May, and a second, smaller peak is clearly shown in the period of $CaCO_3$ precipitation in August to October. The July period that showed an increase in particle volume but not mass (Figure 10.4) occurs at a time of low mass flux. Small flagellated algae were found to dominate the particle pool at this time (Scavia and Fahnenstiel, 1987). These algae have very slow settling velocities. The collection covering November 1 through December 15 had the minimum flux and TSM; the deepening of the thermocline may dilute the biogenic particles in the surface mixed layer, and the $CaCO_3$ has disappeared via settling. Large fluxes are evident in the last collection, covering the (generally unstratified and ice-free) winter months.

The same general pattern of mass flux has now been measured in Lakes Huron and Superior (Figure 10.6). In this representation, three years of Lake Michigan data have been averaged for ease of comparison. The flux profiles for the Huron station are similar to the Michigan station data, although somewhat smaller in magnitude. Mass fluxes in the BNL are approximately twice as high in Michigan, both in summer and winter. The Lake Huron station is in the area of highest recent sediment accumulation (Robbins, 1980) and is expected to represent a region of high flux for deep water. Recent sediment accumulation at the Michigan site is lower (Robbins and Edgington, 1975) and the station is deeper. Station depth, distance from shore, and slope all play a role in mediating local mass fluxes. Near the surface, the summer flux profiles for all three stations are similar. However the summer BNL flux and the entire winter mass flux profile at the Lake Superior station are much smaller than at either of the other locations. It would appear that there is significantly less material in the Lake Superior BNL, an indication that resuspension and sed-

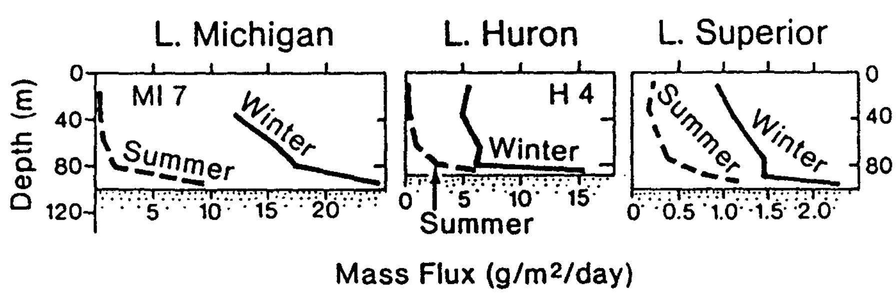

Figure 10.6 Sediment-trap-measured mass flux profiles for the stratified and unstratified periods for the stations shown in Figure 10.1. Note that the mass flux scale for Lake Superior is smaller than for Michigan and Huron. Results extend earlier conslusions for Lake Michigan of a decoupling of surface waters from the influence of sediment resuspension during the period of thermal stratification and the occurrence of a large amount of sediment resuspension, strongly influencing lake water chemistry, during the unstratified period.

iment-water exchange rates are lower in this lake. Their overall importance have to be related to other internal recycling processes and external loads.

10.5 Carbon and Nutrient Fluxes

Trap measurements of carbon and nutrient fluxes are valuable in estimating budgets and for calculating chemical energy transport to the benthos. It has been argued that traps deployed at the base of the thermocline (ca. 35 m) during the stratified period collect a representative sample of the primary flux (Eadie et al., 1984) of (mostly) autohthonous material. Extrapolation of these fluxes to estimate "loads" must be done with care and a consideration for factors that affect the variable to be calculated. For example, the flux of organic carbon calculated by this method would probably be significantly underestimated because the spring bloom generally peaks prior to stratification. With this caveat in mind, fluxes of organic carbon, nitrogen, and total phosphorus for the stratified period are presented in Table 10.1.

The values for Lake Michigan are within the range reported for the four offshore Lake Michigan stations collected in 1980 (Eadie et al.,1984). These values can be considered as the flux of organic matter entering the hypolimnion during this period. Except for the phosphorus in Lake Superior, the chemical flux values are surprisingly consistent among the lakes, but are considerably less than the mean values reported by Rosa (1985) for offshore Lake Ontario. This difference is presumed to be due to higher productivity in Ontario. Carbon fluxes of this magnitude are sufficient to support an abundant benthic biomass. The benthic biomass at a location close to the trap station in Lake Michigan was measured at 3.39 $g \cdot m^{-2}$ (Nalepa et al., 1985).

Gardner et al.(1985) estimated that this abundance of *Pontoporeia hoyi* (the most abundant benthic organism) was equivalent to 13.000 $cal \cdot m^{-2}$ of food for the fish in Lake Michigan. Although not as well studied, the other lakes have sufficient carbon flux to support similarly robust benthic communities.

The carbon and phosphorus values for Lake Michigan are again within the range previously reported, although there were substantial changes in plankton communities (Scavia and Fahnenstiel, 1987) between the trap collections in 1980 and 1984–85. Nitrogen fluxes were almost twice the previously reported mean (Eadie et al., 1984), possibly due to the fact that the earlier

Table 10.1 Nutrient fluxes at 35 m depth during the period of stratification for the three stations shown in Figure 10.1

Nutrient ($mg\ m^{-2} \cdot d^{-1}$)	Lake Michigan	Lake Huron	Lake Superior	Lake Ontario
Organic carbon	74	97	78	176
Nitrogen	4.0	4.1	3.2	26.
Phosphorus (total P)	0.40	0.31	0.11	2.3

nitrogen values were measured by the Kjeldahl procedure, while those reported above were measured by combustion on a CHN analyzer.

10.6 Sediment Resuspension

The rate of sediment resuspension can be calculated from the trap-measured flux profiles, corrected for primary flux by subtracting the near-surface (< 35m) value for the stratified period from each flux measurement. The assumption that these upper water values are uncontaminated by resuspension is supported by measurements of fallout Cs-137 (Eadie and Robbins, 1987). Cs-137 entered the lakes during atmospheric testing of nuclear weapons, primarily during the 1960s, and currently virtually all Cs-137 resides in the sediments. During the stratified period, our measurements show no Cs-137 in traps above the BNL, while measurements in samples collected during the unstratified period have a Cs-137 activity that is similar to that of fine-grained sediments and nearly constant throughout the water column. Other investigators use the same conceptual approach but employ other (and sometimes nonconservative) tracers to make this calculation (Bloesch, 1982; Rosa, 1985). To estimate the flux at the sediment-water interface (J_0) we use a least-squares fit to the flux profiles to the model, resulting in the following equation:

$$J = J_0 \exp^{-bz} \quad (10.1)$$

where J (units, $g \cdot m^{-2} d^{-1}$) is the trap-measured flux of resuspended matter at z(m), the trap height above bottom, while b(m^{-1}) can be viewed as the ratio of settling velocity to eddy diffusivity. The depth-weighted, mean value of resuspension, R ($g \cdot m^{-2} \cdot d^{-1}$), is then the integral of this function (evaluated between 35 m and the bottom for the stratified period and surface to bottom for the unstratified period) divided by the depth. Calculated values for the three lakes are presented in Table 10.2.

These calculations show a similarity between Lakes Michigan and Huron,

Table 10.2 Sediment resuspension parameters for eq. 10.1 calculated by using the least-squares-fitting, trap-measured flux of the three stations in Figure 10.1

	Value during stratified period			Value during unstratified period		
	Lake Michigan	Lake Huron	Lake Superior	Lake Michigan	Lake Huron	Lake Superior
J_0 ($g \cdot m^{-2} \cdot d^{-1}$)	10.5	5.7	1.1	11.6	10.8	2.2
b_z (m^{-1})	0.049	0.060	0.029	0.0092	0.016	0.012
r^2 (corr. coef.)	0.93	0.94	0.92	0.58	0.47	0.71
D_z ($cm^2 \cdot s^{-1}$)	7.6	9.6	9.0	126	57	41
R* ($g \cdot m^{-2} \cdot d^{-1}$)	1.5	0.74	0.15	7.0	5.2	1.1

* R is the estimate of the depth-weighted upward flux from the sediments.

and nearly an order-of-magnitude smaller value of R for resuspension in Lake Superior. It is unclear how much of this difference is due to Superior's greater mean depth (149 m; 86 m for Michigan and 60 m for Huron), lower productivity (40–100 $gC \cdot m^{-2} \cdot y^{-1}$; 140–225 for Michigan and 80–90 for Huron), lower runoff from the granitic shield basin, or to other factors contributing to a smaller pool of active particles.

Eddy diffusivity (D_z) values were calculated using the average settling velocity (3 $m \cdot d^{-1}$ and 8 $m \cdot d^{-1}$ for the stratified and unstratified periods, respectively) for the bottom 10 m (see Figure 10.5). The calculated D_z values are 10 to 100-fold larger than values estimated from radon profiles in the Baldeggersee (Imboden and Joller,1984) and other estimates (Lerman, 1979). One possible explanation for this discrepancy is that steady state is assumed in the calculations of both the exponent b (eq. 10.1) and settling velocities. If the traps are loaded by short-time-scale events (eg., storms) and TSM is measured only during calmer weather (after material has settled out), then calculated settling velocities and diffusion coefficients would be overestimated. In-situ estimates of settling velocities, such as those of Burns and Pashley (1974), and TSM data under turbulent conditions both need to be measured to test this hypothesis.

The magnitude of recycling of nutrients via sediment resuspension can be calculated by fitting the measured profiles of chemical flux to the same exponential model as described above for resuspended mass calculation. Values for the depth-weighted rate of sediment nutrient resuspension (R) for the unstratified period are given in Table 10.3

Earlier (Eadie et al.1984) we reported that resuspension of sediment-bound phosphorus was large compared to new loads for Lake Michigan. Our measurements indicated that 15 to 20% of Lake Michigan winter-trap-collected phosphorus was extractable by 0.1 *N* NaOH, a fraction shown to be readily bioavailable to diatoms (Williams et al., 1980); thus, estimates of this recycling process are important for lake management. Estimates of this component of the phosphorus cycle are shown in Table 10.4 for the three lakes and are compared to both recently measured loads and the target loads agreed upon jointly by the US and Canada through the International Joint Commission (IJC).

Even accounting for the fact that the resuspension term is only for the (6-

Table 10.3 Calculated values of nutrient resuspension from sediments during the unstratified period for the three lake stations

Nutrient ($mg\ m^{-2} \cdot d^{-1}$)	Lake Michigan	Lake Huron	Lake Superior
Organic carbon	250.	212.	58.
Nitrogen	60.	27.	13.
Phosphorus	7.2	5.8	1.2

Table 10.4 Comparison of the calculated flux of phosphorus for Lakes Michigan, Huron, and Superior

	Phosphorus flux (mg $m^{-2} \cdot d^{-1}$)		
	Lake Michigan	Lake Huron	Lake Superior
Resuspension	7.2	5.8	1.2
Estimated load (1981)*	0.24	0.23	0.11
IJC target load*	0.26	0.20	0.12

* From DePinto et al., 1986.

to 9-month) unstratified period and that a smaller fraction of the resuspended phosphorus is readily extractable compared to new load (ca. 15% vs. 50%), it is clear that the recycling rate of sediment-bound phosphorus is much larger than that for newly introduced phosphorus.

The results presented illustrate that, although the Laurentian Great Lakes are deep, the process of sediment resuspension is very important in the cycling of compounds with a high affinity for particulate matter. The annual reinjection of relatively high fluxes of particulate matter from the sediments into the water column helps to precipitate out newly introduced contaminants, but detrimentally re-exposes lake water to contaminants stored in the resuspendible pool. Currently, it is estimated that approximately 90% of the PCB in Lake Michigan is in the sediment inventory. The coupling of bioturbation and resuspension keeps this contaminant (and others) in intimate contact with the overlying water. In attempting to assess the overall importance of this process, seasonal timing is also important. The major phytoplankton bloom occurs prior to lake stratification. In effect, resuspension sets the initial nutrient conditions for lake water in the spring. The efficiency of capture of these nutrients—via primary productivity within the euphotic zone—controls the size of the pool of recyclable epilimnetic nutrients after strafication begins.

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