

SEDIMENT TRAP STUDIES IN LAKE MICHIGAN: RESUSPENSION AND CHEMICAL FLUXES IN THE SOUTHERN BASIN

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ABSTRACT. *The results of 4 years (1977-80) of sediment trap sample collection in the southeastern region of Lake Michigan are summarized and compared with water column and sediment characteristics. Mass flux data indicate strong seasonal patterns, with maximum fluxes recorded during the unstratified period. The large amount of winter resuspension is a mechanism which provides an intimate coupling of recent sediments and the water column. Also these trap study results indicate that there is a near-bottom (10-m-thick) benthic nepheloid layer whose chemical composition approaches that of deep water (fine grain) sediments. The amount of resuspended NaOH extractable phosphorus injected into the euphotic zone is estimated as approximately equal to the load of new phosphorus entering southern Lake Michigan. The role of resuspension in the cycling of organic carbon and contaminants associated with it appears to be important.*

ADDITIONAL INDEX WORDS: *Phosphorus, nepheloid layer, carbon cycle.*

Research into the role of aquatic particles in the cycling, behavior, and fate of chemicals (both natural and anthropogenic) has been increasing over the past decade. Particles can affect the solution chemistry through dissolution and precipitation (Lal and Lerman 1973, Lerman *et al.* 1974, Wahlgren *et al.* 1980); adsorption and desorption (Karickhoff *et al.* 1979); and settling, resuspension, and burial (Edgington and Robbins 1976, Chambers and Eadie 1981, Eadie *et al.* 1983). They also interact directly with the biological community through grazing, filter feeding (pelagic and benthic), and fecal pelletization (Deuser *et al.* 1983, Honjo 1978, Vanderploeg 1981).

There are two complementary techniques for the collection of samples of particulate matter. The first is the traditional instantaneous collection of a water sample followed by filtration or centrifugation. This procedure provides a snapshot of the spectrum of particulate matter present at the moment of collection. Subsequent chemical analy-

sis results in information on local concentrations and inventories of the component chemicals. The second technique is the use of sediment traps. When properly designed, traps collect time-integrated samples of the particles settling out of the water column with an efficiency of 90% or more (Hargrave and Burns 1979; Gardner 1980a, b; Bloesch and Burns 1980). Depending on the depth of the sediment traps relative to the bottom and time of year, materials collected may include a large amount of resuspended matter. At any depth in the water column, particles will collect in traps at the rate of the product of the settling velocity times concentration. Thus rare, rapidly settling particles (i.e., fecal pellets) may dominate over common, slowly settling ones (i.e., phytoplankton), resulting in a significant difference between the composition of materials collected in traps and that of materials filtered from samples. Subsequent chemical analysis results in information on fluxes of the component chemicals. Recently, sediment traps have been used to examine the fluxes of biogenic matter (Honjo 1978, Deuser *et al.* 1983) and specific chemicals (Cobler

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and Dymond 1980, DeBaar *et al.*), and rates of resuspension (Baker and Feely 1978, Chambers and Eadie 1981).

A limited amount of sediment trap work has been done in the Great Lakes. Rathke *et al.* (1981), using two types of traps to estimate seasonal settling velocities and fluxes of particulate organic carbon in the eastern basin of Lake Erie, found that cylindrical traps yielded lower apparent settling rates than *in situ* chambers. Both techniques collected significantly more material when positioned 3 m above bottom (40 m) than when positioned above the thermocline. A companion study in the eastern basin examined seasonal nearshore (9-m depth)-offshore (40-m depth) sedimentation differences (Bloesch 1982). Traps placed 2 to 3 m above bottom collected primarily (>80%) resuspended sediments. For a 6-week period (11 July-22 August), offshore epilimnetic mass fluxes averaged 0.79 ± 0.03 g/m²/d and were approximately 20% organic carbon, while near-bottom fluxes averaged 6.6 ± 0.03 g/m²/d and were approximately 5% organic carbon. Later in the season, epilimnetic mass fluxes increased and carbon content decreased, presumably because of resuspension effects.

Trap data from southern Lake Michigan (Wahlgren *et al.* 1980, Chambers and Eadie 1981) also showed seasonal variations in the particle flux, with maximum values recorded during unstratified periods. These flux profiles exhibited a characteristic "foot" of higher fluxes near the bottom at depths down to 160 m. The exponential half thickness of this foot was approximately 6 m. Chambers and Eadie (1981) reported a near-surface mass flux of 0.70 ± 0.4 (n = 20) g/m²/d during stratification and much higher near-bottom fluxes. The near-bottom traps contained an average of 84% resuspended material. This is remarkably close to the previously mentioned values reported by Bloesch (1982) for offshore eastern Lake Erie.

The object of this paper is to present recent results from 4 years of sediment trap analysis that allow us to estimate the magnitude of resuspended sediments and associated nutrients in southern Lake Michigan. These results indicate that resuspension follows a seasonal pattern and provides a mechanism that influences the observable characteristics of both the sediments and the water column. By providing an intimate contact between recent sediments and overlying water, resuspension appears to play a significant role in the cycling of nutrients and contaminants in Lake Michigan.

METHODS

The study area is shown in Figure 1. In 1978, there were four retrievals of the trap profile covering the periods 28 April through 6 June, 6 June through 15 September, 15 September through 26 October, and 26 October through 15 November. The benthic nepheloid layer was examined in detail; 61 sediment traps at eight locations with fixed trap depths at 1, 3, 5, and 10 m above the bottom and 35 m below the surface. In 1980, a profile of traps was deployed at a station located approximately 35 km off the mouth of the Grand River (1978, Station 4, Fig. 1) and retrieved once for the stratified period (June through October) and once for the unstratified period (October through June). Water samples were collected on trap cruises and several at other times.

Water column samples were collected with 5- or 30-L Niskin bottles and were filtered onboard ship within minutes of collection. For water samples collected 1 m above bottom, a 5-L Niskin bottle was modified to trip when an attached weight touched bottom. Samples for total suspended matter were filtered (1 to 4 L) through prewashed-preweighed 47-mm glass fiber filters, which were later dried and reweighed to the nearest 0.01 mg. All samples to be analyzed for phosphorus were filtered through HCl-washed, distilled, deionized-water-rinsed Nuclepore filters or nylon screens, and both the filtrate and filter were stored frozen in LPE bottles for up to 4 days prior to analysis. Samples were analyzed for phosphorus on a Technicon® AutoAnalyzer II (Murphy and Riley 1962). Samples of particulate matter and sediments were extracted by gently mixing with 0.1 N NaOH for 17 hr at room temperature, and the filtrates were analyzed to provide a measure of weakly bound phosphorus, a chemical analog of bioavailable phosphorus (See Sonzogni *et al.* 1982).

The sediment traps consisted of a plexiglass cylinder with a 5:1 height to diameter collecting ratio (50 cm × 10 cm) above the funnel, optimized for Lake Michigan (Wahlgren and Nelson 1976), and shown to have high collection efficiencies (>90%) by Gardner (1980a, b) and Hargrave and Burns (1979). (Traps of this design efficiently collect the particles passing through the plane of the trap opening; the total downward flux.) The traps had a powder funnel at the bottom connected to a replaceable precleaned and poisoned 500-mL LPE widemouthed bottle. Chloroform (20 mL) was used to preserve inorganic samples and mercuric

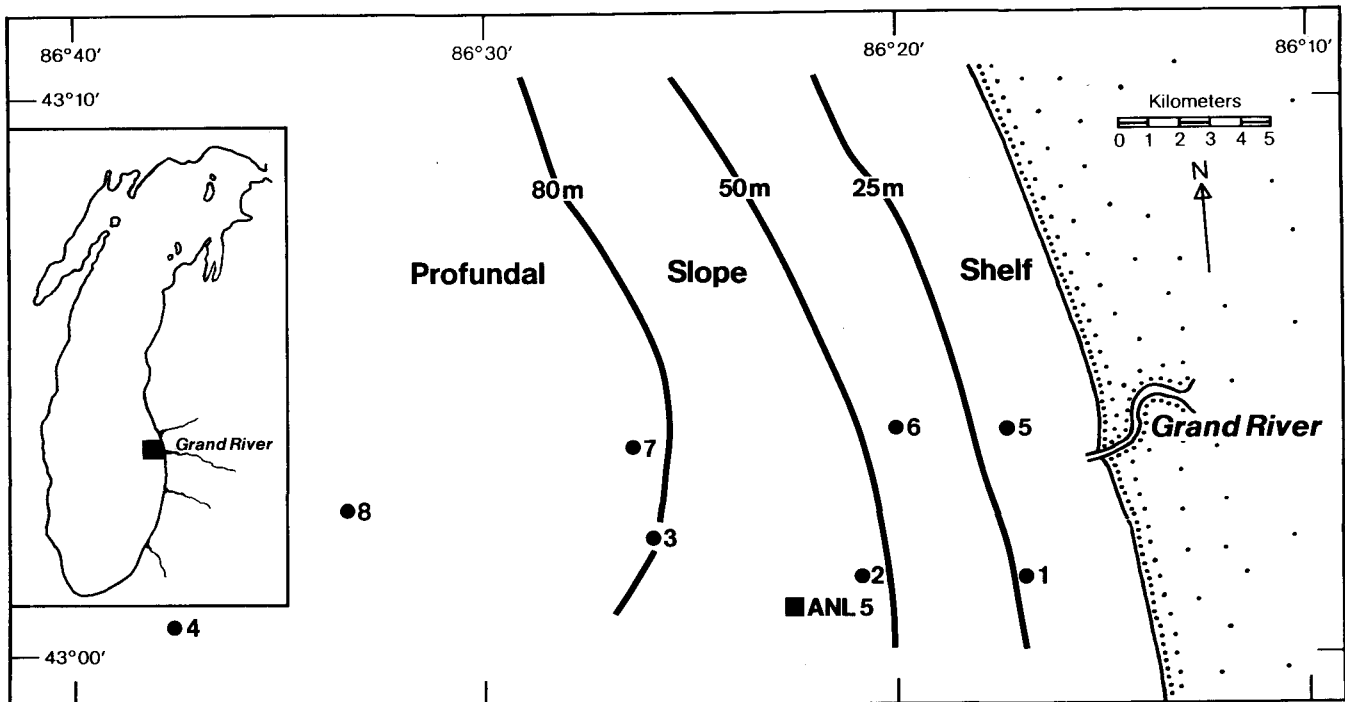


FIG. 1. Map of the study area. Sediment trap locations are numbered. ANL5 is the location of an Argonne National Laboratory trap station (Wahlgren et al. 1980) discussed in the text. Surface (0-1 cm) sediment samples were collected on an equally spaced grid out to 80-m depth (see Chambers and Eadie 1980), as well as at all trap stations. In all, there were 48 samples taken; 13 on the shelf, 12 between 25 and 50 m, 17 between 50 and 80 m, and 6 in the profundal region.

chloride (100 ppm) for organic matter. Although the traps were left out for 20 to 272 days between sample collection, the samples never became anoxic. The samples were refrigerated at 4°C until analysis.

The trap samples were allowed to settle for 18 to 60 hr, then approximately 400 mL of the overlying water was siphoned from the bottles. The samples were dried in their collection containers at 50°C under vacuum and weighed to the nearest 0.01 g. This weight was subsequently used for flux calculations. Sediment traps placed in triplicate at four stations in 1978 indicated coefficients of variation in sample weights from 1 to 10%, with an average of 5.5%. Eight trace metals (cobalt, chromium, iron, manganese, nickel, lead, and zinc) were analyzed by standard flame atomic adsorption procedures on sediment trap samples after peroxide and aqua regia digestion. Total phosphorus (TP) and total Kjeldahl nitrogen (TKN) were analyzed after block digestion (H_2SO_4 , 370°C) on a Technicon® AutoAnalyzer II. Organic carbon (OC) was measured by wet oxidation (after acidification) on an Oceanography International total carbon system.

Inorganic carbon (IOC) was measured by acidification of a dried (250°C) sample on the same system. Coefficients of variation (%) for the data reported in this paper are: Iron (10), lead (2), TP (7.7), TKN (7.1), OC (7.1), IOC (5.6).

Contaminant flux calculations were made as follows:

$$CF = TM \times CC / (DS \times TA)$$

CF = contaminant flux (mg/m²/day)
 TM = total mass collected (g)
 CC = contaminant concentration (mg/g)
 DS = duration of sampling period (days)
 TA = trap collection area; 78.5×10^{-4} (m²).

The precision associated with the flux calculation is equal to the square root of the sum of the squares of the coefficients of variation (CV) for total mass flux (1 to 10%; Avg. = 5.5%) and contaminant concentrations (2 to 20%). For the worst case, this equals 14.1%.

RESULTS AND DISCUSSION

Significant resuspension of sedimentary material during the stratified period creates a benthic

nepheloid layer (BNL) in the slope region extending far out into the lake. Chambers and Eadie (1981) reported that the 5- to 20-meter-thick BNL was characterized by higher concentrations of total suspended matter and greater light attenuation than overlying waters. A similar feature has recently been described in Lake Ontario (Sandilands and Mudroch 1983), and Bell *et al.* (1980) have described it as a feature common to all the Great Lakes.

Particle Mass Flux from Sediment Traps

From 28 April through 15 November 1978, sediment traps were deployed and samples were collected for four time intervals from stations 1 to 8 (Fig. 1). All of the mass flux profiles exhibited an exponential increase near the bottom (Fig. 2). Scale lengths for these exponential profiles were calculated to be approximately 6 m (Chambers and Eadie 1981), similar to that calculated by Wahlgren *et al.* (1980) and Marmorino *et al.* (1980) for deep stations in southern Lake Michigan and to the 6 m calculated from Charlton's (1983) data for a 100-m-deep station in Lake Ontario. At steady state, the scale length can be considered the ratio of eddy diffusivity to settling velocity, two parameters about which we know very little in the BNL.

The lake was isothermal and well mixed

throughout the first collection period, which accounts for the high fluxes throughout the water column. The next two collections were during periods of strong thermal stratification, when the epilimnion of the deep water stations was effectively isolated from resuspension. The final collection was in the fall when the thermocline was deepening. Table 1 gives mass fluxes ($\text{g}/\text{m}^2/\text{d}$) at 1 m above bottom for the nearshore stations (1 and 5) for the four collection periods.

TABLE 1. Mass fluxes ($\text{g}/\text{m}^2/\text{d}$) at 1 m above bottom for the four collection periods at the nearshore stations.

Station	Depth (m)	Collection Period			
		1	2	3	4
1	24	7.2	4.9	65.0	83.0
5	18	22.7	—	—	77.0

Our 1978 experimental design included profiles of traps at 1, 3, and 5 m above the bottom to examine the near-bottom downslope transport. Depth weighted average mass fluxes for the bottom 5 m were calculated by integrating the mass flux data over this depth range and dividing by 5 m. The results show that maximum fluxes occur on the slope (Fig. 3). Similar high mass fluxes in the slope region were reported by Wahlgren *et al.* (1980) for the ANL5 station (67-m depth; see Fig. 1). This indicates other sources that do not contribute to shelf fluxes, such as longshore transport and local resuspension. In 1978, near-bottom

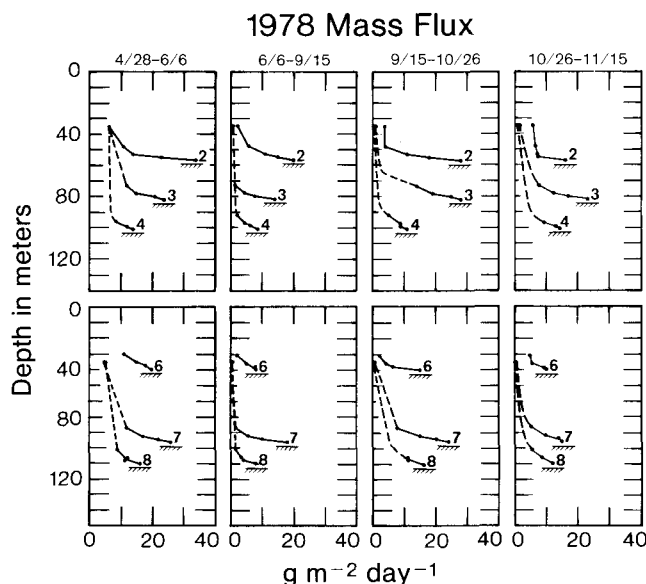


FIG. 2. Mass flux profiles of the 1978 sediment trap data. Units are $\text{g}/\text{m}^2/\text{d}$. The numbers correspond to 1978 station locations (see Fig. 1). The four panels correspond to four collection periods.

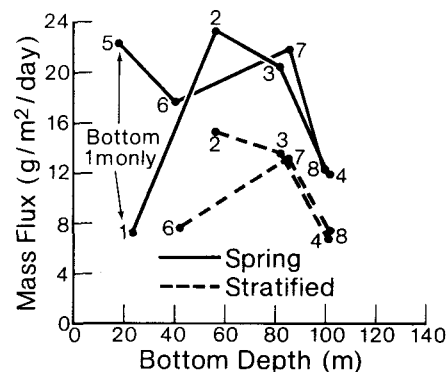


FIG. 3. Depth weighted average mass fluxes for the bottom 5 m at trap stations 1-8. Values were calculated by integrating the bottom 5-m mass flux profile and dividing by 5 m. The spring and stratified periods are both shown.

fluxes were significantly larger during the unstratified spring period than during the period of stratification (mid-June through mid-November). This was not true for the 1977 data (Wahlgren *et al.* 1980; ANL5 station; Chambers and Eadie 1981) and probably represents the result of the greater frequency of high winds during this period (>20 mph) in 1978 (eight occurrences) versus 1977 (two occurrences) NOAA 1977, 1978). Nearshore resuspension in shallow environments is probably quite variable from year to year.

During the period when the lake was thermally stratified, offshore traps located within or immediately below the epilimnion collected settling material apparently uncontaminated with resuspended sediments. Trap accumulation rates during thermal stratification (~160 days) ranged from 0.24 to 1.2 g/m²/day, with a mean of 0.65 (s = 0.26; n = 12). Rates for the spring prestratified condition (42 days) ranged from 5.1 to 6.8 g/m²/day, with a mean of 6.2 g/m²/day (s = 0.64; n = 6). The fluxes during stratification were similar to sediment accumulation rates in cores calculated from radioisotopes (x = 0.64 g/m²/day, s = 0.30; Robbins and Edgington 1975, Edgington and Robbins 1976) and from the Ambrosia (ragweed) pollen (0.74 g/m²/day; Davis *et al.* 1971) in the vicinity of our study area. This implies that trap materials collected at 35 m (below the thermocline, >50 m above the bottom) are sampling something

approaching the net flux, whereas the materials collected during spring are primarily resuspended sediments.

If this assumption is true, materials from these near-surface traps can be analyzed to estimate the primary flux of persistent contaminants entering the lake from atmospheric sources, a notoriously difficult estimate to make. These traps must be offshore (>20 km) to avoid contamination from resuspended sediments and BNL material introduced through upwellings (Bell and Eadie 1983), and outside of the influence of river inputs. Offshore near-surface fluxes from the stratified period, along with values from the unstratified period, are presented in Table 2 for iron, lead, phosphorus, nitrogen, and organic carbon.

Simple annual flux estimates were made by assuming that the stratified flux is the yearly average for new material entering the lake. Our calculated lead flux of approximately 12(±9) mg/m²/yr is similar to that estimated by Edgington and Robbins (1976) for the southern basin (13 mg/m²/yr) but smaller than the 29 mg/m²/yr reported by Eisenreich (1982). More substantial differences are apparent in iron flux estimates; our traps indicate a load of 3,000 (±1,700) mg/m²/yr while an estimate of 50 mg/m²/yr was reported by Eisenreich (1982). A similar disagreement occurs in organic carbon flux estimates. Primary productivity (the major source of particulate organic carbon) mea-

TABLE 2. 35-m trap chemical fluxes estimated from four offshore traps.

	Period ¹	(mg/m ² /day) measured mean	s	Flux ratio U/S	Annual (g/m ² /yr) ²
Mass	U	6,191.0	643.	9.5	240
	S	650.0	263.		
Fe	U	162.2	19.6	19.9	3.0
	S	8.15	4.72		
TP	U	5.92	1.0	7.5	0.29
	S	0.79	0.31		
TKN	U	36.4	10.1	5.7	2.3
	S	6.36	3.66		
Pb	U	0.65	0.11	19.1	0.012
	S	0.034	0.026		
Org. C	U	259.	40.5	4.1	23.0
	S	63.0	36.0		

¹U = Unstratified collection period (42 days; one collection period).

S = Stratified collection period (160 days; three collection periods).

²Annual flux estimated by 365* stratified flux.

surements for offshore southern Lake Michigan (139 g C/m²/yr; Fee 1973) were considerably larger than our trap estimate of 23 g C/m²/yr for settling organic carbon. This could be the result of internal recycling of carbon within the epilimnion, with a large fraction of the organic matter decomposing prior to settling through the thermocline. Our measured C:N:P ratio of 79:7.9:1 is considerably higher in carbon than the 41:7.2:1 ratio of Redfield *et al.* (1963) for plankton. This also indicates considerable reworking of the organic matter prior to settling.

All chemical fluxes measured from the sediment traps were significantly higher during the unstratified period. The ratios of fluxes in the unstratified period to those in the stratified period were calculated and compared to the mass flux ratio. The ratios for lead and iron were twice the ratio for mass, while the organic components were lower than the mass ratios. Concentrations of iron and lead in the spring surface traps were similar to our deep resuspension influenced traps throughout the whole year. During the stratified period, surface trap concentrations were depleted, which indicates that these traps were isolated from the source (resuspended sediments). Concentrations of nitrogen and phosphorus in trapped material were lower in spring than during stratification. This, combined with the iron and lead information, supports the idea that a large fraction of the enhanced spring flux into the surface traps is due to local sediment resuspension.

In 1980 a profile of sediment traps was placed at the location of station 4 (Fig. 1) and samples were collected twice, one set for the period of stratification (mid-June through mid-October), the second set from mid-October through mid-June 1981. Mass flux profiles for the summer of 1980 (shown in Fig. 4) were similar to those for the same location and collection period of 1978. Particle fluxes measured for the winter period were much larger. During winter, large amounts of resuspended sediments were mixed throughout the water, providing a mechanism for intimate contact of surficial sediments and overlying water.

The use of near-surface sediment traps to estimate primary flux allows us to estimate the flux of resuspended material (near-bottom trap flux—primary flux). As shown in Figures 2 and 4, gross downward mass fluxes into traps placed in the benthic nepheloid layer are up to an order of magnitude higher than near-surface fluxes. Profiles of elemental fluxes of lead, iron, total phosphorus,

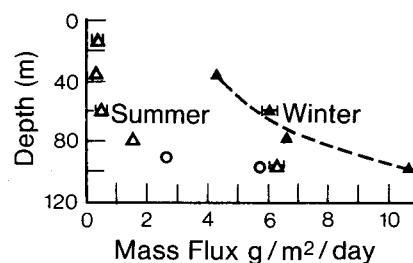


FIG. 4. Mass flux profiles at station 4 for the total stratified period (mid-June through mid-November, labeled summer, 1978) (○) and 1980 (△) and for the total unstratified period (mid-November 1980 through June 1981, labeled winter) (▲). Error bars indicate 1 standard deviation in mass flux.

and Kjeldahl nitrogen increase from the traps at 35-m depth to those located 1 m above bottom (Fig. 5). During the period of stratification, the 35-m trap elemental fluxes are similar to recent (upper 1 cm) local sediment accumulation. In spring, the fluxes at all levels are higher than during the stratified period. This is most evident in the 35-m traps. During both periods, the highest fluxes for iron and lead were found at the slope base, indicating a source along the slope. For the nutrients, the slope base and mid-slope fluxes were approximately equal. The apparent nutrient homogeneity may be due to internal biological recycling, giving them a longer residence time in the water column than iron and lead. The exponential increase in chemical fluxes toward the bottom corresponds to the increase in mass flux.

Resuspension and the Local Sedimentary Environment

Resuspension and transport play a major role in determining the characteristics of the local sediments. The physical characteristics of the nearshore (to a depth of approximately 75 m) sediments have been described in detail (Chambers and Eadie 1980). Briefly, shelf sediments (out to a depth of approximately 25 m; approximately 5 km offshore) are coarse sands with less than 2% (by weight) finer than 64 μ m. The sediment at the top of the slope is very silty sand grading into very clayey, medium gray colored silts at the slope base (approximately 75-m depth; approximately 15 km offshore). Deeper water sediment are very fine clays, with over 90% (by weight) finer than 64 μ m.

Although the shelf in this area is subject to massive amounts of wave-induced resuspension (Chambers and Eadie 1981), it is the small amount

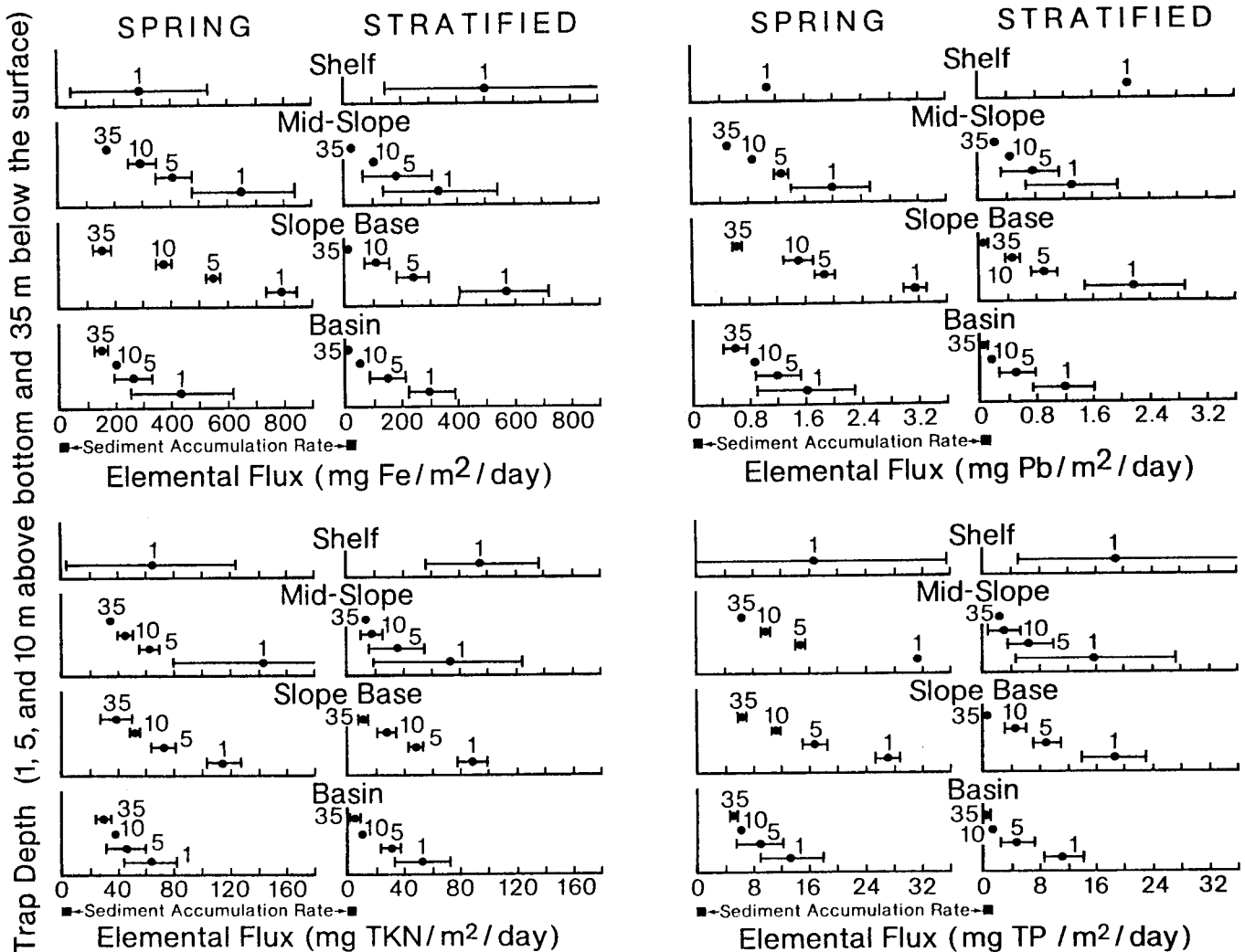


FIG. 5. Chemical fluxes of particulate iron, lead, total Kjeldahl nitrogen, and total phosphorus measured from the spring and stratified trap collections. Stations shown in Figure 1 are as follows: shelf (traps 1 and 5), mid-slope (traps 2 and 6), slope base (traps 3 and 7), and basin (traps 4 and 8). Local slope base-basin sediment accumulation rates for each compound are shown below each panel. These values were calculated from the nearby sedimentation rate ($0.65 \text{ g/m}^2/\text{d}$) times concentrations analyzed in surficial sediments.

of fine-grained material that is sorted out and transported lakeward. Surficial sediment concentrations of organic and inorganic carbon, nutrients, and metals collected at the stations indicated in Figure 1 (caption) all increase with distance from shore and correlate well with fine-grain-size material. Concentration contours follow the bathymetry, which is nearly parallel to the shoreline.

The physical processes that act to sort sediments by grain size also mediate the distribution of sediment contaminants. This is evident from the histo-

grams of data presented in Figure 6. In deeper water, concentrations of chemical species analyzed in the near-bottom sediment traps are greater than or equal to concentrations in the $<200\text{-}\mu\text{m}$ sized sediments. These bottom traps (1 to 5 m above bottom) primarily collect particles from a resuspendable pool near the sediment/water interface, material difficult to collect by standard sediment collection procedures. The data in Figure 6 indicate that the trap collected material is composed of both locally resuspended sediments and the chemically enriched fine-grained fraction of resuspended

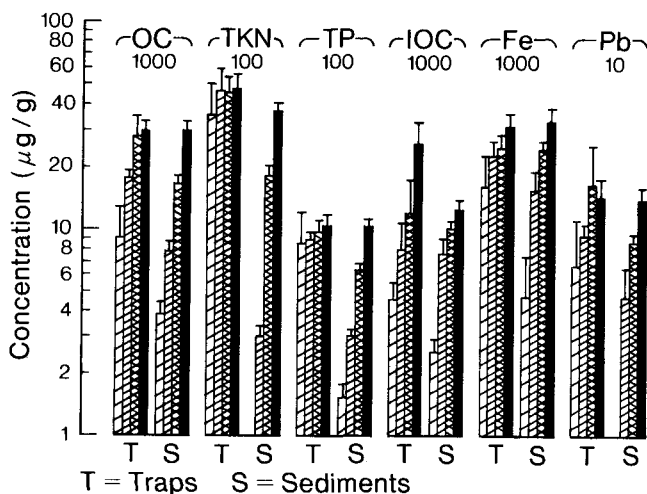


FIG. 6. Surficial sediment ($200\ \mu\text{m}$) and near-bottom sediment trap concentrations of organic carbon, total Kjeldahl nitrogen, total phosphorus, inorganic carbon, iron, and lead. The values at the top of each panel (10–10,000) indicate the magnitude of the bottom log cycle of the two-cycle plot. Each panel has two sets of bars. Sediment trap concentrations are on the left, sediments on the right. The four bars within each set represent (from left to right): shelf, upper slope, lower slope, and basin. One standard deviation is indicated. See Figure 1 for location of samples.

nearshore material, which is gradually being size sorted as it moves offshore. In this area, at depths greater than approximately 80 m (where recent sediments are accumulating) near-bottom trap material is almost indistinguishable from local surface sediments.

The behavior of sediment nutrients is shown in Figure 7. The organic nitrogen changes dramatically with respect to phosphorus as a function of depth. In the $<200\text{-}\mu\text{m}$ sized fraction (which reduces the dilution effect of large quartz grains), the ratio of nitrogen to phosphorus increases from an average of 0.3 on the shelf to 3.7 in the basin. The phosphorus to organic carbon ratio remains nearly constant and is consistently higher (1:36–30) throughout the entire area than average plankton (1:41). At the same time, the carbon to nitrogen ratio declines by a factor of 10, from approximately 80:1 to 8:1 from shelf to basin. There are several factors contributing to the observed patterns. First, the enrichment of phosphorus with respect to organic matter is probably due to the coprecipitation of the phosphorus with oxides and hydroxides of iron and manganese. The correlation of phosphorus to iron is 0.79 and to manga-

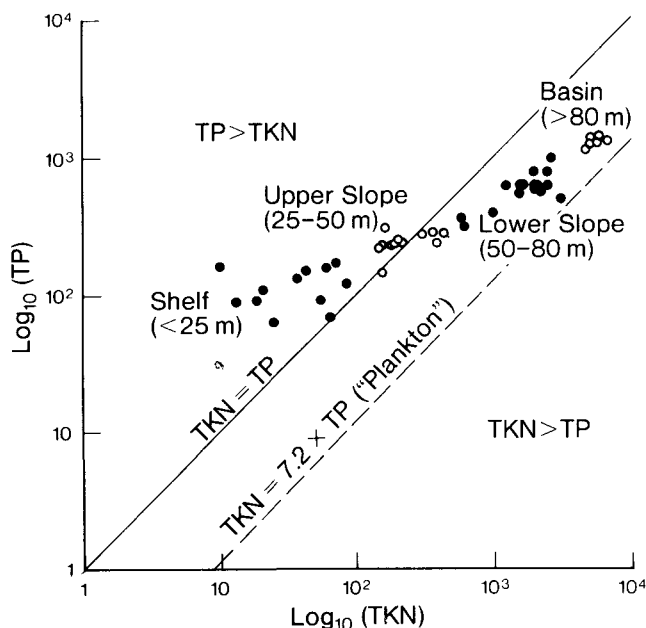


FIG. 7. Surficial sediment ($<200\ \mu\text{m}$) concentrations of total phosphorus and total Kjeldahl nitrogen. See Figure 1 (caption) for location of samples.

nese 0.90 for the 48 samples of oxidized surficial sediments. Second, the apparent depletion of nitrogen can be due to mineralization and/or sediment denitrification reactions and to higher concentrations, in the nearshore region, of land-derived organic debris. Land derived materials have C:N ratios of about 12 to 14 (Prahl *et al.* 1980) compared to approximately 6 for plankton. Also, as previously discussed, the finer-grained fraction of sediments is more easily resuspended and transported offshore, leaving behind sand grains enriched in inorganically precipitated phosphorus and depleted in nitrogen.

Resuspension and Local Water Column Characteristics

Characteristics of the dissolved and particulate nutrient chemistry for September 1978 are illustrated in Figure 8. The profiles represent a transect offshore (Stations 5 to 8, Fig. 1) from the Grand River (Mich.) and are generally similar to other profiles from this region during the stratified period. The top of the thermocline was approximately 25 m deep, resulting in an isothermal condition for the nearshore station. The profiles of total suspended matter (TSM) (see also Chambers and Eadie 1981) exhibited the characteristic

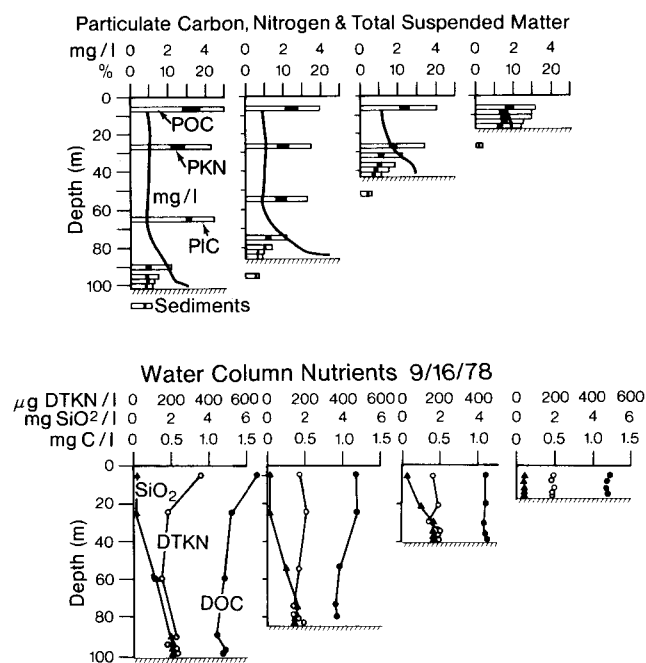


FIG. 8. Top—Carbon and organic nitrogen composition of the suspended particulate matter collected at four stations on a transect offshore, stations 5-8 (see Fig. 1) 18 September 1978. The cumulative composition is given in weight percent. Total suspended matter profiles are shown as a solid line. Bottom—Dissolved silica, Kjeldahl nitrogen, and organic carbon for the same stations.

increase in concentration near the bottom. For the three offshore stations, particulate carbon (organic and inorganic) and organic nitrogen decreased dramatically near the bottom, approaching the composition of bulk surficial sediments, strongly implying that the source of the excess TSM is local sediment resuspension. This transect was sampled during the period of intense CaCO_3 precipitation (Strong and Eadie 1978), accounting for the elevated concentrations of inorganic carbon (50 to 75% CaCO_3 by mass if all of the particulate inorganic carbon is in calcium carbonate) in the upper water column samples. The nearshore, well-mixed profile is rich in organic matter and carbonates compared to local or even deep water sediments and most closely resembles the fresh epilimnetic material collected offshore.

During several cruises at different times of the year, we have observed a range of approximately 10 to 25% organic carbon content in the suspended matter with similar decreases in the profile as described above. The concentration of TSM dur-

ing the stratified period is remarkably consistent and the profiles illustrated in Figure 8 (top) can be considered a reasonable representation for this region.

Profiles of dissolved nutrients from the same stations show a surprising consistency for DOC and DTKN, with only a slight gradient near the bottom (Fig. 8, bottom). In agreement with earlier results from Lake Michigan (Conway *et al.* 1980), a marked increase in near-bottom silica concentration was observed. Strong near-bottom gradients of dissolved SiO_2 have also been observed for deep stations on Lake Ontario (Nriagu 1978, Sandilands and Mudroch 1983). Nriagu (1978) postulated that the gradient was generated by the bioturbation enhanced diffusion of SiO_2 from sediment pore waters, while Parker *et al.* (1977) implied that dissolution rates of settling diatom frustules were sufficiently rapid to account for the near-bottom dissolved SiO_2 increase. Silica concentrations in near-bottom trap material from station 4 (Fig. 1) decrease from June through November (Shelske *et al.* 1984). This indicates that the local pool supplying material to the near-bottom traps becomes progressively depleted in silica during this 5-month period, supporting the hypothesis of relatively rapid dissolution within the BNL or at the sediment/water interface.

The Role of Resuspension in the Cycling of Contaminants

Analysis of trap samples allows us to estimate net particle-associated chemical flux (from near-surface offshore trap samples collected during the stratified period), as well as the input of resuspended materials into the water column (trap chemical flux at any depth—net flux). The magnitudes of both of these terms are important in estimating the time-dependent response of the lake to contaminants. Fanning *et al.* (1982) proposed that sediment resuspension could play an important role in the cycling of nutrients in the shallow coastal ocean. In this section, we will estimate the reintroduction into the water column, by resuspension, of the contaminants phosphorus and carbon.

Phosphorus

Profiles of water column total (TP), soluble reactive (SRP), and particulate (PP)($>1 \mu\text{m}$) phosphorus for September 1978 are shown in Figure 9. The increase within the BNL was primarily in the particulate phase although a small but significant

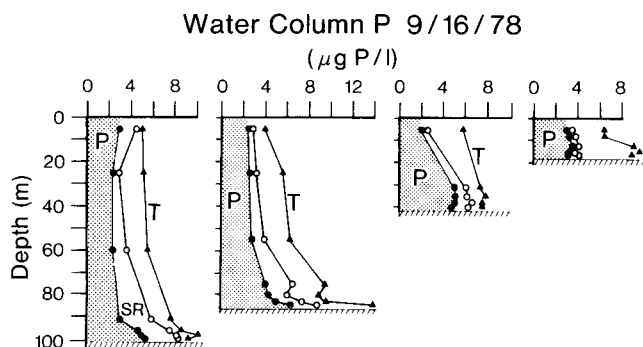


FIG. 9. Phosphorus profiles [total (T), soluble reactive (SR), and particulate (P)] measured for the 16 September 1978, cruise. Dissolved, non-SRP is the difference between total and particulate + soluble reactive.

increase in SRP was also measured. The near-bottom increase in SRP is smaller than that measured by Marmarino *et al.* (1980) or by Sandilands and Mudroch (1983). Their near-bottom SRP concentrations approached 10 ppb in August, while ours ranged from 2 to 3 ppb. One-third to one-half of the total phosphorus in the water column was particle associated.

Particle-bound phosphorus was studied in more detail in 1979 at the 85-m deep station. The profiles of TSM and total particulate phosphorus in mid-September were nearly identical for the 2 years. In this study, particles were size fractionated by filtering through nylon screens, and each fraction was extracted with 0.1 N NaOH to remove the weakly bound phosphorus (Fig. 10). Very little phosphorus was associated with particles greater than 64 μm . This was also true for five other cruises between April and October. Except for the BNL sample, virtually all of the less-than-64- μm particulate phosphorus was loosely bound. Within the

Extractable Fraction of the Particulate Phosphorus as a Function of Particle Size

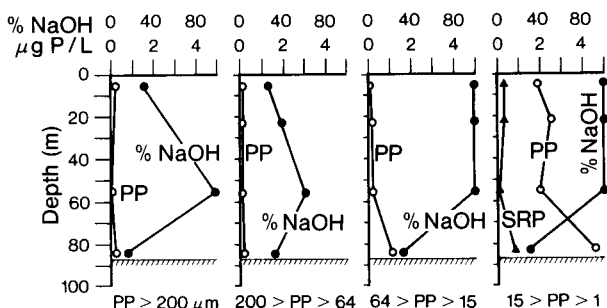


FIG. 10. Phosphorus profiles at the 85-m station 7 (see Fig. 1) for 16 September 1979. Particulate phosphorus (PP) associated with different particle sizes are shown as open circles (○); 0.1 NaOH extractable (as percentage of total particulate) P are shown as closed circles (●). SRP (<1 μm) is shown as filled triangles (▲) in the right-hand panel.

BNL, all size fractions were approximately 30% extractable. Surficial sediments from this location contain approximately 10% NaOH extractable phosphorus. A seasonal summary of the extractable particle phase phosphorus in surface and BNL (3 m above bottom) samples is given in Table 3. The sample from the end of May, when the lake was isothermal, had the same particulate phosphorus concentration and extractable fraction throughout the water column that the BNL had throughout the summer. By mid-October, phosphorus concentration in the BNL decreases and the extractable fraction increases significantly. This might be due to the coprecipitation of phosphorus with CaCO_3 . The high percentage of apparently available phosphorus in a phosphorus limited lake was unexpected.

TABLE 3. Percentage of NaOH extractable particulate (>1 μm) phosphorus at the 85-m-deep station 24 km off Grand Haven, Michigan.

Date	Depth (m)	TPP ($\mu\text{g P/L}$)	NaOH-P ($\mu\text{g P/L}$)	% Extractable
30/5	5	5.39	2.07	38.4
	82	5.41	2.08	38.4
9/8	5	3.21	1.70	53.0
	82	5.51	2.15	39.0
16/9	5	2.27	2.27	100.0
	82	5.68	1.74	30.6
17/10	5	2.98	0.60	20.1
	82	3.40	2.83	83.2

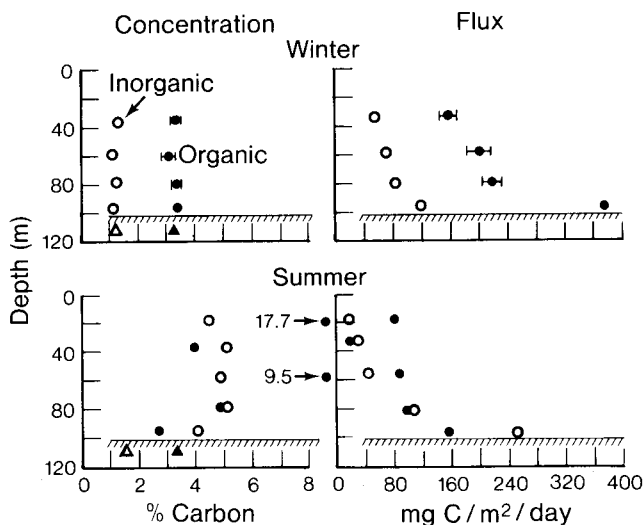


FIG. 11. Phosphorus [total (○) and 0.1 N NaOH extractable (<)] concentration (left) and flux (right) for the 1980-81 unstratified (top) and stratified (bottom) trap samples from station 4.

Trap samples from station 4 were analyzed to estimate both total phosphorus and the NaOH extractable phosphorus of the settling particulate matter (Fig. 11). In winter, concentration profiles were constant and about 15 to 20% of the phosphorus was extractable. In the summer profile, relatively high concentrations were measured in the 15-m trap, with the extractable fraction decreasing from about 40% to about 30% with depth. Below the epilimnion, the concentration of the NaOH extractable fraction remained constant at about 30%. This was considerably different from the high proportion (nearly 100% of total) of weakly bound phosphorus in the fine-grain fraction of the suspended matter (Fig. 10). Because sediment traps collect settling material, they are biased toward the larger grain size fraction of the TSM in the water column. The TSM greater than $64 \mu\text{m}$ had approximately 30 to 60% extractable phosphorus throughout the summer (see Fig. 10 and Table 3), which is similar to the trap material. Similar fractions of NaOH extractable phosphorus (31 to 46%) in sediment trap samples were reported for eastern Lake Ontario and the Niagara Bar region (Charlton 1983). In our study area, basin sediments have approximately 10% extractable phosphorus and a total of approximately 1.1 mg P/g. Thus the phosphorus associated with the particulate matter falling out of the water column appears to be more loosely bound than sedimen-

tary phosphorus. The summer flux of total particulate phosphorus near the surface was $0.68 \text{ mg/m}^2/\text{d}$ or $0.25 \text{ g/m}^2/\text{yr}$, which agrees well with our 1978 value (see Table 2). Local sediment accumulation of phosphorus is estimated to be $(0.65 \text{ g/m}^2/\text{d} \times 365 \text{ d} \times 1.1 \text{ mg P/g}) 0.26 \text{ g/m}^2/\text{yr}$.

This information is placed in perspective in a phosphorus budget diagram (Fig. 12) for a 100-m-deep, 1 m^2 water column in southern Lake Michigan. The load of phosphorus to the lake ($200 \text{ mg P/m}^2/\text{yr}$) taken from Murphy and Doskey (1976) and Chapra and Sonzogni (1979) corresponds to a lake load of approximately 8 to 9,000 MT P/yr and is somewhat lower than our estimated annual surface trap flux of 250 (1978) to 290 (1977) $\text{mg P/m}^2/\text{yr}$. This flux of new material is much smaller than our estimate for the input from resuspension.

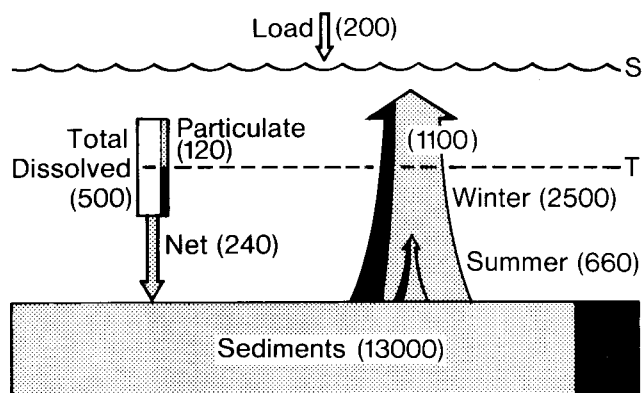


FIG. 12. Phosphorus budget for a 100-m-deep, 1 m^2 water column in southern Lake Michigan. Shaded areas represent particle-bound phosphorus. Black areas represent 0.1 N NaOH extractable P. Numbers in boxes (reservoirs) have units of mg P . Numbers associated with arrows (fluxes) have units of $\text{mg P/m}^2/\text{yr}$. Widths of arrows and boxes are proportional. T (dashed line) represents the thermocline.

In the BNL, the annual flux of resuspended phosphorus is approximately $3,200 \text{ mg P/m}^2/\text{yr}$, and approximately $1,100 \text{ mg P/m}^2/\text{yr}$ reaches the euphotic zone during the unstratified period. Approximately 20% of the phosphorus reaching the euphotic zone is extractable. These calculations indicate that sediments resuspended during the winter and mixed throughout the water column load the lake with weakly bound phosphorus.

Carbon

Carbon data for the September 1978 trap samples from station 4 (Fig. 13) were compared to the suspended matter samples collected at the same time and location (first panel of Fig. 8, top). Surface trap samples for this period were about 20% lower in organic carbon than the TSM. At 10 m above bottom, the trap materials were 50% lower in organic carbon than the TSM and at 1 m above the bottom, TSM and trap organic content were essentially equal. Similar results have been reported for Lake Ontario (Charlton 1983). Differences between trapped material and TSM in the upper trap are probably a reflection of temporal heterogeneity, and due to the fact that, in contrast to TSM sampling, the trap integrates over time. The organic composition of material from traps at 5 and 10 m above the bottom approximately fits a linear mixing model using sediments and 35-m trap material as end members. However, the trap 1 m above the bottom did not fit the linear mixing model. Organic carbon in the bottom trap is approximately 25% higher than calculated. Total phosphorus and TKN concentrations were also higher than predicted in the trap 1 m above bottom. The 1-m-above-bottom trap collects from two to four times as much material as the one 5 m above bottom, presumably from localized resus-

pension. Migrating benthic organisms may be responsible for the additional organic matter. Another possible source would be downslope transport of terrigenous material at the bottom of the BNL. Meyers *et al.* (1980) analyzed fatty acids and hydrocarbons from our trap station 3 and found highest concentrations of terrigenous organic matter at 1 m above bottom, and proposed near-bottom downslope transport as a potential source of this material.

The carbonate data (Fig. 13) show the pulse of material generated during the late summer whiting (Strong and Eadie 1978). Near-surface concentrations of particulate inorganic carbon increased from approximately 1% to almost 5% of the total mass during collection period 3. The near-bottom concentrations also increased during this period and continued to be high through November, indicating rapid settling and local resuspension of fresh material. Local bulk surficial sediments have less than 2% inorganic carbon—close to the near-bottom values from earlier in the year. The lack of carbonate buildup in the sediments indicates a fairly rapid dissolution of much of the CaCO_3 . This seasonal flux of CaCO_3 plays a major role in the cycling of plutonium in Lake Michigan (Wahlgren *et al.* 1980) and may be important in the seasonal cycles of other contaminants.

Carbon concentrations and fluxes, as measured in the 1980–81 traps from station 4 (Fig. 14), showed considerable differences between winter and summer. In winter, concentration profiles of both organic and inorganic carbon were constant and were approximately equal to the carbon content of local sediment. Summer concentrations of inorganic carbon in trap samples were nearly constant throughout the water column but three to four times as high as winter trap and sediment values, a result of collecting the freshly precipitating CaCO_3 . In agreement with the 1978 data, summer organic carbon values (Fig. 13) were high (17.7%) for the 15-m trap and decreased with depth, approaching local sediment values in the trap 5 m above bottom. Carbon flux profiles for winter clearly illustrate the impact of resuspension. Concentrations of inorganic carbon were much lower in winter than in summer, but the near-surface flux was much higher in winter; the only source of carbonates in winter would be sediments. The near-surface flux of organic carbon for summer 1980 was approximately $75 \text{ mg C/m}^2/\text{day}$ or $27 \text{ g C/m}^2/\text{yr}$, in excellent agreement with our 1978 value but again considerably lower than that estimated by

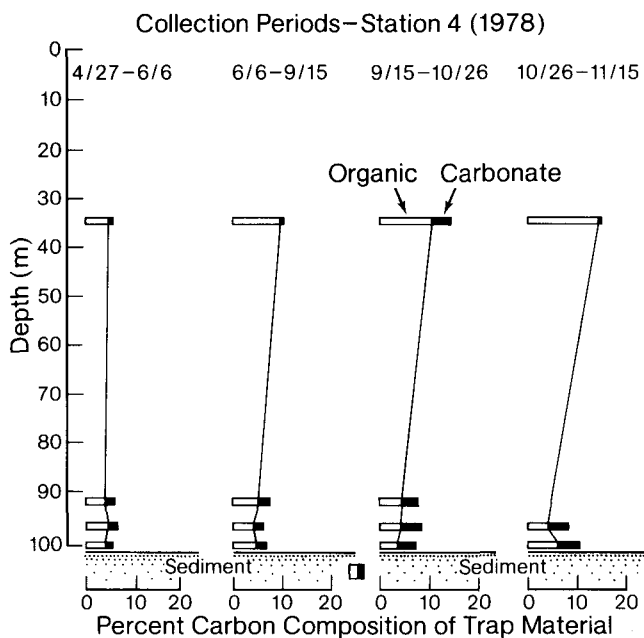


FIG. 13. Seasonal profiles of the carbon composition of trap material from station 4.

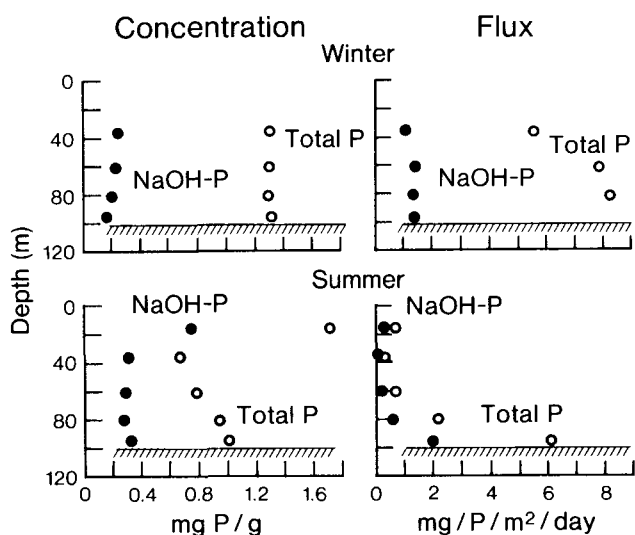


FIG. 14. Carbon [organic (<) and inorganic (0)] concentrations (left) and flux (right) of the 1980-81 unstratified (top) and stratified (bottom) trap samples from station 4. Error bars indicate 1 standard deviation. Local sediment composition and fluxes are shown as triangles at the bottom of each panel.

Fee (1973). The difference of approximately 115 g C/m²/yr (>80% of the total productivity) is presumably lost through respiration. Local sediment accumulation of organic carbon is estimated to be (0.65 g/m²/day × 365 days × 35 mg OC/g) 8 g/m²/yr. This indicates that considerable (~16 g C/m²/yr) decomposition occurs in the deep hypolimnion, the BNL, and at the sediment/water interface.

To place resuspension in perspective, these data have been assembled into a mass balance for organic carbon for a 100-m deep, 1 m² water column in southern Lake Michigan (Fig. 15). The load of organic carbon to the lake was taken from Strand (1978) and primary productivity from Fee (1973). The sediment reservoir of organic carbon represents the material in the upper 1 cm; cores from this region show little mixing by bioturbation (Robbins and Edgington 1975). Steady-state oxidation or respiration estimates are based on the differences between organic carbon production and fluxes as measured by traps. Resuspension into the BNL is approximately 75 g C/m²/yr or 10 times local accumulation. During winter, approximately 20 g C/m² reaches the euphotic zone.

While particulate organic carbon is not a contaminant, it does serve as a host for hydrophobic compounds, such as PCBs. An order of magnitude

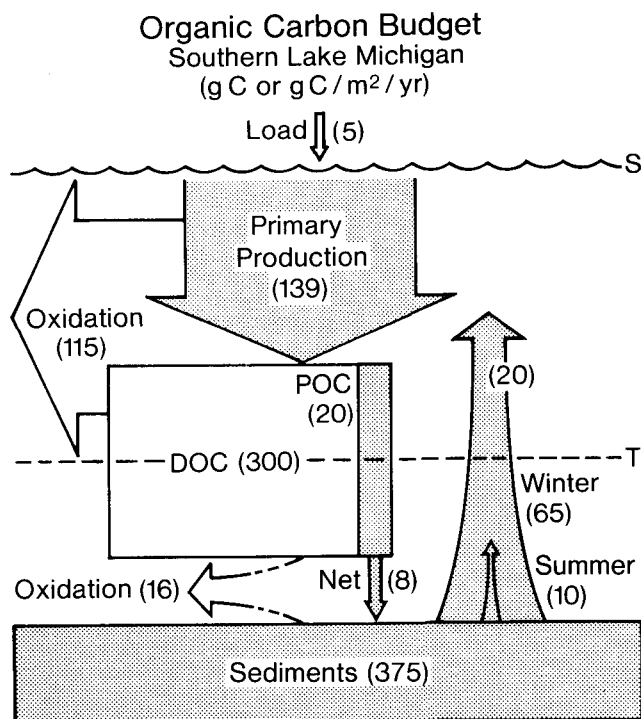


FIG. 15. Organic carbon budget for a 100-m-deep, 1 m² water column in southern Lake Michigan. Shaded areas represent particulate organic carbon. Numbers in boxes (reservoirs) have units of g C. Numbers associated with arrows (fluxes) have units of g C/m²/yr. Widths of arrows and boxes are proportional. T (dashed line) represents the thermocline.

calculation illustrates that, for a trace contaminant at a concentration of 100 ng/g [a reasonable organic rich (5%) sediment value], approximately 40 μg/m²/yr of contaminant will be injected into the euphotic zone by winter resuspension. This corresponds to approximately 2 MT/yr for the whole lake, and is greater than the estimated current external load of approximately 1 MT PCB/yr to Lake Michigan (Andren 1983).

Thus, for both phosphorus and carbon, reintroduction of sediment-bound material into the upper water column during winter by resuspension could play an important role in the long-term behavior of these and associated compounds.

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