J. Great Lakes Res. 28(3):324–337
Internat. Assoc. Great Lakes Res., 2002

Particle Transport, Nutrient Cycling, and Algal Community Structure Associated with a Major Winter-Spring Sediment Resuspension Event in Southern Lake Michigan

Brian J. Eadie[1], David J. Schwab[1], Thomas H. Johengen[2], Peter J. Lavrentyev[3], Gerald S. Miller[1], Ruth E. Holland[4], George A. Leshkevich[1], Margaret B. Lansing[1], Nancy R. Morehead[1], John A. Robbins[1], Nathan Hawley[1], David N. Edgington[5], and Patricia L. Van Hoof[1]

[1]*NOAA Great Lakes Environmental Research Laboratory*
Ann Arbor, Michigan 48105

[2]*Cooperative Institute for Limnology and Ecosystem Research*

[3]*University of Akron*
Akron, Ohio 44325

[4]*University of Michigan*
Department of Atmospheric, Oceanic and Space Sciences
Ann Arbor, Michigan 48109

[5]*Center for Great Lakes Studies*
University of Wisconsin-Milwaukee
Milwaukee, Wisconsin 53204

ABSTRACT. *Over the past decade, intermittent satellite imagery revealed the presence of an extensive plume of resuspended sediments in late winter-early spring with a clear offshore projection coinciding with the region of maximum sediment accumulation in the lake. The large scale of the plume implied that this process was important in sediment, and associated constituent, cycling and transport, but it had never been sampled due to severe conditions. The onset of the 1996 event coincided with a major March storm. Within a few days the plume was approximately 10 km wide and over 300 km in length, implying that the source of the reflective materials was widely distributed. An estimate of the total mass of resuspended sediment, 12 days after the storm, was similar to the annual external load of (sand-free) particulate material to the southern basin. The high turbidity plume persisted for over a month, progressing northward along the eastern shore with a major offshore transport feature. Sediment traps within this feature recorded a major mass flux event. The plume was sampled on two occasions and was found to contain 5 to 10 times as much suspended matter as open-lake locations outside the visible plume. Total particulate phosphorus was high within the plume making this episodic process important in sediment-water exchange. The diatom community structure within the plume was significantly different from outside the plume and was characteristic of more eutrophic waters. Abundance of non-diatom phytoplankton and microbial food web organisms were highest at the plume edge. The episodic nature of this process makes it difficult to sample, but the scale makes it important in designing monitoring programs and mass-balance modeling efforts.*

INDEX WORDS: *Sediment resuspension, sediment-water exchange, episodic events, fluxes, diatoms, heterotrophs, Lake Michigan.*

*Corresponding author. E-mail: Brian.Eadie@noaa.gov

INTRODUCTION

Episodic events can exert major influences on ecosystems. Energy, sediment particles (and their associated nutrients), radionuclides, and exotic organic compounds are predominantly transferred within the coastal zone of large lakes and enclosed seas in episodic pulses (storms, spring runoff). The resuspension of surface sediments in the Great Lakes, containing the large inventories of nutrients and contaminants deposited over the past few decades, presently results in greater fluxes to the water column than from external inputs (Eadie *et al.* 1984, 1989; Eadie and Robbins 1987; Robbins and Eadie 1991; Brooks and Edgington 1994). In addition to their influence on nutrient, temperature, and light fields, storms and turbidity fronts are recognized as important factors that structure planktonic communities (Mullin *et al.* 1985, Haury *et al.* 1992), determining whether primary producers remain in near-surface waters where solar irradiance is high or whether they are mixed into deeper waters. Resuspension of sediments may also inject resting stages of "meroplanktonic" diatoms into the water column (Schelske *et al.* 1995).

Circulation in Lake Michigan is also highly episodic. The most energetic currents and waves occur during storms. In the southern basin of Lake Michigan, alongshore currents are initially driven by pulses of wind, but can subsequently reverse direction as the characteristic two gyre wind-driven circulation pattern rotates around the basin as a two cell vorticity wave (Saylor *et al.* 1980, Schwab 1983). The relaxation time of this response is on the order of several days. Because the predominant winds are from the west, circulation in the southernmost part of the southern basin is more frequently counterclockwise (cyclonic) than clockwise. Because of the orientation of Lake Michigan, northerly winds generate the largest waves (in the southern basin), and therefore the greatest energy available for resuspension of nearshore sedimentary material, and would also contribute to southward transport very near the shore in the southwestern part of the lake (Lou *et al.* 2000).

One major event, which appears to occur annually in southern Lake Michigan, is the formation of a coastal turbidity plume in late winter-early spring. These events were first documented by Mortimer (1988) from satellite images obtained during the late 1970s and early 1980s. For the past several years, intermittent satellite coverage has revealed the presence of the plume in the visible wavelengths with a clear offshore projection that coincides with the region of maximum sediment accumulation in the lake (Lineback and Gross 1972; Edgington and Robbins 1990; Eadie *et al.* 1996). In 1996, exceptionally clear conditions provided the first opportunity to observe the initiation, development, and decay of this extensive coastal plume (Fig. 1) and to collect water samples by helicopter, small boat, and moored instruments. The rapid onset of the plume in 1996 coincided with melting of the last shore ice in late March, and with the occurrence of a major storm. The goal of this study was to characterize the materials in the plume, infer their sources, and assess their potential impact on the cycling and transport of nutrients and other constituents. Results show that the plume contained a large amount of resuspended phosphorus as well as other constituents, that there was a major nearshore-offshore transport associated with the event, and that the distribution of biota was consistent with enhanced nutrients.

METHODS

Satellite Imagery

Satellite imagery was obtained through the NOAA Great Lakes CoastWatch program (Schwab *et al.* 1992, Leshkevich *et al.* 1993). High-resolution (1 km at nadir) Local Area Coverage (LAC) data are obtained twice a day from the NOAA polar orbiting satellites for one visible (0.58–0.68 μm), one reflected infrared (0.725-1.0 μm), and three thermal infrared channels (3.55–3.93 μm, 10.3–11.3 μm, 11.5–12.5 μm). The raw satellite data are calibrated, earth located, quality controlled, remapped to a Mercator projection, resampled for several different 512×512 pixel scenes, and made available within a few hours of the satellite overpass through the CoastWatch regional node (www.coastwatch.glerl.noaa.gov). In addition, several masks are generated for each image indicating the results of various types of cloud tests (Maturi and Pichel 1993). Figure 1 shows four of the visible channel images from 16 March 1996 to 10 April 1996 with cloud cover (as indicated by a thermal gross cloud test) masked out. The reflectance in the raw image has been scaled so that areas with greater than 10% reflectance appear completely white. All of the images are from the afternoon pass of the NOAA 14 satellite, except the 16 March 1996 image, which is from the morning pass of the NOAA 12 satellite.

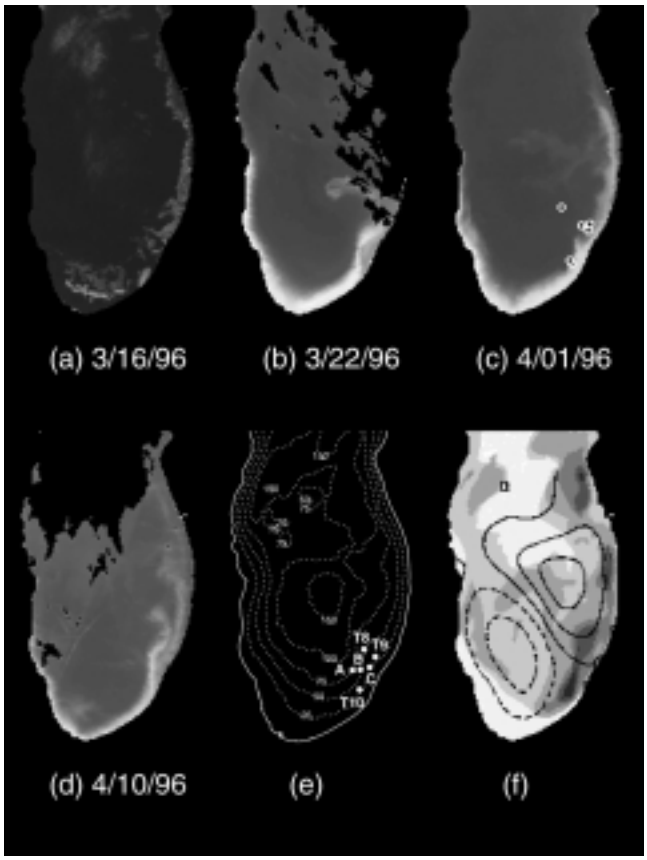

FIG. 1. Visible band satellite imagery: the region of southern Lake Michigan shown is approximately 300 km long by 130 km at the widest point. In the satellite images, black represents zero reflectance and white is 10% reflectance. The 16 March image (a) shows ice along the eastern shore of the southern basin and large ice floes at the south end of the lake. The 22 March image (b) shows the highly reflective plume which is approximately 300 km long by 10 km wide. The 1 April image (c) shows locations of the six stations (+) sampled for surface water from the Coast Guard helicopter. The 10 April image (d) illustrates the major offshore transport feature. Bathymetry (e) of the southern basin shows depths in meters and the location of three sediment trap stations (T8–T10) and the 10 April small boat water sampling and CTD stations (A—offshore, background sample, B—at the visible plume edge, and C—within the plume; Table 1). The thickness of post-glacial sediment and streamlines of a two gyre circulation pattern (Schwab 1983) are shown in (f); white represents zero sediment accumulation, the lightest gray represents regions with less than 1 m of accumulation. The rest of the contours are in 4-m intervals, with the darkest region having greater than 14 m of accumulation. The dashed streamline is counterclockwise flow, solid is clockwise. North is up.

Moored Instrumentation

Based on the coincidence of offshore transport of the plume in satellite imagery from Mortimer (1988) and the early 1990s with the region of maximum sediment accumulation (Linebeck and Gross 1972), moored sequencing sediment traps were deployed at station T8 (Fig. 1) covering the period August 1994 through August 1995, sampling for 15-day intervals. Results from these collections stimulated trap redeployment at this location with supplementary 15-m-deep traps further inshore where the water depth was approximately 35 m. Stations T8, T9, and T10 (Fig. 1) sampled from February through May 1996 at 5-day intervals. During the 1994-95 deployment at Station T8 the traps were located at mid-depth (30 m) and 5 m above bottom at this 56-m-deep site of high sediment accumulation. In the 1996 deployment, traps were placed at a depth of 15 m below the surface and one EG&G Vector Averaging Current Meter (VACM) was attached directly below each trap. The traps were 20 cm in diameter with an aspect ratio of 8 above the collection funnel. There were 23 independently programmable carrousel positions, each with a 60 mL sample bottle (Eadie 1997). After retrieval the chloroform-poisoned samples were allowed to settle, the overlying water was siphoned off, then the samples were passed through a 720 μm screen to remove "swimmers" (never more than a few percent of the mass), freeze-dried, weighed, then distributed for analyses. During the period of highest flux in 1995, the near-bottom trap became plugged and subsequent samples were not collected. In order to avoid overfilling, the 1996 traps were modified by replacing the 20-cm ID by 160-cm-tall chimneys above the funnel with a 5-cm ID × 40-cm-tall pipe thereby reducing the cross sectional area by a factor of 16 while maintaining the same aspect ratio. Samples were processed as above. Vector-averaged current components and water temperatures were recorded at 15-minute intervals and averaged to hourly values. The VACM at Station 9 leaked and data were lost.

Sample Collection

Based on the visible satellite images in late March, 1996, support was requested from the Air Station Traverse City, U.S. Coast Guard, Ninth District to obtain water samples in the plume. On 1 April they provided a search and rescue helicopter, equipped with GPS and an electronic winch. Five surface water samples were collected near the three

trap station locations, along with a surface sample of open lake water outside the plume using a stainless steel pail on the rescue winch cable (Fig. 1). Samples were immediately transferred to precleaned polyethylene bottles and stored in coolers containing frozen blue ice. Within 5 hours the sample coolers were transferred to storage in a 4°C cold room and processed within 48 hours. A second sampling effort was conducted on 10 April using a 26-ft boat to collect a set of three surface water samples from within and offshore of the plume (Stations A to C, Fig. 1) including large samples for ^{137}Cs analyses. Samples were collected from the surface with a stainless steel pail. CTD-transparency profiles were taken at each station. Coastal bluff materials were collected from six sites along a 100 km stretch of the western shore of the lake as a representative of the erodable material that is the primary source of particulate materials to the lake (Colman and Foster 1994). In an attempt to place the sampling within a temporal context, turbidity and temperature data, recorded three times daily at an intake 1.5 km offshore, were acquired from the water treatment plant near St. Joseph, MI, located inshore of station C (Fig. 1).

Analytical

Sample volumes were generally small and replication was restricted to duplicates or single values (^{137}Cs). Precision for analyses are reported below based on dozens to hundreds of samples of similar size and composition measured over 1995 to 1997. Total suspended matter (TSM) was measured in duplicate on each sample. Whatman GF/F 47mm glass fiber filters were rinsed with distilled water, then precombusted at 450°C for 4 hours. After cooling, filters were weighed, then placed in clean petri dishes. Water was vacuum-filtered (approximately 25 cm Hg) until the filtering rate slowed; volumes were measured by graduated cylinder. The filter was dried at 70°C, then reweighed and the mass calculated. Duplicates of calculated TSM concentrations differed by less than 5%. The filter was again placed on the filtration apparatus and 2 mL of 1N HCl was pipetted onto the surface. After 5 minutes of exposure, the acid and follow-up rinse with 2 mL of distilled water were removed by vacuum. These filters were subsequently combusted at 650°C in Vycor tubes and the resultant gases separated by cryogenic distillation with CO_2 and N_2 collected for stable isotope mass spectrometry (Eadie *et al.* 1994). Total carbon and nitrogen were measured (on 25 mm GF/F filters prepared as above) in duplicate on a Perkin Elmer CHN analyzer (925°C combustion). Organic carbon was calculated from the volume of CO_2 collected for stable isotope analysis. This procedure is intercalibrated with the Perkin-Elmer CHN elemental analyzer. Both measurements have an accuracy and precision (1 sd) of less than 3%. Carbonate concentration on the particles was calculated as the difference between total C and organic C and reported as $CaCO_3$ in Table 1.

TABLE 1. Composition of surface water collected 10 April 1996.

		Plume	Edge	Background
Station label (from Fig. 1)		A	B	C
Latitude		42.158	42.141	42.137
Longitude		86.588	86.677	86.752
Station depth	m	33	59	76
TSM	mg/L	7.1	1.5	1.0
^{137}Cs (ashed)	mBq/g	35 ± 3	na	100 ± 33
Chlorophyll a	µg/L	1.55	1.83	1.81
Diatoms (total frustules/ml))		1,198	1,007	1,630
Diatom *Stephanodiscus minutulus*	%	52	64	70
Diatom *Stephanodiscus parvus*	%	24	4.0	3.0
heterotrophic C/ phytoplankton C		0.22	0.70	0.43
Bacteria	µg/L	10.8	15.8	10.5
Picocyanobacteria	µg/L	5.9	11.6	5.3
Heterotrophic nanoflagellates	µg/L	2.6	3.5	2.4
Dinoflagellates	µg/L	0.3	2.9	1.0
Tintinnid ciliates	µg/L	5.0	5.6	4.4
Aloricate ciliates	µg/L	0.6	15.8	8.8

All nutrient concentrations were determined on a Technicon Autoanalyzer II using standard colorimetric procedures (APHA 1990). Total particulate phosphorus (TPP), available particulate phosphorus (APP), and biogenic silica (BSi) were determined on material retained on a 0.4 mm Nucleopore filter. For each analysis, 100 mL of lake water was filtered and the filters stored frozen until analysis; 3 days for TPP and APP and 7 days for BSi. TPP was determined by digestion with potassium persulfate in an autoclave (Menzel and Corwin 1965) and then analyzed for soluble reactive phosphorus (SRP) using the molybdate/ascorbic acid method. Historically, the coefficient of variation (cv) for TPP on filters is 9.8% and for traps/sediments is 4.6%. APP was estimated, with a cv of 6.7%, from the amount of phosphorus extractable with 0.1N NaOH (Williams *et al.* 1971, Sagher *et al.* 1975). Filters were placed in 50-mL polyethylene centrifuge tubes with 30 mL 0.1N NaOH and samples shaken for 17 h in a water bath at 25°C. After extraction, samples were neutralized with 3 mL 1.0N HCl, brought up to 50 mL with distilled-deionized water, and then analyzed for SRP. BSi was determined, with a cv of 5.5%, by wet alkaline extraction with 0.2N NaOH (Krausse *et al.* 1983) and then analyzed for soluble silica using the heteropoly blue method. Chlorophyll a was determined fluorometrically, with a cv of 3.2%, according to the procedures of Strickland and Parsons (1972) after extraction of a 200 mL aliquot collected on a 47 mm Whatman GF/F filter with N,N-Dimethyformamide (Speziale *et al.* 1984).

To determine the activity of ^{137}Cs on solids, water from within the plume (67 liters; TSM=7.1 mg/L) and offshore (52.6 L; TSM = 1.0 mg/L) were filtered through 293 mm (0.45 micron Millipore HAWP) filters which, along with two unexposed (blank) filters (for background), were subsequently ashed at 450°C in a muffle furnace. Finely powdered radiocesium-free alumina (0.5 g) was added to the pair of blank filters prior to ashing in order to recover a measurable amount of ash, since the filters have essentially no ash content. Ash from the two samples and background was loaded into standard 4 mL plastic vials and counted on an intrinsic germanium well detector for up to one week to obtain sufficiently precise net counts from the 661.6 KeV gamma emitted by ^{137}Cs. Comparable weights of dry doped sediment with a precisely determined (± 2%) amount of NIST-traceable ^{137}Cs standard solution were also counted to provide the means of calculating absolute activities. Larger, freeze- dried samples from sediment traps were similarly counted without the need for ashing (Robbins and Eadie 1991).

Diatoms were counted on 500-mL samples of water that were collected at each of the three stations on 10 April (A–C, Fig. 1). Samples were strained through a membrane filter (Millipore HA) with a pore size of 0.45 mm. Diatom frustules were identified and counted directly from a portion of dried filter which had been made transparent with immersion oil. At least 500 frustules were counted for each sample using a Zeiss phase research microscope at a magnification of 970X. Hyrax slides were made of concentrated, unfiltered material to aid in species identification.

Bacteria, picocyanobacteria, and nanoflagellates (preserved with 4% glutaraldehyde) were enumerated and their linear dimensions were measured under a Leitz Laborlux fluorescent microscope (magnification × 1,000) as described by Bratbak (1993), Fahnenstiel and Carrick (1992), and Sherr *et al.* (1993), respectively. Non-diatom phytoplankton and ciliates (preserved with 1% acid Lugols iodine) were counted in settling chambers under a Wild phase-contrast inverted microscope (125-500×). Bacterial, picoplanktonic algal, and protozan biovolumes were converted to carbon, based on studies of Norland (1993), Montagnes *et al.* (1994), and Putt and Stoecker (1989), respectively.

RESULTS

The temporal pattern of mass fluxes collected in the trap at Station T8 (Fig. 1) from August 1994 through August 1995 in 15-day intervals illustrates the episodic nature of particle transport. The mid-depth trap, located in the vicinity where the plume meanders offshore, collected approximately 85% of the annual input of particulate material to this region of maximum sediment accumulation in a ten week period centered on the first 2 weeks of February 1995 (Fig. 2). Although there were two smaller mass flux events in November and April, this interval was the largest sustained resuspension event that was recorded during the 1994-95 deployment at the water treatment plant intake near St. Joseph, MI (Fig. 2). During the mass flux events recorded in the traps the C/N ratio of the organic matter jumps from about 9 to over 12. Higher C/N is characteristic of terrestrial or degraded sedimentary material (Meyers and Eadie 1993). The ^{137}Cs activities in the trap materials ranged from 72 to 98 mBq/g (Fig. 2). These activities are lower than surface sed-

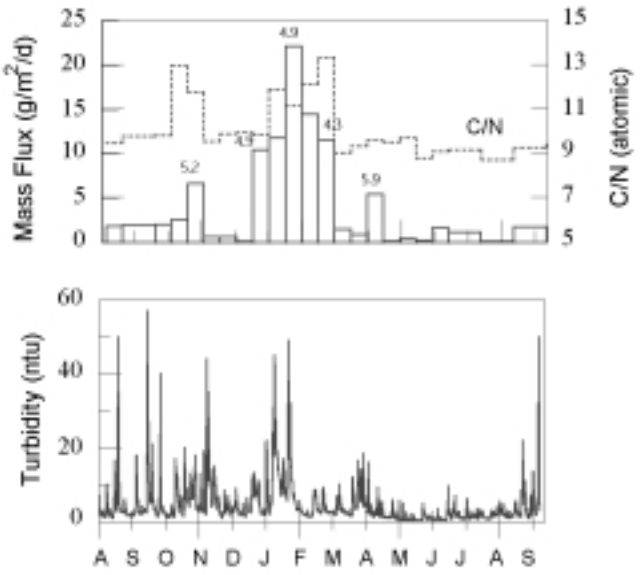

FIG. 2. a) Mass fluxes (solid line) from a mid-depth (30 m) trap at Station T8, sampling at 15-day intervals from mid-August, 1994 through mid-August, 1995. The C/N ratio is overplotted as a dotted line. Numbers are the ^{137}Cs activities (mBq/g) of the trap materials; counting errors were less than 0.5 mBq/g. b) Turbidity for the same period from the water intake inshore of the trap site.

iment from the depositional region near the trap (107 to 157 mBq/g; J.A. Robbins, pers. comm.). The 1994-95 trap data showed that the majority of particle transport into this deposition zone was associated with the early season episodic event, supporting our hypothesis that these events were important in particle transport, and encouraging us to attempt a more ambitious sampling program.

In 1996, the rapid onset of the plume in the southern basin coincided with the disappearance of coastal ice and the occurrence of a major storm with strong northerly winds on 20 March. For over a month prior to this storm, winds measured at the Milwaukee airport had been predominantly out of the west. In the first available satellite image after the storm, on 22 March, the plume was already approximately 10 km wide and over 300 km in length (Fig. 1). The feature persisted for over a month, with the wind direction predominantly from the north during this entire period. Images of the plume show it dispersing offshore in the southeastern portion of the lake coincident with sediment deposition patterns (Fig. 1).

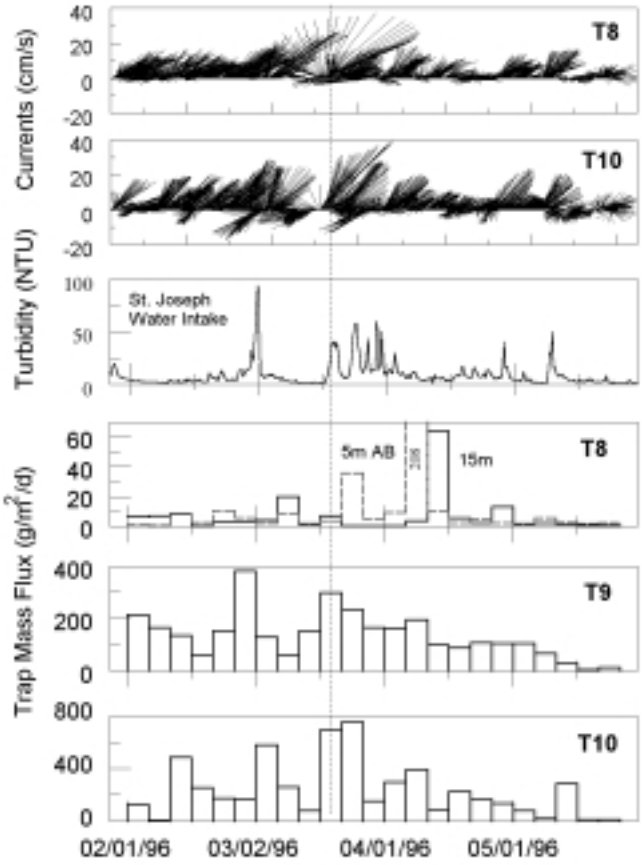

FIG. 3. Hourly averaged currents from Stations T8 (upper panel) and T10 (second panel). Direction was predominantly to the northeast. The dashed line represents the 20 March storm. Turbidity (ntu) during the same period from the water intake located 1.5 km offshore approximately midway between Stations T9 and T10 (third panel). Mass fluxes collected at 5-day intervals in traps at mid-depth (15 m) from Stations T8 (dashed line represents the trap at 5 m above bottom with a maximum flux of 208 g/m²/d), T9 (fourth panel), and T10 (bottom panel). Collections covered the period 1 February through 27 May 1996.

The current meters at approximately 17 m depth at stations T8 and T10 (Fig. 1) recorded predominantly northeasterly flowing currents, exceeding 15 cm/s for a substantial portion of the month prior to the onset of the plume (Fig. 3). The 20 March storm produced currents of greater than 40 cm/s for a few hours, followed by a few subsequent pulses in the 20 to 30 cm/s range, predominantly parallel to the shore-parallel depth contours. The offshore transport features observed in the satellite imagery (Fig.

1) were consistent with the two counter-rotating gyre circulation model described by Saylor *et al.* (1980). It appears that the current meters at both stations were south of the convergence.

Traps at stations T9 and T10 (Fig. 1) were located 15 m below the surface at 35-m-deep stations, approximately 10 km offshore. Both nearshore traps show an increase in collection coinciding with the 20 March storm (Fig. 3), with fluxes generally decreasing over the observed plume period. Mass fluxes at the southern station (T10) were approximately twice those at Station T9. The water treatment plant, located inshore of station C (Fig. 1), recorded a series of high turbidity events during the plume period. Other periods of increased flux were recorded by these nearshore traps, although not synchronously. The late February peak flux at Station T10 corresponded with an intense, but brief, turbidity maximum at the water treatment plant.

Further offshore at the 56 m deep station (T8, Fig. 1), the traps 15 m below the surface and 5 m above bottom collected substantially less material. When summed over the entire deployment, the total mass collected in the 15-m-deep trap at T8 was only 5% of the amount collected at Station T9, and the trap 5 m above the bottom collected 2.2 times the mass of the 15-m-trap above. The flux at the offshore 15-m-deep trap (T8) displayed a different temporal pattern than the nearshore traps (T9 and T10). Mass flux was low at the beginning of the plume period, then a large mass was collected about 3 weeks after the initiation of the event, one (5 day) collection interval after the large flux was recorded in the near-bottom trap. The timing of these large fluxes corresponds to small flux peaks at Stations T9 and T10 and to a pulse in the currents at both stations. At the observed currents, trap Reynolds numbers (velocity*trap diameter/viscosity) were below 25,000 for over 90% of the deployments. This is a region where cylindrical trap collection efficiency is high (Gardner *et al.* 1997). The 1996 mass flux to this region of maximum sediment deposition was even more concentrated in time than the 1995 trap flux, again supporting our hypothesis of the episodic nature of particle transport to offshore depositional environments.

The composition of trapped material collected during the interval that included the 20 March storm was different than the remainder of the 115 day deployment at station T10 (Fig. 4). Organic carbon was at a minimum in the initial plume event sample, it then returned to a level below the pre-plume trap samples and remained nearly constant

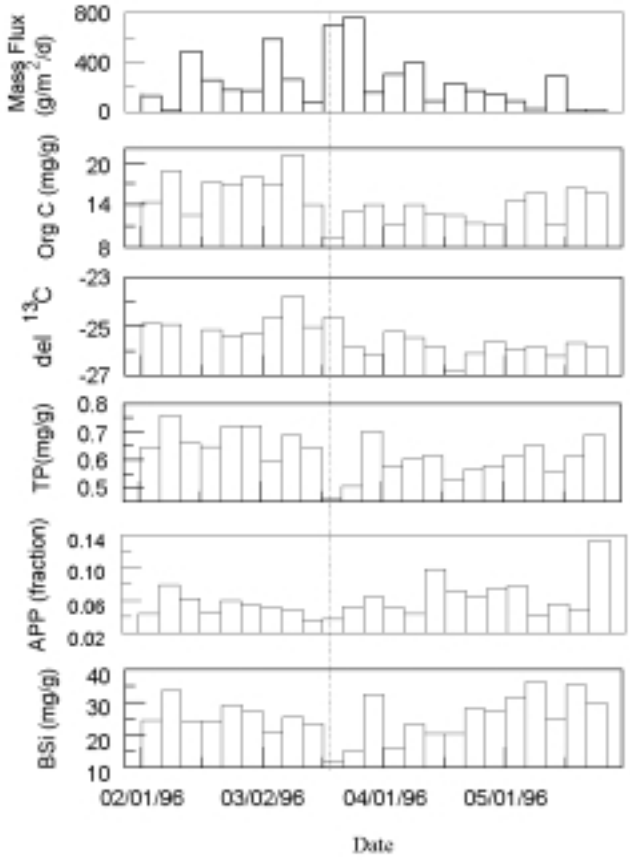

FIG. 4. Composition of the materials collected in the trap at Station 10. Mass flux is in the upper panel, followed by the organic carbon concentrations and isotopic composition in the trapped materials, the total particulate phosphorus concentration, the fraction of available particulate phosphorus, and biogenic silica. Collection intervals were 5 days. The dashed line represents the 20 March storm.

throughout the remaining collection intervals. The $\delta^{13}C$ of the post-event organic matter was 0.5 to 1 ‰ lighter than before the event. This could be a consequence of reduced primary production, perhaps due to light reduction or the introduction of isotopically light material (from an unknown source) into the resuspended materials captured by the traps. With the exception of the two samples immediately after the storm, the materials collected in the trap at Station T10 had a relatively constant TP concentration (0.63 ± 0.07 mg/g) throughout the deployment (Fig. 4). However, the fraction of TP classified as biologically available began to increase within a few weeks of the initiation of the

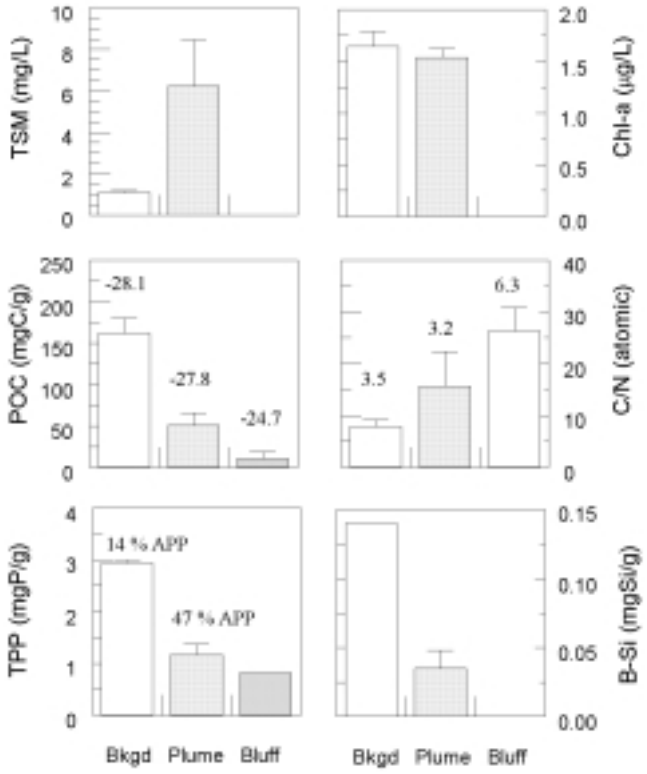

FIG. 5. Organic composition of surface particulate matter in the plume, lake background and bluff materials, including all samples collected from 1 April and 10 April 1996. Error bars denote 1 sd. Numbers in the POC panel are organic $\delta^{13}C$, in the C/N panel are $\delta^{15}N$. Numbers in the TPP panel are APP values.

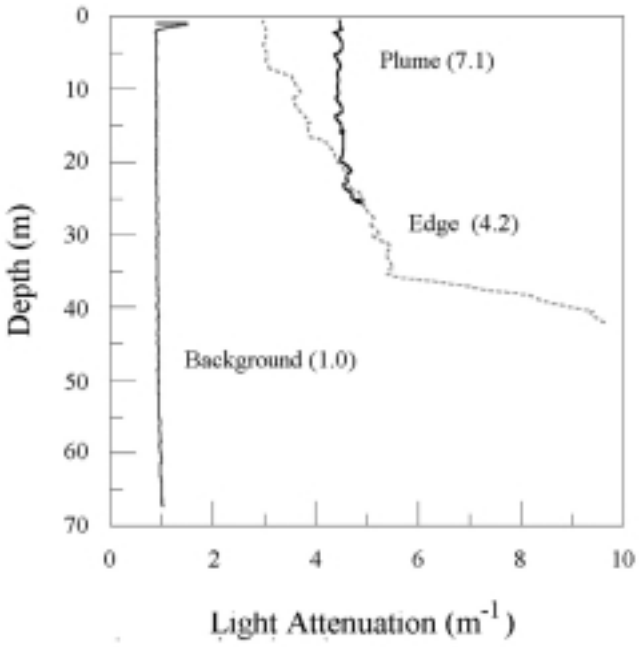

FIG. 6. CTD-transmissometer profiles of light attenuation at the three 10 April stations (Figure 1). Numbers in parentheses are the surface TSM concentrations in mg/L. The background (C) and plume (A) profiles of light attenuation were constant, while plume edge (B) profile showed some increase in attenuation with depth.

plume event (Fig. 4) and stayed elevated for several weeks. The fraction of available-P measured in the trap samples at station T10 for the month after the storm (Fig. 4) was 6 ± 2%, lower than the concentration in surficial sediments (13 ± 4%) collected within a 10 km radius of this location (T. H. Johengen, pers. comm.). Trapped biogenic silica was at its lowest during the first two trap intervals after plume initiation (Fig. 4). This is consistent with dilution by sand or silica-poor sediments due to resuspension. Biogenic silica concentration rebounded rapidly to levels at or above the pre-plume samples by the third (5-day) trap interval.

Particle concentrations from water samples collected within the visible plume reached a maximum of 10.2 mg/L on 1 April 1996 (Fig. 1c) and 7.1 mg/L on 10 April 1996 (Fig. 1e). Open water (background) samples (n = 4) had nearly constant TSM concentrations of 1.0 to 1.2 mg/L at both times (Fig. 5). In order to determine the vertical structure of the plume, CTD-transmissometer profiles were collected from the 10 April stations (Fig. 6) revealing approximately constant attenuation with depth at both open-lake and plume stations. At station B (Fig. 1) located visually at the offshore edge of the plume, attenuation increased significantly with depth, suggesting differential settling or different horizontal advection with depth. With the exception of the edge of the plume, the water column was well mixed in the study area. Temperature profiles (CTD, not shown) were isothermal (1.2 ± 0.1 °C) at station A and 1.4 ± 0.1 °C at station C. Surface temperature, estimated from the thermal band in the satellite imagery, was nearly uniform at approximately 1°C throughout the southern basin.

In order to use satellite data to estimate the total amount of material suspended in the plume, the AVHRR channel 1 reflectance for the 1 April 1996 image was compared with measured TSM in the corresponding pixel. The result was TSM = 2.87*R – 6.48 (r^2 = 0.996, n=6), where TSM is in mg/L and R is percent reflectance (0 to 100). This equation

was applied to all pixels in the 1 April image (Fig. 1c). TSM was limited to a conservative maximum of 10 mg/L, the maximum value that was measured in plume surveys that did not include any stations less than 20 m deep. The plume was defined as areas where calculated TSM was greater than 2.5 mg/L, a value greater than twice the measured open lake concentrations. This yields a plume area of 7.55×10^8 m^2. In comparison, the surface area of the entire southern basin is 2.10×10^{10} m^2. Based on the CTD-transmissometer results, it was assumed that TSM was uniform with depth. The calculated total mass of material in the plume is then 1.0×10^9 kg, which is approximately equal to the estimated annual load of "mud" to the southern basin (Colman and Foster 1994). This amount of material would yield a TSM concentration of 0.7 mg/L if distributed uniformly throughout the southern basin. This estimate must be considered as lower than the potential maximum amount of sediments resuspended based on the assumptions given above and because the timing was late in the turbidity sequence measured at the water treatment plant (Fig. 3); 12 days after the major storm.

All of the water samples collected on 1 and 10 April were analyzed for organic content (Fig. 5). Several more extensive analyses were also performed on the larger samples collected from the small boat on 10 April (Table 1). Particulate matter from within the plume was characterized by low organic content compared with background lake particles. In addition to the lower concentration of organic matter, there was a substantial change in its composition across the TSM range (Fig. 5 and Table 1). Samples from the open lake, offshore of the plume, had a lower C/N ratio characteristic of fresh biogenic material while those in the high TSM plume region have a higher C/N characteristic of sediments. The $\delta^{13}C$ and $\delta^{15}N$ of plume and background samples were similar, but different from bluff organic materials.

TPP in the particles of the plume (1.2 ± 0.2 mg/g) were similar to levels measured on surficial sediments (0.90 ± 0.10 mg/g) collected within a 10 km radius of this location (T.H. Johengen, pers. comm.). Trap samples from 1995, Station T8, had a TPP concentration of (0.89 ± 0.11 mg/g) during January to March 1995. During the plume event in 1996, the near-shore trap samples from Station T10 had a TPP concentration of (0.63 ± 0.07 mg/g). The lower concentration in these trap materials may be attributable to particle sorting; more dilution by sand-sized materials would be expected in the nearshore trap (T10) than in the offshore trap (T8) or plume TSM more than a week after the storm. The portion of phosphorus measured as APP in the plume sample (Fig. 5) was much greater (47%) than nearby sediments (13 ± 4%), T10 trapped materials (6 ± 2%), or the offshore particulate samples (14%).

Fallout ^{137}Cs may potentially be used as a tracer of source materials and can contribute to estimating the residence time of new materials in the lake. The lake background sample (0.028 g ash recovered), had a ^{137}Cs activity of 100 ± 33 mBq/g total solids (Table 1), similar to trap and surface sediment values. The plume sample (0.41 g ash recovered), had an activity of 35 ± 3 mBq/g total solids. The large standard deviations principally reflect counting errors because the samples were so small and activities low. The low ^{137}Cs in the plume particulate matter implies significant dilution with particles that are ^{137}Cs depleted, which could be a combination of coarse-grained resuspended sediments or bluff material which had virtually no ^{137}Cs activity.

The organic concentration and composition of the bluff materials (Fig. 6) were generally distinct from any of the samples collected in the lake. The coastal bluffs between north Chicago and the Door Peninsula have been identified as the major source of particulate material to Lake Michigan (Colman and Foster 1994). If the assumption that these are the materials being resuspended during events is correct, then the particles must acquire a signature from the lake fairly rapidly.

Diatoms dominated the phytoplankton at this time and chlorophyll was nearly constant for all locations (Table 1). Total diatoms were most abundant at the open-lake station (1,630 frustules/mL) and slightly less at the plume edge (1,007 frustules/mL) than in the plume (1,198 frustules/mL). A small centric species (ca 7 µm in diameter), *Stephanodiscus minutulus* (Kützing) Cleve & Möller, accounted for over 50% of the diatoms at all stations (Table 1), and was most numerous at the open-lake station (70%). The plume station was distinguished by the abundance of another small centric, *Stephanodiscus parvus* Stoermer & Håkansson (24%), and trace amounts of *Diatoma tenue* var. *elongatum* Lyngbye. *Aulacoseira (=Melosira) italica* (Ehrenberg) Simonsen was observed at the open-lake station (11%) and the plume edge (3%), as were small numbers of *Rhizosolenia eriensis* H.L. Smith. Prominent because of their size, and common to all stations were *Asterionella formosa* Hassall, *Tabellaria flocculosa* (Roth) Knudson, *Fragilaria crotonensis* Kitton, and various

*Synedra*s. The non-diatom phytoplankton, largely comprised of unicellular picocyanobacteria and nanoplanktonic cryptophytes, peaked at the edge of the plume.

At the plume edge, the numbers and biomass of aloricate ciliates, mainly *Strobilidium humile* and *Urotricha* spp., and the heterotrophic dinoflagellate *Gymnodinium helveticum* was an order of magnitude higher than in the mid-plume (Table 1). The biomass of heterotrophic nanoflagellates, mainly represented by chrysophytes and choanoflagellates, was also highest at the plume edge. In contrast, the abundance of tintinnids, chiefly *Tintinnidium fluviatile* and *Tintinnopsis* sp. (140–210 µm cell length), were distributed more or less evenly along the turbidity gradient. Bacterial biomass was also elevated at the plume edge compared to the background and mid-plume stations. The overall heterotrophic microbial biomass and the ratio of heterotrophic to photosynthetic carbon were highest at the plume edge (Table 1).

DISCUSSION

Lake Michigan is the sixth-largest lake in the world and has a hydraulic residence time of about 62 years (Quinn 1992). For particle-reactive constituents, internal removal through sedimentation is much more rapid than outflow. Radiotracer studies with ^{239}Pu ($t_{1/2}$ = 25,000 years) and ^{137}Cs ($t_{1/2}$ = 30.2 years) show that > 95% of these tracers were removed from the water and transferred to sediments within a few years (Wahlgren *et al.* 1980, Thomann and DiToro 1983, Edgington and Nelsen 1986, Eadie and Robbins 1987). Although initial removal of particle-reactive tracers from the water is rapid (a few years), a small residual concentration remains in the water (either on particles, in biota, or in solution) and now diminishes exponentially on a time scale of decades. Studies of Thomann and DiToro (1983), Eadie *et al.* (1984), and Robbins and Eadie (1991) have shown that the small amount remaining in the system is primarily the result of an annual cycle of sediment resuspension and re-deposition that releases constituents from sediments back into the water. Observations of this plume event imply that this episodic process may be responsible for much of this sediment-water coupling.

The data collected in this study allow examination of three questions related to the winter-spring episodic event:

1) Are episodic events important in nearshore-offshore transport? Processes that may contribute to cross-shore flow are: flow reversals during changes in wind forcing, vorticity waves, and topographic steering (Lou *et al.* 2000). The observations support the hypothesis that the 20 March storm was responsible for the rapid initiation of the plume. Northerly winds can generate large waves in the southern part of the lake and produce currents that tend to run southward along the east and west coasts of the southern basin. These currents typically converge to produce offshore flow somewhere along the southeast shore, the exact location depending on the strength, direction, and duration of the wind. Long-period (4-day) vorticity waves, which progress cyclonically around the southern basin, are seen as anticyclonic rotation of the current vector at these nearshore locations (Saylor *et al.* 1980). The slight bulge in bathymetry and shoreline near Benton Harbor may contribute to the separation of the plume from the nearshore region. During the plume event in 1996, the flow at both mooring sites was predominantly northeastward, parallel to the isobaths, and cross-shore transport was evident in the satellite images just north of the moorings. The mass flux patterns in the traps from station T8 imply that most of the particle flow into this offshore depositional region was mediated by these storm events.

2) What are the sources of the resuspended sediment? With measured currents of only a few km/d, the materials observed in the plume must have been widely distributed in temporary sediment repositories prior to the onset of the event for it to have reached a scale of hundreds of km by the 22 March image (Fig. 1). Particles within the plume were much depleted in organic matter compared with lake background (Fig. 5). Since there is so little organic matter in the bluff sample, most of the particulate organic matter, even in the plume materials, must be autochthonous. The molar C/N ratio of the open-lake material was similar to fresh plankton, while the plume values were elevated, a consequence of mixing with degraded or terrigenous material. The ^{137}Cs activity of the plume sample was much lower than open lake or depositional sediment levels, implying a source of "dead" materials. Bluff material is a good candidate. After a period of time in the lake this material would acquire an organic component from autochthonous processes, but would remain depleted in ^{137}Cs.

3) Are the nutrient and light climates sufficiently altered to modify local community structure? Since this study examines only a single event and a small sample set, these results can only be

speculative. On a lake scale, it is known that the quantity and composition of phytoplankton strongly depends upon available resources (Holland and Beeton 1972, Kilham and Hecky 1988, Makulla and Sommer 1993) including light, phosphorus, silica, and nitrogen. Food quality (the composition of phytoplankton) is a major factor affecting the composition and production rates of invertebrates (pelagic and benthic) that in turn serve as prey for forage fish in coastal ecosystems (Barnhisel and Harvey 1995, Rand *et al.* 1995, Almond *et al.* 1996).

Phosphorus is the nutrient in least relative abundance for biota within the Great Lakes and is generally thought to limit annual primary productivity. While TPP is lower in the plume samples, the fraction of APP is higher in the plume than in the open lake. This result indicates that forms of phosphorus on the plume particles may be very distinct from those in the open lake. The NaOH extraction has been shown to be a good indicator of the amount of P which may be biologically available in sediments (Sagher *et al.* 1975) and represents non-apatite inorganic forms of P typically associated with Al and Fe hydrous oxides (Sonzogni *et al.* 1982). One possible explanation for the higher plume APP would be rapid adsorption of dissolved P by the clay particles. Depletion of the dissolved P pool within the water column would generate a potential for dissolution/re-equilibration of the large inventory of sediment P mineral phases, effectively creating a nutrient pump from the sediments (Froelich 1988) when they are resuspended. The estimate of approximately 1,000 kg of excess TPP in the plume over background, almost 2 weeks after the initiation of the plume, implies that this is an important process in sediment-water nutrient exchange. The resuspension and transport of particles from the coastal margin to the deeper water during these events may provide the explanation for the increase in total phosphorus in the water coincident with the development of the spring phytoplankton bloom observed by Brooks and Edgington (1994).

In the water column samples collected approximately 2 weeks after the initiation of the event and in the trap samples covering the event, the system appears to be responding to elevated nutrients provided by this resuspension event. The distribution of planktonic diatoms during the plume event in this study appears to be related in part to an affinity for nutrient levels. For example, *Diatoma tenue* var. *elongatum*, a species associated with high nutrients (Tarapchak and Stoermer 1976), was observed in trace amounts only in the plume and *Stephanodicus parvus*, also associated with high nutrient environments (Stoermer *et al.* 1987), comprised 24% of total diatom numbers there and only 3 and 4% at the other stations. Conversely, *Rhizosolenia eriensis*, a species associated with lower nutrient concentrations (Holland 1980), was observed at both the clear water station and at the plume edge, but not in the plume. *Stephanodicus minutulus*, the most abundant species observed (Table 1), is a cosmopolitan planktonic diatom, sometimes confused with other small centrics (Krammer and Lange-Bertalot 1991). It was found to be part of the spring flora of Lake Michigan, especially in the waters near the eastern shore by Holland (1969), where it was called *Stephanodicus tenuis* Hustedt. Figure 3d in Holland (1969) best illustrates the form found in this study. The post-event changes in biogenic silica and the $\delta^{13}C$ of the organic matter imply an increase in fresh diatoms into the traps. The combination of isotopically lighter, but lower organic carbon concentration in the traps suggests that these fresh materials were being rapidly remineralized.

The microbial food web biomass peaked at the edge of the plume (Table 1), suggesting that elevated concentrations of inorganic nutrients in the mid-plume become available for phytoplankton as light limitation associated with the high turbidity in the plume decreases. Under this scenario, POM and DOM produced by small but fast growing algae and cyanobacteria, along with resuspended organic matter will fuel bacteria and micrograzers that, in turn, result in higher nutrient cycling rates and carbon transfer through the overall planktonic community. The high heterotrophic biomass at the plume edge seems to support the above hypothesis. The small size of *S. minutulus* and *S. parvus* may predispose them to selective predation by microzooplankton. Grazing might account for the relatively low percentage of small diatoms at the plume edge, where nutrient-light interactions should be optimized for their production.

SUMMARY

The results imply that the mass of reflective substances in the plume is approximately equal to the total annual particle load to the southern basin of the lake. Since these fine-grained materials are excellent substrates for sorption it is hypothesized that this episodic event may play an important role in both the nutrient and contaminant cycling within the lake. Also, the offshore eddies in the southeastern portion of the plume coincide with the area of

maximum sediment accumulation in the lake, implying that this event, and others like it, also play an important role in shaping observed depositional patterns and in mediating subsequent sediment-water interactions. Results from this effort allow the following hypotheses to be posed for further consideration:

1) that the forced, two-gyre vorticity wave response of the lake to episodic wind events (Fig. 1f), modified by topographic steering, is a major mechanism for nearshore-offshore transport of particulate matter and associated constituents in the Great Lakes
2) that the plume is a result of the first winter-spring storm after ice-out and represents the resuspension of particulate materials (and associated constituents) that have been stored in the lake as surface sediment "floc" for a distribution of times, during which they have undergone differential diagenesis, and
3) that physical processes (resuspension, turbulence) associated with the plume event are important in determining the nutrient and light climate, and in structuring the biological communities throughout the spring isothermal period, and in setting the conditions for the critical "spring bloom" period

Proposed here is a conceptual model consistent with the compositional results. Silty-clay materials eroding from bluffs along the shore of Lake Michigan (Jibson *et al.* 1994) or from exposed glacio-lacustrine clays in relatively shallow waters form temporary deposits of particles in patchy, transient reservoirs at the sediment-water boundary. These reservoirs serve a very important function in mediating the movement and characteristics of particles, nutrients, and contaminants between their source and their ultimate sink. Bluff materials contain low concentrations of constituents commonly associated with sediments, including organic carbon, nutrients, and radionuclides. Initially, these particles are transported into temporary sinks or repositories within the coastal margin that are non-depositional in the long term (years to decades). With time, these common constituents will be absorbed, thereby labeling the particles, and modifying their properties. Local mixing processes blend these materials with the inventory of resuspendable sediments within the lake. Large episodic events like the plume event massively resuspend and transport these materials and re-expose them to the pelagic system where they are further altered by autotrophic and geochemical processes. This material serves as a food source for surface deposit feeders, suspension feeders, and the microbial food web.

ACKNOWLEDGMENTS

U.S. Coast Guard, Ninth District—Air Station Traverse City for helicopter support in the collection of water samples in the plume. Dave Morse and Jeff Johnson for their assistance in water sample collection from a small boat, Michael O'Malley, Superintendent of the St. Joseph water treatment plant, for providing intake turbidity data, and the University of Texas Marine Science Institute for providing a quiet environment to complete the manuscript. Partial funding for this effort was provided by the US EPA-GLNPO and ORD, NOAA-Coastal Ocean Program and the NSF-CoOP programs. The manuscript was substantially improved by comments from reviewers. This is GLERL contribution # 1093.

REFERENCES

Almond, J.M., Bentzen, E., and Taylor, W.D. 1996. Size structure and species composition of plankton communities in deep Ontario lakes with and without *Mysis relicta* and planktivorous fish. *Can. J. Fish. Aquat. Sci.* 53:315–325.

APHA. 1990. *Standard Methods for the Examination of Water and Wastewater*, 17th ed. American Public Health Assoc., Washington, DC.

Barnhisel, D.R., and Harvey, H.A. 1995. Size-specific fish avoidance of the spined crustacean *Bythotrephes*—field support for laboratory predictions. *Can. J. Fish. Aquat. Sci.* 52:768–775.

Bratbak, G. 1993. Microscope methods for measuring bacterial biovolume: epifluorescence microscopy, scanning electron microscopy, and transmission electron microscopy. In *Handbook of methods in aquatic microbial ecology*, Kemp, P.F., Sherr, B.F., Sherr, E.B. and Cole, J.J. (eds.), pp. 309–317. Boca Raton, FL: Lewis Publishers.

Brooks, A.S., and Edgington, D.N. 1994. Biogeochemical control of phosphorus cycling and primary production in Lake Michigan. *Limnol. Oceanogr.* 39: 962–968.

Colman, S.M., and Foster, D.S. 1994. A sediment budget for southern Lake Michigan: source and sink models for different time intervals. *J. Great Lakes Res.* 20: 215–228.

Eadie, B.J. 1997. Probing particle processes in Lake Michigan using sediment traps. *Water, Air, and Soil Pollution* 99:133–139

_____, and Robbins, J.A. 1987. The role of particulate matter in the movement of contaminants in the Great Lakes. In *Sources and Fates of Aquatic Pollutants*, pp. 319–364. ACS Advances in Chemistry Series No 216.

_____, Chambers, R.L., Gardner, W.S., and Bell, G.L. 1984. Sediment trap studies in Lake Michigan: Resuspension and chemical fluxes in the southern basin. *J. Great Lakes Res.* 10:307–321.

_____, Vanderploeg, H.A., Robbins, J.A., and Bell, G.L. 1989. The Significance of sediment resuspension and particle settling. In *Large Lakes: Ecological Structure and Function*, M.M. Tilzer and C. Serruya, eds. pp. 196–209, Springer Verlag.

_____, McKee, B., Lansing, M.B., Robbins, J.A., Metz, S., and Trefry, J.H. 1994. Nutrient enhanced coastal ocean productivity recorded in sediments from the Louisiana continental shelf. *Estuaries* 17:754–766.

_____, Schwab, D.J., Leshkevich, G.A., Johengen, T.H., Assel, R.A., Hawley, N., Holland, R.E., Lansing, M.B., Lavrentyev, P., Miller, G.S., Morehead, N.R., Robbins, J.A., and Van Hoof, P.L. 1996. Recurrent Coastal Plume in Southern Lake Michigan. *EOS (AGU transactions)* 77:337–338.

Edgington, D.N., and Nelson, D.M. 1986. The persistence of pollutants in large lakes: The lessons from studies of radioactivity. In *Application of distribution coefficients to radiological assessment models*, p. 250–266, T.H. Sibley and C. Myttenaere (eds.) Elsevier.

_____, and Robbins, J.A. 1990. Time scales of sediment focusing in large lakes as revealed by measurement of fallout Cs-137. In *Large Lakes: Ecological Structure and Function*, pp. 210–223, M.M. Tilzer (ed.). Springer-Verlag.

Fahnenstiel, G.L., and Carrick, H.J. 1992. Phototrophic picoplankton in Lakes Huron and Michigan: Abundance, distribution, composition, and contribution to biomass and production. *Can. J. Fish. Aquat. Sci.* 49: 379–388.

Froelich, P.N. 1988. Kinetic control of dissolved phosphate in natural rivers and estuaries: A primer on the phosphate buffer mechanism. *Limnol. Oceanogr.* 33: 649–668.

Gardner, W.D., Biscaye, P.E., and Richardson, M.J. 1997. A sediment trap experiment in the Vema Channel to evaluate the effect of horizontal particle fluxes on measured vertical fluxes. *J. Mar. Res.* 55: 995–1028.

Haury, L.R., Yamazaki, H., and Fey, C.L. 1992. Simultaneous measurements of small-scale physical dynamics and zooplankton distributions. *J. Plankton Res.* 14: 513–530.

Holland, R.E. 1969. Seasonal fluctuations of Lake Michigan diatoms. *Limnol. Oceanogr.* 14:423–436.

_____. 1980. *Seasonal fluctuations of major diatom species at five stations across Lake Michigan, May 1970–October 1972.* USEPA Report. EPA-600/3-80-066.

_____, and Beeton, A.M. 1972. Significance to eutrophication of spatial differences in nutrients and diatoms in Lake Michigan. *Limnol. Oceanogr.* 17:88–96.

Jibson, R.W., Odum, J.K., and Staude, J. 1994. Rates and processes of bluff erosion along the Lake Michigan shoreline in Illinois. *J. Great Lakes Res.* 20:135–152.

Kilham, P., and Hecky, R.E. 1988. Comparative ecology of marine and freshwater phytoplankton. *Limnol. Oceanogr.* 33:776–798.

Krammer, K., and Lange-Bertalot, H. 1991. *Susswasserflora von Mitteleuropa. Bacillariophyceae 3. Teil: Centrales, Fragilariaceae, Eunotiaceae.* New York: Gustav Fischer Verlag.

Krausse, G.L., Schelske, C.L., and Davis, C.O. 1983. Comparison of three wet-alkaline methods of digestion of biogenic silica in water. *Freshwater Biology* 13:73–81.

Leshkevich, G.A., Schwab, D.J., and Muhr, G.C. 1993. Satellite environmental monitoring of the Great Lakes: A review of NOAAs Great Lakes Coastwatch Program. *Photogrammetric Engineering & Remote Sensing* 59:371–379.

Lineback, J.A., and Gross, D.L. 1972. Depositional patterns, facies, and trace element accumulation in the Waukegan member of the Late Pleistocene-Lake Michigan formation in southern Lake Michigan. Illinois State Geol. Survey, Environ. Geol. Notes EGN-58.

Lou, J., Schwab, D.J., Beletsky, D., and Hawley, N. 2000. A model of sediment resuspension and transport in southern Lake Michigan. *J. Geophys. Res.* 105: 6591–6610.

Makulla, A., and Sommer, U. 1993. Relationships between resource ratios and phytoplankton species composition during spring in five north German lakes. *Limnol. Oceanogr.* 38:857–871.

Maturi, E.M., and Pichel, W.G. 1993. Cloud masking for CoastWatch satellite imagery. In *Proceedings, Oceans '93*, p. 369–374. Soc. Inst. Electrical and Electronics Engineers.

Menzel, D., and Corwin, N. 1965. The measurement of total phosphorus in seawater based on the liberation of organically bound fractions by persulfate digestion. *Limnol. Oceanogr.* 10:280–281.

Meyers, P.A., and Eadie, B.J. 1993. Sources, degradation and recycling of organic matter associated with sinking particles in Lake Michigan. *Org. Geochem.* 20:47–56

Montagnes, D.J.S., Berges, J.A., Harrison, P.J., and Taylor, F.J.R. 1994. Estimating carbon, protein, and chlorophyll a from volume in marine phytoplankton. *Limnol. Oceanogr.* 39:1044–1060.

Mortimer, C.H. 1988. Discoveries and testable hypotheses arising from Coastal Zone Color Scanner imagery

of southern Lake Michigan. *Limnol. Oceanogr.* 33:203–226.

Mullin, M.M., Brooks, E.R., Reid, F.M.H., Napp, J., and Stewart, E.F. 1985. Vertical structure of nearshore plankton off southern California: A storm and a larval fish food web. *Fish. Bull.* 83:151–170.

Norland, S. 1993. The relationship between biomass and volume of bacteria. In *Handbook of methods in aquatic microbial ecology*, P.F. Kemp, B.F. Sherr, E.B. Sherr,and J.J. Cole (eds.), p. 303–307. Boca Raton, FL: Lewis Publishers.

Putt, M., and Stoecker, D.K. 1989. An experimentally determined carbon:volume ratio for marine oligotrichous ciliates from estuarine and coastal waters. *Limnol. Oceanogr.* 34:177–183.

Quinn, F.H. 1992. Hydraulic residence times for the Laurentian Great Lakes. *J. Great Lakes Res.* 18:22–28.

Rand, P.S., Stewart, D.J., Lantry, B.F., Rudstam, L.G., Johannsson, O.E., Goyke, A.P., Brandt, S.B., Ogorman, R., and Eck, G.W. 1995. Effect of lake-wide planktivory by the pelagic prey fish community in Lakes Michigan and Ontario. *Can. J. Fish. Aquat. Sci.* 52:1546–1563.

Robbins, J.A., and Eadie, B.J. 1991. Seasonal cycling of trace elements, Cs-137, Be-7 and Pu-239+240 in Lake Michigan. *J. Geophys Res.* 96:17081–17104.

Sagher, A., Harris, R.F., and Armstrong, D.E. 1975. *Biological availability of sediment phosphorus to microorganisms*. Technical Report No. OWRT A-040-WIS, Water Resources Center, Univ. of Wisconsin, Madison, WI.

Saylor, J.H., Huang, J.C.K., and Reid, R.O. 1980. Vortex modes in southern Lake Michigan. *J. Phys. Oceanogr.* 10(11):1814–1823.

Schelske, C.L., Carrick, H.J., and Aldridge, F.J. 1995. Can wind-induced resuspension of meroplankton affect phytoplankton dynamics? *J. N. Am. Benthol. Soc.* 14:616–630.

Schwab, D.J. 1983. Numerical simulation of low-frequency current fluctuations in Lake Michigan. *J. Phys. Oceanogr.* 13(12):2213–2224.

_____, Leshkevich, G.A., and Muhr, G.C. 1992. Satellite measurements of surface water temperature in the Great Lakes: Great Lakes CoastWatch. *J. Great Lakes Res.* 18(2):247–258.

Sherr, E.B., Caron, D.A., and Sherr, B.F. 1993. Staining of heterotrophic protists for visualization via epifluorescence microscopy. In *Handbook of methods in aquatic microbial ecology*, P.F. Kemp, B.F. Sherr, E.B. Sherr, J.J. Cole (eds.), pp. 213–228. Boca Raton, FL: Lewis Publishers.

Sonzogni, W.C., Chapra, S.C., Armstrong, D.E., and Logan, T.J. 1982. Bioavailability of phosphorus inputs to lakes. *J. Environ. Qual.* 11:555–563.

Speziale, B.J., Schreiner, S.P., Giammatteo, P.A., and Schindler, J.E. 1984. Comparison of N,N-Dimethyformamide, Dimethyl Sulfoxide, and Acetone for extraction of phytoplankton chlorophyll. *Can. J. Fish. Aquat. Sci.* 41:1519–1522.

Stoermer, E.F., Kociolek, J.P., Schelske, C.L., and Conley, D.J.1987. Quantitative analysis of siliceous microfossils in the sediments of Lake Erie's central basin. *Diatom Research* 2:113–134.

Strickland, J. D. H., and Parsons, T.R. 1972. *A Practical Handbook of Seawater Analysis*, 2nd ed., Bull. Fish. Res. Bd. Can., No. 167.

Tarapchak, S.J., and Stoermer, E.F. 1976. Phytoplankton of Lake Michigan. In *Environmental Status of the Lake Michigan Region*. Vol 4. Argonne National Laboratory. ANL/ES-40.

Thomann, R.V., and DiToro, D.M. 1983. Physico-chemical model of toxic substances in the Great Lakes. *J. Great Lakes Res.* 9:474–496.

Wahlgren, M.A., Robbins, J.A., and Edgington, D.N. 1980. Plutonium in the Great Lakes. In *Transuranic Elements in the Environment*, W.C. Hanson (ed.), p. 639–683. Technical Information Center/U.S. Department Energy.

Williams, J.D.H., Syers, J.K., Harris, R.F., and Armstrong, D.E. 1971. Fractionation of inorganic phosphate in calcareous lake sediment. *Soil. Sci. Soc. Amer. Proc.* 35:250–255.

Submitted: 24 March 2000
Accepted: 28 February 2002
Editorial handling: Paul F. Hamblin