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VARIATIONS IN THE DISTRIBUTION OF SUSPENDED PARTICLES DURING AN UPWELLING EVENT IN LAKE MICHIGAN IN 1980

Gerald L. Bell and Brian J. Eadie
National Oceanic and Atmospheric Administration
Great Lakes Environmental Research Laboratory
2300 Washtenaw Avenue
Ann Arbor, Michigan 48104

ABSTRACT. To test the hypothesis that suspended fine-grained particles moving downslope within the nepheloid layer in Lake Michigan are periodically reintroduced into the nearshore and euphotic zones during upwelling events, temperature and transparency profiles were recorded and water samples analyzed for total suspended materials (TSM) during a strong upwelling event. The resultant data confirmed that there is periodic reintroduction of suspended materials into the nearshore and epilimnion during such events, and provided insight into the importance of the general resuspension process, especially in regard to differences between known sedimentation rates and the rate indicated by trap collections. Both upwelling and downwelling currents are disruptive processes that tend to keep the suspended particulates in motion and prevent them from rapidly becoming a permanent part of the bottom sediment. These currents redistribute suspended particulates and the associated chemical load, and may resuspend surficial sediments, especially from the slope and shelf regions. The reintroduction of fine-grained materials into the euphotic zone through upwelling events can play a large role in the long-term behavior and fate of persistent contaminants.

ADDITIONAL INDEX WORDS: Nepheloid layer, transparency, temperature, resuspension, suspended sediments.

INTRODUCTION

Analysis of nearshore water temperature data indicates that upwelling is a common event throughout the period of stratification in Lake Michigan (Mortimer 1971, Church 1945, Ayers *et al.* 1958, Noble and Wilkerson 1970). Upwelling events normally extend 10 to 20 km offshore during summer and may be even more extensive in late fall (Mortimer 1971). In 1966 Nobel and Wilkerson (1970) observed an upwelling event extending from the eastern shore to midlake. Temperature variations are greatest near shore in the middle reaches (north to south) of the lake; the magnitude of these changes is larger along the Michigan shore, and is lowest in the southern end of the lake (Chicago to Michigan City) (Mortimer 1971). Although the magnitude of the temperature variations is less along the Wisconsin shore, the upwellings last longer and the water temperatures are generally lower than those along the eastern side of the lake because of the prevalent winds from the southwest (Bell and Chambers 1976, Bell 1980).

Data from a detailed sediment trap program in southeastern Lake Michigan during 1977 and 1978 revealed the presence of a near-bottom nepheloid layer characterized by high concentrations of suspended particles and low water transparency (Chambers and Eadie 1981). A nepheloid zone with similar characteristics has been found in all of the Great Lakes (Bell *et al.* 1980). In the region of the study (Fig. 1), shelf (less than 25 m in depth) sediments are sandy, with less than 2% (by weight) of material finer than 64 μm. Sediments at the top of the slope are composed of silty sand and become finer-grained down the slope. The gradation from sand to silty clay is irregular to a depth of 40 to 50 m where the sand fraction is 50% of the total dry weight (Chambers and Eadie 1980). Below a depth of 50 m the gradation is more uniform, with silty clay comprising approximately 90% of the surface sediment at the base of the slope.

In the deeper water beyond the slope, the top 2 to 3 cm of the surface layer are composed of clayey to silty, light brown to reddish, very soft sediment

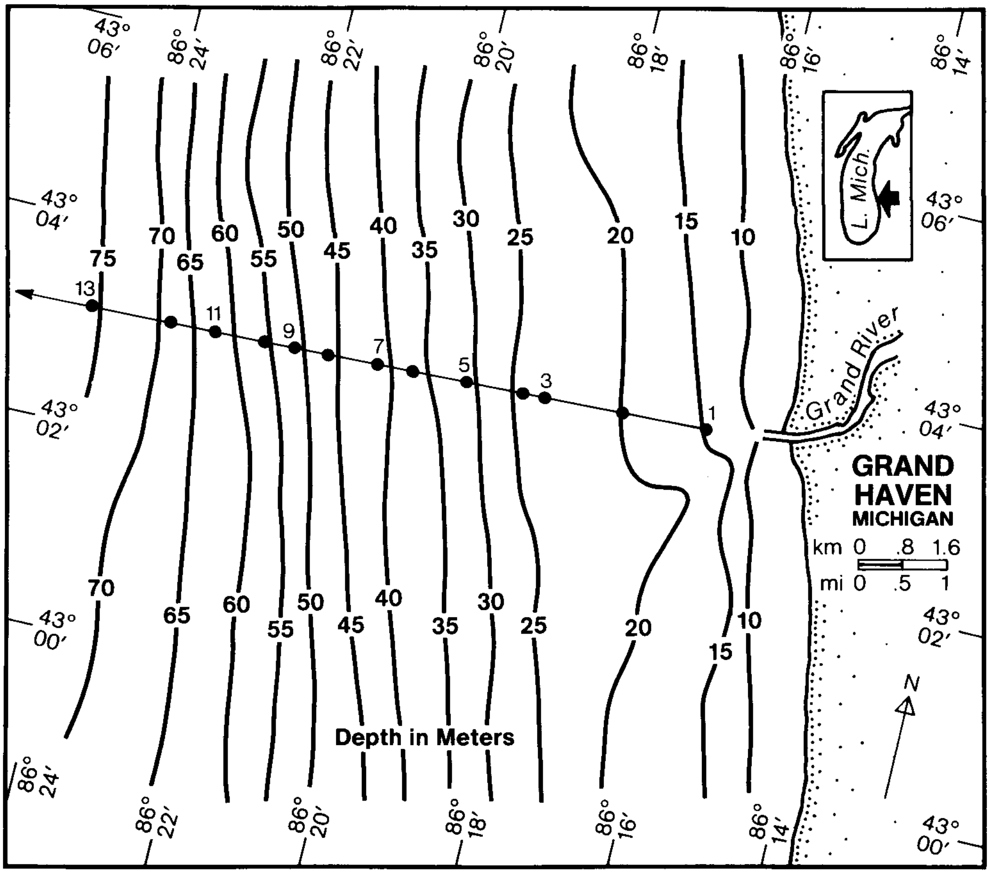

FIG. 1. Bathymetry contours (m) and sampling locations in the nearshore region of the study area. Stations 14 through 19 continue on the same bearing. The relative locations are shown along the top of Figure 2a-c. Bathymetry from Chambers and Eadie (1980).

with some easily disturbed brown floc at the surface. Divers observed a brown flocculated clayey material, which collected in ephemeral patches on the shelf and was present in all samples at depths greater than 11 m (Chambers and Eadie 1980, Nalepa and Quigley 1980). A surface layer of fine, organic-rich particles that collects in this region during the nonstratified winter period is resuspended and transported offshore during the early storms of spring to form the initial nepheloid layer (Chambers and Eadie 1981). Chambers and Eadie (1980) related the collection of fine particles along the shelf area to the quiet conditions provided by a cover of lake ice. The concentrations of flocculated clayey materials are not presumed to be unique to the Grand Haven area and are likely to be found in the other Great Lakes. The downslope movement of fine particles within this layer could be a significant transport mechanism for sediment-associated contaminants, such as chlorinated organic compounds and trace metals. Chambers and Eadie (1981) proposed that upwelling currents may reintroduce undesirable materials into the euphotic zone and that the ephemeral flocculated deposits on the shelf were most probably carried from the slope and deep basin by upslope transport.

Some process or processes are required to replenish the nepheloid layer, maintain its integrity as observed throughout the period of thermal stratification, and account for the large mass of resuspended materials that collects in the near-bottom traps (Chambers and Eadie 1981). Some instances of modification of the nepheloid layer by upwelling currents were observed during 1975 and again during 1979 along the eastern shore between Grand Haven and South Haven, Michigan (Bell *et al.* 1980). However, there were insufficient data to document these events carefully. Detailed documentation was needed to test the hypothesis that the suspended fine-grained particulates moving downslope within the nepheloid layer were periodically reintroduced into the nearshore and euphotic zones during upwelling events.

In this study, suspended particulates within the nearshore water column were measured during an upwelling event. The study confirmed that there was periodic reintroduction of suspended materials during such events and provided new insight into the importance of the general process.

METHODS

Previous studies in this area indicated that suspended particle concentrations in the slope region were more variable than those farther from shore, and that the stations should be spaced closer together along the slope. It was considered important to extend the sampling grid beyond any upwelling or other nearshore effect, to include the sediment trap station 18 (Fig. 2a) and to sample as rapidly as possible. This was accomplished by starting approximately 1 km west of the breakwater and sampling at approximately each 5-m change in bottom depth and extending the traverse to the topographic low lying east of the midlake high. Stations 1 to 17 were sampled during a 7-hr period on 14 October and stations 18 and 19 were sampled 20 hours later during a 1.7-hr period on 15 October. time on station ranged from 8 to 40 min. The internal wave period in Lake Michigan is very near, but slightly less than, the inertial period of 17 to 17.5 hours (Mortimer 1971), and the amplitude is expected to be in the 1- to 2-m range. Considering the magnitude of the upwelling event, any distortion by long internal waves is expected to be minimal.

Station locations were determined by a Loran C navigation system. Light transmission and temperature profiles were recorded at each station. A profile of water samples for total suspended matter (TSM) weights were taken in 5-L Niskin bottles at the even numbered stations. The deepest sample, at 1 m above bottom, was taken in a 5-L Niskin bottle modified to close when a weight suspended from the release mechanism contacted bottom. Sampling depths were selected to collect from discrete water masses based on the transparency profile. TSM weights were determined by filtering replicate 1- to 2-L water samples through a pre-weighed Gelman type A/E, 47-mm diameter glass fiber filter and drying the residue for 24 hr at 60°C. For control, blank filters were reweighed once for every 20 samples. The TSM values had a coefficient of variation of 6%. Samples were analyzed for particle-size distribution using a HIAC® particle analyzer in 11 size categories between 2.5 and 128 μm. The technique is similar to that used by Chambers and Eadie (1981). Continuous profiles of transparency and temperature were plotted on an XY recorder versus depths as determined by a pressure transducer. A Kahlsico transmissometer was calibrated to 100% light transmission in air along a 50-cm path. Each transparency profile was recorded while lowering the sensor from the surface to the bottom of the water column. A temperature profile was then recorded as the sensor was being raised back to the surface. The temperature sensor consisted of a YSI thermolinear thermister having a range of 0 to 25°C and a time constant of approximately 2.5 sec. Bias in the temperature profile was removed by shifting the entire temperature curve to agree with a bucket thermometer temperature taken at a depth of 2 m. The average correction was 0.22°C. Variations in the transmissometer calibrations were normalized from Secchi disc readings taken at each station. The entire profile was shifted to an average response determined by a plot of Secchi depths against the average transparency for the interval (Pinsak 1976). Surface samples were analyzed for specific conductance. Figures of temperature, transparency, and TSM were generated by manually contouring the data and the points derived by linear interpolation between all adjacent data.

Wind speed and direction data collected aboard the R/V *Shenehon* and from National Weather Service stations at Milwaukee and Green Bay, Wisconsin, and Muskegon, Michigan, as well as municipal water intake temperatures at Muskegon and Grand Rapids, Michigan, were used to interpret the changes in water temperatures. The Muskegon municipal water intake is 18.2 km north of the Grand Haven breakwater, 1.7 km from shore, and has a minimum depth of 12.2 m. The Grand Rapids intake is 9.75 km south of Grand Haven, 1.8 km from shore, and has a 3-m crib with a minimum depth of 12.5 m.

RESULTS

Climatological data from Milwaukee and Green Bay, Wisconsin, and Muskegon, Michigan, show that the upwelling event described in this paper was preceded by a period of approximately 1.75 days of northeast to southeast winds starting in the afternoon of the 8th. This was followed by approxi-

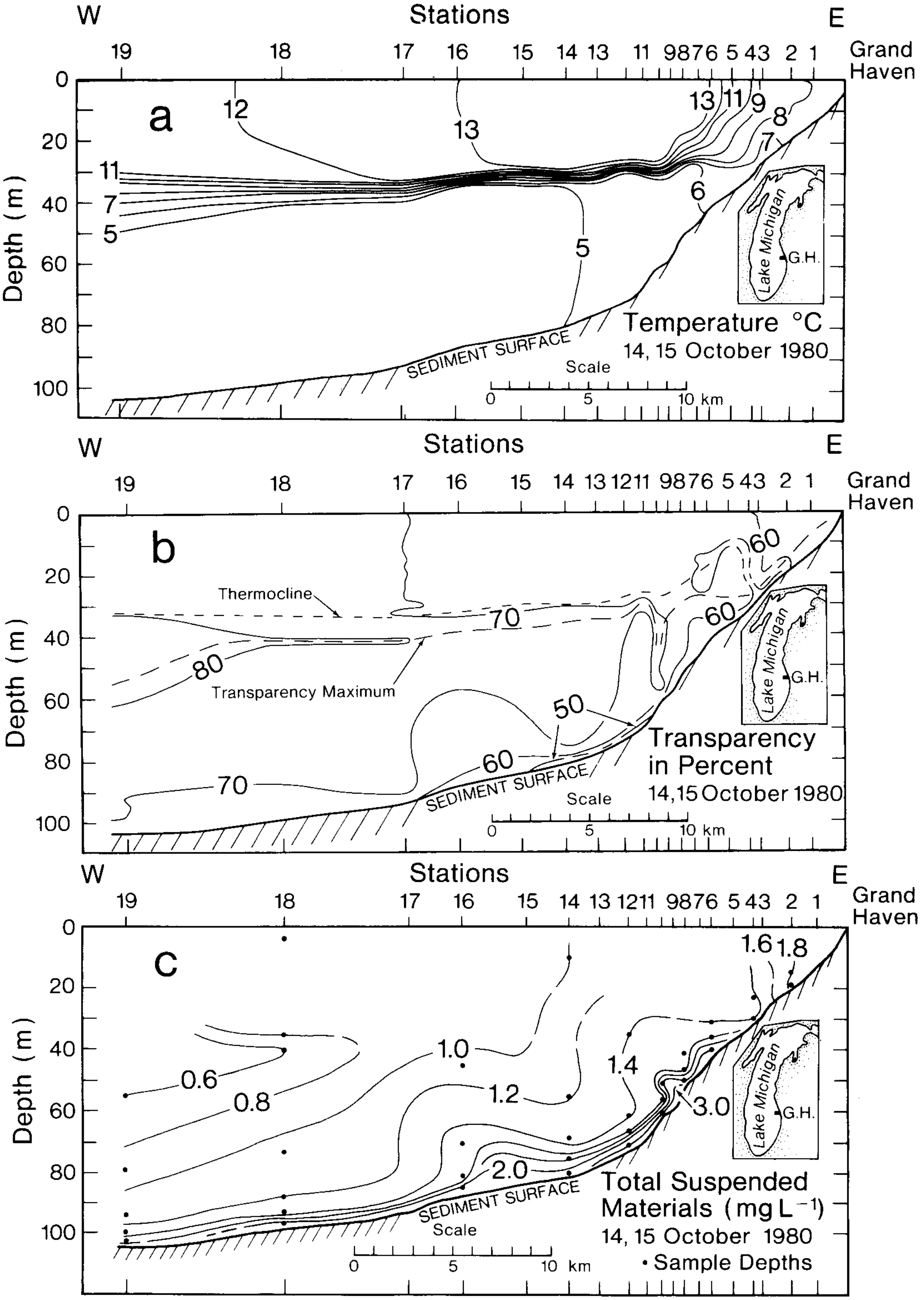

FIG. 2. Cross sections showing contours of temperature (a), transparency (b), and total suspended materials (c) through the study area. Temperature contours show upwelling along the eastern shore. Stations are numbered along the top of each cross section and sampling depths for TSM shown by dots on Fig. 2c. An average of 75% of the suspended particles within the 16-m internval above bottom were in the 2.5- to 4-μm size range, and 13% within the 4- to 8-μm range.

mately 12 hr of southwest winds, then by northwesterly to northerly winds on the 11th to 13th ranging from 3.6 to 9.3 m/s at Milwaukee and 3.4 to 8.7 m/s at Muskegon. The upwelling was reinforced by 2.5 days of easterly winds on the 13th to 15th, which ranged from 4.1 to 8.2 m/s at Milwaukee. Nearshore water temperatures show an influx of cold water during the first week in October. That event was also preceeded by strong northerly winds commencing on 2 October which ranged from 3.1 to 8.2 m/s at Milwaukee and 2.1 to 5.7 m/s at Muskegon. The northerly winds were followed by decreasing easterly winds.

The temperature structure shows a well developed thermocline tipped upward toward the shore between stations 9 and 17 (Fig. 2a). In the first 8 km offshore, the upwelling broke up this stratification and the warm water was forced offshore between stations 6 and 16. The highest surface water specific conductance values are at stations 8 and 10, and the lowest value is at station 4 in the region of intense upwelling, indicating that the nearshore water mass has been moved offshore by the upwelling water.

Lowest transparencies were observed in the nearshore area and immediately above the sediment-water interface near the base of the slope (Fig. 2b). Variations in turbidity were less regular and the water generally more transparent than had been anticipated. The highly variable conditions in the region between stations 3 and 12 are believed to have been produced by the pronounced upwelling event in progress. The sampling time of 3.9 hr for stations 3 through 12 represents approximately 3% of the total upwelling event. The upward and westward curving of the 60% transparency contour near shore suggests that the near-bottom suspended materials were being swept up the slope and mixed back into the water column. The lakeward movement of suspended materials above the thermocline is indicated by variations in the 60% transparency contour (Fig. 2b) between stations 2 and 7, by the region of 60% to 70% transparency that extends westward to station 17, and by the upward and westward deflection of the contours of TSM (Fig. 2c) between stations 2 and 18.

Since the optical system was approximately 15 cm (6 in.) above the sediment-water interface when the transmissometer frame contacted the bottom, any turbidity observed above the point of contact should not have been caused by lowering the instrument into the sediment. If there were easily disturbed materials present at the sediment-water interface, they may have been recorded on the lowermost part of the recorder trace.

The bottom portion of each transparency profile was examined for indications of easily disturbed materials at the sediment-water interface. Profiles at stations 1 and 2 showed only slight deflections (decreased transparencies) at the bottom of the recorded traces. This absence of turbidity suggests a surface essentially swept clean of such materials. A zone of more transparent water immediately above the bottom supported this inference. As the upwelling currents resuspend the easily disturbed sediments and sweep the initial concentration of suspended particulates from the area, a subsequent decrease in turbidity is to be expected as the less turbid offshore water is continually moved shoreward. In support of our findings, Dr. Barry M. Lesht (Argonne National Laboratory, Argonne, Illinois, personal communication, 4 and 7 May 1982) observed an initial flow of turbid water accompanied by increased current velocity at the beginning of upwelling events; this was then followed by a flow of less turbid water. His observations are based on transmissometer, current, and water temperature data recorded within 1 m of bottom during a study in October 1981 at a station near the top of the slope and 2.5 km SSE of our station 4.

Profiles at stations 3 and 4 had zones of high transparency close to the bottom, and showed only a minor decrease in transparency immediately above the bottom. An abrupt decrease in transparency occurred within the bottom 1 m of nearly all profiles lakeward from station 4. The thickness of this zone of concentrated suspended materials overlying the bottom varied from 3 to 6 m and increased down the slope, but nowhere reached the thickness of 10 to 20 m or the high particulate concentration and the corresponding low water transparency (0 to 20%) observed by Chambers and Eadie (1981) during summer of 1977 and 1978. The water within the nepheloid layer was more transparent than that commonly present during the season of thermal stratification. The presence of low-turbidity water and relatively more uniform transparency profiles westward from the bottom of the slope reflects the redistribution and thinning of the suspended materials by encroaching deep lake water. The minor increase in water clarity at 95 m (station 19) and variations in the 70% transparency contour at stations 13, 14, and 17 (Figs. 2b, 3) also suggest the encroachment of less turbid water. The overall thickness of the nepheloid layer below the

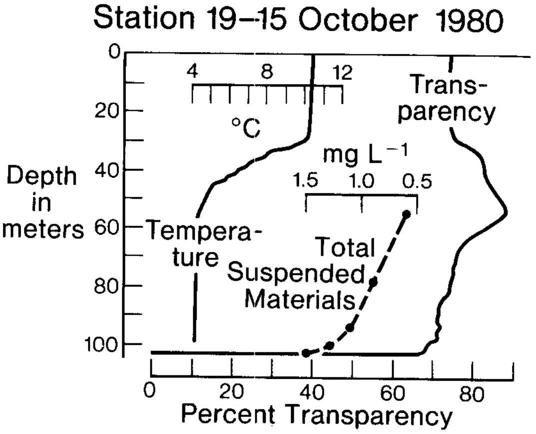

FIG. 3. Profiles of temperature and transparency showing the top of the nepheloid layer near 55 m and an increase in suspended materials downward through the hypolimnion. Note the reversed scale for the TSM curve.

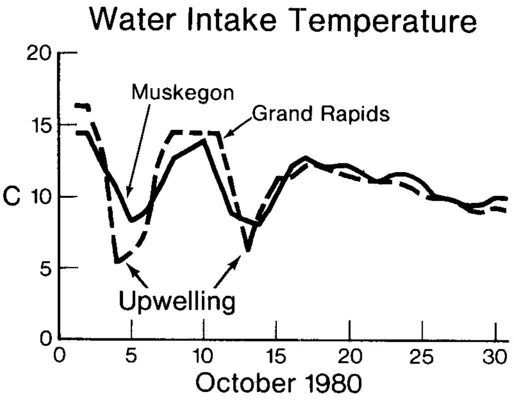

FIG. 4. Plot of daily average water temperature at two municipal intakes showing two pronounced upwelling events.

zone of maximum transparency increased lakeward, suggesting upward mixing of the suspended materials at least as far as 29 km from shore. Upward mixing of the suspended materials within the hypolimnion is indicated by the vertical deflection of the transparency, suspended materials, and temperature contours at stations 10 to 12 and 15 to 17 (Figs. 2a-c).

In general, there was a very good agreement between the distributions of TSM and percent transparency throughout the study area. This agreement is especially reflected by the similarity in the contour patterns between stations 8 and 17 (Figs. 2b and c). The mid-depth wedge of clear water at stations 18 and 19 (Figs. 2b, 2c, and 3) also correlates well with the region of lowest TSM values.

DISCUSSION

Daily average water intake temperatures for both Muskegon (18.2 km north) and Grand Rapids (9.75 km south) illustrate a pronounced 5-day period of upwelling with a maximum nearshore cooling on 13 and 14 October 1980 (Fig. 4). Data from both municipal intakes show that a more intense upwelling during the first week in October preceded this event. On 4 October a minimum daily temperature of 5.6°C was recorded at the Grand Rapids intake. Between 10 and 15 other upwelling events exceeding 2 days in duration were recorded at the Grand Rapids intake from May through September 1980.

A review of recent and historic water temperature data shows that upwelling and downwelling events are common along both sides of Lake Michigan. The daily intake temperatures from Muskegon and Grand Rapids for the period 1975 through 1981 show a succession of events occurring yearly during the period of thermal stratification. These events continue late into the year, but become increasingly difficult to discern from temperature variations. At times, the area affected by upwelling may extend along most of the eastern shore and may extend farther lakeward later in the year (Mortimer 1971). One such event recorded in 1955 (Ayers *et al.* 1958) was produced by strong northerly and easterly winds similar to those preceding the upwelling in progress at the time of our study. Therefore, it is presumed that most of the eastern shore area was affected by the upwelling on 13–15 October. Ayers *et al.* (1958) showed the bottom currents approach from the south to southwest and then moving up the slope near Grand Haven on 9 August 1955. He showed large variations in the direction of bottom current flow from the northern to the southern part of the lake during each survey. A study by Scott (1980) in 1972 showed the presence and distribution of nearshore currents at five sites around Lake Ontario under varied water temperature and wind conditions. Very strong longshore currents were repeatedly observed by Scott over the shelf and upper slope regions; similar currents are to be expected around Lake Michigan.

Strong winds from the north and east produce downwelling along the western shore, which then forces the bottom water into the nearshore area along the eastern shore. As the encroaching water mass moves upslope toward the shore during an upwelling event, the currents within this water mass impinge on the bottom and are deflected upward along the slope. This should result in increased velocities along the bottom. Depending upon the magnitude of the event, these increased currents transport the suspended materials and may be strong enough to erode and resuspend materials from the bottom along the slope and shelf regions. Chambers observed bottom currents greater than 10 cm/s at a depth of 25 m in the study area that were capable of moving silt and very fine sand (Chambers and Eadie 1980).

Lesht *et al.* (1982, Fig. 1) observed current speeds near bottom ranging from 2 to 16 cm/s during an upwelling event from 6 to 10 October 1981. A graph of water temperatures from the Muskegon and Grand Rapids municipal intakes during October 1981 was compared with Figure 4. The temperature variations of 10 to 15 October 1980 are similar to those of 6 to 10 October 1981. It seems reasonable to presume that the current speeds during the 10 to 15 October 1980 upwelling event were in the same general range as those observed by Lesht.

The data obtained during this study allow us to make an order of magnitude estimate of the amount of fine-grained materials reintroduced into the surface water of the southeastern region of Lake Michigan through upwelling events. The amount of reintroduced fine-grained TSM is equal to the volume of upwelled water reaching the euphotic zone [conservatively estimated as: 28 km longshore (water intake data) X 5 km offshore (Fig. 2a) X 30 m depth of thermocline = 4.2×10^9 m^3] times the increased TSM concentration within the upwelled water (estimated as 0.2 mg L^{-1} from Fig. 2). This amounts to 8.4×10^5 kg suspended matter reintroduced per event. If there are 10 such events per year, then approximately 8.4 million kg of fine-grained materials are reintroduced into the euphotic zone from the nepheloid layer. In terms of sediment-associated contaminants with concentrations of 100 part per billion, such as PCB (Rice *et al.* 1982, Eadie *et al.* 1982), this amounts to 6.7 g km^{-2} yr^{-1}. To put this in perspective, whole lake atmospheric PCB input estimates range from 6,900 kg yr^{-1} (Eisenreich *et al.* 1981) to approximately 500 kg yr^{-1} (Andren 1982). Dividing this load by the lake surface area (57,750 km^2) yields a load range of 8.7 to 119 g km^{-2}yr. These calculations indicate the potential impact that could be produced by the reintroduction of sediment-associated contaminants.

Both upwelling and downwelling currents are disruptive processes that tend to keep the suspended particulates in motion and prevent them from rapidly becoming a permanent part of the bottom sediment. The large volume of materials recovered in sediment traps within the lower part of the nepheloid layer far exceeds the calculated sedimentation rates determined for the area by Robbins and Edgington (1975). Chambers and Eadie (1981) calculated that an average of 84% of the materials collected in traps placed near the bottom could be resuspended materials.

We suggest that these upwelling and downwelling currents, as well as other deep currents, keep the particulate materials suspended and in motion. Most of these slowly settling particles do not fall to the bottom and remain there, but continue in motion, providing a continuous supply of materials to the traps. Somewhat like a giant conveyor, these currents circulate the suspended materials into the vicinity of the trap, where a portion of this resuspendable pool is collected.

Contours of temperature, transparency, and TSM are useful in showing the distribution of particulates and provide a basis for determining the suspended material load. Data on the currents, especially near bottom along the slope as well as at selected sites farther offshore, are needed to complete any similar study. The importance of municipal water intake temperature data near the area of study should not be underestimated. Such data provided continuous temperature records which supported the results of our study and permitted insight into the duration and magnitude of the upwelling event.

CONCLUSIONS

A better understanding of the general role of the upwelling and downwelling processes in the resuspension and movement of particles has been obtained by documenting the effects of upwelling currents on the suspended particle distribution during this study. Our data confirmed the hypothesis that upwelling currents redistribute suspended materials within the nepheloid layer, and also reintroduce these materials into the nearshore and epilimnion. Upslope transport and redistribution of these materials are indicated by the distribution patterns of temperature, transparency, and TSM. The suspended materials were apparently being mixed into the overlying water in the nearshore region and then deflected lakeward over the top of the encroaching water mass. Most of the return (westward) flow was above the thermocline. The distribution of temperature, transparency, and specific conductance all indicated a westward flow above the thermocline.

We should not expect to see the same turbidity patterns develop during each upwelling event. In general, these patterns will vary with the velocity, direction, and proximity to the bottom of the upwelling currents; the timing with respect to the maximum upwelling; the variations in the available suspended materials; and the degree of thermal stratification. However, with each upwelling event there should be some resuspension and transfer of suspended materials upslope and reinjection of these materials into the upper part of the water column. Additional studies of both upwelling and downwelling events are needed. The distance offshore and the depth to which the nepheloid layer is modified during downwelling events is not well known.

Resuspension and the reintroduction of fine-grained particulates into the euphotic zone through upwelling events can play a large role in the long-term behavior and fate of persistent contaminants such as PCB. This role will become more important as the loading of contaminants to the lake decreases and the particle-associated contaminants already in the system are repeatedly reintroduced into the euphotic zone.

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