J. Great Lakes Res. 19(2):368–378
Internat. Assoc. Great Lakes Res., 1993

Measurement of Horizontal Sediment Transport in Green Bay, May-October, 1989

Nathan Hawley and Joseph Niester

Great Lakes Environmental Research Laboratory
National Oceanic and Atmospheric Administration
2205 Commonwealth Boulevard
Ann Arbor, Michigan 48105

ABSTRACT. Time series measurements of water transparency were made at stations located in the passages on either side of Chambers Island from May through October, 1989. These data were combined with the current measurements of Miller and Saylor (1993) to determine the sediment transport into and out of southern Green Bay. The data show that the sediment flux past Chambers Island is driven primarily by the non-tidal circulation in the two channels; both tidal and storm effects are of secondary importance. The cumulative sediment flux is southward through the western channel and northward in the eastern channel with a small net transport of sediment into the southern bay. Since the sediment load from tributaries to the bay is much greater than the transport in the channels, this excess sediment must be stored in the southern bay.

INDEX WORDS: Sediment Transport, Transparency, Lake Michigan.

Introduction

Green Bay (Fig. 1) is a long, narrow, and relatively shallow bay connected to the western side of Lake Michigan's northern basin. The primary tributary is the Fox River which empties into the bay at its southern end. Both the water and sediment in the southern part of the bay (defined as the area south of Chambers Island) are heavily polluted, primarily due to the discharge of inadequately treated waste water by municipalities and industrial plants. Since many of these pollutants are adsorbed onto and transported by fine sediments, any attempt at improving the bay's environmental quality requires some knowledge of the movement of suspended sediment into and out of the bay. Measurements of both the water movement and the suspended sediment concentration are required for this calculation. This paper presents the first calculations of lateral sediment transport into and out of southern Green Bay.

Very few current velocity measurements have been made in Green Bay. In 1970 Moldin and Beeton made conductivity measurements in the bay and found that the Fox River plume flows northward along the eastern side of the bay. They suggested that there should be compensatory flow of Lake Michigan water southward along the western coast. This speculation was confirmed by Miller and Saylor (1985), who reported the first current measurements made in the bay. They found that the non-tidal circulation is affected by the winds, with counterclockwise circulation when the wind is from the southwest and clockwise circulation when the wind is from the northeast. They also found that although there are fairly strong semidiurnal tidal currents (dominated by the M_2 tide and the lowest mode of the Lake Michigan seiche), the short periods of these oscillations (12 hours or less) limit the maximum excursion of water to about 3 km in a single tidal cycle.

More recent current measurements described by Gottlieb *et al.* (1990) confirm previous work and also show that two layer flow exists during the stratified period (roughly June through October). During this time the upper layer (above the thermocline) acts as described by Miller and Saylor (1985), but flow in the hypolimnion is generally in the opposite direction. Gottlieb *et al.* (1990) also found that a wind-driven internal seiche strongly enhances mixing and transport both above and

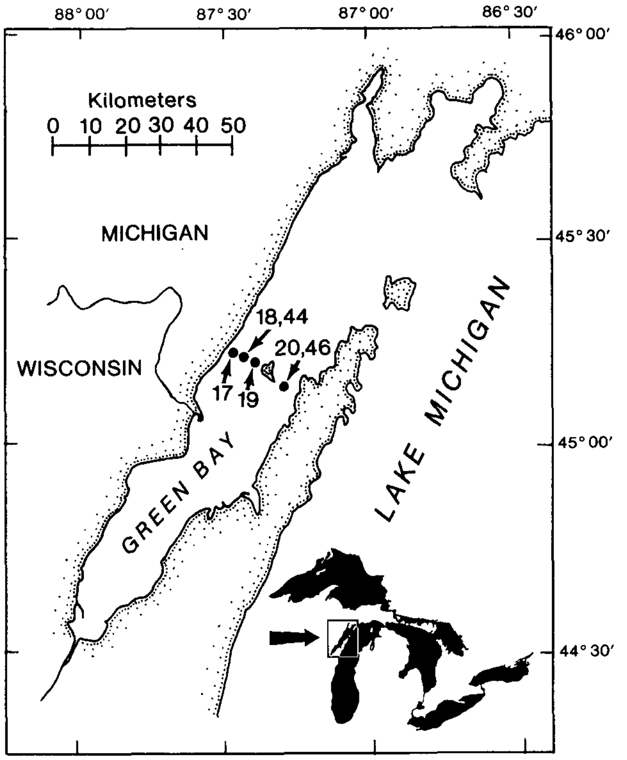

FIG. 1. Locations of monitoring stations in Green Bay.

below the thermocline, and that flow in the western channel is spatially non-uniform, with return flow occurring in both layers near Chambers Island.

Although some point measurements of suspended sediment concentration have been made by the U.S. Environmental Protection Agency, to date there has been no systematic attempt to determine the lateral transport of suspended sediment in the bay. In this paper we report the suspended sediment concentrations observed at a pair of moorings deployed during 1989 as part of the Green Bay Mass Balance Study. We then combine those measurements with estimates of the water volume flux to calculate the advective transport of suspended material into and out of southern Green Bay.

OBSERVATIONS

Instrumented moorings were deployed at two sites (stations 44 and 46, Fig. 1)—one in each of the passages around Chambers Island—beginning in May, 1989, and continuing until May, 1990. At both stations measurements of current velocity, water transparency, water depth, water conductivity, and water temperature were made at 1 Hz for 1 minute every 15 minutes. The averages of these measurements were computed and recorded. Difficulties with the instruments during the winter period (October-May) make those data very difficult to interpret, so this paper deals only with measurements made between May and October. During this period several current meters were also deployed in the two channels (stations 17,18,19, and 20 of Gottlieb *et al.* 1990). These flow data are more extensive than ours, so we have used them in the calculations below. Details of the station locations and deployment intervals are given in Table 1. Measurements from all of the current meters are only available from 22 May through 9 October, so we have restricted our discussion to this interval. Except for about 30 days at both the beginning and end of this period, the water in the bay was stratified. Figure 2 shows the locations of the instruments in each of the channels. As can be seen, the western channel is both wider and deeper than the eastern one. This is reflected in the higher velocities observed in the eastern channel. The substrates in the two channels are also different. In the western channel the bottom is a soft silty clay, while the bottom in the eastern channel is a hard clayey sand.

Only the transparency measurements recorded at stations 44 and 46 are used in this paper. These were made with Sea Tech transmissometers at three elevations: 0.9 m above the bottom (mab), 5 mab, and 6 m below the surface (Table 1). The pathlength of the transmissometers was 5 cm for the two transmissometers located 0.9 mab, and 25 cm for the other instruments. Conversion of the signal recorded by the transmissometers to beam attenuation coefficient allows direct comparison between the results obtained using instruments with different pathlengths. The moorings were serviced approximately every 5 weeks until October, 1989. At these times the batteries were changed, the data collected, and the sensors cleaned. Other than the times when the moorings were serviced, the transparency records are almost completely continuous, although there are a few instances when some data were lost. In these cases (which are at most two or three consecutive measurements) we made a linear interpolation from the neighboring observations to fill the gaps. The transparency readings were also examined in order to remove anomalously low values in the data. These occurred at irregular intervals and usually lasted less than an hour. We believe that they may have been caused by fish or other organ-

TABLE 1. Station locations and deployment periods.

Station	Latitude	Longitude	Water Depth (m)	Sensor Heights (mab)	Deployment	Deployed	Retrieved
44	44.24°	87.45°	28	0.9,5,21	1	9/5/89	21/6/89
44					2	21/6/89	25/7/89
44					3	25/7/89	29/8/89
44					4	29/8/89	4/10/89
44					5	4/10/89	15/5/90
46	45.15°	87.29°	17	0.9,5,10	1	9/5/89	22/6/89
46					2	22/6/89	25/7/89
46					3	25/7/89	29/8/89
46					4	29/8/89	4/10/89
46					5	4/10/89	15/5/90
17	45.24°	87.46°	20	10	*	21/5/89	13/10/89
18	45.22°	87.43°	30	5,13,18	*	21/5/89	12/10/89
19	45.21°	87.41°	33	5,14,21	*	4/5/89	12/10/89
20	45.14°	87.29°	17	5	*	20/5/89	12/10/89

* Stations 17-20 were occupied continuously between 21/5/89 and 12/10/89.

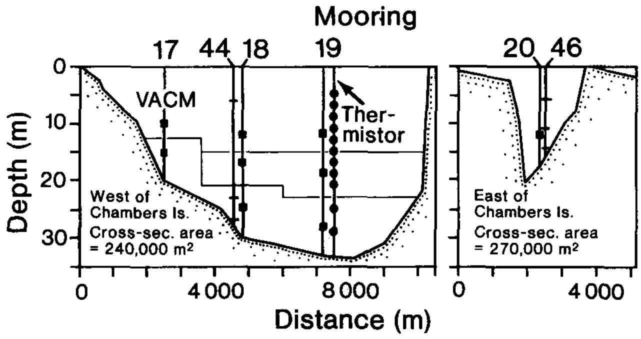

FIG. 2. ***Cross section of the two channels. The positions of the VACM current meters (squares) and transmissometers (horizontal lines), and the boundaries of the water masses used in the transport calculations are also shown.***

isms entering the light path of the transmissometer. These anomalous values were also replaced by a linear interpolation from the neighboring data.

To convert the beam attenuation coefficient (c) to total suspended material (TSM), aliquots of water were collected in triplicate at various times, depths, and stations. These samples were filtered through glass fiber filters (nominal pore size 1 micrometer), dried, and weighed. The results were then combined with transparency measurements made at the same time to produce a calibration curve relating TSM to beam attenuation. Based on 210 measurements (three measurements at each of 70 different stations, Fig. 3a)

$$\mathrm{TSM} = -1.09 + 2.33{*}c \qquad (1)$$

where TSM is measured in mg/L and c has units of m^{-1}. The r^2 value of Eq. 1 is 0.86. The equation gives negative TSM concentrations for values of c less than 0.47, but we never observed values that low. The good fit of Eq. 1 to data collected from throughout the southern bay at various times and depths suggests that the suspended material in the bay is relatively homogenous. Eq. 1 is similar to the equation determined by Hawley and Zyrem (1990) for southern Lake Michigan.

We estimate that the error in weighing the filters is about 0.2 mg/L. The calculated standard deviations of the replicates (Fig. 3b) range up to more than 1 mg/L, but most of the values are less than 0.5 mg/L. This variability is probably due to a combination of measurement error and real differences in TSM concentration from the separate aliquots (the triplicate samples were collected separately over a period of about 5 minutes), so we cannot resolve concentration differences to better than about 0.5 mg/L. The beam attenuation values are point measurements, so we have no way to determine their variability.

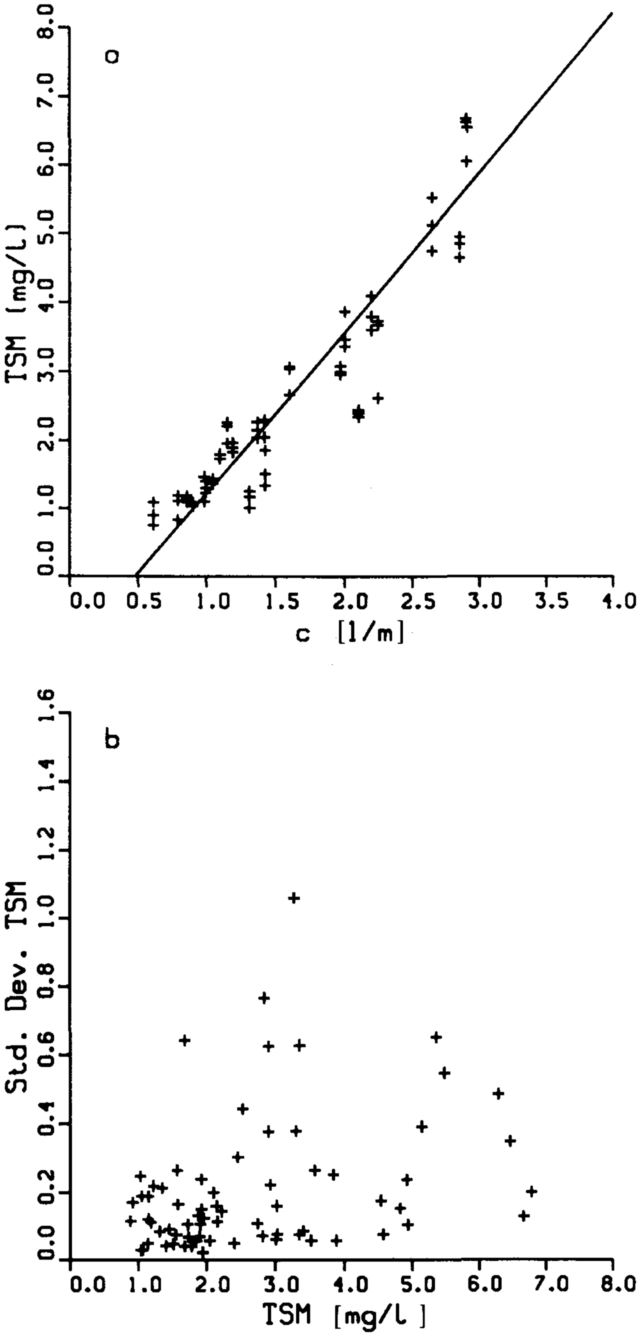

FIG. 3. a. TSM observations and the beam attenuation coefficients (c) used in the regression analysis. The line shown is Eq. 1. b. TSM concentration measurements and their standard deviations.

The TSM measurements at stations 44 and 46, and the component of the flow parallel to the channel measured at stations 18 and 20, are shown in Figures 4 and 5. In addition to tidal oscillations the measurements at all the stations in the western channel show an oscillation with about an 8-day period; this is the wind-driven internal seiche described by Gottlieb *et al.* (1990). Their spectral analysis shows that this seiche is more energetic than any of the shorter period oscillations. Since the tidal oscillations move material only a short distance, this seiche activity may be important in the transport of material through the western channel. Progressive vector plots show that the net transport was strongly southwesterly (into the southern bay) at stations 17 and 18 (all depths) but much less so at station 19 (again, at all depths).

At station 20 (Fig. 5) the seiche is less evident. Velocities are generally higher in this channel because of the smaller cross-section, but Gottlieb *et al.* (1990) found no significant peaks in the velocity spectra except for those at the tidal frequency. Flow at station 20 was predominantly to the northeast (out of the southern bay).

The uncorrected TSM concentrations shown in Figures 4 and 5 show that there was considerable fouling (due to biological growth) of the transmissometers during the deployments. Fouling was most severe during the summer, particularly at the upper levels, with uncorrected TSM concentrations reaching over 60 mg/L at station 46. In order to correct the measurements, arrangements were made to visit each station once a week and make a vertical profile of the water temperature, transparency, and conductivity with a clean set of sensors. Due to a variety of circumstances these profiles were not made as often as planned. Although the average time between the measurements is about 2 weeks, during one deployment (that beginning on 25 July) they were made only once at station 46 and not at all at station 44. Profiles were also made just prior to each retrieval.

By comparing the time series measurements to the corresponding profile measurements, we were able to estimate the degree of fouling for each transmissometer. Although the shape of the uncorrected TSM measurements suggests that the fouling might be modeled as either an exponential or a power curve, we were not able to develop a set of satisfactory corrections in this form. Instead we constructed a series of linear corrections as a function of time for each transmissometer during each deployment. The corrected TSM concentrations are also shown in Figures 4 and 5. Although the corrections do remove most of the error, in several cases (in order to avoid extremely small attenuation values) the corrections do not completely remove the

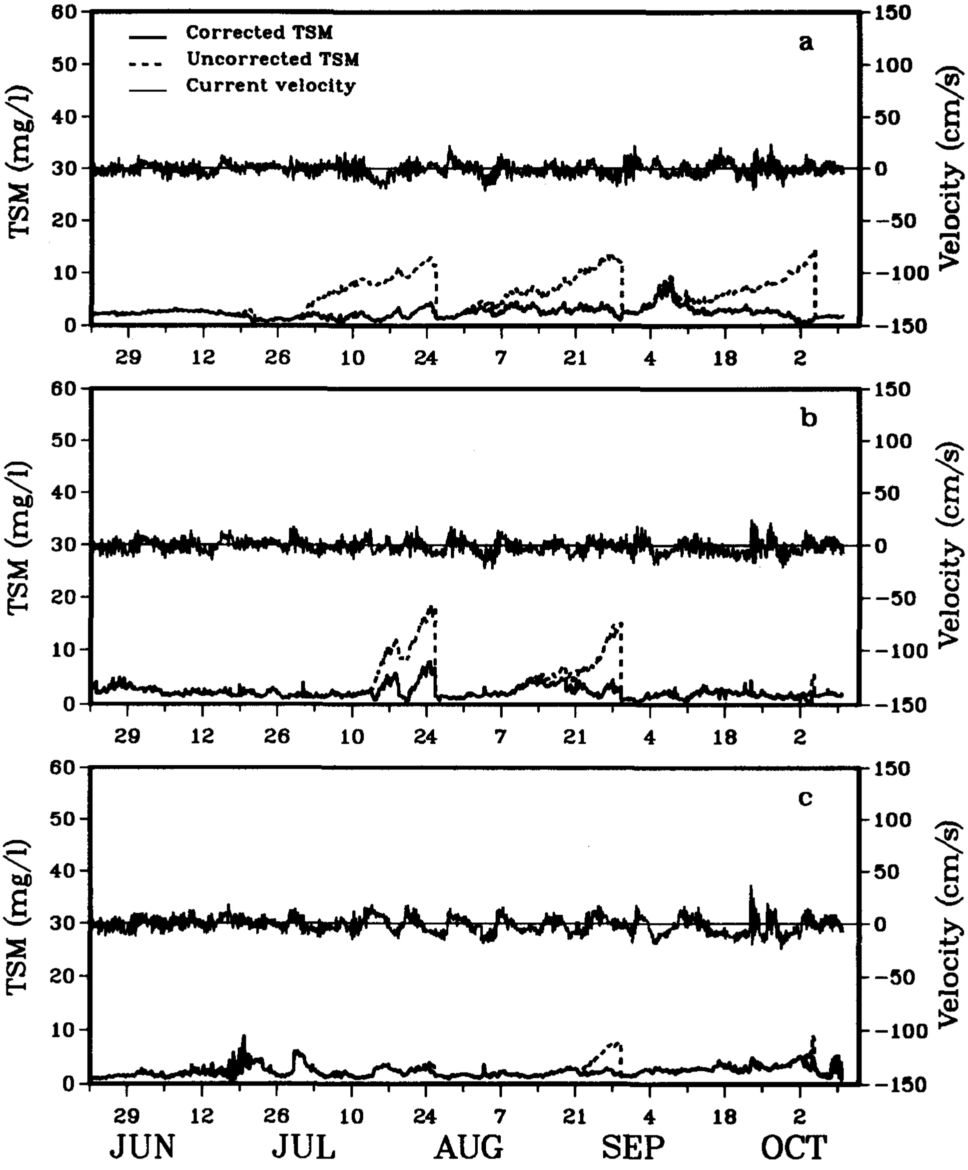

FIG. 4. Corrected and uncorrected TSM concentrations measured at station 44 and the along-channel component of the velocity measured at station 18. Negative velocities indicate flow into the southern bay. a. TSM concentrations from 0.9 mab and velocity measurements from 5 mab. b. TSM concentrations from 5 mab and velocity measurements from 13 mab. c. TSM concentrations from 21 mab and velocity measurements from 18 mab.

differences between the profile and time series measurements. Table 2 lists the differences between the corrected TSM measurements and those determined from the profiles. In some cases the remaining error is quite large, and there are instances in which the TSM values have been overcorrected. Since we do not know the true values of most of the TSM concentrations, it is impossible to determine exactly how wrong the corrected TSM measurements are. Further treatment of this problem is given below in the discussion section.

The corrected TSM concentrations usually are between 1 and 5 mg/L, although concentrations of up to 10 mg/L were observed during a storm on 23-29 September. High TSM concentrations are usually not correlated with high velocity measure-

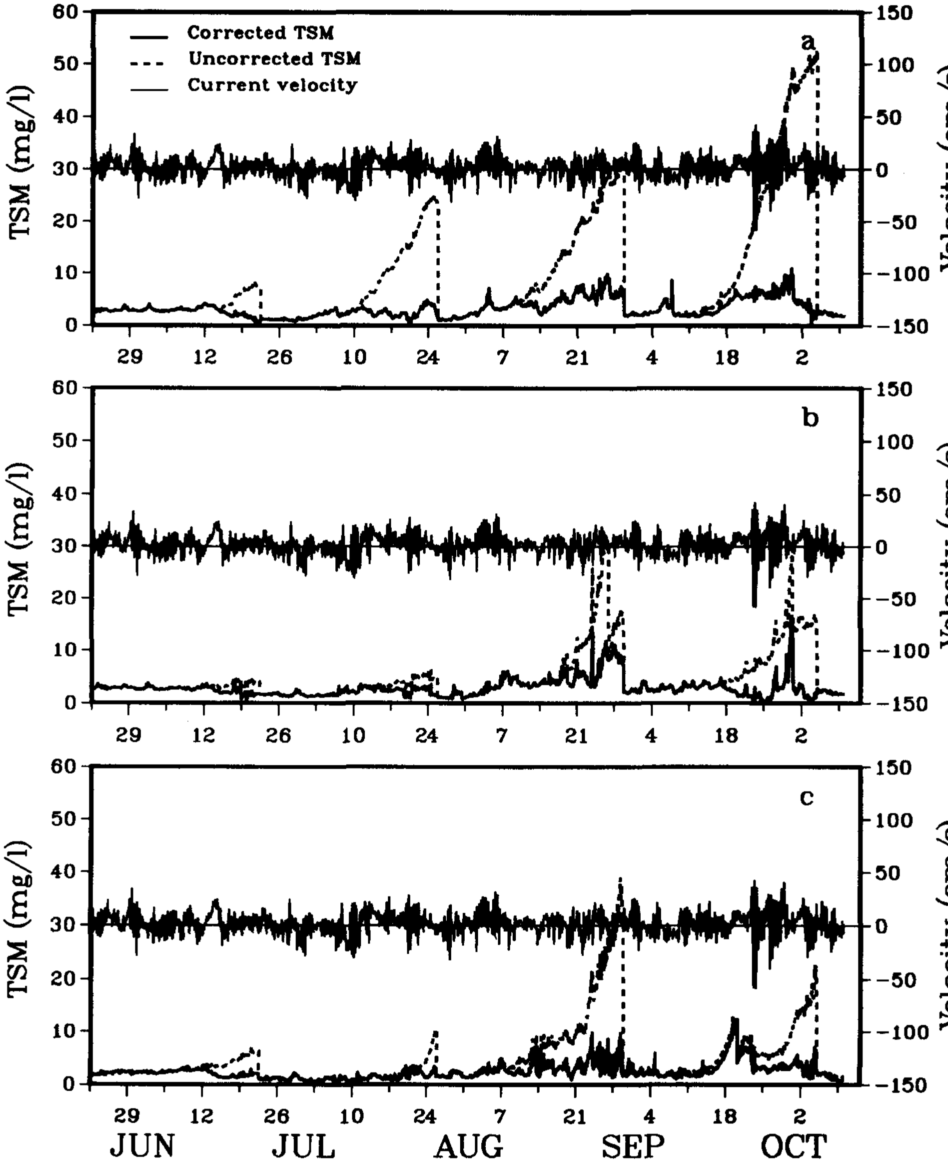

FIG. 5. Corrected and uncorrected TSM concentrations measured at station 46 and the along-channel component of the velocity measured at station 20. Negative velocities indicate flow into the southern bay. There was only one current meter at this station. a. TSM concentrations from 0.9 mab and velocity measurements from 5 mab. b. TSM concentrations from 5 mab and velocity measurements from 5 mab. c. TSM concentrations from 10 mab and velocity measurements from 5 mab.

ments, although there is some indication of sediment resuspension during the storm. Power spectra analysis shows no significant peaks in the TSM concentrations, nor do the TSM records show any significant correlation with the velocity measurements. The vertical profiles of TSM sometimes show a slight bottom nepheloid layer at station 44, but there was never one at station 46. Thus the transport of suspended sediment is due mostly to the ambient load transported by the residual circulation, and not to either local resuspension events or tidal activity.

TABLE 2. Difference between the corrected tripod and the profile TSM measurements in mg/L. Negative values indicate that the profile measurement was larger than the corrected tripod measurement.

	Station 44			Station 46		
Date	Top	Middle	Bottom	Top	Middle	Bottom
9 May	*	*	*	-0.11	0.19	-0.43
20 June	0.35	-0.41	0.06	-0.03	-0.42	-0.21
21 June	-0.69	-0.52	0.32	*	*	*
22 June	*	*	*	-0.17	-0.03	-0.07
29 June	0.67	0.56	1.05	0.45	0.37	-0.85
6 July	0.10	0.99	0.10	0.46	0.51	0.15
14 July	0.26	-0.43	-0.15	1.54	1.16	-1.31
20 July	0.07	-0.25	-0.01	1.25	-0.34	-0.65
25 July	1.49	4.23	-0.29	0.62	0.28	1.92
24 Aug	*	*	*	2.73	1.89	2.16
29 Aug	-0.15	1.60	-0.08	4.73	5.30	1.02
30 Aug	0.62	-0.76	-0.55	-0.45	-0.43	-0.61
6 Sept	4.85	-0.76	-0.73	2.43	0.63	-0.64
12 Sept	0.51	-0.51	-0.46	-0.41	0.54	-0.29
4 Oct	-0.47	-1.52	-0.17	0.15	-0.65	5.40

* indicates no profile measurement on this date.

LATERAL SEDIMENT FLUX CALCULATIONS

Miller and Saylor (1993) used low-pass filtered daily velocities from stations 17-20 to calculate the water volume flux in the two channels. They calculated the flux in the western channel by dividing the channel into segments—each containing one current meter—multiplying the measured current velocity by the cross-sectional area of each segment, and summing the results. The vertical boundaries were equidistant from the three deployment locations (Fig. 2), while the horizontal boundaries were midway between the current meters—except during the stratified period, when the thermocline (taken to be the 15° isotherm) was used as the upper boundary. The flux in the eastern channel was calculated by simply multiplying the measured current velocity by the cross-sectional area. Details of these calculations can be found in Miller and Saylor (1993). We used the same method to calculate the water volume flux, but in order to better incorporate temporal variations in TSM concentrations in our calculations, we used the hourly average current velocities rather than the daily velocities. Also, since we made TSM measurements at only one station in the western channel, we combined Miller and Saylor's segments into three slabs—using the same vertical boundaries—for our volume flux calculations (Fig. 2).

Use of hourly averages rather than the individual 15-minute measurements is justified by the relatively small variation in TSM over the averaging period—the variation in TSM over an hour is generally less than 5%. Lateral TSM gradients may also have been present, but we did not have enough equipment to monitor more than one location in each channel. The only information we have on lateral gradients comes from one occasion when we measured TSM profiles at both station 44 and station 19. The measurements (made an hour apart) show a TSM variation of about 15%. Since we have no way to estimate how large lateral TSM gradients were at other times, our calculations assume that TSM is laterally homogeneous in each channel. Although assuming lateral and short—term temporal homogeneity introduces some error into our calculations, we feel that these errors are relatively minor compared to the other measurement errors (see below).

The vertical profiles show that the TSM concentration usually varied with depth. To determine the sediment mass transport, we had to devise a method to determine the average TSM concentration in each slab from our time series measurements. By comparing the vertical profiles of TSM made at station 44 to the time series observations made at the three heights, we constructed three empirical equations that relate the time series observations to the vertically averaged TSM concentration in each of the slabs. In the bottom segment

$$TSM_B = 1.05*((TSM_{0.9} + TSM_5)/2) \qquad (2)$$

in the middle segment

$$TSM_M = 0.80*((TSM_5 + TSM_{21})/2) \qquad (3)$$

and in the top segment

$$TSM_T = 0.90*TSM_{21} \qquad (4)$$

where the numerical subscripts denote the height at which the TSM concentration was measured. The hourly average TSM in each slab was calculated and multiplied by the corresponding transported water volume. The results from each slab were then added to give the total sediment mass flux through the channel each hour.

Similar empirical calculations were made at station 46, but since there was only one velocity measurement, we computed the average TSM concentration for the entire water column prior to multiplying it by the water volume. The average TSM concentration for the entire water column was calculated as a weighted average of the measurements at the three heights

$$TSM_{46} = (0.6*TSM_{0.9} + 1.1*TSM_5 + 1.4*TSM_{10})/3. \quad (5)$$

Table 3 shows the differences between the results from Eqs. 2-5 and the average TSM concentrations calculated from the profile measurements. The results are quite good—in all but one case the difference in estimated concentration is less than 0.5 mg/L (the limit of our resolution for TSM). The weights in Eqs. 2-5 were determined by a least-squares criterion, and represent the vertical variations in the measured TSM profiles.

TABLE 3. ***Difference in the measured (from the profiles) and computed (from Eqs. 2-5) TSM concentrations in mg/L for the three water masses at station 44 and for the entire water mass at station 46.***

	Station 44			
Date	Top	Middle	Bottom	Station 46
9 May	*	*	*	0.00
20 June	-0.26	-0.38	-0.19	-0.11
21 June	-0.13	0.17	0.49	*
22 June	*	*	*	-0.09
29 June	-0.08	0.08	-0.31	-0.23
6 July	0.25	0.06	0.15	-0.06
14 July	-0.09	0.47	0.39	-0.14
20 July	-0.06	-0.04	0.06	-0.05
25 July	-0.05	-0.19	-0.02	-0.01
24 Aug	*	*	*	0.01
29 Aug	-0.05	0.20	-0.02	-0.10
30 Aug	-0.14	0.09	0.06	0.04
6 Sept	0.25	-0.71	0.06	0.07
12 Sept	-0.04	0.26	0.11	0.04
4 Oct	-0.06	-0.01	0.18	0.10

*indicates no profile measurement on this date

RESULTS AND DISCUSSION

The cumulative mass transport of sediment and the volume transport of water through the two channels are shown in Figures 6a and 6b. The net flow for both water and sediment is into the southern bay in the western channel and out of the southern bay in the eastern channel. The similarity in the shape of the curves for the sediment and water volume indicates that changes in the water volume transport are the primary causes of changes in the sediment transport. The effects of tidal action appear only as small perturbations; it is clear that the residual circulation and seiche action are the primary causes of sediment movement. The seiche action is particularly evident in the western channel, where several instances of flow reversals can be seen. Although secondary, the effects of changes in sediment concentration are not negligible. The increased sediment concentration in the eastern channel due to the storm on 23-29 September shows up clearly in Figure 6 and accounts in part for the relatively close agreement in the sediment transport estimates for the two channels. Although the storm also increased sediment concentrations in the western channel, its effect on the transport there is due more to flow reversals than to increased sediment concentration.

The cumulative net transport (the sum of the transport in the eastern and western channels) is shown in Figure 6c. The amount of sediment transported in each of the two channels during the observation period is approximately equal (1.99×10^7 kg into the southern bay through the western channel and 1.75×10^7 kg out of the southern bay through the eastern channel), with a net transport of 2.4×10^6 kg into the southern bay. This agreement is, in fact, better than the balance for the water volume (1.10×10^{10} m^3 in the western channel compared to 4.42×10^9 m^3 in the eastern channel). The maximum net sediment transport occurs on 23 August, when the transport into the bay exceeds that out of the bay by 1.06×10^7 kg—approximately four

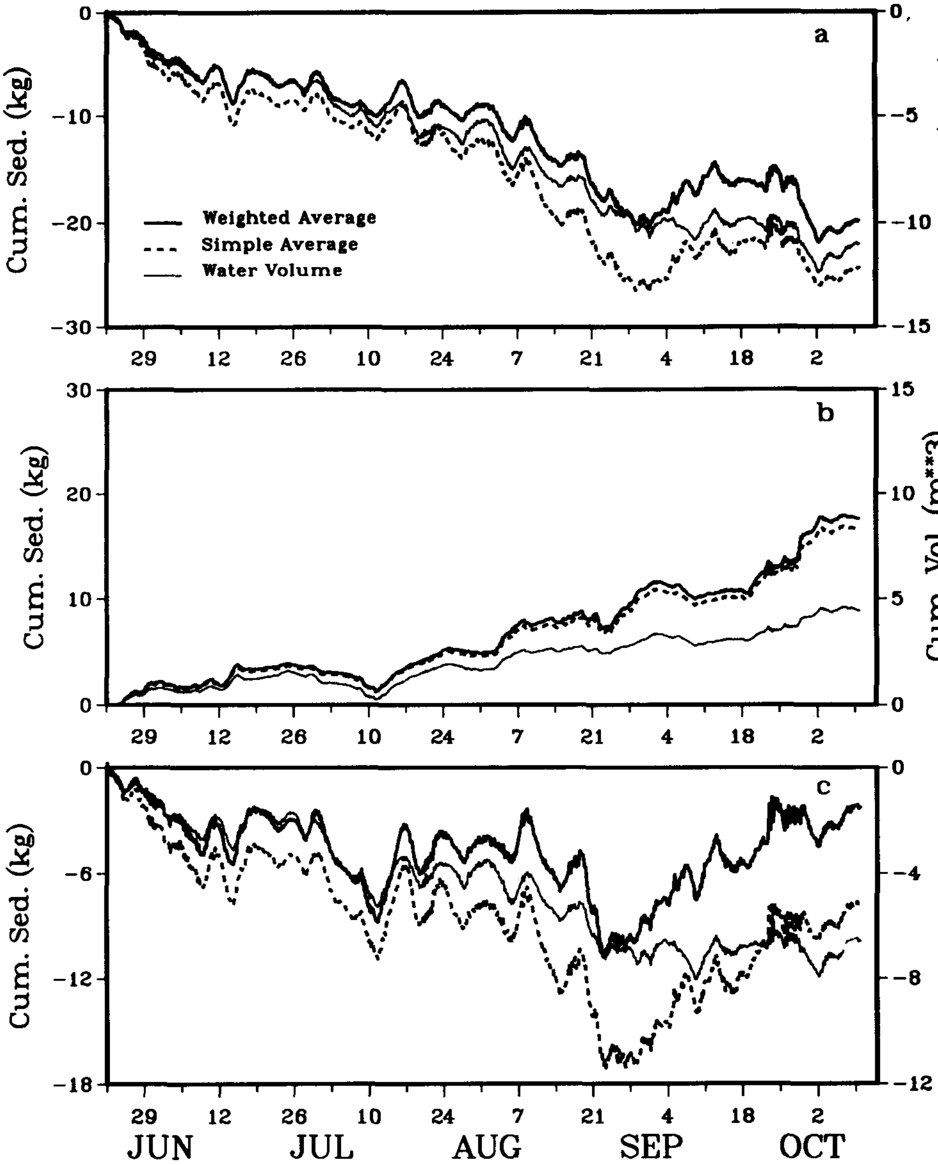

FIG. 6. Cumulative water volume and sediment transport. The weighted averages were computed using the formulas in Eqs. 2-5. Negative numbers indicate flow into the southern bay. Sediment masses in the plots have been divided by 1,000,000. Water volumes in the plots have been divided by 1,000,000,000. a. Transport through the western channel. b. Transport through the eastern channel. c. Net transport through the two channels.

times the net transport at the end of the observation period.

The volume of water transported through the two channels is highly variable—Miller and Saylor (1993) found that the mean daily discharge is -3.36 × 10^7 m^3/day in the western channel and 2.16 × 10^7 m^3/day in the eastern channel. This gives a net daily transport of -1.20 × 10^7 m^3/day, but the standard deviation of this transport is more than an order of magnitude larger (4.06 × 10^8 m^3/day). G. Miller (Great Lakes Environmental Research Laboratory, pers. comm.) estimates the error in the water volume flux calculations to be about 50%, so our estimates of sediment movement can be no better than that.

In addition to the errors in the water volume calculations, there are three major sources of error in the computed average sediment concentrations: the errors in the measurements used to determine Eq. 1, the errors in the fouling corrections, and the errors in the calculation of the average sediment concentration in each of the water masses (Eqs. 2-5). Weighing errors and natural variability limit the resolution of the calculations using Eq. 1 to no better than 0.5 mg/L. This value is greater than the maximum error introduced by using the equation (0.3 mg/l at a concentration of 10 mg/L). This sets a limit on the resolution for all subsequent calculations.

Table 2 shows that the errors remaining after the fouling corrections have been applied are frequently much greater than 0.5 mg/L. Unfortunately, there is no way to assess the actual error in the corrected TSM concentrations. These errors are, however, mitigated to a large extent by the use of Eqs. 2-5, since these equations use the corrected TSM concentrations (which include the errors shown in Table 3) as the input data. To investigate the effects of the weights used in Eqs. 2-5, we also computed the sediment mass transport using simple averages of the point measurements (Fig. 6). The results in the eastern channel are almost identical to those using Eq. 5, but in the western channel the sediment mass transport into the channel increases by about 5 x 10^6 kg. Although the general pattern of the net cumulative mass transport is similar to that calculated using Eqs. 2-5, the increased transport into the bay through the western channel increases the net transport into the bay during the entire observation period to 7.84 x 10^6 kg—about three times that calculated using Eqs. 2-5.

As the results in Table 3 show, the errors after Eqs. 2-5 have been applied are (with one exception) less than 0.5 mg/L. We thus feel fairly confident that the total error in determining the average TSM concentration in each of the channels is approximately 0.5 mg/L. Average sediment concentrations in the channels are about 2 mg/L in the western channel and 4 mg/L in the eastern channel, so the maximum error in the sediment concentration calculations is about 25% in the western channel and 12.5% in the eastern channel—considerably less than the error in the water volume calculations. Standard propagation of error methods show that the error in the computed sediment transport calculations is 56% for each of the three water masses in the western channel and 52% in the eastern channel. The total error for the net sediment transport is 1.38 x 10^7 kg. This is about six times the value calculated for the net transport, so actually the net transport could be in either direction. The magnitude of the net transport during the observation period is, therefore, between -1.14 x 10^7 and 1.62 x 10^7 kg.

Miller and Saylor (1993) found that the net water volume transport was out of the southern bay during the winter prior to our measurements, so on a yearly basis it seems likely that sediment is transported out of the southern bay. If we use their water volume measurements and assume an average concentration of 3 mg/L, then the total sediment transport during the winter is approximately 2 x 10^7 kg. Thus it seems likely that on an annual basis between 1 x 10^7 and 3 x 10^7 kg of sediment is transported out of the southern bay.

Data from the sediment trap study by Eadie *et al.* (1991) shows that the maximum vertical transport of sediment during the observation period is approximately 3.06 x 10^5 kg in the western channel and 1.9 x 10^4 kg in the eastern channel (errors in these values are 30% or less). Since these values are two to three orders of magnitude less than the corresponding lateral transport, lateral transport is apparently far more important than particle settling. In turn however, the lateral transport values are considerably lower than the estimated sediment loading to the bay. Data collected by the U.S. Geological Survey (House *et al.*, in press) show that the loading from the Fox River during the observation period is approximately 9.4 x 10^7 kg with an estimated error of 25% (P. Hughes, U.S. Geological Survey, pers. comm.). This is far more than is transported through the channels, so even if the net sediment flux through the channels is out of the southern bay, the bulk of the tributary load must be deposited and stored in that area. In addition, most of the tributary load was supplied during the spring runoff (25 May-19 June, 7 x 10^7 kg) when the sediment transported through both of the channels was an order of magnitude less (2.52 x 10^6 kg).

Tributary loadings are probably moved through the bay in a series of discrete resuspension-transport-deposition events until they either become permanently buried or are transported out of the bay. Our data are not comprehensive enough to state exactly how much of the tributary loadings are transported out of the southern bay or how long the process takes. They do, however, indicate that the bulk of the material must accumulate in the southern bay. Even if we assume that none of the sediment transported into the southern bay is exported back out during the same year, our data indicate that at most about one-third of the annual tributary load is transported into the northern bay. If we assume that all of the material transported into the bay is also transported out during the same year, then only about 10% of the tributary load can be exported into the northern bay.

CONCLUSIONS

In spite of the assumptions that we had to make and the errors inherent in the calculations, it seems clear that there is little or no net transport of sediment out of the southern bay during the summer. During this period the masses of sediment transported into and out of the southern bay are approximately equal, and are considerably less than the amount deposited in the southern bay by tributaries. This suggests that most sediments introduced into the southern basin (and any pollutants associated with them) are probably deposited and buried in the bay, at least temporarily. Material may be transported into the northern bay during the winter, although we have no measurements to calculate the actual amount. Rough calculations, however, suggest that between 10 and 33% of the annual tributary loading is transported into the northern bay.

Most of the observed sediment movement is due to transport of the ambient suspended sediment load by the non-tidal residual circulation. Transport by tidal or storm action, or in a bottom nepheloid layer, is of only secondary importance. Further refinement of these estimates will require far more detailed measurements of both the currents and the suspended load. In particular, our assumption of the horizontal homogeneity of TSM concentrations needs to be checked. Good winter measurements of the TSM concentration are also needed, as are both flow and TSM measurements made just south of Chambers Island

ACKNOWLEDGMENTS

We wish to thank the crew of the RV *Shenehon,* the engineering staff at the Great Lakes Environmental Research Laboratory, and H.J. Harris of the University of Wisconsin-Green Bay for field assistance. The Wisconsin DNR generously gave us permission to dock at their Sturgeon Bay facility. Barry Lesht of Argonne National Laboratory collaborated in the field program and made many useful suggestions regarding the manuscript. G. Miller also made suggestions regarding the manuscript. In addition, he and E. Gottlieb generously gave us access to their data and explained the water volume flux calculations to us. Helpful comments by P.F. Hamblin and an anonymous reviewer helped improve the manuscript. This contribution was written while the author was a visiting scientist at Argonne National Laboratory. This is GLERL contribution # 802.

REFERENCES

Eadie, B.J., Bell, G.L., and Hawley, N. 1991. *Sediment trap study in the Green Bay Mass Balance Program: Mass and organic carbon fluxes, resuspension, and particle settling velocities.* NOAA Technical Memorandum ERL GLERL-75, Ann Arbor, MI.

Gottlieb, E.S., Saylor, J.H., and Miller, G.S. 1990. *Currents and water temperatures observed in Green Bay, Lake Michigan, Part I: Winter 1988- 1989,* and *Part II: Summer 1989.* NOAA Technical Memorandum ERL GLERL-73, Ann Arbor, MI.

Hawley, N., and Zyrem, J.E. 1990. Transparency calibrations for Lake St. Clair and Lake Michigan. *J. Great Lakes Res.* 16:113-130.

House, L.B., Hughes, P., and Waschbusch, R.J. In press. Concentrations and loadings of polychlorinated biphenols to Green Bay from major tributaries, 1989-1990. U.S Geological Survey Open File Report. Madison, WI.

Miller, G.S., and Saylor, J.H. 1985. Currents and temperatures in Green Bay, Lake Michigan. *J. Great Lakes Res.* 11:97-109.

_______, and Saylor, J.H. 1993. Low frequency water volume transport through the midsection of Green Bay, Lake Michigan, calculated from current and temperature observations. *J. Great Lakes Res.* 19: 361–367.

Moldin, R., and Beeton, A.M. 1970. Dispersal of Fox River water in Green Bay, Lake Michigan. In *Proc. 13th Conf. Great Lakes Res.*, pp. 468-482. Great Lakes Res. Div. Publ. # 13. Univ. Michigan, Ann Arbor, MI.

Submitted: 7 July 1992
Accepted: 22 February 1993