

## Sediment Transport Model Validation in Lake Michigan

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**ABSTRACT.** A multiple sediment type, three-dimensional hydrodynamic and sediment transport model was applied to Lake Michigan to simulate conditions during the Spring 2000 resuspension event. Model predictions were compared to data gathered by the EEGLE project including turbidity and downward mass flux. The model predictions for turbidity compared well to observed data, especially in capturing the distinctive peaks in turbidity due to advection that occurred in the area of the resuspension feature. The advection peaks seemed tied to the presence of a highly-resuspendable pool of sediments that was transported by weaker winds during early Spring 2000. The model predictions at depths of 40 m in the area of the resuspension feature were more problematic, as the observed data in one location showed a significant turbidity peak at the time of maximum winds. The model underestimated turbidity at that particular location, yet model predictions of a very similar turbidity peak were seen at a similar depth. The different turbidity predictions at these locations were due to underestimation of offshore flow by the hydrodynamic model. The model generally underestimated downward mass flux, though the predictions for the time-intervals that included the time of peak winds and the following week were good to excellent. These intervals generally showed the highest downward mass flux. This work highlights the importance of multiple sediment types, their associated critical shear stresses for resuspension, and the presence of a very easily resuspendable sediment layer. The availability of comprehensive data set was also important.

**INDEX WORDS:** Sediment transport, Lake Michigan, resuspension.

### INTRODUCTION

Material in large lakes is thought to reside in resuspendable pools for decades or longer before eventually being transported to purely depositional areas. Radionuclide data show that resuspension is the primary mechanism of sediment-water exchange of this material, and that the time to transport materials to depositional basins is, on average, over 20 years (Eadie and Lozano 1999.) The sediment, while in a resuspension zone, can be a large source of contamination to the overlying water column. The details of sediment and contaminant

transport from the resuspendable areas to depositional basins are not well understood.

Lake Michigan is the fifth-largest lake in the world, and the third largest of the North American Laurentian Great Lakes. Lake Michigan has a volume of 4,920 km<sup>3</sup> and a surface area of 57,800 km<sup>2</sup>. The bottom sediments in Lake Michigan are contaminated with chemicals. These include PCBs, PAHs, transnonachlor, mercury, and atrazine. Bottom sediments can be resuspended and transported by energetic, episodic events (for example, storms with high winds.) Once the sediments are resuspended, contaminants, which are often hydrophobic and generally associated with bottom sediments,

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can desorb from the sediments and contaminate the water column. Researchers have estimated that re-suspension of bottom sediments is the main source of these chemicals to the water column (Eadie *et al.* 1984, Eadie and Robbins 1987, Robbins and Eadie 1991, Brooks and Edgington 1994). In a study of Grand Traverse Bay, an episodic event increased the water column inventory of PCBs and PAHs by as much as 30% (Schneider *et al.* 2002.)

In order to further develop understanding of long-term transport of sediments and associated contaminants from resuspendable pools to depositional basins, numerical models of sediment transport and fate in Lake Michigan were developed. An objective of the Episodic Events—Great Lakes Experiment (EEGLE) project was the study of the cross-margin (nearshore-to-offshore) transport due to episodic events. A large resuspension feature, first observed by satellite in 1980, tends to occur during mid-March to late-April off the southern coast of Lake Michigan. This resuspension feature was viewed as a candidate for cross-margin transport. A large amount of data was gathered as part of the EEGLE program, as well as the Lake Michigan Mass Balance program. These data were invaluable in the initialization and validation of the numerical model and included sediment grain size, measurements of suspended material, and downward flux as measured by sediment traps.

Sediment transport in Lake Michigan was previously modeled in two, quasi-three, and three dimensions (Schwab *et al.* 2000, Lou *et al.* 2000, Chu *et al.* 2000). In Schwab *et al.* 2000, depth-averaged hydrodynamics and wind-waves were used to drive a two-dimensional sediment transport model of Lake Michigan. Model predictions of suspended solids concentration were compared to satellite imagery of turbidity, and compared well, although they were not able to describe the spiral eddy seen in satellite imagery. Predictions of deposition amounts were reported, and were similar to long-term sediment accumulation. A quasi-three-dimensional sediment transport model of Lake Michigan (Lou *et al.* 2000) was driven by results from a three-dimensional circulation model and wind-wave model. Model predictions were compared to suspended solids concentrations at two locations. Predictions were generally good, with a tendency to overestimate turbidity, most likely due to their unlimited sediment bed, and assumption of a single-grain size. Multiple grain-size sediment transport work has been applied to the Adriatic Sea using the CH3D-SED model (Welsh *et al.* 1999, 2000).

CH3D-SED with two grain-size classes was applied to Lake Michigan (Chu *et al.* 2000). An idealized test case with uniform wind input showed some indication of plume-like behavior.

The work presented here includes three-dimensional hydrodynamics, wind-waves, and three-dimensional sediment transport modeling. Multiple grain-size classes were used. In previously mentioned sediment transport studies, the handling of the sediment bed (the aging of the bed such that all deposited material ended up in the same bed layer) caused the sediments and contaminants in the bed to be well mixed in the vertical direction. Because of this mixing, it was often difficult to track changing grain-size fractions in the bed, especially if deposition occurred over a very thick initial sediment bed. In the present model, discrete layers of sediment can be suspended and/or deposited without mixing between layers. This capability was essential in accurately predicting the long-term transport and fate of sediments and associated contaminants because the critical shear stress for resuspension was a function of sediment bed grain size fraction. Model inputs included wind, bathymetry, and sediment grain size data. A uniform initial sediment bed thickness was assumed. Tunable parameters included critical shear stress for resuspension as a function of fine-grained fraction; settling velocities for the two sediment classes; and critical shear stresses for deposition. The Spring 2000 wind event was simulated and the model was calibrated using suspended solids data and sediment trap data. Model predictions of suspended solids concentration were compared to the turbidity data at eight locations, and model predictions of deposited sediment were compared to the sediment trap data at ten locations.

## DESCRIPTION OF DATA

The period from 1 Mar through 30 Apr 00 was modeled. Figure 1 shows wind data from one of the meteorological stations for the period from 1 Mar through 30 Apr 00. The peak winds occurred around 9 Apr 00, with magnitudes of approximately 17 m/s, from the north.

### Turbidity Data

Turbidity was measured at eight locations in Lake Michigan (Fig. 2). Seven of the transmissometers were located in the area of the resuspension feature, which was generally seen in

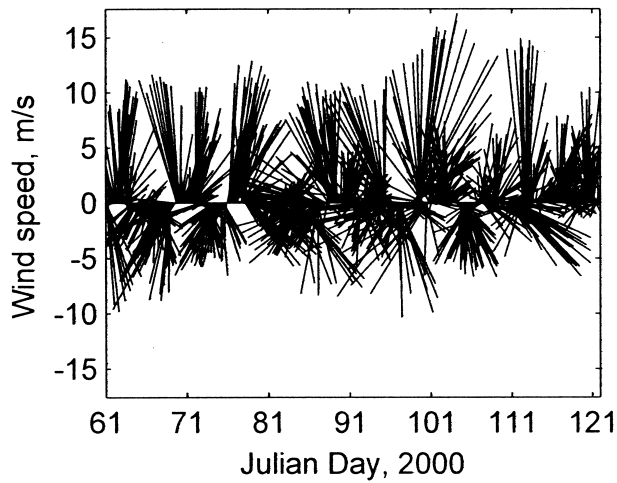


FIG. 1. Time series of observed wind at the meteorological station at St. Joseph from 1 Mar through 30 Apr 00.

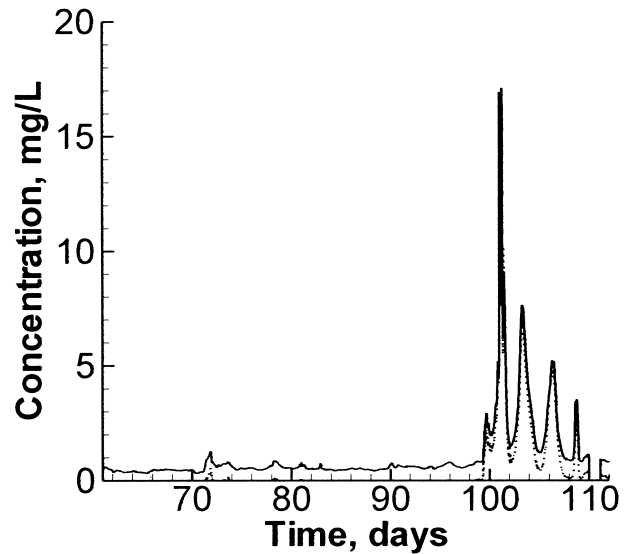


FIG. 3. Concentration versus time for transmissometer station M24 for 1 Mar through 21 Apr 00. The solid line is 10 mab and the dotted line is 30 mab.

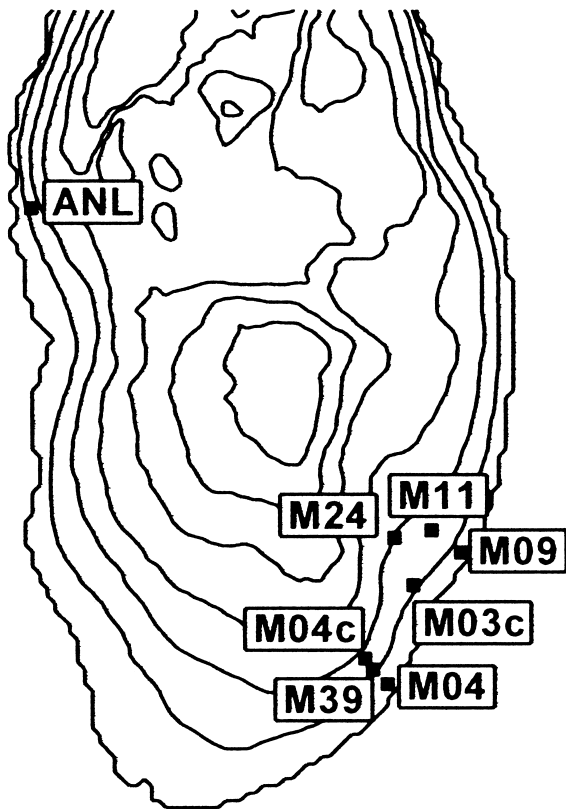
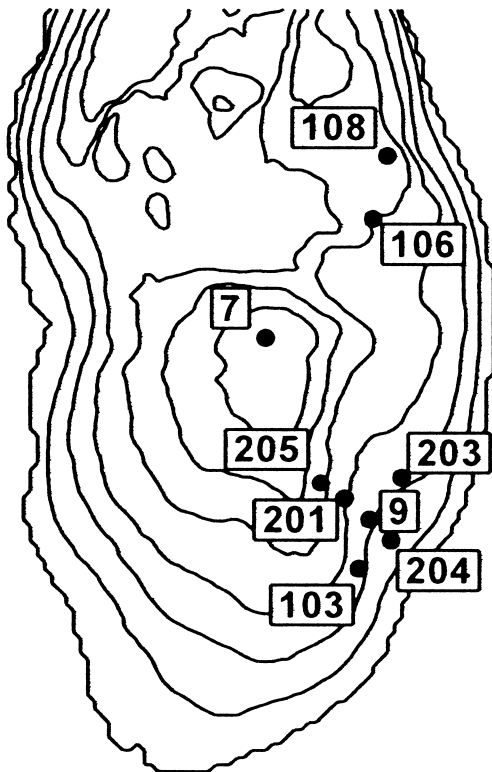


FIG. 2. Bathymetry of southern Lake Michigan and locations of transmissometers. Isobaths are every 25 m. Black boxes indicate the transmissometer locations.

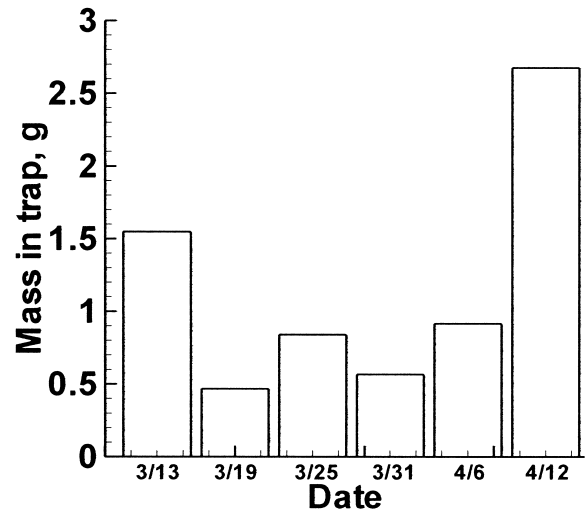
south-eastern Lake Michigan. One transmissometer (ANL) was located in western Lake Michigan. The transmissometers were moored with steel cable lines, and had 10- or 25-cm path-lengths. Measurements were taken every 20 or 30 minutes, depending on location. Figure 3 shows turbidity measurements made at station M24 during Spring 2000. Station M24 is off the southeastern coast of Lake Michigan, at a bathymetric depth of 53 m; it is north and west of St. Joseph, Michigan. Measurements were taken at 10 and 30 m above bottom (mab). Maximum winds occurred around 9 Apr 00 (days 99 to 100 in Fig. 1), and there was a corresponding peak in the suspended solids concentration of around 3 mg/L. There are subsequent peaks of 18 mg/L, 8 mg/L, and 6 mg/L on days 101, 103, and 105 (10 Apr, 12 Apr, and 14 Apr 00, respectively.) These subsequent peaks in turbidity occurred when the wind magnitudes were less than 10 m/s (recall that the peak winds were approximately 17 m/s). The turbidity peak at this station did not correspond to the time of the peak winds; the turbidity peaks were thought to be due to advection of sediment (which was resuspended elsewhere in the lake) into the area, and not to locally-resuspended sediments. The turbidity observations at 10 and 30 mab only differed by about 1 mg/L.

### Sediment Trap Data

Data on downward flux of particles has been measured in Lake Michigan since 1978 (Eadie 1997), and more than 1,200 sediment trap samples were collected as part of the EEGLE program. Most of these data were gathered using sequenced sediment traps (Muzzi and Eadie 2002). Sediment traps are passive devices that intercept particles settling downward in the water column. A typical sediment trap used in Lake Michigan consisted of a carousel of twenty three 60-mL polyethylene bottles that were individually exposed to the downward sediment flux for a specified sampling interval (either 6 or 12 days). The devices were deployed on steel cable mooring lines either at 30 m below the surface, or 5 m above the bottom. The mass of the deposited particles in the each of the bottles in the carousel was measured. In Muzzi and Eadie (2002), examination of the correspondence between sediment mass deposited in the traps and the turbidity measurements were made. Eadie *et al.* (2002) examined sediment trap data for a yearly period from



**FIG. 4.** Bathymetry of southern Lake Michigan and locations of sediment traps. Isobaths are every 25 m. Filled black circles indicate the sediment trap locations.



**FIG. 5.** Sediment trap data for trap 204 from 5 Mar through 16 Apr 00. The bars indicate the observed mass in the trap during each 6-day interval.

August 1994, and concluded that a majority of the particle transport in the depositional zone was associated with a wind event occurring in the spring of 1995. These data also showed that much of the particle transport in Lake Michigan was due to large storms during the six-month unstratified period.

Figure 4 shows 9 locations in Lake Michigan where data were gathered. Six of the sediment traps (9, 103, 201, 203, 204, and 205) were located in the area of the resuspension feature. Figure 5 shows sediment trap data for trap 204, which is located in the southeastern part of Lake Michigan. The bathymetric depth was 35 m and the instrument depth was 30 m below the air/water surface. Six-day sampling interval data are presented for dates 5 Mar through 16 Apr 00. These data show a significant downward flux of particles during this period, especially around the peak of the storm (the bar centered on 12 Apr 00), which shows a mass of 2.7 g collected in trap 204 during that 6-day sampling interval. Note that in early March, a mass of 1.5 g was collected. There were no significant wind events in early March. The other three sediment traps (7, 106, and 108) were located well north of the resuspension feature.

### DESCRIPTION OF NUMERICAL MODELS

To describe the hydrodynamics and sediment transport in Lake Michigan, three-dimensional, time-dependent equations of motion were used. The

Princeton Ocean Model (*POM*) was used to simulate the hydrodynamics (Blumberg and Mellor 1987). *POM* is a three-dimensional, primitive equation, time-dependent,  $\sigma$ -coordinate, free surface circulation model. A Great Lakes version of *POM* was applied to Lake Michigan (Schwab and Beletsky 1998) and to Lake Erie; this model was validated using observed currents, water level fluctuations, and surface temperature distributions in Lake Erie (Kuan *et al.* 1994) and Lake Michigan (Beletsky *et al.* 2003.)

The wave model was developed by Donelan (1977) and modified by Schwab (Schwab *et al.* 1984.) It is a numerical finite-difference solution to the two-dimensional wave momentum conservation equation. The wave model was described in rectilinear coordinates in Schwab and Beletsky (1998) and in curvilinear coordinates in Hydroqual (2002). Wave model outputs of height, period, and direction were used in the bottom shear stress calculation (Grant and Madsen 1979, Glenn and Grant 1987.)

The sediment transport model consists of three-dimensional, time-dependent conservation of mass equations, coupled to a three-dimensional, time-dependent bed. The sediment transport model was based on SEDZL (Gailani *et al.* 1991) and ECOMSED (Hydroqual 2002). Some applications of SEDZL include Lake Erie (Lick *et al.* 1994), Fox River (Gailani *et al.* 1991), and the Saginaw River (Cardenas and Lick 1996.) ECOMSED has been applied to Green Bay (Shrestha *et al.* 2000) and Pawtuxet River (Ziegler and Nisbet 1994), among others.

The description of the sediment bed dynamics was based on experimental work in the laboratory and in the field (Ziegler and Lick 1986, Ziegler *et al.* 1993). For fine-grained cohesive sediments, an essential result of this work was that only a finite amount of sediment could be resuspended at a particular shear stress. A reasonable approximation to the existing data was given by

$$\varepsilon = \begin{cases} a_0 \left( \frac{\tau - \tau_0}{\tau_0} \right)^m & \tau > \tau_0 \\ 0 & \tau \leq \tau_0 \end{cases} \quad (1)$$

where  $\varepsilon$  was the net amount of resuspended sediment per unit surface area ( $\text{g}/\text{cm}^2$ );  $a_0$ ,  $n$ , and  $m$  were parameters fitted to the data;  $t_d$  is the time after deposition in days;  $\tau$  was the bottom shear stress ( $\text{dynes}/\text{cm}^2$ ) produced by wave action and

currents; and  $\tau_0$  was an effective critical shear stress for erosion which varied from approximately 0.1  $\text{dynes}/\text{cm}^2$  for freshly-deposited sediments to 5.0  $\text{dynes}/\text{cm}^2$  for coarser, older sediment layers. Based on shaker tests on one cohesive sediment core from Green Bay (Lick *et al.* 1995),  $a_0$  was 0.0016,  $m$  was 2.5, and  $n$  was 0.8, for a critical shear stress  $\tau_0$  of 1  $\text{dynes}/\text{cm}^2$ . Although the work presented in this article indicated the use of a larger critical shear stress in some areas of Lake Michigan, these values of  $a_0$ ,  $m$ , and  $n$  were used in equation (1).

In contrast to ECOMSED's description of cohesive and non-cohesive sediments, where a sediment bed cell was designated solely as cohesive, non-cohesive, or hard bed, and no mixing of different sediment types occurs, a SEDZL-like description of the sediment bed was used, where different sediment types can occur in a single sediment bed cell, and changing composition of the bed can be tracked (Cardenas and Lick 1996). In this work, use was made of equation (1) to describe resuspension of the sediment types, and did not use ECOMSED's description of non-cohesive sediments. Resuspension predicted by equation (1) was divided between the fine and medium sediments by utilizing the fraction of each sediment type in the sediment bed at that bed cell.

The critical shear stress for resuspension,  $\tau_0$ , was assumed to be function of fine-grained fraction and age of the sediment bed (Table 1).  $\tau_0$  was a fitting parameter during model validation. The top layer of the sediment bed had  $\tau_0$  of 0.15  $\text{dynes}/\text{cm}^2$ , independent of fine-grained fraction. The layers immediately below the top layer had  $\tau_0$  of 0.15  $\text{dynes}/\text{cm}^2$  for fine-grained fractions from 0.5 to 1.0 (the finer fractions), and  $\tau_0$  of 0.20  $\text{dynes}/\text{cm}^2$  for

**TABLE 1. Critical shear stress for resuspension as a function of fine-grained fraction and bed layer.**

Layer	$\tau_0$ [ $\text{dynes}/\text{cm}^2$ ]	Fraction
Top	0.15	0.0–1.0
Middle	0.15	0.5–1.0
	0.20	0.0–0.5
Bottom	0.15	0.8–1.0
	0.5	0.6–0.8
	1.0	0.5–0.6
	2.0	0.2–0.5
	6.0	0.0–0.2

fine-grained fractions from 0 to 0.5 (the coarser sediments.) In the bottom layers of the sediment bed (where the sediment is initially assumed to be located),  $\tau_0$  ranged from 0.15 dynes/cm<sup>2</sup> for the finest sediments, to 6.0 dynes/cm<sup>2</sup> for the coarsest sediments.

The sediment bed was assumed to consist of layers in the vertical direction; each layer's properties depended on time after deposition and composition (relative fractions of finer and coarser sediments) and were allowed to vary in the horizontal direction as well as in the vertical. The top layer was assumed to be newly deposited sediment less than 1 day old. It was assumed to have a very high water content, a low critical shear stress of 0.15 dynes/cm<sup>2</sup>, and was easily resuspended. Below this layer were multiple layers—one for each day of simulation time—each with increasing age with depth at a rate of 1 day per layer. Therefore, any sediment deposited in the top layer was moved to the second layer after 24 hours (which was defined as an empty layer at the beginning of the simulation), and the now-empty top layer would be available to be filled by any new deposition that occurred. At 48 hours, material in layer 2 was moved to the previously-empty layer 3, and layer 1 was moved to the now-vacant layer 2. So at every 24-hour interval, the layers would move down, freeing the top layer for any deposition predicted by the model. Mixing of sediments only occurred in the top layer during the 24-hour period that the layer was available for deposition; after 1 day of deposition, the layer would be defined as the second layer, and a new surface layer would be defined and available for sediment deposition. Sediment bed layers retained their identity and properties during the calculation, except of course when they were completely eroded.

The net sediment flux was given by the difference between the resuspension rate and the deposition rate. Deposition was assumed to be due to the settling of the suspended particles, so that the deposition rate was given by

$$D = \sum_{k=1}^2 p_k \omega_{sk} C_k \quad (2)$$

where  $\omega_{sk}$  was the effective settling speed,  $p_k$  was the probability of deposition, and  $C_k$  was the concentration of the  $k^{\text{th}}$  class of particles. While both ECOMSED and SEDZL included functions to calculate settling speed as a function of suspended solids concentration and shear stress, constant set-

ling velocities were used as tuning parameters. This was done in order to more easily understand the results of the analyses. The settling speed for the fine/medium class (less than 60  $\mu\text{m}$  in size) was set at 40  $\mu\text{m/s}$ , while the coarse sediment class (greater than 60  $\mu\text{m}$ ) was assumed to have a settling speed of 500  $\mu\text{m/s}$ . The Partheniades formulation (Partheniades 1992) for the probability of deposition was used for the finer sediments, with a critical shear stress for deposition of 1 dynes/cm<sup>2</sup>. For the coarser sediments, a critical shear stress for deposition of 5 dynes/cm<sup>2</sup> was used, which acted as a binary switch for when deposition was allowed for the coarser sediments.

### SPRING 2000 MODEL RESULTS

The numerical grid consisted of 131 by 251 2-km square elements, 14,458 of which described Lake Michigan. Hourly wind data were obtained from NOAA buoy wind records and available observed meteorological conditions at 30 land stations, and the "Natural Neighbor" interpolation (Sibson 1981, Watson 1994) was used to grid overwater wind fields. A good description of various overland-overlake wind speed adjustments and their application to Lake Michigan can be found in Beletsky *et al.* 2000. Figure 1 shows an example of wind data from one of the meteorological stations for the period from 1 Mar through 30 Apr 00. The peak winds occurred around 9 Apr 00, with magnitudes of approximately 17 m/s, from the north. Isothermal conditions were modeled, which was a good assumption during conditions seen during the spring season of 2000.

The model loading excluded river and tributary sediment input; the majority of the sediment transport was assumed to be due to resuspension from and deposition to the existing sediment bed. Colman and Foster (1994) gave deposition in the deep basin as a major term in a sediment budget for southern Lake Michigan, arguing it was more than two orders of magnitude greater than suspended sediment transport out of the basin. As mentioned in the *Introduction*, Eadie and others have argued that contaminant and nutrient fluxes due to sediment resuspension are of much greater magnitude compared to that from external loadings. Loading of sediments due to bluff erosion was also ignored, though bluff erosion is a major source of sediments to Lake Michigan. This was a more serious exclusion, because during the validation process, it

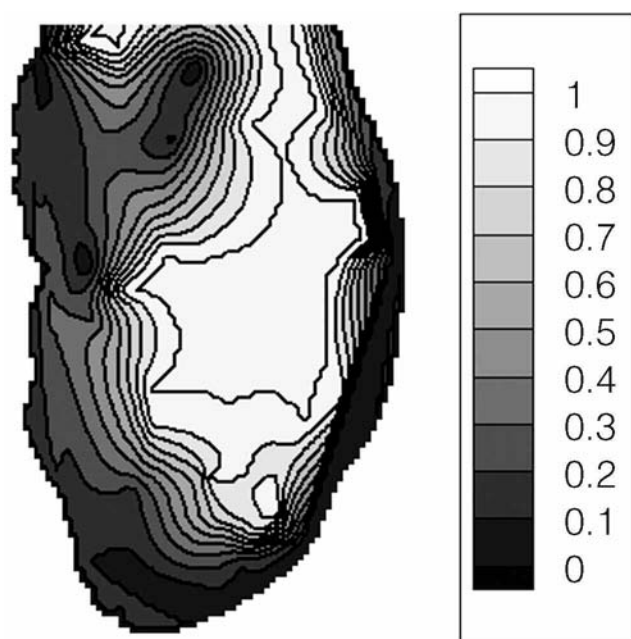


FIG. 6. Sediment grain size as a fraction below 60 microns.

could likely lead to overprediction of sediment bed resuspension both in locations where the sediment loading to the water column may have been due to bluff erosion, and also in locations where this material may have been transported by advection from currents. Bluff erosion was determined to be the dominant term in a sediment budget for southern Lake Michigan, being an order of magnitude larger than rivers or aerosol sources (Colman and Foster 1994.) Estimates of sediment volume load due to bluff erosion were given in Jibson *et al.* 1994. They estimated an annual total of 112,300 m<sup>3</sup>/yr of sediment was added to the lake from the Illinois shoreline, based on 1937–1987 rates.

The initial sediment bed was assumed to be of 1-cm uniform thickness, was located in the bottom layer of the bed, and included variation in grain size. As part of the Lake Michigan Mass Balance program, box cores, PONAR cores, and gravity cores were obtained, and the top 1 cm of sediment was analyzed for grain size. For modeling purposes, the data were spatially interpolated using the natural neighbor technique. The data were presented in two bins: below 60  $\mu\text{m}$ , and above 60  $\mu\text{m}$ . The fine-grained fraction was defined as the amount of material less than 60  $\mu\text{m}$ . A contour plot of the fine-grained fraction data is shown in Figure 6. The fine-grained sediments are more prevalent in the deeper basins of the lake, and also in repositories

offshore on the southeast shore. Coarser-grained sediments (greater than 60  $\mu\text{m}$ ) are prevalent on the western shore of Lake Michigan, and near the southern shore. These data were used in the model to initialize the fine-grained fractions in the sediment bed. 60  $\mu\text{m}$  was chosen as the divider between the bins because it represented the division between coarser, sandy sediments and the fine-grained sediments.

### TURBIDITY RESULTS

Model predictions for four locations will be presented; three locations were in the area of the resuspension feature and one is off the western side of Lake Michigan. All the results are for Mar and Apr 00. In order to compare the model predictions to the experimental data, the station locations (where the experimental data were gathered) were mapped to the model's numerical grid. Model predictions of total suspended solids concentration from the grid location corresponding to the station were compared to the experimental data. Figure 7a shows the model prediction of suspended solids concentration at station ANL (dotted line), along with the measured data (solid line). Station ANL was located off the western shore of Lake Michigan. The bathymetric depth at ANL was 20.3 m, and the instrument was located at 10 *mab*. This was the only measure-

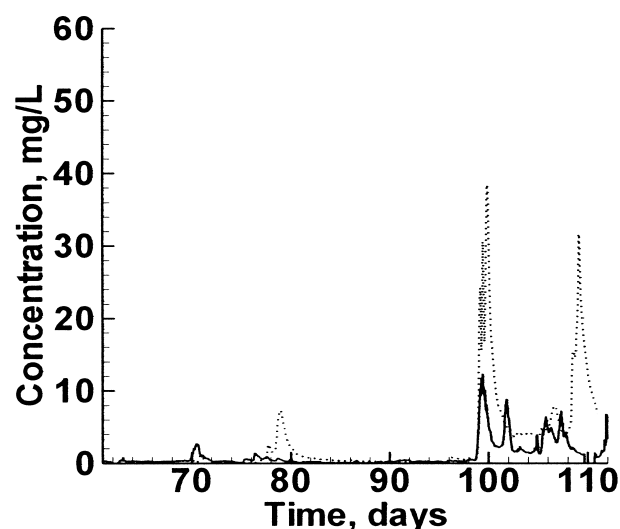
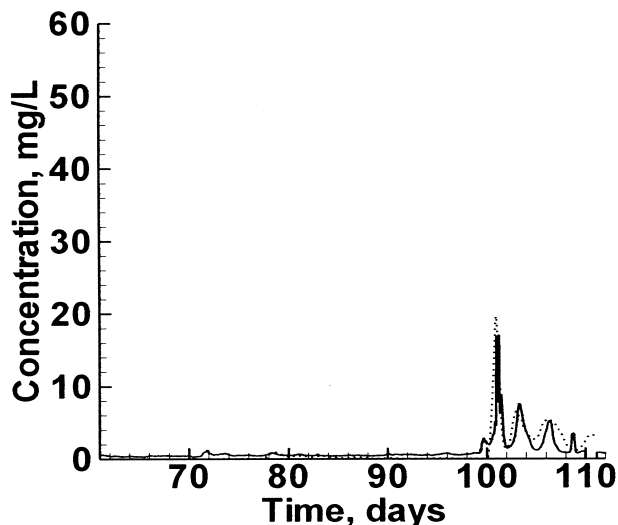


FIG. 7a. Suspended solids concentration at station ANL for 1 Mar through 21 Apr 00. Measured data are shown as the solid line, and the model prediction is the dotted line. The bathymetric depth at this location is 20.3 m, and the observations are taken at 10 *mab*.

ment location on the western side of Lake Michigan. This location was in an area where significant bluff erosion was expected. As stated earlier, bluff erosion was neglected in this model. Therefore, given that some of the sediment loading here is most likely due to bluff erosion, it was concluded that this model overestimated resuspension in this area. Generally, the model prediction was higher compared to the field data; the model overestimated turbidity on 20 Mar 00 (day 80) by about 7 mg/L. During and after the peak winds (9 Apr 00, days 99–100) the model predictions were higher compared to the data by 30 mg/L. The model prediction of suspended sediment at this location was due to advection into the area, and local resuspension. For example, the second large peak predicted by the model on 19 Apr 00 (day 110) was due to a combination of local resuspension and advection; model predictions indicated erosion of newly-deposited sediments, and advection into the region, as there was resuspension of sediments upstream of this location and currents indicated transport of that sediment into this location. The “thinner” peaks in the turbidity prediction generally tended to indicate local resuspension, while “thicker” peaks seemed indicative of advection into the area.

Figure 7b shows model predictions and measured data for suspended solids concentration at station



**FIG. 7b.** *Suspended solids concentration at station M24 for 1 Mar through 21 Apr 00. The solid line indicates the measured data, and the model predictions are the dotted line. The bathymetric depth is 53 m and the observations are taken at 10 mab.*

M24. M24 was located in the area of the resuspension feature at a bathymetric depth of 53 m. Data were taken at 10 mab. The measured data at M24 showed very distinct turbidity peaks after the peak winds. The conclusion was that the turbidity peaks were due to advection of sediment (resuspended elsewhere in the lake) into the area, and were not due to locally-resuspended sediments. This conclusion was reached by examining the wind magnitude and the predicted bottom shear stresses, which did not exceed 0.1 dynes/cm<sup>2</sup> after 11 Apr 00. The bed model assumed that recently-deposited layers of sediment did not compact quickly, and therefore had critical shear stresses for resuspension of 0.15 to 0.20 dynes/cm<sup>2</sup> for up to 30 days after deposition. The model predictions compared very well to the observed suspended solids concentration at M24, matching the three advection peaks both in magnitude and time of occurrence. Note, however, that the model did not predict the initial resuspension peak of 3 mg/L at the time of maximum winds (days 99–100.) Model predictions that used a bed that compacted quickly (these had a critical shear stress for resuspension greater than 0.2 dynes/cm<sup>2</sup> for deposited sediments “older” than 7 days) did not predict suspended solids concentration above 1 mg/L at any time, and therefore did not predict the advection peaks seen in the field measurements. Little-to-no resuspension or transport to M24 occurred when the model included 7-day consolidation of re-deposited sediments.

Figure 7c shows the suspended concentration at station M04c. The water depth at M04c is 40 m, and the instrument was 30 mab. The station was south and west of St. Joseph, MI. The measured data showed a very large turbidity peak of magnitude of 40 mg/L occurring at the time of the highest wind magnitude. This turbidity peak was believed to be due to local resuspension, rather than advection, because it occurred at the time of the peak winds. The predicted bottom shear stresses at this location never exceeded 1.0 dynes/cm<sup>2</sup>, which meant that very little resuspension was predicted by the model. The model prediction did not show high turbidity at the time of peak winds; only approximately 15 mg/L was predicted, and occurred days after the peak wind magnitudes (and was due to advection into the area instead of local resuspension.) The prediction at M04c was not significantly affected by consolidation of the sediment bed; in order to predict a large amount of local resuspension at this location, critical shear stress for resuspension well below 0.1 dynes/cm<sup>2</sup> would be



required. The model did not predict enough energy at this location to induce resuspension of 40 mg/L. However, Figure 7d shows the suspended concentration at M11, which is also located at a depth of 40 m. Here the model prediction showed a sharp re-

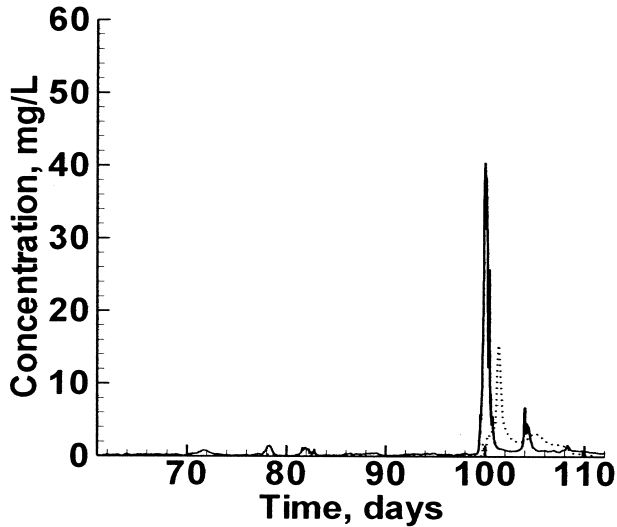


FIG. 7c. Suspended solids concentration at station M04c for 1 Mar through 21 Apr 00. The solid line indicates the observed data, and the model predictions are the dotted line. The bathymetric depth is 40 m, and the observations were taken at 30 mab.

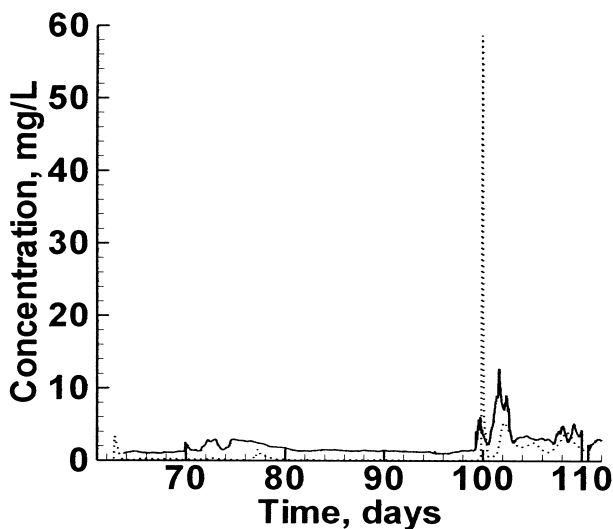


FIG. 7d. Suspended solids concentration at station M11 for 1 Mar through 21 Apr 00. The solid line indicates the observed data, and the model predictions are the dotted line. The bathymetric depth is 40.1 m, and the observations were taken at 10 mab.

suspension peak of 60 mg/L at the time of the highest winds, and model-predicted bottom shear stresses were greater than 1 dyne/cm<sup>2</sup>. The model prediction did not match the data at M11, which showed no turbidity peak at the time of maximum wind magnitude but which showed a larger advection peak later. These observations are similar to the model prediction for M04c, not for M11. The model prediction for M11 was similar to the data for M04c, with its peak in turbidity at the time of maximum winds. Though these two transmissometers were at the same depth, the velocity field is such that the shear stresses are higher at M11, and therefore the model predicted the peak in turbidity here.

### SEDIMENT TRAP RESULTS

In order to compare the model predictions to the experimental data, the sediment trap station locations were mapped to the model's numerical grid. Model predictions of the amount of sediment deposited in a specified period of time (either 6- or 12-day intervals, depending on the sediment trap) at these locations were compared to the data recorded in the mass traps. Figure 8a shows the measured data and model predictions of mass accumulated in a sediment trap at station 204. Station 204 is in the southeastern part of Lake Michigan (Fig. 4) and has

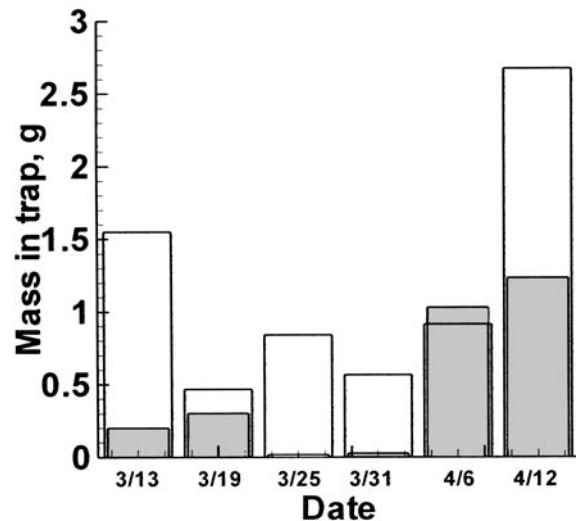
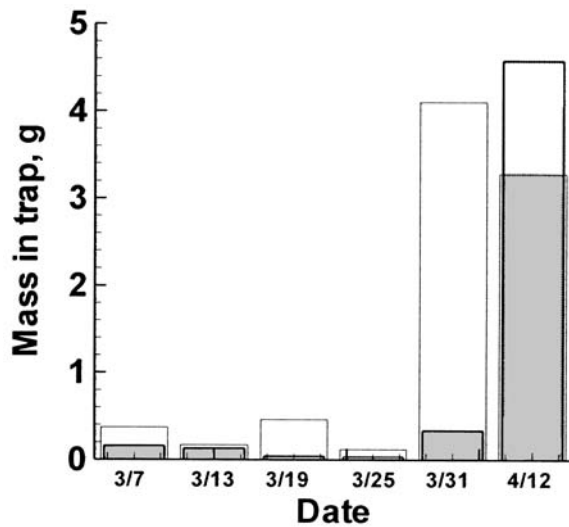


FIG. 8a. Sediment trap data and prediction at trap 204 from 5 Mar through 16 Apr 00. The unfilled bars show the observed mass in the trap during the 6-day interval; the filled bars indicate the model prediction of mass caught in the trap. The bathymetric depth is 35 m, and the trap is located at 30 m below the surface.



**FIG. 8b.** Sediment trap data and prediction at trap 103 for 5 Mar through 16 Apr 00. The unfilled bars show the observed mass in the trap during the 6-day interval; the filled bars indicate the model prediction of mass caught in the trap. The bathymetric depth is 62 m and the trap is 30 m below the surface.

a bathymetric depth of 35 m. The model underestimates the amount of mass that would accumulate in a sediment trap in this location, except during the peak winds, where the prediction was excellent. The 6-day interval during which the peak winds occurred showed the model predicting 1.1 g in the trap, compared to an observation of 0.9 g in the trap. The data showed the most mass in the trap, 2.7 g, during the 6-day interval after the peak winds (the box centered on 12 Apr 00.) The model predicted 1.25 g in the trap during that time period. This seemed to indicate that the model did not predict enough suspended material at this location, whether localized resuspension or advection. This station is at a depth of 35 m, where this numerical model will not predict much resuspension, as discussed previously in the turbidity results. Figure 8b shows the measured data and model predictions of mass accumulated in a sediment trap at station 103. Station 103 is located in the area of the resuspension feature, at a depth of 62 m. The model prediction differs from trap 204, as the model underestimated the accumulation during the peak winds, and overestimated accumulation following the peak winds. This indicated that the model was predicting advection of suspended material to this location following the peak winds. The large

amount of accumulation observed during the interval of the peak winds indicated the possibility of local resuspension and advection into this area earlier than the model predicted.

In general, the model underestimated the amount of mass that would accumulate in settling traps, compared to the field data, especially at stations 7, 106, 107, 108, and 201. The model predictions were better for the time intervals during the peak winds and immediately following the peak winds. This made sense, since the model was driven by the wind energy, and the highest winds occurred here, which caused resuspension of material that would then be transported and available for re-deposition. The model did not match field data for settling trap locations that showed a large amount of mass accumulated in the periods for middle to late March. The model predicted little accumulation for these periods, while the observations often showed a significant amount of mass accumulation during periods of relatively low wind magnitudes. This indicated there may be some resuspension of material that the model was not predicting.

## DISCUSSION

The model turbidity predictions were generally good at the time of the peak winds, and the period following the peak winds. The model was able to capture local resuspension and advection behavior, especially at station M24, which showed distinctive peaks in turbidity following the peak winds. The advection peaks at M24 were only seen in the model simulations that began on 1 Mar 00; if the simulations were started on 1 Apr 00, the model did not show advection peaks at M24. Also, if the re-deposited sediment consolidated and assumed a higher  $\tau_0$ , the advection peaks at M24 would not be predicted. Though the wind magnitudes in March were not as large as those in April, sediment was resuspended, transported and re-deposited in areas that, when acted upon by the peak winds in April, produced the advection behavior seen in M24. This suggested that a layer of very-easily resuspendable sediment could exist in the top layers of the sediment bed.

If such a layer exists, it could explain why the model did not correctly predict some of the March data. In the area of the resuspension feature, some of the mass trap and turbidity data showed peaks that the model was unable to duplicate using the initial conditions and assumptions described here. During those periods, the wind magnitudes were

not significantly high. If an easily-resuspendable sediment layer already existed in early March, it could account for the peaks seen in the turbidity and mass trap data. In terms of the modeling, this could be addressed this by adding a top layer of easily-resuspendable sediment that does not consolidate quickly, or by using the existing sediment bed description, but changing the  $\tau_0$ -fine-grained-fraction description so that areas with finer-grained sediments have a lower  $\tau_0$ . Another possibility is examining the binning of the sediment fine-grained fraction, perhaps looking at using a smaller grain size as the cutoff between the two bins, or by going to a higher number of grain size classes. Of course a unique solution to this problem is not obtainable with this data set; it is possible that both an easily-resuspendable layer, plus a different  $\tau_0$ -fine-grained-fraction description would be needed, and that different combinations of these would give similar results. The main conclusion is that an easily-resuspendable layer was needed in order to match advection behavior seen after the period of peak winds, and that such a layer, if it existed in early March, would also help explain turbidity and mass trap behavior seen in the field data.

The model had more difficulty in predicting turbidity at depths of 40 m in the area of the resuspension feature in Lake Michigan. The model underestimated the large turbidity peak at station M04c, although it predicted a similarly large turbidity peak at station M11. The timing of the peak at M04c suggested that local resuspension, and not advection from material resuspended near shore, was responsible for the increase in turbidity. In order to predict these high turbidities, the model either needed higher bottom shear stresses (this is related to the predicted currents) or a layer of extremely resuspendable sediments in this location. Given that the model was able to predict high turbidities at station M11, which was also at a depth of 40 m, suggests that perhaps the model velocity calculation may not be as good as needed. In a previous study, it was noted that the hydrodynamics model tended to underestimate strong offshore flow in this area of Lake Michigan (Beletsky *et al.* 2003), possibly due to the spatial resolution of the wind field data. This underestimation of offshore flow could be enough to cause the slightly-lower bottom shear stress at M04c, thus leading to the underestimation of the turbidity peak seen at the time of the highest winds. It is also possible that the model was not predicting the location at which the currents veer off the shore correctly, which could explain why stations M39

and M04c tended to have lower predictions of peak turbidities, while the model overestimated peak turbidity at M09 and M11. This could also explain why the model prediction of M11 looks like the observations at M04c, and vice versa, if the currents veered off the shore at a more southward location than the model predicted.

$\tau_0$  as a function of fine-grained fraction and bed layer was a fitting parameter; the model prediction only began to match the majority of the observations when this type of sediment bed representation was used. When the model assumed a single type of sediment, model predictions matched at perhaps one or two locations, but the remaining comparisons would be inaccurate. It is not a new observation that prior knowledge of the sediment bed is essential for this type of modeling, but validating it with this particularly comprehensive data set, with multiple turbidity and mass trap data, further reinforced this observation. The  $\tau_0$ -fine-grained-fraction correlation used in this analysis captured much of the behavior seen in this data set. For the turbidity data, this meant the model predictions matched the shape of the turbidity trace, including similar peak magnitudes and times of occurrence of the peak, and similar "dips" in magnitude at the appropriate times. Qualitative comparisons between the turbidity at the peak winds versus observed satellite imagery showed the border between turbid water and clear water had approximately the same shape for the model predictions and observations.

Bluff erosion was neglected for these simulations, which was a significant omission, and one that will be corrected in future work. By neglecting bluff erosion but attempting to match turbidity in near-shore areas to field data, the model must be over-predicting the resuspension in near-shore areas. It was likely that much of the sediment loading near-shore was due to material eroding from the bluffs rather than material being eroded from the bottom sediments. The error was most significant on the western shore of Lake Michigan, where a significant amount of bluff erosion has been measured. In future work, sediment input from bluff erosion will be considered, and will allow further refinements in predicting resuspension in Lake Michigan. Since overestimation of near-shore resuspension was a known problem, the model sediment bed thickness was initialized to 1 cm. The only locations where the model eroded the entire sediment bed were near shore; for most of Lake Michigan, increasing the initial bed thickness would cause no difference in local resuspension.

However, thicker initial sediment beds would cause some difference in the predictions near shore, and in advection of this material. Using an initial sediment bed thickness greater than 1 cm would further exacerbate the overestimation in nearshore resuspension that is already present due to the omission of bluff erosion.

### SUMMARY AND CONCLUDING REMARKS

A three-dimensional hydrodynamic and sediment transport model was used to simulate a wind event on Lake Michigan for Spring 2000. Multiple grain-class sizes were used, and a correlation between grain size and critical shear stress for resuspension was used as a model fitting parameter. The EEGLE project gathered a comprehensive set of data that enabled validating the sediment transport model. Model results were compared to field data of turbidity at eight locations and downward flux at nine locations. The model matched the field data very well in some locations, including capturing a set of advection peaks seen in the area of the resuspension feature. In locations with depths of 40 m or greater, the model had more trouble matching the field data in terms of turbidity and downward flux; differences in bottom shear stress predictions of 0.5 dynes/cm<sup>2</sup> seemed capable of producing significantly different turbidity predictions. For example, at M04c, the model did not predict a 40 mg/L turbidity peak at the height of the wind event, yet at M11 (located at a similar depth), the model predicted a 60 mg/L turbidity peak. Unfortunately, the data showed the turbidity peak at M04c, and not at M11; the small difference in bottom shear stress prediction caused the difference in turbidity between these two locations. The difference in bottom shear stress could be explained by the underestimation of currents in that location. Even though the model was unable to match all the data, a more significant understanding of some of sediment transport processes and how to model them was gained. The sediment trap data were especially useful in determining critical shear stresses for deposition, and ranges of settling speeds. The initialization of the model using grain size data was invaluable to taking the modeling to a point where the suspended solids concentrations and downward mass fluxes were more accurately predicted; when working with a single grain size class, the model was unable to match more than one or two locations at a time. Therefore, having good data on grain size distribution was essential to this modeling.

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### REFERENCES

- Beletsky, D., Schwab, D., McCormick, M., Miller, G., Saylor, J., and Roebber, P. 2000. Hydrodynamic modeling for the 1998 Lake Michigan coastal turbidity plume event. In *Proc. 6<sup>th</sup> Internat. Conf. on Estuarine and Coastal Modeling*, pp. 597–613. American Society of Civil Engineers.
- , Schwab, D.J., Roebber, P.J., McCormick, M.J., Miller, G.S., and Saylor, J.H. 2003. Modeling wind-driven circulation during the March 1998 sediment resuspension event in Lake Michigan. *J. Geophys. Res.* 108(C2):20-1 to 20-13.
- Blumberg, A.F., and Mellor, G.L. 1987. A description of a three-dimensional coastal ocean circulation model. In *Three-Dimensional Coastal Ocean Models*, ed. N. Heaps, pp. 1–16. American Geophysical Union.
- Brooks, A.S., and Edgington, D.N. 1994. Biogeochemical control of phosphorus cycling and primary production in Lake Michigan. *Limnol. Oceanogr.* 39:962–968.
- Cardenas, M., and Lick, W. 1996. Modeling the transport of sediments and hydrophobic contaminants in the lower Saginaw River. *J. Great Lakes Res.* 22:669–682.
- Chu, Y., Bedford, K., and Welsh, D. 2000. Lake Michigan forecast system and the prospects for a sediment transport model. In *Proc. 6<sup>th</sup> Internat. Conf. on Estuarine and Coastal Modeling*, pp. 755–764. American Society of Civil Engineers.
- Colman, S., and Foster, D. 1994. A sediment budget for southern Lake Michigan: source and sink models for different time intervals. *J. Great Lakes Res.* 20:215–228.
- Donelan, M.A. 1977. *A simple numerical model for wave and wind stress application*. National Water Research Institute, Burlington, Ontario, Canada.
- Eadie, B.J. 1997. Probing particle process in Lake Michigan using sediment traps. *Water, Air and Soil Pollution* 99:133–139.
- , and Lozano, S. 1999. *Grain Size Distribution of the Surface Sediments Collected During the Lake Michigan Mass Balance and Environmental Mapping and Assessment Programs*. NOAA Technical Memorandum ERL GLERL-111.
- , and Robbins, J.A. 1987. The role of particulate matter in the movement of contaminants in the Great Lakes. In *Advances in Chemistry Series No. 216, Sources and Fates of Aquatic Pollutants*, eds. R.A.

- Hites and S. J. Eisenreich, pp. 319–364. American Chemical Society.
- , 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.
- , Schwab, D.J., Johengen, T.H., Lavrentyev, P.J., Miller, G.S., Holland, R.E., Leshkevich, G.A., Lansing, M.G., Morehead, N.R., Robbins, J.A., Hawley, N., Edgington, D.N., and Van Hoof, P.L. 2002. Particle transport, nutrient cycling, and algal community structure associated with a major winter-spring sediment resuspension event in southern Lake Michigan. *J. Great Lakes Res.* 28:324–337.
- Gailani, J., Ziegler, C.K., and Lick, W. 1991. Transport of suspended solids in the lower Fox River. *J. Great Lakes Res.* 17:479–494.
- Glenn, S.M., and Grant, W.D. 1987. A suspended sediment stratification correction for combined waves and current flows. *J. Geophys. Res.* 92(C8):8244–8264.
- Grant, W.D., and Madsen, O.S. 1979. Combined wave and current interaction with a rough bottom. *J. Geophys. Res.* 84(C4):1797–1808.
- Hydroqual, Inc., 2002. *A Primer for ECOMSED, Version 1.3*. Hydroqual, Mahwah, New Jersey.
- Jibson, R., Odum, J., and Staude, J. 1994. Rates and processes of bluff recession along the Lake Michigan shoreline in Illinois. *J. Great Lakes Res.* 20:135–152.
- Kuan, C., Bedford, K., and Schwab, D. 1994. A preliminary credibility analysis of the Lake Erie portion of the Great Lakes Forecasting System for springtime heating conditions. In *Quantitative Skill Assessment for Coastal Ocean Models, Coastal and Estuarine Studies. Vol. 48*, eds. D.R. Lynch and A.M. Davies, pp. 397–423. American Geophysical Union.
- Lick, W., Lick, J., and Ziegler, C.K. 1994. The resuspension and transport of fine-grained sediments in Lake Erie. *J. Great Lakes Res.* 20:599–612.
- , Xu, Y., and McNeil, J. 1995. Resuspension properties of sediments from the Fox, Saginaw, and Buffalo rivers. *J. Great Lakes Res.* 21:257–274.
- Lou, J., Schwab, D., Beletsky, D., and Hawley, N. 2000. A model of sediment resuspension and transport dynamics in southern Lake Michigan. *J. Geophys. Res.* 105 (C3):6591–6610.
- Muzzi, R., and Eadie, B. 2002. The design and performance of a sequencing sediment trap for lake research. *Marine Technology Society Journal* 36(2):23–28.
- Partheniades, E. 1992. Estuarine sediment dynamics and shoaling processes. In *Handbook of Coastal and Ocean Engineering, Vol. 3*, ed. J. Herbich, pp. 985–1071. Gulf Professional Publishing.
- 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.* 97:17081–17104.
- Schneider, A., Eadie, B., and Baker, J. 2002. Episodic particle transport events controlling PAH and PCB cycling in Grand Traverse Bay, Lake Michigan. *Environ. Sci. Technol.* 36(2):1181–1190.
- Schwab, D.J., and Beletsky, D. 1998. *Lake Michigan Mass Balance Study: Hydrodynamic Modeling Project*. NOAA Technical Memorandum ERL GLERL-108.
- , Bennett, J.R., Liu, P.C., and Donelan, M.A. 1984. Application of a simple numerical wave prediction model to Lake Erie. *J. Geophys. Res.* 89(C3):3586–3592.
- , Beletsky, D., and Lou, J. 2000. The 1998 coastal turbidity plume in Lake Michigan. *Estuarine, Coastal and Shelf Science* 50:49–58.
- Shrestha, P.L., Blumberg, A.F., Di Toro, D.M., and Hellweger, F. 2000. A three-dimensional model for cohesive sediment transport in shallow bays. In *Building Partnerships—2000 Joint Conference on Water Resource Engineering and Water Resources Planning & Management*, pp. 278. ASCE.
- Sibson, R. 1981. A brief description of natural neighbor interpolation. In *Interpreting Multivariate Data*, ed. V. Barnett, pp. 21–36. New York, NY: John Wiley & Sons.
- Watson, D. 1994. *ngridr—An Implementation of Natural Neighbor Interpolation*. Claremont, Australia: Dave Watson Publisher.
- Welsh, D.J.S., Wang, R., Sadayappan, P., and Bedford, K.W. 1999. *Coupling of marine circulation and wind-wave models on parallel platforms*. The Ohio State University, Columbus, OH. Technical Report ERDC MSRC/PET TR/99-22.
- , Bedford, K.W., Wang, R., and Sadayappan, P. 2000. *A parallel-processing coupled wave/current/sediment transport model*. The Ohio State University, Columbus, OH. Technical Report ERDC MSRC/PET TR/00-20.
- Ziegler, C.K., and Lick, W. 1986. *A numerical model of the resuspension, deposition, and transport of fine-grained sediments in Shallow Water*. University of California, Santa Barbara. UCSB Report ME-86-3.
- , and Nisbet, B.S. 1994. Fine-grained sediment transport in Pawtuxet River, Rhode Island. *ASCE J. Hyd. Engr.* 120(5):561–576.
- , Lick, W., and Lick, J. 1993. The transport of fine-grained sediments in the Trenton Channel of the Detroit River. In *Transport and Transformation of Contaminants Near the Sediment-Water Interface*, ed. J. DePinto, W. Lick, and J. Paul, pp. 225–252. New York, NY: Springer-Verlag.

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