SUSPENDED SEDIMENT TRANSPORT MODELING IN LAKE MICHIGAN

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ABSTRACT

Recent observations reveal an annually occurring major event of sediment resuspension in Lake Michigan in late winter and early spring. The sediment plume extends along the southern shore of the lake, and may significantly influence the biogeochemical processes in the coastal region.

A quasi-3D suspended sediment transport model has been developed and applied to Lake Michigan to study sediment transport processes. The model was coupled with a 3-D circulation model and a wind wave model. The nonlinear wave-current interaction influencing sediment transport has been taken into account in two dynamical processes: the turbulence intensity and the enhancement of the bottom shear stress. The sediment entrainment, suspension and deposition processes have been parameterized by laboratory measurement and field data. The model was calibrated with the measured sediment concentration data during a sediment plume episode in November-December 1994. The settling velocity, grain size, and critical shear stress have been optimized based on the measured data.

In addition, the model was applied to the March 1998 Lake Michigan sediment plume event. The model results were compared with the available satellite imagery. The separate effects of waves, currents, as well as the combined effect of waves and currents on sediment resuspension and nearshore-offshore transport in Lake Michigan are investigated.

INTRODUCTION

The presence of contaminated sediments in Lake Michigan poses a serious environmental problem. For many constituents in the Great Lakes, sediment resuspension results in much greater fluxes than from external inputs (Eadie et al., 1984; Eadie and Robbins, 1987; Robbins and Eadie, 1991; Brooks and Edgington, 1994). In the past few years, satellite images illustrated an annually occurring major sediment resuspension event in Lake Michigan in late winter and early spring. Despite the significant scale of that event, the dominant mechanisms for sediment resuspension and transport in the lake have not been extensively studied. It is necessary to identify and quantify the physical processes that are responsible for the sediment transport and material exchange. To this end, a multidisplinary research program jointly sponsored by NOAA (National Oceanic and Atmospheric Administration) and NSF (National Science Foundation) was initiated to study the recurrent turbidity plume in southern Lake Michigan.

Lesht and Hawley (1987), Hawley and Lee (1998), and Lee and Hawley (1998) used an instrumented tripod to make continuous observations of current, temperature, and turbidity in southern Lake Michigan. During the stratified period the water turbidity is low, sediment resuspension may sometimes occur due to episodic mixing during upwellings. In the unstratified period (winter and spring), the lake is well mixed, and higher turbidities were observed due to winter storms. Long-term sediment trap studies in Lake Michigan were made by Eadie et al., 1984, 1994, and Robbins and Eadie, 1991. The seasonal changes in mass flux, the resuspension rates of phosphorus, PCBs, and organic carbon from sediment traps were estimated. Erosion properties of Lake Michigan sediments were measured by the Sedflume, a water flume designed for measuring erosion rate under different shear stresses (Taylor et al., 1996).

Numerical modeling can be an effective method to study sediment transport in the Great Lakes. A two-dimensional sediment transport model, SEDZL, was applied to Green Bay and the Lower Fox River (Ziegler and Lick, 1986, 1988; Gailani et al., 1991), Lake Erie (Lick et al., 1994), and the Pawtuxet River, Rhode Island (Ziegler and Nisbet, 1994) to study sediment entrainment and resuspension. In that model, sediment mixtures were divided into three different classes: non-cohesive coarse particles; very fine-grained particles with zero settling speed; and cohesive fine-grained sediment particles. The sediment compaction effect was also incorporated by using a sediment bed model. Lee et al. (1994) used a similar model to study the deposition and erosion in Sandusky Bay, Ohio. However, such depth-integrated models neglect the important three dimensional transport mechanisms in sediment resuspension processes.

Recent satellite observations of turbidity in Lake Michigan (Eadie et al., 1996) offer a unique opportunity to investigate a recurrent episode of sediment resuspension and transport. The bathymetry and geometry of southern Lake Michigan are given in Figure 1. The sediment plume of March 1998 was one of the largest events on record. Satellite imagery (Figure 2) showed a well-developed plume extending along over 300 km of coastline from Milwaukee, Wisconsin to Muskegon, Michigan with several dominant offshore features originating from the southeastern shoreline. The plume occurred around

March 10 following several days of intense storms that produced northerly winds up to 17 m/s and generated waves over 5 m high in the southern lake basin.

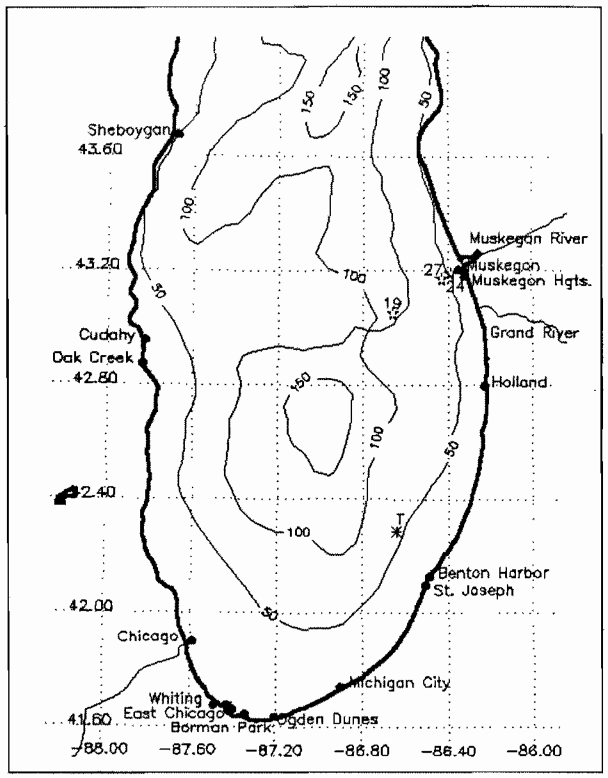

Figure 1. Bathymetry and measurement sites of southern Lake Michigan.

Considerable progress has recently been made in developing three-dimensional circulation models for the Great Lakes. Numerical hydrodynamic models are now able to simulate large-scale circulation in the lakes with reasonable accuracy (Schwab and Bedford, 1994; Beletsky et al., 1997). In addition, a parametric wind wave model developed by Schwab et al. (1984) has been shown to provide excellent estimates of wave height and wave direction for fetch-limited waves in the Great Lakes (Liu et al., 1984; Schwab and Beletsky, 1998). The circulation model and wind wave model provide a reliable basis for sediment transport studies.

In this paper, a quasi-3D numerical suspended sediment transport model has been coupled with the circulation and wind wave models to study sediment resuspension and transport in southern Lake Michigan, where a well-defined data record is available. The sediment entrainment, suspension and deposition processes have been parameterized by laboratory measurement and field data. The model was calibrated with the measured sediment concentration data for a sediment plume period in November-December 1994. The settling velocity, grain size, and critical shear stress have been optimized based on the measured data. Furthermore, the model was applied to the March 1998 sediment plume events. The model results were compared with satellite images. Finally, the separate effects of waves, currents, as well as the combined effects of both waves and currents on sediment resuspension and nearshore-offshore transport in Lake Michigan are investigated by several model studies. The dominant mechanisms of sediment resuspension and transport in southern Lake Michigan are discussed.

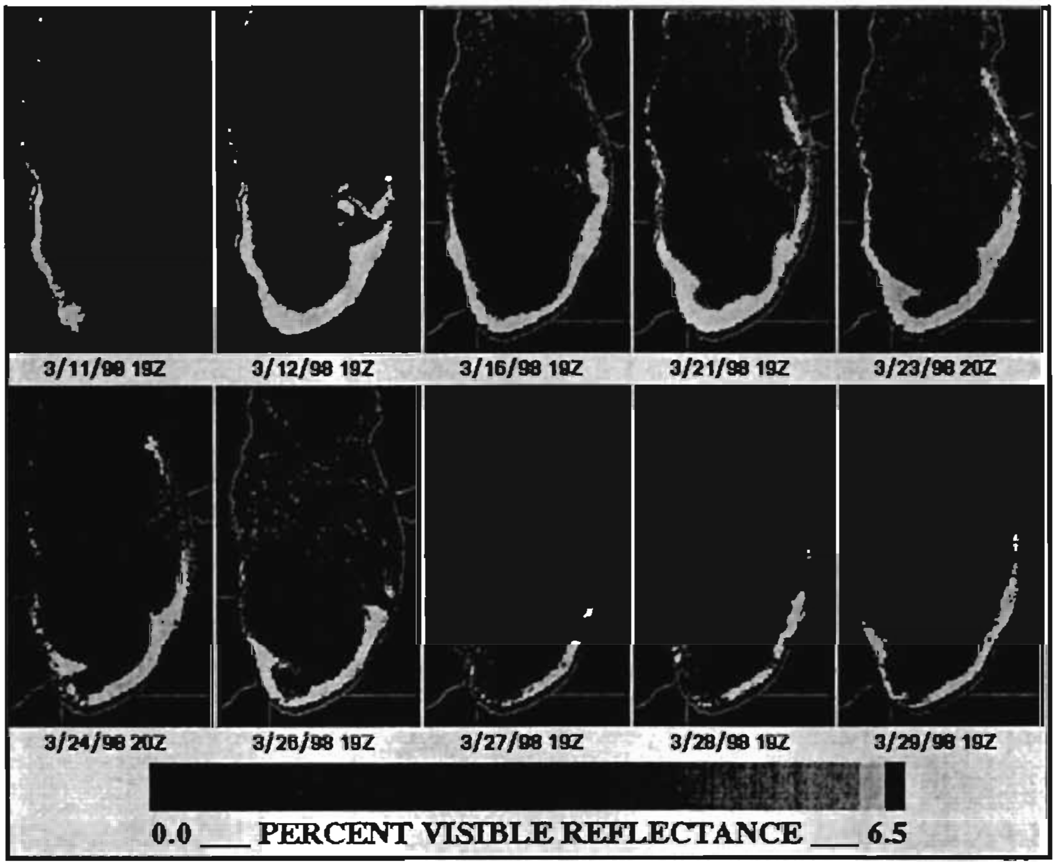

Figure 2. Satellite images of suspended sediment concentrations in March 1998.

MODEL DESCRIPTIONS

Circulation Model

Circulation in Lake Michigan is highly episodic since it is primarily wind-driven. The most energetic currents occur during winter and spring storms. The characteristic wind-driven circulation pattern in the lake consists of two counter-rotating gyres, a counterclockwise-rotating (cyclonic) gyre to the right of the wind and a clockwise-rotating (anticyclonic) gyre to the left (Bennett, 1974). Because the predominant winds are from the west, wind-driven circulation in the southern basin is more frequently cyclonic than anticyclonic.

In this study, a Great Lakes version of the three-dimensional Princeton Ocean Model (Blumberg and Mellor, 1987) was applied to Lake Michigan. The model is hydrostatic and

Boussinesq. It uses wind stress and heat flux at the surface, free-slip lateral boundary conditions, and quadratic bottom friction. The drag coefficient in the bottom friction formulation is spatialy variable. It is calculated based on the assumption of a logarithmic bottom boundary layer using a constant bottom roughness of 1 cm. The model includes the Mellor and Yamada (1982) level 2.5 turbulence closure parameterization. The circulation model of Lake Michigan uses 20 vertical levels and a uniform horizontal grid size. The model was extensively calibrated with various field data (temperature, water level, current velocity) and was able to realistically reproduce the main features of thermal structure and circulation in Lake Michigan (Beletsky and Schwab, 1998; Schwab and Beletsky, 1998).

Wind Wave Model

Because of strong winds and frequent storms, large wind waves occur in the Great Lakes more often in the spring and in the ice-free winter than in the summer. With Lake Michigan's orientation, northerly winds generate the largest waves in southern Lake Michigan, and therefore the largest energy available for resuspension of nearshore sediment in the southern lake basin.

A parametric 2-D surface wind wave model for the Great Lakes developed by Schwab et al. (1984) was used to provide wave field. It is a numerical finite-difference solution to the two-dimensional wave momentum conservation equation. The wave energy is parameterized in terms of total wave energy, peak energy period, and predominant wave direction. Model output consists of significant wave height, wave period and wave direction. This wind wave model was shown to provide excellent results for deepwater waves in Lake Michigan (Schwab and Beletsky, 1998).

Sediment Transport Model

A quasi-3D suspended sediment transport model has recently been coupled with the circulation and wind wave models to provide estimates of suspended sediment concentration at similar resolution. The nonlinear wave-current interaction is taken into account by the modified eddy viscosity coefficient, as well as by an enhanced bed shear stress. In cases where suspended load is the main mode of sediment transport, an asymptotic solution of the convection diffusion equation is used. As a result, the three-dimensional concentration problem is separated into two parts: a two-dimensional depth-averaged sediment transport model and the vertical concentration profile at every grid point, which depends on the velocity profile and the mixing coefficient, and thus can be calculated in advance.

The wave-current interaction has two significant effects on sediment transport processes: the changes in turbulence intensity, and the enhancement in bottom shear stresses. A simple three-layer wave-induced diffusion coefficient (Van Rijn, 1986) was proposed. Its intensity is determined by the wave height, wave period, orbital velocity, particle size, and the wave breaking coefficient. The sediment mixing coefficient due to the combined waves and currents is assumed to be given by the sum of the squares of the current-induced and wave-induced values. The current-induced diffusion coefficients were provided by the turbulence closure scheme in the three-dimensional circulation model. The bottom shear stress required in the sediment transport study is calculated by a bottom boundary layer model (Lou and Ridd, 1997). The effect of wave-current interaction on the bottom shear stress is calculated based on the concept of Grant and Madsen (1979) in an iterative form.

It is assumed that the location of the fluid-sediment interface has been averaged over the wavelength of bedforms such as ripples or dunes. Garcia and Parker (1991) developed an empirical relation of the entrainment coefficient, and this relation has been generalized to sediment mixtures with the aid of field data. It has been indicated that this empirical fit can provide reasonable estimates of the entrainment coefficient. The suspended sediment concentration at the reference level is given as suggested by Van Rijn (1989).

The sediment transport model has been coupled with the circulation and wind wave model. The circulation model results (3-D current fields, eddy viscosities, and current-induced bottom stresses), and the wave model output (wave height, wave period and direction) are used to provide the forcing input for the sediment transport model.

In the model application to Lake Michigan in November-December 1994, a uniform 5 km horizontal grid mesh, 20 vertical layers, and a staggered C-grid arrangement were employed for all models. For the March 1998 sediment plume study, a finer 2 km horizontal grid mesh was used, while all other model features were kept the same.

SEDIMENT RESUSPENSION EVENTS IN NOVEMBER-DECEMBER, 1994

Instrumented moorings were deployed during the winter of 1994-95 at three stations, M19, M24, and M27 (Figure 1) in southern Lake Michigan to measure sediment resuspension and transport (Hawley and Lee, 1998). The sites were located in water depths of 101 m, 58 m, and 28 m respectively. Temperature, current velocity, and water transparency were measured at different depths at each station. The transparency readings correspond to the Beam Attenuation Coefficient (BAC) from 25 cm path length transmissometers, which has a linear relationship with the suspended material concentration in the lake (Hawley and Zyren, 1990; Hawley, personal communication). During the above period, no resuspension was detected at the deep water station M19.

The only available direct field measurement of critical stress was made at a 65 m deep station in southern Lake Michigan (Hawley, 1991). Tests on material from the bottom of Lake Erie (Fukuda and Lick, 1980) showed that erosion began when the shear stress was on the order of 0.1 - 0.2 N/m^2. In the present model study, a value of 0.13 N/m^2 was adopted as the critical bottom stress. Particle settling velocity was estimated from the ratio of mass flux trap data at station M19 to ambient suspended matter concentration (Eadie, 1997). As a result, the settling velocity of $5x10^{-5}$ m/s was chosen. It is also found that most suspended particles in the water column are less than 30 microns (Eadie, et al., 1990), which is consistent with the surficial sediment grain size distribution (Eadie, personal communication). In the model, for simplicity, a uniform grain size of 30 microns with an unlimited sediment source on the bottom is assumed.

The hydrodynamic and sediment transport models were calibrated and validated for a 60-day period from Julian day 301-360, 1994. The sediment transport model started running from an initial condition of zero suspended sediment concentration in the water column and unlimited bottom sediment source. The sediment measurement at M24 and M27 for high turbidity events will be studied. The capability of the sediment transport model to realistically simulate high concentration events is of critical importance because a high fraction of sediment is resuspended and transported during these episodic events.

Results of the sediment concentration for Julian days 320-340, 1994 at station M24 (0.9 mab - meters above bottom, 7 mab and 17 mab) and M27 (35 mab) are presented in Figure 3. In the winter of 1994-1995 (Lake Michigan was practically ice-free in that mild winter), most observed sediment resuspension events occurred in the above mentioned 20-day period. The model generally reproduces the high sediment resuspension events very well at both stations.

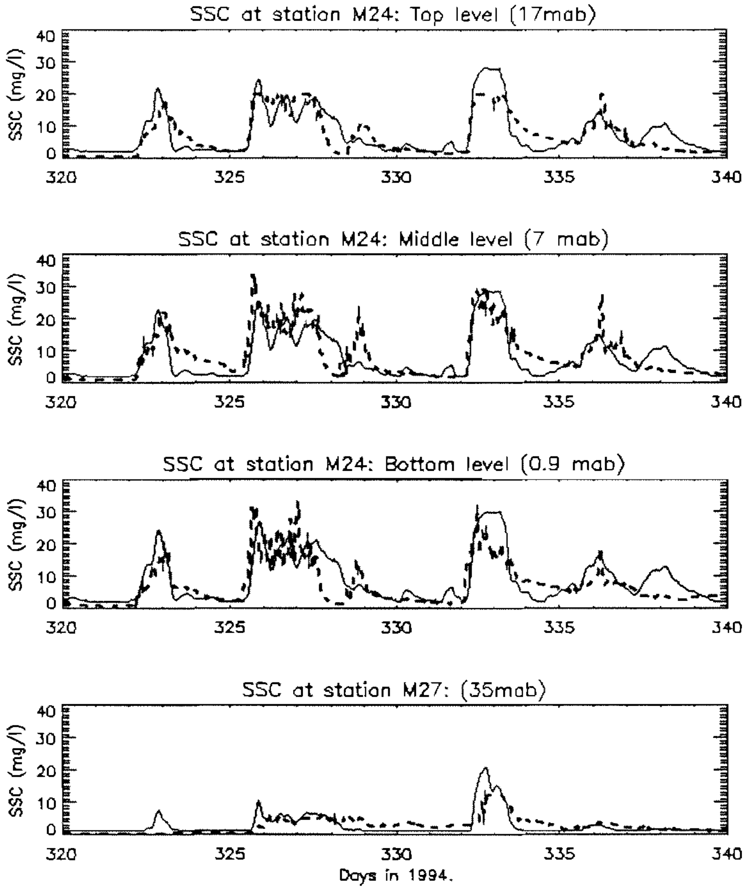

Figure 3. Suspended sediment concentration observations and predictions at station M24 and M27 during 20-day period in 1994 (Dashed line: observed data, solid line: model result).

Examination of modeled waves and bottom currents at station M24 reveals that the current at this station is usually not strong enough (< 0.2 m/s) to cause sediment resuspension. Except for the event during Julian days 325-328, which was induced by strong southerly currents (0.25 m/s) and large waves (3.7 m wave height), all other major resuspensions were mainly caused by strong waves. The subpeak observed on Julian day 329 was probably the result of high sediment load discharge from the Grand River on Julian day 328 moving northwest across station M24. Because no sediment loads from lateral boundaries and tributaries were considered, the model cannot respond to this effect.

The discrepancy between model results and observations on Julian day 338 is probably the result of the unlimited sediment source assumption in the model. Due to shallow water and frequent high wave activity, the area around station M24 forms one of the temporary, transient sediment reservoirs in the lake. The sediment material in these transient reservoirs is biogeochemically transformed within the lake, then redistributed throughout the year by a series of energetic events as suggested by Eadie (1997). Large episodic events resuspend and transport most of these materials from temporary sinks to more permanent depositional basins, leaving less erodible materials for subsequent energetic events. To deal with this problem, a more realistic sediment mixture and sediment source distribution based on field surveys should be considered.

At station M27, the resuspension is weak due to deeper water and smaller currents. Sediment concentration at this station increases only during higher energetic events. The model simulation reproduced the basic features of observed data at M27. At station M19, no obvious resuspension has been detected in either field data or model results, so the M19 data are not presented here.

THE MARCH 1998 SEDIMENT RESUSPENSION EVENT

In the March 1998 sediment plume study, a finer uniform 2 km horizontal grid mesh was employed. The model started from zero suspended sediment concentration over the whole lake as the initial condition on March 1, 1998. The dominant sediment particle size is assumed to be 15 microns, the settling velocity is set to 0.5 m/day.

Sediment concentration results (Figure 4) showed that at least some suspended sediment was present during most days of March 1998. The strongest sediment resuspension mainly occurred in the southern lake and the shallow waters near the coastline. This is caused by the larger waves in southern Lake Michigan due to the dominant northerly wind in this early spring period. The two most significant sediment resuspension events were detected in the model results on 9-12 March and 20-22 March, which coincide with the strongest winds as shown in Figure 5. The first storm caused strong sediment resuspension (with concentration values above 10 mg/l) in coastal areas within the 30 meter isobath after March 8. Large waves (over 5 m) were responsible for the local resuspension along the coastline, and the strong currents determined the plume advection. The most significant sediment resuspension events occurred along the southern and southeastern shoreline during March 10-12 and March 21-23 (seen in Figure 2). The sediment model was not able to simulate the observed spiral eddy structure on March 12. The second resuspension event also occurred under northerly wind conditions on March 21. The sediment concentration results showed a similar pattern but with somewhat smaller magnitudes. Another noticeable phenomenon in the model results is evidence of strong offshore sediment transport near the southeastern corner of the lake during the 9-12 March storm, and a similar pattern after March 21. From the circulation model results (Schwab et al., 1999), it is clearly seen that this offshore transport resulted from the characteristic two-gyre circulation pattern present in the lake during that time. Due to the two-gyre circulation structure, a convergence zone was formed at this site with a strong offshore flow, which moved suspended sediment material from the coastal area to the deep waters. The sediment model results are consistent with the particle trajectory simulations (Schwab et al., 1999). Similar offshore sediment transport was also seen in previous plume events (Eadie et al., 1996), with the offshore transport occurring at slightly different sites along the southeastern shoreline depending on wind direction. Comparing Figure 4 with the satellite reflectence imagery of Figure 2, the model results appear to reproduce the occurrence, development and decline of the sediment plume well.

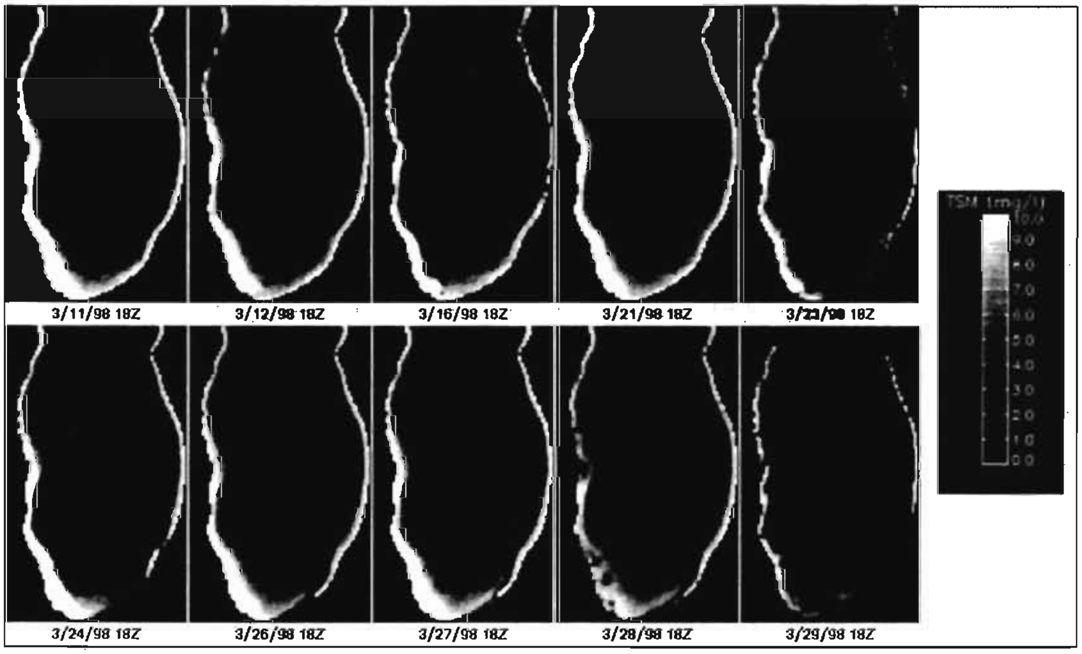

Figure 4. Modeled suspended sediment concentrations at times corresponding to that of Figure 2.

Because the offshore structure of the sediment plume depends strongly on the circulation patterns, it is believed that inaccuracies in the hydrodynamic model results could well be responsible for the missing features of spiral eddy pattern in the model results in the central part of southern lake plume. To study this unique process further, more hydrodynamic and sediment transport studies are needed in the future.

Assuming that the bottom sediment dry bulk density is 1450 kg/m^3, the calculated time series of suspended sediment mass in the lake is given in Figure 6. It shows clearly the two strong resuspension events in March 1998. The estimated total resuspended sediment mass in March, 1998 in Lake Michigan was 6.71×10^9 kg, while in the southern lake basin the total amount of resuspended material is 3.76×10^9 kg.

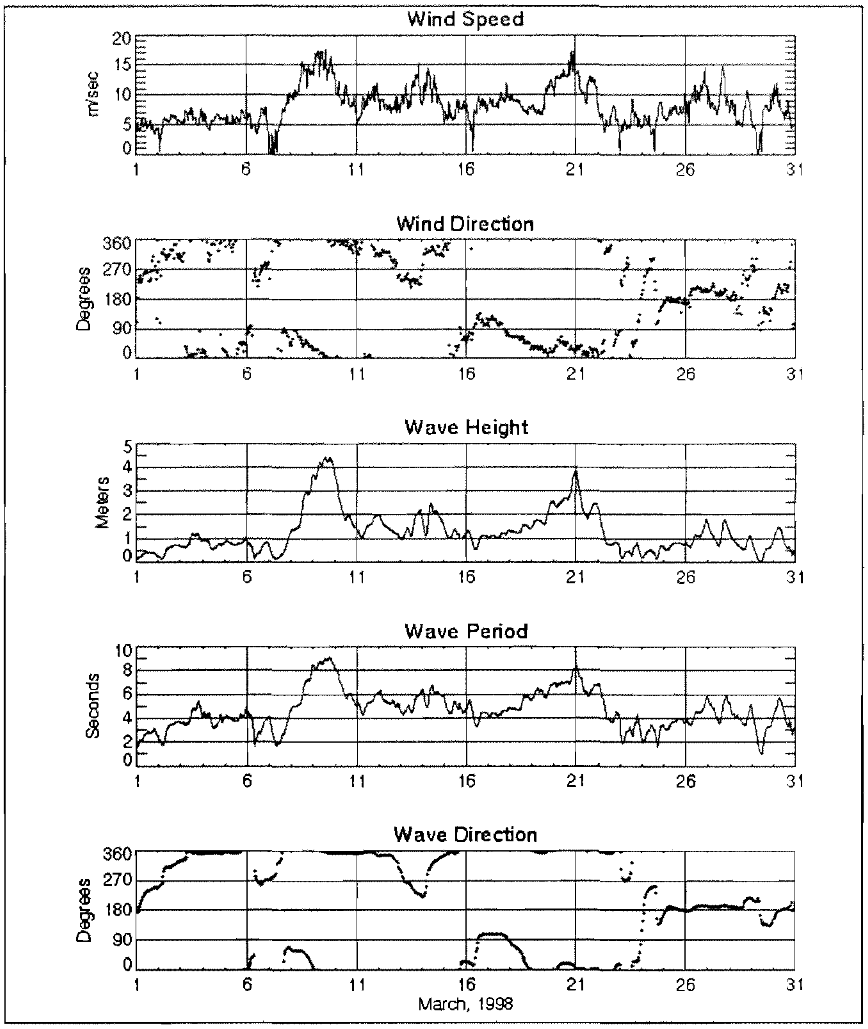

Figure 5. Time series of interpolated wind and modeled waves at a location in the center of southern Lake Michigan for 1-30 March, 1998.

SEDIMENT TRANSPORT MECHANISMS IN LAKE MICHIGAN

The coupled hydrodynamic/sediment transport model makes it possible to investigate the physical mechanisms for sediment resuspension and transport in Lake Michigan. In this section, the effects of waves, currents, and advection on sediment resuspension and transport are discussed.

Wave Effects on Sediment Transport

In this model study, only the wave field was used as the input for sediment transport calculation. All model parameters were kept the same. The modeled suspended sediment amount in March 1998 is given in Figure 7.

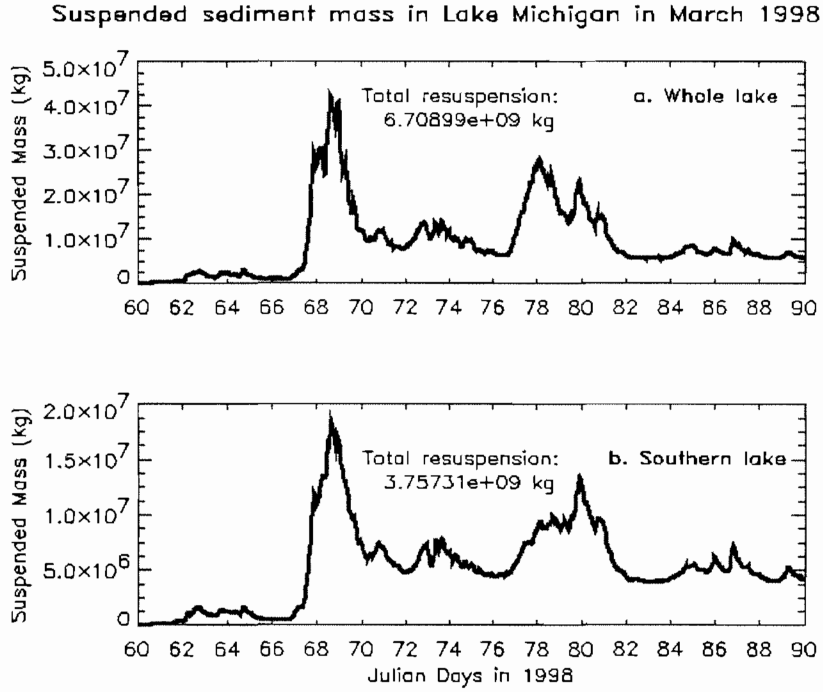

Figure 6. Modeled time series of suspended sediment amount in Lake Michigan.

Without currents, the sediment resuspension occurred only in shallow water region (< 20 m water depth) very close to shoreline. In this case, because there was no advection and the diffusion was very small, no sediment movement to deep water was detected. The coastal sediment plume resulted solely from local sediment resuspension by strong waves. The sediment concentrations were maintained in the water column until waves declined, then the sediment started settling down to the bottom. Even though the wave-induced sediment resuspension occurred only very close to shoreline, this case shows that the waves are the most important mechanism in sediment entrainment and resuspension. The wave-induced resuspended mass accounts for over 85% of the total resuspension under combined wave-current condition (Figure 7). The two most significant wave-induced resuspension events were consistent with that occurred in previously presented wave-current situtation in Figure 6.

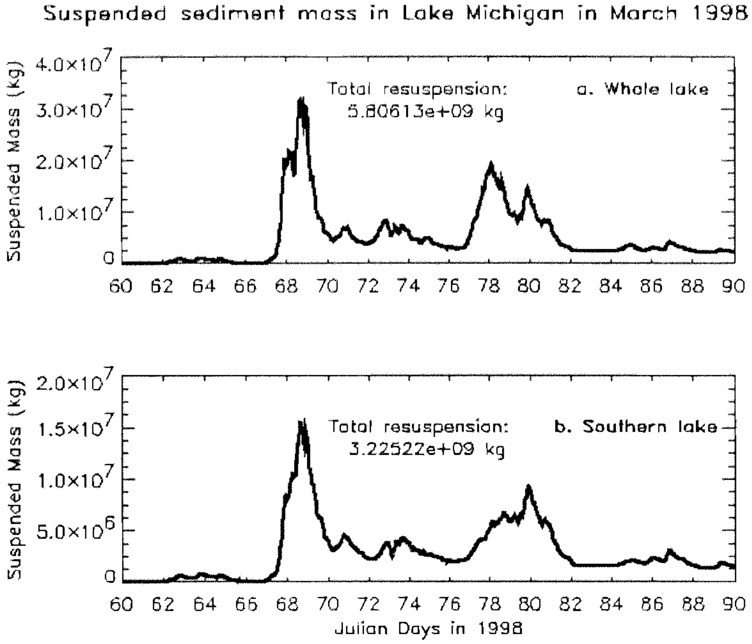

Figure 7. Wave-induced suspended sediment mass in Lake Michigan in March, 1998.

Current Effects on Sediment Transport

In this test, the sediment transport model was run with forcing from the circulation model only. The wave field was assumed to be zero. Because the current-induced bottom shear stresses were not big enough to exceed the critical bottom shear stress during most days of March 1998, no detectable sediment plume was produced from the model results. Though some resuspension did occur during March 9-11, and around March 21, the magnitude of suspended sediment concentration was much smaller (< 1.2 mg/l) than the wave-induced resuspension. We therefore conclude that the current itself cannot cause the significant sediment resuspension observed in the lake during this period.

From the above tests, it follows that the current cannot generate the suspended sediment plume by itself. On the other hand, waves play an important role in sediment entrainment and resuspension in southern Lake Michigan. However, the wave-induced sediment resuspension can only occur in the narrow near shore area, therefore no onshore-offshore sediment transport visible in the satellite images was found in the model results. In an additional model run, the wave data was used together with the advection due to the currents, while no current-induced bottom friction stresses were considered. The results showed features similar to the combined wave-current case as in Figure 4, but with smaller amplitudes. Therefore, we conclude that the strong waves are the main mechanism for sediment resuspension, and the circulation is responsible for the horizontal sediment transport.

CONCLUSIONS

The quasi-3D sediment transport model was applied together with hydrodynamic circulation and wind wave models to study the resuspension dynamics in southern Lake Michigan. The model successfully predicted the major sediment resuspension events at two field stations in November-December, 1994. The capability of the sediment transport model to realistically simulate high concentration events in southern Lake Michigan is of critical importance, because a large fraction of sediment is resuspended and transported during these relatively infrequent events. The predicted sediment resuspension was consistent with our current knowledge based on the satellite images.

Despite the simple assumptions and the limitations of the sediment transport model, it illustrates the importance of hydrodynamic effects on sediment resuspension and transport in southern Lake Michigan. The model results show that the sediment resuspension in southern Lake Michigan is mainly caused by waves. Whenever there are big waves, sediment resuspension can be expected. Due to the circulation effects, the nearshore plume is diffused and moved in alongshore and onshore-offshore directions. The nonlinear wave-current effects were not important in these plume events, and accounted for less than 20% of the total resuspended sediment material in the lake.

Although the modeling framework used in the present study has proven effective, the model does possess some limitations. Several areas have been identified that require further laboratory and field research and improvement of the model. A sediment mixture based on the field survey of grainsize distribution should be included; sediment source input from shoreline erosion, tributary discharge and bottom sediment availability function need to be included; cohesive flocculation should also be taken into account. More field data on the settling velocity, critical bottom shear stresses, and sediment concentration under various conditions need to be collected.

ACKNOWLEDGEMENT

This work was performed while JL held a National Research Council -- NOAA/GLERL Research Associateship. DJS and DB were partially supported by the NSF/NOAA Episodic Events-Great Lakes Experiment project. This is NOAA/GLERL contribution No.xxxx.

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