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USING WAVE STATISTICS TO DRIVE A SIMPLE SEDIMENT TRANSPORT MODEL

Barry M. Lesht[1] and Nathan Hawley[2]

Abstract: Because both contaminant and nutrient cycles in the Laurentian Great Lakes depend on particle behavior and movement, sediment transport is a critical component of many of the water quality models being developed to understand and manage this important resource. To avoid complicated models that cannot be supported by the available field data, we have used observation-based, empirical analysis as the basis for developing methods of predicting sediment resuspension from relatively simple measurements of the surface wave field. Our modeling is based on data obtained from instrumented tripods designed to measure near-bottom hydrodynamic and sedimentological conditions for extended periods of time. Because of the long duration of the deployments, it usually is impractical to both sample and record the data at the high frequency that would be needed to resolve the effects of individual surface waves. Instead, we have used a system of burst sampling, in which we sample the sensors at high frequency during a period of time that is repeated at an interval appropriate for the deployment duration. Rather than record the individual samples during the burst, we record only statistics obtained from the individual samples. Our results show that simple representations of the surface wave field obtained from the burst statistics can be used to model sediment transport in wave-dominated environments. We also show that once the model parameters are determined, the forcing wave conditions can be derived from other sources, including wind-driven wave models, with comparable success.

[1] Associate Director, Environmental Research Division, Argonne National Laboratory, Argonne, Illinois 60439, barry.lesht@anl.gov
[2] Research Oceanographer, Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration, Ann Arbor, Michigan 48105, hawley@glerl.noaa.gov

INTRODUCTION

Although wind-driven, large-scale circulations are important in the Great Lakes, sediment transport in the lakes is almost always initiated by surface wave action (Lesht, 1989; Hawley and Lesht, 1995). Sediment transport is included in the detailed water quality models being developed for the lakes via sub-models that can be quite complicated, with high spatial resolution, many sediment layers, several sediment size classes, and various parameterizations describing the space- and time-dependent response of the sediment bed to the imposed hydrodynamic forcing, which usually is computed by other sub-models. See Lick *et al.* (1994), Lou *et al.* (2000), Li and Amos (2001), and Harris and Wiberg (2001) for examples. Though impressive in formulation, these combined sediment transport-hydrodynamic models are generally much more detailed and complex than are the available field data (either hydrodynamic or sedimentological), and therefore the model output cannot easily be compared with, or evaluated against, field observations. This limitation makes it difficult either to quantify the uncertainty associated with the model forecasts or to have confidence in the model calibrations. Furthermore, the output of the high-resolution sediment transport models often must be aggregated spatially to match the much lower resolution of the water quality models. In an alternative approach, we have used observation-based, empirical analysis as the basis for developing simple methods of predicting sediment resuspension from relatively basic measurements of the surface wave field. The purpose of this paper is to describe our method for converting measurements of wave statistics to information that can be used to drive sediment transport models and to demonstrate the application of these models to a recent study of sediment transport in Lake Michigan.

METHODS

Our modeling is based on data obtained from instrumented tripods designed to measure near-bottom hydrodynamic and sedimentological conditions for extended (weeks to months) periods of time. The tripods (Lesht and Hawley, 1987) are equipped to measure horizontal flow velocity, wave conditions, suspended sediment concentration, and water temperature. In the configuration described here, the instruments included a Marsh-McBirney* 512 OEM two-dimensional electromagnetic current meter, two SeaTech* 25-cm-pathlength transmissometers, a Paroscientific* 8130 digital quartz pressure transducer, a solid state temperature sensor, and a compass and tilt sensors to monitor the tripod orientation on the bottom.

Data Sampling

Because of the long duration of the deployments, it usually is impractical to both sample and record data at the high frequency that would be needed to resolve the detailed

* Mention of trade names is for information only and does not constitute endorsement of any commercial product by Argonne National Laboratory, the National Oceanic and Atmospheric Administration, or the U.S. Department of Energy.

effects of individual surface waves. Instead, we have used a system of burst sampling, in which we sample the sensors at high frequency for a defined period of time, repeated at an interval appropriate for the deployment duration, and record only burst statistics obtained from the individual samples. These statistics include the means, standard deviations, and minima and maxima for all sensors; the covariance of the pressure deviations with each horizontal component of the horizontal flow; and the number of times the pressure deviations change sign during a burst. For the experiments described here, all the sensors were sampled at 4 Hz, the burst length was 5 minutes, and the bursts occurred every 30 minutes. Thus, rather than recording 1,200 samples per sensor per burst, we record between 4-6 statistics per sensor per burst.

Wave Pressure Analysis

Extracting information about wave processes from the burst statistics requires that we make several assumptions. First, we assume that the fluctuating pressure is Gaussian and stationary within bursts. Thus, we use only the first and second moments to characterize the wave distribution. This assumption is not terribly restrictive, because we are interested in the processes occurring near the bottom, not at the surface. By making our measurements near the bottom, we take advantage of the filtering effect of depth to reduce contributions of higher-frequency components, and the signal that remains tends to be nearly monochromatic. Second, we assume that the 5-minute burst length is sufficient to collect stable statistical values. Our choice of a 5-minute burst results from our desire to minimize power consumption. By using this value, along with a 2-minute warm-up period in each burst, the sensors are energized for only 14 minutes every hour, considerably extending the potential duration of our deployments. Finally, we assume that our near-bottom pressure measurements are sufficiently sensitive to sample the range of wave processes that will have a sedimentological effect on the bottom. The data acquisition system allows us to measure a pressure change corresponding to about 0.7 mm of water.

Because we use an absolute pressure sensor, each individual pressure sample includes contributions from the atmospheric pressure, from the mean water depth, and from the deviation in water depth due to surface waves. We do not make direct, real-time measurements of atmospheric pressure, but we assume that the contribution from atmospheric pressure will vary slowly relative to the time scale of our measurements and can be removed in post-processing. However, we have found it useful to subtract the contribution of the mean water depth to the total pressure signal in real time to facilitate calculation of the average wave period and of the covariances between the pressure and horizontal velocity fluctuations. We estimate the mean depth by sampling the pressure during the two-minute instrument warm-up period and subtract this value from the pressure measurements made during the five-minute data burst. We also calculate the average total pressure measured during the data burst so that we can compare both the means and variances of the two estimates. The agreement between the two is excellent.

During the more than 12,000 data bursts we have collected in deployments done since 1998, the maximum absolute difference between the average water depths recorded during the warm-up and data sampling periods was 0.13 m (with fewer than 0.2% greater than 0.05 m), the average difference was 0.0003 m, and the standard deviation of the differences was 0.009 m.

Determining the average wave period from the pressure fluctuations is critical for estimating near-bottom wave orbital velocity. We estimate the average wave period, which in a monochromatic field is equivalent to the peak energy period, by dividing the data burst length in seconds by the average number of pressure fluctuation sign changes during the burst.

Current Meter Analysis

We also sample both axes of the current meter at 4 Hz and record burst statistics. For each burst, we record the mean, standard deviation, and range of the individual axis values, the mean speed, the magnitude and direction of the mean velocity vector, the standard deviation of the current direction, and the covariance of the magnitude of each flow component and the pressure fluctuations. These values are sufficient for us to estimate the mean horizontal current speed, the near-bottom wave orbital velocity, and the direction of the waves relative to the mean flow.

We assume that the near-bottom current velocity components $u(t)$ and $v(t)$ consist of steady, or slowly changing relative to the burst length, components U and V, along with fluctuating components $u'(t)$, $v'(t)$. Further assuming that the fluctuating components result from monochromatic wave of frequency ω ($\omega = 2\Pi/T$, where T is the wave period in seconds), traveling in direction Θ relative to the V axis of the current meter and having a maximum near-bottom orbital velocity of R, we have,

$$u'(t) = R\cos\theta\cos(\omega t)$$
$$v'(t) = R\sin\theta\cos(\omega t)\ . \qquad (1)$$

Clearly, calculating the averages of $u(t)$ and $v(t)$ over long periods of time relative to the time scale of the fluctuations provides estimates of U and V. The magnitude of the near-bottom orbital velocity (R) is simply obtained from σ_u^2 and σ_v^2, the variances of $u(t)$ and $v(t)$, by

$$R = \sqrt{2\left(\sigma_u^2 + \sigma_v^2\right)}\ . \qquad (2)$$

The relationship between the near-bottom pressure fluctuations due to surface waves and the wave orbital velocity may be obtained from linear wave theory (*e.g.*, Kinsman, 1965) and written as

$$R = P\kappa/\rho\omega\ , \qquad (3)$$

in which P is the amplitude of the pressure fluctuation measured at distance z above the bottom, κ is the wave number ($2\Pi/L$ where L is the wave length in m), and ρ is the water density. Taking $\Delta p = P\cos(\omega t)$, we can use σ_p, the measured standard deviation of Δp, to estimate P by $P = \sqrt{2}\bullet\sigma_p$. Thus, with Eqs. 2 and 3, we have two independent measurements of the near-bottom wave orbital velocity obtained from the burst statistics. The agreement between these two independent estimates (Fig. 1) is excellent.

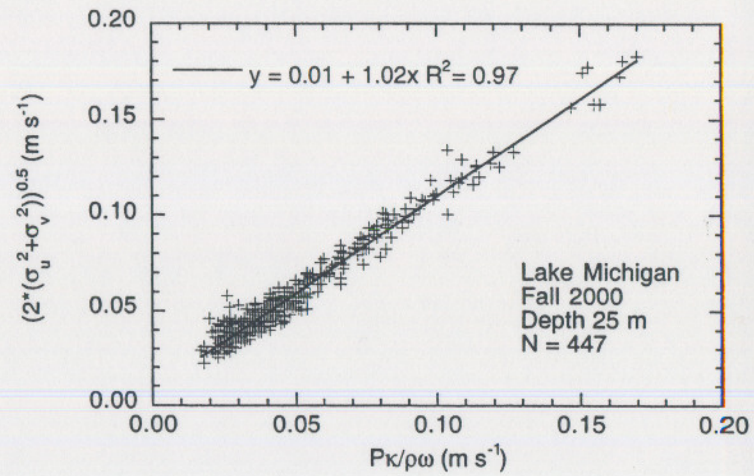

Fig. 1. Current meter [Eq. 2] and pressure sensor [Eq. 3] estimates of wave orbital velocity for fall 2000 experiment. Bursts without waves are not included.

Sediment Resuspension Model

We use a very simple model (Hawley and Lesht, 1992) that relates the suspended sediment concentration near the bottom to the local properties of the sediment and to the hydrodynamic forcing. The model, which includes the upward flux of bottom sediment due to resuspension and the downward flux due to settling, may be written

$$D\frac{dC}{dt} = \alpha\left|\frac{\tau-\tau_c}{\tau_r}\right| - w\left(C - C_{bak}\right) \quad \text{for} \quad \tau > \tau_c$$

and (4)

$$D\frac{dC}{dt} = w\left(C - C_{bak}\right) \qquad \text{for} \quad \tau \le \tau_c\ ,$$

where D is total water depth, C is the depth-averaged suspended sediment concentration (kg m^{-3}), C_{bak} is a background concentration, τ is the bottom shear stress (Pa), τ_c is a threshold stress value for the initiation of sediment transport, τ_r is a reference stress value used to make the excess stress term dimensionless, w represents the sediment settling velocity (m s^{-1}), and α (kg m^{-3}) represents the rate at which sediment is eroded from the bottom.

Although we have found that it is possible to express the hydrodynamic forcing directly in terms of wave orbital velocity (Lesht and Hawley, 1987), thereby eliminating the problem of estimating the bottom shear stress, we use shear stress as the forcing in the present example. Because we use our observations to estimate the parameter values, the choice of forcing flow parameter is arbitrary so long as it is used consistently in applying the model to different locations.

Field Experiments

The goals of our research are to document the frequency and intensity of sediment transport events, to establish constraints on the output of the detailed sediment transport models, and to provide the basis for developing simple empirical models that relate sediment transport to some easily measured or modeled feature of the flow. We have conducted studies in the Great Lakes using these methods since the mid 1980s (Lesht, 1989; Hawley and Lesht, 1995; Hawley and Murthy, 1995; Lee and Hawley, 1998; Hawley and Lee, 1999). A common result of this research is that although other processes such as coastal upwelling have a role, sediment transport in the Great Lakes is dominated by the effects of wind-driven surface waves. In this paper, we use data collected during the recent Episodic Events – Great Lakes Experiment (EEGLE) program (Eadie *et al.*, 1996) to demonstrate how simple empirical models based on wave forcing can be constructed from field observations.

RESULTS

The basic data obtained from a recent (fall 2000) tripod deployment are shown in Fig. 2. A major sediment resuspension event, the only one during the 48-day deployment, occurred on day 264. At its peak, the near-bottom optical attenuation reached 5.9 m^{-1}, roughly corresponding to a suspended sediment (TSM) concentration of 11 kg m^{-3} (Hawley and Zyren, 1990). This resuspension event was clearly associated with a concurrent increase in near-bottom wave orbital velocity that reached 0.18 m s^{-1}. Although the near-bottom wave orbital velocity exceeded 0.10 m s^{-1} later in the deployment at day 280, there is only a slight increase in attenuation, suggesting that wave-driven local resuspension did not occur at this time. Although unidirectional currents near the bottom also exceeded 0.10 m s^{-1} at times, our goal here is to find a consistent set of model parameters that will allow us to reproduce the near-bottom sediment concentration time series from knowledge of the surface wave conditions alone. Having such a set of model parameters will greatly simplify the process of integrating sediment resuspension and transport into large-scale water quality models.

We determined a set of optimal model parameters by minimizing the differences between the observed and predicted sediment concentration time series through use of

Willmott's (1982) index of agreement and percent unsystematic error statistics as our criteria for evaluating the fit of the model to the data. The simplicity of the model formulation makes it easy to compare the success of different choices of the forcing variable (*e.g.*, bottom shear stress, wave orbital velocity) and to evaluate the variability in model parameters with bottom type.

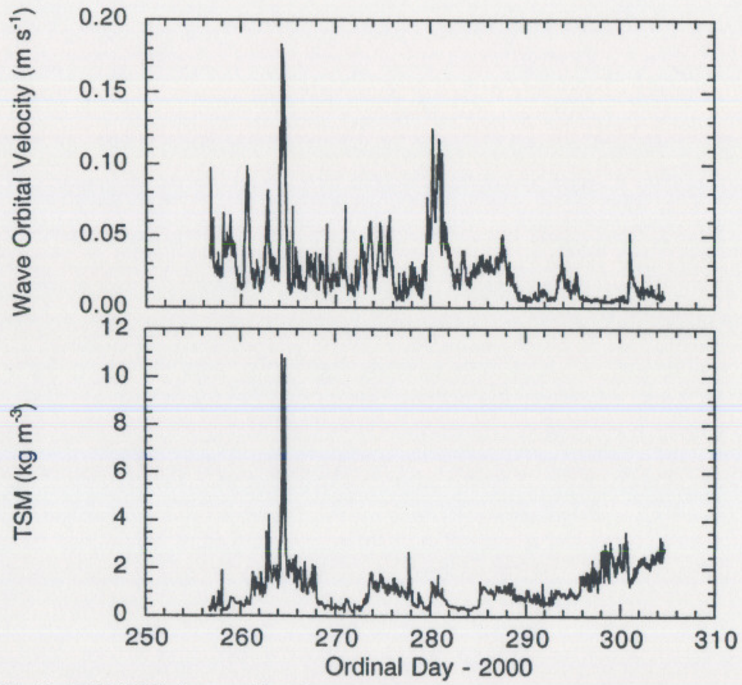

Fig. 2. Fall 2000 time series of near-bottom wave orbital velocity and sediment concentration 0.7 m above the bottom at 25-m depth in southern Lake Michigan.

Figure 3a shows the suspended sediment concentration predicted by using our model (Eq. 4) with optimized model parameters and two different estimates of the wave bottom shear stress: that estimated from the wave statistics measured by the tripod and that estimated from wave properties calculated with a simple wind-driven surface wave model (Schwab *et al.*, 1981). Because biological fouling began to affect the transmissometer late in the experiment, we limited the modeling to the 38-day period between the beginning of the deployment (day 257) and day 296.

DISCUSSION

The calibrated model forced with wave bottom shear stress estimated from the tripod observations did well in reproducing the observed near-bottom sediment concentrations.

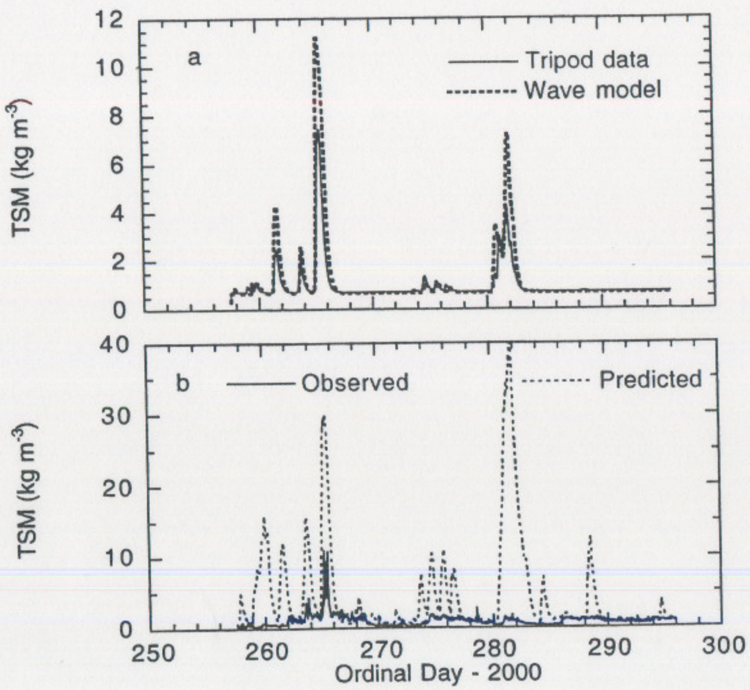

Fig. 3. Time series of suspended sediment concentrations predicted using estimates of (a) wave bottom shear stress made from the tripod data and from the wave model and (b) combined wave-current stress from the tripod data.

The same model parameter values produced a very similar result when the model was forced with shear stress estimated from the wave conditions calculated by using the wind-driven wave model. Both models successfully reproduce the major resuspension event that occurred on day 265, and both over-predict the observed concentration on day 282. The fact that the model results shown in Fig. 3a are so similar indicates that the wind-driven wave model fairly accurately simulates the observed wave conditions. We found that for this deployment, the wave model wave heights tended to be higher than those measured at the tripod, but the model's wave periods were shorter than the observations. These factors tended to offset one another when the wave stress was calculated.

A combined wave-current shear-stress model (Lou and Ridd, 1996) used with the same set of parameter values (Fig. 3b) greatly over-predicted the sediment concentration. The amount of over-prediction depended on the magnitude of the current component, which suggests that either our model assumptions are violated when currents dominate the flow field or that our point measurements of sediment concentration are insufficient to represent the flux of material off the bottom into the flow. Of course, there may also

be a problem with the estimated shear stress. In any event, further analysis of this case is required. The degree to which the model results depend on the shear stress calculation is an important point. Because we do not measure shear stress directly, we must rely on values calculated from other measurements, typically current velocities, or, as in the case described here, wave orbital velocities. Although modeling the sediment response in terms of shear stress is theoretically sound, models may suffer from the uncertainty added to the calculation by converting the current or wave orbital velocities to shear stress.

CONCLUSIONS

Our simple sediment resuspension model was very successful in reproducing the major features of the observed sediment concentration when forced with either the wave properties derived from the statistics recorded by the tripod or the wave properties predicted by the wind-driven wave model. Because sediment resuspension in the Great Lakes is primarily wave driven, this result suggests that large-scale modeling of sediment transport in these waters can be simplified by limiting resuspension calculations to shallower regions near the shore and by using a parameterization of resuspension based on modeled wave properties. Further work is needed to understand how best to incorporate combined wave-current flows into the simple model formulation. We also need to better understand the sensitivities of the model parameters and how they vary with sediment type. Given the limitations of sediment transport field observations, we believe that this simple approach provides adequate accuracy and precision for most modeling applications.

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