A Multi-Size, Multi-Source Formulation for Determining Impacts of Sediments on Near-Shore Sensitive Sites

Panagiotis Velissariou[1], Vasilia Velissariou, Yong Guo and Keith W. Bedford

Abstract

The unconfined placement of dredged material raises the issue of potential adverse impacts on sensitive near-shore areas (e.g. water intakes) located some distance away from the placement site. Two management questions arise: first, whether the material from the placement site is actually transported to the sensitive area; and second what is the relative intensity of this load compared to other sites.

In an effort to evaluate the relative impact of different sediment sources on sensitive near-shore areas we considered a multi-grain size, multi-source sediment transport model formulation. Calculations were performed using the CH3D circulation model coupled with a sediment model known as the CH3D-SED, which includes a suspended sediment and a mobile-bed sediment module.

The location of interest has been the Toledo, Ohio, water intake area in the western basin of Lake Erie. The sediment disposal site is located a few miles northeast of the sensitive site. The four sediment sources selected are: the Maumee River, the Detroit River, the entrained bottom sediments and the sediments originating from the disposal site. Three representative grain sizes, one from each sediment size class (sand, silt, clay), were assigned for each source.

The model was run on a 2 km spatial grid for the test period from April 1, 1997 to December 31, 1997. Model outputs include: 3-D velocity, temperature and concentration (all grain sizes) fields, vertically integrated velocities and grain size distributions at the lake bottom, from which hourly trajectory maps and time traces are generated.

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A first evaluation of the model results implies that the major contributor to suspended sediment load is the bottom sediment, which overwhelms the sensitive site. The impact from the disposal site seems to be minimal while more significant contributions are observed from the river inputs. In fairly calm weather conditions the finer sediment classes are the major contributors to the suspended sediment loading, while during storm events the resuspension and transport of sands is also significant.

Introduction

This paper summarizes some of the first findings of a research project funded under the US Army Corps of Engineers cooperative agreement whose objectives were to determine: a) if dredged sediments disposed at the new unconfined sediment disposal site at the western basin of Lake Erie are actually being transported to the Toledo water intake area under various meteorological conditions, and b) to compare the relative intensities of the water intake area particle load from the disposal site to those water intake area loads originating from other sediment sources such as local resuspension and tributary inputs.

The Toledo, Ohio, water intake area, is located 12600 m south to southeast the disposal site. The disposal site is located at 41°48.6' N, and 83°17.0' W, in water of 6.1 m to 7.0 m depth relative to IGLD Low Water Datum (Figure 1).

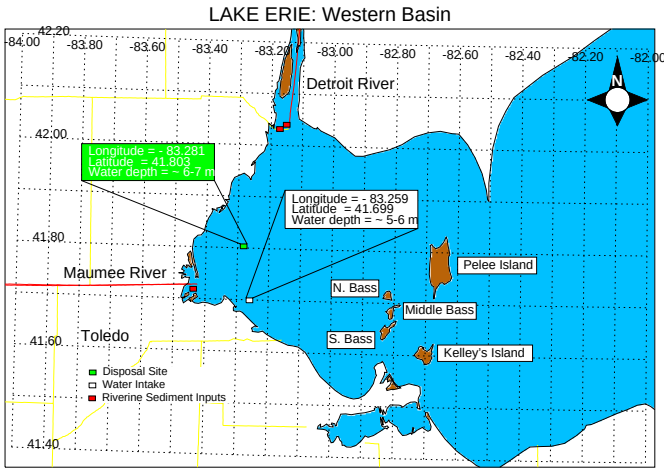

Figure 1: Location of the disposal and water intake sites at the western basin of Lake Erie.

To answer the above questions a multi-grain, multi-source sediment transport formulation was used. Three sediment sources were selected to represent the sediments originating from the disposal site, from the Maumee River, and from

the Detroit River. A fourth sediment source selected was associated with the entrainment and transport of the lake bottom sediments. The sediments of each source are represented using three size classes (sand, silt, and clay). The sediment particle diameters for these classes are set to vary slightly among the different sources. This approach allows both the identification of the sources of the sediment material transported at the water intake area and, the evaluation of the relative intensity of the sediment load transported from each source, to the total load transported.

Model Selection

The calculations were performed using the CH3D circulation model coupled with a sediment model, known as CH3D-SED model (Spasojevic and Holly, 1994. The decision to engage CH3D-SED in this project came out of its ability to model sediments of various grain sizes and its ability to model the sediments originating from different sources.

CH3D is a three dimensional, non-linear primitive equation circulation model. The equations governing the circulation of the lake include the continuity equation, the momentum equations and the conservation equation for the thermal energy. CH3D-SED describes the advection and turbulent diffusion of the suspended sediments, as well as the entrainment of the bottom sediments and the evolution of the lake bottom (as bottom sediments are being transported). The sediment equations of the model describe the behavior of a non-uniform sediment mixture, which is represented by an appropriate number of sediment size classes.

Using the concept of an elemental volume ΔV that includes the upper layer of the bed and the bed surface, and assuming a uniform sediment size distribution within this volume, the conservation of mass equations for each size class are given by (Spasojevic and Holly, 1994):
For each size class separately:

$$\rho_s(1-p)\frac{\partial(\beta E_m)}{\partial t} + \nabla\vec{q}_b + S_e - S_d - S_F = 0 \qquad (1)$$

For the sum of all size classes:

$$\rho_s(1-p)\frac{\partial E_m}{\partial t} + \sum(\nabla\vec{q}_b + S_e - S_d - S_F) = 0 \qquad (2)$$

with the constraint: $\sum\beta = 1$.

In the above equations, p is the porosity of the bed material and ρ_s is the density of the sediment (both assumed to be constant); β represents the fraction of the mass of one particular size class over the mass of all sediment particles in the elemental volume; and $\vec{q}_b$ is the bedload mass flux expressed as a two-

dimensional vector parallel to the bed surface. The bedload is calculated in CH3D-SED by using an empirical relation proposed by Van Rijn (1984a). For one particular size class the bedload flux is given as:

$$\left(q_b\right)_s = 0.053 \cdot \rho_s \cdot \sqrt{(s-1)gD_s}\,\frac{D_s}{D_{*s}^{0.3}}\left[\frac{u_*^2 - u_{*c}^2}{u_{*c}^2}\right]^{2.1} \tag{3}$$

where, D_s is the particle diameter; D_{*s} is the dimensionless particle diameter defined as:

$$D_{*s} = D_s\left[\frac{\sqrt{(s-1)\,g}}{\nu^2}\right]^{1/3} \tag{4}$$

u_* is the bed shear velocity; and u_{*c} is the critical shear velocity.

The source term, S_e represents the entrainment of the bed sediments into the water column, S_d represents the settling of suspended sediments and S_F describes the exchange of sediment particles between the active layer elemental volume and an elemental volume immediately underneath, called the active stratum elemental volume (Spasojevic and Holly, 1994).

Similarly, the mass conservation equations for an elemental active stratum volume can be written as:
For each size class separately:

$$\rho_s(1-p)\frac{\partial}{\partial t}\left[\beta_s\left(z_b - E_m\right)\right] + S_F = 0 \tag{5}$$

For the sum of all size classes:

$$\rho_s(1-p)\frac{\partial}{\partial t}\left(z_b - E_m\right) + S_F = 0 \tag{6}$$

with the constraint: $\sum \beta_s = 1$, where, z_b is the bed elevation and β_s is the active stratum fraction of the mass of one particle size class over the mass of all sediment particles.

The advection and turbulent diffusion of each particular size class of the suspended sediment can be expressed in mathematical form as:

$$\frac{D(\rho C)}{Dt} = \frac{\partial}{\partial x}\left[D_h\frac{\partial(\rho C)}{\partial x}\right] + \frac{\partial}{\partial y}\left[D_h\frac{\partial(\rho C)}{\partial y}\right] + \frac{\partial}{\partial z}\left[D_v\frac{\partial(\rho C)}{\partial z}\right] + \frac{\partial}{\partial z}\left(\rho C w_f\right) \tag{7}$$

In the above equation, C is the ratio of the mass of one particular sediment size class to the mass of all size classes within an elemental volume ΔV, ρ is the

density of the sediment-water mixture, represented by all size classes, w_f is the settling velocity of the sediment particles and D_h, D_v are the horizontal and vertical mass diffusion coefficients.

The hydrodynamic part of the CH3D-SED model provides information about the fluid velocities, water depths and temperature changes that are required input for the sediment part. The sediment model in return provides information about the changes of the bed elevation, the bed surface roughness due to the changes of the bed-surface size distributions and changes of the density of the water-sediment mixture (Spasojevic and Holly, 1994).

Data Analysis

The availability of the extensive databases of the Great Lakes Forecasting System (GLFS) made it a natural choice to use these databases to obtain the meteorological data required by CH3D-SED. The database chosen was the year 1997, and for the ice-free period between April 1 to December 31, 1997. The meteorological data obtained from GLFS were the wind speed and temperature fields, at the free water surface of Lake Erie. The hourly wind speed data are adjusted to reflect: a) a common anemometer height and b) the over-water conditions. Further manipulation of the wind and the temperature data is not required for use in CH3D-SED. From these data the model internally calculates the wind stresses.

The daily flow rates of the three tributaries considered in this study were obtained from the U.S.G.S databases (1998). The daily flow rates for Maumee and Niagara rivers were available for the simulation year 1997 and were directly used as model input. Measured data for the Detroit River are sparse and not available for the simulation year. Considering the fact that the flow rates of Detroit river over the years have a very close resemblance and small value variations (G. F. Koltun, 1990), the latest available data from the USGS database (USGS Water Resources of the United States) were used, which are the data from the year 1977. The flow rate data are shown in Figure 2.

The sediment modeling requires the inclusion of all the major sediment sources. The sediment sources considered in Lake Erie are the bottom sediments (source 1), the disposal site unconfined sediments (source 2) and the riverine sediment inputs (sources 3 and 4). Despite the fact that shore erosion is extremely important in sediment forecasting, and a very significant sediment source, it was not considered in this study simply because the purpose is to determine the relative intensity of the impacts of the other four sources on the water intake site.

Qualitative information about the bottom sediments and their grain size distribution for Lake Erie was obtained by Thomas et al. (1976) who used both sediment sampling and acoustic profiling to examine 275 sampling locations all over the lake. Their results show a distribution of the bottom sediments based upon four basic types which are identified as follows: a) sand and/or gravel (S), b)

post-glacial mud (M), c) soft gray mud with some sand (SM) and d) glacial sediments (GL).

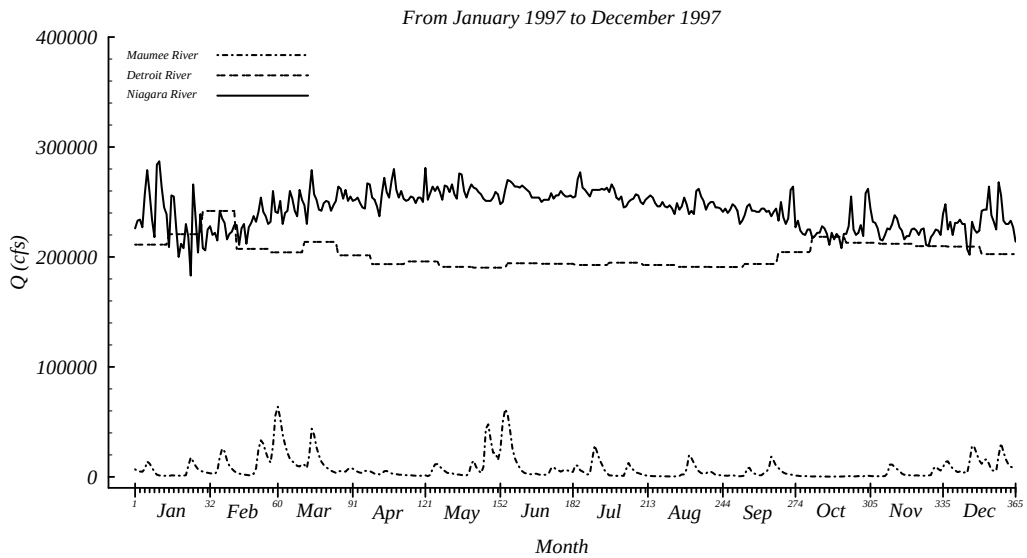

Figure 2: Daily flow rates for the Maumee, Detroit and Niagara Rivers for the simulation year 1997.

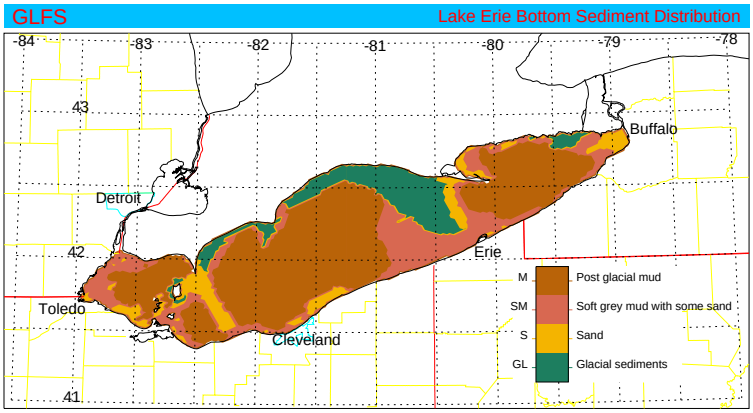

Figure 3: Distribution of the bottom sediment types for Lake Erie.

Following the qualitative distribution of the bottom sediments described above, each grid point at the bottom of the lake, depending upon its location, is assigned one of these types (Figure 3). With this information, the analysis continues with the identification of the fractions representing the sediment grain sizes. Quantitative information about the bottom sediments of Lake Erie has been obtained from the technical report prepared by Herdendorf et al., 1978. The

results were reported as the percentages of sand, silt and clay contents of the samples (according to the Wentworth sediment grade scale).

To estimate the percent of sand, silt and clay contained in each one of the four sediment types the samples taken within the region of each sediment type were first identified and then the average percent of each size class for each sediment type was calculated using the following formula:

$$F_{ji} = \frac{1}{N_i} \sum_{k=1}^{N_i} f_{jk} \tag{8}$$

where F_{ji} is the average percent of each size class for each sediment type; i, is each sediment type (M, S, GL, SM); N_i is the number of samples corresponding to each sediment type; f_{jk} is the percent of each size class for each sample N_i; and j, is each size class (sand, silt, clay). The results of this analysis are shown in Table 1.

Table 1: Definition of the sediment fractions for the sediment types in Lake Erie.

Sediment Type	***No. of Samples N***	***Sand***	***Silt***	***Clay***
M	759	0.0 %	70.0 %	30.0 %
SM	137	70.0 %	20.0 %	10.0 %
S	361	97.0 %	2.0 %	1.0 %
GL	410	55.0 %	35.0 %	10.0 %

The average sediment concentration for the disposal site used in this study is 35 mg/L (Bedford et al., 1999). This value was calculated by adjusting the data collected during a field study project contacted the summer of 1996 (Fan and Bedford, 1998). Grain size distributions for the bottom sediments at the disposal site have been reported by the Toledo Harbor Planning Group in 1998. The average of four samples showed a 96.2 % of silts and clays and a 3.8 % of sands and gravel. Further analysis on the silts and clays at the disposal site performed by the Automatic Particle Size Analyzer (HIAC Model-320), at the Coastal Engineering Laboratory at O.S.U, revealed that a 72.2% are silts and 24% are clays (Bedford et al., 1999).

Detailed suspended sediment concentration data for both Maumee and Detroit rivers are sparse to non-existent and the main source of sediment data for the Maumee river used in this study is the annual USGS Water-Data Report of Ohio for the water year October 1991 to September 1992 (US Geological Survey, 1993). Using the suspended sediment concentration and flow rate data obtained

for Maumee River for the water year 1992 the following linear relationship was obtained:

$$C = 0.015 \cdot Q + 12.116 \tag{9}$$

where C (mg/L) is the daily average suspended sediment concentration and Q (ft^3/s) is the daily average flow rate for the Maumee River. Using Equation (9) and the flow rates for the water year 1997, the daily average suspended sediment concentrations for the Maumee River were obtained. Detailed suspended sediment concentration data for the Detroit River are not available. Kemp et al., 1976, have reported the sediment loadings from various sources in Lake Erie. Using their findings an average coefficient $\bar{f} = 0.77$ which reflects the relative loading between the Detroit and the Maumee Rivers was calculated. The following equation was used to determine the daily suspended sediment concentrations for the Detroit River:

$$C_D = \bar{f} \cdot C_M \cdot \frac{Q_M}{Q_D} \tag{10}$$

where, C (mg/L) is the average daily concentration, Q (ft^3/s) is the average daily flow rate, and the subscripts "D" and "M" denote the Detroit and Maumee Rivers respectively.

In addition to suspended-sediment loads, the particle-size distribution of the suspended sediment for the two rivers needed to be estimated. Available data for the Detroit River describe a suspended sediment mixture with 87 to 100 percent particles classified as silt and clay (US Geological Survey, 1975b). An average of 6 percent by weight for the sand size class was used in the present study for the Detroit River. An average of 7.5 percent by weight for the sand size class has been estimated for the Maumee River (Toledo Harbor Planning Group in 1993). Finally, a 30 to 70 percent contribution from the clay and silt size classes respectively has been assumed for both the Detroit and the Maumee Rivers.

Numerical Domain, Boundary and Initial Conditions

Lake Erie is 388 km long and 92 km wide with a southwest to northeast alignment. In order to establish the "x" coordinate axis along the longitudinal axis of the lake the flow domain is rotated by 27.33^o clockwise. The resolution of the numerical grid used in CH3D-SED is 2x2 km, which yields 209 grid points in the "x" direction and 57 grid points in the "y" direction (normal to the "x" direction). All the land grid points are assigned with a water depth equal to zero, so they can be identified during the model calculations.

In the vertical direction CH3D-SED uses the σ-coordinate system in order to accommodate for the depth variation throughout the lake. In this study fourteen

grid points in the vertical direction were used, resulting in thirteen irregularly spaced vertical slices in the (x, y, z)-coordinate system. The free surface is identified at $\sigma = 0$, while the lake bottom is identified at $\sigma = -1$.

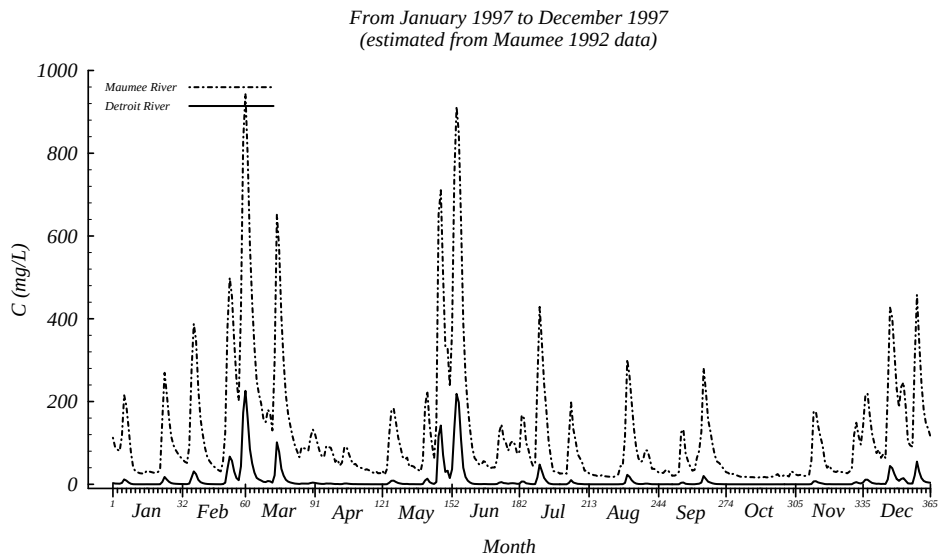

Figure 4: Estimated concentrations of the suspended sediments for Maumee and Detroit Rivers (simulation year 1997).

The boundary conditions can be divided into three categories: a) meteorological boundary conditions, b) hydrodynamic boundary conditions, and c) sediment boundary imposed at the river boundaries and at the bottom of the lake.

The meteorological boundary conditions imposed at the free water surface of the lake are the 2-D wind and temperature fields. The wind velocities, required for the above calculations, were obtained from the Great Lakes Forecasting System (GLFS). CH3D-SED has been slightly modified to accept space and time varying temperature at the free water-surface for each time step. These data are readily available from GLFS for the whole simulation period. The riverine boundary conditions require the definition of the flow-rates, imposed at the river boundaries. The boundary conditions for the inflow and the outflow boundaries are simply the daily averaged flow rates, Q.

The simulation of the sediment distribution in Lake Erie required the definition of twelve sediment size classes (Table 2). These twelve sediment classes were equally divided among the four sediment sources and the grain sizes were selected to represent the typical sediment particle sizes found in Lake Erie. While the flow-rates for the hydrodynamic part of the simulation were specified at all three

tributaries, in the case of the sediment boundary conditions, the Niagara River was treated as an open boundary.

Table 2 Definition of the twelve sediment size classes and their fractions for the four sediment sources in Lake Erie.

Location	*Size Class*	*Grain Diameter (μ)*	*Grain Size Fractions (%)*
Lake Bottom (Source #1)	1	150	Refer to Table 1
	2	50	
	3	4	
Disposal Site (Source #2)	4	149	3.8
	5	49	72.2
	6	3.7	24.0
Maumee River (Source #3)	7	148	7.5
	8	48	65.0
	9	3.3	27.5
Detroit River (Source #4)	10	147	6.0
	11	47	65.0
	12	3	29.0

The daily concentration C (mg/L) of each sediment class was found by multiplying the fraction for that class with the average daily concentrations at each tributary. The concentration profiles at the tributaries (fourteen vertical grid points) were assumed constant for each sediment class.

Both the flow velocities and the concentrations were initialized to be zero everywhere in the lake. The concentration profile of the suspended sediment at the disposal site was initialized with a constant value of 35 mg/L (all sediment classes). For each sediment class, the constant concentration profile was determined by multiplying the total concentration of 35 mg/L with the fraction of that class. The bottom sediments in Lake Erie were assigned three sediment classes throughout the lake, but for each grid point, a different class fraction distribution was assigned. For the grid point corresponding to the disposal site the class fractions used are the same as the ones used for the suspended sediment.

Results and Discussion

This study covers, a one year ice-free test period, from April 1, 1997 to December 31, 1997. The model results include: a) the full 3-D velocity field, b) the 2-D vertically averaged velocity field, c) the 3-D temperature field, d) the 3-D sediment concentration field, e) the bottom sediment fraction distributions and, f) the changes of the bottom elevation. From these results, contour maps and time traces of the variables have been generated. Figures 5 and 6 present contour maps

of the water surface wind speed, and the total suspended mass of the "global sediments" originating from the lake bottom and the disposal site. The term "global sediments" is used inclusively here and describes all the sediment classes assigned to the sediment source (sand, silt and clay).

The units used in the total suspended mass contour maps are metric tons per unit depth (tons/m). The total suspended mass is calculated using the equation:

$$\mathrm{TSSM} = 10^{-6} \cdot \frac{\overline{C} \cdot V_{eff}}{d} = 10^{-6} \cdot \frac{\overline{C} \cdot A_{eff} \cdot d}{d} = 10^{-6} \cdot \overline{C} \cdot A_{eff} \qquad (11)$$

where TSSM, is the total suspended mass of the sediments (tons/m), $\overline{C}$, is the vertically averaged concentration (mg/L), V_{eff}, is the effective volume (m^3) where the total suspended mass is calculated, A_{eff}, is the corresponding effective area (m^2), and d, is the water depth (m). The effective area, A_{eff}, is defined as the area of the horizontal square extending half a grid point from the grid point where $\overline{C}$ is calculated. For the grid resolution used for this simulation it is: $A_{eff} = 4\ km^2$.

The plots in Figure 7 present the time traces of the "relative intensity" of the "global sediments" originating from the different sources. The term "relative intensity" is defined as the ratio of the "global sediments" from one source to the "global sediments" from all the sources and is dimensionless (expressed as %).

The average relative intensity for the simulation period of the TSSM originating from the disposal site is approximately 0.5 %, while the corresponding seasonal peaks do not exceed the 3.5 % mark. The average relative intensity for the simulation period of the TSSM originating from the lake bottom is approximately 90 %, and that of the TSSM originating from the Detroit and the Maumee Rivers is approximately 9.5 %. From early June to late September the riverine contributions increase significantly. The contribution of the sediments originating from the disposal site is fairly constant throughout the simulation period, but occasional peaks are observed during storm events. In any case, these peaks do not exceed the 3.5 % mark.

Overall the impact at the water intake site of the sediments originating from the disposal site is fairly small (during storm events) to insignificant.

Acknowledgments

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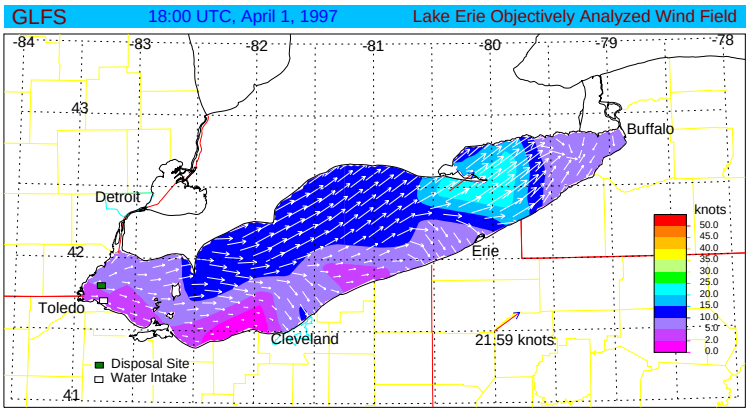

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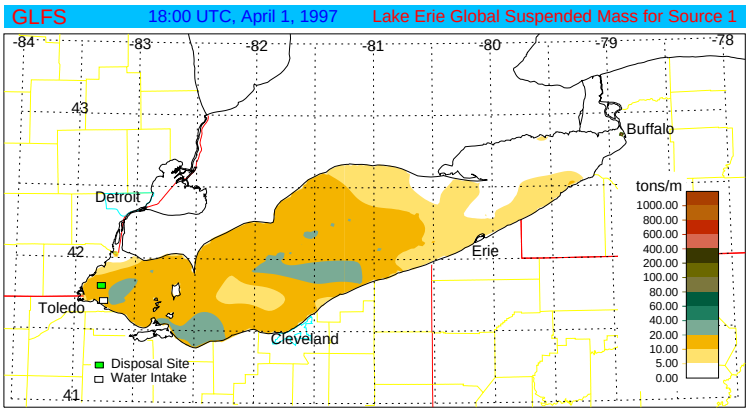

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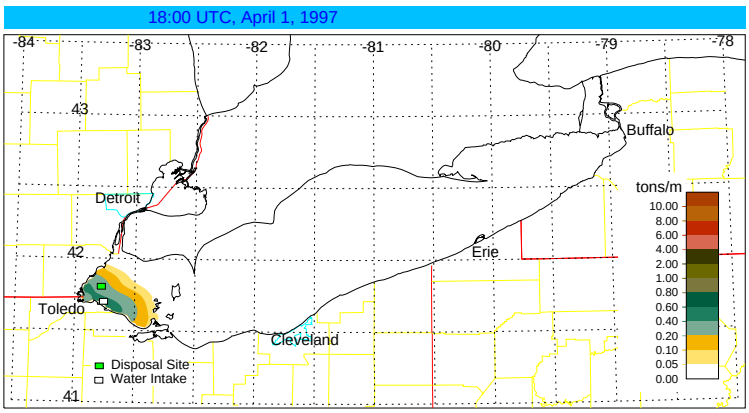

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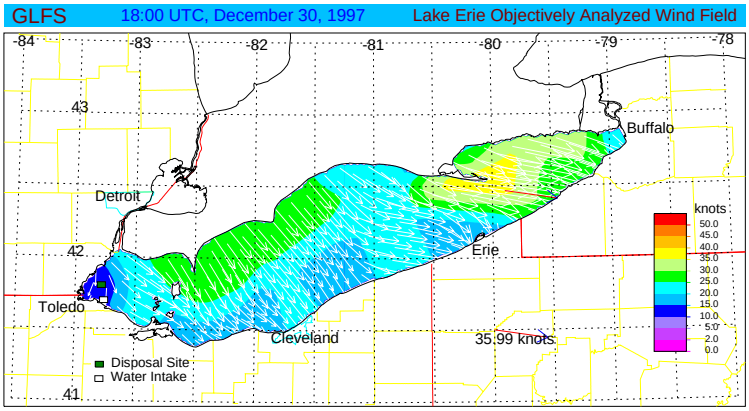
Figure 5: Water-surface wind speed distribution (a), and horizontal distributions of the global suspended mass of the sediments originating from (b) source 1 (lake bottom), and (c) source 2 (disposal site) for April 1, 1997.



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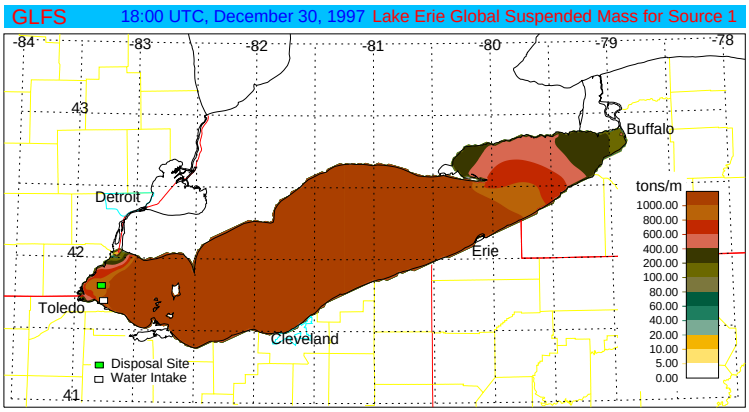

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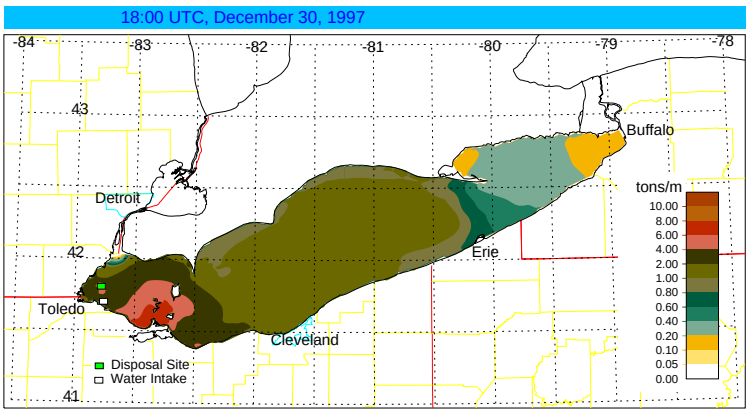

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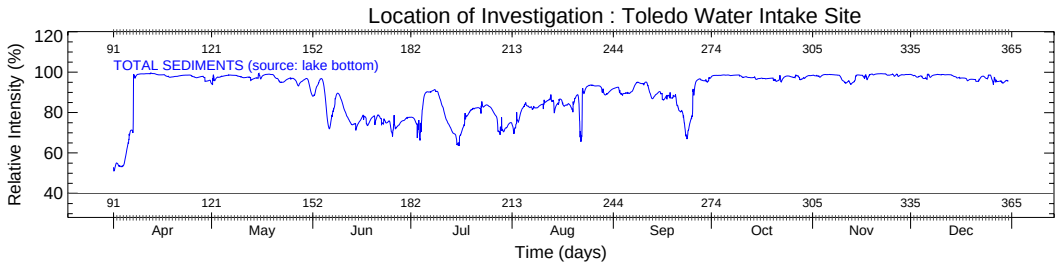
Figure 6: Water-surface wind speed distribution (a), and horizontal distributions of the global suspended mass of the sediments originating from (b) source 1 (lake bottom), and (c) source 2 (disposal site) for December 30, 1997.



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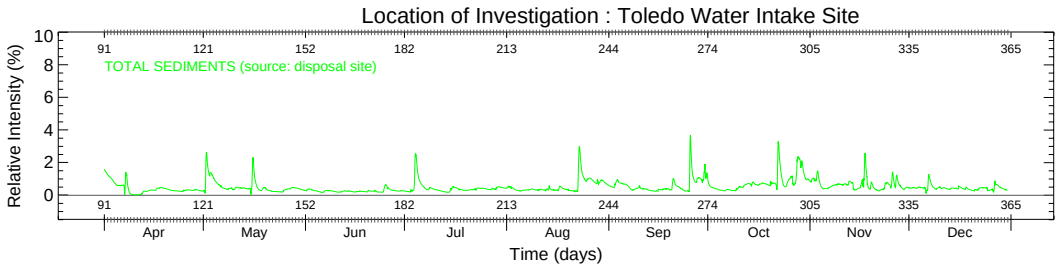

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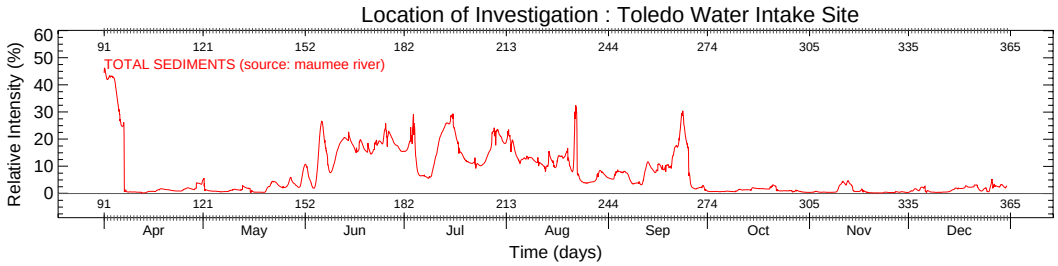

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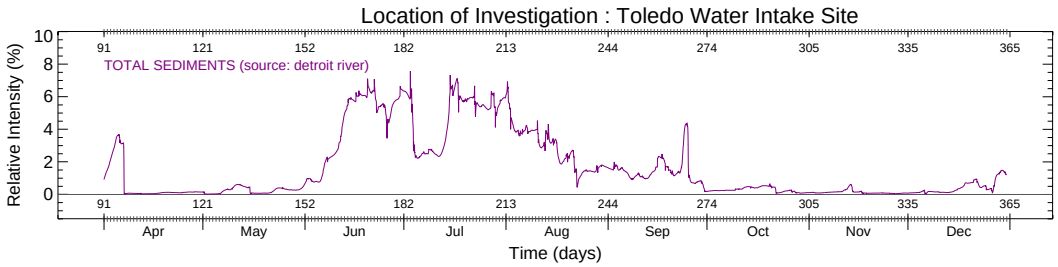

(d)

Figure 7: Relative intensity, percent of the total suspended sediment mass from all sources, at the water intake site of the global sediments originating from: a) the lake bottom, b) the disposal site, c) the Maumee River and d) the Detroit River.

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