SEDIMENT STABILITY AT CONTAMINATED SEDIMENT SITES

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INTRODUCTION

Sediment transport processes are controlling factors in the fate and transport of hydrophobic chemicals of concern [(COCs); e.g., polychlorinated biphenyls (PCBs), heavy metals] in an aquatic system. These COCs also tend to be problematic because of their persistence in natural environments. The rate of reduction of these COCs in surface sediment (also possibly in water and biota) at many contaminated sediment sites is determined primarily by the long-term sedimentation rate, which is affected by resuspension and deposition processes, as well as sediment loading to the aquatic system.

Peak inputs of hydrophobic COCs to many aquatic systems occurred over 20 years ago. Generally, higher COC concentrations are found below cleaner sediments that were deposited after historical inputs occurred. Subsequently, naturally occurring processes (e.g., sedimentation, bioturbation) typically caused significant reductions in surficial bed concentrations. Thus, peak bed COC concentrations are often sequestered from the bioavailable zone in many aquatic systems.

The possibility exists, however, that a rare storm can cause sufficient erosion to allow elevated bed COC concentrations to be introduced into the bioavailable zone and, thus, negatively impact system biota. Rare storm events (e.g., 100-year flood in a river or hurricane in coastal waters) can generate high levels of turbulence in the water column of an aquatic system. The water column turbulence imposes high bottom shear stresses relative to conditions occurring during common storm events on the sediment bed. Depth of scour during these storms is determined by evaluating hydrodynamic processes (i.e., generation of bottom shear stress) and site-specific erosion properties of the sediment bed. Realizing that such conditions can occur in a particular system allows control measures to be incorporated in the sediment management strategy. Key questions that will aid in defining the potential for bed instability during storm events are as follows:

- What scour depths will be caused by the storm?
- Where will scouring and deposition likely occur within a specific site?
- What effects will scour, resuspension, and deposition have on the availability of COCs to the biological system, and, if these effects are likely to be significant, will controls result in appropriate mitigation of the impacts of COC release and availability?

Poor comprehension of sediment dynamics can lead to sediment management strategies that are ineffective and incorrect. Without proper understanding of sediment transport processes, strategies can be driven toward mass removal rather than in-place management due to perceived sediment stability concerns about future storm events. These concerns about sediment stability may or may not be warranted. Site-specific conditions (i.e., hydrodynamics and sediment erosion properties) determine sediment stability during rare storms.

The science of sediment dynamics in aquatic systems has greatly advanced in the last ten years, and quantitative estimates of flood impacts are possible if the appropriate data are available. Effective evaluation of sediment stability must be founded on scientifically credible sediment transport analyses. A two-tiered approach is applied when analyzing sediment stability in an aquatic system. Tier 1 utilizes relatively simple qualitative and quantitative analyses to evaluate sediment stability. The level of uncertainty associated with Tier 1 is higher than that achievable through more rigorous analyses, but this type of analysis can be effectively used as a screening tool. Tier 2 involves the application of a sediment transport model to evaluate the impacts of rare storms. Previous studies have shown that state-of-the-science models can be successfully used as a management tool to evaluate potential impacts in the movement of sediment-bound COCs in aquatic systems due to a rare storm and potential remedial options to mitigate these impacts. The level of analysis applied to a particular site is dependent on a variety of factors, including data availability, level of accuracy required, and time and budget constraints. The level of analytical sophistication required often is directly correlated to the extent of action contemplated and the desire to ensure that such action is properly directed and cost effective.

SEDIMENT TRANSPORT PROCESSES

The stability of contaminated sediment deposits at a particular site are determined by hydrodynamic and sediment transport processes that are specific to the aquatic system. The system types are separated into four broad hydrodynamic categories: rivers, lakes, estuaries, and coastal oceans. The circulation in each category is typically dominated by different hydrodynamic forcing (e.g., wind and seiche motion in lakes and tides, density-driven circulation in estuaries). Local and regional climatological conditions and watershed characteristics affect the strength and frequency of rare storm events. Sediment loading to a system during a rare storm is dependent on the physiographic characteristics and land use conditions of the surrounding watershed. Man-made structures in aquatic systems also affect the impact of a rare storm on sediment stability. For example, dams on a river create impoundments that trap sediments and control floods.

For the purpose of evaluating sediment transport, sediment deposits can be separated into two broad categories: cohesive and noncohesive sediments. Cohesive sediments are muddy sediments and are composed of varying amounts of clay, silt, and fine sand. Noncohesive sediments are coarser, do not tend to adhere to each other, and are primarily composed of sand and gravel. Cohesive sediment deposits are of particular importance to a contaminated sediment stability evaluation because hydrophobic COCs preferentially adsorb to finer sediment particles and organic carbon. Remedial efforts usually focus on cohesive sediment deposits and the fate of COCs buried within because these areas generally contain the highest concentration of hydrophobic COCs. As a result, the discussion below concentrates on the erosion properties of cohesive sediments.

Erosion Properties

Sediment transport processes in aquatic systems involve complex interactions between hydrodynamics, sediment dynamics in cohesive and noncohesive bed areas, and external sediment loading. Sediment erosion rates are controlled primarily by bottom shear stress, which is the shearing force that hydrodynamic processes apply to the sediment bed due to friction. Site-specific bed properties affect resuspension and are a primary factor in determining erosion rates and scour depths.

- *Bottom Shear Stress*

  Bottom shear stress is the common thread among all systems when evaluating sediment stability. Generally, two types of hydrodynamic processes generate bottom shear stress: current velocity and waves. In rivers, current velocity is the dominant component of bottom shear stress. Wind-generated waves are the primary contributor to bottom shear stress in lakes during storms. Estuarine circulation can be complex and a combination of wind waves and currents generate bottom shear stress, with system-specific conditions determining the relative contribution of each component to the total. Bottom shear stress (τ) can be calculated using the quadratic stress law (Christoffersen and Jonsson 1985):

  $$t = r_w \left(C_{f,c} u_c^2 + C_{f,w} u_w^2 \right) \qquad (1)$$

  Here $C_{f,c}$ and $C_{f,w}$ are the bottom friction factors due to currents and waves, respectively; u_c is the vertically averaged velocity due to currents; u_w is the bottom orbital velocity due to waves; and ρ_w is the water density [approximately 1 gram per cubic centimeter (g/cm^3)]. Calculation of the bottom friction factors, $C_{f,c}$ and $C_{f,w}$, is discussed below.

- *Site-Specific Bed Properties*

  Laboratory and field studies concerning the resuspension of cohesive sediments have been conducted by many researchers over the last 30 to 40 years. The notable contributions of

R.B. Krone (1962), E. Partheniades (1965), A.J. Mehta (1985), and W. Lick (1988) have resulted in formulations to predict cohesive bed erosion rates or depths.

The bed properties, principally the grain size distribution and interparticle cohesion, significantly affect resuspension from a cohesive sediment bed. Increased consolidation with depth through the sediment profile, indicated by a decrease in bed porosity with depth, causes surface sediments to be resuspended more easily than sediments buried deeper in the bed. Bed particle size heterogeneity and consolidation effects result in bed armoring, resulting in only a finite amount of sediment being resuspended from a cohesive sediment bed at a particular bottom shear stress. Cohesive bed armoring has been observed and quantified in various laboratory (Parchure and Mehta 1985, Tsai and Lick 1987, and Graham, et al. 1992) and field studies (Hawley 1991 and Amos, et al. 1992).

Past laboratory research on cohesive sediment erosion (Krone 1962, Parchure and Mehta 1985, and Tsai and Lick 1987) demonstrated that the amount of sediment resuspended depends on the turbulent stress at the sediment-water interface and the state of consolidation of the bed, which is indicated by bed porosity. Based on existing laboratory and field data, the following formulation was developed to approximate the mass of sediment resuspended from a cohesive bed (Gailani, et al. 1991):

$$E = \frac{a_o}{T_d^m}\left(\frac{t - t_{cr}}{t_{cr}}\right)^n , \; t > t_{cr} \qquad (2)$$

Here E is the resuspension potential [net mass of resuspended sediment per unit surface area in milligrams per square centimeter (mg/cm^2)], a_o is the site-specific constant, T_d is the time after deposition (days), ô is the bottom shear stress due to waves and currents, and $ô_{cr}$ is the effective critical shear stress (typically 1 dyne/cm^2). Previous laboratory studies (Tsai and Lick 1987 and MacIntyre, et al. 1990) indicate that consolidation effects on cohesive sediment resuspension are typically minimal after about seven days of consolidation. The consolidation exponent (m) is dependent on the deposition environment; m varies from 0.5 to 2 depending on whether the sediment bed is in a higher energy environment (0.5) or a relatively quiescent body of water (2). The shear stress exponent (n) is dependent on local bed properties.

The nonlinear relationship between E and bottom shear stress in Equation 2 is important. The quadratic stress law, Equation 1, shows that bottom shear stress increases as the square of the current velocity (u_c) and bottom orbital velocity (u_w). Thus, for a current-dominated environment, (e.g., a river) the mass of resuspended cohesive sediment (E) is a highly nonlinear function of the current velocity, with E being proportional to u_c raised to the fourth to sixth power. For rivers, this nonlinear dependence on current velocity or equivalently flow rate causes rare floods to be of great importance. Similarly, in wave-dominated environments, nonlinear effects cause rare, large storms to have more significant impact than smaller, frequent storms (Lick 1992).

Of particular importance in Equation 2 are the site-specific parameters, a_o and n. Previous studies demonstrated that the resuspension properties of cohesive beds in different aquatic systems can differ substantially (Ziegler and Nisbet 1994, 1995 and Lick, et al. 1995), with the shear stress exponent (n) ranging from 2 to 3 and the constant a_o possibly varying by an order of magnitude. The site-specific parameters for a particular aquatic system can be determined by conducting a field study to measure the in situ resuspension potential of cohesive sediments. A portable resuspension device (commonly called a shaker) is used to test cohesive bed cores (Tsai and Lick 1986). A method for analyzing shaker data and estimating the values of a_o and n is described in Ziegler and Nisbet (1994).

Site-specific values of a_o and n are determined from field data collected using the shaker. However, the maximum shear stress that can be applied with the shaker is 9 dynes/cm^2, which is a moderate shear stress in many aquatic systems. Cohesive sediment beds generally are exposed to higher shear stresses (e.g., 50 to 100 dynes/cm^2) during rare storms.

As a result, it is necessary to address the validity of extrapolating resuspension potential data beyond the 9 dynes/cm^2 limit. Investigating cohesive sediment resuspension properties at high shear stresses (up to 100 dynes/cm^2) is performed using a new type of flume called Sedflume developed by Professor Wilbert Lick at the University of California, Santa Barbara. Lick and co-workers have been studying the effects of various sediment properties (e.g., bulk density, grain size distribution) on cohesive sediment erosion rates over a wide range of applied shear stresses (Jepsen, et al. 1997 and Roberts, et al. 1998). Results of a series of erosion rate experiments by Jepsen, et al. (1997) on cohesive sediments collected from the Detroit River in Michigan are presented on Figure C-1.

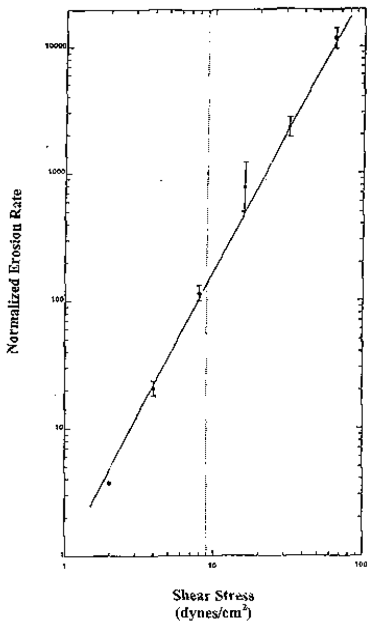

Figure C-1. Results of cohesive erosion rate experiments conducted by Jepsen, et. al 1997. Measured erosion rates were normalized with respect to bed bulk density.

The experimental data ranged from 2 to 64 dynes/cm^2, and the main purpose of the study was to investigate the effects of bulk density on erosion over this range. To eliminate the effects of bulk density and standardize data, erosion rate values presented in Jepsen, et al. (1997) were normalized with respect to the reported bulk densities. The data normalization shows that erosion rate is a continuous function over the range of shear stresses used in the study. This result indicates that extrapolation of resuspension potential data beyond the 9 dynes/cm^2 limit is valid and generally applicable to maximum bottom shear stresses occurring in a rare storm.

QUANTITATIVE EVALUTION METHODS

Sediment stability at a contaminated sediment site is evaluated by using quantitative analysis techniques to ensure an objective determination of the efficacy of various remedial alternatives. Qualitative analyses or conceptual models may be useful for developing quantitative analysis tools; however, qualitative techniques alone typically are insufficient for conducting scientifically defensible remedial alternative evaluations.

Various levels of quantitative analysis can be used to evaluate the impact of a rare storm on sediment stability. These analyses range from an order-of-magnitude estimate using simple engineering equations to a complex analysis using a sophisticated computer model. Regardless of the analyses performed, a two-tiered approach to quantitatively analyze sediment stability is necessary. The level of analysis applied at a particular site depends on the following factors:

- Data availability
- Level of accuracy or uncertainty required
- Time and budget constraints

Tier 1 analysis uses an approximate approach to yield order-of-magnitude estimates of scour depth during a rare storm. Tier 2 analysis involves the development and application of a comprehensive sediment transport model to evaluate bed stability. Please note that the enhanced predictive capabilities associated with a Tier 2 analysis come at the expense of significantly greater investment in time and effort.

Tier 1 Analysis

The first step in the Tier 1 analysis is to estimate bottom shear stress during a rare storm. The estimation method depends on whether bottom shear stress in the aquatic system is dominated by currents (e.g., rivers) or waves (e.g., large, shallow estuary).

- *Current-Dominated Environment*

  For a river, maximum current velocities during a rare flood must be estimated. A hydraulic or hydrodynamic model ranging in complexity from one- to three-dimensional can be applied to the river to calculate flood velocities. Alternately, a crude estimate of velocity can be made using an empirical relationship between flow rate and velocity. This type of empirical relationship has been developed for various rivers and, typically, velocity is a nonlinear function of discharge (Q; Leopold and Maddock 1953):

  $$u_c = aQ^b \qquad (3)$$

  Here the coefficient (α) and exponent (β) are site-specific, although bounding estimates can be determined using the upper limits of the observed range. The bottom friction factor ($C_{f,c}$) is site-specific because it depends on local depth ($C_{f,c}$ decreases as depth increases) and bed roughness. An approximate upper limit for $C_{f,c}$ is 0.006 for cohesive sediment beds. This information ($u_{c,max}$ and $C_{f,c}$) is used in Equation 1 to calculate the maximum bottom shear stress (τ_{max}) during the flood.

- *Wave-Dominated Environment*

  In a wave-dominated environment (e.g., large, shallow bay or lake) the maximum bottom orbital velocity due to waves during a rare storm is determined. A wind wave model can be applied to the lake, bay, or estuary to determine bottom orbital velocity for the maximum wind velocity during a storm. Wind wave models generally require significant time and effort to develop and apply for a particular site.

In the absence of a model, bottom orbital velocities can be estimated using wind wave curves for shallow water environments [U.S. Army Corps of Engineers (USACOE) 1977]. The following three pieces of information are needed to estimate bottom orbital velocities:

— Wind speed
— Fetch (i.e., distance that wind blows over the water body)
— Average water depth along the fetch

Using this information and the wind wave curves (USACOE 1977), the significant wave height (H_s) and significant wave period (T_s) are determined. Peak orbital velocity (u_w) is calculated using the following equation:

$$u_w = \frac{\pi H_s}{T_s \sinh\left(\frac{2\pi h}{c_o T_s}\right)} \qquad (4)$$

Here h is the local water depth, c_o is the wave speed (equal to $(gh)^{1/2}$ for shallow water systems), and g is the acceleration due to gravity [980 centimeters per square second (cm/s^2)]. The bottom friction coefficient for waves is estimated using the following equation:

$$C_{f,w} = 0.09\left(\frac{u_w A_w}{\nu}\right)^{-0.2} \qquad (5)$$

Here ν is the kinematic viscosity of water (approximately 0.15 cm^2/s) and A_w is the peak orbital excursion, with:

$$A_w = \frac{H_s}{2 \sinh\left(\frac{2\pi h}{c_o T_s}\right)} \qquad (6)$$

After estimating maximum bottom shear stress due to currents or waves, scour depth (D_{scour}) is determined using τ_{max} in Equation 2 to calculate E_{max} (in mg/cm^2) and then (for D_{scour} in cm):

$$D_{scour} = \frac{E_{\max}}{1000\, \rho_{dry}} \qquad (7)$$

Here ρ_{dry} is the dry density of cohesive sediment (g/cm^3). An average or typical value of ρ_{dry} is determined from site-specific data. If no system data are available, a value of 1 g/cm^3 for dry density is used as a first approximation.

The scour depth calculation requires the determination of E_{max} using Equation 2. Ideally, a field study is performed to determine site-specific values of a_o and n. If shaker data cannot be obtained for the site, resuspension potential data obtained from previous studies is used to make order-of-magnitude estimates of these parameters. For convenience, Equation 2 is simplified and expressed as the following:

$$E_{\max} = A\left(\frac{\tau_{\max} - \tau_{cr}}{\tau_{cr}}\right)^n \qquad (8)$$

Here τ_{cr} is 1 $dyne/cm^2$ and

$$A = \frac{a_o}{T_d^m} \qquad (9)$$

Average values of A and n for eight aquatic systems are listed in Table C-1. The eight aquatic systems are as follows:

- Thompson Island Pool, Upper Hudson River (HydroQual, Inc. 1995)
- Pawtuxet River, Rhode Island (Ziegler and Nisbet 1994)
- Watts Bar Reservoir, Tennessee (Ziegler and Nisbet 1995)
- Upper Mississippi River
- Fox River, Wisconsin (Lick, et al. 1995)
- Green Bay (Lick, et al. 1995)
- Saginaw River, Michigan (Lick, et al. 1995)
- Buffalo River, New York (Lick, et al. 1995)

Table C-1
Site-Specific Resuspension Potential Parameters

Study Site	**Site-Specific Constant, A (mg/cm^2)**	**Site-Specific Exponent, n**
Thompson Island Pool, Upper Hudson River	0.027	3.0
Pawtuxet River	0.24	2.0
Watts Bar Reservoir	0.10	2.7
Upper Mississippi River	0.11	2.6
Fox River	0.75	2.3
Green Bay	0.34	2.5
Saginaw River	0.053	2.7
Buffalo River	0.081	3.1

Based on these data-based parameter values, the average and 95% confidence interval for A is 0.21 $\pm$ 0.20 mg/cm^2. Similarly, $n = 2.6 \pm 0.3$. Note that τ_{max} needs to have units of $dynes/cm^2$ in Equation 8, which is achieved if $u_{c,max}$ or $u_{w,max}$ have units of cm/s and ρ_w has units of g/cm^3. Thus, the mean values of A and n (0.21 and 2.6, respectively) are used in Equation 8 to calculate an order-of-magnitude estimate of E_{max}. A measure of the uncertainty in this estimate is determined by using the 95% confidence interval limits for these values. Variation of scour depth with bottom shear stress for average values of A and n is illustrated on Figure C-2. Uncertainty in D_{scour} due to uncertainty in the parameter values (95% confidence interval limits) is also shown on Figure C-2.

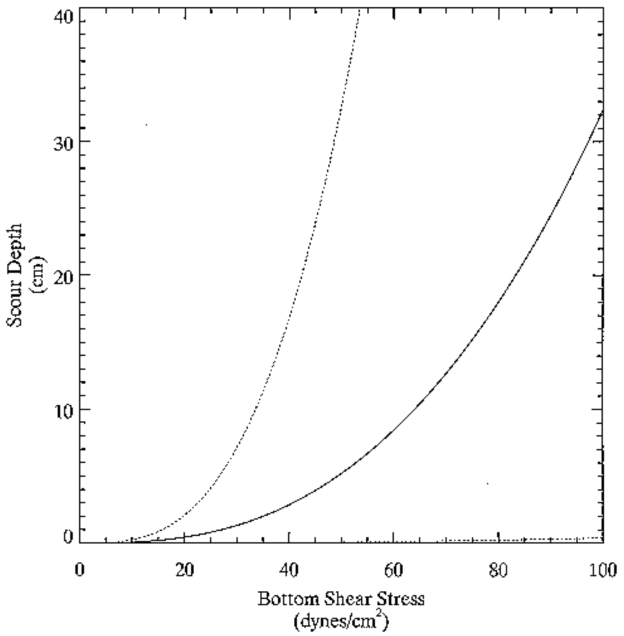

Figure C-2. Estimated scour depth as a function of bottom shear stress for average (solid line) and 95% confidence interval limit (dashed lines) erosion parameters (A and n).

Tier 2 Analysis

More accurate estimates of scour depth during a rare storm can be determined using a comprehensive sediment transport model. Development, calibration, and application of a sediment transport model generally requires a substantial effort for data acquisition, data analysis, and modeling. The significant commitment of resources for a modeling study must not be a deterrent if preliminary analyses using either qualitative or Tier 1 analysis techniques indicate that scour depths cannot be estimated with sufficient accuracy. Under these conditions, credible evaluation of various remedial options is achieved only by using a Tier 2 analysis.

Contaminant fate and transport models that use simplistic, empirical resuspension formulations that exclude the effects of bed armoring, which limits erosion depths during a rare storm, generally are inadequate for use in a Tier 2 analysis. When a study site requires a Tier 2 analysis, sufficient accuracy for credible evaluation of sediment stability during rare storms is achieved by using a state-of-the-science sediment transport model. This type of model uses mechanistic formulations developed from experimental data to simulate cohesive resuspension and deposition processes. Site-specific data are needed to develop model inputs (i.e., parameters and boundary conditions) and perform calibration and validation. Generally, a field study program must be conducted to obtain the necessary data to support the modeling effort. While significant data requirements may appear to be a drawback of this type of analysis, reliability of remedial option evaluation results is significantly increased.

To apply a Tier 2 model and ensure model accuracy and precision, adequate calibration and validation are required. Sensitivity analyses also must be conducted to investigate the impact of parameter and boundary condition uncertainty on model results. Once a sediment transport model is calibrated properly and validated, the model is used as a management tool to evaluate objectively the efficacy of various remedial alternatives to mitigate the impacts of a rare storm. For example, quantitative comparisons are made of contaminant concentrations in the surficial layer of the bed after a rare storm for natural recovery, limited action, and dredging scenarios. Uncertainty in model predictions due to data and model limitations are included in the remedial alternative evaluation.

Tier 2 analysis requires using a sediment transport model, as discussed above. A number of models are available for contaminated sediment sites, but choosing a model for a particular site depends on the capabilities of the model and the study requirements. The state of cohesive sediment transport modeling has improved considerably during the last ten years, with SED2D and SEDZL representing state-of-the-science models (see descriptions below). In fact, modeling capabilities have improved to the point that state-of-the-science models can be and have been used as management tools to evaluate remedial alternatives in a rational and credible manner.

- *HEC-6*
  A numerical model that has been widely used for evaluating sediment transport processes in rivers is HEC-6 (USACOE 1976 and 1990). This model has proven to be quite useful in a number of studies; however, it has some limitations. First, HEC-6 includes a one-dimensional hydrodynamic model so that lateral variations in the river flow cannot be resolved. This limitation is especially important when studying contaminated sediment transport in rivers. Typically, cohesive sediment deposits are located in shallow, near shore zones that are conducive to deposition of fine-grained sediments, and the deeper main river channel has a coarser, noncohesive sediment bed. Thus, lateral variations in bathymetry and bottom shear stress must be resolved to predict adequately erosion in the cohesive sediment deposits. Second, the original version (1976) of HEC-6 did not simulate erosion of cohesive sediments—only the deposition of clays and silts. A new version (1990) of the model incorporates the work of Partheniades (1965) and Ariathuri and Krone (1976) on cohesive sediment erosion.

- *SED2D*
  The SED2D model is a two-dimensional, vertically-averaged model employing the sediment dynamics of Ariathuri and Krone (1976) that is part of the TABS modeling framework developed by the USACOE. This model is capable of simulating cohesive and noncohesive sediment transport. In a review by the Fine Sediment Processes Task Committee of the American Society of Civil Engineers (ASCE) in 1989, applications were limited primarily to cohesive sediment transport in estuaries and coastal waters, with no presentation of studies in rivers.

- *SEDZL*
  SEDZL is a sediment transport model that has been used in over 15 contaminated sediment studies. SEDZL was originally developed for the U.S. Environmental Protection Agency (USEPA) by Ziegler and Lick (1986), and a public-domain version of the model is available. SEDZL is capable of accurately and realistically simulating the resuspension, deposition, and transport of cohesive and noncohesive sediments. The model predicts temporal and spatial variations in suspended sediment concentration (typically two particle size classes), sediment bed elevation, and bed composition (relative fractions of different particle size classes). The effects of wind waves on resuspension can be included during simulations. Bed load transport of noncohesive sediment (coarse sand and gravel) is not simulated by the model.

  Two- and three-dimensional versions of SEDZL were developed and applied to various aquatic systems, including Fox River in Wisconsin (Gailani, et al. 1991), Pawtuxet River in Rhode Island (Ziegler and Nisbet 1994), Lake Erie (Lick, et al. 1994), Saginaw River in Michigan (Cardenas, et al. 1995), Buffalo River in New York (Gailani, et al. 1996), and Watts Bar Reservoir in Tennessee (Ziegler and Nisbet 1995). To illustrate the effectiveness of evaluating sediment stability with a Tier 2 model, two applications of SEDZL are discussed in “Evaluating Sediment Stability.”

EVALUATING SEDIMENT STABILITY

The importance of rare storm events on the fate and transport of contaminated sediments has been recognized by the environmental community during the past ten years (Lick 1992). Researchers in the areas of geomorphology and sediment transport, however, began studying episodic erosion and deposition caused by rare storms in the 1960s (Ager 1981). Thus, the concept that erosion and deposition are episodic, nonlinear processes (with the majority of the annual transport occurring during a few storms each year) is relatively well established.

A common belief is that a rare storm will have catastrophic effects on an aquatic system. Generally, statements about the catastrophic effects of a rare storm on cohesive sediment deposits are speculative and are not based on credible data or analysis. While a rare storm may have a catastrophic impact on cohesive sediment deposits (i.e., massive erosion that reexposes highly contaminated sediments buried at depth), it also is possible that a rare storm will have only minor impacts. Determining whether minor or major effects will result from a rare storm requires a quantitative analysis that is scientifically credible. As discussed previously, the level of quantitative analysis can range from simple to complex and choosing the appropriate evaluation procedure for a particular site is determined by data availability, level of acceptable uncertainty in the results, and available resources.

Case Studies

The case studies presented below demonstrate the use of a Tier 2 model as a management tool for evaluating sediment stability during a rare storm. Please note that the results of these studies demonstrated that rare storms (i.e., 100-year flood and hurricane) will not cause catastrophic erosion in those systems. Modeling results indicate that rare storms will cause relatively minor erosion to occur in the cohesive sediment deposits of the Thompson Island Pool (QEA 1999) and Lavaca Bay (HydroQual, Inc. 1998).

- *Thompson Island Pool, Upper Hudson River (UHR)*
  The UHR is a run-of-the-reservoir system in New York that extends from Fort Edward (upstream limit) to Troy (downstream limit), a distance of about 40 miles. A series of eight dams regulate stage height in the backwaters of each reach. Of particular interest in this study is the reach immediately downstream of Fort Edward [the Thompson Island Pool (TIP)]. The Thompson Island dam is a low-head dam (approximate height of 4 feet) that terminates the TIP. The average width and depth of the TIP are 680 and 9 feet, respectively. The mean flow rate at Fort Edward is about 5,200 cubic feet per second (cfs), and the average velocity in the TIP is approximately 0.8 feet per second (ft/s).

  Impacts of a rare flood (i.e., 100-year flood) on the TIP sediment bed were investigated because elevated PCB concentrations exist at depth in cohesive bed areas. Historical PCB discharges (prior to 1977) from two General Electric capacitor manufacturing facilities near Fort Edward were the source of high PCB bed concentrations. Facility operations ceased in 1977, and the PCB concentrations are presently sequestered from the bioavailable zone due to burial by cleaner solids. The USEPA is presently conducting a reassessment remedial investigation/feasibility study (RRI/FS) of the UHR to determine “the future impact of PCBs in the Hudson River system under conditions of no action and various remedial alternatives” (USEPA 1992). The USEPA is addressing the following primary question to guide its investigation: Are there sediments now buried and effectively sequestered from the food chain that are likely to become “reactivated” following a major high flow event, resulting in an increase in contamination of the fish population?

  As a first step in answering this question, a sediment transport model of the TIP was developed, calibrated, and validated using SEDZL (QEA 1999). Relatively high resolution was used for the

TIP numerical grid, with 10 lateral and about 70 longitudinal grid elements (see Figure C-3). Extensive data from the TIP were collected and analyzed to develop site-specific parameters and boundary conditions. In addition, a field study was conducted using a shaker to measure the resuspension potential of cohesive sediments in the TIP. Approximately 20% of the TIP has a cohesive sediment bed, with the rest of the bed area composed of noncohesive and rocky areas.

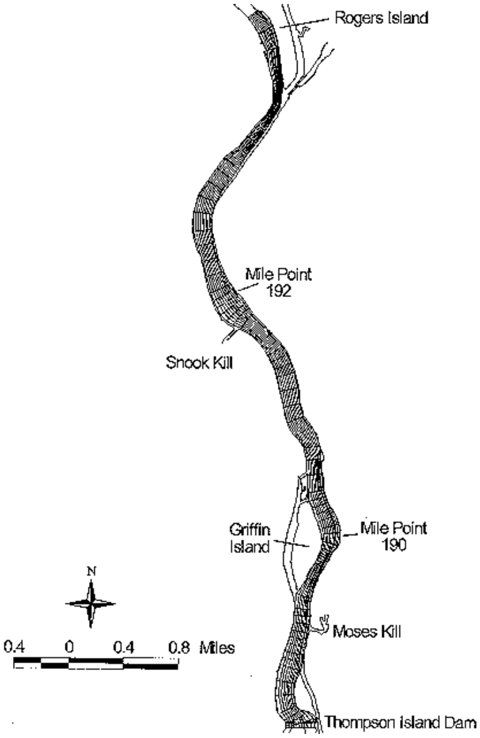

Figure C-3. Two-dimensional numerical grid for Thompson Island Pool.

The TIP sediment transport model was calibrated using total suspended solids (TSS) concentration data collected during the 1994 spring flood, which had a peak daily average flow rate of 27,700 cfs. The 30-day calibration period extended from March 31 to April 29, 1994. The calibration process involved comparing predicted and observed TSS concentrations at three locations in the TIP: upstream of Snook Kill, MacDonald's dock, and Thompson Island dam (see Figure C-4).

The model predicted net erosion from the noncohesive sediment bed [1,250 metric tons (MT)] and net deposition in the cohesive bed areas. Overall, the model predicted 370 MT of net erosion from the TIP during this flood, which compares well with the data-based estimate of 450 MT of net erosion (18% error).

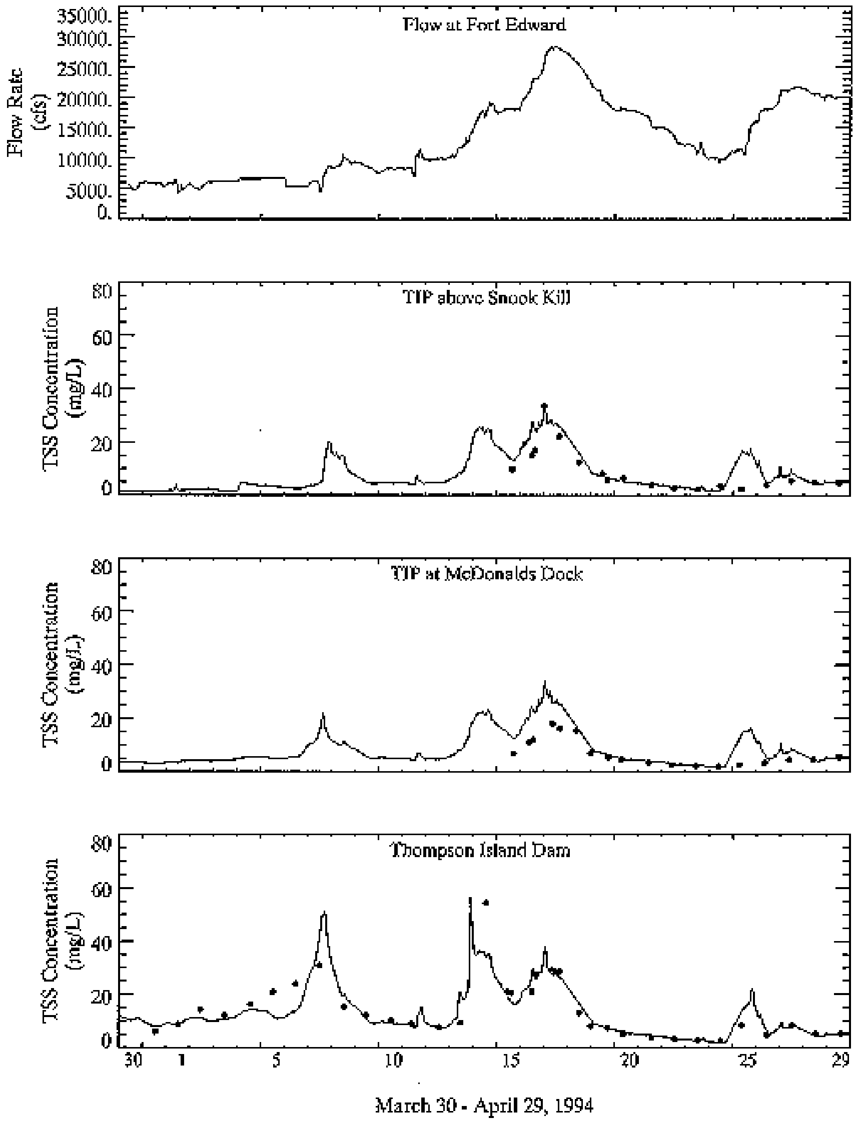

Figure C-4. Comparison of predicted (solid line) and observed suspended sediment concentrations at three locations in the TIP during the 1994 flood.

The following three simulations were conducted to validate the sediment transport model:

— 1997 spring flood
— 1993 spring flood
— 22-year (1977 to 1998) period

Validation results were similar to the calibration simulation with regard to level of accuracy. Thus, the model was capable of accurately simulating solids dynamics during high flow events when most of the sediment transport in the TIP occurred. The model also was capable of simulating long-term deposition rates, which are important determinants of the long-term fate of PCBs in the river.

Successful calibration and validation of the TIP sediment transport model made it possible to evaluate confidently the impacts of a rare flood event. The 100-year flood, which is defined statistically as a discharge that has a 1% chance of occurring in any given year, has been estimated to correspond to a daily average flow rate of 47,330 cfs at Fort Edward (USEPA 1996). This rare flood event will generate high current velocities in the TIP, resulting in erosion at various locations, but it also will cause large quantities of sediment to be transported into the river from upstream and tributary sources. High sediment loads in the river will make it possible for net deposition to occur at some locations during a 100-year flood, indicating that a rare flood event does not necessarily cause erosion to occur throughout the river.

The model predicted mean erosional depths of 0.84 and 0.14 cm for the cohesive and noncohesive bed areas in the TIP, respectively. Maximum erosional depths for the cohesive and noncohesive bed were approximately 9 and 8 cm, respectively. In the eroded portions of the TIP cohesive bed, erosional depths of 2 cm or less were predicted for 78% of the total cohesive area and approximately 4% of the area had erosional depths greater than 5 cm (see Figure C-5). Scour depths of 1 cm or less were predicted in approximately 97% of the noncohesive bed area. Peak PCB bed concentrations are typically buried at depths greater than 10 cm throughout the TIP. Therefore, the model indicates that the 100-year flood causes relatively minor erosion and that this rare flood would not significantly increase surficial PCB bed concentrations in the TIP.

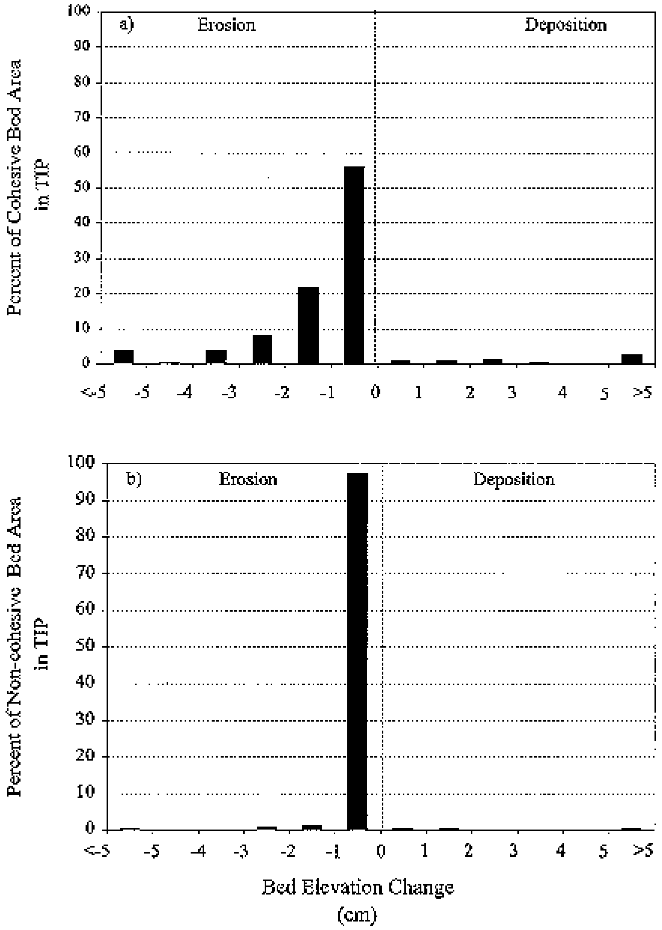

Figure C-5. Probability distributions of (a) cohesive and (b) noncohesive bed elevation changes in the TIP at the end of the 100-year flood.

- *Lavaca Bay, Texas*

  Lavaca Bay is a shallow bay that is connected to Matagorda Bay, which is situated along the Texas Gulf coast. Because this bay is shallow with typical depths of 1 to 2 m and tidal currents are relatively low, wind-wave resuspension significantly affects the transport and fate of sediments. In addition, a large fraction of Lavaca Bay has a cohesive sediment bed, primarily due to fine-grained sediments transported into the bay from the Lavaca River (see Figure C-6).

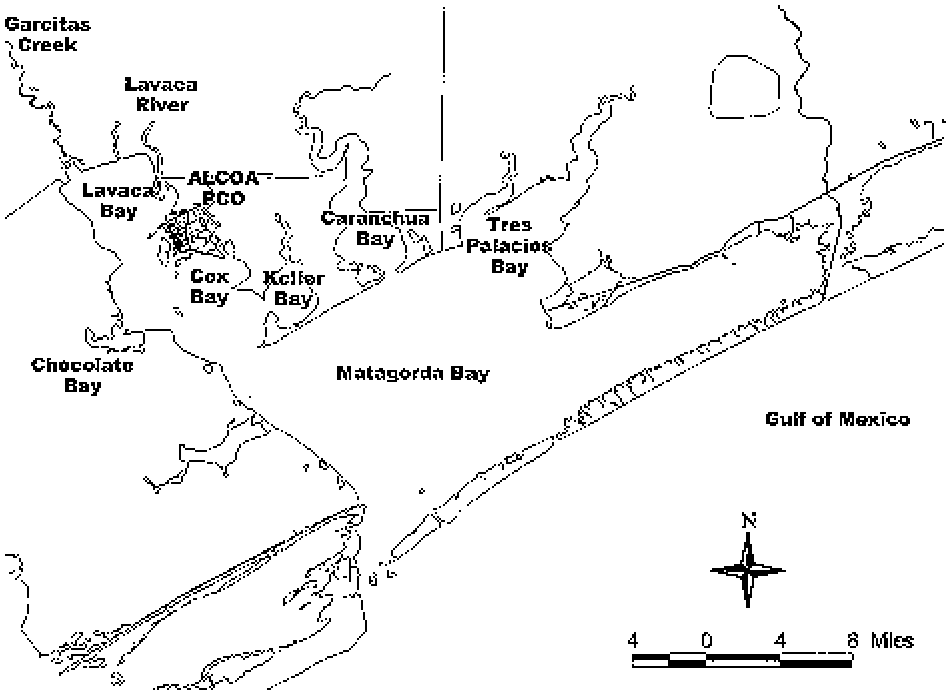

Figure C-6. Location map for Lavaca and Matagorda Bays.

Mercury was released in the late 1960s from a chlor-alkali facility operated by Alcoa at its Point Comfort Refinder. A portion of the mercury that escaped from the facility in wastewaters and through other losses was deposited into the sediments of Lavaca Bay. The Alcoa (Point Comfort)/Lavaca Bay site was placed on the National Priority List in 1994. As part of the RI/FS at the site, a number of studies were directed to determine the fate of mercury fate in the bay.

Mercury concentrations in the sediment bed of Lavaca Bay typically exhibit a pattern of increasing concentration with depth below the surface to peaks at depths ranging from 10 cm to greater than 50 cm. Concentrations generally change slightly from the surface to a depth within about 2 to 5 cm of the peak, increase rapidly to the peak, and then decrease rapidly with depth below the peak. The narrowness of the peak is attributable to the short duration of active mercury discharge (1966 to 1970), the shallowness of the bioturbed surface layer, and the relatively high rate of sediment deposition within the bay. Generally, the peak concentrations are sequestered from biota by the depth of less contaminated sediment overlying them.

One concern that was identified during a preliminary analysis of long-term management options for the bay sediments is whether the buried sediments with high mercury concentrations would be disturbed by an extreme storm such as a hurricane and whether such a disturbance would increase mercury concentrations in the bioavailable zone and in biota. Hence, the objective of the study was to quantitatively investigate the impacts of a hurricane on surficial mercury concentrations in Lavaca Bay. To meet this goal, a modeling framework was developed to simulate the fate and transport of mercury in Lavaca Bay during a hurricane (HydroQual, Inc. 1998). The hydrodynamic, wave, sediment transport, and mercury transport models were coupled together to perform the hurricane simulation. This modeling framework was applied to the Lavaca and Matagorda Bay system so that transport processes in Lavaca Bay could be realistically simulated.

A three-dimensional version of SEDZL was used to simulate the resuspension, deposition, and transport of fine-grained sediments in the bay system. A significant amount of data from Lavaca Bay were used to develop model inputs, including site-specific data on the erosion properties of cohesive sediments in the bay. Data collected at a sampling station located in Lavaca Bay during December 1996 were used to calibrate the sediment transport model. This period was characterized by low river inflows and sediment loadings and by three storms during which wind speeds exceeded 30 miles per hour. Comparisons between predicted and observed TSS concentrations at the sampling station during the calibration period are presented on Figure C-7.

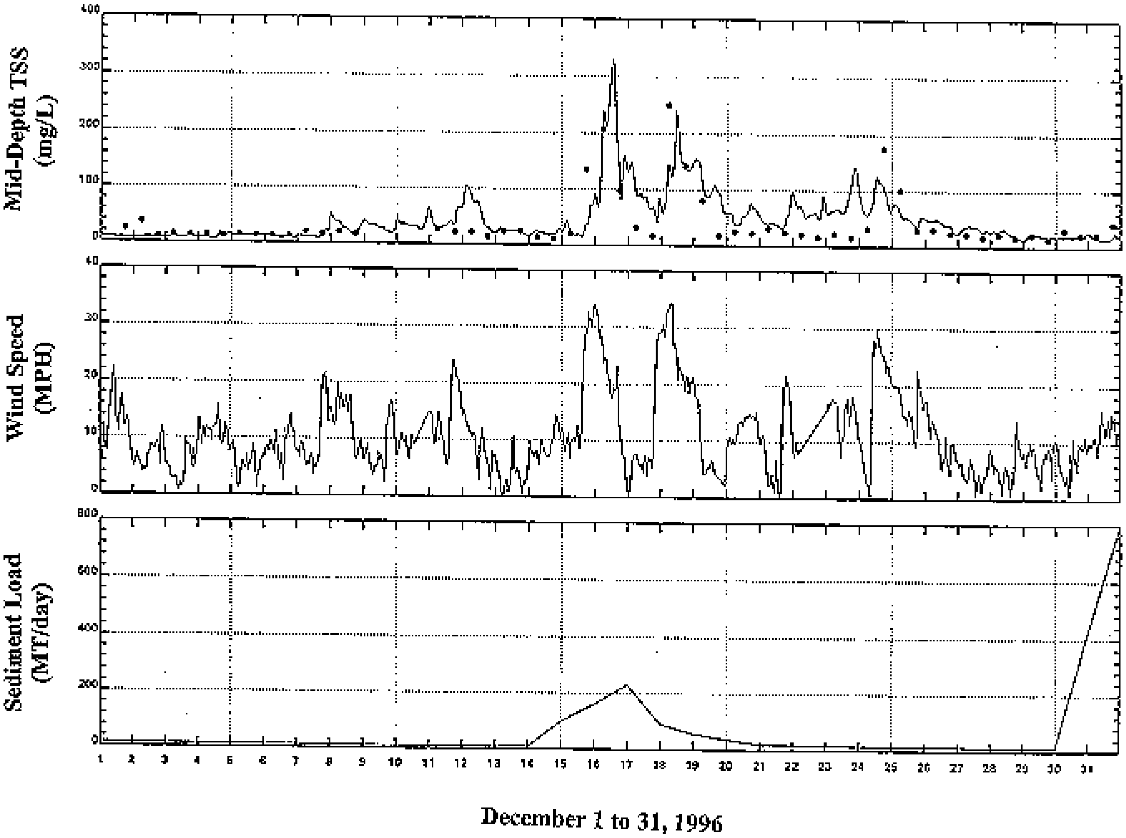

Figure C-7. Comparison of predicted mid-depth sediment concentration (solid line) at the Hydromet station to measured TSS (top panel) during December 1996.

Modeling results indicate that in the event of an extreme storm such as a hurricane, most of the sediment bed will be subjected to high shear stresses as a result of currents and waves. As a result, large quantities of sediment will be resuspended into the water column, with the mass of eroded sediment at a particular location dependent on the applied shear stress and local bed properties. The hydrodynamic circulation resulting from the complex interaction of tides, storm surges, winds, and river inflows will determine how the resuspended sediments are advected and dispersed throughout the bay and subsequently redeposited in areas of low bottom shear stress.

The modeling framework was used to simulate Hurricane Carla, which was a Category 3 hurricane (Category 5 offshore) that struck the bay system on September 11, 1961. The model predicted changes in the distribution of surficial mercury concentrations in Lavaca Bay if a storm of this magnitude were to strike the bay system. The simulation showed that net erosion would occur over 82% of the bay but that the average erosional depth would be approximately 3 cm. Erosional depths greater than 10 cm were predicted for about 2% of the bay area and occurred in small, localized areas in the bay (see Figure C-8). Significant deposition was predicted in the ship channels of Lavaca Bay, which is qualitatively correct due to the increased depths. The dredged ship channels are efficient sediment traps because of their great depth (about 12 m deep) in comparison to typical depths (1 to 2 m) in the remainder of Lavaca Bay; regular dredging is required because enhanced deposition occurs naturally in the channels.

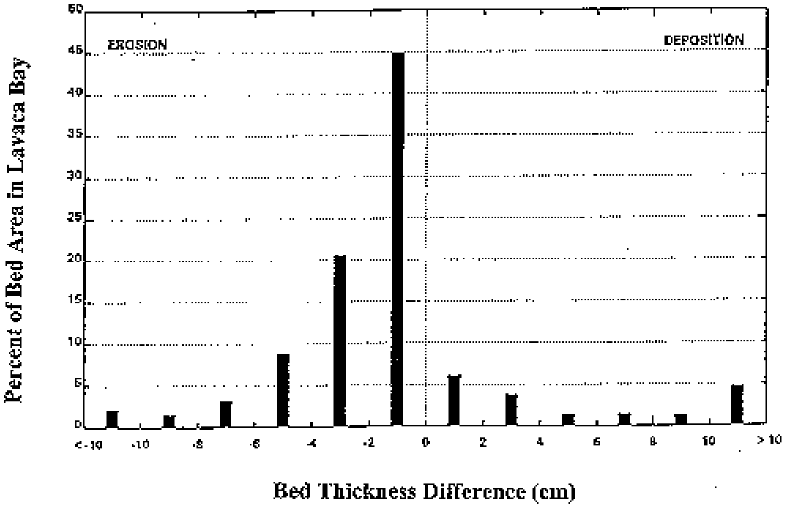

Figure C-8. Predicted changes in sediment bed elevation in Lavaca Bay caused by Hurricane Carla.

Generally, surficial mercury concentrations in Lavaca Bay were predicted to decrease slightly as a result of the hurricane (see Figure C-9). The reduction is attributable to relatively clean solids from tributaries and bay sediments that are eroded from areas of low mercury bed concentrations mixing with and diluting resuspended sediments with elevated mercury concentrations prior to deposition after the hurricane passes. Approximately 85% of the bed area in the bay showed bed concentration changes ranging between an increase of 0.05 parts per million (ppm) and a decrease of 0.05 ppm. Less than 5% of the sediment bed in Lavaca Bay had surficial mercury bed concentration increases greater than 0.05 ppm, with these increases primarily occurring in the regions that experienced erosional depths greater than 10 cm. It is important to note that variation of key model parameters and inputs does not significantly change model predictions.

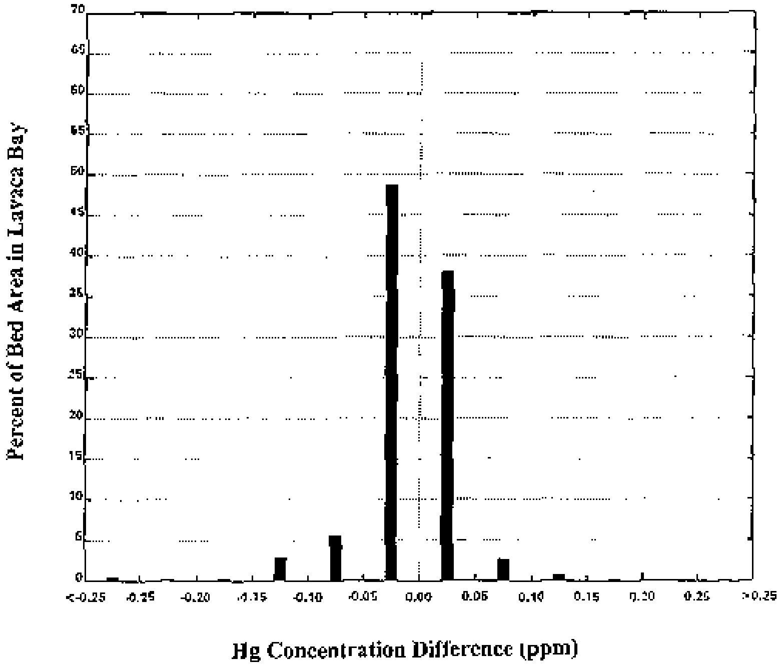

Figure C-9. Predicted changes in surficial mercury concentrations in Lavaca Bay
caused by Hurricane Carla with a 2 cm well mixed layer.

These modeling results indicate that a hurricane will not expose elevated mercury concentrations buried at depth in Lavaca Bay. In addition, a major storm event will not cause an overall increase in surficial mercury bed concentrations in the bay. Confidence in these conclusions is based on the following factors:
— Extensive use of site-specific data for model development
— Conservative assumptions when developing various model inputs and parameters
— Successful model calibration

CONCLUSIONS

Effective and correct evaluation of sediment stability is accomplished using rigorous and scientifically credible sediment transport analyses that employ quantitative procedures. This approach yields a methodology that can be used to objectively evaluate different remedial scenarios. In fact, the stability of cohesive sediment deposits during a rare storm is a critical component in evaluating remedial options at a contaminated sediment site. Estimating the scour depths during a rare storm and determining the resulting COC concentrations in the surficial layer of the bed is necessary for comparing the efficacy of various remedial alternatives. Qualitative analyses or conceptual models can be useful for developing and validating the quantitative analysis tools; however, qualitative techniques alone generally are insufficient for conducting remedial alternative evaluations that are scientifically defensible.

Two tiers of quantitative analysis were discussed. A Tier 1 analysis involves the use of approximate equations to estimate scour depths during a rare storm. The accuracy of these equations and associated parameters is such that only order-of-magnitude estimates result. The second tier of this analysis scheme employs the development and application of a comprehensive sediment transport model to evaluate bed stability. Tier 2 analyses produce the most accurate results, but require significantly more time and effort than Tier 1. The level of analysis used for a specific site depends on data availability, the level of accuracy required, and time and budget constraints.

State-of-the-science sediment transport models have been effectively used as management tools for evaluating remedial options at several contaminated sediment sites. It should not be presumed that rare storm events will have catastrophic impacts on the site under review. In fact, two case studies clearly demonstrate that a rare storm is not necessarily catastrophic; significant increases in surficial bed concentrations caused by reexposure of elevated concentrations buried at depth in the bed will not necessarily occur during a rare storm. However, it is important to note that sediment stability is site specific. Contaminated sediment sites with elevated bed concentrations caused by historic discharges buried at depth in the bed may not be severely impacted by a rare storm. Depending on the site-specific hydrodynamic and sediment transport factors, the effects of a flood or hurricane can be significant at sites where relatively recent discharges have occurred and elevated bed concentrations are near the sediment surface.

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