SEDIMENT STABILITY ASSESSMENT TO EVALUATE NATURAL RECOVERY AS A VIABLE REMEDY FOR CONTAMINATED SEDIMENTS

WORKING DRAFT, JUNE 2004

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ABSTRACT

Natural recovery processes have been shown at some contaminated sediment sites to provide sustained reductions in contaminant bioavailability over time as indicated by contaminant trends in biota tissue, sediment and water column samples. Evaluation of the future effectiveness of monitored natural recovery (MNR) as a potential long-term remedy requires an assessment of sediment stability, especially when long-term burial of contaminated sediments is the primary recovery mechanism. The Remediation Technologies Development Forum (RTDF) has outlined a framework for MNR evaluation (Davis et al., 2004). Components of the framework are detailed in a suite of companion papers, including this paper presenting a framework for a weight-of-evidence evaluation of sediment stability. When assessing sediment stability, the key question is typically, "*What is the potential for increased risks due to re-mobilization of buried contaminants due to extreme events?*" The specific objectives of sediment stability assessment vary from site to site and may include related concerns such as the potential effects of contaminated sediment transport to other areas.

Sediment stability evaluation is best conducted using a weight-of-evidence approach because of the uncertainties associated with available empirical and predictive modeling approaches. The weight-of-evidence approach proposed here includes multiple components: geomorphic assessment; historical site review; bathymetric analyses; chemical profile analyses; sedimentation and erosion measurements; transport measurements; and prediction of sediment stability using empirical or mechanistic models. No single method provides

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This working draft paper outlines a "weight-of-evidence" approach for evaluating the use of monitored natural recovery (MNR) for the remediation of contaminated sediments. This paper is one in a series of five papers proposing a framework, based on site-specific information, of five interrelated elements to assess the use and effectiveness of MNR. Developed by individual members of the Sediments Remediation Action Team under the Remediation Technologies Development Forum (RTDF), the papers are meant to serve as a resource to interested parties, but are not intended to be comprehensive or provide detailed information.

The five working draft papers represent the views of the authors and have not been subjected to EPA peer review. Therefore, it does not necessarily reflect the views of the EPA, and no official endorsement should be inferred. The working draft papers are not a regulation, and therefore, they do not impose legally binding requirements on EPA, States, or the regulated community, and may not apply to a particular situation based upon the circumstances. Interested parties are free to raise questions and objections regarding the "weight-of-evidence" approach provided in the papers. The RTDF Sediments Remediation Action Team is seeking and welcomes public comments on the papers. The papers are working drafts and may be revised periodically without public notice. Use or mention of trade names does not constitute endorsement or recommendation for use.

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unequivocal evidence for sediment stability, although when multiple lines of evidence demonstrate historical sediment stability and unacceptable exposure is not predicted to occur during future events, MNR is supported as a viable remedy providing long-term risk reduction. This paper presents technical approaches for evaluation of sediment stability within the weight-of-evidence framework. Presentation of sediment stability in this framework is advocated to provide a sound basis for evaluation of MNR as a potential remedy where site conditions are appropriate.

INTRODUCTION

Natural recovery processes affecting contaminants in surface sediments can be shown to provide significant, sustained reductions in contaminated bioavailability and related human and ecological risks over periods of decades. When tissue, sediment, or water column contaminant trends from a contaminated sediment site exhibit natural recovery trends, and burial by clean sediment is known to be a primary recovery mechanism, Monitored Natural Recovery (MNR) may be a viable long-term remedy. To evaluate the future effectiveness of MNR as a long-term remedy, a sediment stability assessment must be conducted.

As discussed by Davis et al. (2004), evaluations of MNR as a potential remedy are best conducted using a weight-of-evidence framework that relies on multiple lines of evidence. The Remediation Technologies Development Forum (RTDF) Sediment workgroup has developed a framework for performing an appropriate MNR evaluation. A collection of companion papers presented at this venue detail components of the framework and present example applications from various sites (Davis et al., 2004; Dekker et al., 2004; Magar et al., 2004; and Patmont et al., 2004).

Principle Number Four of the United States Environmental Protection Agency (USEPA) Principles for Managing Contaminated Sediment Risks at Hazardous Waste Sites (USEPA, 2002) requires the development of a Conceptual Site Model (CSM) that considers sediment stability to understand whether contaminant availability is likely to change under various future scenarios. When assessing sediment stability, the key question is typically, "*What is the potential for increased risks due to re-mobilization of buried contaminants due to extreme events?*" When contaminated sediment deposits can be shown to have been historically stable, and no unacceptable risks are projected to occur if an extreme event occurred in the future, selection of MNR is supported as a viable remedy for long-term risk reduction.

Sediment stability assessment should utilize multiple lines of evidence because of the inherent uncertainty in natural processes, measurement technologies, and predictive modeling. In practice, sediment stability assessments have used various methods from site to site, including empirical and predictive methods, although presentation of results for use by regulators has been hampered in some cases by over-reliance on specific methods and unbalanced presentation of empirical information and model predictions. Specific technical guidance to facilitate use of sediment stability assessment information for contaminated sediment management decision-making is not yet available. To help fill this need, this paper provides a sediment stability assessment framework assembled by members of the RTDF (Davis et al., 2004). This paper advocates use of multiple approaches to assemble a weight-of-evidence evaluation of sediment stability for decision-making in support of MNR.

SEDIMENT STABILITY ASSESSMENT FRAMEWORK

The sediment stability assessment framework outlined here essentially involves a listing and description of the various empirical and predictive lines of evidence that can be assembled, and recommendations on presentation of results in a manner that should facilitate use of the information by decision-makers. Investigation of long-term sediment stability may include multiple components, including empirical methods and predictions through mathematical modeling. These are not clearly distinguished, because predictive modeling relies on historical data and empirical information to judge model performance and prediction ability. Empirical methods essentially use historical observations to infer likely behavior in the future and include the following:

- historical data review
- geomorphology assessment
- hydrodynamic measurements and modeling
- sediment erosion and transport measurement
- sediment core chemistry profiling
- hydrographic surveying.

Predictive modeling tools range from calculations of maximum erosion potential at specific locations based on erosion rates studies and hydrodynamic information, to use of detailed mechanistic sediment transport models that represent sediment sources, deposition and erosion, and transport of sediment. Modeling approaches rely primarily on accepted erosion algorithms to relate near-bottom shear stresses to resuspension, but also may represent the effects of event deposition to compute net erosion. Use of modeling tools requires that they first be shown to reproduce historical information and/or are well-calibrated to high-shear stress event data (e.g., flood flows, high wave conditions, large tidal fluctuations, etc.).

One of the first comprehensive discussions of using these multi-disciplinary approaches for contaminated sediment sites occurred at the *Sediment Stability Workshop*, co-sponsored by the USEPA and other organizations in January 2002 (workshop materials available at http://www.smwg.org/). Investigators of contaminated sediment sites have applied these techniques in practice for years, although their integration into a weight-of-evidence framework for contaminated sediment sites has not been fully developed.

A number of factors preclude use of any single approach to adequately assess sediment stability. These include natural variability and the resulting uncertainties associated with measurements; limitations of measurement technologies; limitations of the state of the science of modeling sediment dynamics; natural meteorological variability that imparts uncertainty to future predictions; and practical study cost limitations. In light of these uncertainties, a weight-of-evidence approach is proposed, wherein multiple types of data and analysis are used to develop an understanding of long-term contaminated sediment stability. Table 1 lists potential components of a weight-of-evidence approach and their utility.

Historical Review. Historical review is an important step in CSM development for contaminated sediment sites. Many such sites occur on waterways with a history of hydraulic modifications, such as dams, shoreline filling and armoring, bridge construction, dredging, watershed development, stormwater outfalls, and other anthropogenic impacts that affect sedimentation. The historical review should identify and create timeline information on these types of impacts, which may have affected sediment supply and deposition patterns at the site. This information is required to guide interpretation of historical data on sedimentation rates and sediment chemical profiles.

A review of hydrodynamic information (e.g., flow records, tide or stage records, velocity data, high water marks, wave records, etc.) is commonly conducted to statistically define magnitudes and return probabilities for high-energy events that are used as the "design event" for sediment erosion predictions or remediation designs. On river systems, the 100-year or 500-year flood event is typically used. In reservoirs, lakes, estuaries, or coastal embayments, wind, tide, and wave records may be used to define extreme events that occurred during the historical period of interest (e.g., from the time contaminant discharge began). Time-trend plots of these data can be compared to information on sedimentation or transport to assess impacts of historical events on the sediments.

The popular press can also be a source of information on impacts of historical events, for example, the extent of flooding or failure of structures, or accumulation/loss of sediment in some areas. The historical review should include a search for this type of information.

The potential for historical changes in sediment supply should also be investigated. Reductions in sediment supply can shift sedimentation rates and may alter sediment stability, particularly in transitional areas that are periodically erosional and depositional. Dam construction or removal, changes in watershed agricultural practices, periods of significant development, point source controls, and other factors may be important. Historical or future dam demolition may also have consequences to sediment stability by changing local hydrodynamic conditions and/or peak flow conditions during flood events.

In summary, the historical review should provide the time series of natural high-energy events, a timeline of major anthropogenic impacts to hydrodynamics and sedimentation, a description and timing of factors affecting historical sediment loadings, and historical observations of the impacts of high-energy events. Not only is this information useful in considering future sediment stability, but it is also very important in interpreting some of the other types of data presented below.

Geomorphology Assessment. Geomorphology is primarily concerned with landforms and their processes of change. Fluvial geomorphology is the branch of science that studies the landforms associated with river channels and the processes that form them (Kellerhals and Church, 1989). Geomorphology science applied to sediments provides a hypothesis as to whether sediment deposits are most likely long-term depositional, erosional, or near a state of dynamic equilibrium. Application of geomorphology science to contaminated sediment sites provides a long-term cause-and-effect basis for expected sediment transport processes and the effect of these processes on sediment bed stability. The advantage of evaluating site geomorphology is that the various types of information developed in the weight-of-evidence approach tend not to be of questionable coincidence, but rather mutually consistent with expected geomorphologic behavior. A geomorphic assessment should include identification of the geomorphic setting of the site, key geomorphic features, and important regional and local geomorphic processes.

By considering geomorphic processes and current system morphology (e.g., shoreline configuration, bathymetry, man-made structures, etc.), long-term depositional or erosional tendencies for specific areas of the site can be identified. Conducting the geomorphic assessment early in the process of contaminated sediment site investigation provides information of value for sampling design and evaluation of remedial alternatives. Early examples of geomorphic assessments are works by Renwick and Ashley (1984) who present a geomorphic assessment of the Raritan River Estuary to develop insights into contaminated sediment transport, and Suskowski (1978) who studied the sedimentology of Newark Bay for the same purpose.

Bathymetric maps, sediment texture and thickness maps, hydrology/ hydrodynamic data, and sediment transport data are very useful in conducting a geomorphic assessment. Side-scan sonar data can be particularly helpful in mapping sediment texture, in addition to conventional probing and sample collection techniques. Side-scan sonar provides a black and white reflected image of the sediment surface, but does not provide depth data.

Bathymetric Change Analysis. Analysis of bathymetric changes is an intuitively straight-forward approach to assessing bed stability (i.e., aggradation or degradation), but is typically fraught with uncertainty when historical survey data is used. Typically, historical bathymetric data are available as a series of depth soundings (manual or sonar) along tracklines crossing the water body of interest. Modern multi-beam survey methods collect a swath of depth measurements, providing nearly 100% coverage (grid data) over the survey area. Bed elevation changes are determined either by comparison of repeat measurements along individual trackines, or comparison of surface models (e.g., Triangulated Irregular Network [TIN] models) created from repeated surveys. Bed elevation change can also be determined by periodic measurement of the sediment surface elevation relative to fixed objects (e.g., stakes).

Uncertainty in bathymetric comparisons arises from multiple factors. Trackline positions tend not to be precisely matched. Historical bathymetric measurement equipment and horizontal and vertical positioning equipment are relatively imprecise compared to modern methods. Uncertainty due to imprecise horizontal positioning is compounded by variations in the bottom slope and changing water elevations. In areas of high bottom slope, small differences in horizontal position yield large apparent differences in bed elevation. While these factors impart larger uncertainty in historical datasets, the also affect modern survey accuracy. Data processing for development of surface models can add additional uncertainty due to nuisances in numerical or statistical approaches and available routines in the software used for data analysis.

The U.S. Army Corps of Engineers (USACE) Hydrographic Survey Manual provides guidance on survey methods and analysis (USACE, 2002). The manual recommends accuracy criteria for various survey methods and minimum performance standards for survey control. For acoustical methods over soft sediments, the minimum 95% accuracy recommended for water depths < 15 feet (ft) is ± 0.5 ft, increasing to ± 1 ft for depths from 15 to 40 ft. Survey contractors using modern survey methods can provide greater accuracy; however, accuracy can be calculated by survey of fixed objects and precision can be established by repeat survey of specific tracklines.

The level of uncertainty in bathymetric comparisons may preclude determining direction of change (i.e., net erosion or deposition), let alone actual rates of change in short time periods and over relatively large areas. Thus, comparison of computed changes to other lines of evidence is useful to address uncertainties. Furthermore, bathymetric change analysis only provides the net change over the survey period; the effects of large depositional or erosional events within the survey period cannot be distinguished without other types of data. Inspection of vertical chemistry profiles and sediment core stratigraphy may identify mixed layers or depositional bands that may provide insight into how events affected sedimentation trends.

For some sites, quantitative data on historical bathymetric changes can be obtained from review of dredging records. Where dates of dredging, depth of cut, volume removed, and dredged area delineations are available, an estimation of the rates and areas of sediment accumulation may be possible. Aerial photography review also can reveal historical site changes that may be of importance to near-shore sediment stability. For example, variation in mudflats, sediment bars, and shoreline conditions may be evident by comparing historical aerial photos.

Sediment core thickness, when cores are taken to refusal, or sediment probing depths provide a surrogate for long-term sediment accumulation rates and are particularly useful to estimate relative differences in depositional characteristics of areas within a site or over time.

Continuous observation of bed response to events is possible using in situ, fixed-mounted sonar devices to record bed elevation changes over small intervals. This approach has the advantage of being able to observe the temporal responses of the sediments during events of varying energy levels, particularly high-energy events. Two limitations to this technique include: 1) fixed sonar devices provide data only at specific locations, requiring extrapolation beyond the fixed location or between locations; and 2) the probability of measuring a high-energy event is small.

Depositional Record Indicators. Vertical concentration profiles in depositional sediment beds reflect past loading of particle-bound chemicals. Use of sediment core chemistry for historical loading analysis and use of radionuclides such as ^{137}Cs and ^{210}Pb for core dating and burial rate determination are common components of contaminated sediment site investigation (Brenner et al., 2001, 2004; Magar et al., 2002). The peak ^{137}Cs level in a depositional core is assumed to correspond to peak nuclear weapons testing circa 1963, and occurrence of detectable levels of ^{137}Cs circa 1954, and these horizons are used to measure of sediment accumulation. Sediment burial rate can also be estimated from ^{210}Pb profiles based on the half-life of ^{210}Pb (22 years) and its fairly constant atmospheric deposition rate. ^{7}Be, which has a short half-life (53 days) may be used to provide an indication of whether or not recently deposited sediments are present, and to estimate surface sediment mixing depths.

Sediment core chemistry profiles also provide insight to historical bed stability, particularly for chemicals with relatively high environmental stability (e.g., high sediment-water partition coefficients and low degradation/transformation rates) with known historical time markers, such as: a) a known loading horizon (the time when the chemicals first appear in detectable levels or levels of concern), b) a known period of loading, c) a known maximum loading period or event, or d) a known loading pattern relative to another chemical (Patmont, 2004). Environmentally stable chemicals are unlikely to exhibit “smearing” of the profiles vertically due to advection/dispersion within the core, which tends to degrade the depositional record.

When evaluating sediment stability based on these markers, the general approach is to form a hypothesis concerning the expected profile in depositional areas where the depositional record is most likely to be preserved, and then to inspect sediment cores in support of this hypothesis. If the expected historical deposition patterns are observed, it can be concluded that sediments have been reasonably stable over the time period considered. In areas where a predictable contaminant profile is not preserved, inherent stability cannot be supported (Brenner et al., 2004), although a lack of stability cannot be immediately concluded either. Potential "non-erosion" factors, such as human disturbance of the bed and potentially unknown local source activity may cause non-conforming profiles.

In depositional areas subject to bioturbation, burial of historical layers of peak contamination by "clean" sediment causes a profile of declining concentrations from the buried peak levels toward the sediment-water interface. The shape of the profile indicates if attenuation proceeds steadily or is periodically disrupted by mixing. Layers showing deviation from the trends can be compared to the historical record of events to see if there is time-correspondence. If the trends are continuous in spite of historical high-energy events, it provides some indication of the ability of the bed to withstand these events such that increased exposure concentrations do not result. However, the effect of events on the profile depends on the burial rate and intensity of bioturbation, and these factors must be considered in the evaluation.

If sediment core chemical profiles can be grouped based on location within similar geomorphic units (e.g., river point bars, dredged channels, depositional embayments, main channel areas, etc.), the core profiles can be compared to evaluate profiles for consistency within units and relative differences between units. When profiles within a given geomorphic unit show consistent profiles and evidence of (or lack of) event impacts, it supports formation of conclusions regarding the behavior of the sediment bed in that area.

Sedimentation/Erosion Process Measurements. Sedimentation and erosion process measurements are often required to support modeling to predict responses to high-energy events that may occur in the future. However, these data can also be used to quantitatively assess effects of large events by providing information on sedimentation rates and erosion rates as a function of applied shear stress. Sedimentation measurements include deployment of sediment traps to measure sediment particle depositional flux. Sedimentation rates can also be computed from measurements of water column suspended sediment concentrations and grain size distributions, potentially supported by settling column tests. Measurement of sediment bed erosional properties provides more salient data to assess bed stability, and can be used outside of mechanistic models to compute bed response to high-energy events for cohesive sediments (e.g., probabilistic Depth-of-Scour analysis of Hudson River sediments, USEPA, 1999).

Cohesive sediment erosion rates are highly site-specific, requiring site-specific measurement for accurate erodability prediction. Erosion measurements involve specialized devices, including various types of in-situ and ex-situ flumes and sediment "shaker" devices. Typically, these measurements identify a critical shear stress and an erosion rate coefficient based on fitting various erosion models to experimental data (Ziegler, 1999).

Mass balance analyses are suitable for river systems where water quality sampling of inflows and outflows can close the mass balance where internal sources of sediment and contaminants (i.e., from bed resuspension) can be estimated reasonably well. Sampling during high-energy events provides an indirect measurement of net bed response, useful when calibrating a model (QEA, 1999).

Predictive Modeling. Qualitative methods (e.g., geomorphic assessment, chemical profile inspection, and historical review) and empirical methods (e.g., depositional record indicators and bathymetric change analysis) provide the bases for evaluating performance of models designed to predict future sediment stability based on historical observation. The main limitation of empirical methods is that they provide an indication of what happened in the past, and only at locations where information is available.

Properly constructed predictive models provide the only quantitative means to assess sediment response to future events. However, model predictions are uncertain, difficult to verify, usually require extrapolation from calibration conditions to high-energy event conditions, and may be met with skepticism by regulators due to the technical complexity involved. The acceptance of predictions for decision-making generally depends on the degree of consistency between model predictions and empirical information. When predictions are presented without the benefit of the supporting empirical information described above, acceptance of results for decision-making is compromised.

Predictive modeling tools range from calculations of maximum erosion potential at specific locations based on erosion rates studies and hydrodynamic information, to detailed mechanistic sediment transport modeling that represents sediment sources, deposition and erosion, and transport of sediment. The more advanced models simulate not only the net effect of large events, but also the gross deposition and erosion rates and depth of disturbance of the sediment bed, and can provide more insight into event dynamics. However, these models typically require higher-level expertise and extensive model calibration datasets.

When coupled with contaminant fate and transport models, sediment transport models can be used to relate sediment stability (or instability) to exposure concentrations and consequent risks to humans and ecological receptors. When only depth of scour predictions are available, the scour depths can be compared to chemical concentration profiles to evaluate whether or not estimated event impacts would cause an unacceptable increase in exposure concentrations. Modeling predictions of sediment bed response should be considered in the context of impacts on exposure in order to facilitate risk-based decision-making.

Synthesis of Results. The most important aspect of the weight-of-evidence approach advocated here is balanced presentation of findings from multiple methods, with a description of the limitations and uncertainties associated with each of the empirical and predictive methods utilized. It is suggested that over-reliance on one or two approaches with incomplete accounting for uncertainty in the predictions or results is counter-productive to use of the information by decision-makers, and can lead to precautionary decisions. To facilitate consideration of results by decision makers, the following approach to synthesis of information is suggested:

- Identify geomorphic features or contiguous areas with similar sedimentation patterns and contaminant concentrations as a basis for presentation of results. This is important because the weight-of-evidence concerning sediment stability will be strongest where differing patterns exist, implying "noise" or uncertainty in results.
- Organize in matrix or graphical format the geomorphic descriptions (key processes and long-term tendencies) for each area, consistent patterns (if any) in the sediment

profile data (chemicals used for dating as well as contaminants), bathymetric analysis results, information on sedimentation or erosion, and model predictions for extreme events.

- State conclusions regarding the long-term stability in each area along with the rationale, supported by findings from each method.
- Identify the implications of sediment stability predictions or findings on contaminant exposure based on sediment chemistry profiles – are future events likely to elevate exposure or not?
- Discuss the uncertainty associated with conclusions for each area – provide bounding simulations with modeling predictions if possible
- State overall conclusions, addressing how they are impacted by uncertainty.

TABLE 1. Potential Components of Sediment Stability Assessment.

Category	Data Type
Historical review	Timeline and description of system modifications, such as dams, revetments, bridges, dredged channels, or other structures that may have impacted sedimentation dynamics and the velocity regime
	Hydrodynamic record review to identify and characterize historical high-energy events
	Local history, popular press concerning impacts of storms (often anecdotal or qualitative information)
	Suspended sediment loading review – have historical sediment sources and burial changed over time?
Geomorphic assessment	Characterize geomorphic processes and key geomorphic features to infer general mechanisms of sediment transport, depositional areas, and expected decadal-scale system changes
	Sediment texture mapping using sediment collection or side-scan sonar techniques
Bathymetric analyses	Comparison of repeat bathymetric surveys to evaluate sedimentation patterns and rates
	Review of dredging records as an indicator of sediment accumulation rates and areas of deposition in channels
	Sediment thickness probing, a surrogate for deposition rate and relative deposition within a site
	Aerial photography review of shoreline changes
	Measurement of sediment loss through erosion pin deployment or similar methods
	Remote sensing of bed response to high velocities, such as through deployment of fixed-mounted sonar devices
Sediment core profile analyses	Sediment core stratigraphy characterization to identify banding or sediment sorting due to events
	Sediment dating and burial rate calculation based on radionuclide profiles, as well as inspection of radionuclide profiles for discontinuities associated with event impacts
	Evaluation of short-lived tracers (e.g., ^{7}Be) for mixed depth and mixing rate determination
	Anthropogenic chemical profile inspection based on known historical markers (e.g., loading horizons) to assess if profiles are consistent with hypothesis concerning long-term sedimentation dynamics; chemical profiles also provide basis to assess potential for increased exposure to result due to potential instability
Sedimentation and erosion measurements	Burial rate estimation from radio-dated sediment cores
	Resuspension rate measurements for erosion prediction
	Sediment trap measurement of deposition fluxes
	High-flow event water quality sampling for mass balance analysis of sediment and contaminant erosion (rivers)
	Sampling or remote-sensing of particle concentration dynamics in the water column
Predictive modeling	Qualitative long-term prediction through application of geomorphology theories
	Bounding-case mobility threshold or depth-of-scour calculations of high-energy event response
	Sediment transport model predictions

***** Time-frame refers to the period over which conclusions drawn from the data apply

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