ERDC TR-14-9

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Technical Guidelines on Performing a Sediment Erosion and Deposition Assessment (SEDA) at Superfund Sites

Earl Hayter, Karl Gustavson, Steve Ells, Joseph Gailani, John Wolfe, Tim Dekker, and Todd Redder

September 2014

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Final report

Prepared for US Army Corps of Engineers
Washington, DC 20314-1000

Abstract

This report outlines processes influencing sediment transport and describes methods to use in developing a Sediment Erosion and Deposition Assessment (SEDA) at a site designated as a Superfund site. A SEDA is a complex procedure that overlaps multiple disciplines. Processes and properties that should be assessed include sediment characteristics, groundwater movement, surface water stresses, sediment loadings, anthropogenic activity, and weather and oceanographic influences. Historical data can also provide a long-term record on evolution of the system, which is not only critical in assessing sediment erodibility, but will also support conceptual site model development.

The most successful SEDA studies have been guided by a technical review panel working with a Remedial Project Manager in SEDA development. Understanding of processes at a specific site, coupled with experience from other sites, is also critical to success.

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Preface

This technical resource document was developed by the US Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC), Environmental Laboratory (EL), Vicksburg, Mississippi. This document provides technical guidelines for assessing the potential for sediment beds to undergo erosion or deposition over time. It also provides guidelines for using that information in decision-making at contaminated sediment sites.

The document was prepared for the US Environmental Protection Agency (EPA), Office of Solid Waste and Emergency Response, Washington, DC, under agreement No. DW96957990. The EPA project manager was Stephen Ells, Sediments Team Leader, Office of Site Remediation and Technology Innovation (OSRTI). The report was developed in conjunction with a Federal Workgroup who provided direction on the document and reviewed the initial draft. The members of the workgroup were from EPA (Steve Mangion, Region 1; Eduardo Naranjo and Eugenia Naranjo, Region 2; Bonnie Eleder, David Petrovski, Mary Logan, and Rosauro Delrosario, Region 5; Allison Hiltner, Region 10; Dennis Timberlake, Ed Barth, and Marc Mills, Office of Research and Development; Mark Sprenger, Environmental Response Team); USACE (John Wakeman, Seattle District; Joseph Gailani, and Earl Hayter, ERDC); and U.S. Navy (Stacey Curtis and Pei-fang Wang, Space and Naval Warfare Systems Command; Thomas Spriggs, Naval Facilities Engineering Command). The Workgroup was co-chaired by Stephen Ells, EPA and Karl Gustavson, USACE-ERDC. The document underwent independent peer review based on procedures established by the EPA, coordinated by EMS Consulting. Reviewers included Faith Fitzpatrick, US Geological Survey; Craig Jones, SEA Engineering; and Jim Quadrini, Anchor QEA.

At the time of publication, the Deputy Director of ERDC-EL was Dr. Jack Davis and the Director of ERDC-EL was Dr. Elizabeth C. Fleming. Commander of ERDC was COL Jeffrey R. Eckstein. The Director was Dr. Jeffery P. Holland.

Acronyms

ADCP	Acoustic Doppler current profiler
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CSM	Conceptual site model
DQO	Data quality objectives
EL	Environmental Laboratory
ENR	Enhanced natural recovery
EPA	Environmental Protection Agency
ERDC	Engineer Research and Development Center
FS	Feasibility Study
IC	Institutional control
INSSEV	In situ settling velocity instrument
LISST	Laser in situ scattering and transmissometry device
LOE	Line of evidence
MLW	Mean low water
MLLW	Mean lower low water
MNR	Monitored natural recovery
MSL	Mean sea level
MTL	Mean tide level

NAVD	North Amercian Vertical Datum
NCP	National Contingency Plan
NOAA	National Oceanic and Atmospheric Administration
O&M	Operations and Maintenance
OSRTI	Office of Site Remediation and Technology Innovation
PICS	Particle Imaging Camera System
RI	Remedial investigation
RI/FS	Remedial investigation/feasibility study
ROD	Record of decision
RPM	Remedial Project Managers
SEDA	Sediment Erosion and Deposition Assessment
SPI	Sediment profile imaging
SSC	Suspended sediment concentration
TSS	Total suspended solids
USACE	US Army Corps of Engineers
USEPA	US Environmental Protection Agency
USGS	US Geological Survey

1 Introduction

1.1 Background and objectives

Understanding the dynamics of sediment erosion, deposition, and transport is essential to selecting an appropriate and effective remedy at contaminated sediment sites. One of the US Environmental Protection Agency's (USEPA) 11 Sediment Management Principles (2002) is to "Develop and refine a conceptual site model that considers sediment stability." USEPA's *Contaminated Sediment Remediation Guidance for Hazardous Waste Sites* (2005) further discusses the importance and complexities of understanding sediment transport and fate, along with various empirical and modeling methods for evaluating sediment and contaminant movement and its consequences. The 2005 Guidance describes environmental and physical characteristics of surface water bodies (e.g., rivers, lakes, estuaries, coastal seas), conducive to various remedies, with particular emphasis on bathymetry, flows, and the geotechnical characteristics that impact site hydrodynamics. The Guidance recommends that EPA Remedial Project Managers (RPMs):

- Understand the geomorphological setting and processes (e.g., resuspension, transport, deposition) affecting the erodibility of sediment.
- Evaluate the long-term stability (i.e., resistance of the sediment to eroding forces) of the sediment bed and the mobility of contaminants within the sediment.
- Develop a conceptual site model that considers sediment erodibility and stability and key site uncertainties.

The goal of this document is to guide RPMs in conducting a Sediment Erosion and Deposition Assessment (SEDA) to be used as a line of evidence in evaluating remedial alternatives for contaminated sediment sites. Guidance provided herein should be used in conjunction with the guidelines provided in *Contaminated Sediment Remediation Guidance for Hazardous Waste Sites* (USEPA 2005). That guidance recommended that "The project managers should include a scientific analysis of sediment stability in the remedy selection process for all sites where sediment erosion or contaminant transport is a potential concern."

This document provides greater detail on sediment transport analyses and a framework for using that information. The methodology described herein can be modified based on site complexity and the significance of the site decision. It should be used to guide consideration of historical data, the collection of new data, and the development of approaches to predict future conditions. The purpose of a SEDA is to support informed risk management decisions, always in combination with other information and with reference to the National Contingency Plan (NCP) criteria. The SEDA primarily focuses on physical processes driving sediment transport. But, in the context of risk-based decision-making, the SEDA will support an understanding of contaminant exposure and risk. Site project managers can perform a SEDA and use it when developing and evaluating remedial options.

The current document has two primary objectives. The first is to provide general methodology for conducting the SEDA and using its results to support site remedy decisions. The second is to provide a resource for understanding the science underlying sediment dynamics in aquatic systems and the tools used to monitor and predict sediment movement over time. Better and more comprehensive understanding of sediment erosion and deposition processes can lead to selection of cost-effective remedies that are effective in the long and short term. A SEDA only considers physical processes that affect the transport of sediment; it does not consider any associated chemical or biological processes.

1.2 Introduction

Environmental contaminants such as hydrophobic organic contaminants and metals often partition to sediment, where they can persist for decades or centuries. These contaminated sediments can be transported, deposited, and buried or they can undergo further cycles of resuspension, transport, and deposition. The environmental conditions dictating these dynamics drive the ultimate fate of the contaminants and, hence, exposures to aquatic organisms over time. At many sites, contaminants in the sediment are a legacy of historical sources that have since been controlled. At these sites, the most heavily contaminated sediments likely exist close to their point of entry to the system or in depositional areas where they were transported and have accumulated. Over time, contaminated sediment may be buried by subsequent layers of cleaner sediment with commensurate declines in human and ecological risks. The persistence of these deposits over time demonstrates some degree of long-term net stability of the sediment bed (i.e., if the sediment was inherently unstable, the deposits would no longer remain).

Understanding the potential for disruption (e.g., erosion) of buried contaminated sediment is critical for predicting future site risks as well as determining whether (or which) remedial actions should be taken to address that risk. There are two common causes for disruptions to the sediment bed: high-energy natural events (e.g., flooding, waves, and ice scour), and anthropogenic activity (e.g., vessel-induced surface waves and propeller wash). These events may increase exposure to the contaminants of concern by uncovering or remobilizing buried contaminated sediment. Alternatively, the events may not be of sufficient magnitude or duration to expose or resuspend contaminated sediment. In either case, it is critical to understand the significance of these phenomena when investigating contaminated sediment sites and evaluating remedial alternatives. In considering potential remedies, it is important to determine the likelihood that buried contamination will stay buried and not be eroded as a result of a) extreme events such as a 100-year or longer event, b) a significant increase in shipping traffic, or c) deepening of navigation channels to accommodate new deeper draft vessels or supertankers. A SEDA will help to make this determination.

Site-specific information on sediment transport collected and evaluated using approaches presented herein can be used to develop and refine the Conceptual Site Model (CSM) for the site. A CSM describes, among other things, how the sediment became contaminated, the current distribution of contamination in relation to the sources, and the current and future pathways that could result in exposure. As such, it is necessary to know how the contaminants were transported to and within the water body. This requires knowledge of the transport behavior for both the contaminants and sediment. Some of this knowledge should be gathered during the Remedial Investigation (RI) when conducting the SEDA and incorporated into the CSM. Existing hydraulic data, bathymetric data, and sediment data (e.g., grain size distribution) collected during the RI can be used in the SEDA.

A SEDA is an evaluation of processes that affect transport or burial of contaminated sediment. Physical and biological processes at a site can erode, resuspend, and transport contaminated sediment or serve to isolate and bury that sediment. To be most useful, a SEDA should support future predictions of those processes with enough certainty to inform risk management decisions in conjunction with other information relevant to contaminant exposures and risk (See Box 1).

A SEDA is generally applicable to both freshwater and near-shore marine sediment sites and, although not a required part of the Remedial Investigation/Feasibility Study (RI/FS) process, it fulfills the EPA recommendation that RPMs perform a "scientific analysis of sediment stability." A SEDA involves using a systematic approach that 1) identifies the processes and mechanisms that might result in erosion, 2) determines the most appropriate methods to use in assessing sediment resuspension, transport, and deposition, and 3) quantifies sediment resuspension and deposition rates under varying flow conditions. As such, a SEDA provides important information needed for the FS.

The SEDA may be used to address one or more of the following six questions that are typical of many sediment site evaluations. Additional information is provided in Chapter 7.

1. Available data indicate that exposures to surface sediment concentrations do not pose unacceptable risks, but that buried sediment concentrations are substantially higher and would pose unacceptable risk if exposed. What is the likelihood of erosion of the surface layer and resulting exposure of the buried sediment?
2. Available data indicate that exposures to surface sediment pose an unacceptable risk, but that concentrations are also declining over time. What is the likelihood that risks will be reduced to acceptable levels in a reasonable time?
3. Available data indicate that an unacceptable risk from surface exposures could be mitigated by an armored sand cap. What is the likelihood that the resulting risk reduction will be permanent?
4. In situ amendments (e.g., activated carbon) could reduce bioavailability when applied to the sediment, especially where porewater advection may occur. Is armor needed to protect those amendments from loss because of erosion?
5. Contamination often occurs in adjacent layers of higher and lower concentration. Dredging could remove a surface layer of higher concentrations, leaving an intermediate "natural buffer layer" of acceptable concentrations, beneath which is another contaminated layer that would pose unacceptable

risks if exposed. What is the likelihood of erosion of the natural buffer layer?

6. Sand backfill could be used to reduce residual surface concentrations to acceptable levels, in terms of risk, after dredging. How permanent is the protection provided by this backfill in combination with any additional deposition of clean sediment, and how does this depend on the thickness of the sand backfill layer?

This document includes four appendices that provide supplemental information on the topics discussed herein. Specifically, a number of terms used throughout the guidance are defined in Appendix A, the glossary. Appendix B, entitled ‘Primer on Sediment Transport and Channel Geomorphology,” describes the sediment transport processes and geomorphology of water bodies. Appendix C, entitled ‘Types of Water Bodies and Applicable Modeling Approaches,’ describes the different types of surface waters in which contaminated sediment has been found along with the modeling approaches that are generally applicable for those waters. Appendix D, entitled ‘Fundamentals of Hydrodynamic Modeling,’ provides basic information on hydrodynamic modeling.

Box 1. SEDA and Other Information in the Context of Risk Management

The SEDA is intended to evaluate a critical component of the site’s CSM. However, it is not sufficient to support decision making by itself. Other evaluations are necessary to address the suite of questions critical to developing a comprehensive CSM and assessing future risk under various remedial scenarios. For example, do buried contaminants constitute a potential risk through transport of contaminated porewater? Are natural processes (e.g., burial, degradation, and dispersion) reducing risk and if so, over what time frame? Do current levels of risk require remedial action regardless of future sediment erosion and deposition? Overall, the SEDA is one important tool in developing a site CSM to support remedial decisions.

2 Sediment Erosion and Deposition Assessment

2.1 What is a SEDA?

A SEDA is an evaluation of processes that affect transport or burial of contaminated sediment. To be most useful, the assessment should support future predictions of those processes with enough certainty to make remedial decisions. The SEDA primarily focuses on physical processes driving sediment transport. But, in the context of risk-based decision-making, the SEDA will support an understanding of contaminant exposure and risk. Some of the relevant processes influencing risk are independent of the SEDA, but can be coupled to the SEDA to predict future contaminant risk and evaluate alternatives to remediate unacceptable risks. For example, ongoing releases from uncontrolled sources of contamination will affect the ability of any remedy to achieve and maintain targeted contaminant cleanup concentrations. Contaminant fate and transport modeling will couple the influence that ongoing contaminant sources have with the sediment transport processes investigated in the SEDA to predict contaminant levels associated with areas of the sediment bed, from which risk can be assessed. Bioturbation, which is a continual, biological mixing process that occurs in surface sediment, can also affect a sediment remedy by transporting deeper sediment to the surface or mixing deposited sediment with underlying sediment. Bioturbation evaluations are not described herein, but can also be included as a process in contaminant fate and transport modeling.

There is no single design for a SEDA. This guidance provides a framework for conducting a SEDA appropriate for the complexity of the site and the significance of the decision to be made at the site. At simple sites, representative sediment cores and an understanding of the physical environment may be sufficient to predict that contaminants are buried and not prone to disturbance. Perhaps a better understanding of flow stage and sediment transport will help to predict future sediment stability; sediment transport rating curves (flow versus transport) from empirical and modeled relationships may also need to be established. Or, perhaps the site is large and complex, and a model that links hydrodynamics, sediment transport, and contaminant transport is required to estimate where and under which conditions sediments are expected to be transported or buried.

Thus, a SEDA integrates information on the site's physical environment and history with empirical data on sediment characteristics into an analysis framework (whether that's a simple relationship or a model) to answer questions about contaminated sediment management.

2.2 Data quality objectives

It is essential that data collected for the SEDA be well-targeted in terms of their nature, quality, and quantity to support site decisions. As described in Guidance for the Data Quality Objectives (DQO) Process (USEPA 2006), seven steps generally guide the DQO process:

- State the problem
- Identify the decision
- Identify inputs to the decision
- Define boundaries of the study
- Develop a decision rule
- Specify limits on decision errors
- Optimize the design for obtaining data

Adherence to these steps will help to plan an effective SEDA. The DQO process is intended to ensure that data are collected for a specified purpose (e.g., to support a cleanup decision) and that analysis of the collected data can achieve that purpose. The objective is to identify those alternatives most appropriate for the site by framing and answering study questions. The planning of the SEDA is explicit about the nature and boundaries of information to be gathered to answer study questions, formulating decision rules that specify how the answers to those questions are to be used to evaluate alternatives per the NCP criteria, for example, short-term and long-term effectiveness. If possible, it is also important to be explicit about the acceptable level of uncertainty to support decisions. Data gathering should be optimized in accordance with DQO principles, in the sense that the additional data should be directly relevant to the study question, limited to the boundaries of the study, and consistent with the scale of the site and the magnitude of its potential benefit in supporting remedy selection.

2.3 SEDA purposes and possible outcomes

A SEDA is developed during the RI to better understand the contaminant fate processes that relate to sediment transport and particles/solids, as described in the CSM. The primary use of the SEDA is in the FS to evaluate the permanence of in-place management options (e.g., isolation caps, dredged residual caps, and thin layer caps) and the evaluation of risk reduction from monitored natural recovery (MNR) remedies. Those FS analyses often center on the future probability and magnitude of sediment bed disruption and the probability of unacceptable risks resulting from that disruption. To accomplish this, a SEDA can be performed during the RI to develop a quantitative understanding of sediment transport processes in the contaminated water body. This includes identification of sediment sources (i.e., areas undergoing sediment erosion and resuspension), entrainment, transport, settling, deposition, consolidation of the sediment bed, resuspension, and related processes such as bioturbation-induced mixing in the upper sediment bed.

Evaluating future risks at a contaminated sediment site also includes simulating the effects of natural and institutional controls (ICs) on the sediment bed. Natural controls include the ability of sediment to resist the erosion or mixing that drives unacceptable risk and ongoing sedimentation and burial that serves to lessen risks. ICs minimize human causes of erosion that could result in unacceptable risks (example ICs are restrictions on ship draft/anchor/wake, etc.). The SEDA can be used to evaluate the need for and expected effectiveness of ICs based on environmental conditions. The SEDA can also be used to evaluate an enhanced natural recovery (ENR) remedial alternative, such as a thin-layer cap intended to immediately reduce risks while natural deposition occurs to a thickness that permanently reduces risks to an acceptable level.

Surface particles in most sediment beds are subject to some degree of movement, and usually show a daily response to tides, currents, winds, vessels, or other forces such as bioturbation. While understanding the long-term effects of routine processes is necessary to evaluate the potential effectiveness of in-place management options, the SEDA is primarily concerned with understanding the effects that more intense hydrologic/meteorologic events may have on greater erosion or deposition at the site.

The SEDA may determine that the probability of erosive events is low, or that the magnitude of increased exposure or short-term risk from such an event is low. In these cases, the sediment may be considered “stable” for the purposes of remedial decision-making. The magnitude of the risk posed by disruptive events is determined by both the resulting exposure concentration and the spatial and temporal extents over which the impact would occur. Small localized impacts (e.g., anchor scarring of the bed, limited area of prop-scour erosion to bed layers of concern, or other localized disturbances) may have minimal risk consequence even if the concentrations exposed are relatively high. Heavy waterway vessel traffic and increased port development accompanied by deeper-drafted vessels, however, could potentially impact large areas of bottom sediment.

The SEDA may determine that there is a significant probability of an event occurring that produces unacceptable increase in risk. In these cases, the sediment is not sufficiently stable. As discussed later, the SEDA includes appropriate hydrologic/hydraulic (see definitions of hydrology and hydraulics in Appendix A) analyses to determine the probability that unacceptable increases in exposure and risk will occur from erosion or disruption of the sediment bed in the future. Thus, to address sediment erodibility, it is necessary to define: a) which future conditions or events will be considered, b) what future period will be considered (e.g., next 50 years), and c) what levels of increased exposure and risk to human health and ecological receptors are considered unacceptable. The probability of unacceptable risks occurring may need to be estimated for each scenario considered (e.g., a 100-year flood, a partial dam break, deep-draft vessel (e.g., supertanker) scour, dredging, or alternate site uses).

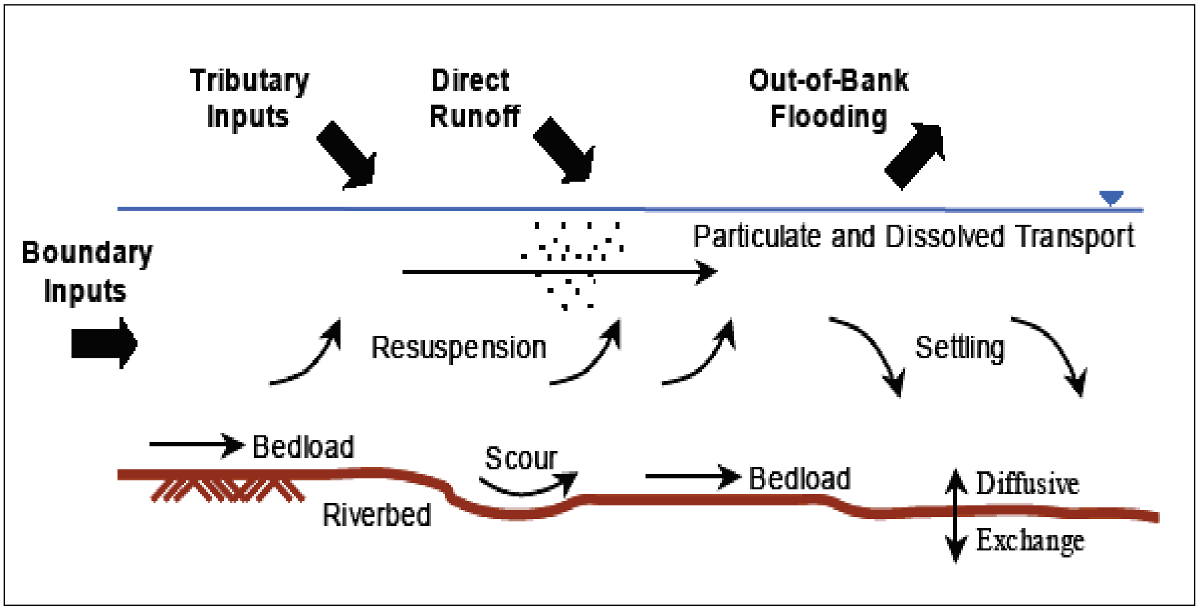
3 Conceptual Site Model

The CSM is a critical tool for understanding the site and evaluating risk and the expected effectiveness of risk reduction approaches (USEPA 2005). A CSM is especially important for sediment sites because the interrelationships among floodplain soil, surface and groundwater, sediment, and ecological and human receptors is often complex. The CSM provides a framework to understand specific processes relevant to the site, the interactions between site water and sediment/soil processes, the site-related and non-site-related point and non-point sources of contamination, and the potential consequences of these processes. Sediment management principle No. 4 of the EPA's 11 risk management principles is *Develop and refine a conceptual site model that considers sediment stability* (USEPA 2002).

The SEDA serves several purposes with respect to the CSM. It depicts how several key processes (sedimentation, erosion, etc.) and site characteristics (geomorphology, topography-bathymetry, habitat, human use and exposure, ecological use, etc.) relate to exposure and risk. For example, the SEDA will qualitatively describe the existing distribution of sediment throughout the site in terms of the sediment transport processes that occur in the water body at the site. Development of a CSM usually requires examining existing site data (e.g., the current distribution of contamination throughout the site in relation to the locations of sources) to assist in determining the significant physical and biogeochemical processes and interactions.

The CSM should be revised using the findings from the SEDA and other studies to address key questions, and to serve as a centerpiece for communicating and understanding sediment transport issues. The CSM usually will include maps of the site configuration and geomorphic features within the site, as well as a representation of natural processes and human activities that are of consequence to sediment transport. A graphical representation of key sediment transport and contaminant transport processes, as shown in Figure 3.1, is often included in a CSM. The CSM should be modified as new information and data are obtained and the site understanding is refined.

Figure 3.1. Sediment and contaminant transport and fate processes that are often represented in a conceptual site model (after WESTON 2004).



Analyses of sediment erodibility and contaminant transport are integral to the development of a complete CSM for a given contaminated sediment site. Contaminant transport and fate may include processes that affect sediment bed erodibility as well as those processes that govern dissolved-phase releases of contaminants from the sediment bed. Contaminant transport and fate will normally be considered in the RI. Similar to sediment erodibility, appropriate data collection for contaminant transport analysis should be considered early in the RI planning.

4 Fundamentals of Sediment Transport

4.1 Background

This chapter provides basic information on sediment transport, including a brief description of the factors that control the erodibility of sediment beds. More detailed information on sediment properties and transport processes is given in Appendix B as well as in textbooks (e.g., Mehta 2014, Lick 2009, Yang 1996).

Inorganic sediment consists of weathered rock material that is transported, suspended, and/ors deposited by flowing water. All constituents of the parent rock material are usually found in the sediment. Quartz, because of its abundance and larger mean particle size, is the most common material found in sediment. However, numerous other minerals (e.g., feldspar, calcite, and various clays) as well as carbonate particles, and igneous and metamorphic rocks, are also usually present. Even when material other than quartz particles is present in sediment, the average particle density of sediment is usually very close to that of quartz – 2.65 gm/cm^3 (Yang 1996).

The sediment gradation scale (presented in Table 4.1) classifies sediment in size classes, ranging from very fine clays to very large boulders. Sediment particles with diameters less than 63 µm are classified as fine-grained sediment (clays and silts). These sediments are, as a general rule, cohesive in nature, i.e., individual sediment particles stick together, with the degree of cohesiveness increasing significantly with decreasing particle size. Sediment particles with diameters greater than 63 µm are classified as noncohesive sediment (Mehta 2014), and are mostly composed of sands and coarser sediment, e.g., gravels, cobbles. Particle shape, as measured by roundness and sphericity, and specific gravity of the particles can have measureable effects on their transport, specifically on their settling velocities and critical shear stresses for erosion (Yang 1996).

Cohesive sediments are composed of clay and non-clay mineral components, silt-sized particles, and organic material, including biochemicals (Grim 1968). Clays are defined as particles with an equivalent diameter of less than 4 µm, and usually consist of one or more clay minerals. The non-clay minerals include quartz, calcium carbonate, feldspar, and mica. Organic matter sometimes present in clay materials can be discrete particles, adsorbed organic molecules, or constituents inserted between clay layers (Grim 1968). The inset box on the next page describes the surface electrochemical forces that largely govern the behavior of cohesive sediment.

Table 4.1. Sediment Gradation Scale (adapted from American Society of Civil Engineers (ASCE) 1975)

Sediment Class Name	Size Range (mm)	Size Range (µm)
Very large boulders	4096 - 2048	
Large boulders	2048 - 1024	
Medium boulders	1024 - 512	
Small boulders	512 - 256	
Large cobbles	256 - 128	
Small cobbles	128 - 64	
Very coarse gravel	64 - 32	
Coarse gravel	32 - 16	
Medium gravel	16 - 8	
Fine gravel	8 - 4	
Very fine gravel	4 - 2	
Very coarse sand	2 - 1	2000 - 1000
Coarse sand	1 - 0.5	1000 - 500
Medium sand	0.5 - 0.25	500 - 250
Fine sand	0.25 - 0.125	250 - 125
Very fine sand	0.125 - 0.063	125 - 63
Coarse silt	0.063 - 0.031	63 - 31
Medium silt	0.031 - 0.016	31 - 16
Fine silt	0.016 - 0.008	16 - 8
Very fine silt	0.008 - 0.004	8 - 4
Coarse clay	0.004 - 0.002	4 - 2
Medium clay	0.002 - 0.001	2 - 1
Fine clay	0.001 - 0.0005	1 - 0.5
Very fine clay	0.0005 - 0.00024	0.5 - 0.24

Mud is a term often used to describe natural sediment that contains abiotic (inorganic) sediment, aquatic biota matter at various levels of decomposition, and benthic organisms and their organic waste products. Also typically present in large populations are bacteria, microalgae, and their extracellular secretions (Mehta 2014). In general, mud is a sediment-water mixture that consists of organic carbon and inorganic particles that are predominantly less than 63 µm in size. Mud is very sticky when picked up, and is highly viscous (like a high-weight motor oil) when in a fluid-like state (modified from Mehta (2014)).

Detritus is a term used for a mix of cohesive sediment, organic material, and microbial organisms that accumulate and eventually mix with sediment. In aquatic ecosystems, detritus is often suspended in water, and settles in quiescent areas. After depositing, detritus containing contaminants can mix with clean sediment and cause the latter to become contaminated.

As streams and rivers flow from mountains to coastal plains, noncohesive sediment such as sand tend to deposit more rapidly because they have relatively high settling speeds, creating a sediment bed with a decreasing slope and grain size in the downstream direction, i.e., fining. When the sediment transport capacity (which is a function of the flow velocity and average sediment size) in a given reach of a river exceeds the total sediment load transported from upstream reaches, the difference between the capacity and total load is supplied from the bed. The total

Interparticle Electrochemical Forces

For clay-sized sediment particles, surface physicochemical forces influence the behavior of the particles because of the large specific area, *i.e.*, ratio of surface area to volume. In fact, the average surface force on one clay particle is several orders of magnitude greater than the gravitational force (Partheniades, 1962).

The relationships between clay particles and water molecules are governed by interparticle electrochemical forces. Interparticle surface forces are both attractive and repulsive. The attractive forces present are the London-van der Walls, which result from the electrostatic attraction of the nucleus of one atom for the electron cloud of a neighboring atom (Grimshaw, 1971). These electrical attractive forces are weak and are only significant when interacting atoms are very close together. However, the electrical attractive forces are strong enough to cause structural build-up as they are additive between pairs of atoms. The cohesiveness of fine-grain (cohesive) sediment such as illite or bentonite is a result of these electrical attractive forces.

The repulsive forces of clay materials, due to negatively charged particle forces, increase in an exponential fashion with decreasing particle separation. In fact, the net electrical charge on the surface of these particles is usually negative. An increase in the salinity, however, causes a decrease in the magnitude of the repulsive forces. It should be noted that even fine-grained particles that do not include strong physiochemical forces may behave in a cohesive manner (attraction between particles, *etc.*) because of naturally occurring coatings on the particles.

In contrast, gravitational forces are typically orders of magnitude larger than inter-particle forces for non-cohesive sediments.

sediment load is the mass of sediment being transported as both bedload and in suspension. This means that the river channel will undergo erosion, i.e., degradation. In a river with non-uniform bed material, the finer surficial bed sediment will be eroded more rapidly than the coarser sediment. By this process, the median diameter of the surficial bed sediment becomes coarser. If the degradation continues, the finer surficial bed sediment will eventually be depleted, leaving a surficial layer of coarser sediment, e.g., sand, over an underlying finer bed. This process is called armoring and the surficial layer of coarser sediment is called the armor layer (Yang 1996). Similar processes occur in estuaries and coasts, where waves also influence deposition and erosion processes.

The dominance of mud or sand in a given water body depends on many factors such as the sources of the sediment, gradient (i.e., bottom slope) of the water body, and the physical forces (e.g., tides, waves, winds, gravity) that cause water to move. Sources of sediment for rivers include uplands, ephemeral channels, streambanks, streambeds, and (in cold climates) ice-rafting. Sources of sediment for a lake or reservoir can include rivers and streams, and for estuaries and bays, sources include rivers and tide- and wave-induced currents from adjacent sandy or muddy shorelines.

In a water body dominated by sands, sand particles begin to move when flows overpower the resistance forces. Flow-induced forces are the bed shear stress that exerts a force on the surface of the sediment bed in the direction of flow, and a lift force caused by the difference in flow-induced pressure between the middle and top portion of a sediment particle. Physical processes that can generate a bed shear stress are currents and nearbed wave-induced water motion in the horizontal direction. Resistance forces (i.e., shear strength) are the frictional forces between sediment particles in contact with one another and the submerged weight of the particles (gravitational forces).

In a water body dominated by fine-grained (i.e., cohesive) sediment, erosion of the sediment bed occurs whenever the shear stress is great enough to break the electrochemical interparticle bonds (Partheniades 1965, Paaswell 1973) – see inset box. When this happens, erosion takes place by the removal of individual sediment particles and/or aggregates of clumped particles. This type of erosion is time-dependent and is referred to as resuspension. In contrast, mass erosion (i.e., the removal or entrainment of relatively large pieces of sediment) occurs more or less instantaneously. It occurs when the flow and/or wave-induced shear stress on the bed exceed the shear strength along some deep (i.e., sub-surface)-seated plane.

Sands do not consolidate after deposition, so their resistance to erosion does not change over time. In contrast, the erosion rates for fine-grained sediment beds are highly dependent on porosity (density). Decreased porosity enhances electrochemical interparticle bonds, resulting in increased resistance to erosive forces. Porosity of cohesive beds is generally a function of elapsed time after deposition and self weight consolidation (mass of sediment on top of a specific layer). Flow-deposited beds of cohesive sediment typically possess vertical profiles of density and bed shear strength (sediments lower in the profile are typically more dense). Bed shear strength is a direct measure of the sediment bed's resistance to a flow-induced shear stress at the bed surface. It is expressed as units of stress, e.g., pounds per square foot in English units and Pascals (i.e., Newtons per square meter) in SI units. Another term that is commonly used for this parameter is critical shear stress for erosion. Unlike that for non-cohesive sediment beds, the average values of bed density and bed shear strength in cohesive sediment beds typically increase over time and their vertical profiles change with time, primarily because of consolidation. Consolidation is caused by the weight of overlying deposited sediment that forces porewater upward in the bed, thereby increasing the bulk density of the underlying sediment.

In rivers and other water bodies such as estuaries, sediment beds will often be composed of a mixture of cohesive and noncohesive sediment. The percentage of cohesive sediment in any given water body that is dominated by fine-grain sediment often varies widely. Lick et al. (2004) found that percentages of fine-grained sediment as low as 2% in such beds can have a large effect on erosion rates because of the binding effect of cohesive sediment. That is, the cohesive sediment can serve as a kind of cement between particles of sand, and the result is that a higher force (i.e., bed shear stress) is required to erode the sediment. This demonstrates the importance of determining site-specific variation in grain size distributions and sediment erosion rates.

4.2 Sediment transport processes affecting erodibility

Sediment transport and erodibility are governed by the sum of natural and human impacts that impart mixing or erosive forces to the sediment bed, either through direct disturbance of the bed or by moving water. Table 4.2 is a list of possible natural and human disturbances from different types of impacts.

Because many contaminated sediment sites contain organic compounds that have a strong affinity for organic carbon and silts and clays, they are often located in areas of the water body that are primarily depositional, or in areas where only a limited surface layer of fine-grain (i.e., cohesive) sediment is routinely mobilized (USEPA 2005). This thin surface layer is sometimes called a fluff or benthic nepheloid layer, and is often less than 1 cm in thickness. Cohesive sediment and organic material in this layer are usually easily resuspended by tides, currents in rivers, vessels, or other forces. These sediments re-deposit when the kinetic energy of the gravity-generated currents, tides, waves, winds, or atmospheric pressure fronts (e.g., tropical storms) acting on the water body is reduced. The sediment below this surface layer, which can be composed of muds and sands as well as organic matter, is normally more consolidated. These consolidated sediments are more resistant to erosive forces because the increased packing produces stronger electro-chemical bonding between particles.

Table 4.2. Possible natural and human disturbances to the sediment bed.

Natural Disturbances	Human Disturbances
<u>Hydraulic impacts</u> • Currents, tides, wind waves, sieches • Storm events – high flows, waves, or surges • Breach of natural dams (*e.g.*, beaver dam, ice jam) • Flow and turbulence under ice cover <u>Direct impacts</u> • Activity of fish, waterfowl, and mammals (e.g., livestock walking down into streams) • Bioturbation and benthic activity (activity of organisms that dwell in or on the sediment bed) • Impact by debris or ice • Groundwater advection and gas ebullition	<u>Hydraulic impacts</u> • Hydraulic structure operations (locks and dams, sewer outfalls, *etc.*) • Watershed development (altered runoff and sediment loading) • Breach of dams <u>Direct impacts</u> • Commercial fishing • Vessel activity (including propeller, bow wake, anchoring, etc.) • Construction • Placement of fill or structural stone • Dredging/excavation

Highly concentrated sediment suspensions, also called fluid mud, can form just above the bed surface in depositional environments such as harbors and navigation channels. Fluid mud can move downslope under the action of gravity and normally behaves as a non-Newtonian fluid. Such movement is known as a gravity flow, which is the general term used for any case where a fluid and suspended sediments are kept in motion by the force of gravity acting on small differences in density. Turbidity currents denote density currents for which the excess density is produced by suspended sediment. It is important to account for turbidity currents, if present, in the SEDA. Detailed field measurements (description of which are beyond the scope of this document) are required to determine if fluid mud is present and whether the fluid mud is always stationary or if it moves as a gravity current under certain conditions.

It is important to differentiate between routine processes, which tend to only affect the surface layer, and extreme events, which may disrupt deeper sediment. Both routine processes and extreme events play an important part in understanding potential future exposure and risk for a given site. Routine processes should be understood and quantified because they affect the rate of potential natural recovery of contaminant concentrations in fish, water, and sediment. However, sediment erodibility under extreme event conditions is one of the primary considerations in evaluating the permanence of in-place management options such as engineered capping and thin-layer capping of dredged residuals.

A shear stress acts parallel to the surface of the sediment bed, whereas a normal stress acts in the vertical direction. Currents generate horizontal shear stress, while waves induce shear and normal stresses. Normal stresses applied to a cohesive sediment bed may decrease bulk density, and therefore the bed shear strength, and ultimately lead to liquefaction of the bed. Liquefaction results from the loss of the yield strength of an intact sediment bed. It occurs when shear and normal stresses exceed the yield strength up to some depth in the sediment bed. The sediment bed above this depth is liquefied. The yield strength, which is a bulk property of the sediment, is characterized by the Bingham-plastic yield stress (Barnes et al. 1989).

5 SEDA Methodology

Prior to collection of any new data, project scoping should be completed, and then a thorough compilation of existing data should follow. After these two components are completed, new data collection efforts usually include bathymetric surveys, hydrodynamic assessments, geomorphic assessments, sediment characterization, and an evaluation of anthropogenic impacts. Although the order and emphasis of the tasks included in the SEDA methodology can be modified for a particular site, project scoping and data review should always be performed before the others.

5.1 Project scoping

For efficient data collection, it is important to coordinate the collection of critical data for the SEDA with other RI/FS data collection activities. Project scoping includes formulating key site-specific questions (e.g., what is the spatial extent of the buried deposits of heavily-contaminated sediment?) that will reflect the level of study expected and form the basis of the SEDA's DQOs. Study questions should focus on identifying the most relevant information needs concerning the SEDA for remedial decision-making. Careful framing of the study questions during the SEDA, and their refinement as the CSM evolves, will greatly facilitate the comparative analysis of alternatives in the FS and the subsequent decision making. Site-specific information that should be considered when scoping the SEDA is given in Table 5.1.

Table 5.1. Site-specific information to consider in scoping the SEDA.

- Availability of historical data, including geomorphic assessment data.
- Understanding of site characteristics, including geomorphic setting (i.e., landforms, processes associated with the site) and classification, sediment and contaminant properties, and sediment dynamics provided from existing information.
- Probability of natural events that may impact sediment erodibility (increased flow, large waves, storm surge, ice-induced scour, tropical storms, etc.).
- Potential human activities that may impact sediment erodibility (navigation, construction, land use, etc.).
- Sediment and contaminant sources for the potential remediation area.
- Transport of contaminated sediment into and out of the site.
- Historic and future use of hydraulic control structures such as dams, etc.

5.2 Current and historical site information review

Historical site information may include a study of past events, or may be simply a compilation of relevant, available site information such as that listed in Table 5.1. All available hydrologic, hydraulic, geomorphic, sediment, and contaminant data should be thoroughly reviewed along with the anthropogenic uses of the water body (e.g., shipping, recreation). These data sets are invaluable in determining: a) sources of sediment for the site; b) spatial (both horizontally and vertically) extent of contamination, both within the water body and its floodplain; c) concentrations of contaminants; and d) changes in contaminant concentrations with time. Useful sources of information are: water quality studies; flood insurance studies; bathymetric and topographic surveys (including navigation channels); hydrodynamic measurements (parameters measured include flow rates, current speeds, water surface elevations, water densities); ecological studies of aquatic and floodplain habitat; geomorphic assessments; and modeling. For example, most riverine Superfund sites are parts of rivers that have been monitored for decades by the US Geological Survey (USGS). These data can generally be found online. Unless significant changes have occurred to the watershed or water body since the previous data collection, these data generally represent site conditions and can be extremely valuable for the SEDA.

Sediment bed data (e.g., grain size distributions and bulk densities) collected at the site or in proximity to the site can normally be directly used in the SEDA. Historic bed data may reflect existing conditions if the bed is in relative equilibrium, or in cases where the bed only evolves significantly during relatively large events and no such event has occurred since the earlier sampling. Recent data are needed to determine if the historic data reasonably represent present conditions. Sources for these data (given below as well) may include the USGS, the National Oceanic and Atmospheric Administration (NOAA), USEPA, US Army Corps of Engineers (USACE), and state environmental and natural resource agencies.

In addition, a historic geomorphologic classification (e.g., drowned river valley) and assessment of the water body should be conducted, followed by an evaluation of the timeline and description of system modifications, such as dams, revetments, bridges, dredged channels, or other structures that may have impacted the flow regime, and, therefore, the sediment transport in the water body. Case studies by Fitzpatrick (2005) and Fitzpatrick et al. (2008) provide useful examples in which new and historic data sources were compiled to elucidate a river system's history of streamflow, sedimentation, and sediment chemistry.

A variety of historic data resources are described below.

Federal Government agencies:

- U.S. Army Corps of Engineers (USACE): One way to gather historic dredging and bathymetric data is to contact the USACE District Office. If maintenance dredging is or has been performed in this water body, ask for copies of dredging surveys, or check the following web site (http://www.ndc.iwr.usace.army.mil/dredge/dredge.htm). Dredging records can be used to determine average sediment accumulation rates, areas of deposition, channel deepening, and areas of potential sediment column disturbance, which may be useful in the design of coring programs and interpretation of profiles. Although paper records of historic navigation surveys may not be available, more recent data are available digitally. Some of the most advantageous data may still reside in old research studies on development of the site. Besides navigation, USACE has an important role in managing many dams and reservoirs. Other government agencies that may manage important dams near or on the water body include the Department of Interior and the Tennessee Valley Authority.
- U.S. Geological Survey (USGS): The USGS maintains elevation maps and regional flood frequency studies for many navigable and non-navigable water bodies. The USGS Water Resources Division (WRD) office houses a list of gaging stations in the site's watershed. Also check the WRD web site (http://water.usgs.gov/) for information. On that web page, select the state in which the contaminated water body is located, and look for stage, discharge, sediment, and water quality data. The web site http://www.usgs.gov/pubprod/ provides access to most online USGS maps and products.
- NOAA: Go to http://www.noaa.gov and look for data on the contaminated water body. Nautical charts that contain bathymetric data are available online for all coastal areas, including the Great Lakes. Contact regional offices to find people who study specific water bodies.
- The federal government has a clearinghouse web site for geospatial data (http://gos2.geodata.gov/wps/portal/gos). This site is extremely valuable for collecting additional information/data about the site. There is also a website for bathymetry data: http://www.usgs.gov/science/science.php?term=80.

State agencies:

The State's Natural Resources and Environmental Regulation Agencies may have information and data on the contaminated water body. Also, if there are any bridge crossings in the area of contamination, check with the State's Department of Transportation for hydraulic information/data at the location of the bridge.

Local governments (city, county, etc.):

Extension agencies and water boards may have information and data on the contaminated water body. Authorities in charge of storm sewer outfalls often have relevant information on loadings.

Local and state universities:

The Colleges of Science and Engineering at local and state universities may have access to studies conducted by current or past faculty on the water body. University libraries may list all library holdings on their web site. This allows archives to be made of all holdings that contain the name of the contaminated water body or the name(s) of the Potentially Responsible Party (PRP).

County/city archives, libraries, and newspapers:

County/city archives, libraries, and newspapers may have articles on the source(s) of contamination, and records of previous floods, tropical storms, nor'easters, etc., that impacted the area of contamination (often anecdotal or qualitative information). Information on pre-restoration geomorphic assessments, river cross-section surveys, etc., and shoreland development may be found at these facilities as well.

Some private entities also have reason to collect data, e.g., industrial plants near the water body, port authorities, tug and ship operating companies, drinking water authorities (if there are surface water intakes), and sewage processing plants. In general, it is best to directly contact the person responsible for water quality issues.

5.3 Data collection to support a SEDA

Data needed to perform a SEDA and to develop a comprehensive CSM that considers sediment stability depend on the type of water body, the type of sediment present in the water body, and the forces that govern the motion of the water. The level of effort and amount of data required to perform the SEDA are site-specific and reflect the potential role that a SEDA could play in reducing uncertainties in site characterization and remedy selection.

5.3.1 Data needs for most sites

Table 5.2 gives examples of the types of data needed at most sites to perform a SEDA. Contaminant data collected during the RI will inform the SEDA (e.g., the distribution of contaminants in the sediment column compared to the time of contaminant release, if known), but guidance on assessing the nature and extent of contamination is available elsewhere. Table 5.3 charts the data needs in the context of common sediment management questions, indicating that these types of data are typically needed to address common remediation questions. Magar et al. (2009) also discuss several lines of evidence that can be used to assess sediment stability.

Table 5.2. Data needs for most sites.

Bathymetry and Topography
Water Surface Elevation
Flow Rate (discharge)
Current Velocity
Wave Properties (height, period, direction)
Wind Velocity
Salinity
Water Temperature
Sediment Bed Erodibility
Grain Size Distribution in Sediment Bed
Bulk Density of Sediment Bed
Settling Velocity of Cohesive Sediment
Suspended Sediment Concentration

Table 5.3. Typical sediment management questions and associated data needs (adapted from Blake et al. 2007).

Question	Site Characteristics (a)	Water Column Properties		Sediment Bed Properties			
		Waves, Tides, Currents	Suspended Sediment Concen-trations	Sediment Properties (b)	Sediment Erosion Properties	Sediment Accumulation Rate	Bioturbation
Could erosion of the sediment bed lead to exposure of buried contamination?	X	X (c)	X(d)	X	X	X(e)	X(f)
Could sediment transport lead to the redistribution of contamination within the site, or movement of contamination off site?	X	X	X	X	X	X(g)	X(h)
Will natural processes lead to burial of contaminated sediment by relatively clean sediment?	X	X	X	X	X	X	X
If a site is actively remediated, could sediment transport lead to the recontamination of the site?	X	X	X	X(i)	X(j)	X(k)	X(l)

(a) Water body configuration, bathymetry, sediment sources, contaminant sources, horizontal and vertical distributions of sediment bed contaminants, and anthropogenic activities, and frequency of extreme events.

(b) Particle size distribution, bulk density, and total organic carbon (TOC).

(c) For typical conditions and extreme events such as a 100-year storm.

(d) Are suspended contaminated sediments originating from buried sediment spreading within or beyond the site?

(e) Can an eroded site be replaced naturally by site-specific sediment accumulation characteristics without having to recourse to remediation?

(f) If the site is heavily subjected to benthic recolonization, will that foster sufficient bioturbation to further disturb eroded sediment?

(g) If the eroded site sediments are disturbed, would the sediment type reaccumulate/resettle beyond or within the affected site? Would existing natural sedimentation rates in the area negate the need for remediation?

(h) Bioturbation could potentially influence contaminated sediment transport from eroded sites.

(i) Sediment types and properties can determine the potential for transport and recontamination to the immediate site or beyond.

(j) Comment (i) applies equally here.

(k) Comments (i) and (j) apply here because the affected site sediment types and properties would influence the sediment accumulation rate (e.g., silt vs. sand).

(l) Bioturbation influences at the site would be a function of sediment types, and could contribute to recontamination at the site and beyond.

Rigorous controls are placed on data collection associated with any ongoing Superfund study. Therefore, data uncertainties are generally less than for historic data. The types of data and subsequent analyses listed in Table 5.2 are typically needed at multiple locations over time. Even then, the collection efforts will have limitations because of spatial domain or temporal constraints (for example, does the time period of data collection include a storm?). Examples of different types of data collection encompassing various temporal and spatial scales include:

1. Field sample analysis data: sediment or water column samples collected once or a few times at several locations in the water body. Water and sediment samples can be analyzed for suspended sediment concentration, temperature, grain size distribution, etc. Although these samples are usually at poor spatial and temporal resolution, they provide accurate values that can be retested.
2. Stationary time series data: Instrumentation is placed at one or several locations and left for some time period ranging from hours to years. Data collected include total suspended solids (TSS), bedload transport rates, flow velocities, and water level. Data are collected automatically, typically using acoustic and optical instruments. TSS values are back-calculated from optical backscatter. Water samples need to be collected for a range of TSS values in order to calibrate the relationship between optical backscatter and TSS. The instrument station is left unmanned, though routine maintenance and recalibration of the instruments are usually required. The data provide excellent temporal resolution, but are typically collected at only a few locations. If applied and maintained appropriately, velocity and water level data should be very accurate (inappropriate application or lack of routine maintenance/recalibration can result in noise or drift in the signal). Water column profiles of particle size distributions can be collected using a LISST (Laser In Situ Scattering and Transmissometry) device. This instrument relies on varying degrees of laser diffraction to differentiate between particle sizes.
3. Roving survey data: A survey vessel moves through the water body continuously collecting data. This is often performed with optical or acoustic velocity instruments (e.g., acoustic Doppler current profilers ADCPs) to provide cross-section velocity and TSS profiles. Multiple surveys may be performed under different flow conditions. The data cover a spatial area of interest, but provide poor resolution on temporal variability since the data are collected at a few snapshots in time.

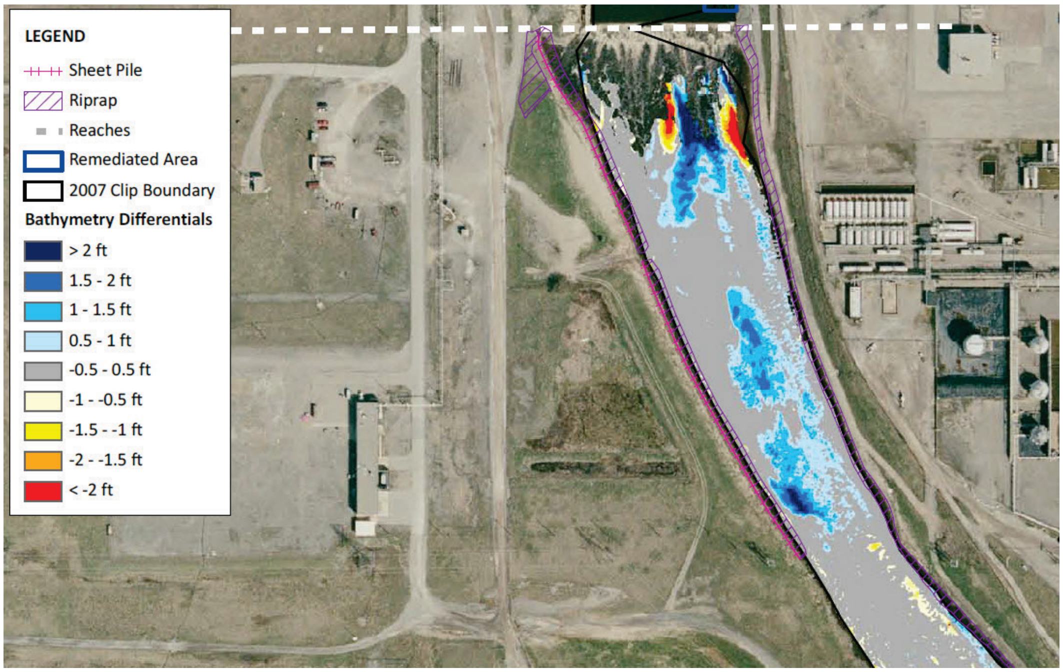
5.3.2 Bathymetric analysis

Bathymetric data reflect water body depth. Comparing bathymetric data over time will show changes from sediment accumulation, erosion, dredging, filling, or other actions. Bathymetric data exist for most US waterways. Bathymetric surveys are usually performed with sonar technology, e.g., multi-beam sonar systems. Underwater sound waves are emitted by surface vessels or towed underwater platforms. The emitted sound waves bounce back to recording units that record the lapsed time, which is then converted to water depth. Sonar software enables investigators to produce an image of the underwater environment, including features and bottom topography. The USGS, USACE, NOAA, and some state agencies collect bathymetric data in navigational channels and adjacent to shoreline or marine structures on large water bodies. The USACE collects data on navigable waterways. These surveys are generally at higher spatial and temporal frequency than NOAA charts, but are often confined to the navigation channel. USACE generally surveys channels before and after dredging. This can provide high-frequency data going back 100 years or more. However, available information may be confined to more recent, digital surveys. On smaller water bodies and on rivers, state transportation departments may have bathymetric records at bridge crossings.

A datum is a base elevation used as a reference from which to reckon water depths. Typical datums used in bathymetric analysis include the following: mean tide level (MTL), mean sea level (MSL), mean low water (MLW), mean lower low water (MLLW), and a geodetic datum such as the North American Vertical Datum of 1988 (NAVD 88). All bathymetric surveys are referenced to some datum, which may differ among surveys in the same water body and may change over time. The user must know the datum for each bathymetric survey used for historic analysis. Bathymetric data can be used to evaluate long-term sedimentation or erosion rates by determining the differences between two or more bathymetric surveys. In addition, comparisons of bathymetric data can be used to assess impacts of extreme events, e.g., out-of-bank floods, when surveys preceding and following events are available. These data help locate areas that are subject to erosion and deposition during extreme events.

Figure 5.1 is an excerpt from a differential bathymetry analysis at the Tittabawassee River, near Midland, Michigan (excerpted from Dow Chemical, 2011). Two bathymetric surveys were taken approximately 1 year apart and the surveys were compared to assess differences in sediment bed elevation. The figure provides a spatial depiction of areas undergoing deposition (positive differentials) and erosion (negative differentials) between survey periods. Areas with differences between +0.5 ft and -0.5 ft (gray shading in figure) were considered to be within the zone of measurement uncertainty.

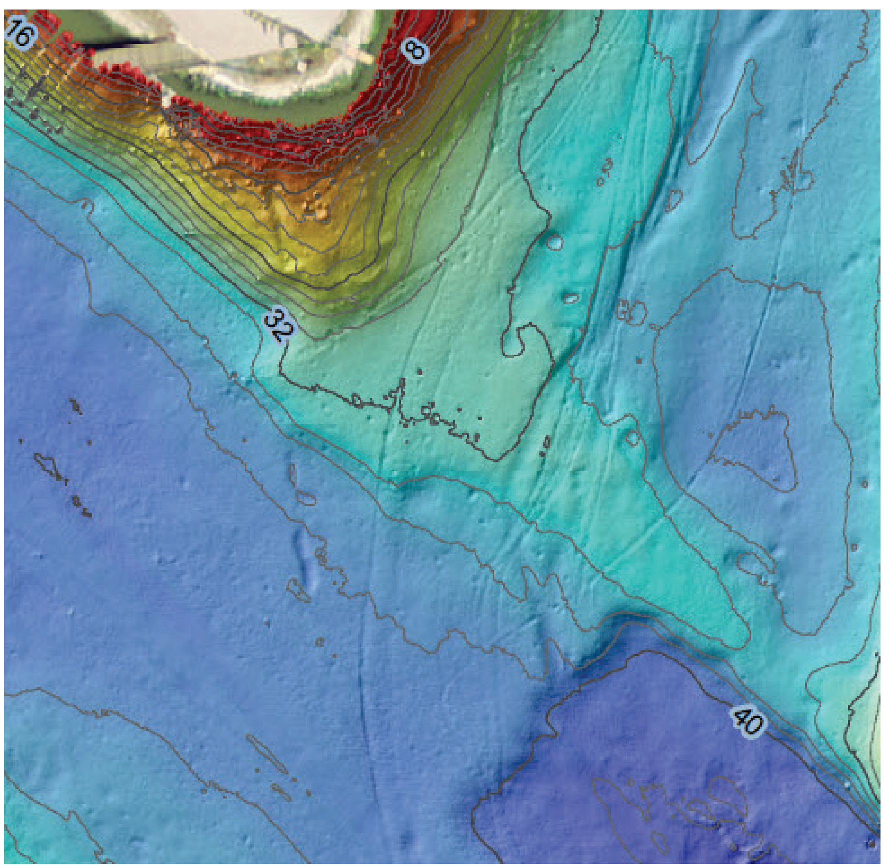
Figure 5.1. Comparison of bathymetric surveys performed in 2007 and 2008 in Reach E of the Tittabawassee River, Michigan. Source: Dow Chemical Company (2011).



When comparing bathymetric surveys it is important to quantify the uncertainty in both horizontal and vertical measurements, particularly if the bathymetric surveys were performed by different surveying contractors, used different vertical datums, or used different types of survey instruments (e.g., single-beam versus multi-beam echo sounder). There is typically a ±15-cm uncertainty band associated with bathymetric surveys made from a moving boat, which needs to be considered in calculations using repeated surveys. It is recommended that a site-specific assessment of measurement error should be conducted if the appropriate data are available. As an example, an average rate of deposition or erosion can be calculated as the difference in bottom elevation between two surveys at a given location, e.g., 25 cm of net deposition between two surveys 10 years apart results in a rate of 2.5 cm/year. Such a deposition rate should be strictly viewed as a 10-year average, and the uncertainty factors mentioned above need to be estimated and included in this average rate. That is, the 25-cm difference should be 25 ± 15 cm, or the difference between the two surveys at this location should be considered to be in the range of 10-40 cm. This gives a 10-year average deposition rate of 2.5 ± 1.5 cm/year. Interpretation of average rates of deposition and erosion must recognize that even at a location where the 10-year average deposition is 2.5 cm/year, erosion could have occurred during a single high-flow event. When the difference between two bathymetric surveys is not substantial, average deposition rates should be calculated more carefully, recognizing greater uncertainties.

Bathymetric data can also be used to elucidate bottom conditions and establish the types of forces that can impact sediment bed stability. For example, high-resolution bathymetry from multi-beam surveys can depict the presence of sand waves or anthropogenic impacts such as anchor pockets or prop wash scars. Figure 5.2, from near the entrance to an industrial harbor, shows the presence of linear furrows in the sediment bed likely related to ship movement. The terminus of the navigation channel can also be seen in the lower right of the figure.

Figure 5.2. High-resolution multi-beam bathymetry from an industrial waterway (figure provided by Sea Engineering Inc, San Cruz, CA).



The project team is strongly encouraged to consult USACE technical manual EM 1110-2-1003, “Engineering and Design - Hydrographic Surveying” (USACE 2002) before performing any analysis involving bathymetric surveys. This manual provides technical guidance for performing hydrographic surveys that support the planning, engineering design, construction, operation, maintenance, and regulation of navigation, flood control, river engineering, charting, and coastal engineering projects. The guidance provided in this manual can be applied to Superfund sites.

5.3.3 Hydrodynamic analysis

In riverine and estuarine systems, water flows will be the primary driver of sediment transport, so it is critical to develop a robust understanding of flow rates (i.e., hydrodynamics) and their variation during daily, seasonal, and extreme events. The USGS and NOAA maintain inland and coastal water elevation and flow gages for rivers, coastal regions, tidally dominated river reaches, lakes (not including the Great Lakes), and reservoirs. The USGS data are available at http://waterdata.usgs.gov/nwis/rt. NOAA gaging stations for tidally dominated areas include inland gages on coastal rivers, while others are directly on the coast. The USGS web site is designed for obtaining historic water elevation and flow rate graphics. State, county, water district, and other local agencies also maintain flow or water elevation data for various streams and rivers.

Flow rates in rivers and estuaries and water elevation data are very important in developing a CSM. These data can provide a better understanding of the range of flow conditions expected. This range of conditions will help define the potential for event-induced erosion. For rivers and estuaries, it is important to know the frequency of flow events or high-water levels over the period of record. The maximum event on record or the 100-year storm event may be the “design event” needed to model the impact of an extreme event on the sediment bed.

For estuarine or coastal contaminated sediment sites, tidal forces, including water level fluctuations with storm events, should be considered. Tidal records are available from NOAA’s website and others. In estuarine settings where river flow is not a dominant hydraulic influence, water velocities associated with extreme tides or storm surges are needed to perform the SEDA. Historical tide gage records should be reviewed during the SEDA to be aware of past extreme events.

Wave records are useful in assessing storm histories for coastal contaminated sites. Historic and current water level and wave data for coastal regions (including the Great Lakes) are available from NOAA at http://www.ndbc.noaa.gov. These data are excellent for assessing the impact of tide-induced flows as well as coastal storms, e.g., tropical storms and nor'easters, and seiches and storm surges in the Great Lakes. NOAA buoys are generally located offshore, but data are extrapolated to nearshore conditions in many cases). NOAA performs this extrapolation for hundreds of coastal locations (benchmarks) and the data are available online. Besides NOAA, organizations with shoreline facilities (port authorities, shipping companies, industry, etc.) often maintain elevation databases. The NOAA website provides a link to some of these data, but RPMs may need to contact them directly to obtain additional data. For example, in a study at New Bedford Harbor, Massachusetts (Hayter et al., 2014), 20-year time series of wind and tidal current data collected from NOAA web sites were used to drive a wave transformation model and calibrate a hydrodynamic model.

Relevant hydrodynamic events may also include ship passage and maneuvering. Shipping generates hydrodynamic forces through propeller wash, bow wakes (that can travel to shore), thrusters, and increased velocity under the ship. In addition, tugboat and ship maneuvering can cause extreme local scour within berthing areas. In berthing areas (or locations where a ship runs aground), ships and tugs often use thrusters and propellers for positioning. This causes excessive local scour because the ship or tug is stationary. As an example, the Final Feasibility Study for the Lower Duwamish Waterway, Seattle, Washington, calculates local scour from ships and tugs to estimate the exposure concentrations of the contaminants of potential concern at the bottom of the scour hole. As a component of that study, ship passage through the Lower Duwamish Waterway was monitored using logs of bridge openings to quantify the number, duration, and frequency at which large vessels enter and move through the Lower Duwamish Waterway (AECOM Technology Corporation 2012). RPMs should talk to local operators to gain information on operations and to determine whether or not they regularly generate visible plumes.

Another issue at many contaminated sediment sites is suspension of sediment induced by recreational craft. Contaminated sediment can deposit in low-energy, shallow areas frequented by recreational craft.

While these craft produce much less energy than large ships, the propeller proximity to the sediment bed is a sediment erodibility issue.

For reference purposes, an introduction to hydrodynamic modeling is given in Appendix D. This includes basic information on fluid mechanics, driving forces of flows in surface waters, turbulence, hydrodynamic governing equations, scale analysis, and types of hydrodynamic models. Hydrodynamic models are well-developed, and many sites can benefit from hydrodynamic modeling and analysis. For example, hydrodynamic modeling can be used to determine residence times of dissolved contaminants, and identify areas of the water body that would be expected to be erosional and/or depositional during simulated flow events. The latter can be determined using a contour map of flow-induced bed shear stresses that can be generated from hydrodynamic models.

5.3.4 Geomorphology assessment

Rivers and other water bodies with moving water are constantly changing. Over time, the geometry and bathymetry of a river will respond to environmental and man-made changes. For example, river meanders may be cut off, riverbanks may erode, and river bottoms can be scoured or filled, i.e., undergo degradation or accretion. These processes occur over various timeframes, spanning from hours to centuries. Understanding past changes in a water body helps to estimate future changes. In contaminated sediment management, that historical understanding is a critical line of evidence when seeking to predict the future disposition of contaminated sediment deposits (i.e., is a deposit likely to be eroded or buried?).

For contaminated sediment sites, geomorphology is primarily concerned with the study of the characteristics, configuration, and factors influencing the long-term evolution of the sediment bed and surrounding landforms. Sedimentation patterns as well as stratigraphy and sediment bed dynamics may be highly variable within a site, especially for rivers, estuaries, and nearshore sites with large variation in water depths. Appendix B provides an introduction to one methodology for riverine-based geomorphology, classification, and channel evolution and succession. In addition to the methodology described in that appendix, assessments and evaluations are available for other environments (e.g., Dickson 2003).

A geomorphology assessment performed during a SEDA should consider local and watershed-scale processes governing formation and ongoing geomorphological changes in the water body. Examples of local scale factors include a) bar formation; b) scour zones; c) accretion or degradation of nearshore shallow areas, channel infilling/dredging; and d) bank erosion. Some of these local factors can have far-reaching effects on sediment transport at a site. Example watershed-scale factors include change in sediment and water loadings from changes in land use. Some examples of these factors are a) managed agricultural crop lands that routinely disturb loose soils and apply contaminants that drain into adjacent aquatic environments; b) development of commercial industries on former agricultural lands; c) flood control projects; d) urbanized runoff; and e) navigation controls (locks, channels, jetties).

Over time, flows and sediment transport cause geomorphological changes in most water bodies owing to sedimentation, erosion, avulsion, and lateral migration. Landslides and bank erosion can also cause significant changes. These geomorphological changes may be accelerated or slowed by changes in the watershed or shoreline conditions, including anthropogenic changes. Historical site review should include an inspection of available mapping information including historical maps and air photos. A site visit will also yield useful information on shoreline changes. This type of information can be very important in performing the SEDA, especially when contamination resides in near-shore areas, e.g., banks, floodplains.

Several governmental agencies record shoreline or riverbank position over time. These historic records are often available through user-friendly GIS systems and online aerial imagery. Historic shoreline or bank position data are invaluable in understanding past system evolution and in performing the SEDA. This can be especially dramatic for meandering rivers where cutoffs and new meanders develop over time; other rivers demonstrate very little lateral migration and geomorphic evolution over time. Many rivers and estuaries have anthropogenic controls for erosion, such as dams, hardened shorelines, and surge barriers that were developed to stabilize geomorphology and reduce flooding. In these cases, bank erosion or contamination of the floodplain is less probable. Rivers flowing through unconsolidated materials can exhibit active channel meandering. In some cases, riverbank profiles may actually be available from multiple surveys over time to assess bank succession. Where bank changes are of particular importance, such as when the banks contain contaminated sediment, various survey methods may be used to monitor bank changes. Erosion pins are one such method, where stakes are placed and the elevations and changes in the bank profile are monitored and resurveyed over time.

5.3.5 Sediment stratigraphy

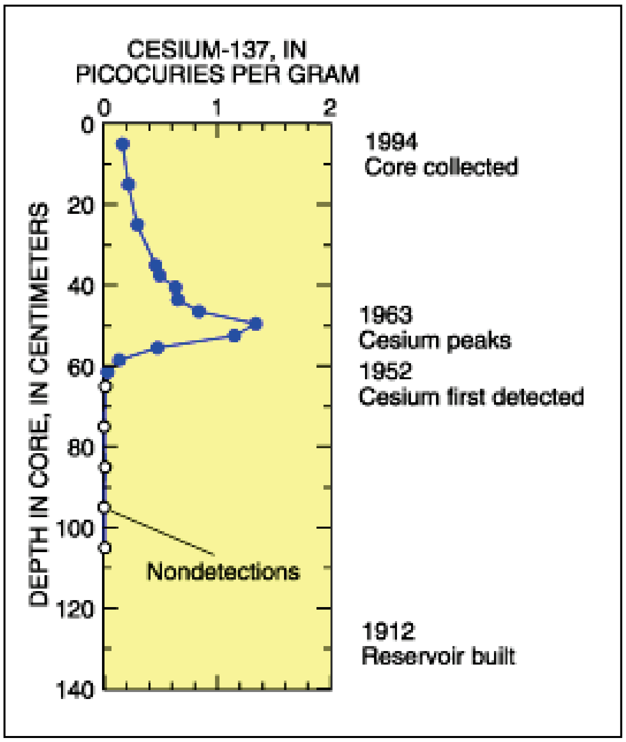
Sediment stratigraphy refers to the characteristics and ordering of layers in the sediment bed. Sediment stratigraphy is useful for interpreting long-term erosion and deposition processes, as well as possible changes in the size and source of sediment coming into a site over time. If combined with floodplain features, such as abandoned channels, it gives an idea of lateral and vertical stability of the channel. The stratigraphic record can provide useful information about deposition patterns. Stratigraphy is especially useful when it can be compared to radio-dated sediment cores from which geochronology of the sediment can be inferred. High-flow events that have had a significant impact on sediment transport may be revealed as distinct bands of sediment in the core that depend on the types of sediment in transport and the flow velocity during the event. However, later events can disrupt the record of earlier events. Any interpretation must be mindful of the potential for misinterpretation of radio-dated sediment, particularly given the relatively short (geologic) timeframe under consideration. Stratigraphic interpretations should include a thoughtful and comprehensive examination of all data. For example, cores are strongest if tied to elevation surveys and in a nest of cross-sectional and longitudinal transects.

A Sediment Profile Imaging (SPI) camera can be used to help characterize the stratigraphy and the physical and biological condition of surface sediment (usually the top 10 to 15 cm). The camera is pushed into the sediment bed and provides an in situ view of the sediment structure, e.g., layers of sediment strata, and possibly benthic organisms, feeding tubes, etc. These data can be helpful in determining the potential erodibility of the sediment bed and provide information on benthic communities.

5.3.6 Geochronology analysis

A geochronology analysis uses depth profiles of radioisotope measurements to estimate sedimentation rates by radio-dating layers in the core. Geochronology analyses are generally conducted using three types of radioisotope data: cesium-137 (^{137}Cs), lead-210 (^{210}Pb), and beryllium-7 (^{7}Be). Each radioisotope provides a specific type of geochronologic information. For example, the peak level of detectable ^{137}Cs in sediment occurred in 1963. The best estimate of the long-term average sedimentation rate for a particular core is computed by dividing the depth of sediment between the sediment surface and the buried ^{137}Cs peak by the number of years between 1963 and the time of core collection. For example, Figure 5.3 shows a ^{137}Cs peak 50 cm below the top of a core. Since the core was collected in 1994, the average sedimentation rate would be calculated as 50 cm/31 years = 1.6 cm/yr.

Figure 5.3. Vertical profiles of ^{137}Cs from the Trinity River, TX. Distinct ^{137}Cs peak is seen at a depth of 50 cm into the core (after Land et al. 1996).



The structure of the ^{137}Cs profile may also provide insights into the sediment transport environment at the core location. The relative "sharpness" of the profile around the ^{137}Cs peak is indicative of the strength of mixing processes in the surface bed layer, e.g., a sharp, well-defined peak generally suggests a relatively low rate of surficial mixing (see Figure 5.3). However, a broad, poorly-defined peak suggests a relatively high rate of mixing, lack of significant deposition, or dredging events that, in general, make it nearly impossible to interpret radioisotope data.

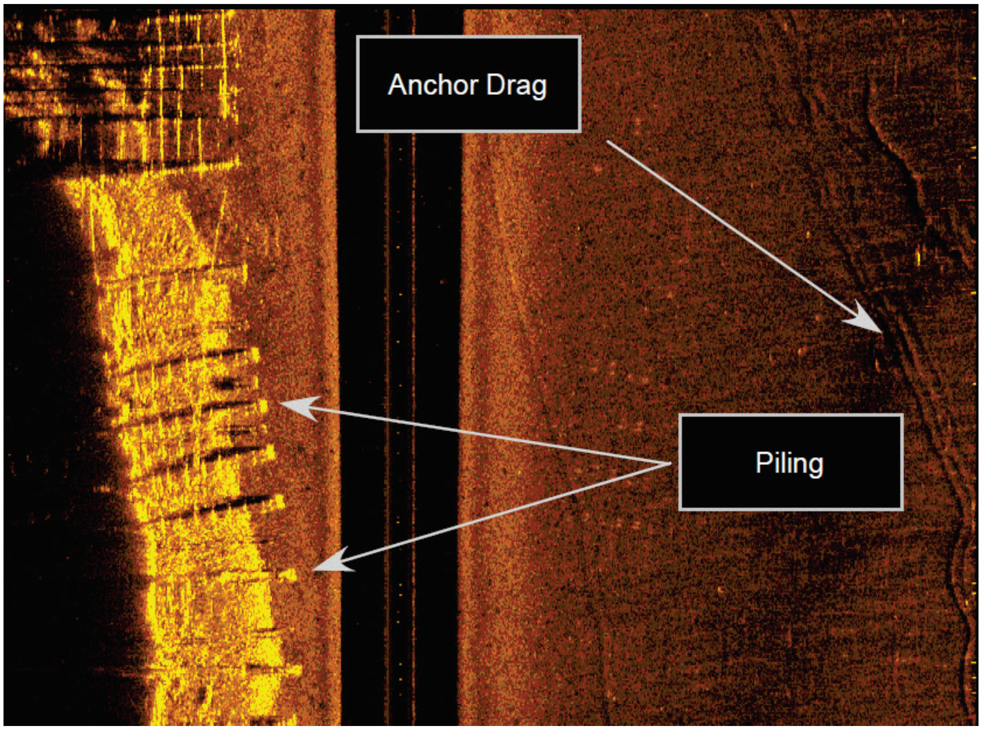
While lead and cesium can provide independent estimates of deposition rates over the past 20-50 years, beryllium-7 (^{7}Be) is only useful for indicating recent deposition and possible mixing in the top bed layer over a period of months because of its half-life of 53.3 days. The degree of short-term mixing can be estimated from the maximum depth of occurrence of this isotope. The uncertainty implicit in geochronology analysis needs to be considered when the results of these analyses are used.

5.3.7 Evaluation of anthropogenic impacts

At many contaminated sediment sites, the sediment bed is not in a natural state, i.e., it is not being modified by solely natural processes. River and estuarine systems where contaminants are present as a result of industrial activity are typically altered by dredged navigational channels, bridge abutments, bulkheads, hardened structures on banks, etc. These structures may have localized impacts (e.g., depositional areas immediately downstream of large bridge piers), or large-scale impacts (e.g., dam control of water levels, or dredged navigational channels). In some cases, the trend is toward reversing prior construction, e.g., to remove dams on some rivers. Elsewhere, construction is planned with new shipping terminals, bridges, etc. In addition, land-use changes (from new construction/development in the watershed of the contaminated water body to runoff of agricultural fields and urban areas) may result in an increase in the load of contaminants and sediment transported to the water body during big rainfall events. These historical or planned changes are important when using historic data to understand future behavior; compiling these changes over time will be helpful in understanding the potential impacts of extreme events when developing the SEDA. Stratigraphic data (see below) may indicate past erosion or deposition events that are no longer possible at this site. As such, anthropogenic activity needs to be considered when analyzing stratigraphic records during the SEDA.

Information collected to support a SEDA can also be used to establish the extent of anthropogenic disturbances in localized areas. For example, physical disturbances such as keel drags, anchor drags, spud holes, and other impacts to the sediment bed can be readily visualized using multibeam bathymetry (Figure 5.2) or side-scan sonar (Figure 5.4). These data can be used to indicate the location, magnitude, and density of sediment bed disturbances under current uses. Figure 5.4 is an excerpt from a side-scan imaging report for the Willamette River, Portland, Oregon (Anchor QEA 2009). The figure shows the presence of anchor drags and pilings; the black vertical strip is the area under the boat (not observable with side-scan) in the direction of travel.

Figure 5.4. Side-scan imaging of sediment bed conditions.



5.3.8 Measuring sediment erodibility

To better estimate the location and depths to which sediment will erode, sediment erodibility usually needs to be quantified at several locations throughout the site for each type of bed sediment characterization. This need especially applies at sites where the contaminated sediment is not in an isolated, low-energy environment such as a protected harbor. Table 5.4 summarizes some of the more common research and commercially available methods that can be used to measure sediment erodibility parameters. All of the devices measure the critical shear stress of erosion and the erosion rate; the primary differences between them are related to whether they can be used in situ and whether they can measure sediment erodibility below the surficial sediment layer. SEDFLUME (McNeil and Lick 2004), ASSET, and SEA WOLF have advantages over other devices such as Sea CAROUSEL (Maa et al. 1993) and FLUME (a straight flume, Ravens 2007). The former group of devices allow erosion rates, critical shear stresses for erosion, and bulk densities to be determined with depth into the sediment bed. The other devices are only capable of determining the erosion rate and critical shear stress of the bed surface. At sites where contaminated sediments occur at depth, SEDFLUME is recommended over the other devices. It needs to be noted that no erodibility measurement technique is without disadvantages.

Table 5.4. Comparison of various sediment stability measurement devices (adapted from Blake et al. 2007).

Device	Flow Conditions (over sediment surface)	In situ	Ex situ	Transport Measured	Crit. shear stress	Erosion Rates*	Sediment Type	Depth Measured	Shear Stress Range
Straight Flume	Linear/ Oscillatory	Yes	Yes	Total load	Yes	Yes	Clay/silt/ sand	Surficial layer	0-4 Pa
Annular Flume/Sea Carousel	Linear	Yes	Yes	Suspended load only	Yes	No	Clay/silt/ sand	Surficial layer	0-1 Pa
Shaker	Unknown	No	Yes	Suspended load only	Yes	No	Clay/silt/ sand	Surficial layer	0-1 Pa
SEDFLUME	Linear	No	Yes	Total load	Yes	Yes	Clay/silt/ sand	0-1 m	0-10+ Pa
ASSET Flume	Linear	No	Yes	Suspended and bedload	Yes	Yes	Clay/silt/ sand	0-1 m	0-10+ Pa
SEAWOLF Flume	Linear/ Oscillatory	No	Yes	Total load	Yes	Yes	Clay/silt/ sand	0-1 m	0-10+ Pa

*The erosion rate column in this table is interpreted in this manner: a 'yes' indicates that the erosion rate of the sediment bed is explicitly measured, whereas a 'no' indicates that the erosion rate is calculated as a function of the measured suspended sediment concentration.

Disadvantages of using SEDFLUME and the other devices as well include: 1) results vary to a small degree when different operators use them; and 2) when the results are to be used in a sediment transport model, interpolation of the results from a relatively small number of cores (usually less than 20) to the entire water body introduces an unknown degree of uncertainty.

SEDFLUME (Figure 5.5) is a field- or laboratory-deployable flume for quantifying cohesive sediment erosion (McNeil et al. 1996). It is constructed of clear polycarbonate materials to permit observation of sediment-water interactions during the course of erosion experiments. Figure 5.6 includes a photograph of the flume, a close-up photograph of the test section, and a table of flow rate/shear stress relationships.

Figure 5.5. Schematic illustrating operating principles of SEDFLUME. Pictured are SEDFLUME channel, flow development region, testing section, and sediment core.

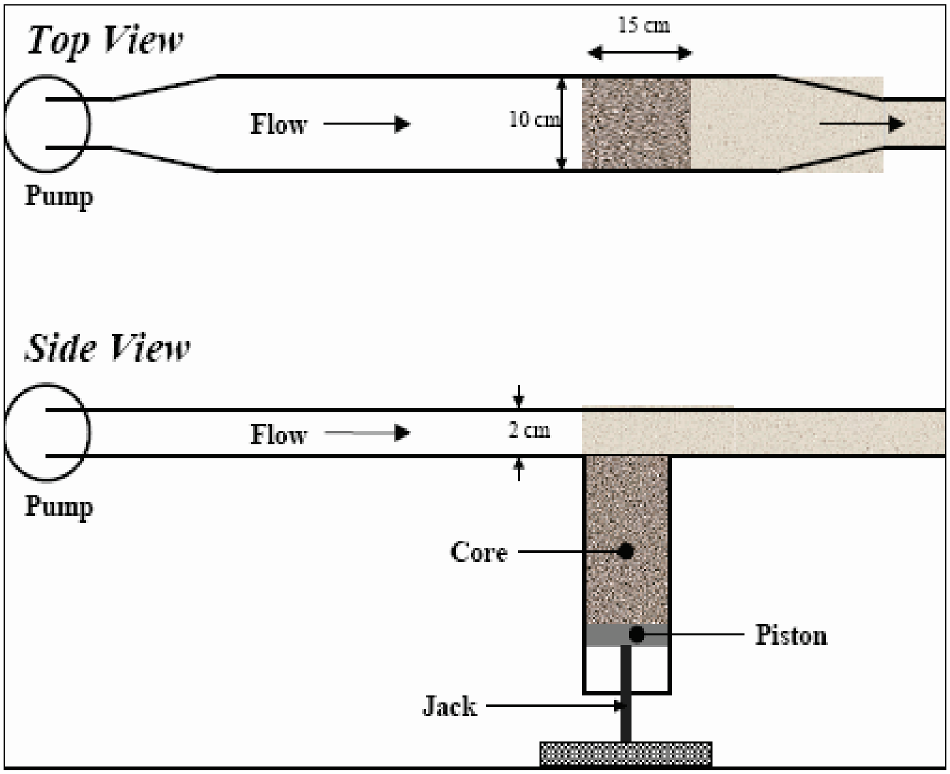
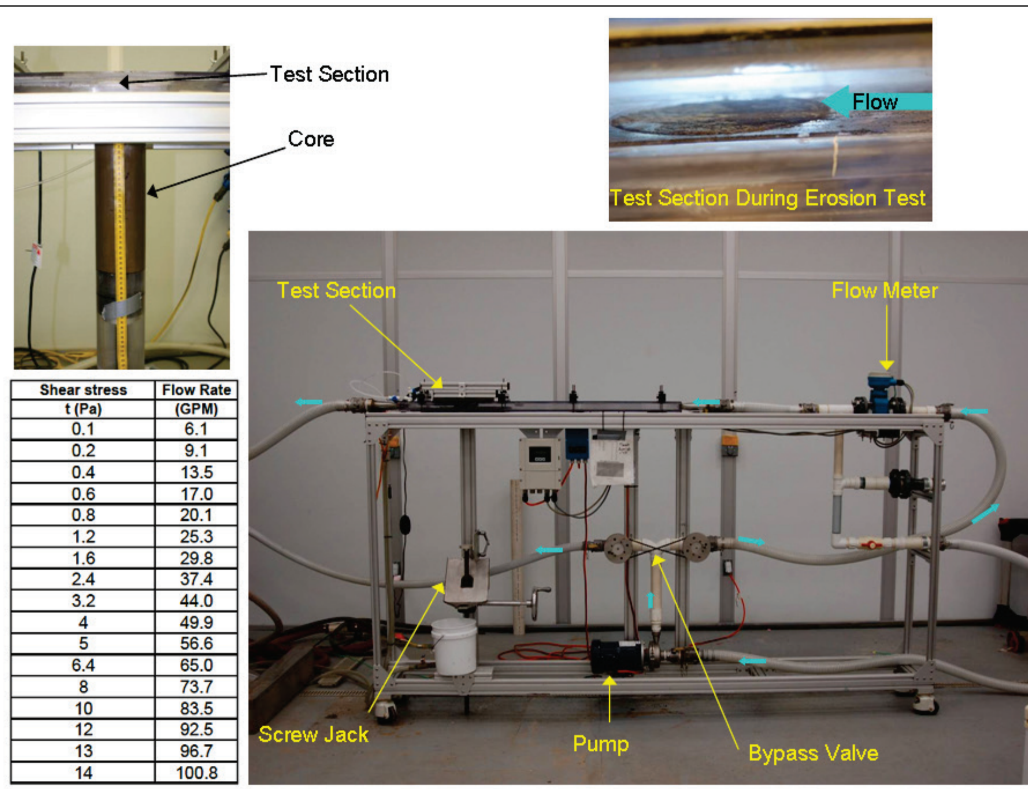


Figure 5.6. SEDFLUME.



Shear stress t (Pa)	Flow Rate (GPM)
0.1	6.1
0.2	9.1
0.4	13.5
0.6	17.0
0.8	20.1
1.2	25.3
1.6	29.8
2.4	37.4
3.2	44.0
4	49.9
5	56.6
6.4	65.0
8	73.7
10	83.5
12	92.5
13	96.7
14	100.8

To date, SEDFLUME has been applied at several Superfund Sites, including those listed below.

Region 1:	Derecktor Shipyard, RI Gould Island, RI Housatonic River, MA New Bedford Harbor, MA
Region 2:	Ackerman's Creek, NJ Berry's Creek, NJ Gowanus Canal, NY Lower Passaic River, NJ Lower Grasse River, NY Maurice River, NJ Newark Bay, NJ Newtown Creek, NY
Region 3:	Holston River, TN
Region 4:	12 Mile Creek, Lake Hartwell, SC
Region 5:	Kalamazoo River, MI Fox River, WI
Region 6:	Patrick Bayou, TX San Jacinto River Waste Pits Superfund Site, TX
Region 9:	Palos Verdes Shelf, CA United Heckathorn, Lauritzen Channel, CA Hunters Point Shipyard, CA
Region 10:	East Waterway, WA Lower Duwamish Waterway, WA Portland Harbor, OR

The ASSET and SEA WOLF flumes listed in Table 5.4 are specialized versions of SEDFLUME. The ASSET flume can be used to measure sediment core resuspension rates and the ratios of bedload to suspended load transport (Roberts et al. 2003, Jepsen et al. 2010). The SEA WOLF flume is capable of measuring resuspension rates of sediment cores under the action of both a unidirectional current and waves (Jepsen et al. 2004). Thus, a SEA WOLF flume should be considered for use in relatively shallow water bodies when wind-generated waves are identified as one of the processes that could resuspend the sediment bed.

5.3.9 Measuring sediment settling velocity

The settling velocities of cohesive sediment are a function of factors such as the salinity of the water, the mineralogy of the clays present, the fraction of organic matter suspended in the water column, and the concentration of suspended matter. As discussed in detail in Appendix B, small amounts of salts (i.e., on the order of 1–3 parts per thousand) are sufficient to repress the electrochemical surface repulsive forces among the particles, with the result that the clay particles coagulate to form flocs. Depending primarily on chemical properties of the clay minerals, flocs can form even in fresh water. Each floc can contain thousands of clay particles. The settling velocities of cohesive sediment are also a function of the structure and density of the flocs. As such, settling velocities of cohesive sediment cannot be predicted using a universally applicable equation such as the one used to predict the settling velocities of noncohesive sediment. Ex-situ measurement of the settling speeds of cohesive sediment should be performed at sites where the CSM reveals that the transport of the fine-grain sediment is a significant factor in understanding the transport and fate of contaminants.

One method that can be used to measure the settling velocities of cohesive sediment is the Particle Imaging Camera System (PICS) that was developed at the Engineer Research and Development Center (ERDC) to measure in situ floc sizes and settling velocities (Smith and Friedrichs 2010). To date, PICS has been used at the New Bedford Harbor Superfund Site; Mississippi Sound, Mississippi; Grays Harbor, Washington; and San Francisco Bay. PICS is similar to other video devices for insitu particle settling measurements such as the IN Situ SEttling Velocity instrument (INSSEV, Fennessy et al. 1994) and the visible (VIS) instrument (Van Leussen and Cornelisse 1993), Sternberg et al. (1996), Mikkelsen et al. (2004), and Sanford et al. (2005).

5.4 Evaluating sediment transport during a major hydrologic event

5.4.1 Determining hydrodynamic driving forces

Major meteorological and hydrologic events such as floods induced by rain or snow melt, tropical storms, nor'easters, and water level fluctuations in the Great Lakes usually have a very significant impact on the transport of sediment and associated contaminants. The vast majority of sediment transport in a given year usually occurs during these events. EPA often uses the 100-year-recurrence-interval event to represent extreme events for evaluating remedial alternatives. However, at some sites, the most extreme hydrodynamic driving forces may occur during an event with a smaller return period (for example, in river systems where flooding causes the flow to leave the channel, the most extreme hydrodynamic conditions may occur just before water overtops the riverbanks). Top-of-bank flow conditions in many rivers usually have a two-year or less return period. After a site-specific determination of what is likely to cause extreme hydrodynamic driving forces, it is important to quantify the hydrodynamics in the contaminated water body during these aperiodic events. To the extent possible, the parameters listed in Table 5.2 should be measured before, during, and after these events. It can be too dangerous to manually collect data from boats or sometimes even from land-based observation stations such as bridges during these events, so the data may have to be measured using in situ auto-samplers, e.g., bottom-mounted ADCPs and pressure gages, USGS gaging stations, local meteorological stations, etc.

5.4.2 Determination of sediment transport

Determination of the suspended sediment load and bedload, including the concentration and grain size distribution in suspension during major events, are important to estimate the fluxes, i.e., transport rates, of the associated contaminants during these major events. It is also possible through detailed analysis to determine the empirical relation between ADCP signals and the concentration of suspended sediment. Such a regression relation should not be the first choice, as the empirical relation could change with changing composition of suspended sediment throughout the event.

It is also advisable to perform a bathymetric survey immediately after a large event to have a direct measurement of changes in bottom elevations throughout the water body from erosion and deposition of sediment from the event. The survey can be used to help calibrate a sediment transport model (if one is needed for the site) and also in calculating the mass transport of contaminants during the event. However, as stated previously, when comparing bathymetric surveys, it is important to quantify the uncertainty in both horizontal and vertical measurements, particularly if the bathymetric surveys were performed using different types of survey instruments (e.g., single-beam versus multi-beam echo sounder), and consider this uncertainty when comparing the surveys.

5.5 Determining the level of analysis needed at a site

Level of analysis refers to the degree of quantitative analyses to be performed on both historic data and new data collected at the sediment site. For some areas and purposes, simple extrapolation from empirical data may be sufficient to support decisions; at others, a more advanced tool such as a numerical model may be needed. Project managers should use the following series of questions, as well as the information presented in the remainder of this section, to determine the appropriate level and type of analysis for a particular site:

- Have the SEDA study questions/hypotheses been determined? If not, these should be determined during the development of the CSM and before the SEDA is performed.
- Are historical data and/or simple quantitative techniques available to answer these questions with the desired accuracy? If not, a data collection program will have to be developed.
- Have the spatial extent, heterogeneity, and levels of contamination at the site been defined? If not, these data will need to be collected as part of the RI.
- Have both site-related and off-site significant ongoing sources of contamination and contaminant fluxes been defined?
- Do sufficient data exist to support the use of a particular level of analysis, and if not, are time and resources available to collect the required data to achieve the desired level of confidence in model results?
- If the project team decides to perform a mathematical modeling study, are time and resources available to perform the modeling study itself? These are especially significant factors for the project team to consider. Mathematical models, especially numerical models, are time-consuming to correctly develop and apply, and generally require input from experienced sediment transport modelers.

Modeling experiences at several sediment sites have resulted in the following three recommendations that the project team should consider: 1) because of the uncertain cost and time involved, development of new models should be avoided if at all possible; also, the simplest model that is sufficient to answer critical questions is preferred; 2) to ensure a successful and technically defensible modeling study, competent sediment transport modeling consultants should be contracted to perform the modeling project; and 3) uncertainties associated with the model should be estimated. This is usually more critical than model selection.

5.6 How to use collected data

Project managers may have data from numerous sources. The objective of the SEDA is to use these data to develop multiple lines of evidence, e.g., bathymetric changes and long-term deposition rates are lines of evidence that indicate the spatial extent of erosion and deposition. Spatial extent refers to distances in both the vertical and horizontal directions. Data sets from different years and locations can be analyzed in combination to develop lines of evidence and in performing a SEDA. Examples include time series of flows and suspended sediment concentrations, grain size distributions of bottom sediment located throughout the site, and sediment erodibility and settling velocity studies. Time series data will typically be collected at different times at multiple locations. This section outlines methods for selecting the data analysis method and the use of properly analyzed data.

5.6.1 Data analysis

Data analysis is a key component in optimizing the results of the SEDA. Analysis of individual and combined data sets is critical to improving the CSM and developing confidence in conclusions. Data analysis must recognize inherent uncertainties and limitations that are present in every data set. It is beyond the scope of this report to provide analysis methods for each type of data. In addition, data analysis is site-specific and should be approved by experts (similar to data collection). Data can be roughly categorized as follows:

1. Historic data (USGS flow rate, weather conditions, tides, bathymetric surveys, previous site studies, turbidity, historic system usage, extreme event frequency, etc.)

2. Study data that describe present conditions (sediment sample analysis, velocity data, TSS, flow rate, bed scans using side-scan sonar, bathymetry, erosion tests, settling tests, ship usage, etc.)
3. Forensic data – study data that identify previous conditions (sediment core stratification, geochronology, evidence of scarring or inundation, etc.)
4. Model data (use historic and study data to model future conditions)

5.6.2 Methods and limitations of interpolation of sparse data

A particularly complex area of data analysis for both model input and non-model lines of evidence is interpolation of both spatially and temporally sparse data (e.g., sediment bed data) over a large water body that needs to be modeled. Sediment transport models require a significant amount of data to initialize and parameterize the sediment bed. A numerical grid is constructed to represent the water body to be modeled. A grid is formed by dividing the water body into small rectangles or triangles, with each rectangle or triangle called a grid cell. The model will likely include thousands of cells. Each of these cells requires initial condition and parameter input. The easiest option is to have constant initial conditions, but few sites have constant sediment bed characteristics. Therefore, the project team needs to interpolate sparse data over the model sediment bed. Triangularization (i.e., interpolation) methods interpolate sediment property data (such as percent clay, silt, and sand; organic content; and bulk density) over a water body based on the three nearest field data points. This is an automated method, but it may not accurately represent the sediment bed. Sediment bed properties often follow pathways that may align, for example, with flow streamlines or bathymetric contours. Proper data analysis should include these features if they are discernible from the data set. Best professional judgment should also be used when interpolating data. An expert team is essential to this type of data interpolation. Sediment process parameterization data (i.e., erosion rates, consolidation, etc.) are generally not interpolated. In this case, the project team uses sediment property data, hydrodynamic conditions, and other relevant information to divide the water body into specific areas, each with the appropriate parameterization. The modeling team should perform sensitivity runs on various scenarios for sediment property interpolation and sediment parameterization regimes. Initialization and parameterization of the sediment bed will evolve as specific hypotheses inherent in the interpolation methods that are tested and retested. For example, using triangularization and inverse distance weighting to determine bed properties results in testable hypotheses that can be used to support methods for extrapolation.

The data sets described above provide lines of evidence relevant to a SEDA. Historic, forensic, and study-specific field/laboratory data are generally sparse and represent either specific locations (TSS measurements) or specific snapshots in time (bathymetric surveys). The project team generally requires an understanding of what is happening over the entire study site to perform a SEDA. Modeling is a method to extrapolate sparse data to the entire domain and time period of interest based on the best understanding of system dynamics and transport processes. As discussed in Chapter 6, a model is an approximate representation of what will likely happen to the system based on an understanding of hydrodynamics, sediment processes, and site-specific behavior of the water body. The modeling provides additional lines of evidence, similar to data analysis.

6 Predicting Future Conditions with Modeling

Model output may be used as a line of evidence in a SEDA. As described below, these models can range from simple extrapolation of past conditions to complex linked hydrodynamic and sediment transport models. Since predictions of future conditions are of such importance in sediment remediation, and models (of some sort) are necessary to predict future conditions, modeling lines of evidence are of great importance. This chapter discusses model uses and principles relating to the selection and application of models in a SEDA.

Sediment transport models are inherently limited by the current understanding of the physical factors governing these processes and the ability to quantify them (i.e., represent mathematically their interactions and effects on the transport and fate of sediment and contaminants). Even the most complex sediment model may be a relatively simplistic representation of the movement of sediment through natural and engineered water bodies. It may be simplistic because of:

- Limitations in understanding natural systems, as reflected in the current state of the science;
- Empiricism inherent in predicting flow-induced sediment transport, bank erosion, and nonpoint source loads;
- The relatively large space blocks and time-steps used for modeling the water body; and
- The inability to realistically simulate geomorphological processes such as river meandering, bank erosion, and localized effects (e.g., natural debris or beaver dams).

Nevertheless, sediment transport models generally are useful tools when properly applied, although they are data-intensive and require specialized expertise to correctly apply and interpret the results.

6.1 Model uses

In most cases, mathematical models complement environmental data and address data gaps. Examples of model uses at sediment sites include:

- Identifying data gaps during the initial stages of a remedial investigation;
- Illustrating how sediment properties and contaminant concentrations vary spatially at a site.
- Predicting sediment transport over years to decades, or during episodic, high-energy events (e.g., tropical storms or low-frequency flood events);
- Predicting future contaminant concentrations in sediment and water that can then be used to predict biota contaminant uptake. Model output can be used to evaluate relative (not absolute) differences in predicted effectiveness among the proposed remedial alternatives, ranging from MNR to dredging and capping; and
- Comparing modeled results to measurements to show convergence of information. Both modeling results and data have a measure of uncertainty, and modeling can help to quantify the uncertainties (e.g., through extensive sensitivity analysis) and refine estimates of remediation effectiveness.

When the model is used to predict the response of the system to various remedial alternatives, it is important to continue to test the model predictions by monitoring during the remedy implementation and post-remedy phases to assess whether cleanup of the site was accurately predicted by the model. Where it is not, the model should be modified or recalibrated and then used to develop more accurate future predictions.

If some level of mathematical modeling is appropriate, the following section can assist project managers in deciding the type of model that should be used.

6.2 Types of models

A sediment transport model typically is a mathematical representation, i.e., mathematical model, of the movement of sediment as governed by the driving forces (discussed in Appendix C) and other physical factors in water bodies. Mathematical models are a set of equations that quantitatively represent the physical processes and interactions identified by the CSM that govern the transport of sediment. Types of mathematical models include analytical, regression, and numerical, and are described below.

Analytical Model: Consists of one or more equations (e.g., simplified - a linearized, one-dimensional form of the advection-diffusion equation) for which a closed-form solution exists. This type of model may not be applicable at most sites because of the complexities associated with the hydrodynamics, and the spatial and temporal heterogeneities in sediment properties.

Regression Model: Consists of a statistically determined equation that relates a dependent variable to one or more independent variables. A stage-flow rating curve is an example of a regression model in which stage (e.g., water level) and flow rate (e.g., amount of water flow) are the independent and dependent variables, respectively.

Numerical Model: Consists of an approximate solution of the set of governing differential equations that is obtained using a specific numerical technique. Examples of numerical techniques include finite difference and finite element methods. A numerical model is used when the processes modeled are represented by nonlinear equations for which closed-form solutions do not exist.

Two general guidelines regarding the use of models are as follows:

1. Mathematical modeling is usually not warranted for small sites where cleanup may be relatively easy and inexpensive; and
2. Mathematical modeling is generally recommended for large or complex sites, especially where it is necessary to predict contaminant transport and fate over extended periods of time to evaluate relative differences among possible remedial alternatives.

The most complex numerical models are linked hydrodynamic and sediment transport models that represent systems using two- or three-dimensional grids. These models can be time-intensive and expensive to apply, and their use generally requires specialized expertise. Because of this, numerical modeling is not recommended for every site. It is recommended that USEPA (2009) be read by the project team before deciding if modeling is required at a particular sediment site.

6.3 How to determine the appropriate model level

When it is decided that a mathematical model is appropriate at a site, project managers should generally consider the following three steps in determining the level of modeling to use:

Step 1: Develop conceptual site model

As stated previously, development of a CSM should be the first step. If this step is not performed, then the appropriate level of modeling cannot be determined. This step includes defining the appropriate boundaries of the system to be represented in the CSM. The system boundaries will normally be far removed from the boundaries of the Superfund Site. Implicit in this step is the understanding that at least the first version of a CSM should be developed before deciding whether modeling is needed and, if so, what level of modeling is appropriate.

Step 2: Determine processes that can currently be modeled

This step concerns determining if the most significant processes and interactions that control the transport of sediment can be simulated with one or more existing sediment transport models. Numerical models can simulate most of the processes controlling the transport of sediment in water bodies. If it is determined that existing models are capable of simulating the most significant (i.e., first-order) processes and interactions, then the project manager should identify the types of models (e.g., analytical, regression, numerical) that have this capability. Models not having this capability should be eliminated from further consideration.

Depending on the needs at the site, models or model components (commonly called modules) may link many of the processes represented in the CSM. Examples of the processes that can be modeled include:

- *Land:* Physical processes that result in loading of sediment to water bodies may include point discharges from non-modeled tributaries, and nonpoint discharges via overland flow (i.e., runoff) and eroding banks.
- *Water column:* Physical processes that may result in movement of sediment include advective transport, diffusion, and settling of sediment particles. See Appendix B for a discussion of these processes.
- *Sediment bed:* Important physical processes include the formation of sediment beds from multiple depositional events, subsequent erosion during higher flows, and consolidation (or compaction) of sediment beds that contain a significant fraction of cohesive sediment.

If there are significant (i.e., first-order) processes and interactions that cannot be realistically modeled, then other tools may be needed to evaluate proposed approaches, or develop and test new models. Examples of processes that cannot be dynamically simulated, even using state-of-the-art sediment transport models, include geomorphological processes such as the development of meanders in streams and rivers, bank cutting/erosion, fluid mud formation and transport, and mud wave phenomena. However, there are empirical methods for simulating some of these processes, including estimating the total quantity of sediment introduced to a water body because of the failure of a river bank due to, for example, flow-induced erosion of the bank toe and/or surface, or cattle walking into and out of streams. Likewise, there are empirical tools to estimate the importance of fluid mud, or nepheloid layer transport (i.e., relatively high sediment flux occurring immediately above the sediment-water interface). Empirical tools and new mathematical models are currently under development to simulate mud wave transport processes resulting from wave-induced liquefaction, and sediment disturbances from dredging, as well as the dispersal, deposition, and resuspension of contaminated sediment residuals.

Step 3: Select an appropriate model

If one or more types of mathematical models capable of simulating the controlling transport and fate processes and interactions exist, then project managers should use the process described above to choose the appropriate type of model (i.e., level of analysis). If the decision is made to apply a numerical model at a sediment site, selection of the most appropriate sediment transport model is critical. During this process, familiarity with existing sediment transport models is essential. Though dated, a comprehensive technical review of available models was conducted by the USEPA (Imhoff et al. 2003).

6.4 Modeling procedure

The methodology for performing a technically defensible sediment transport modeling study is described in this section. When any type of numerical model is used, model calibration and validation should be performed. Definitions of these terms, along with that of model verification, as they are used in this document are provided here since they are used throughout this section.

Model verification: Evaluating the model theory, the consistency of the computer code with model theory, and the computer code itself for integrity in the calculations. This is an extremely important process for new models. Model verification should be thoroughly documented, or the model should be peer-reviewed by an independent party if it is a new model.

Model calibration: Using site-specific information from a historical period of time to adjust model parameters in the governing equations (e.g., bottom friction coefficient in hydrodynamic models) to obtain an optimal agreement between a measured data set and model calculations for the simulated state variables.

Model validation: Demonstrating that the calibrated model accurately reproduces known conditions over a different period of time than that used for model calibration. The parameters adjusted during the calibration process should not be adjusted during validation. Model simulations during the validation period should be compared to the measured data set. If an acceptable level of agreement is achieved, then the model can be considered validated as an effective tool, at least for the range of conditions defined by the calibration and validation data sets. If an acceptable level of agreement is not achieved, then further analysis should be conducted to determine possible reasons for the differences between the model simulations and data. The latter sometimes leads to refinement of the model (e.g., using a finer model grid) or to the addition of one or more physical processes in the model.

Recommendations and/or guidelines that should be considered when performing a sediment transport modeling study are discussed in the sections that follow.

6.4.1 Recommendations for performing modeling studies

Modeling experience at several sediment sites has led to the development of the following five general recommendations that the project team should consider:

1. Because of the uncertain cost and time involved, development of new models (i.e., new computer code) should be avoided.

2. To ensure a successful and technically defensible modeling study, experienced modelers should be contracted to perform the modeling project. This is usually a more critical step than model selection.
3. The extent to which components of a modeling study are performed using verified models can determine to a large degree the technical defensibility of the modeling project. However, if a verified model is used, but it is not sufficiently calibrated and validated for a specific site, then the modeling study may be of little value. Where possible, project managers should use verified models in the public domain, i.e., open source models, that have been calibrated and validated to site-specific conditions. Proprietary models may also be useful, but project managers should be aware that they contain computer code that has not been shared publicly and may not have been verified. The interpretation of modeling results and the reliance placed on those results should heavily consider the extent of documented model verification, calibration, and validation. All of this information should be considered when deciding whether a proprietary model should be used.
4. It is highly recommended that EPA and the PRP group use a collaborative approach to model development and use. For example, at the Lower Duwamish Waterway, a sediment transport modeling team (whose members consisted of modeling consultants for the PRPs and sediment transport experts providing technical support to EPA Region 10) operated on a consensus basis and was successful in developing a calibrated and validated model that was accepted by both EPA and the PRPs.
5. A phased approach to modeling is also highly recommended. With this approach, the decision to develop a sediment transport model is not made up front, i.e., before the SEDA is begun. The phased approach used at the Lower Duwamish Waterway site consisted of the following steps: a) develop a calibrated and validated hydrodynamic model; b) perform a sediment transport analytical study using results from the hydrodynamic model (e.g., predicted bed shear stresses) and a SEDFLUME study to estimate maximum scour depths at areas of high contamination; and c) develop the sediment transport model to reduce uncertainty in the analytical study results that were caused by simplifications made during the latter. The decision to perform the third step was made after the conclusion of the first two steps, and not a priori as is typically done. Following these three steps, researchers should implement the simplest modeling approach that is capable of answering study questions.

The following recommendations pertain to the performance of the modeling study, and the project team should ensure that their modeling contractor incorporates these steps in the modeling study.

1. Site-specific measurements of erosion properties (i.e., sediment bed erosion rates, critical shear stresses for resuspension, grain size distributions and bulk densities in the surficial bed layer as well as with depth into the bed), e.g., from a SEDFLUME study, and settling velocities of flocculated cohesive sediment should be made. These properties serve to reduce fundamental uncertainties in sediment transport modeling.
2. Mass balance analysis for water and sediment needs to be evaluated using model results to ensure that water and sediment mass are adequately conserved during model simulations. This analysis should be performed at every site, and is absolutely critical for models that simulate water bodies in which extensive wetting and drying of mud flats, tidal marshes, or river floodplains occur.
3. All assumptions made in the model framework (e.g., simulated morphologic changes owing to erosion and deposition in the water body do not have to be dynamically linked to the hydrodynamic model) need to be justified based on the physics/chemistry of the system modeled. A decrease in model runtimes is not a technically defensible reason to use decoupled hydrodynamic and sediment transport models.

6.4.2 Model setup, calibration, and validation

Steps involved in setting up a sediment transport model include the following:

1. Choose an appropriate model domain. A modeling domain is normally a rectangular area that encloses the spatial extent of the water body to be modeled. The domain includes both the water body and surrounding land. Two guidelines for choosing an appropriate modeling domain are the following:

    - Open-water boundaries should be sufficiently far removed from the area of interest in the water body.
    - Open-water boundaries should be chosen where boundary values are known or can be measured.

    Model domains are discussed in further detail in Appendix D.6.

2. Develop the computational model grid that has sufficient resolution in proximity to the sites of interest. Numerical models require the use of either a grid or mesh to represent the chosen model domain. A grid is a series of interconnected quadrilaterals that cover the entire domain being modeled. A mesh is a matrix of nodes that cover the entire domain, and either triangular or quadrilateral elements are formed by connecting three or four nodes, respectively.

3. A sensitivity analysis should be performed on the chosen grid resolution to determine the optimal resolution required to be able to successfully calibrate and validate both the hydrodynamic model and the sediment transport model. In some cases, the hydrodynamic model cannot adequately represent flow phenomena such as density-stratified flows owing to vertical salinity gradients in estuaries and temperature gradients in lakes and reservoirs using the chosen numerical grid. When this occurs, the grid resolution should be altered to improve the agreement between the model and the data. Compromises in grid resolution usually need to be made to ensure satisfactory agreement and reasonable model runtimes.

4. Hydrodynamic model setup is described in Appendix D. For sediment transport modeling, the user must provide input for sediment process parameterization and initialization. Sediment boundary conditions must also be provided. Most sediment transport models for cohesive sediment will require input that parameterizes processes (erosion, settling speed, and consolidation for each class of sediment) and initializes the sediment bed (composition of each layer, thickness, and erosion parameterization). Model grid and bathymetry are input as part of the hydrodynamic model. Most sediment transport models run on the same grid or mesh as the hydrodynamic model. Sediment transport models typically assume an initial suspended sediment and concentration (SSC) of zero. Concentration increases as sediment is eroded from the bed or introduced by sediment sources (boundary conditions). At each boundary that includes a sediment load, the user is expected to provide a time series of suspended solids load for each class of sediment. For 3D models, this load can be vertically stratified, i.e., a time series of SSC must be provided for each water column layer. Model setup is site and model specific.

Most sediment transport models include guidance that steps the user through model setup.

5. One method to demonstrate confidence in modeling, which itself can be considered a line of evidence, is model validation. Several data sets (that may be used to develop one or more lines of evidence) are typically used to initialize, calibrate, and then validate the model. After calibration and validation, model simulations are performed to predict future conditions.

   During calibration and validation, model results are compared to appropriate independent data sets, i.e., one data set is used for model calibration and another data set is used for model validation. Geochronology data are sometimes used for model validation as they provide an understanding of annual sedimentation rates and possible erosion events (disruption in the geochronology). These data are compared to model predictions to determine whether the model appropriately predicts sedimentation rates at various locations in the water body. Another validation example is the comparison of suspended solids field data to model simulation data for the same time period. It is not uncommon for multiple data sets to be collected at different time periods so that sufficient data exist for model calibration and independent validation. Analysis of data for model validation is inherently site-specific. Interpreting which portions of the model are validated is site-specific, as well.

   When calibrating and validating the model, it is important that both processes be conducted at the space and time scales associated with the questions the model must answer. For example, if the model will be used to make decade-scale predictions, then, when possible, model simulations should be compared to decade-scale data sets. Even when data exist for a much shorter time period than will be used for prediction, it is recommended that the long-term behavior of the model be examined as a part of the calibration process. It is not unusual for a model to perform well for a short-term period, e.g., a few months, but produce unreasonable results when run for a much longer duration, e.g., one or more years.

   Proper data analysis and comparison to model results is critical to demonstrate sufficient confidence in model predictions. Once this confidence is developed, managers can use model-generated lines of evidence for the SEDA.

6.4.3 Sensitivity and uncertainty of models

Sensitivity analysis is another important and widely used tool for understanding model results. This process consists of varying a select number of input parameters by a fixed percent (and within a reasonable range of expected values) while holding the other parameters constant to quantify how the model predictions vary. The resulting variations in the state variables are a measure of the sensitivity of the model predictions to the parameter whose value was varied. This can be very informative, especially in understanding how the various processes modeled affect sediment transport. This analysis is frequently used to identify the model parameters having the most impact on model results, so that the modeling team can ensure these key parameters are well constrained by site data.

Uncertainty in models usually results from one of the following:

- Use of equations that are simplified approximations of complex processes, which results in uncertainty in how well these equations represent the actual processes;
- Unknown accuracy of the values used to parameterize the equations (i.e., uncertainty in how well the input data represent site conditions); and
- Uncertainty in the physical conditions (e.g., future hydrologic and meteorologic conditions, changes in land use) used in models for evaluating remedial alternatives.

Typically, uncertainty analyses focus on only the second source, the accuracy of the input parameters. While quantitative uncertainty analyses are possible and practical to perform with watershed loading models and food chain/web models, they are computationally not possible at present for fate and transport models. An issue intrinsic to conducting uncertainty analyses is that the uncertainty bounds for each parameter are estimates, with their own associated uncertainty. One common method that modeling teams might consider to assess uncertainty is the use of bounding calculations to produce a conservative model outcome to compare to the model's best estimate outcome. This is typically accomplished by performing an extensive sensitivity analysis using multiple model runs to bracket the uncertainty. This model outcome can be developed using parameter values that result in a conservative result, but at the same time do not result in degraded model performance, as measured by comparison to the calibration and validation data sets. A second method of assessing uncertainty involves quantifying “model error” by comparing model results to the data used for model calibration and validation, and then applying that error to model predictions, as described in Connolly and Tonelli (1985).

It is important to view the uncertainty analysis and associated results in an appropriate context. Uncertainty and sensitivity analyses evaluate model output when parameter values are varied; they do not depict the degree to which future predictions will accurately depict observed conditions. Model output is essentially a best estimate based on model setup and performance through past conditions. The validity of that estimate is contingent upon how well the model represents the simulated environment, and a scenario in which the forcing conditions (e.g., river flows) do not vary significantly past those seen in the calibration and validation period. Meeting these two criteria represents a fundamental challenge when considering long time frames in dynamic systems and post-remediation scenarios. Thus, this document emphasizes the use of modeling as a line of evidence rather than an absolute predictor.

7 Using SEDA Results to Make Site Decisions

7.1 Structured decision-making based on the SEDA

A SEDA is performed to support informed remedial decisions, in combination with other information and in light of the NCP criteria (see Figure 7.1). A SEDA can support development and evaluation of remedial alternatives by gathering and assessing evidence of sediment erosion and deposition within the site to improve the CSM. At an early stage of data collection and CSM development, the set of remedial options under consideration often includes removal, capping, MNR, ENR, and in situ treatment. By collecting additional information about erosion and deposition, the SEDA can address information gaps concerning relative effectiveness and support informed management decisions.

Figure 7.1. Using SEDA results to select a remedy.

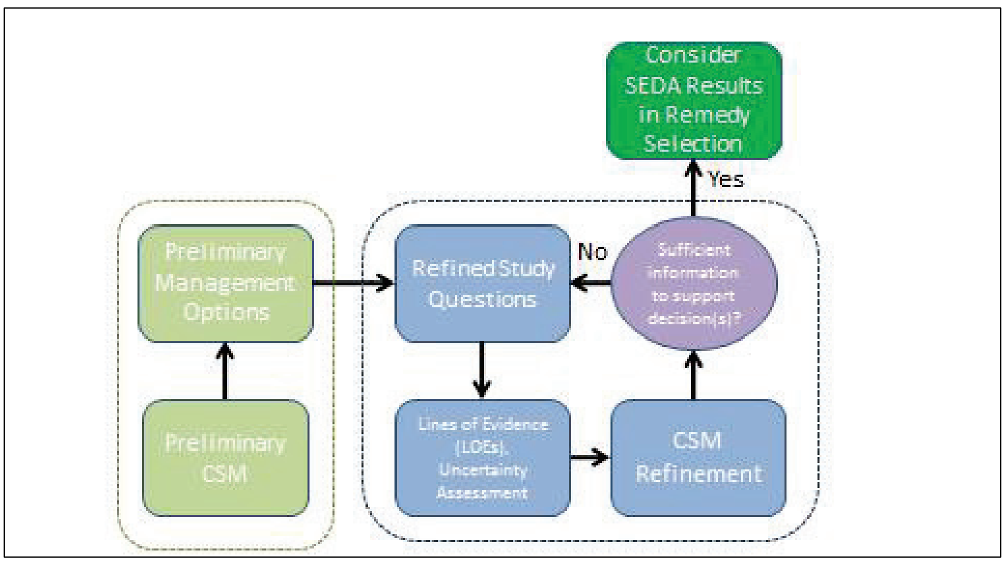


Figure 7.1 illustrates the formulation of study questions, based on a preliminary CSM and considering a range of remedial options. The SEDA assembles lines of evidence (LOEs) to answer those questions, as discussed earlier. Drawing upon the LOEs and taking uncertainties into account, the CSM should be refined and the preliminary set of remedial options should be further developed. For example, the SEDA may identify the portions of a site where a particular remedial option or technology may be suitable, and

may indicate combinations of technologies that should be evaluated. While the SEDA will indicate whether environmental conditions are appropriate for the application of various options, the SEDA should not be used alone to eliminate alternatives from consideration. The SEDA contributes to the selection of a remedial alternative, supported by strong evidence and with uncertainty reduced to an acceptable level. If additional information needs to be obtained to make a decision, after conducting a first round of SEDA studies, the process can be iterative. As Figure 7.1 shows, refined study questions can be posed to address remaining uncertainties, LOEs can be fortified, and alternatives can be further evaluated.

Consistent with DQO principles, the planning of the SEDA is explicit about the nature and boundaries of information needed to answer study questions, formulating decision rules that help to evaluate alternatives per the NCP criteria, reducing uncertainty to an acceptable level to support decisions, and optimizing data gathering.

In practice, and consistent with *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA* (USEPA 1988), remedial decision-making proceeds from development and screening of alternatives, to the detailed analysis of alternatives, to remedy selection. A SEDA can inform each stage of decision-making, but would typically be conducted in parallel with development and screening of alternatives in a feasibility study.

7.2 Developing remedial options and study questions

7.2.1 Using the initial CSM to evaluate remedial options

During an RI, information is gathered on contaminant extent and distribution, fate and transport, exposures, and risks. As this information is assembled and interpreted, a CSM is developed that represents the environmental system and the processes that determine transport of contaminants from sources to receptors. The development of the CSM is an ongoing process, where uncertainties and information gaps are continually identified, additional information is collected, and the CSM is refined.

An important use of the CSM is to identify and narrow the range of potential remedies that are deemed most appropriate for a given site. The universe of remedies for contaminated sediment sites includes dredging, capping, MNR, ENR, and in situ amendments, often in combination for different areas of the site. Not all will be suitable candidates for a particular site or a specific location within a site, and it may be possible to screen out some of these alternatives. For example, MNR may not be appropriate for a discrete area with very high surface exposures. For other areas, shallow waters with the potential for propeller wash may make capping as a stand-alone remedy (i.e., without dredging first) unsuitable.

At many sites, the potential impact of sediment erosion and deposition will have significant influence on the suitability of a remedial approach. Understanding erosion and deposition potential is an important element in selecting candidate remedies, especially with respect to long-term effectiveness and permanence, ease of implementation, and cost. It is usually possible to frame the need for additional information in specific study questions such as the following: "To what extent will an extreme event disrupt natural recovery that is occurring at the site?" The SEDA assembles information needed to answer the study questions, using the information obtained to refine the CSM. Section 7.2.2 presents common examples of sediment transport issues that arise in selecting remedies for contaminated sediment sites, along with study questions that can help support a remedial decision. By providing answers to these questions, the SEDA can help narrow the list of alternatives that need to be fully evaluated relative to the NCP criteria.

7.2.2 Formulating study questions to refine the conceptual site model

While no two sites are the same, there is a set of study questions that very frequently present themselves in connection with remedy selection, and can be addressed in the RI/FS, at least in part, through a SEDA. Some study questions, such as "What will contaminant levels be in future deposited sediment?" are relevant to any remedy. Other questions can help define whether specific remedial approaches are appropriate for a site and should receive further consideration. Six examples are discussed below in connection with MNR, capping, and dredging as prospective remedies. Of these, the questions related to MNR are the most commonly raised and are often critical to remedy evaluation and selection.

7.2.2.1 Questions related to monitored natural recovery

> <u>*MNR-1*</u>*: Available data indicate that exposures to surface sediment concentrations do not pose unacceptable risks, but that buried sediment concentrations are substantially higher and would pose*

unacceptable risk if exposed. What is the likelihood of erosion of the surface layer and resulting exposure of the buried sediment?

To address this question, a SEDA assembles evidence concerning extreme erosion events and the associated areal extent and depth of erosion, relative to the depth of burial of the more contaminated sediment. A decision rule could be developed to indicate that MNR is not appropriate for the area if material posing an unacceptable risk could be exposed during an extreme event having a reasonable probability of occurrence. EPA typically uses the 100-year-recurrence-interval event to represent extreme events for evaluation of remedial alternatives.

MNR-2: Available data indicate that exposures to surface sediment pose an unacceptable risk, but that new deposition of clean sediment is causing surface sediment contaminant concentrations to decline over time. What is the likelihood that concentrations will be reduced to acceptable levels in a reasonable time?

To answer this question, a SEDA can assess the magnitude and consistency over time of long-term burial rates and the depth of mixing, to evaluate the potential of clean sediment to dilute and bury contaminants over time and remain buried. A decision rule for including MNR as an alternative or part of a combination remedy (e.g., dredging and sand cover followed by MNR) could hinge on the strength and consistency of the evidence for natural attenuation of risks, including the measured rates of decline in surface sediment, water, and/or fish concentrations; the consistency over time in those rates; the magnitudes and consistency over time and space of measured sediment deposition rates; and the extent to which vertical mixing of sediment retards the process of contaminant burial.

A SEDA can also address the potential acceptability and relative effectiveness of capping and dredging remedies.

7.2.2.2 Questions related to in situ remediation

C-1: Available data indicate that an unacceptable risk from surface exposures could be mitigated by an engineered cap. What is the likelihood that the resulting risk reduction will be permanent?

To answer this question, the SEDA assesses the potential for erosion of an engineered cap to cause renewed exposures to contaminants. A decision rule could be established based on the extent of cap damage, re-exposure of underlying sediment, and subsequent risk resulting from the extreme event. If a threshold of cap damage were exceeded (e.g., based on acceptable levels of risk and/or operation and maintenance (O&M) needed to mitigate that risk), the alternative could be dropped from further consideration. The assumed event could be an extreme flow event, ice event, navigation event, or a combination, depending on local conditions and activities. The potential stability of a capping remedy may differ in some portions of the site, depending on differences in hydrodynamics, and these differences should be considered in assessing long-term effectiveness and permanence.

> *C-2: In situ amendments (e.g., activated carbon) added to the surface of the sediment bed, mixed directly into the sediment, or added as a component of the cap, could significantly reduce bioavailability. Is armor needed to prevent loss of the amendment materials owing to erosion?*

To address this question, a SEDA would consider the erodibility of the cap and amendment materials, especially where they are of a different density and/or particle size. A decision rule for inclusion of armor could hinge on the selective erodibility of the amendment material under extreme event conditions (such as the 100-year event) and the ability of armor layers to withstand erosion under the same event.

7.2.2.3 Questions related to dredging

> *D-1: Contamination often occurs in adjacent layers of higher and lower concentration. Dredging could remove a surface layer of higher concentrations, leaving in place a less contaminated "natural buffer layer" that covers another high-concentration layer that would pose unacceptable risks if exposed. What is the likelihood of erosion of the natural buffer layer?*

To answer this question, the SEDA characterizes the erodibility of the intermediate layer. The decision rule could specify that the expected depth of erosion of the natural buffer layer during an assumed extreme event, such as a 100-year flow, must be thick enough to ensure that the underlying high-concentration layer would not be exposed, with a reasonable level of certainty.

> *D-2: Sand backfill or a thin-layer sand cap could be used to reduce post-dredging residual surface contaminant concentrations to acceptable levels. How permanent is the protection provided by this cover in combination with any additional deposition of clean sediment, and how does this depend (if at all) on the thickness of the sand backfill layer?*

To address this question, a SEDA assesses the erodibility of the backfill layer under circumstances of an extreme erosion event, in combination with expected rates of burial and vertical mixing. In cases where the rate of burial with clean sediment is rapid, it may be appropriate to include this new sediment deposition when evaluating the effect of extreme events on the sand cover. The decision rule could hinge on the predicted movement or stability of the backfill material under the assumed event conditions.

7.2.3 Extreme events and long-term trends

As the examples above illustrate, evaluating alternatives from a sediment transport perspective often depends on assessing the potential effects of extreme events and on expected long-term conditions. In the examples above, five of the study questions required an understanding of the potential effects of extreme events, one example involved assessment of long-term trends, and one question involved both.

In order to evaluate the long-term effectiveness and permanence of a remedy, the potential impacts of extreme events should be considered. The magnitude of an extreme event and its effect on each prospective remedy should be assessed by considering physical processes and event data (preferably site-specific), and extrapolating observed erosive and/or depositional impacts to a reasonable maximum extreme event. Modeling is usually used to perform this extrapolation.

To assess long-term trends, the SEDA uses a combination of historical data, such as time series of exposure concentrations, bathymetries, and dredging records, and specialized tools, such as radionuclide dating. The availability of site-specific historical information may be limited. In addition, there may be apparent changes in trends over the long term, such as land-use trends, changes in precipitation patterns due to climate change, installation or removal of dams, or changes in the extent of navigational dredging. A forward-looking assessment takes such changes into account, comparing more recent data to data from periods preceding changes. If conditions are expected to change in the future (e.g., upstream dam removal or decreases in permeable watershed surfaces over time), modeling will be needed to depict expected conditions and the acceptability of remedial alternatives.

7.3 Using lines of evidence to answer the study questions

Once the remedial options and pertinent study questions have been identified, the next step is to apply components of the SEDA methodology to develop LOEs that can be used to further focus on and answer the study questions. The potential components of a SEDA methodology are described in Chapter 5. The extent to which each of these components is developed to support decisions for a particular site depends on the nature of the study questions, their importance in selecting the remedy, the spatial complexity of the site, and available resources. This section provides guidance on which SEDA components are most critical to answer the study questions from the previous section. The level of effort associated with specific SEDA components is also considered. Section 7.4 builds on the discussion by describing the process of evaluating the strength and uncertainty of the various LOEs for the SEDA to support decision-making.

The broad study questions framed in the previous section are fundamental for many contaminated sediment sites. Certain SEDA components will typically provide the greatest value in answering each of those questions, and therefore should be considered priorities when planning the SEDA in the context of available resources. These are discussed below. The following sections organize the discussion for specific questions related to MNR, capping, in situ amendments, and dredging remedies, respectively.

7.3.1 Questions related to monitored natural recovery

As discussed in the previous section, the following questions are pertinent when considering a potential MNR alternative:

- *MNR-1: Available data indicate that exposures to surface sediment concentrations do not pose unacceptable risks, but that buried sediment concentrations are substantially higher and would pose unacceptable risk if exposed. What is the likelihood of erosion of the surface layer and resulting exposure of the buried sediment?*
- *MNR-2: Concentration data indicate that exposures to surface sediment pose an unacceptable risk, but that concentrations are also*

declining over time. What is the likelihood that concentrations will be reduced to acceptable levels in a reasonable time?

In order to answer question MNR-1, LOEs should be developed to understand the likelihood, locations, and vertical extent of erosion occurring under various conditions in the water body (e.g., reasonably expected extreme events). In this case, the fact that the most highly contaminated sediments are buried below the surface provides anecdotal evidence that the site, or a particular area of the site, has experienced deposition subsequent to the time of greatest contaminant release and deposition. Historical site information, such as agency records and aerial photographs that document shoreline configurations and in-water structures, can be used to ascertain whether burial occurred primarily during infrequent episodic events (e.g., failure of an upstream dam), or whether burial processes have been more or less continuous during recent decades. If net burial of sediment has been ongoing and is expected to continue into the future, then the focus of the analysis should shift to evaluating the potential for extreme event conditions (including conditions associated with excessively high flows and severe tidal, wind, and ice conditions) to induce scour that might expose buried contaminated sediment. To assess the likelihood and extent of erosion during extreme events, the following should be estimated: 1) magnitude and duration of the extreme event condition(s), 2) bottom shear stresses associated with the extreme conditions during that time period, and 3) shear strength and erodibility properties of the sediment bed.

The magnitude and duration of an extreme event can be estimated by statistical analysis of relevant historical hydrodynamic and meteorological data sets. As discussed in Chapter 5, this analysis should also be informed by historical site information (e.g., introduction of flow control structures) to ensure that the time periods evaluated are appropriate for predicting future site behavior. Estimating the shear stress conditions produced by an extreme event is typically very challenging because historical monitoring data are unlikely to be available for conditions as extreme as the event(s) of interest. Available historical and/or current bathymetry data should be evaluated, preferably with more current or new bathymetry data sets. For riverine systems where downstream current velocity is the key driving force during an extreme event, it may be possible to use estimates of flow rates in conjunction with bathymetry data to infer bottom shear stress under the most extreme conditions that have been monitored. For these situations, a one-dimensional hydraulic model can also be applied with a relatively low level of effort to successfully simulate an assumed extreme flow. For systems where tidal dynamics and/or wind-wave action are the dominant forces during extreme events (e.g., in the case of estuaries, harbors, or lakes), a more sophisticated model, such as a multi-dimensional hydrodynamic model, may be needed (see Section 5.4 and Appendix B). Once calibrated and validated to water level and/or velocity data for the site, the model can be applied to simulate the extreme conditions and predict shear stresses.

The level of detail and effort required to evaluate the erodibility of the sediment bed will depend on the range of maximum shear stresses that occur throughout the site during events. If estimated shear stresses for the prescribed extreme event(s) are lower than typical *critical* shear stress values for the distribution of sediment particles present in the bed, then it may not be necessary to estimate or measure erosion properties for the bed. However, if event-driven shear stresses are expected to be near or higher than typical critical shear stresses, then developing site-specific estimates of sediment bed critical shear stress and erosion rates is important. If erodibility studies have not been conducted previously, then a new study using one or more of the techniques described in Section 5.3.8 should be considered. If sufficient resources are available, the hydrodynamic model discussed above can be used to drive a sediment transport model that provides the capability to simulate the depth of scour for the sediment bed based on predicted shear stresses and measured sediment bed erodibility properties (see Section 6.3).

The analyses described above can be used to evaluate whether it is likely that the sediment bed would be eroded under the assumed conditions to the point of exposing the highly contaminated sediment sufficiently to cause unacceptable risks. If exposure of this material is unlikely to occur in the future based on the SEDA, then MNR can be considered as an effective management alternative in the context of the SEDA. However, if the SEDA indicates that unacceptable exposure is likely at some point in the future, then MNR would be a less desirable option.

Answering question MNR-2 requires the following: 1) establishing the MNR mechanisms responsible for declining contaminant concentrations (e.g., burial as the major mechanism driving declining surficial concentrations), 2) estimating burial rates over the past few decades, and 3) identifying likely concentrations of the surficial sediment over time, considering the current and predicted contaminant concentrations of newly deposited sediment. As discussed in Section 5.7, sediment stratigraphy and geochronological analysis are tools that can be used to effectively identify deposition patterns and characteristics, including an estimated burial rate for net depositional locations. These evaluations may indicate a consistent long-term pattern of burial and dilution by clean sediment. Alternatively, these analyses may suggest that the site is not consistently depositional, and that reductions in surficial concentrations are the result of intermittent periods of erosion and deposition. In this case, the analysis is more complicated and may require more sophisticated approaches, such as in situ measurements of the magnitude of short-term erosion and deposition rates and/or the application of a sediment transport model.

If the analysis suggests that burial is the primary process driving the reduction in surficial concentrations, then it is important to estimate the burial rate and to understand the level of contamination associated with newly deposited sediment. The potential for short-term and long-term disruptions owing to infrequent extreme events and the likely impact on observed burial rates and recontamination should also be considered, using the approaches outlined for question MNR-1. Valuable data sets to obtain and analyze for contaminant spatial and temporal trends include vertical profiles of contaminant concentration in the sediment bed and water column concentration data. Note, however, that these evaluations fall outside of the SEDA methodology discussed in this document. In general, for areas that are identified as net depositional, it should be possible to combine burial rate estimates obtained through a SEDA with contaminant concentration information and trend analysis to estimate the time required for contaminant concentrations in surficial sediment to decline to acceptable values.

The analyses described above can be used to evaluate whether it is likely that concentrations in the surficial sediment over a given area would decline to a specific acceptable level over a prescribed duration of time. If the SEDA shows that burial is occurring and can be expected to occur at consistent rates in the future, then a reliable estimate of the recovery time is possible. If the recovery time projection is within an acceptable time range, then MNR can be considered as a potentially effective management option in the context of the SEDA. If burial is not occurring, or the rate of burial cannot be quantified with a high level of certainty, then the surficial sediment recovery time cannot be reliably estimated, and MNR would be a less desirable management option.

7.3.2 Questions related to capping

As discussed in the previous section, the following questions are pertinent when considering capping remedies:

- *C-1: Available data indicate that an unacceptable risk due to surface exposures could be mitigated by using an engineered cap. What is the likelihood that the resulting risk reduction will be permanent?*
- *C-2: In situ amendments (e.g., activated carbon) to the surface of the sediment bed, or mixed directly into the sediment, could significantly reduce bioavailability. Is armor needed to prevent loss of the amendment materials due to erosion?*

The risk reduction provided by placement of an engineered cap (e.g., armored sand) described in question C-1 could be compromised by several different processes: 1) erosion during extreme events resulting in exposure of existing contaminated sediment below the cap, 2) contamination of the cap surface with deposited (or re-deposited) sediment with high contaminant concentrations, or 3) recontamination from deeper buried contaminated sediment (i.e., resulting from mixing or dissolved phase transfer of contaminant mass via diffusion, groundwater advection, or bioturbation processes). Erosion during extreme events is relevant to question C-2 as well. The SEDA can be used to evaluate the potential importance of sediment transport components of the first two processes, in association with additional information provided by contaminant fate and transport analyses. The third process requires further information on advection and mixing processes within the sediment bed; this information falls outside the scope of the SEDA.

The potential for erosion of the cap and armor material during an extreme event can be evaluated using an approach similar to that described for question MNR-1. As for the MNR-1 case, evaluating the potential for erosion during an extreme event requires an estimate of: 1) the magnitude and duration of the extreme event condition(s), 2) the bottom shear stresses associated with the extreme conditions during that time period, and 3) the erodibility properties of the cap/sediment bed. If event conditions and bottom shear stress estimates were already developed based on data and modeling analyses to support an evaluation of MNR-1 (or for other reasons), the same information can be extended to help answer questions C-1 and C-2. The key difference relative to the MNR analysis is that to evaluate the erodibility of a cap, the SEDA must consider the cap design and characteristics of possible cap materials (including sand and armoring material and any amendments) instead of the existing, pre-remediation sediment bed.

Several approaches can be used to assess the erodibility of a proposed cap. For caps that do not have amendments, the existing sediment transport literature, including results from flume studies, can typically be used to evaluate erodibility potential. This approach is likely to be adequate for situations where sand and/or armoring materials of a specific size are planned. However, cap-specific measurements may be necessary for sand caps that have been significantly amended and therefore may have different erosion properties than the parent cap material. If resources and logistical considerations allow, an ideal approach to evaluate amended caps would be to conduct a pilot study by placing the cap and amendment materials over a small area. One or more cores could then be collected from that area and the erodibility properties could be measured using techniques such as the SEDFLUME studies described earlier. Alternatively, it may be feasible to create a representative synthetic core in the laboratory using appropriate mixtures and layering of the cap material. For either of these approaches, the objective is to quantify the critical shear stress and erosion rates for the matrix of cap materials, with a particular focus on the erodibility of the amendment material (e.g., activated carbon).

Similar to the other remedial options, it is important that potential contamination via deposition be evaluated, consistent with the general approach described above for question MNR-2. Key aspects of that evaluation include estimating the burial rate and the range of contaminant concentrations associated with suspended solids that deposit to the local sediment bed. Possible approaches for quantifying the latter include concurrent analysis of total contaminant concentration and suspended solids concentrations for water column solids and/or for material collected in a designed sediment trap.

Developing a decision rule for the armored sand cap described in question C-1 requires determination of a level of acceptable recontamination; for example, as a surface-weighted average concentration over a specific bioavailable depth interval (e.g., 0-10 cm). Once that threshold has been defined, the analyses described above can evaluate whether it is likely that contaminant exposure concentrations can be permanently maintained below that threshold level. If erosion potential is an issue, it may be possible to address that concern through the use of heavier armoring materials. However, if deposition of contaminated material is an issue, use of different armoring materials will not prevent exposure to that deposited material.

For question C-2, the decision rule to determine whether armoring would be required to retain the alternative of an amended sand cap can be based on the likelihood that the sand and amendment material will be eroded during future moderate to extreme events. If significant erosion of the amended sand cap is expected to occur, then specific options for over-cap armoring should be considered to prevent the cap from becoming compromised by erosion. As discussed above, the sediment transport literature can be used to provide information regarding the erodibility of aggregate materials that might be selected for armoring the cap.

7.3.3 Questions related to dredging

As discussed in the previous section, the following questions are pertinent when considering potential dredging remedies:

- *D-1: Contamination often occurs in adjacent layers of higher and lower concentration. Dredging could remove a surface layer of higher concentrations, leaving an intermediate "natural buffer layer" of acceptably lower concentrations, beneath which is another high-concentration layer that would pose unacceptable risks if exposed. What is the likelihood of erosion of the natural buffer layer?*
- *D-2: Sand backfill could be used to reduce residual surface concentrations to acceptable levels, in terms of risk, after dredging. How permanent is the protection provided by this cover in combination with any additional deposition of clean sediment, and how does this depend (if at all) on the thickness of the sand backfill layer?*

The risk reduction provided by dredging to a clean layer or placement of sand backfill could be compromised by several different processes, including: 1) erosion during extreme events resulting in exposure of existing contaminated sediment, 2) contamination of the sediment surface with deposited (or re-deposited) sediment with elevated contaminant concentrations.

Similar SEDA components can be used to assess the potential erosion of the natural buffer layer described in question D-1 or the sand backfill described in question D-2. For either case, erosion potential during moderate and extreme events should be assessed. This evaluation can be conducted using the approaches described above for both the MNR-related and capping-related questions. Question D-2 posits that ongoing deposition of cleaner sediment may occur following completion of dredging activities. Therefore, it may also be important to evaluate the burial rate, as this information is needed to estimate the thickness of the deposition layer at various time points in the future (e.g., 10 years after dredging). As discussed previously, sediment stratigraphy and geochronological analysis are effective data-based tools that can be used to estimate past and current burial rates, and to use those estimates to infer future rates of sediment burial at the site. Information about concentrations of deposited material, derived from contaminant fate and transport analyses, can inform whether that material would constitute a clean cover for the sand backfill.

With respect to question D-2, it is important that potential contamination via deposition be evaluated, consistent with the general approach described above for question MNR-2. Key aspects of that evaluation include estimating the burial rate and the range of contaminant concentrations associated with suspended solids that deposit to the local sediment bed. Possible approaches for quantifying the latter include concurrent analysis of total contaminant concentration and suspended solids concentrations for water column solids and/or for material collected in a designed sediment trap.

A decision rule for question D-1 could be developed based on whether a specific minimum thickness of the buffer layer can be expected to be maintained when subjected to an extreme event(s) following dredging, taking into account any changes in hydrodynamics from increased post-dredging water depth. Similar logic can be applied for question D-2, although the decision rule for that case would be based on the likelihood that the sand cover would be significantly eroded by the extreme event(s). A conservative assumption is that no additional sediment is deposited following implementation of the dredging remedy. This assumption ensures that the remedy is not compromised even if an extreme event(s) occurs immediately after implementation.

7.4 Assessing the strength/uncertainty of lines of evidence

The previous section describes the process by which the SEDA methodology is used to develop LOEs that help to refine and evaluate the relevant study questions. These LOEs are usually subject to a degree of uncertainty, requiring analysis and interpretation of the strength, consistency, and precision needed to answer the study questions. Even when LOEs are strong and clearly support a specific course of action, questions are raised regarding the applicability of the evidence to unusual or extreme conditions. This section describes the evaluation of uncertainty among LOEs, and how the likelihood and probable effects of infrequent events can be considered.

7.4.1 Evaluating the strength and consistency of the various lines of evidence

LOEs used to answer the management questions described in the previous section are sometimes consistent with each other and uniformly strong in their ability to support and strengthen a CSM and alternatives evaluation. However, LOEs are often ambiguous, or are actually in conflict: for example, contaminants are buried to significant depth, suggesting persistent ongoing burial processes, but the record of geochronological tracer data suggests some variability in historic deposition that cannot be explained by known past processes. Depending on the mix of data strength and consistency, unexpected or conflicting data will require different approaches in the decision process outlined in Figure 7.1.

Analysis of LOEs can result in a number of possible outcomes, ranging from strong, consistent evidence in support of a given CSM and answers to the study questions, to more ambiguous outcomes. Table 7.1 provides a simple matrix of possible decision scenarios, ranging from strong, consistent evidence in support of a given CSM, to more weak and ambiguous outcomes. In cases where LOEs are consistent and sufficiently strong to point to a single conceptual model for site behavior, or for specific areas within a site, site managers have a sound basis to proceed with decisions regarding appropriate remedial actions. Where LOEs are consistent but not strong and conclusive, the site manager may elect to

Table 7.1. Decision scenarios: LOE consistency and strength.

	Strength of LOEs	
Consistency of LOEs	Strong	Weak
Consistent	Proceed; include findings in detailed analysis	Collect confirmatory data before proceeding
Inconsistent	Reassess data and interpretations to choose between competing CSMs	Collect additional data to refine CSM

gather additional data to provide more assurance before finalizing a decision based on the CSM. In cases where the LOEs are inconsistent, next steps depend on the strength of the conflicting evidence. If there is strong scientific evidence in apparent support of competing site models, with different implications for remediation, the data should be carefully reviewed and the analysis reassessed, with the objective of choosing between or reconciling the competing views of erosion and deposition at the site. Where LOEs are both inconsistent and weak, additional data or studies may be appropriate to refine and test the CSM. Where data are persistently ambiguous, it may not be possible to justify an alternative on the basis of information collected in the SEDA. In the latter three cases, an adaptive management approach may be useful in resolving uncertainties (see Section 7.5.3).

7.4.2 Considering uncertainty in long-term sediment behavior

Even after inconsistencies among LOEs are resolved and the CSM is refined to support decision making, understanding and managing uncertainty continues to play a significant role in the long-term management of the site. Often a site CSM is formalized into a numerical model or set of models that can be used to predict long-term site and sediment behavior, and can incorporate new data as the site is monitored over the long term. As models are developed, uncertainty can be expressed more formally and quantitatively as uncertainty bounds on model predictions or alternative model predictions that result from a systematic uncertainty analysis (USEPA 2009). This type of quantified uncertainty can be very valuable in framing expectations for remedy success, measuring progress toward remedial action objectives, and formulating plans for confirmatory sampling investigations. For example, when the depth of contamination is below predicted erosion depths and associated uncertainty bounds, managers have confidence (to the extent provided by a modeling exercise) that the buried deposit will not be eroded and transported.

An important part of establishing the strength of a collection of LOEs is assuring that the observed processes contributing to a particular CSM will remain in place for a specified period of time, usually the design life of the remedy. This typically requires demonstrating two conditions: 1) that the relevant processes can be expected to persist through time (e.g., solids deposition will continue as it has historically), and 2) that the processes will not be interrupted by some future episodic event that will invalidate the original site management decision or render the remedy ineffective (e.g., a 50-year period of solids deposition followed by a storm-based erosion event that scours to the depth of buried contaminants).

Establishing the first condition necessitates an understanding of the fundamentals of the natural systems contributing to remedy effectiveness or recovery processes: anticipating whether the watershed hydrology will remain the same for the design life of the project, or if factors like urbanization, agricultural practices, and other land-use changes will affect water flow rates, velocities, and sediment delivery downstream. An understanding of river and coastal geomorphology may also be important. Understanding whether a river or estuarine site is geomorphologically stable or actively changing can have significant implications for the permanence of a selected remedy.

To address the influence of episodic events, a good understanding of the historical intensity of rain events, flood flows, and other types of conditions, with a focus on the most extreme events, is needed. This assessment typically relies on statistical evaluation of historical flow rates and rainfall intensity, and focuses on the 100-year event as a critical condition to be considered for decision making.

Changing land use and the increased urbanization of the last half of the 20th century are important considerations that tend to increase the intensity of flows and potential for remedy disruption. Given the uncertainty presented by changing conditions in river and estuarine systems, and the often non-linear responses of river systems to these conditions, models can play an important role in evaluating the effects of episodic events. Numerical models can be used to predict the effects of changing land use on flow fields, extrapolate to events not seen historically, and also to consider the combined effects of major factors affecting stability, such as tidal flows, storm surges, watershed inputs, and ice effects. When simulating combinations of extreme events, it is also important to keep in mind that combinations have a reduced likelihood of occurring, relative to the component events: for example, a 100-year flow in combination with an extreme wind event or tidal surge typically occurs much less frequently than once every 100 years. When assessing the potentially more adverse effects of combined events, it is important to acknowledge the longer recurrence intervals of those scenarios.

7.5 Decision-making

7.5.1 Updating the conceptual site model

Based on the LOE analysis, the CSM can be refined to better inform remedy selection. As Sections 7.3 and 7.4 have discussed, this refinement will usually incorporate improved understanding of:

- Expected long-term trends in deposition and erosion; and
- The likely effects of extreme meteorological and/or anthropogenic events.

Refinement of the CSM should be specific to the study questions asked and answered, which in most cases concern the likelihood of short- and/or long-term exposure at concentrations exceeding acceptable levels. For example, if MNR is under consideration, there may be areas of the site where MNR-1 and/or MNR-2 are important questions for remedy selection. In such cases, the objective should be to refine the CSM to the point where these questions can be answered confidently with reference to those specific areas of the site. In this way, the CSM can provide a sound basis for expectations of future site risks under an MNR alternative. Similarly, for dredging, capping, and combination remedies, the CSM should be refined sufficiently to answer site-specific study questions and inform expectations of future risk under those alternatives.

7.5.2 Refining the management alternatives

A refined CSM, informed by the SEDA, can be used to identify alternatives that are most appropriate for each subarea of a site, including combinations of technologies, based on current and predicted erosion and deposition characteristics. This is accomplished by applying decision rules developed for the SEDA based on information gained through SEDA investigations and analyses. The SEDA is only part of the remedy selection process, and does not in itself result in a final remedy selection, which must consider all of the NCP criteria. Nevertheless, the SEDA can play a critical role by establishing the bounds of remedies that are expected to be protective and effective in the short and long term, which can be of great value in the FS evaluation of alternatives.

After analyses have been conducted as planned, significant uncertainty may remain in applying the decision rules. For example, based on inconsistent and weak LOEs from initial SEDA studies, it may be uncertain whether scour in an extreme event would be deep enough to expose a buried layer of high-concentration material. In general, additional analyses should be conducted to resolve the questions in these situations if additional information can be gathered at a reasonable cost and without causing an unreasonable delay in remedy decision making. These analyses may involve refinement of the study question(s), based on what has been learned, leading to new avenues of data gathering and analysis. The goal should be timely resolution of the study question(s) to achieve a reasonable level of certainty that is sufficient to support a decision identifying the most appropriate alternative.

7.5.3 Uncertainty and the role of adaptive management

One objective of the SEDA is to assess whether an alternative should be considered, with reasonable certainty, as a candidate for selection according to the NCP criteria. Even if an alternative is retained as a candidate for selection, it is unlikely that the SEDA can eliminate all uncertainty surrounding the potential effects of extreme events or the long-term stability of buried contamination. Thus, even when a SEDA is thorough and complete, uncertainties concerning erosion and sedimentation are likely to remain at the time of remedy selection. Decisions must be made, and further data collection and analysis are unlikely to yield complete certainty.

When crafting alternatives for evaluation in the FS, several approaches can be taken to account for SEDA uncertainties. One is to specify alternatives conservatively - for example, incorporating a large factor of safety in capping alternatives relative to anticipated extreme events, with the effect of increasing the diameter of armor stone considered for caps. A second approach is to rely more on O&M to meet risk goals. This could include options such as requiring frequent monitoring of cap thickness, including monitoring after potentially erosive events, with plans in place for repair if needed, in lieu of a very conservative factor of safety in design. A second approach might be to implement smaller-scale actions – pilot studies, removal actions, or interim RODs for portions of the site and evaluate performance before selecting larger-scale actions. A third approach to managing these uncertainties might be to implement the least costly, least invasive remedy that is believed to attain the appropriate risk reduction, with a contingency to modify the approach if it is not working as predicted. An adaptive management approach can be fit into this plan as part of the decision-making process. Alternatives following these approaches can be considered in the FS. Careful consideration and discussion of uncertainty in the SEDA can support the development of sufficiently conservative options and protective adaptive management approaches.

In any case, short- and long-term monitoring plans should be designed to verify remedy performance and the sediment erosion and deposition processes relied upon by the remedy. Most sediment sites will be subject to USEPA's five-year review requirement to evaluate whether implemented remedies remain protective. This periodic review of the remedy may benefit from additional SEDA analysis at that time, particularly if a high-energy event has occurred in the interval. The five-year review is a good point to reevaluate the CSM, particularly the sediment erosion and deposition processes expected at the site.

7.6 Documenting the decision as a data quality objectives process

Levels of erosion and deposition can play an important role in deciding among MNR, dredging, capping, and combination remedies. Because of differences in cost, duration, community impacts, short- and/or long-term contaminant effectiveness, and other potential impacts, the findings of the SEDA may influence decisions for a wide range of stakeholders. However, much of the information assembled and evaluated in the SEDA (e.g., areas such as hydrodynamics, sediment transport, bathymetric measurement, radionuclide dating, numerical modeling, and uncertainty analysis) is highly technical. For these reasons, transparency and clear communication of the findings and their significance are important objectives.

Expressing methods and findings in clear language that is understandable to interested nontechnical readers is fundamental to transparency. In addition, the DQO process facilitates clear documentation of the process of data gathering and use for decision support. Following the path planned at the outset of the SEDA, a SEDA report can be constructed as follows:

- Restate the problem and the decision to be made, including any refinements since the SEDA was initiated.
- Identify input data and boundaries as actually applied.
- Report findings, addressing uncertainties and the degree of internal consistency within the LOEs.
- Answer study questions and present refinements in the CSM.
- Develop alternatives for detailed comparative analysis.

If the process of gathering data to answer refined study questions is iterative, this aspect of the study can also be discussed in the report.

Specifically and transparently addressing each of the elements above in a SEDA report ultimately provides the site manager with a document that clearly explains the following:

- Why each piece of data was collected for the SEDA.
- How the data were used.
- What study questions were asked and answered.
- How those answers contribute to decision making.
- How stakeholders can understand the role of the SEDA in remedy selection.

8 Summary

This document outlines processes influencing sediment transport and describes methods to use in developing a Sediment Erosion and Deposition Assessment (SEDA). A SEDA is a complex procedure that overlaps multiple disciplines. Processes and properties that should be assessed include sediment characteristics, surface water stresses, sediment loadings, anthropogenic activity, and weather and oceanographic influences. The SEDA will identify which of these factors are critical at a specific site. Although the SEDA may seem like a daunting task, relevant data already exist for most sites. Some level of data collection must have already been performed for this site to be designated as a Superfund Site. Relevant hydrodynamic (and other) data generally exist at these sites and will support SEDA development. The importance of an exhaustive historic data collection effort and review cannot be overemphasized. These data can provide a long-term record on evolution of the system. This long-term evolution is not only critical in assessing sediment erodibility; it will also support CSM development. Historic records, coupled with geochronology data, will support a forensic study of system evolution. This evolution, in turn, is critical to understanding sediment transport processes, especially erodibility and deposition. In addition to short-term project needs and ongoing project-specific evaluations, consideration should also be given to collection of additional monitoring data to assist future project evaluations or other sites.

Assessment of sediment transport requires very specific expertise. Sediment processes at each site are unique and appropriate methodology should be tailored for each site. Given the uncertain nature of this area of study, it cannot be expected that one person or organization can develop an optimized plan to develop a SEDA. The most successful SEDA studies have been guided by a technical review panel working with the RPM in SEDA development. Understanding of processes at a specific site, coupled with experience from other sites, is critical to success. In addition, the successful performance of a SEDA typically requires an interactive approach. The work plan needs to be adaptable so it will reflect improved process understanding as the study progresses.

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Appendix A: Glossary

Adsorption	Process by which contaminants adhere via chemical bonds to the surface of fine-grained (cohesive) *sediment*.[1]
Aggradation	Process by which the bottoms of water bodies are raised due to *deposition*[1] of sediment.
Alluvial channel	*Channel* completely in sediment (i.e., *alluvium)*; no bedrock is exposed in channel.
Alluvial fan	A landform shaped like a fan (in plan view) and deposited where a channel issues from a narrow valley of high slope onto a low-slope, broad valley.
Alluvium	Sediment deposited in a channel, *floodplain*, *alluvial fan*, or delta.
Antidunes	*Bed forms* that form in alluvial channels under *supercritical flows* (with Froude number greater than one). Antidunes are usually more symmetrical (in their longitudinal profile) than dunes.
Armoring	See *bed armoring*.
Avulsion	A sudden cutting off of land by a flood, currents, or change in course of a body of water.
Baroclinic circulation	Vertical circulation in a water body generated by vertical density gradients.

[1] Terms that are italicized in the Glossary carry their own definitions herein.

Baseflow — *Groundwater* inflow through the banks and bottom to the water body. This is a portion of a water body's flow hydrograph that occurs between precipitation-induced runoff events.

Bathymetry — Elevation of the bottom of a water body. Bathymetric analysis involves the measurement of the water depths in a water body and calculation of the bathymetry.

Bed armoring — Natural process by which finer-grained bed material is removed from a surficial channel bed by flow-induced *erosion*, leaving behind coarser, more erosion-resistant bed material. This layer of coarser bed material essentially protects or armors the underlying bed material from exposure to flow-induced bed shear stresses.

Bed forms — Recognizable relief features on the bed of an *alluvial channel*, such as *ripples*, *dunes,* and *anti-dunes*.

Bedload — Sediment material moving on top of or near a channel bed by rolling, sliding, and saltating, i.e., jumping.

Bioturbation — Mixing of the sediment bed from biological activity by benthic organisms living in the sediment layer.

Bulk density — Mass of sediment and porewater per unit volume of a sediment bed.

Channel — Natural or man-made water body that is open at the top and that conveys water. A river is an example of a natural channel.

Chutes — See *riffles*.

Colloids	Particles in water whose equivalent particle diameter is less than 1 µm.
Critical depth	Flow depth at which total energy is minimum, and the *Froude number* is equal to 1.0.
Critical flow	Flow at which the water depth is at *critical depth,* and when the inertial and gravitational forces are equal, *i.e.*, *Froude number* is equal to 1.0.
Critical shear stress	Another term used for the *shear strength* of a sediment bed.
Degradation	Process by which the bottom of a water body is lowered due to erosion of bed sediment.
Deposition	Process of suspended sediment settling on the bed/bottom of the water body.
Dunes	Bed forms bigger than ripples but smaller than bars, and formed under subcritical flows. Dunes develop when the Froude number is greater than 0.3 but less than 1.0.
Embeddedness	Degree to which fine-grained sediments fill the spaces between coarse sediment (e.g., cobbles, gravels, boulders) on the bed surface.
Energy grade line	An inclined line that represents the total energy of a channel flowing from a higher to a lower elevation. It is located a vertical distance equal to the velocity head ($U^2/2g$) above the water surface.

Entrenchment	Geomorphological process by which a channel erodes downward between relatively stable banks.
Equilibrium concentration	Concentration of suspended noncohesive sediment immediately above the channel bed (at a distance equal to the thickness of the bedload transport) under steady flow conditions in an alluvial channel.
Erodibility	Measure of a sediment bed's propensity to lose sediment particles due to the action of currents and/or waves.
Erosion	Wearing away of sediment particles on the sediment bed surface by detachment and transport through the action of wind or moving water.
Floc	Aggregate consisting of hundreds to thousands of coagulated fine-grained sediment particles.
Flocculation	Process that occurs when differential settling and other processes cause particle collisions in the water column, resulting in the formation of flocs.
Fluid mud	A high-concentration aqueous suspension of fine-grained sediment in which settling is substantially hindered (McAnally et al. 2007).[1]
Fluvial geomorphology	Geological study of the configuration, characteristics, origin, and evolution of channels and banks.

[1] Documents cited in this appendix can be found in the References section following the main text.

Froude number	Dimensionless number used in fluid mechanics that is equal to the ratio of inertial to gravitational forces in channel flow. When the Froude number is less than 1.0, equal to 1.0, and greater than 1.0, the flow is termed subcritical, critical, and supercritical, respectively.
Geomorphology	The branch of geology that studies the structure, origin, and development of the topographical features of the earth's surface.
Hydraulics	Branch of science concerned with the study of liquids in motion. Specifically, hydraulics deals with the flow of liquids in pipes, rivers, and channels and the confinement of liquids by dams and tanks.
Hydrodynamics	Branch of science that deals with the dynamics of fluids, especially incompressible fluids such as water, in motion.
Hydrology	Branch of science involving the study of the movement, distribution, and quality of water throughout the earth.
Hyporheic zone	Area immediately beneath the *wetted perimeter* of a channel. Groundwater moves through the hyporheic zone to recharge the channel in a gaining reach and water from the channel moves through the hyporheic zone to recharge the groundwater in a losing reach.
Liquefaction	The loss of the *yield strength* of an initially solid or intact sediment bed that occurs when the bed surface is perturbed by wave-induced cyclical shear and normal stresses

	and the amplitude of the total stress exceeds the *yield strength* up to some depth in the sediment bed. The portion of the sediment bed above this depth is liquefied.
Orbital velocity	Under-surface water motion associated with surface waves. Fluid particles under a wave move in an orbital motion. This motion can induce a stress on the sediment bed surface and can produce sediment *erosion*.
PICS	Particle imaging camera system used to measure settling velocities of cohesive sediment.
Plasticity	Property of a sediment that allows it to be deformed beyond the point of recovery without cracking or appreciably changing volume.
Point bar	An alluvial deposit of sand or gravel that occurs in a channel along the inside bend of a meander loop, usually a short distance downstream from the apex of the loop.
Porosity	Ratio of the volume of void space (i.e., pores) to the total volume of an undisturbed sediment sample.
Redispersion	Erosion or entrainment of a stationary suspension into the water column.
Rheology	The branch of physics that studies the deformation and flow of matter.
Riparian zone	Relatively narrow zone along the banks of a channel.

Ripples	Small triangular-shaped bed forms, similar to dunes but having much smaller heights and lengths. Ripples develop when the Froude number is less than 0.3.
Saltation	Flow-induced movement of sediment in short jumps or bounces above a channel bed.
SEDFLUME	A sediment-water flow system designed to measure the erosion rate and shear strength of sediment in a simulated aquatic environment.
Seepage	Slow movement of water into and through (or out of and through) the sediment that composes the bottom and sides of channels.
Settling speed	Net downward velocity of suspended particles and flocs relative to water velocity.
Shear strength	Resistance force due to frictional forces between sediment particles in contact with one another, the submerged weight of the particles (gravitational forces), and the electrochemical attractive forces between cohesive sediment particles. It is a direct measure of the sediment bed's resistance to a flow-induced shear stress at the bed surface. Another term that is commonly used for this parameter is *critical shear stress* for erosion.
Shear stress	Force per unit bed area that water flowing above the sediment bed exerts on the surface of the bed. The force acts in the direction in which the water is moving.
Sinuosity	Measure of meander intensity. Sinuosity is computed as the ratio of the channel length

	measured along its *thalweg* to the length of the valley through which the channel flows.
Slip	Ship docking area generally connected to a navigation channel. Similar to navigation channels, slips generally require dredging to maintain navigable water depth.
Slumping	Detachment of bank material because of the combined action of gravitational force and a pressure that acts from within the bank toward the face of the channel bank. This pressure occurs when water that is stored in the banks and floodplain soils during a high-flow event seeps towards the riverbank after the high-flow event recedes, which reduces the ability of the bank material to stand as a vertical free face.
SPI	Sediment profiling imaging. This is a camera system used to help characterize the physical and biological condition of surface sediment and to assess the water body's benthic community.
Stability	A measure of a sediment bed's ability to resist erosional forces acting on the bed surface due to the action of currents and/or waves.
Stratigraphy	Sediment layers and layering that can be used to describe the sediment bed.
Subcritical flow	State of flow where the water depth is greater than the critical depth, causing the influence of gravitational forces to dominate the influences of inertial forces, and for which the Froude number is less than 1.0.

Supercritical flow	State of flow where the water depth is less than the critical depth, in which the influence of inertial forces dominates the influence of gravitational forces, and for which the Froude number is greater than 1.0.
Suspended load	Amount of sediment that is supported by the upward components of turbulence in a channel and that stays in suspension for an appreciable length of time.
Thalweg	Line extending down a channel that follows the lowest elevation of the bed. The thalweg marks the natural direction or profile of a watercourse. The thalweg is usually the line of fastest flow in any river.
Thixotropy	The property of a material that enables it to stiffen in a relatively short time on standing, but which changes to a very soft consistency or to a fluid of high viscosity upon agitation or manipulation, the process being completely reversible.
Void ratio	Ratio of the volume of void space to the volume of solid particles in a given soil mass.
Wetted perimeter	Length of wetted contact between water and the channel bottom, measured in a direction normal to the flow.
Wind wave	Waves that occur on the free surface of a water body that result from wind forcings over an open stretch of water surface. Waves produce *orbital velocities* in the water column below the wave.

Yield strength	The stress at which deformation occurs. It is a bulk property of sediment or soil, and is characterized by the Bingham-plastic yield stress.

Appendix B: Primer on Sediment Transport and Geomorphology

Sediment properties

Sediments are weathered rock materials that are transported, suspended, or deposited by flowing water. All constituents of the parent rock material are usually found in the sediment. Quartz, because of its abundance in the earth's crust, is by far the most common material found in sediment. However, numerous other minerals (e.g., feldspar, quartz, calcite, dolomite, and various clays), as well as carbonate particles, and igneous and metamorphic rocks, are also usually present. Even when material other than quartz particles is present in sediment, the average particle density of sediment is usually very close to that of quartz – 2.65 gm/cm^3. The specific gravity of sediment is defined as the ratio of the sediment particle density to the density of water at 4^o C (i.e., 1.0 gm/cm^3), and thus has an average value of 2.65.

Sediment diameter is denoted as D, and has dimensions of length. Since sediment particles are rarely exactly spherical, the definition of diameter requires elaboration. For sufficiently coarse particles, D is often defined to be the dimension of the smallest square mesh opening through which the particle will pass. For finer particles, D usually denotes the diameter of the equivalent sphere with the same fall (or settling) velocity as the actual particle. A sediment gradation scale (Table 4.1 in main text) has been established to classify sediment in size classes, ranging from very fine clays to very large boulders. Sediment particles with diameters less than 63 µm are classified as fine-grained sediment, and are cohesive in nature. Sediment particles with diameters greater than 63 µm are classified as noncohesive sediment. However, Roberts et al. (1998) found evidence of consolidation effects on quartz sediment up to 200 µm; this suggests that some cohesive effects may exist for particles slightly larger than 63 µm.

Cohesive (or fine-grained) sediments are composed of clay and non-clay mineral components, silt-sized particles, and organic material, including biochemicals (Grim 1968). Clays are defined as particles with an equivalent diameter of less than 4 µm, and generally (but not always) consist of one or more clay minerals such as kaolinite, bentonite, illite, chlorite, montmorillonite, vermiculite, and halloysite. The non-clay minerals consist of (among others) quartz, calcium carbonate, feldspar, and mica. The organic matter often present in clay materials can be discrete particles, adsorbed organic molecules, or constituents inserted between clay layers (Grim 1968). Additional possible components of clay materials are water-soluble salts and adsorbed exchangeable ions and contaminants. Clays possess the properties of plasticity, thixotropy, and adsorption in water (van Olphen 1963).

For clay-sized particles, surface physicochemical forces exert a distinct controlling influence on the behavior of the particles due to the large specific area, i.e., ratio of surface area to volume. In fact, the average surface force on one clay particle is several orders of magnitude greater than the gravitational force (Partheniades 1962).

The relationships between clay particles and water molecules are governed by interparticle electrochemical forces. Interparticle forces are both attractive and repulsive. The attractive forces present are the London-van der Walls forces, which are due to the nearly instantaneous fluctuation of the dipoles that result from the electrostatic attraction of the nucleus of one atom for the electron cloud of a neighboring atom (Grimshaw 1971). These electrical attractive forces are weak and are only significant when interacting atoms are very close together.

The electrical attractive forces are strong enough to cause structural build-up since they are additive between pairs of atoms. The magnitude of these forces decreases with increasing temperature; they are only slightly dependent on the salt concentration (i.e., salinity) of the medium (van Olphen 1963). The repulsive forces of clay materials, due to negatively charged particle forces, increase in an exponential fashion with decreasing particle separation. An increase in salinity, however, causes a decrease in the magnitude of these repulsive forces.

Cation exchange capacity (CEC) is an important property of clays by which they adsorb certain cations and anions in exchange for those already present and retain the new ones in an exchangeable state. The CEC of different clays varies from 3 to 15 milliequivalents per 100 grams (meq/100 gm) for kaolinite to 100 to 150 meq/100 gm for vermiculite. Higher CEC values indicate greater capacity to adsorb/exchange cations. Some of the predominantly occurring cations in cohesive sediment are Na, K, Ca, Al, Pb, Cu, Hg, Cr, Cd, and Zn.

In water with very low salinity (less than about 1 psu), individual cohesive sediment particles are often found in a dispersed state. Small amounts of salts, however, are sufficient to repress the electrochemical surface repulsive forces among the particles, with the result that the particles coagulate to form flocs. Depending primarily on the CEC of the clay minerals, flocs can form even in freshwater. Each floc can contain thousands or even millions of particles. The transport properties of flocs are affected by the hydrodynamic conditions and by the chemical composition of the suspending fluid. Most estuaries and some freshwater water bodies contain abundant quantities of cohesive sediment that usually occur in the coagulated form in various degrees of flocculation. Therefore, an understanding of the transport properties of cohesive sediment requires knowledge of the manner in which flocs are formed.

Coagulation of suspended cohesive sediment depends on interparticle collision and cohesion. Cohesion and collision, discussed in detail elsewhere (Einstein and Krone 1962, Krone 1962, Partheniades 1964, Hunt 1980, and McAnally 1999) are briefly reviewed here. There are three principal mechanisms of interparticle collision in suspension, and these influence the rate at which individual sediment particles coagulate. The first is due to Brownian motion that results from the thermal motions of the molecules of the suspending water. Generally, coagulation rates by this mechanism are too slow to be significant unless the suspended sediment concentration exceeds 5 - 10 g/L, as it sometimes does in fluid mud (a high-density, near-bed layer). Flocs formed by this mechanism are weak, with a lace-like structure, and are easily fractured by shearing, especially in the high shears found near the bed in rivers or estuaries, or are crushed easily when deposited (Krone 1962).

The second mechanism is due to internal shearing produced by local velocity gradients in the fluid. Collision will occur if the paths of the particles’ centers in the velocity gradient are displaced by a distance that is less than the sum of their radii. Flocs produced by this mechanism tend to be spherical, and are relatively dense and strong because only those bonds that are strong enough to resist internal shearing can survive.

The third mechanism, differential sedimentation, results from particles of different sizes having different settling velocities. A larger particle, due to its higher settling velocity, will collide with smaller, more slowly settling particles and will have a tendency to pick up these particles. This mechanism produces relatively weak flocs and contributes to the often observed rapid clarification of estuarial waters at slack tide.

All three collision mechanisms operate in most surface waters, with internal shearing and differential sedimentation generally being predominant in the water column, with the exception of fluid mud, where Brownian motion is likely to contribute significantly. The collision efficiency is less than 100%, so not all collisions result in coagulation.

Cohesion of colliding colloidal particles is caused by the presence of net attractive electrochemical surface forces on the particles. Particle cohesion is promoted by an increased concentration of dissolved ions and/or an increased ratio of multivalent to monovalent ions present in saline waters. The CEC, salinity, and ratio of multivalent to monovalent ions all serve to determine the net interparticle force and, thus, the potential for clay particles to become cohesive. Kaolinite becomes cohesive at a salinity of 0.6 psu, illite at 1.1 psu, and montmorillonite at 2.4 psu (Ariathurai 1974). Edzwald et al. (1974) reported that the cohesiveness of clay particles develops quickly at the given salt concentrations, and that little increase in coagulation occurs at higher salt concentrations, implying that the particles must have attained their maximum degree of cohesion. The rapid development of cohesion and the relatively low salinities at which clays become cohesive indicate that cohesion is primarily affected by salinity variations near the landward end of an estuary where salinities are often less than about 3 psu.

Burban et al. (1990) found that the settling speeds of flocs were only a weak function of salinity, whereas the researchers cited here previously have observed salinity effects on both the settling rates and on the erodibility of cohesive sediment. Burban et al. concluded that the changes in settling velocities as they are transported through an estuary are rather small, and that flocculation is a secondary cause of estuarine turbidity maxima with the hydrodynamics of the stratified flow being of more importance.

The rate and degree of flocculation are important factors that govern the transport of cohesive sediment. In addition to the water chemistry and magnitude of surface forces, factors known to govern coagulation and flocculation include: sediment size grading, mineralogical composition, particle density, organic content, suspension concentration, water temperature, depth of water through which the flocs have settled, and turbulence intensity (represented by the rate of internal shearing) of the suspending flow (Owen 1971).

The order of flocculation that characterizes the packing arrangement, density, and shear strength of flocs is determined by: 1) sediment type, 2) fluid composition, 3) local shear field, and 4) concentration of particles available for flocculation. Krone (1962) found that floc structure is dependent on salinity for salinities less than about 10 psu. Primary, or 0-order flocs, are highly packed arrangements of clay particles, with each floc consisting of perhaps as many as a million particles. Typical values of the void ratio (volume of pore water divided by volume of solids) have been estimated to be on the order of 1.2. This is equivalent to a porosity of 0.55 and is a more open structure than commonly occurs in noncohesive sediment (Krone 1963).

Continued flocculation under favorable shear gradients can result in the formation of first or higher order flocs composed of loosely packed arrays of 0-order flocs. Each succeeding order consists of flocs of lower density and lower shear strength. A range of flocs of different shear strengths and densities are typically formed, with the highest order determined by the prevailing shearing rate provided that a sufficient number of suspended clay particles are available for promoting coagulation and flocculation.

Sediment bed properties

As rivers flow from mountains to coastal plains, noncohesive sediment tends to deposit out, creating an upward, concave, long profile of the bed and a pattern of downstream fining of bed sediment. When the sediment transport capacity in a given reach of a river exceeds the total sediment load being transported from upstream reaches, the difference between the capacity and total load is supplied from the bed. This means that the river channel will undergo erosion, i.e., degradation. In a river with nonuniform bed material, the finer surficial bed sediment will be eroded more rapidly than the coarser sediment. By this process, the median diameter of the surficial bed sediment becomes coarser. If the degradation continues, the finer surficial bed sediment will eventually be depleted, leaving a surficial layer of coarser sediment. This process is called armoring and the surficial layer of coarser sediment is called the armor layer.

In response to varying flow conditions, and hence the rate of sediment transport in an alluvial channel, the bed configuration of the water body will change. Simons and Sentürk (1992) define bed configuration as any irregularity in the bed surface larger than the largest size sediment particle forming the bed. Bed form is one of several synonyms used in the literature for bed configuration. Anyone who has ever swum in a sandy bottom river, lake, or ocean has no doubt noticed ripples on the bottom. Ripples are one type of bed form that is created by a certain range of flow conditions. Other types of bed forms include: plane bed, dunes, washed out dunes, anti-dunes, and chutes and pools (Simons and Sentürk 1992). A plane bed is essentially flat or smooth. These will normally only be found in channels with very low flows. With an increase in flow, ripples form in plane bed alluvial channels. Ripples are small, asymmetrical, triangular-shaped bed forms that are normally less than 5 cm in height and less than 30 cm in length. In general, ripples have long, gentle slopes on their upstream sides and short, steep slopes on their downstream sides. Dunes are typically larger than ripples but smaller than bars, and have similar longitudinal profiles as ripples. Dune formation occurs near the upper end of the subcritical flow regime, and as such, dunes are out of phase with the water surface; the water surface decreases slightly above the crest of the dune. Washed-out dunes (also referred to as a transitional bed form) consist of intermixed, low-amplitude dunes and flat areas. These typically occur around the critical flow condition. Antidunes are usually more symmetrical (in their longitudinal profile) than dunes, and form under supercritical flows. Thus, antidunes are in phase with the water surface elevation and move in the upstream direction. Chutes and pools usually occur on relatively steep channel slopes, and as such, high velocities and sediment discharges occur in the chutes.

Noncohesive sediment beds are characterized by temporally constant vertical profiles of porosity (density) since consolidation is almost instantaneous after deposition. Therefore, their resistance to erosion does not change over time. Erosion rates for cohesive sediment beds are highly dependent on porosity (density). Decreased porosity enhances electrochemical interparticle bonds, resulting in increased resistance to erosive forces. Porosity of cohesive beds is generally a function of time after deposition and self weight consolidation (mass of sediment on top of a specific layer). Flow-deposited beds of cohesive sediment typically possess vertical density and bed shear strength profiles. Bed shear strength is a direct measure of the sediment bed's resistance to a flow-induced shear stress at the surface of the bed. It is measured in units of stress, e.g., Pa (or N/m^2) and is expressed in SI units. Another term that is commonly used for this parameter is critical shear stress for erosion. The average values of bed density and bed shear strength usually increase over time and their vertical profiles change with time, primarily due to consolidation and secondarily due to thixotropy and associated physicochemical changes affecting inter-particle forces. Consolidation is caused by the gravitational force of overlying deposited flocs (overburden) that crushes, and thereby decreases, the order of flocculation of the underlying sediment. Consolidation changes the erosive behavior of cohesive sediment beds in two ways: (1) as the shear strength of the bed increases due to consolidation, the susceptibility of the bed to erosion decreases, and (2) the vertical shear strength profile determines the depth into the bed that a bed will erode when subjected to excess shear, i.e., an applied bed shear stress in excess of the bed surface shear strength.

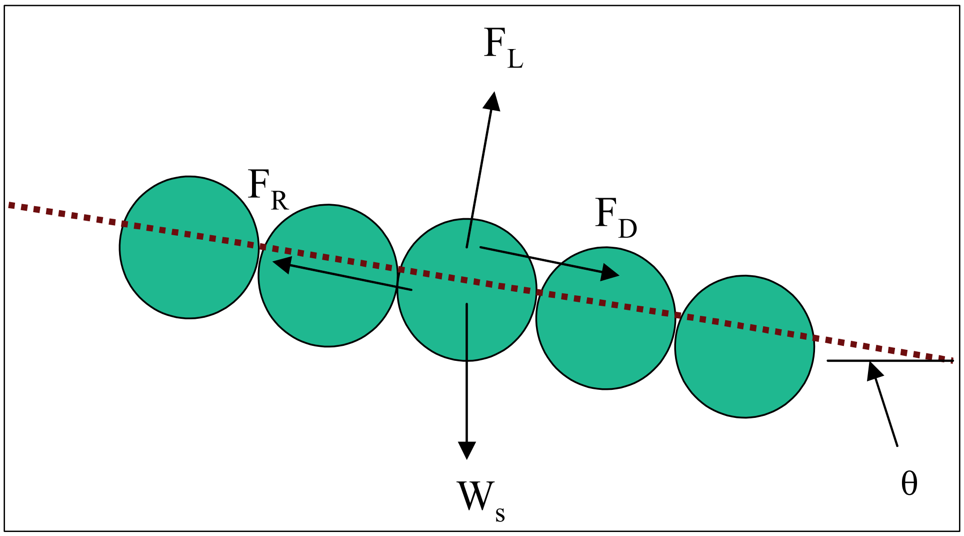
In rivers and other water bodies, sediment beds will often be composed of a mixture of fine-grained and noncohesive sediment. Lick et al. (2004) found that percentages of fine-grained sediment as low as 2% in such beds can have a large effect on erosion rates, thus demonstrating the importance of determining the variation in grain size distributions and erosion rates of sediment throughout the water body.

Sediment transport

Noncohesive sediment transport

Incipient motion of a noncohesive sediment particle occurs when the flow-induced forces are greater than the resistance forces and the particle begins to move across the surface of the sediment bed. Figure B1 is a diagram of the forces acting on a single, spherical sediment particle in the surface layer of a sediment bed. For simplicity, all of the particles are assumed to have the same diameter and to be arranged in the orderly fashion seen in this figure. The dashed brown line in this figure represents the hypothetical bed surface where the mean flow velocity is zero. The angle between the horizontal black line (on the right side of the figure) and the bed surface is shown to be θ. The slope of the bed is equal to $tan\theta$. The forces shown in this diagram are the following: W_s = submerged weight of the particle; F_D = flow-induced drag force; F_L = flow-induced lift force; and F_R = resistance force due to contact between adjacent particles.

Figure B1. Diagram of forces acting on a sediment particle.



Summing the forces in the direction perpendicular to the bed at the onset of incipient motion, i.e., when the particle has not yet started to move, gives:

$$F_L - W_s \cos\theta = 0 \tag{B.1}$$

The lift force that acts on the particle is given by:

$$F_L = C_L \frac{\pi}{4} D^2 \frac{\rho}{2} V_D^2 \tag{B.2}$$

where C_L = lift coefficient; D = particle diameter; ρ = water density; and V_D = velocity at a distance D above the bed. The submerged weight of the particle is given by:

$$W_s = \frac{\pi D^3}{6}(\rho_s - \rho) g \tag{B.3}$$

where g = gravitational acceleration; and ρ_s = sediment particle density.

Summing the forces in the direction parallel to the bed at the onset of incipient motion gives:

$$F_D - F_R + W_s \sin\theta = 0 \tag{B.4}$$

The drag force that acts on the particle is given by:

$$F_D = C_D \frac{\pi}{4} D^2 \frac{\rho}{2} V_D^2 \tag{B.5}$$

where C_D = drag coefficient. Yang (1973) gives the following expression for the resistance force:

$$F_R = \Psi\left(W_s - F_L\right) \tag{B.6}$$

where ψ = friction coefficient.

V_D in Equations B.2 and B.5 can be determined using a logarithmic velocity distribution:

$$\frac{V_y}{u_*} = 5.75 \log \frac{y}{D} + B \tag{B.7}$$

where V_y = velocity at a distance y above the bed; B = roughness function; and $u_* = (\tau_b/\rho)^{0.5}$ = shear velocity, with τ_b = bed shear stress. In the hydraulically smooth regime, as defined by the shear velocity Reynolds number (given below in Equation B.8), B is given by:

$$B = 5.5 + 5.75 \log \frac{u_* D}{v} \text{ for } 0 < \frac{u_* D}{v} < 5 \tag{B.8}$$

In the hydraulically rough regime, B = 8.5 for $u_*D/v > 70$. Substituting y = D into Equations B.7 and B.8 gives $V_D = Bu_*$.

The depth-averaged velocity, V, can be obtained by integrating Equation B.7 over the flow depth:

$$\frac{V}{u_*} = 5.75\left(\log \frac{d}{D} - 1\right) + B \tag{B.9}$$

Three different approaches have been used to develop criteria for incipient motion. These are the shear stress, velocity, and probabilistic approaches.

The shear stress approach by Shields (1936) for determining the critical shear stress at the onset of incipient motion, τ_{cs}, is probably the most well-known of all the approaches. An example of a probabilistic approach is that developed by Gessler (1965, 1970). The Shield's shear stress approach, further developed by van Rijn (1984a), and the velocity approach used by Yang (1973) are summarized below.

The basis of the shear stress approach is that incipient motion of noncohesive sediment occurs when the bed shear stress exceeds a critical shear stress referred to as the Shield's shear stress, τ_{cs}. The latter can be defined by the following nondimensional relationship:

$$\theta_{cs} = \frac{\tau_{cs}}{g'D} = f(R_d) \tag{B.10}$$

where g' = reduced gravitational acceleration, given by:

$$g' = g\left(\frac{\rho_s}{\rho} - 1\right) \tag{B.11}$$

and R_d = sediment particle densimetric Reynolds number, given by:

$$R_d = \frac{D\sqrt{g'D}}{\nu} \tag{B.12}$$

where ν = kinematic viscosity. van Rijn (1984b) gives the following expressions for $f(R_d)$ on the right-hand side of Equation B.10:

$$f(R_d) = \begin{cases} 0.24(R_d^{2/3})^{-1} & for\ R_d^{2/3} < 4 \\ 0.14(R_d^{2/3})^{-0.64} & for\ 4 \le R_d^{2/3} < 10 \\ 0.04(R_d^{2/3})^{-0.1} & for\ 10 \le R_d^{2/3} < 20 \\ 0.013(R_d^{2/3})^{0.29} & for\ 20 \le R_d^{2/3} < 150 \\ 0.055 & for\ R_d^{2/3} \ge 150 \end{cases} \tag{B.13}$$

In his velocity approach, Yang (1973) first assumed that the channel slope was small enough to neglect the component of the sediment particle's weight in the flow direction in Equation B.4, i.e., $W_s \sin\theta = 0$. Assuming that incipient motion occurs when the two remaining terms in

Equation B.4 are equal, i.e., $F_D = F_R$, he then equated Equations B.5 and B.6, substituted Equation A.9 into both sides of the resulting equation, and then solved for the dimensionless parameter V_{cr}/w_s, where V_{cr} = depth-averaged critical velocity at the onset of incipient motion, and w_s = particle settling velocity (i.e., terminal fall velocity). Yang also assumed that the drag coefficient was linearly proportional to the lift coefficient. He then used laboratory data sets collected by several researchers to determine the values of the friction coefficient in Equation B.6 and the proportionality coefficient between the drag and lift coefficient to obtain the following expressions for V_{cr}/w_s:

$$\frac{V_{cr}}{w_s} = \frac{2.5}{\log(u_* D / \nu) - 0.06} + 0.66 \;\text{ for }\; 1.2 < \frac{u_* D}{\nu} < 70 \qquad \text{(B.14)}$$

$$\frac{V_{cr}}{w_s} = 2.05 \;\text{ for }\; 70 \le \frac{u_* D}{\nu} \qquad \text{(B.15)}$$

The friction force exerted along the wetted perimeter of an open channel on the flow is usually quantified using a resistance formula that contains a roughness coefficient. The Manning's roughness coefficient is the one most commonly used for open channels with rigid boundaries. This coefficient is normally used as a calibration parameter in hydraulic models to achieve optimum agreement between measured and predicted stages (i.e., water surface elevations) or discharges. Once the model is calibrated, the Manning coefficient is treated as being temporally constant. For movable boundary problems, i.e., when sediment transport is involved, the resistance coefficient 1) will change with time due to changes in the movable bed that result from aggradation and degradation, and 2) can be attributable to two resisting forces; one force is due to the roughness of the bed surface (this is called grain roughness or skin friction), and the other force is due to the presence of bed forms in alluvial (i.e., movable boundary) channels (this is called form roughness or form drag). Einstein and Barbarossa (1952) and other researchers have developed procedures for calculating both forms of movable boundary resistance.

The approach by Yang (1976) for estimating the grain- and form-related flow resistance in movable boundary open channels does not involve predicting what type of bed form occurs for a given flow regime (Yang 1976). The basis for his formulation is the theory of minimum rate of energy dissipation, which states that when a dynamic system (e.g., alluvial channel) reaches a condition of equilibrium, its energy dissipation rate is minimal. This theory was derived from the second law of thermodynamics. The basic assumption made in this approach is that the rate of energy dissipation due to sediment transport can be neglected. For an open channel, the energy dissipation rate per unit weight of water is equal to the unit stream power *VS*, where *V* is the average flow velocity in the open channel and *S* is the slope of the energy grade line. Therefore, the theory of minimum energy dissipation rate requires that (Yang 1976):

$$VS = V_m S_m \tag{B.16}$$

where the subscript *m* indicates the value of *V* and *S* when the unit stream power is minimized. Yang's approach involves using Equation B.14 or B.15 to determine the value of V_{cr}, and then using the following sediment transport equation developed by Yang (1973) to determine the total sediment transport:

$$\begin{aligned}\log C_{ts} &= 5.435 - 0.286 \log \frac{w_s D}{\nu} - 0.457 \log \frac{u_*}{w_s} \\ &+ \left(1.799 - 0.409 \log \frac{w_s D}{\nu} - 0.314 \log \frac{u_*}{w_s}\right) \log\left(\frac{VS}{w_s} - \frac{V_{cr} S}{w_s}\right)\end{aligned} \tag{B.17}$$

where C_{ts} = total sediment concentration being transported by the flow (in ppm by weight), *D* = median sieve diameter of the sediment, and $V_{cr}S$ = critical unit stream power required at incipient motion. The iterative procedure developed by Yang (1976) to determine the value of the Manning's coefficient in an alluvial open channel uses known values for *Q*, *D*, w_s, C_{ts}, and *A(d)*, where the latter is the functional relationship between the cross-sectional area, *A*, of the open channel and the flow depth, *d*. The Yang iterative procedure consists of the following seven steps:

4. Assume a value for *d* = flow depth.
5. Solve the 1-D continuity equation (*Q* = *AV*) and Equation A.17 for *V* and *S*.
6. Compute the unit stream power, i.e., *VS*.
7. Select another value for *d* and repeat steps 2 and 3.
8. Step 4 should be repeated a sufficient number of times to allow for an accurate determination of the minimum value of *VS*.

9. Once the minimum value of *VS* has been determined, the corresponding values of V, S, and d can be calculated using the one-dimensional (1-D) continuity equation and Equation B.17.
10. The Manning equation (given below) can then be used to calculate the value of the Manning's coefficient, *n*.

$$V = \frac{1}{n} R^{2/3} S^{1/2} \tag{B.18}$$

where R = hydraulic radius, which is equal to the ratio A/P, where P is the wetted perimeter. Equation B.18 is the Manning's equation form to use with metric units. Using the theory of minimum unit stream power, Yang and Song (1979) found good agreement between the following measured and computed parameters: *S*, *V*, *d*, *VS*, and *n*. Parker (1977) also found good agreement for flows where the sediment transport rate was not too high, thus justifying Yang's assumption, mentioned previously, under such conditions. However, Yang's method (1976) should not be used for critical or supercritical flows, or when the sediment transport rate is high, since the assumption is invalid under these conditions.

Immediately after onset of incipient motion, the sediment generally moves as bedload. Bedload transport occurs when noncohesive sediment rolls, slides, or jumps (i.e., saltates) along the bed. If the flow continues to increase, then some of the sediment moving as bedload will usually be entrained by vertical turbulent velocity components into the water column and be transported for extended periods of time in suspension. Thus, it takes more energy for the flow to transport sediment in suspension than as bedload. The sediment that is transported in suspension is referred to as suspended load. The total load is the sum of the bedload and suspended load. Bedload is typically between 10 and 25% of the total load, although for beds with a high fraction of coarse sediment, the percentage will normally be higher. Many different methods have been developed for calculating the bedload transport rate in open channels. Some of these methods (along with their references) are listed next. The specific shear stress approach of van Rijn (1984a) is also described in some detail in the following.

1. Shear Stress Method: Shields (1936), Chang et al. (1965), and van Rijn (1984a).
2. Energy Slope Method: Meyer-Peter and Muller (1948).
3. Probabilistic Method: Einstein (1950).

Utilizing a shear stress approach, the dimensionless form of the bedload transport rate is given by van Rijn (1984a) as:

$$\frac{q_b}{\rho_s D\sqrt{g'D}} = \frac{0.053}{R_d^{1/5}\theta_{cs}^{2.1}}\left(\theta-\theta_{cs}\right)^{2.1} \quad \text{(B.19)}$$

where $\theta = \dfrac{\tau_b}{\rho g' D}$, q_b = bedload transport rate (with units of mass per unit time per unit width), and θ_{cs} is defined in Equation B.10. Sediment is transported as bedload in the direction of the mean flow.

The settling velocity for individual noncohesive sediment particles, w_s, is given by van Rijn (1984b) as the following functions of D, g', and R_d:

$$\frac{w_s}{\sqrt{g'D}} = \begin{cases} \dfrac{R_d}{18} & for\, D \le 100\mu m \\ \dfrac{10}{R_d}\left(\sqrt{1+0.01R_d^2}-1\right) & for\, 100\mu m < D \le 1000\mu m \\ 1.1 & D > 1000\mu m \end{cases} \quad \text{(B.20)}$$

Another commonly used formula for the settling velocity of natural noncohesive sediment particles is given by Cheng (1997) as the following function of D, ν, and R_d:

$$\frac{w_s D}{\nu} = \left(\sqrt{25+1.2\left(\frac{R_d}{\nu}\right)^{2/3}}-5\right)^{1.5} \quad \text{(B.21)}$$

To predict the noncohesive suspended sediment load in a water body, it is necessary to determine whether, for a given particle size and flow regime, the sediment is transported as bedload or as suspended load. van Rijn (1984a) presented the following approach for distinguishing between bedload and suspended load. When the bed shear velocity, u_*, is less than the critical shear velocity, u_{*cs}, no erosion is assumed to occur, and, therefore, no bedload transport occurs. Under this latter flow condition, any sediment in suspension whose critical shear velocity is greater than the bed shear velocity will deposit. When the bed shear velocity exceeds the critical shear velocity for a given particle size, erosion of that size (and smaller) sediment from the bed surface is assumed to occur. Therefore, if the following inequality is true, sediment will be transported as bedload (and not as suspended load):

$$u_{*cs} < u_* < w_s \tag{B.22}$$

Under this inequality condition, any suspended sediment whose critical shear velocity is greater than the bed shear velocity is assumed to deposit. If the bed shear velocity exceeds both the critical shear velocity and settling velocity for a given particle size, then that size sediment (and any smaller) is assumed to be eroded from the bed and transported as suspended load, and any sediment of that particle size (and smaller) already moving as bedload is assumed to be subsequently transported in suspension.

The rate of suspended load transport can be calculated as:

$$q_s = g\rho_s \int_a^d \overline{u}\overline{c}\,dz \tag{B.23}$$

where q_s = suspended load transport rate per unit width of the open channel (with units of kg/s), $\overline{u}$ = time-averaged velocity at a distance z above the bed, $\overline{c}$ = time-averaged suspended sediment concentration (by volume) at a distance z above the bed, and a = thickness of the bedload transport zone. Though not described in this report, Lane and Kalinske (1941), Einstein (1950), Brooks (1963), and Chang et al. (1965) developed alternative methods to calculate q_s.

The two general approaches used to calculate the total noncohesive sediment load in an open channel consist of: 1) adding the separately estimated bedload and suspended load, and 2) using a total load function that directly estimates the total amount of bedload and suspended load transport. Various formulations of the latter are briefly reviewed in this section. The advantage of using a total load approach is that sediment particles can be transported in suspension in one reach of an open channel and as bedload in another reach. In this section, only the unit stream power methods developed by Yang (1973) for estimating the total load will be presented.

The total sediment load function given by Equation B.17 is valid for total sand concentrations less than about 100 ppm by weight. For higher sediment concentrations, Yang (1979) presented the following total load equation, again based on the unit stream power concept:

$$\log C_{ts} = 5.165 - 0.153\log\frac{w_s D}{\nu} - 0.297\log\frac{u_*}{w_s} + \left(1.780 - 0.360\log\frac{w_s D}{\nu} - 0.480\log\frac{u_*}{w_s}\right)\log\frac{VS}{w_s} \quad \text{(B.24)}$$

Yang (1984) also presented the following total load equation based on unit stream power, which is applicable for gravel-sized sediment with median particle sizes between 2 and 10 mm:

$$\log C_{tg} = 6.681 - 0.633\log\frac{w_s D}{\nu} - 4.816\log\frac{u_*}{w_s} + \left(2.784 - 0.305\log\frac{w_s D}{\nu} - 0.282\log\frac{u_*}{w_s}\right)\log\left(\frac{VS}{w_s} - \frac{V_{cr}S}{w_s}\right) \quad \text{(B.25)}$$

For open channels that have bed sediment in the sand to medium gravel size range, i.e., between 0.063 and 10 mm, the total load would be the sum, depending on the value of C_{ts}, of either Equations B.17 and B.25 or Equations B.24 and B.25.

When the sediment transport capacity in a given reach of an open channel exceeds the total sediment load being transported from upstream reaches, the difference between the capacity and total load is supplied from the bed. This means that the channel will undergo erosion, i.e., degradation. In a natural open channel with nonuniform bed material, the finer surficial bed sediment will be eroded more rapidly than the coarser sediment. By this process, the median diameter of the surficial bed sediment becomes coarser. If the degradation continues, the finer surficial bed sediment will eventually be depleted, leaving a layer of coarser sediment on the bed surface. This process is called armoring, and the surficial layer of coarser sediment is called the armor layer.

Garcia and Parker (1991) developed the following approach that accounts for the effect of armoring to estimate the near-bed equilibrium concentration, C_{eq}, for bed material that consists of multiple, noncohesive sediment size classes:

$$C_{jeq} = \rho_s \frac{A\left(\lambda Z_j\right)^5}{\left(1 + 3.33A\left(\lambda Z_j\right)^5\right)} \tag{B.26}$$

where C_{jeq} = near-bed equilibrium concentration for the *j-th* sediment size class, $A = 1.3*10^{-7}$, and

$$\lambda = 1 + \frac{\sigma_\varphi}{\sigma_{\varphi o}}\left(\lambda_o - 1\right) \tag{B.27}$$

$$Z_j = \frac{u_*}{w_{sj}} R_{dj}^{3/5} F_H \tag{B.28}$$

$$F_H = \left(\frac{D_j}{D_{50}}\right)^{1/5} \tag{B.29}$$

where D_{50} = median particle size of the noncohesive bed sediment, σ_φ = standard deviation on the sedimentological phi scale of the bed sediment size distribution, $\lambda_o = 0.81$, and $\sigma_{\varphi o} = 0.67$ (Garcia and Parker 1991). F_H is referred to as a hiding factor.

The near-bed equilibrium concentration is the suspended sediment concentration at a reference height, z_{eq}, above the bed surface. It represents the maximum suspended sediment concentration. Some researchers take z_{eq} to be equal to a, i.e., thickness of the bedload transport zone, in Equation B.22. Einstein (1950) assumed that $z_{eq} = a = 2D_b$, where D_b was defined as the representative bed sediment grain size. van Rijn (1984b) assumed z_{eq} was equal to three grain diameters. DuBoys (1879) derived the following expression for the thickness of the bedload zone:

$$a = \frac{10\left(\tau - \tau_c\right)}{g(1-\lambda)\left(\rho - \rho_s\right)\tan\varphi} \tag{B.30}$$

where λ = porosity of bed material, and φ = angle of repose of the bed material.

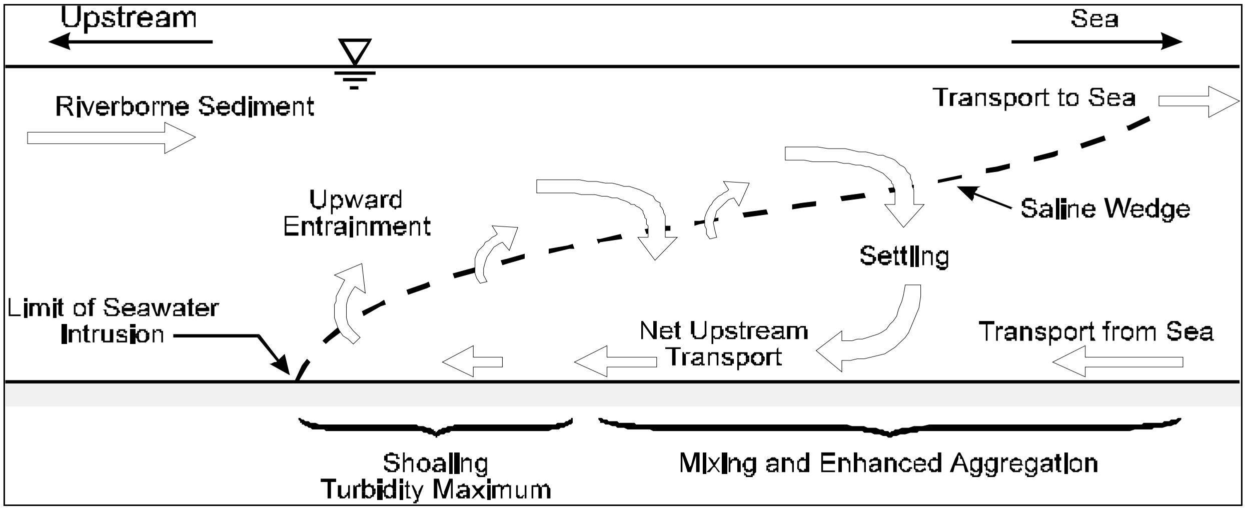
Cohesive sediment transport

The discussion in this section concentrates on cohesive sediment transport in estuaries. The difference between the description given here and that for cohesive sediment transport in rivers and lakes/reservoirs deals primarily with the hydrodynamics of the water bodies and the effect of salt water on the coagulation/flocculation process. The basic transport processes of erosion, advection, dispersion, settling, deposition, and consolidation are essentially the same in all types of water bodies. Thus, this brief overview of cohesive sediment transport processes in estuaries is, for the most part, relevant to all water bodies, and will provide the reader with an expanded description of sediment transport processes.

Cohesive (fine-grained) sediment transport, especially in estuaries and coastal waters, is a complex process involving a strong coupling among tides, baroclinic circulation, and the coagulated/flocculated sediment. For an extensive description of this process, the reader is referred to Postma (1967), Partheniades (1971), Barnes and Green (1971), Krone (1972), Kirby and Parker (1977), Kranck (1980), and Dyer (1986). Figure A.2 is a schematic depiction of the tidally-averaged sediment transport processes in a stratified (i.e., salt wedge) estuary, e.g., Lower Duwamish Waterway, Seattle, Washington. In the case of a partially mixed estuary (e.g., Chesapeake Bay) the description would have to be modified, i.e., there would not be a well-developed salt wedge, but since relatively steep vertical density gradients are sometimes present even in such a case, the sediment transport processes would generally remain qualitatively similar to that depicted.

As indicated in Figure B2, sediments from upstream freshwater sources arrive in the estuarial mixing zone. The high level of turbulence and the increasingly saline waters will cause flocs to form and grow in size as a result of frequent interparticle collisions and increased cohesion. The large flocs will settle to the lower portion of the water column because of their high settling velocities. Results from laboratory experiments show that floc settling velocities can be up to four orders of magnitude larger than the settling velocities of the individual particles (Bellessort 1973). Some of the sediment/flocs will deposit; the remainder will be carried upstream near the bottom until periods close to slack water when the bed shear stresses decrease sufficiently to permit deposition in the so-called turbidity maximum, after which the sediment starts to undergo self-weight consolidation. The depth to which the new deposit scours when the currents increase after slack will depend on the bed shear stresses imposed by the flow and the

Figure B2. Schematic representation of transport and sedimentation processes in the mixing zone of a stratified estuary (after Mehta and Hayter (1981)).



shear strength of the deposit. Net deposition, i.e., sedimentation, will occur when the bed shear during flood, as well as during ebb, is insufficient to resuspend, i.e., erode, all of the material deposited during preceding slack periods. Some of the sediment that is resuspended may be re-entrained throughout most of the length of the mixing zone to levels above the seawater-freshwater interface, and subsequently transported downstream. At the seaward end, some material may be transported out of the estuary, a portion of which could ultimately return with the net upstream bottom current.

In the mixing zone of a typical estuary, the sediment transport rates often are an order of magnitude greater than the rate of inflow of new sediment derived from upland or oceanic sources. The estuarial sedimentary regime is characterized by several periodic (or quasi-periodic) macro-time-scales, the most important of which are the tidal period (diurnal, semi-diurnal, or mixed) and one-half the lunar month (spring-neap-spring cycle). The tidal period is the most important since it is the fundamental period that characterizes the basic mode of sediment transport in an estuary. The lunar month is often significant in determining net sedimentation rates.

From a Eulerian point of view, the superposition of oscillating tidal flows on the quasi-steady state transport phenomenon depicted in Figure B2 results in corresponding oscillations of the suspended sediment concentration with time as shown in Figure B3. Such a variation of the suspended load ultimately results from a combination of advective and dispersive transport, erosion, and deposition. Because of the complexity of the phenomenon, more than one interpretation is possible as far as any schematic representation of these phenomena is concerned. One such representation is shown in Figure B4.

Figure B3. Time and depth variation of suspended sediment concentration in the Savannah River estuary (after Krone (1972)).

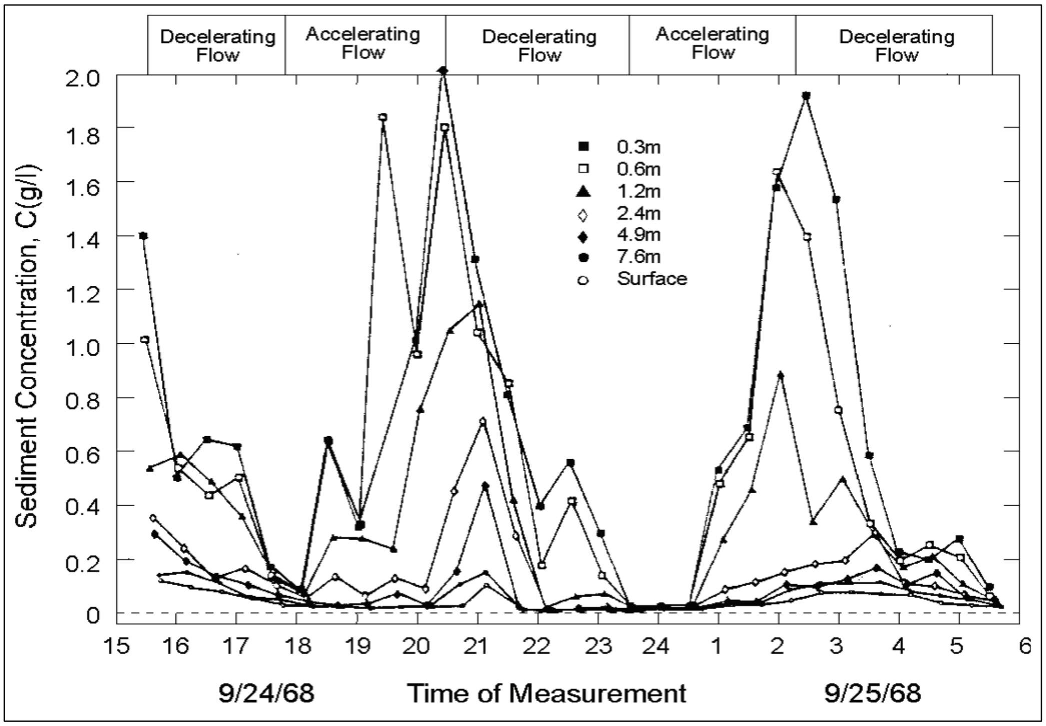
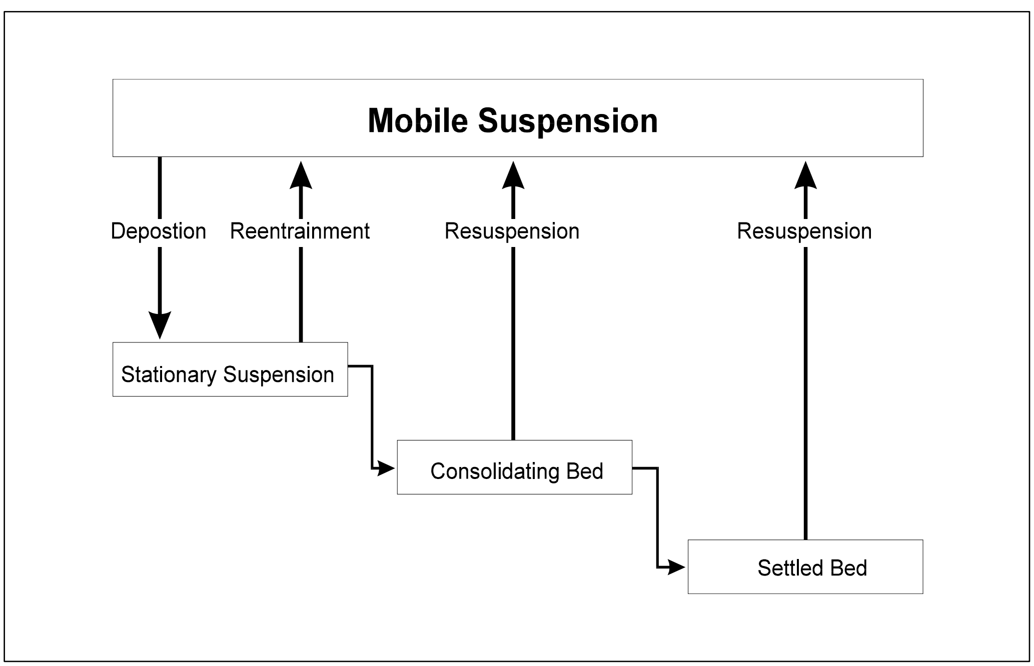


Figure B4. Schematic representation of the physical states of cohesive sediment in an estuarial mixing zone (after Mehta et al. (1982a)).



According to this description, cohesive sediment can exist in four different physical states in an estuary: mobile suspension, stationary suspension, partially consolidated bed, and settled bed. The last two are formed as a result of consolidation of a stationary suspension. Stationary here implies little horizontal movement. A stationary suspension, a partially consolidated bed, and a settled bed can erode if the shear stress exceeds a certain critical value. Erosion of a stationary suspension is referred to as redispersion or mass erosion, whereas erosion of a partially consolidated bed or a settled bed is termed either resuspension or surface erosion.

To summarize, the sediment transport regime is controlled by the hydrodynamics, the chemical composition of the fluid, and the physico-chemical properties of the cohesive sediment. These factors affect the processes of erosion, advection, dispersion, flocculation, settling, deposition, and consolidation. A brief description of these processes follows that of cohesive sediment beds.

A flow-deposited bed of cohesive sediment flocs possesses a vertical density and bed shear, i.e., yield, strength profile. The average values of bed density and bed shear strength increase and their vertical profiles change with time, primarily due to consolidation and secondarily due to thixotropy and associated physicochemical changes affecting inter-particle forces. Consolidation is caused by the gravitational force of overlying deposited flocs (overburden) that crushes, and thereby decreases, the order of flocculation of the underlying sediment.

Consolidation changes the erosive behavior of cohesive sediment beds in two ways: (1) as the shear strength of the bed increases due to consolidation, the susceptibility of the bed to erosion decreases, and (2) the vertical shear strength profile determines the depth into the bed that a bed will erode when subjected to excess shear, i.e., an applied bed shear stress in excess of the bed surface shear strength.

Estuarial sediment beds, typically composed of flow-deposited cohesive sediment, can be assumed to occur in three different states: stationary suspensions, partially consolidated beds, and settled (or fully consolidated) beds (see Figure B4). Stationary suspensions are defined by Parker and Lee (1979) as assemblages of high concentrations of sediment particles that are supported jointly by the water and developing skeletal soil framework and have no horizontal movement. These suspensions develop whenever the settling rate of concentrated mobile suspensions exceeds the rate of self-weight consolidation (Parker and Kirby 1982). They tend to have a high water content (therefore low *bulk density*) and a very low shear strength that must be at least as high as the bed shear that existed during the deposition period (Mehta et al. 1982a).

Thus, they exhibit a definite non-Newtonian rheology. Kirby and Parker (1977) found that the stationary suspensions they investigated had a surface bulk density of approximately 1050 kg/m^3 and a layered structure.

Whether redispersion of these suspensions occurs during periods of erosion depends upon the mechanical shear strength of the floc network. That portion of the flocs remaining on the bed undergoes: 1) self-weight consolidation, and 2) thixotropic effects, defined as the slow rearrangement of deposited flocs attributed to internal energy and unbalanced internal stresses (Mitchell 1961), both of which reduce the order of flocculation of sub-surface bed layers. This implies that the bed becomes stratified with respect to density and shear strength, with both properties typically increasing monotonically with depth, at least under laboratory conditions (Mehta et al. 1982a).

Continued consolidation eventually results in the formation of settled mud, defined by Parker and Lee (1979) as "assemblages of particles predominantly supported by the effective contact stresses between particles as well as any excess pore water pressure." This portion of the bed has a lower water content, lower order of flocculation, and higher shear strength. The settled mud in the Severn Estuary and Inner Bristol Channel, United Kingdom, was found to possess a bulk density ranging from 1300 to 1700 kg/m^3 (Kirby and Parker 1983). The nature of the density and shear strength profiles typically found in cohesive sediment beds has been revealed in laboratory tests by, among others, Richards et al. (1974), Owen (1975), Thorn and Parsons (1980), Parchure (1980), Bain (1981), Dixit (1982), and Burt and Parker (1984). A review of this subject is given by Hayter (1983).

Erosion of cohesive sediment occurs whenever the shear stress induced by water flowing over the sediment bed is great enough to break the electrochemical interparticle bonds (Partheniades 1965, Paaswell 1973). When this happens, erosion takes place by the removal of individual sediment particles and/or flocs. This type of erosion is time-dependent and is defined as surface erosion or resuspension. In contrast, another type of erosion occurs more or less instantaneously by the removal or entrainment of relatively large pieces of the bed. This process is referred to as mass erosion or redispersion, and occurs when the flow-induced shear stresses on the bed exceed the sediment bed bulk strength along some deep-seated plane.

A number of laboratory investigations were carried out in the 1960's and 1970's in order to determine the rate of resuspension, ε, defined as the mass of sediment eroded per unit bed surface area per unit time as a function of bed shear in steady, turbulent flows. An important conclusion from those tests was that the usual soil indices, such as liquid and plastic limit, do not adequately describe the erosive behavior of these sediments (Mehta 1981). For example, Partheniades (1962) concluded that the bed shear strength as measured by standard tests, e.g., the direct-shear test (Terzaghi and Peck 1960), has no direct relationship to the sediment's resistance to erosion that is essentially governed by the strength of the interparticle and inter-floc bonds.

The sediment composition, pore and eroding fluid compositions, and structure of the flow-deposited bed at the onset of erosion must be determined in order to properly define the erosion resistance of the bed. Sediment composition is specified by the grain size distribution of the bed material (i.e., weight fraction of clays, silts), the type of clay minerals present, and the amount and type of organic matter. The compositions of the pore and eroding fluids are specified by the temperature, pH, total amounts of salts, and type and abundance of ions present, principally Cl^-, Na^+, Ca^{2+}, and Mg^{2+}. Cementing agents, such as iron oxide, can significantly increase the resistance of a sediment bed to erosion. Measurement of the electrical conductivity is used to determine the total salt concentration in the pore and eroding fluids. The effect of the bed structure, specifically the vertical sediment density and shear strength profiles, on the rate of erosion is discussed by Lambermont and Lebon (1978) and Mehta et al. (1982a).

The erosive forces, characterized by the flow-induced instantaneous bed shear stress, are determined by the flow characteristics and the surface roughness of the fluid-bed interface. Several different types of relationships between the rate of erosion, ε, and the time-mean value of the flow-induced bed shear stress, τ_b, have been reported for non-stratified beds. These include statistical-mechanical models (Partheniades 1965, Christensen

1965), a rate process model (Paaswell 1973, Kelley and Gularte 1981), and empirical relationships (Ariathurai and Arulanandan 1978).

Ariathurai and Arulanandan (1978) found the following general relationship for the resuspension rate of consolidated beds:

$$\varepsilon = M'\left(\frac{\tau_b - \tau_c}{\tau_c}\right) \tag{B.31}$$

where $M' = M\tau_c$, where M is termed the erodibility constant, τ_b is the flow-induced bed shear stress, and τ_c is the bed shear strength. The term inside the parentheses on the right-hand side of Equation B.31 is referred to as the normalized excess bed shear stress. Values for M and τ_c are normally determined using either laboratory tests (Parchure 1984), or using a device such as the SEDFLUME (McNeil et al. 1996).

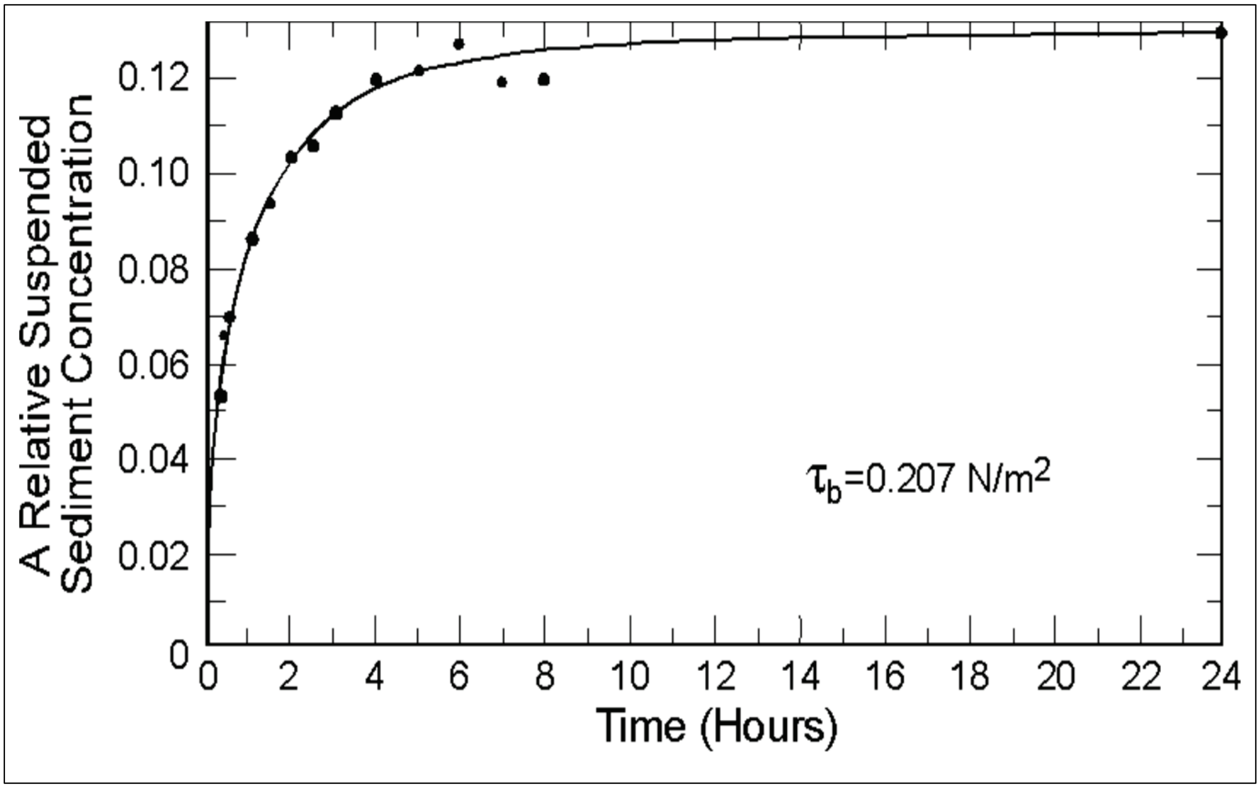
Gailani et al. (1991) found the following relationship between the resuspension potential, E, defined as the total mass of sediment that can be resuspended at a given shear stress, and the normalized excess shear stress:

$$\mathrm{E} = \frac{a_o}{t_d^n}\left[\frac{\tau_b - \tau_c}{\tau_c}\right]^m \tag{B.32}$$

where t_d = time after deposition of sediment in units of days; and a_o, n, m, and τ_c are sediment-specific empirical coefficients. It is stated that n and m are approximately equal to 2 and 3, respectively.

Figure B5 shows the measured variation of C, expressed as a relative concentration by dividing the measured suspended sediment concentration by the initial suspended sediment concentration before a flow-deposited bed was formed, with time typically found by several investigators (Partheniades 1962, Mehta and Partheniades 1979, Mehta et al. 1982a) in laboratory resuspension tests with flow-deposited (i.e., stratified) beds under a constant τ_b. As observed, dC/dt is high initially, decreases monotonically with time, and appears to approach zero. The value of τ_c at the depth of erosion at which dC/dt, and therefore ε that is proportional to dC/dt, becomes essentially zero has been interpreted to be equal to τ_b (Mehta et al. 1982a). This interpretation is based on the hypothesis that erosion continues as long as $\tau_b > \tau_c$. Erosion is arrested at the bed level at

Figure B5. Relative suspended sediment concentration versus time for a stratified bed (after Mehta and Partheniades (1979)).



which τ_b - τ_c = 0. This interpretation, coupled with measurement of $\rho_B(z_b)$, i.e., the dry bed density profile, and the variation of C with time resulted in an empirical relationship for the rate of erosion of stratified beds. Utilizing this above approach, resuspension experiments with deposited beds were performed by Parchure (1980) in a rotating annular flume and by Dixit (1982) in a recirculating straight flume. The following empirical relationship between ε and τ_b - $\tau_c(z_b)$ was derived from these experiments:

$$\varepsilon = \varepsilon_o \exp\left[\alpha \frac{\tau_b - \tau_c(z_b)}{\tau_c(z_b)}\right] \tag{B.33}$$

where ε_o and α are empirical resuspension coefficients. This relationship is analogous to the rate expression that results from a heuristic interpretation of rate process theory for chemical reactions (Mehta et al. 1982a). Christensen and Das (1973), Paaswell (1973), and Kelley and Gularte (1981) have used the rate process theory in explaining the erosional behavior of cohesive sediment beds. By analogy, ε is a quantitative measure of the work done by τ_b on the system, i.e., the bed, and ε_o and $\alpha/\tau_c(z_b)$ are measures of the system's internal energy, i.e., bed resistance to an applied external force.

An important conclusion reached from these experiments was that new deposits should be treated differently from consolidated beds (Mehta et al. 1982a). The rate of surface erosion of new deposits is best evaluated using Equation B.33, while the erosion rate for settled beds is best determined using Equation B.31, in which ε varies linearly with the normalized excess bed shear stress. The reasons for this differentiation in determining ε are twofold. First, typical τ_c and ρ_B profiles in settled beds vary less significantly with depth than in new deposits, and may even be nearly invariant. Therefore, the value of $\left(\tau_b / \tau_c\right) - 1 = \Delta\tau_b^*$ will be relatively small. For $\Delta\tau_b^* << 1$ the exponential function in Equation B.31 can be approximated by $\alpha \cdot \left(1 + \Delta\tau_b^*\right)$ that represents the first two terms in the Taylor series expansion of $\exp\left(\alpha \cdot \Delta\tau_b^*\right)$. Thus, for small values of $\Delta\tau_b^*$ both expressions for ε vary linearly with $\Delta\tau_b^*$ and, therefore, the variation of ε with depth in settled beds can be just as accurately and more simply determined using Equation B.31. Second, the laboratory resuspension tests required to evaluate the coefficients ε_o and α for each partially consolidated bed layer cannot be easily performed using vertical sections of an original settled bed (obtained from cores). Ariathurai and Arulanandan (1978) describe a simpler laboratory test that can be used to evaluate the variability of M with depth.

Parchure and Mehta (1985) developed the following relationship for ε that is applicable for soft, cohesive sediment deposits such as the top, active layer of sediment beds in estuaries:

$$\varepsilon = \varepsilon_f \exp\left[\alpha\left(\tau_b - \tau_s\right)^{1/2}\right] \quad \text{(B.34)}$$

where ε_f = floc erosion rate (gm/m^2-s), τ_s = bed shear strength (Pa), and α = a factor that can be shown to be inversely proportional to the absolute temperature (Parchure 1984). ε_f is defined to be the erosion rate when the time-averaged bed shear stress is equal to the bed shear strength, i.e., $\tau_b = \tau_s$. Even under this condition, some erosion of particles or flocs will occur due to the stochastic nature of turbulence and, therefore, in the instantaneous value of τ_b.

Jepsen et al. (1997) studied the effect of sediment bulk density on erosion rates of three different types of sediment during which the bulk densities of the sediment were experimentally determined as a function of depth into the sediment core for consolidation times varying from 1 to 60 days. The experiments were performed in a SEDFLUME (McNeil et al. 1996) during which the gross erosion rates were measured as a function of bed shear stress and depth into the core (from which the bulk density could be determined). The gross erosion rate, E, was approximated as a function of the bulk density and bed shear stress by the following equation:

$$E = A\tau^{n}\rho^{m} \qquad \text{(B.35)}$$

For the three sediments tested, n varied from 1.89 to 2.23; m varied from -45 to -95; and A varied from 3.65x10^3 to 2.69x10^6. This equation for the gross erosion rate implicitly accounted for the effect of consolidation by including the time- and depth-varying bulk density as one of the independent parameters.

Sea salt is a mixture of salts, with monovalent sodium ions and divalent calcium and magnesium ions prevalent as natural electrolytes. The sodium adsorption ratio (SAR), defined as,

$$SAR = \frac{Na^{+}}{\left[\frac{1}{2}\left(Ca^{2+} + Mg^{2+}\right)\right]^{1/2}} \qquad \text{(B.36)}$$

is a measure of the relative abundance of the three mentioned salts (cations). The cation concentrations in this equation are in milliequivalents per liter. Sherard et al. (1972) have shown that the susceptibility of a cohesive sediment bed to erosion depends on two factors: 1) the pore fluid composition, as characterized by the SAR; and 2) the salinity of the eroding fluid. It was found that, as the eroding fluid salinity decreases, soil resistivity to resuspension decreases. In addition, Kandiah (1974) and Arulanandan et al. (1975) found that erosion resistance decreased and the rate of resuspension increased with increasing SAR (and therefore decreasing valency of the salt cations) of the pore fluid.

Once eroded from the bed, cohesive sediment is transported mostly as suspended load, though clumps of cohesive sediment (i.e., mud) rolling along the bottom of both laboratory flumes and shallow rivers have been observed. The latter form of transport cannot be predicted at present. The transport of both unflocculated and flocculated cohesive sediment in suspension is the result of three processes: 1) advection - the sediment is assumed to be transported at the speed of the local mean flow; 2) turbulent diffusion - driven by spatial suspended sediment concentration gradients, the material is diffused laterally across the width of the flow channel, vertically over the depth of flow, and longitudinally in the direction of the transport; and 3) longitudinal dispersion - the suspended sediment is dispersed in the flow direction by spatial velocity gradients (Ippen 1966).

The principle of conservation of mass with appropriate source and sink terms describes the advective and dispersive transport of suspended sediment in a turbulent flow field. This principle, expressed by the advection-dispersion equation, says that the time-rate of change of mass of sediment in a stationary control volume is equated to the spatial rate of change of mass due to advection by an external flow field plus the spatial rate of change of mass due to turbulent diffusion and dispersion processes. The three-dimensional form of the advection-dispersion transport equation is:

$$\begin{aligned}\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+(w-w_{sc})\frac{\partial C}{\partial z}&=\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial C}{\partial x}+K_{xy}\frac{\partial C}{\partial y}+K_{xz}\frac{\partial C}{\partial z}\right]\\&+\frac{\partial}{\partial y}\left[K_{yx}\frac{\partial C}{\partial x}+K_{yy}\frac{\partial C}{\partial y}+K_{yz}\frac{\partial C}{\partial z}\right]+\frac{\partial}{\partial z}\left[K_{zx}\frac{\partial C}{\partial x}+K_{zy}\frac{\partial C}{\partial y}+K_{zz}\frac{\partial C}{\partial z}\right]+S_T\end{aligned} \quad \text{(B.37)}$$

where K_{ij} = effective sediment dispersivity tensor, and S_T = the net source/sink term that accounts for source(s) (i.e., addition) of sediment to the water column due to erosion and other inputs, and sink(s) (i.e., loss) of sediment due to deposition and other removals. Implicit in this equation is the assumption that suspended material has the same velocity as the water. Sayre (1968) verified the reasonableness of this assumption for sediment particles less than about 100 µm in diameter. Rolling and saltation of sediment that occur during bed load transport can result in a significant difference between the water and sediment velocities. Therefore, the assumption of equal velocity is not applicable to bed load. The net source/sink term in Equation B.37 can be expressed as:

$$S = \left.\frac{dC}{dt}\right|_e + \left.\frac{dC}{dt}\right|_d + S_L \quad \text{(B.38)}$$

where $\left.\frac{dC}{dt}\right|_e$ is the rate of sediment addition (source) due to erosion from the bed, and $\left.\frac{dC}{dt}\right|_d$ is the rate of sediment removal (sink) due to deposition of sediment. S_L accounts for removal (sink) of a certain mass of sediment, for example, by dredging in one area (e.g., a navigational channel) of a water body, and/or dumping (source) of sediment as dredge spoil in another location.

The dispersive transport terms in Equation B.37 include the effects of spatial velocity variations in bounded shear flows and turbulent diffusion. Thus, the effective sediment dispersivity tensor in Equation B.37 must include the effect of all processes whose scale is less than the grid size of the model, or, in other words, what has been averaged over time and/or space (Fischer et al. 1979).

Turbulent diffusion is defined as "the transport in a given direction at a point in the flow due to the difference between the true advection in that direction and the time average of the advection in that direction," and dispersion is defined as "the transport in a given direction due to the difference between the true advection in that direction and the spatial average of the advection in that direction" (Holley 1969). Holley delineates the fact that diffusion and dispersion are both actually advective transport mechanisms, and that in a given flow field, the relative importance of one mechanism over the other depends on the magnitude of the concentration gradient. In Equation A.37, the effective sediment dispersion coefficients are equal to the sum of the turbulent diffusion and dispersion coefficients. This approach follows the analysis of Aris (1956), which showed that the coefficients due to turbulent diffusion and shear flow (dispersion) were additive. Thus, analytical expressions used for the effective sediment dispersion tensor should represent both diffusion and dispersion.

Fischer (1966) showed that the dispersion of a given quantity of tracer injected into a natural stream is divided into two separate phases. The first is the convective period in which the tracer mixes vertically, laterally, and longitudinally until it is completely distributed across the stream. The second phase is the diffusive period during which the lateral, and possibly the vertical (depending on the nature of the tracer), concentration gradient is small, and the longitudinal concentration profile is highly skewed.

Equation B.37 is strictly valid only in the diffusive period. The dispersing tracer is in the diffusive period if it has been in the flow longer than the Lagrangian time scale and has spread over a distance wider than the Lagrangian length scale (Fischer et al. 1979). The latter scale is a measure of the distance a particle travels before it forgets its initial conditions (i.e., initial position and velocity).

Analytical expressions for the sediment (mass) diffusion coefficients can be obtained by analogy with the kinematic eddy viscosity. The Reynolds analogy assumes that the processes of momentum and mass transfer are similar, and that the turbulent diffusion coefficient and the kinematic eddy viscosity are linearly proportional. Jobson and Sayre (1970) verified the Reynolds analogy for sediment particles in the Stokes range (less than about 100 μm in diameter). They found that the "portion of the turbulent mass transfer coefficient for sediment particles that is directly attributable to tangential components of turbulent velocity fluctuations: (a) is approximately proportional to the momentum transfer coefficient and the proportionality constant is less than or equal to 1; and (b) decreases with increasing particle size." Therefore, the effective sediment mass dispersion coefficients for cohesive sediment may be justifiably assumed to be equal to those for the water itself.

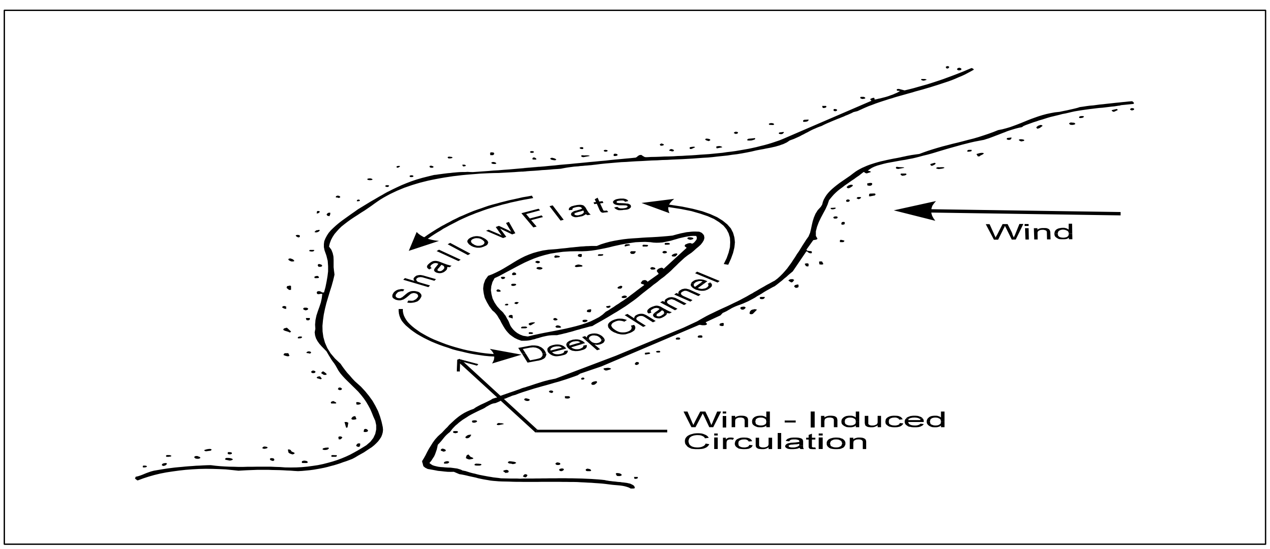
Fischer et al. (1979) define four primary mechanisms of dispersion in estuaries: 1) gravitational circulation, 2) shear-flow dispersion, 3) bathymetry-induced dispersion, and 4) wind-induced circulations. The last three mechanisms occur in freshwater water bodies as well. Gravitational or baroclinic circulation in estuaries is the flow induced by the density difference between freshwater at the landward end and seawater at the ocean end. There are two types of gravitational circulation. Transverse gravitational circulation is depth-averaged flow that is predominantly seaward in the shallow regions of a cross section and landward in the deeper parts. The interaction between the cross-sectional bathymetry and baroclinic flow causes the transverse circulation. Vertical gravitational circulation occurs with predominantly seaward flow in the upper part of the water column and landward flow in the lower part of the water column. Fischer (1972) states that vertical gravitational circulation is more important than transverse circulation only in highly stratified estuaries.

The mechanism of shear-flow dispersion is thought to be the dominant mechanism in long, fairly uniform sections of well-mixed and partially stratified estuaries (Fischer et al. 1979). Holley et al. (1970) concluded that for wide estuaries, the effect of the vertical velocity distribution on shear-flow dispersion is dominant over that of the transverse velocity distribution. The exact opposite situation was found for relatively narrow estuaries.

The joint influence of bathymetry and density differences on dispersion has already been mentioned in reference to baroclinic circulation. Other examples of bathymetry-induced dispersion include: intrusion of salinity or sediment into certain parts of a cross section caused by channelization of flood and ebb tides in tidal inlets or estuaries (Fischer et al. 1979), and enhanced dispersion of dissolved substances (e.g., a contaminant) or intrusion of salinity into tidal flats and side embayments that then serve as storage areas for these substances, caused by the out-of-phase flow that occurs between the main channel and such features (Okubo 1973).

An example of wind-induced circulation is shown in Figure B6. Here, the steady onshore wind causes circulation in the wind direction in a shallow bay, where the smaller water mass per unit surface area results in a higher acceleration and, therefore, quicker response to the wind-induced surface stresses, and circulation in the opposite direction in the deeper sections of the channel. Such a circulation can cause significant dispersion (Fischer et al. 1979).

Figure B6. Illustration of wind-induced circulation (adapted from Fischer et al. (1979))



The settling rate of coagulated sediment particles depends, in part, on the size and density of the flocs, and, as such, is a function of the processes of coagulation and flocculation (Owen 1970). Therefore, the factors that govern these two processes also affect the settling rate of the resulting flocs. The settling velocities of flocs can be several orders of magnitude larger than those of individual clay particles (Bellessort 1973). For flocs from 10 to 1,000 µm in size, settling velocities have been found to range from 10^{-5} to 10^{-1} m/s (Dyer 1989).

The following four settling zones have been identified for flocs: free settling, flocculation settling, hindered settling, and negligible settling. In the free settling zone, the settling velocities are independent of the suspension concentration. In the flocculation zone, the settling velocities increase with increasing suspension concentration due to increased interparticle collisions that result in the formation of larger and denser flocs. In the hindered settling zone, the upward transport of interstitial water is inhibited (or hindered) by the high suspension concentration.

This, in turn, results in a decrease in the floc settling velocity with increasing suspension concentration. At the upper end of the hindered settling zone, the suspension concentration near the bed is so high that no settling of flocs occurs.

Hwang (1989) proposed the following expressions for the floc settling velocity:

$$w_{sf} = \begin{cases} w_{sf} & for\, C < C_1 \\ a_w \dfrac{C^{n_w}}{\left(C^2 + b_w^2\right)^{m_w}} & for\;\; C_1 < C < C_3 \\ 1.1 & C > C_3 \end{cases} \tag{B.39}$$

where w_{sf} = free settling velocity, a_w = velocity scaling coefficient, n_w = flocculation settling exponent, b_w = hindered settling coefficient, m_w = hindered settling exponent, C_1 = concentration between the free settling and flocculation settling zones, C_3 = concentration at the upper limit of the hindered settling zone, and though not included in Equation A.39, C_2 = concentration between the flocculation and hindered settling zones (where w_{sf} is maximum). Ranges of values for C_1, C_2, and C_3 are 100 - 300 mg/L, 1,000 - 15,000 mg/L, and on the order of 75,000 mg/L, respectively (Krone 1962, Odd and Cooper 1989).

Shrestha and Orlob (1996) developed the following expression for the settling velocity of flocs that accounts for the effect of both the suspension concentration and flow shear:

$$w_{sf} = C^{\alpha} \exp\left(-4.21 + 0.147G\right) \tag{B.40}$$

where $\alpha = 0.11 + 0.039G$, and $G = \sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2}$; i.e., G is the magnitude of the vertical shear of the horizontal velocity.

Burban et al. (1990) found that the settling velocity of flocs was related to the following power law function of the median floc diameter, D_f:

$$w_{sf} = aD_f^m \tag{B.41}$$

where $a = B_1(CG)^{-0.85}$ and $b = -[0.8+0.5\log(CG-B_2)]$ with B_1 and B_2 = experimentally determined constants.

Deposition of flocs occurs relatively quickly during slack water. Settling and deposition also occur in slowly moving and decelerating flows, as was observed in the Savannah River Estuary (refer back to Figure B3) during the second half of flood and ebb flows (Krone 1972). Under these flow conditions, only those flocs with shear strengths of sufficient magnitude to withstand the highly disruptive shear stresses in the near bed region will actually deposit and adhere to the bed. Thus, deposition is governed by the bed shear stresses, turbulence structure above the bed, settling velocity, type of sediment, depth of flow, suspension concentration, and ionic constitution of the suspending fluid (Mehta and Partheniades 1973). Specifically, deposition has been defined to occur when τ_b is not high enough to resuspend sediment material that settles onto and bonds with the bed surface. This process, therefore, involves two other processes, settling and bonding.

Laboratory studies on the depositional behavior of cohesive sediment in steady turbulent flows have been conducted by, among others, Krone (1962), Rosillon and Volkenborn (1964), Partheniades (1965), Lee (1974), Mehta and Partheniades (1975), Mehta et al. (1982b), Mehta and Lott (1987), Shrestha and Orlob (1996), and Teeter (2000).

The most commonly used expression for the sediment mass deposition rate, given initially by Einstein and Krone (1962), is:

$$\frac{dC}{dt} = -\frac{w_{sc}C}{d}\left(1 - \frac{\tau_b}{\tau_{cd}}\right) \quad \text{(B.42)}$$

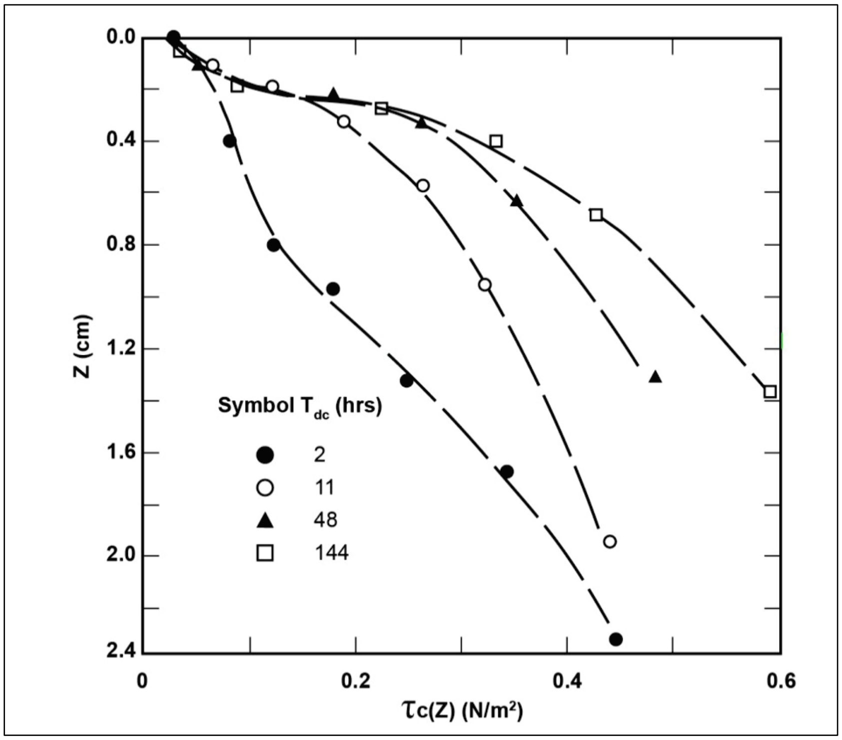
where τ_{cd} = critical shear stress for deposition, above which no deposition occurs. The value of τ_{cd} was found to be equal to 0.06 Pa for San Francisco Bay mud with C < 300 mg/L (Krone 1963), and values from 0.02 to 0.2 Pa have been reported in the literature. Mehta and Lott (1987) found Equation B.42 to agree reasonably well with laboratory data for suspended sediment concentrations up to approximately 1,000 mg/L.

A cohesive sediment bed is formed when deposited sediment particles and/or flocs comprising a stationary suspension begin to interact and form a soil that transmits an effective stress by virtue of particle-to-particle contacts. The self-weight of the particles, as well as deposition of additional material, brings the particles closer together by expulsion of pore water between the particles. A soil is formed when the water content of the sediment-water suspension decreases to the fluid limit. Unfortunately, there is not a unique water content value for cohesive soils at which the suspension changes into a soil (Been and Sills 1981).

During the transition from suspension to soil, an extremely compressible soil framework or skeleton develops (Been and Sills 1981). The strains involved in this first stage of consolidation are relatively large and can continue for several days or even months. The straining and upward expulsion of pore water gradually decreases as the soil skeleton continues to develop. Eventually, this skeleton reaches a state of equilibrium with the normal stress component of the overlying sediment (Parker and Lee 1979).

During the early stages of consolidation, the self-weight of the soil mass near the bed surface is balanced by the seepage force induced by the upward flow of pore water from the underlying sediment. As the soil continues to undergo self-weight consolidation and the upward flux of pore water lessens, the self-weight of this near-surface soil gradually turns into an effective stress. This surface stress and the stress throughout the soil will first crush the soil floc structure and then the flocs themselves. Primary consolidation is defined to end when the excessive pore water pressure has completely dissipated (Spangler and Handy 1982). Secondary consolidation that can continue for many weeks or months is the result of plastic deformation of the soil under its overburden.

Figure B7. Bed shear strength versus distance below the initial bed surface for various consolidation periods (after Dixit (1982)).



Geomorphology

Rosgen (1996) states the following:

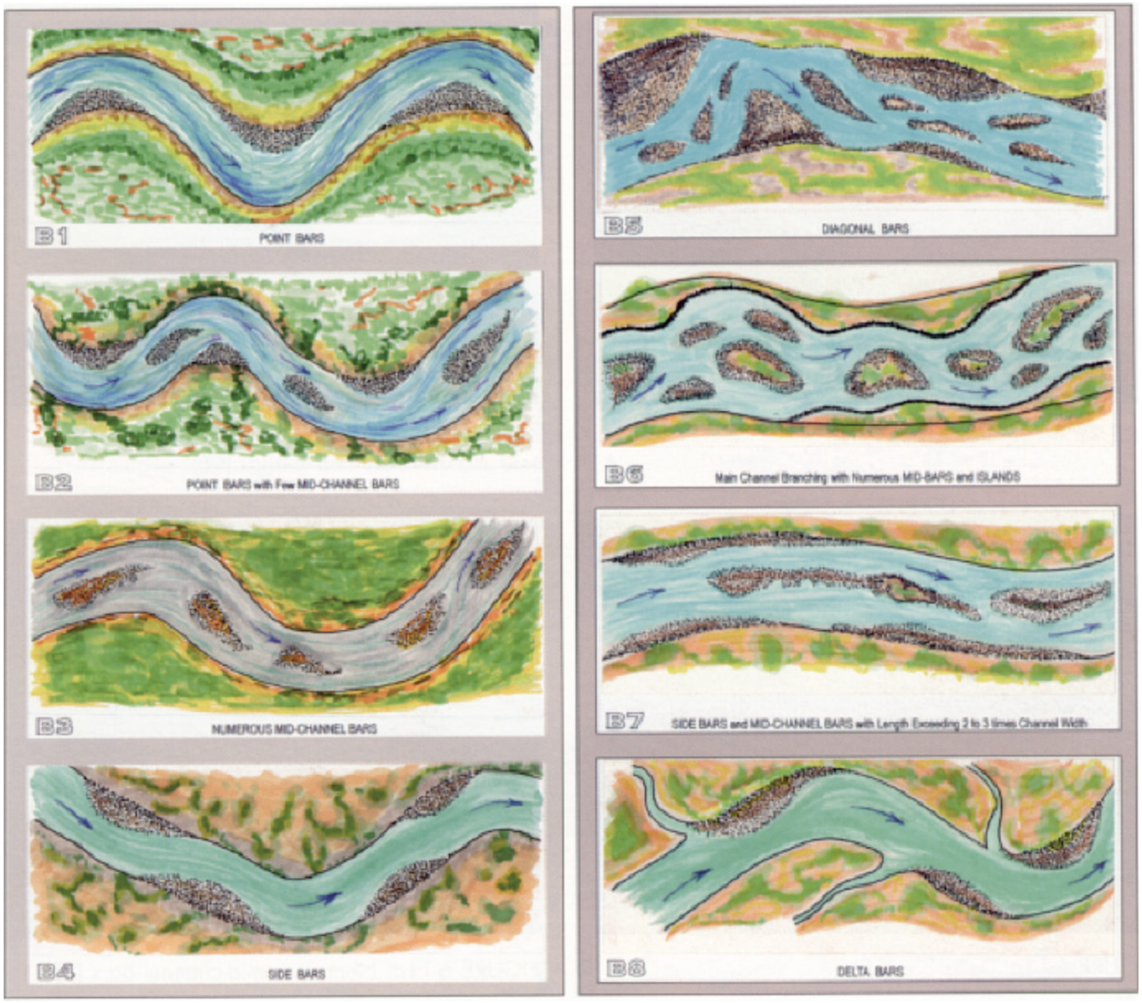
> The morphology of the modern river reflects not only the events of the past, but also the streamflow and sediment regime determined by climate and landform. The fundamental components of river morphology are its dimension, pattern, and profile. These components represent the integrated response of a river that enables it to be in balance with the prevailing energy gradients, sediment supply, and sediment transport characteristics. Stream systems can be described with increasing detail at subsequent levels of organization by identifying the driving variables at finer scales of resolution.

In this section, abbreviated descriptions of four morphological features of rivers and streams - bars, riffles and pools, meanders, and channel debris - are presented. These same features are often found in parts of other bodies of water, e.g., estuaries, as well. The term channel, which is frequently used in the following material, is a generic term for any water body in which water is moving due to gravity, tides, winds, or waves. The reader is referred to Rosgen (1996) and Leopold (1994) for more information on geomorphology of water bodies.

Bars are depositional features with lengths of the same magnitude as the channel width and with heights of the same magnitude as the mean flow depth. Several types of bars form in streams and rivers. Point bars are sediment deposits that form on the inside of bends in the channel (see Figure B8). Alternate side bars form on opposite sides of the channel, e.g., first along the left bank and then a short distance downstream along the right bank (see Figure B8), and normally move slowly in the downstream direction. Mid-channel bars usually form near the middle of the river and slowly move in the downstream direction (see Figure B8). Diagonal bars are wider side bars (see Figure B8) that usually occur along with numerous mid-channel bars. Delta bars are deposits of sand that form immediately downstream of the mouth of a tributary (see Figure B8) to a larger river or estuary.

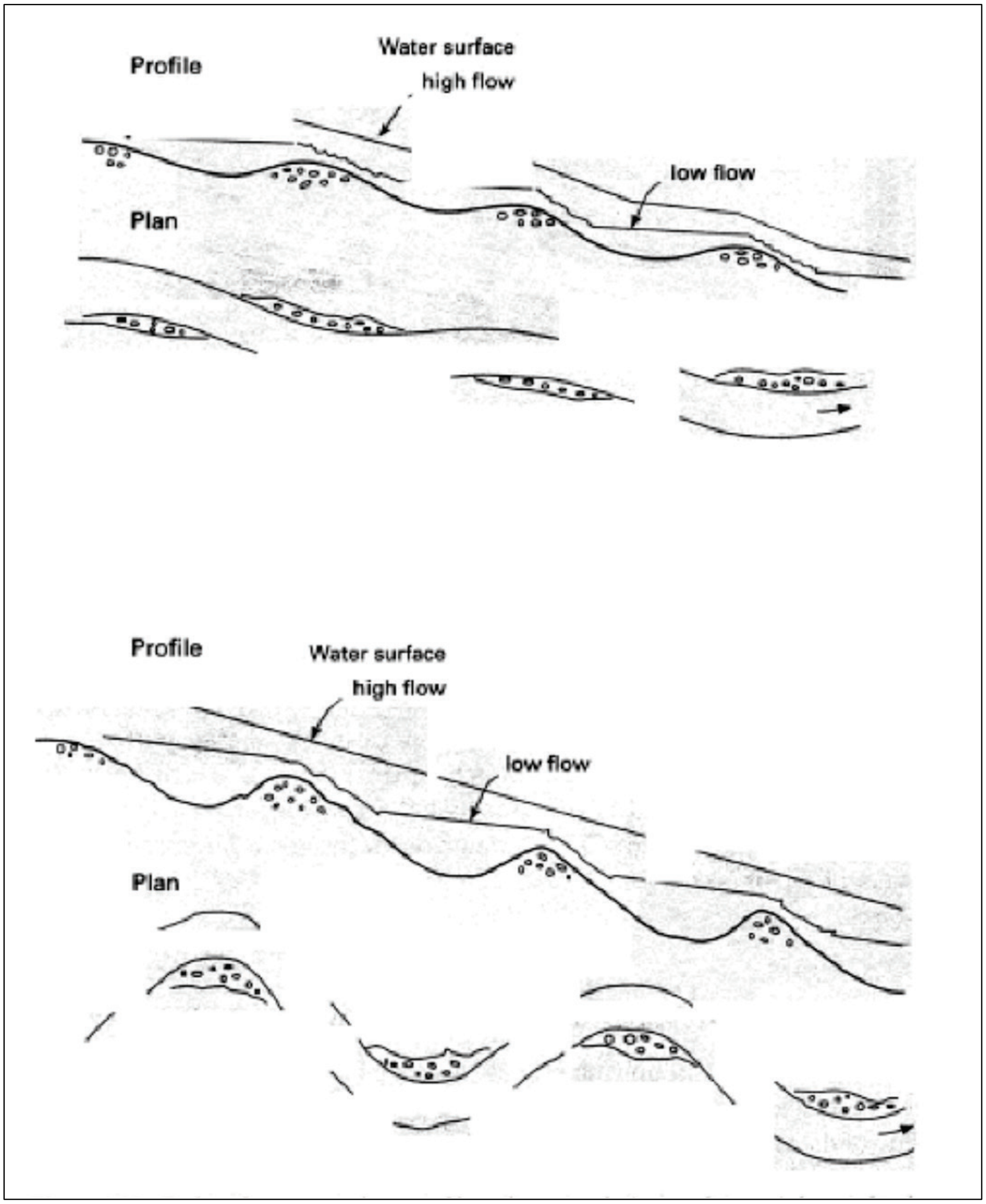
In most natural channels in which the bed material is larger than coarse sand, the bed elevation undulates between shallow areas (called riffles) and deep areas (called pools) in the longitudinal direction. Riffles are mounds of sediment (ranging in size from fine gravel to large boulders) on the channel bottom. The spacing between pools and riffles is on the order of five to seven channel widths (Leopold 1994). This spacing occurs in both straight and meandering channels. In meandering channels, the pools are found on the outside half of bends due to degradation of the channel bottom and outside channel bank. Leopold suggests that the similarity in spacing of riffles and pools in both straight and meandering channels implies that the processes that create the tendency for meandering are present even in straight channels. Figure B9 is a schematic sketch of a riffle-pool sequence in both a straight (top sketch) and meandering channel (bottom sketch). The plan views show the locations of alternate bars. For the meandering channel, the alternate bars would be termed pointbars. The small circles in Figure B9 below the crest of riffles indicate that the bed material found at riffles is larger than that found at pools. Leopold (1994) also notes the following two observations about riffles/pools: 1) the downstream movement of riffles in gravel-bed channels appears to be relatively slow, and 2) some degree of heterogeneity of bed material size appears to be required for riffles and pools to form in non-meandering channels.

Figure B8. Types of bars (after Rosgen (1996)).



Eight categories of meander patterns are depicted in Figure B10. These categories are the following: M1 - regular meander; M2 - tortuous meander; M3 - irregular meander; M4 - truncated meander; M5 - unconfined meander scrolls; M6 - confined meander scrolls; M7 – distorted meander loops; and M8 - irregular with oxbows and oxbow cutoffs (Rosgen 1996). Meandering is a natural morphological response of a river. Some of the factors that cause/affect the onset and degree of meandering include: 1) difference in channel and valley gradients; 2) degree of valley confinement; 3) valley topography; and 4) erosion-resistant side slopes and/or valley slopes. The latter factor leads to M4 and/or M6 type meanders. Highly irregular topography can lead to the development of M8 meanders. Rosgen (1996) states the following regarding the importance of understanding the morphologic structure of meanders:

Figure B9. Bed and water surface profiles showing riffle - pool sequence in a straight and meandering channel (after Leopold (1994)).



Meander geometry relationships are useful for designing channel restoration and interpreting channel adjustment processes, such as avulsion and lateral accretion rates. Meander patterns can be analyzed to indicate the potential onset of disequilibrium and evolutionary adjustments in an appropriate stream type. Meander geometry interpretations can be used to assess the effects of changes in width/depth ratios, bank erosion estimates, sediment supply, and changes in pattern, dimension, and slope on channel stability.

Figure B10. Illustrations of eight categories of meander patterns (after Rosgen (1996)).

More information on meander patterns is given by Mollard (1973), Galay et al. (1973), and Rosgen (1985).

Leopold (1994) examined the occurrence of meanders from an energy perspective. He discussed the relationship of: 1) meander wave length to channel width and curvature, 2) radius of curvature to energy loss by friction, 3) shape of the meander to the distribution of energy use, and 4) energy use to distance along the meandering channel. It is important to remember the following pertinent points:

- Channels in which bounded shear flow occurs are "transporting machines" in that potential energy at the upstream end is changed to kinetic energy along the channel length. Some of the kinetic energy does work in transporting sediment and eroding bed material, and the remainder of the energy is transformed into heat through the action of friction and turbulence along the channel boundaries.
- A channel is an open system (as the term is used in thermodynamics) in that (typically) both influxes and effluxes of mass occur over a defined channel reach.
- The utilization of energy in an open system conforms to the laws of physics, i.e., conservation of energy and mass.
- Open systems have the characteristic that they tend toward the condition of minimum work (i.e., minimum energy expenditure) and that of uniform distribution of work (or energy use) as water flows down the channel. However, it is not possible for both of these conditions to be satisfied simultaneously, so a compromise toward the most probable state must be reached. This compromise explains many features of open channel mechanics, and is exhibited in, for example, the formation of meanders (Rosgen 1996).
- Bends in a channel cause at least as large a flow resistance as all other forms of roughness, i.e., skin friction and form drag. This is consistent with the fact that the average relation of radius of meander curvature to channel width minimizes the resistance to flow, i.e., minimum energy loss (see Leopold (1994) for a discussion of this principle).

Leopold (1994) proposed that the theory of minimum variance explains the formation and development of meanders and presented the following discussion of this hypothesis:

> The processes of erosion and deposition are carried out by forces of shear closely associated with the distribution of velocity. If any local point is an area of unusually large shear, erosion occurs. A local lowering in shear is a place of reduced transport or deposition. The end result is an averaging of the anomalies and an approach to the most probable state, or the locus of minimum variance. When many adjustable factors are operative, as in rivers, minimum variance is a term that includes the variance of several factors simultaneously. All factors participate, and no one factor takes a larger fraction of the total adjustment.

Leopold concludes his discussion with the hypothesis that "meanders represent a most probable configuration that is a compromise between minimum total work and uniform distribution of power expenditure." It is important to keep this in mind when evaluating the stability of a channel and when estimating the nonpoint source sediment load from eroding banks of a meandering channel, such as the eroding banks shown in Figure B11.

Figure B11. Eroding banks along a meandering reach of the Housatonic River, MA.

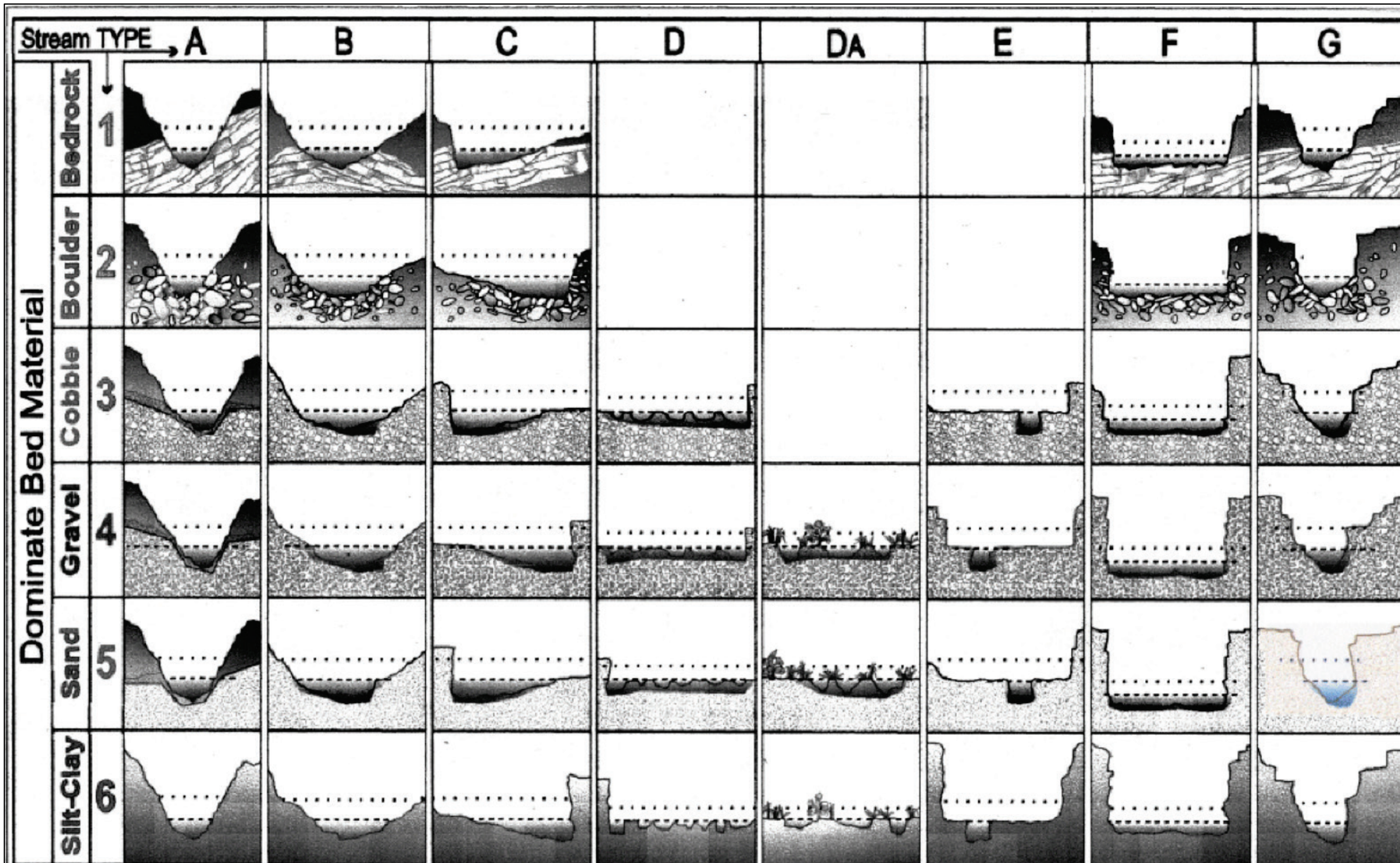
Debris in channels normally consists of organic materials such as limbs, branches, and tree trunks. The latter enter channels due to the activity of beavers and channel bank erosion, which causes trees to fall into the river. Such debris can have a profound effect on the stability of channels, on their W/D ratios, *bank erosion*, aggradation/degradation processes, and fish habitat (Rosgen 1996). Debris dams that typically span the width of the channel and consist of tree trunks and smaller materials often cause a pooling effect, i.e., backwater, upstream of the dam. At several debris dams along the South Fork Broad River, GA, and its tributaries, local scour holes (often more than 1 m deep) are frequently found underneath these dams. The scour holes are produced by the eroding force of the flow that plunges underneath and around the debris. Backwater often occurs upstream of beaver dams as well. Rosgen (1996) states that channel types (discussed in the next section) such as A1, A2, and B1-B6 can withstand a significant quantity of organic debris and dam-induced flow blockages without incurring adverse effects. However, riffle/pool channel types such as C3-C6, D3-D6, and E3-E6 can be adversely impacted.

Channel classification

The Rosgen (1996) methodology for classifying the morphology of streams and rivers, which is the most familiar and widely used classification method, is briefly described in this section. The objectives of this classification system are to: 1) "predict a river's behavior from its appearance," 2) "develop specific hydraulic and sediment relationships for a given stream type and its state," 3) "provide a mechanism to extrapolate site-specific data to stream reaches having similar characteristics," and 4) "provide a consistent frame of reference for communicating stream morphology and condition among a variety of disciplines and interested parties." The Rosgen channel morphology classification uses channel sinuosity (i.e., amount or degree of meandering), channel slope (i.e., gradient), *entrenchment* ratio, width-to-depth ratio of the bankfull cross-section, bed material particle size, and degree of confinement or constraint to lateral movement. Channel sinuosity is defined as the ratio of channel length to down-valley distance, and the entrenchment ratio is the width of the floodplain at an elevation twice the bankfull depth (Rosgen 1996). The entrenchment ratio is a measure of the degree of vertical containment of the channel. The basis of the Rosgen classification is a four-level hierarchical river inventory system. Level I is a geomorphic characterization that uses channel slope (including valley slope and channel sinuosity), channel shape (e.g., narrow/deep versus wide/shallow), and channel patterns (e.g., single thread, multiple thread, anastomosed) to define nine stream types - designated as types Aa+, A, B, C, D, DA, E, F, and G. Table B1 defines the Level I geomorphic characterization.

Level II is the morphological description. The following characteristics of the channel cross-section, longitudinal profile, and planform features are accounted for in the Level II delineation criteria: entrenchment ratio, width/depth (W/D) ratio, dominant channel sediment material (as quantified by d_{50}), water surface slope, bed features, sinuosity, and meander width ratio. Figure B12 shows stream types A through G, as defined in Table B1, and six classes of dominant bed material. As seen in

Figure B12. Primary delineative criteria for Level II stream types (after Rosgen (1996)).



Stream TYPE	A	B	C	D	DA	E	F	G
Entrchmnt.	< 1.4	1.4 - 2.2	> 2.2	n/a	> 4.0	> 2.2	< 1.4	< 1.4
W/D Ratio	< 12	> 12	> 12	> 40	< 40	< 12	> 12	< 12
Sinuosity	1 - 1.2	> 1.2	> 1.2	n/a	variable	> 1.5	> 1.2	> 1.2
H_2O Slope	.04-.099	.02-.039	< .02	< .04	<.005	< .02	< .02	.02-.039

Table B1. Rosgen Level I stream type classification (adapted from Rosgen (1996)).

Stream Type	General Description	Entrenchment Ratio	W/D Ratio	Sinuosity	Slope	Landform/ Soils/Features
Aa+	Very steep, deeply entrenched, debris transport, torrent streams.	< 1.4	< 12	1.0 to 1.1	> 0.1	Very high relief. Erosional, debris flow potential. Deeply entrenched streams. Vertical steps with deep scour pools.
A	Steep, entrenched, cascading, step/pool streams. High debris transport associated with depositional soils. Very stable if bedrock or boulder dominated.	< 1.4	< 12	1.0 to 1.2	0.04 to 0.1	High relief. Erosional or depositional and bedrock forms. Entrenched and confined streams with cascading reaches. Frequently spaced, deep pools in associated step/pool bed morphology.
B	Moderately entrenched, moderate gradient, riffle-dominated channel, with infrequently spaced pools. Stable plan, profile, and banks.	1.4 to 2.2	> 12	> 1.2	0.02 to 0.039	Moderate relief, colluvial deposition, and/or structure. Moderate entrenchment and W/D ratio. Narrow, gently sloping valleys. Rapids predominate with scour pools.
C	Low-gradient, meandering, point-bar, riffle/pool, alluvial channels with broad, well-defined floodplains.	> 2.2	> 12	> 1.4	< 0.02	Broad valleys with terraces, in association with floodplains, alluvial soils. Slightly entrenched with well-defined meandering channels. Riffle/pool bed morphology.
D	Braided channels with longitudinal and transverse bars. Very wide channel with eroding banks.	n/a	> 40	n/a	< 0.04	Broad valleys w/alluvium, steeper fans. Glacial debris and depositional features. Active lateral adjustment, aggradational processes, high bedload and bank erosion.
DA	Anastomosing narrow and deep w/extensive, well-vegetated floodplains and wetlands. Very gentle relief with highly variable sinuosities and W/D ratios. Very stable streambanks.	> 2.2	Highly variable	Highly variable	< 0.005	Broad, low-gradient valleys w/fine alluvium and/or lacustrine soils. Anastomosed geologic control creating fine deposition w/vegetated bars that are laterally stable with broad floodplains. Very low bedload, high waste load sediment.
E	Low-gradient, meandering riffle/ pool stream w/low W/D ratio and little deposition. Very efficient and stable. High meander width ratio.	> 2.2	< 12	> 1.5	< 0.02	Broad valley/meadows. Alluvial materials with floodplains. Highly sinuous with stable, well-vegetated banks. Riffle/pool morphology with very low W/D ratios.

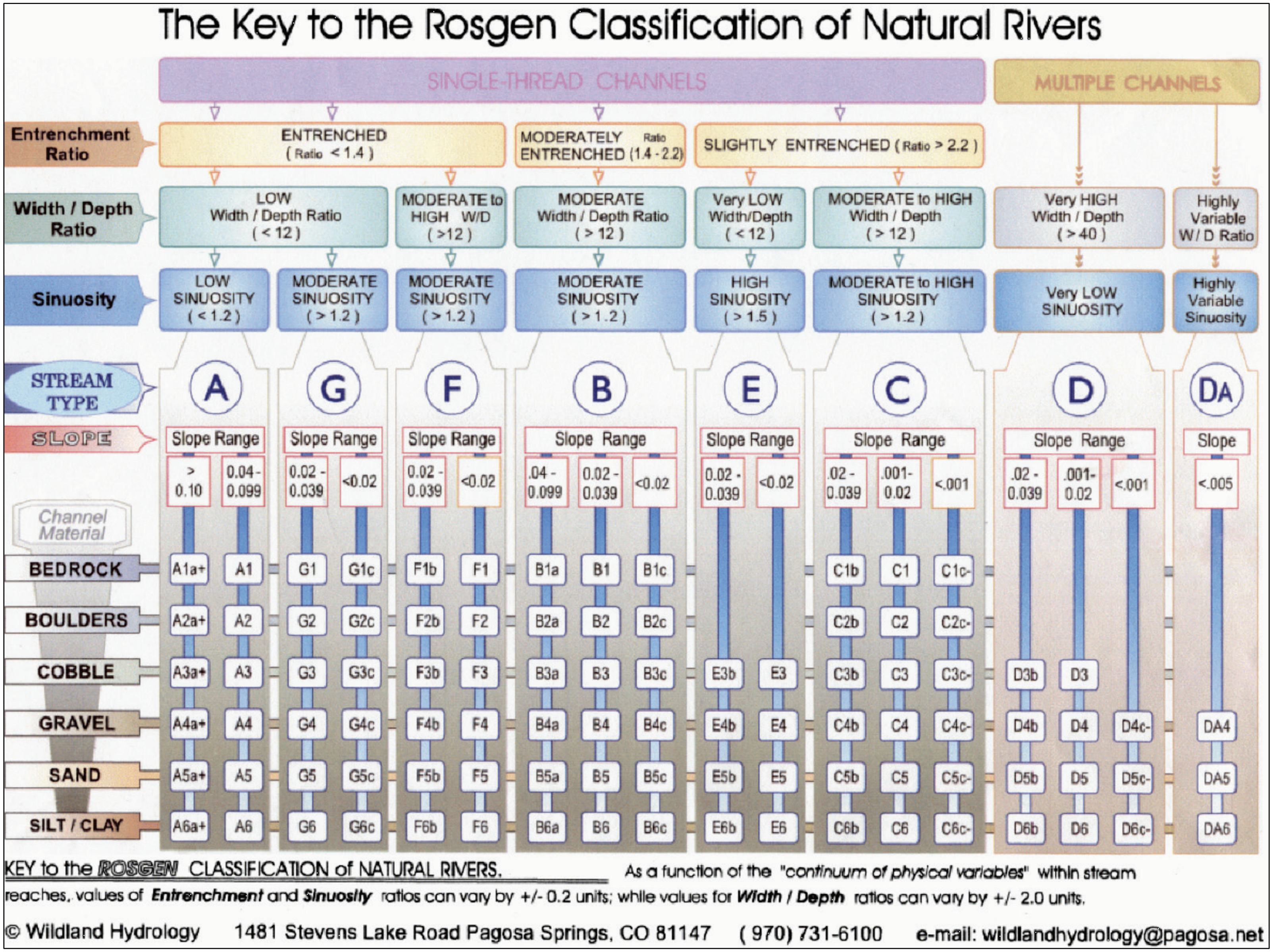
Stream Type	General Description	Entrenchment Ratio	W/D Ratio	Sinuosity	Slope	Landform/ Soils/Features
F	Entrenched meandering riffle/pool channel on low gradients with high W/D ratio.	< 1.4	> 12	> 1.4	< 0.02	Entrenched in highly weathered material. Gentle gradients, with a high W/D ratio. Meandering, laterally unstable w/high bank erosion rates. Riffle/pool morphology.
G	Entrenched "gully" step/pool and low W/D ratio on moderate gradients.	< 1.4	< 12	> 1.2	0.02 to 0.039	Gullies, step/pool morphology with moderate slopes and low W/D ratio. Narrow valleys, or deeply incised in alluvial or colluvial materials, i.e., fans or deltas. Unstable, with grade control problems and high bank erosion rates.

this figure, the six classes are bedrock, boulder, cobble, gravel, sand, and silt-clay, and there are a total of 41 stream types, i.e., A1 - A6, B1 - B6, C1 - C6, D3 - D6, Da4 - Da6, E3 - E6, F1 - F6, and G1 - G6. Note the morphologic criteria (i.e., entrenchment, W/D ratio, and sinuosity) and hydraulic criterion (i.e., water surface slope) given at the bottom of this figure.

Figure B13 further expands on the classification methodology by providing a key or structure to assist in determining the type of a particular river. For example, a multiple-channel river is either going to be a D or DA type. The main difference between these two types of multiple channels is the sinuosity - a D type has a very low sinuosity whereas a DA type has a highly variable sinuosity. A D type channel is further classified depending on the gradient of the channel (e.g., D6b, D6, D6c) and the type of channel bed material (e.g., D3b, D4b, D5b, D6b). A single-thread river is going to be an A, G, F, B, E, or C type channel. Starting at the top of Figure B13, if the channel's entrenchment ratio is less than 1.4, then it is an A, G, or F type channel. If the channel's W/D ratio is less than 12, then it is either an A or G type. If the channel's sinuosity is greater than 1.2, then it is a G type. Continuing further down the figure, the channel's slope and predominant bed material determine which one of the 12 G types (i.e., G1 through G6c) the channel would be classified as. This example illustrates the distinction between the Level I and Level II stream classification.

Level III analyses define the stream state or condition. The objectives of the Level III analysis are the following: 1) "develop a quantitative basis for comparing streams having similar morphologies, but which are in different states or conditions," 2) "describe the potential natural stability of a stream,

Figure B13. Level II classification key (after Rosgen 1996).



as contrasted with its existing condition," 3) "determine the departure of a stream's existing condition from a reference baseline," 4) "provide guidelines for documenting and evaluating additional field parameters that influence stream state (e.g., flow regime, stream size, sediment supply, channel stability, bank erodibility, and direct channel disturbances)," 5) "provide a framework for integrating companion studies (e.g., fish habitat indices, and composition and density of riparian vegetation)," 6) "develop and/or refine channel stability prediction methods," and 7) "provide the basis for efficient Level IV validation sampling and data analyses" (Rosgen 1996). The parameters accessed in this level include riparian vegetation, flow regime, channel debris, stream size and order, streambank erosion potential, channel stability, depositional pattern, meander patterns, aggradation/degradation trends, and altered channel features. Rosgen (1996) defines what he terms companion inventories that are used to evaluate these parameters. The companion inventories access the following characteristics: aquatic and terrestrial habitats, riparian successional processes, aquatic habitat inventories, fish viability evaluations, hydraulic studies, nonpoint pollution sources, sediment budgets, cumulative watershed effects, and restoration priorities.

As stated previously, the Level III analysis includes determination of the channel condition and its departure from its potential state. Rosgen (1996) defines channel potential as the "best channel condition, based on quantifiable morphological characteristics, for each stream type." Rosgen also states that the following methods can be used to used to determine a channel's degree of departure from its "full operating potential": 1) compare the channel's condition to that of similar channel types to determine if one or more geomorphic criteria are within or outside of the defined range of desired parameter values; 2) compare historical photographs of the channel to determine if the current state/condition of the channel is noticeably altered, and if so, the photographs may help determine the factor(s) that caused the change; and 3) compare the channel condition at different locations (both upstream and downstream) along the channel to evaluate anthropogenic and/or naturally caused changes to the channel.

Level IV analyses are conducted to "verify process-based assessments of stream condition, potential, and stability as predicted from preceding analyses" (Rosgen 1996). The channel condition is verified by analyses (using data collected/measured in the channel) of sediment condition, channel flow, and channel stability measurements. The data used to perform these analyses can also be used to "establish empirical relationships for testing, validating, and improving the prediction of velocity, hydraulic geometry, sediment transport characteristics, bank erosion rates, and channel stability" (Rosgen 1996). In addition, data on fish populations can often be related to the channel morphology and condition.

The reader should refer to Rosgen (1996) for a very detailed (and expertly illustrated) description of the Rosgen method for classification of rivers and other water bodies.

Channel adjustments: Channel evolution and succession

Two channel evolution models are briefly described in this section. The author has seen the types of channel adjustments described below in both rivers and estuaries. As seen in Figure B14a, Simon and Hupp (1986) defined six stages of channel evolution. Kuhnle and Simon (2000) state that "disturbances in parts of the watershed resulting in dramatic shifts in the amount of sediment delivered to the channel system will manifest themselves in diagnostic characteristics of channel form such as bank failures, tree stems buried by deposited sediment, and actively growing bars and berms." Such increases in the sediment delivery rate (input) can disrupt the dynamic equilibrium of the channels in the watershed, the result of which are changes in channel geometry. Destabilization of channels usually results in degradation of upstream channel reaches and aggradation of downstream reaches. Simon and Hupp (1986) defined the pre-disturbed Stage I (see Figure B14) to be in dynamic equilibrium. A channel in a state of dynamic equilibrium is one in which the flow-induced shear stress along the wetted perimeter is balanced by the resisting force due to skin friction and form drag. Stage II is defined to be the perturbed condition, with Stage III being the evolutionary stage at which the channel undergoes relatively rapid degradation. As indicated in Figure B14A, the bottom elevation of the channel decreases in Stage III due to the degradation process. The latter results in milder channel gradients that in turn reduce the available stream power. As depicted in this figure, banks are often steepened during this stage. The steepening is due to fluvial undercutting and pore-pressure-induced bank failures near the toe of the bank (Kuhnle and Simon 2000). The consequence is often bank failure (Stage IV) when bank heights and slope angles exceed the bank material's critical shear strength. Bank failure by this mechanism is referred to as mass-wasting, and leads to channel widening. It is during this mass-wasting and channel-widening process that trees that had been growing on the banks fall into channels (as depicted in

Figure B14. Channel evolution (A) and bank-slope (B) development models for alluvial channels (after Simon and Hupp (1986)).

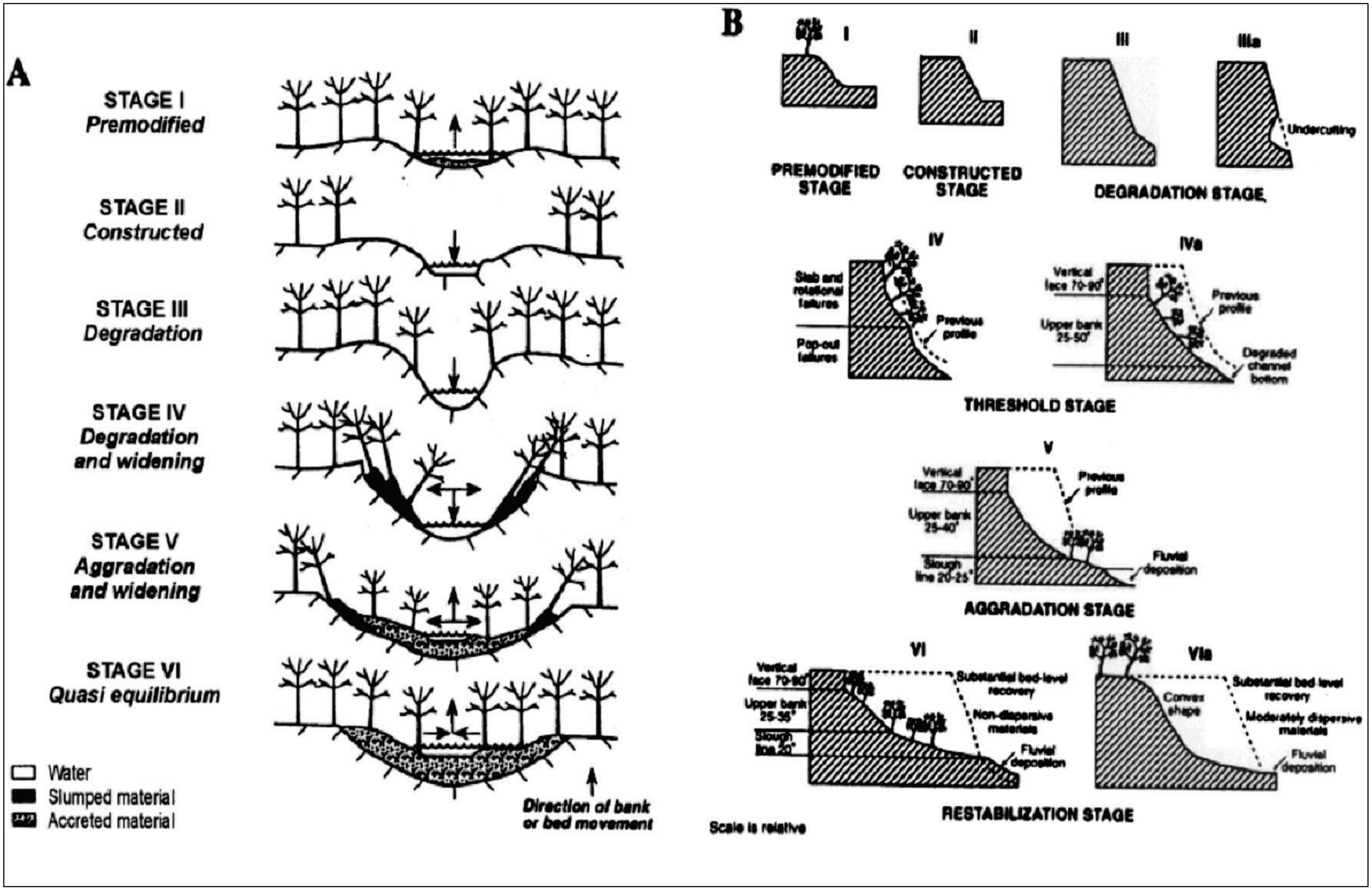


Figure B14A). [The reader should also study the bank slope evolution schematic shown in Figure B.14B.] The next stage, Stage V, is associated with aggradation and continued widening as the degradation processes that occurred in Stage IV migrate downstream. The degraded channel's gradient is less steep, and thus the resulting decreased stream power cannot transport the sediment loads from degrading channel reaches further upstream; thus, aggradation occurs. Simon (1992) found that this aggradation process typically occurs at rates approximately 69% less than the preceding degradation rate. Kuhnle and Simon (2000) state that "these milder aggradation rates indicate that bed level recovery will not be complete and that attainment of a new dynamic equilibrium (Stage VI) will take place through (1) further bank widening and the consequent flattening of bank slopes, (2) the establishment and proliferation of riparian vegetation that adds roughness elements, enhances bank accretion, and reduces the stream power for given discharges, and (3) further gradient reduction by meander extension and elongation."

Rosgen (1996) states that channels adjust, i.e., evolve, over time in response to changes or alterations in the hydrologic, hydraulic, and geomorphic driving forces, and that the rate of channel adjustment varies significantly. The adjustment rate depends on initial channel type and magnitude of the altered driving force (or physiographic process). The latter include "climate change, adverse watershed impacts, vegetative composition changes, reservoir construction, and direct channel disturbances" (Rosgen 1996). This author has observed numerous instances of bank collapse from cattle that walk down the banks to get into the channel. Rosgen states that this type of land and channel use can result in a shift in stream type. One example of a commonly observed channel adjustment/evolution due to an imposed change in bank stability is illustrated in Figure B15 as five progressive stages (from E4 to C4 to G4 to F4 and back to E4). Note both the plan and cross-section views in this figure, and the similarity to the evolutionary stages defined in Figure B14. Figure B16 shows more detail of the changes from one channel type to another. Numerous other sequences of channel evolution have also been observed to occur. For example, Rosgen (1996) states that G channel types located on alluvial fans can evolve to B channel types when degradation processes cause moderate entrenchment and an increase in the W/D ratio, and emerging riparian vegetation stabilizes the banks.

Figure B15. Channel adjustment through five progressive stages (after Rosgen (1996)).

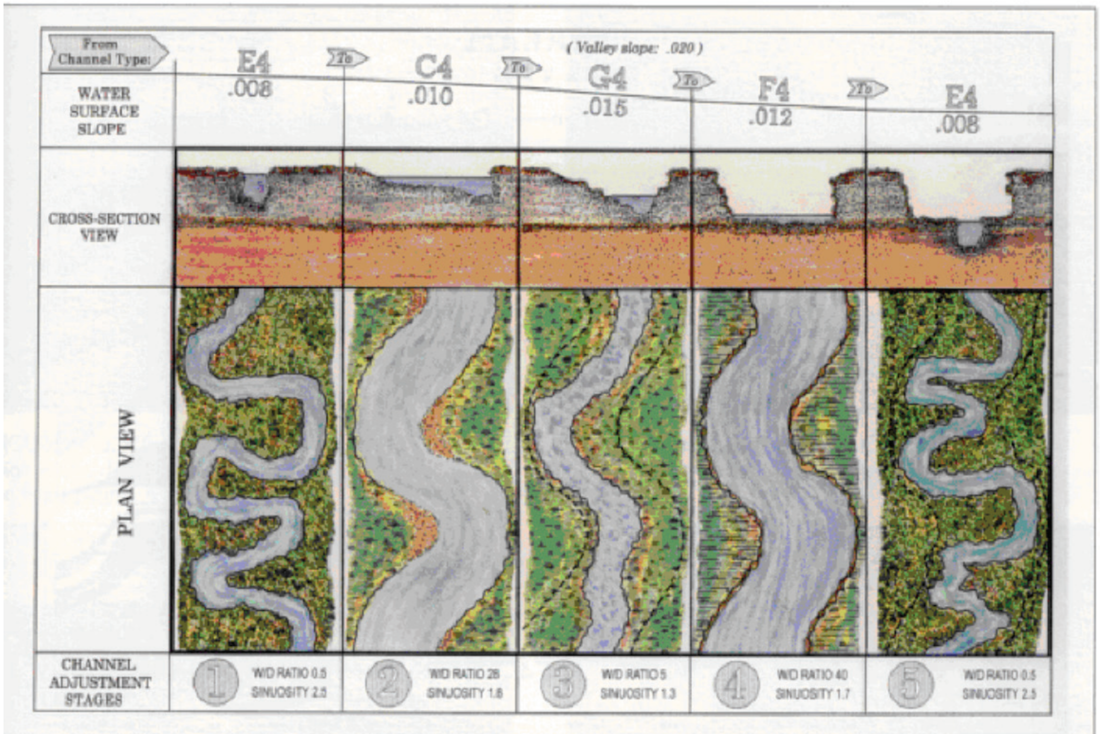
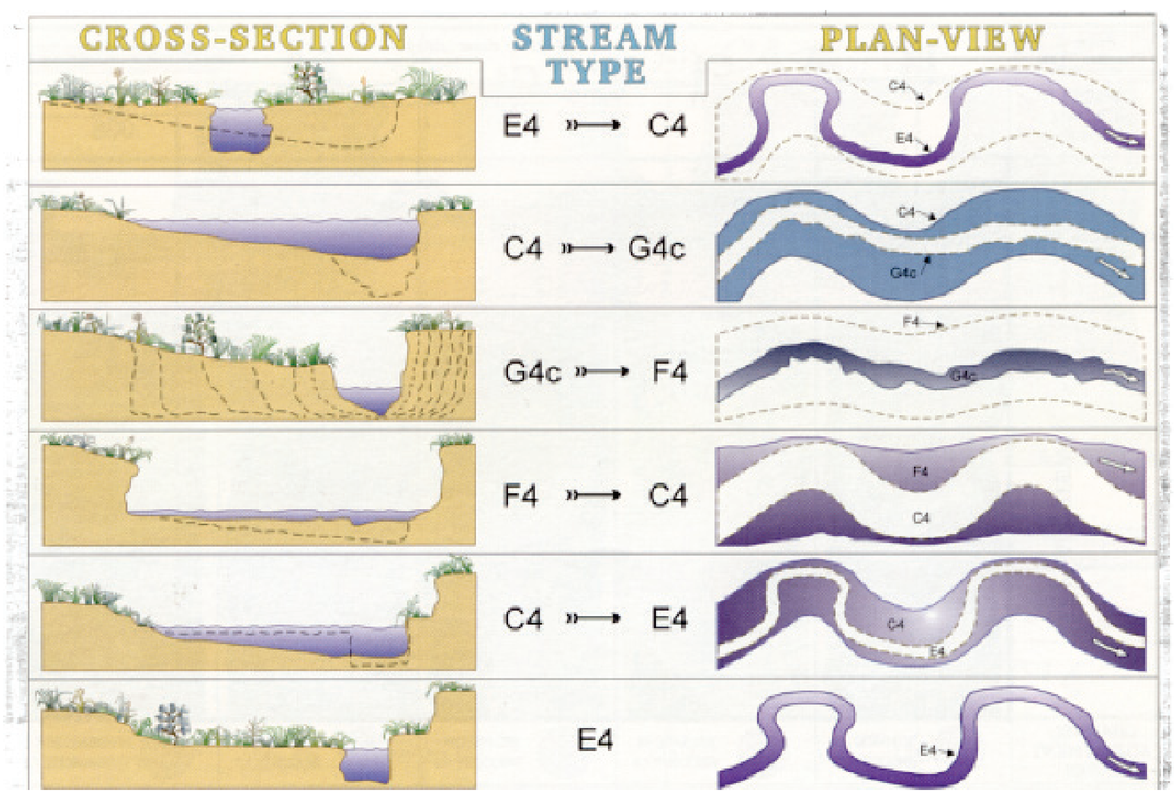


Figure B16. Adjustment of channel cross-sections and plan-view patterns through five progressive stages (after Rosgen (1996)).



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Appendix C: Types of Water Bodies and Applicable Modeling Approaches

The type of a given water body will determine to a large degree the approach that should be used in assessing sediment erosion and deposition in that water body. In this section, types of water bodies are described along with modeling approaches that are generally applicable for those systems. Nine water body types are described in this section: 1) free-flowing freshwater streams, 2) freshwater rivers, 3) tidal rivers, 4) well-mixed lakes, 5) stratified lakes and reservoirs, 6) well-mixed tidal embayments, 7) stratified narrow estuaries, 8) stratified broad estuaries, and 9) coastal ocean. An estuary is defined as "a semi-enclosed coastal body of water which has free connection to the open sea, extending into the river as far as the limit of tidal influence, and within which sea water is measurably diluted with fresh water derived from land drainage" (Dyer 1997). The largest estuary in the continental United States is the Chesapeake Bay.

Free-flowing freshwater streams: Streams are classified as low-order channels with a steep bottom gradient that results in a relatively high-velocity, shallow stream characterized by gravel, cobbles, and rocks in the streambed. The geomorphology of such streams usually includes repeated occurrences of braids, and riffles and pools along their lengths. Coarse sands and finer particles are washed out by the high-velocity conditions. Multiple branched low-order streams interact by hydrologic routing. The dominant gradient of water quality constituents is along the longitudinal axis in the direction of flow. A one-dimensional, laterally and vertically averaged model is thus appropriate for describing flow of water and the mass transport of solids. Transport in many streams is characterized as a waterway dominated by inertia, and as such, the transport in a free-flowing stream can be appropriately represented using a kinematic wave hydraulic model. The key feature of a kinematic wave model is that the slope of the free water surface matches the slope of the streambed. The practical implication of this hydraulic condition is that downstream conditions do not exert an influence upstream on velocity or depth. In a free-flowing stream, backwater effects are not present. Mass transport in a stream is dominated by advection with dispersion determined to account for a minor component of the mass flux of a constituent. Dispersion can thus be neglected in a stream model. Time variable upstream boundary conditions of flow and/or stage elevation must be able to be assigned for a kinematic hydraulic model of a stream.

Freshwater rivers: Rivers are classified as higher order channels located in alluvial and lowland valleys with a moderate bottom gradient. The low grade of the riverbed results in a low-velocity waterway characterized by a sediment bed consisting of a mixture of fine-grained cohesive particles and fine sands. The dominant gradient of water quality constituents in many rivers is along the longitudinal axis of flow. A one-dimensional, laterally and vertically averaged model can thus be appropriate for describing the flow of water and the mass transport of solids and toxic chemicals in many rivers of moderate width and depth. Transport in a river, dominated by the influence of downstream backwater effects, can be appropriately represented using a dynamic hydraulic model. The key feature of a dynamic model of sub-critical flow is that the free water surface is allowed to pile up and increase the depth of the water column in the upstream direction. The practical implication of this hydraulic condition is that downstream conditions can exert a considerable influence on upstream velocity and depth through the backwater effects of a dam, impoundment, or some other blockage (e.g., debris) to flow in a moderate-gradient river. Mass transport in a river, especially the larger, high-order rivers, is characterized by advection and dispersion, both accounting for comparable magnitudes of the mass flux of a constituent. Dispersion must therefore be represented in a model applied to rivers. For a dynamic hydraulic model of sub-critical flow in a river, it must be possible to assign time-variable upstream and downstream boundary conditions of flow and/or stage elevation. In wide and deep higher-order rivers, such as the Hudson River, the Missouri River, and the Mississippi River, transport can be characterized by significant spatial gradients both laterally and vertically. A lower-order river such as the Housatonic River is typically laterally and vertically well mixed. The presence of significant lateral or vertical gradients for a constituent such as salinity or suspended solids would require the application of a two- or a three-dimensional hydrodynamic model rather than a one-dimensional hydraulic model.

Tidal rivers: Tidal rivers are defined as relatively narrow waterways with transport controlled by freshwater inflow at the upstream boundary and tidal forcing of water surface elevation at the downstream boundary. Tidal rivers, particularly small rivers and creeks that flow into an estuary or bay (e.g., Christina River flowing into Delaware Estuary), can often be appropriately characterized as a one-dimensional river where lateral and vertical water quality gradients are negligible. Since the downstream boundary condition of tidal fluctuation in water surface elevation influences upstream velocity and stage height, the class of one-dimensional hydraulic models presented above for high-order freshwater rivers is also applicable to tidal rivers. Mass transport in a tidal river can be characterized by both advection and dispersion accounting for comparable magnitudes of the mass flux of a constituent, or dispersion alone can account for the dominant mass flux component. In a tidal river, advection and dispersion must both be represented. For a one-dimensional model of flow in a tidal river, it must be possible to assign values to time-variable upstream boundary conditions of flow and/or stage elevation and downstream boundary conditions of the tidal forcing of water surface elevation. In large tidal rivers, such as the Lower Hudson River and the Lower Potomac Estuary, transport can be characterized by significant water quality gradients either laterally, vertically, or both. The presence of significant lateral or vertical gradients of salinity in a tidal river from freshwater inflows, wind forcing, or bottom water salt intrusion requires application of a two- or a three-dimensional hydrodynamic model rather than a one-dimensional hydraulic model. The application of a one-dimensional model to a tidal river characterized by pronounced lateral or vertical gradients of salinity (i.e., either partially of fully stratified) is not an appropriate choice.

Well-mixed freshwater lakes and bays: A well-mixed freshwater lake, or an embayment of a large lake, is typically classified as a relatively broad and shallow body of water. Horizontal water quality gradients in broad, shallow lakes, arising from winds and inflows of freshwater, are almost always significant along the lateral and longitudinal directions of transport. Because of vigorous vertical mixing in shallow water, vertical gradients of water quality constituents are minimal. For “broad” and “shallow” lakes, two-dimensional, vertically averaged [2D(xy)] models of circulation are appropriate where circulation is governed by winds, freshwater inflow, the geometry of the shoreline, basin bathymetry, and the flow control structure at the outlet end of the lake. Where field data and the ‘conceptual model’ demonstrate a stratified water column, a two-dimensional, depth-averaged model is not an appropriate choice; a three-dimensional model is required to represent such conditions. A one-dimensional hydraulic model is most certainly not an appropriate choice for a well-mixed lake characterized by horizontal gradients of water quality. In a two-dimensional, depth-averaged hydrodynamic model of a shallow lake, advection and dispersion must both be represented in the horizontal dimensions. Horizontal dispersion coefficients, at a minimum, must be defined by appropriate length scale empirical formulations. For a two-dimensional, depth-averaged model of flow in a shallow lake, it must be possible to assign values to time-variable upstream and lateral boundary conditions of flow and/or stage elevation and downstream boundary conditions for the outlet of either flow and/or a rating curve of stage height and flow.

Stratified lakes and reservoirs: Freshwater lakes and reservoirs are classified as relatively flat bodies of water characterized by relatively large surface areas. With one or more upstream inflows and a downstream outlet, water quality gradients in lakes and reservoirs are almost always significant along the longitudinal axis of transport. Because of deep water conditions and restricted vertical mixing in many lakes and reservoirs, vertical gradients of water quality constituents can arise from seasonal winter-summer stratification and/or from inflows of cold water rivers into a warmer water lake or reservoir. For "narrow" and "deep" lakes (e.g., Finger Lakes in New York State) and reservoirs, two-dimensional, laterally averaged models of circulation can be appropriate where transport is governed by winds, vertical density gradients, freshwater inflow, the geometry of the shoreline, basin bathymetry, and the flow control structure(s) at the outlet end of a lake or reservoir. A one-dimensional hydraulic model is not appropriate for a lake or reservoir. For some lakes and reservoirs characterized by a large surface area, lateral gradients in water quality may be significant features that require selection of a three-dimensional hydrodynamic model. In a two-dimensional, laterally averaged hydrodynamic model of a lake or reservoir, advection and dispersion must both be represented in the longitudinal and vertical dimensions. Horizontal and vertical dispersion coefficients, at a minimum, must be defined by appropriate length scale empirical formulations. One-equation and two-equation methods can provide increasingly realistic approximations for horizontal and vertical diffusivity estimates required by turbulence closure. For a two-dimensional, laterally averaged model of flow in a lake or reservoir, it must be possible to assign values to time-variable upstream and lateral boundary conditions of flow and/or stage elevation and downstream boundary conditions for a control structure based on a rating curve of stage height and flow over the outlet.

Well-mixed tidal bays: A well-mixed tidal embayment is typically classified as a relatively broad and shallow body of water influenced by tidal forcing at the open boundary of the bay. Horizontal water quality gradients in shallow bays, such as the bays and lagoons inshore of the barrier islands on the east coast from Long Island to Cape Hatteras, arise from winds, tidal exchange, and, possibly, inflows of freshwater. These gradients are almost always significant. Because of vigorous vertical mixing in shallow bays, primarily from tidal mixing, vertical gradients of salinity and other water quality constituents are minimal. For “broad” and “shallow” bays, a two-dimensional, vertically averaged model of circulation is an appropriate choice where circulation is governed by winds, freshwater inflow, geometry of the shoreline, basin bathymetry, and tidal forcing across the open boundary of the bay. In a two-dimensional, depth-averaged hydrodynamic model of a shallow bay, advection and dispersion must both be represented in the horizontal dimensions. Horizontal dispersion coefficients, at a minimum, must be defined by appropriate length scale empirical formulations that reflect tidal mixing processes. For a two-dimensional, depth-averaged model of flow in a shallow coastal bay, it must be possible to assign values to time-variable upstream and lateral boundary conditions of flow and/or stage elevation and the open boundary condition allowing for the tidal variation of sea surface elevation. Where field data and the ‘conceptual model’ demonstrate a stratified water column in a coastal bay, a depth-averaged model is not an appropriate choice; a three-dimensional model is required to represent such conditions. A one-dimensional hydraulic model is most certainly not an appropriate choice for a well-mixed bay defined by horizontal gradients of water quality.

Stratified “narrow” estuaries: Many “narrow” estuaries, including very deep fjords and river mouths, are characterized by strong or partially stratified conditions arising from freshwater inflow at the upstream boundary flowing seaward in the surface layer and tidal forcing of heavier salt water flowing landward along the bottom layer from the downstream open boundary with the ocean. In a stratified estuary, such as the Patuxent River, a two-dimensional, laterally averaged model of circulation can be appropriate where transport is governed by winds, vertical density gradients, freshwater inflow, geometry of the shoreline, basin bathymetry, and tidal forcing at the open boundary with the ocean or a larger estuary such as Chesapeake Bay. In a two-dimensional, laterally averaged hydrodynamic model of a stratified estuary, advection and dispersion must both be represented in the longitudinal and vertical dimensions. Horizontal and vertical dispersion coefficients, at a minimum, must be defined by appropriate length scale empirical formulations. One-equation and two-equation methods provide increasingly realistic approximations for horizontal and vertical diffusivity estimates required by turbulence closure. For a two-dimensional, laterally averaged model of flow in a stratified estuary, it must be possible to assign values to time-variable upstream and lateral boundary conditions of flow and/or stage elevation and tidal forcing of sea surface elevation at the downstream open boundary.

Stratified "broad" estuaries: "Broad" estuaries and other tidal bodies of water characterized by sharp horizontal and vertical gradients of salinity should be represented with a three-dimensional hydrodynamic model. Advection and dispersion must both be represented in the horizontal and vertical dimensions. Horizontal and vertical dispersion coefficients, at a minimum, must be defined by appropriate length scale zero-order empirical formulations. One-equation and two-equation methods provide increasingly realistic approximations for horizontal and vertical diffusivity estimates required by turbulence closure in three-dimensional models. For a three-dimensional model of flow in a stratified estuary, it must be possible to assign values to time-variable upstream and lateral boundary conditions of freshwater inflow and/or stage elevation and tidal forcing of sea surface elevation and salinity at the downstream open boundary of the estuary. Hydrodynamic models appropriate for simulation of estuarine circulation are essentially identical to models that would be chosen for coastal and open ocean hydrodynamic models. The key difference between an ocean and estuary model is that, because of the smaller spatial scale of an estuary (compared to the ocean), it is not necessary to select a hydrodynamic model that accounts for the rotation of the earth using the artificial Coriolis 'force.'

Coastal ocean: The key characteristics of the coastal ocean that must be represented in a hydrodynamic model include sharp horizontal and vertical gradients of salinity and other water quality constituents and the need to represent a coastline defined by an open offshore boundary at the continental shelf break and 'upstream' and 'downstream' open boundaries. Sharp density gradients result from the inflow of freshwater rivers into the coastal ocean and the mixing of the fresh water with salt water of the open ocean. Horizontal salinity and density gradients tend to parallel the bottom contours of the continental shelf. Pronounced cross-shelf vertical gradients of salinity, temperature, and nutrients also arise from wind forcing and resulting onshore and offshore flow from coastal upwelling and downwelling. Advection and dispersion must both be represented in the horizontal and vertical dimensions. Horizontal and vertical dispersion coefficients, at a minimum, must be defined by appropriate length scale zero-order empirical formulations. One-equation and two-equation methods provide increasingly realistic approximations for horizontal and vertical diffusivity estimates required by turbulence closure in a three-dimensional model. Although tidal forcing at the open boundaries can be represented in coastal ocean models, the more important boundary condition is the specification of the spatial gradient of longshore and cross-shelf sea surface elevations at the offshore, upstream, and downstream open boundaries. In the Middle Atlantic Bight, for example, there is a difference of approximately 10 to 15 cm in sea surface elevation over ~700 km from Cape Cod to Cape Hatteras that drives the mean southwest current of ~3 to 5 cm/sec. For a three-dimensional model of circulation in the coastal ocean, it must be possible to assign values to time-variable boundary inputs of river discharge from the coast, in addition to the description of sea surface elevation as an open boundary condition. A full three-dimensional model of coastal ocean circulation should account for both the barotropic and baroclinic components of flow. In addition, the Coriolis term must be incorporated in the hydrodynamic model to account for rotation of the earth.

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Appendix D: Introduction to Hydrodynamic Modeling

D.1 Basic hydrodynamics

Hydrodynamics deals with the movement of water when an external force such as wind or gravity acts on a water body. The water movement can be calculated using the following fundamental principles of Newtonian physics: conservation of mass, linear momentum, and energy, and an equation of state (which is used to calculate the water density as a function of temperature, salinity, and pressure). These governing equations are given in most texts on fluid mechanics. The forces that cause water to move are discussed in Section E.2, followed by a very brief introduction to turbulence in Section E.3. A brief review of the basics of fluid mechanics, which covers the subject areas of fluid statics and fluid dynamics, is given below.

Fluid statics involves calculating pressure on submerged objects in a water body. The pressure on an object at a given depth in a water body is equal to the weight of the water above that depth per unit surface area of the object; this value increases linearly with depth. The pressure distribution deviates from being linear when the vertical component of the acceleration of the fluid is not negligible. The latter often occurs beneath waves, adjacent to vertical structures, e.g., bridge piers and dams, and in waters with large vertical flow velocities due to large bathymetric gradients or cooling of surface waters.

Fluid dynamics deals with the movement of water that occurs when a body of water is acted on by one or more external forces. It is governed by the principles of conservation of mass and conservation of linear momentum. The conservation of fluid mass equation is also called the continuity equation. Continuity is based on the conservation of mass as it applies to the flow of fluids. The continuity equation states that the mass rate of flow out of a control volume (which can be thought of as a cubic-shaped container in the fluid that does not move but whose walls are 100% permeable) minus the rate of flow into the control volume is equal to the rate of change of fluid mass in the control volume.

The conservation of linear momentum is based on Newton's second law of motion – the sum of the external forces acting on a body is equal to the time rate of change of the linear momentum of the body.

D.2 Driving forces

The equations governing the motion of waters contain the forces that cause water to move (referred to as driving forces) as well as other forces that act to decrease the water's acceleration (referred to as retarding forces). Friction is the main retarding force. Common driving forces in various types of water bodies are listed below.

- Freshwater stream/river with uni-directional flow
    - Gravitational force (proportional to gradient)
    - Tributary inflows
    - Direct runoff into water body during runoff events
    - Wind
- Lake/reservoir
    - Wind
    - Tributary inflows
    - Discharge from dam
    - Thermal stratification
    - Direct runoff into water body during runoff events
- Stream/river with oscillatory flow
    - Gravitational force (proportional to gradient)
    - Astronomical tides
    - Tributary inflows
    - Spatial (horizontal and vertical) salinity gradients
    - Direct runoff into water body during runoff events
    - Wind
- Estuary/bay/coastal sea
    - Astronomical tides
    - Freshwater discharge
    - Spatial (horizontal and vertical) salinity gradients

- Wind
- Coriolis force
- Atmospheric pressure gradients
- Direct runoff into water body during runoff events

D.3 Turbulence

Turbulence or turbulent flow is a flow regime characterized by chaotic, stochastic property changes. Flow that is not turbulent is called laminar flow.

Consider the flow of water over a simple smooth object, such as a sphere. At very low speeds the flow is laminar, i.e., the flow is smooth. As the speed increases, at some point the transition is made to turbulent ("chaotic") flow. In turbulent flow, unsteady vortices appear on many scales and interact with each other. These vortices enhance mixing of particulate in a water body. Examples of turbulent flows are the following:

- A jet exhausting from a nozzle into a quiescent fluid.
- Smoke rising from a cigarette - for the first few centimeters it remains laminar, and then becomes unstable and turbulent.
- Flow over a golf ball or other rough surfaces.
- The mixing of warm and cold air in the atmosphere by wind, which causes poor astronomical seeing (the blurring of images seen through the atmosphere).
- Most of the terrestrial atmospheric circulation and oceanic currents.
- Flows in rivers (e.g., Hudson River, New York), estuaries (e.g., Lower Duwamish Waterway in Seattle, Washington); and coastal seas (e.g., continental shelf at Palos Verdes, California).
- The external flow over all kinds of vehicles such as cars, airplanes, ships, and submarines.
- Oscillatory flow under surface wave action.

It can be seen from this list that the majority of flow conditions relevant to sediment erodibility and transport will be turbulent. Therefore, the effects of turbulence must be acknowledged when assessing contaminated sediment transport processes. Existing hydrodynamic models are capable of representing temporally and spatially averaged turbulent flows. Time averaging occurs over a time period greater than the so-called time scale of turbulence, whereas spatial averaging occurs over a length (averaged over a model grid cell) much greater than the size of the smallest-scale turbulent eddies that typically form near the bottom of rivers and estuaries due to water flowing around small-scale features, e.g., ripples, on the bed surface. In contrast, the ability to predict turbulence at the micro-scale (on the length scale of primary turbulent eddies) is not as advanced as the ability to predict contaminant behavior in sediment.

D.4 Initial and boundary conditions

Boundary processes are the driving forces for all fluid movements. While the governing equations for hydrodynamics guarantee the inner consistency of the variables and enforce the conservation of the physical properties, e.g., mass and linear momentum, only boundary processes make the solution of these equations mathematically unique. Boundary processes enter the governing equations through boundary conditions that must be applied to the equations. Different boundary conditions can be used depending on the type of problem that has to be modeled.

There are two types of boundary conditions. The first type is called a Dirichlé condition, which specifies either temporally constant or varying value(s) of one or more of the state variables, e.g., water surface elevation or horizontal velocity components. The second type of boundary condition is called a von Neuman condition and specifies a temporal flux of one or more of the state variables at open-water boundaries.

For example, in solving the energy equation, the short-wave radiation coming from the sun heats up the upper layer of a water body. This can be taken into account by prescribing the time-variable surface temperature of the water if temperature measurements have been recorded at one or more monitoring stations. This case corresponds to the first type of boundary conditions.

However, the heat flux from the sun (in units of Joules/s per unit surface area) can also be prescribed. In this case the value of the water temperature in the upper layer is not specified, but is solved for using the specified heat flux. This condition is of the second type. Both types of boundary conditions will change the surface water temperatures, and through advection and diffusion processes, they will also change the subsurface temperatures throughout the model domain.

D.4.1 Initial conditions

Every mathematical equation that contains time as one of the independent variables must have initial conditions for all unknowns, i.e., state variables; otherwise, the solution is not unique. However, most often the initial values of all state variables through the model domain are not known. For example, the initial tide-induced current velocities in a hydrodynamic model of an estuary will not be known throughout the entire estuary.

Fortunately, the unknown initial conditions do not prevent obtaining realistic, time-varying solutions to the governing equations. Most physical problems converge, after a certain period of time, to a solution that is the same for different initial values of the state variables. These types of problems are not sensitive to the specified initial conditions. An example is a hydrodynamic model applied to an estuary where the initial water surface elevations and initial current velocities throughout the model domain are not known. The solutions of the hydrodynamic governing equations tend to converge even if different initial conditions are imposed. This is due to the fact that energy transmitted into the estuary by astronomical tides is dissipated by internal and bottom frictional forces. After a given period of time, all the energy that was in the system due to the initial state (as specified by the initial water surface elevations and initial current velocities) is dissipated. From that point on, water movements that occur in the estuary are due only to the time variable tidal forcing applied at the open-water boundary that connects the estuary to the ocean. In other words, solution of the governing equations is no longer influenced by the specified initial state. Or, the solution after a certain time no longer remembers the initial conditions. The period of time for the effect of initial conditions to be eliminated depends mostly on the magnitude of frictional forces, i.e., how long it takes to remove the initial energy from the system. For simulations of physical systems using numerical models, this period of time is called the ‘*spin-up’ time* of the simulation. After this initial spin-up, the model is in equilibrium with the boundary conditions and the effects of the unknown initial conditions have been damped out. The spin-up time varies from system to system, and is mostly a function of the state variables being simulated. In the case of a stratified estuary, e.g., the Lower Duwamish Waterway, the spin-up time for a hydrodynamic model that is simulating the circulation and salinity transport is normally much longer than for a hydrodynamic model applied to an unstratified, i.e., vertically well-mixed, estuary. The spin-up time for the former will usually be on the order of at least one month, whereas for the latter, it will be closer to three to five days.

D.4.2 Boundary conditions

Boundary conditions on land boundaries must be specified for both scalar quantities, e.g., heat and salinity, and transport of water. At these boundaries, no-flux conditions are applied for the scalar quantities. That is, there is no heat or salinity flux at (or exchange through) these boundaries. For transport of water, two conditions must be considered. The first is the condition that the transport through a land boundary must be zero.

For flows of viscous fluids such as water and air, another boundary condition also has to be prescribed. This condition is that at solid boundaries, fluid particles must actually adhere to the boundary, and in the region very close to the wall, there must be no tangential movement of the fluid. This phenomenon is observed only very close to solid boundaries since it is due to molecular friction. However, the length scales used in hydrodynamic modeling are much larger than molecular scales; therefore, it is inappropriate to impose a condition of no tangential flow immediately adjacent to solid boundaries.

Although it is feasible to impose a frictional force on lateral solid boundaries, e.g., shorelines of water bodies, very often this lateral friction is set to zero. This is a suitable approximation if the surface area-to-boundary area ratio of the water body is high, meaning that the influence of lateral solid boundaries can be neglected. In this case the boundary condition imposed is called a '*free slip*' condition. However, it must be clear that in using this approximation, the only process that can remove energy from the water body is bottom friction (discussed below). For coastal and inland waters, where the surface area-to-boundary area ratio is normally high, this approximation is usually justified; but when dealing with deep-water bodies, it may not be justified.

There is actually no such thing as an open boundary in nature. However, open-water boundaries are created when a boundary that divides a water body into different segments or regions is used to limit the size of the water body to be modeled. Mathematically speaking, fluxes have to be described at open boundaries. In the case of surface water flows, the water surface elevations or the current velocities along the open boundary must be provided. For scalar state variables (e.g., heat, dissolved salt, suspended sediment), fluxes have to be prescribed. Or, as described above, the values of the scalar variables can be specified. This corresponds to a boundary condition of the first type. However, for this type of boundary condition, the values of the state variables only need to be prescribed during inflows to the model domain. No values are needed during outflows since the values of the state variables at the boundary are adjusting dynamically to the values that are advected out of the water body. This makes it very convenient to apply hydrodynamic models to large water bodies, since it is not normally economically feasible to measure time series of state variables (such as current velocities, temperature, and salinity) along the entire open-water boundary. Open-water boundary conditions include the following types:

- Time-variable upstream and lateral boundary conditions of flow and/or water surface elevation.
- Time-variable downstream boundary conditions of water surface elevation.
- Downstream boundary conditions that represent a control structure (e.g., dam) based on a rating curve of stage height versus flow over the outlet.

In most water bodies, the water surfaces and bottoms of the water bodies will be, by far, the largest surface the water is in contact with. This is true because the horizontal dimensions of these water bodies are normally much larger than the vertical ones for a typical basin. Therefore, the fluxes across these two interfaces will be very important and must be accurately specified.

Several kinds of fluxes occur at the water surface. For example, there is momentum input due to wind blowing across the water surface. It is this forcing that drives circulation in lakes, shallow bays, and lagoons.

Other fluxes through the sea surface concern mass of water, salt flux, and heat flux. Mass and salt flux are due to precipitation and evaporation at the water interface. Solar radiation heats the upper part of water bodies through absorption of short waves, while outgoing long-wave radiation and evaporation contribute to a heat loss, i.e., sink, to the water. Sensible heat flux (due to conduction of heat) also plays a role in the heat budget of surface bodies of water.

The bottom of the water body represents a solid boundary to the fluid. As such, the above-mentioned no-flux condition also applies to this lower boundary. However, a very important momentum flux that cannot be ignored occurs across the bottom boundary. The bottom exerts a drag (friction) on the water immediately above it. This drag force slows down the fluid layers in proximity to the bottom. This is the same principle as the action of wind at the water surface, which accelerates the upper layers of the water column in water bodies.

D.5 Simplifications and scale analysis

The equations that relate to conservation of linear momentum, which were discussed previously, were derived from conservation principles. The equations that can be derived from these first principles are still too complicated to be used for modeling. This is mainly due to the variability of spatial and temporal scales to which these equations are applicable. Since no assumptions have been made, these equations can describe ocean circulation down to scales where molecular effects become important. Therefore, these equations must describe scales from 10^6 meters on the ocean scale down to about 10^{-6} meters (micrometers) where turbulent energy dissipation becomes important.

The same is true for time scales to which the equations apply. These time scales go from years for the oceanic circulation down to microseconds for turbulence dissipation. One is generally interested in describing flows that take place in coastal seas, estuaries, and rivers. Therefore, not all processes included in these equations are equally important and simplifications can be made.

In comparison to air, water is a relatively incompressible fluid. There is, however, some compressibility of water, as evidenced by the fact that acoustic waves can travel in water. Acoustic waves depend completely on the compressibility of the fluid. Excluding acoustic waves, however, it can be shown that the effect of compressibility is negligible on the dynamics of the oceans and shallower water bodies. Therefore, water is usually assumed to be an incompressible fluid.

In the shallow water bodies identified above, the maximum values of the vertical component of the velocity vector are usually two or more orders of magnitude smaller than the horizontal velocity components. An order of magnitude analysis allows simplifying the vertical conservation of linear momentum equation to the hydrostatic equation, which states that the pressure at a depth z is equal to the weight of the water column above it. The hydrostatic equation is a very good approximation of the vertical component of the momentum equation. Most hydrodynamic models that are applied to surface waters incorporate the hydrostatic assumption. These hydrodynamic models are commonly referred to as hydrostatic models.

D.6 Basic principles of hydrodynamic modeling

The basic principles of modeling the hydrodynamics in a water body are listed below.

- Identify and quantify driving forces – these are given in Section E.2.
- Identify and quantify sources and sinks of water mass. Typical sources of water include input from tributary flows, non-point source runoff into water bodies during runoff events, precipitation, discharge of groundwater to surface waters, and hydraulic connections to larger water bodies such as coastal seas. Usual sinks include evaporation, infiltration into the bottom of the water body, and outflows of water into both natural and man-made discharge rivers/channels.
- Choose an appropriate modeling domain. A modeling domain is normally a rectangular area that encloses the spatial extent of the water body to be modeled. The domain includes both the water body and surrounding land. The latter usually includes areas that always are dry, i.e., not flooded, as well as land areas that flood during the hydrologic conditions to be simulated, e.g., tidal marshes and riverine floodplains. A grid is constructed by dividing the modeling domain into hundreds to thousands of small rectangular cells, called grid cells. Two guidelines for choosing an appropriate modeling domain are the following:

  - Open-water boundaries should be sufficiently far removed from the area of interest in the water body; and
  - Open-water boundaries should be chosen where boundary values are known or can be measured.

- Decide what type of hydrodynamic model should be applied to the modeling domain. The different types of models are described in the next section.
- Decide what level of spatial discretization, i.e., how small the grid cells need to be, is needed to adequately represent the water body's

geometry and bathymetry as well as the driving forces and significant physical processes that determine the water's movement.

D.7 Types of hydrodynamic models

The four commonly used types of hydrodynamic models are described below. These models are classified based on the number of spatial dimensions in the equation(s) of motion solved in the model.

- **One-dimensional (1D) model** - solves the cross-sectionally averaged conservation of mass and momentum equations for the water surface elevation (i.e., stage) and discharge (i.e., flow) at discrete locations along the modeled water body. A 1D hydrodynamic model is an appropriate representation for water bodies in which the most significant constituent gradient is along the longitudinal axis in the direction of flow of the stream or river. The vertical and lateral dimensions are assumed to be well-mixed, since the gradients of constituents in these directions are considered to be negligible in relation to the dominant longitudinal gradient. A stream or up to a fourth-order river is usually modeled using a 1D model. An example of a public-domain 1D model is HEC-RAS.
- **Two-dimensional depth-averaged (2D-H) model** - solves the depth-averaged conservation of mass and momentum equations for the water surface elevation (i.e., stage) and horizontal flow velocity at discrete locations (called nodes or cells) throughout the modeled water body. A 2D-H hydrodynamic model is an appropriate representation for water bodies in which the most significant gradients are in the horizontal direction. The vertical dimension is assumed to be well-mixed, since the gradients of constituents in this direction are considered to be negligible in relation to the dominant horizontal gradients. A well-mixed freshwater lake, or an embayment of a large lake, is typically modeled using a 2D-H model. An example of a public-domain 2D-H model is RMA2.
- **Two-dimensional laterally-averaged (2D-V) model** - solves the laterally-averaged conservation of mass and momentum equations for the water surface elevation (i.e., stage) and the x- and z-components of the velocity at discrete locations throughout the modeled water body. A 2D-V hydrodynamic model is an appropriate representation for vertically stratified water bodies in which the most significant gradients are in the longitudinal and vertical directions. The lateral dimension is assumed to be well-mixed, since the gradients of constituents in this

direction are considered to be negligible in relation to the dominant longitudinal and vertical gradients. A stratified, relatively narrow estuary, reservoir, or river may be modeled using a 2D-V model.

- **Three-dimensional (3D) model** - solves the 3D conservation of mass and momentum equations for the water surface elevation and the x-, y-, and z-components of the velocity at discrete locations throughout the modeled water body. A 3D hydrodynamic model is an appropriate representation for vertically stratified estuaries, reservoirs, and coastal seas water bodies. A 3D model should also be used in large rivers; for example, the Mississippi, Lower Hudson, and Lower Columbia Rivers, in which both lateral and vertical gradients in temperature, salinity, and suspended sediment concentrations occur. Using the full 3D equations is probably always the best choice if nothing is known about the geometrical constraints or physical simplifications that are applicable to the water body being modeled. In this case, all terms in the governing equations might be important, and no *a priori* scale analysis can be performed. A typical example is a large deep lake where stratification can develop. The lake is large enough so that no direction can be identified with the main axis, or, if there is a main axis, the dynamics in the direction perpendicular to it cannot be neglected. Stratification will prevent treating the whole water column as vertically mixed and uniform. Therefore, vertical and horizontal internal pressure gradients, due to density differences between different water masses, will be important for the acceleration of the fluid body in these cases. An example of a public-domain 3D model is EFDC.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
September 2014

2. REPORT TYPE
Final report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Technical Guidelines on Performing a Sediment Erosion and Deposition Assessment (SEDA) at Superfund Sites

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Earl Hayter, Karl Gustavson, Steve Ells, Joseph Gailani, John Wolfe, Tim Dekker, and Todd Redder

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Research and Development Center
Environmental Laboratory, Coastal and Hydraulics Laboratory
3909 Halls Ferry Road, Vicksburg, MS 39180-6199;

US Environmental Protection Agency, OSRTI
1200 Pennsylvania Ave. NW, Washington, DC 20460;

LimnoTech
501 Avis Drive, Ann Arbor, MI 48108

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC TR-14-9

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report outlines processes influencing sediment transport and describes methods to use in developing a Sediment Erosion and Deposition Assessment (SEDA) at a site designated as a contaminated Superfund site. A SEDA is a complex procedure that overlaps multiple disciplines. Processes and properties that should be assessed include sediment characteristics, biologic and contaminant activity, groundwater movement, surface and subsurface water stresses, sediment loadings, anthropogenic activity, and weather and oceanographic influences. Historical data can also provide a long-term record on evolution of the system, which is not only critical in assessing sediment erodibility, but will also support conceptual site model development.

The most successful SEDA studies have been guided by a technical review panel working with a Remedial Project Manager in SEDA development. Understanding of processes at a specific site, coupled with experience from other sites, is also critical to success.

15. SUBJECT TERMS
Contaminants
Groundwater
Sediment Erosion and Deposition Assessment (SEDA)
Sediment transport
Superfund Site

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		181	