

TECHNICAL REPORT 1960
September 2007

User's Guide for Assessing Sediment Transport at Navy Facilities

A. C. Blake
D. B. Chadwick
SSC San Diego

P. J. White
CH2M HILL

C. A. Jones
Sea Engineering, Inc.

Approved for public release;
distribution is unlimited.



SSC San Diego
San Diego, CA 92152-5001

EXECUTIVE SUMMARY

The Navy has more than 200 contaminated sediment sites, with a projected remediation cost of \$1.3 billion. Space and Naval Warfare Systems Center San Diego (SSC San Diego) developed this guide to ensure that sediment investigations and remedial actions are successful and cost effective. It provides the latest guidance on evaluating sediment transport at contaminated sediment sites, and describes how to use sediment transport information to support sediment management decisions.

When Navy Remedial Project Managers (RPMs) and their technical support staff do not adequately characterize or predict sediment transport at a contaminated site, the range of potential response actions can be limited because technical defensibility is inadequate. As contaminated sediment site investigations move into the Feasibility Study phase, a lack of accurate and defensible information regarding sediment transport and sediment deposition patterns can potentially lead to selection of unnecessary removal or treatment actions, potentially costing the Navy millions of dollars. Alternatively, the failure to contain or remove contaminated sediments that may be subject to destabilizing hydrodynamic events may lead to larger contamination footprints, movement of contamination off site, and potentially increased future cleanup costs.

Little practical guidance has been available for performing a sediment transport assessment at a contaminated sediment site. This guide provides Navy RPMs and their technical support staff with practical guidance on planning and conducting sediment transport evaluations. It identifies and reviews methods and tools that can be used to characterize sediment transport, and provides a framework that can be used to more clearly identify the types of measurements and data analysis methods that can be used at a contaminated sediment site. It also provides guidance on how the results of a well-designed sediment transport evaluation can be used to develop management decisions for contaminated sediment sites.

Regulatory and stakeholder acceptance of sediment management decisions will be facilitated by using sound science and engineering principles and targeted, consensus-based data collection efforts. The framework developed in this report has been applied at three demonstration sites: Hunters Point Shipyard in San Francisco, CA; Bremerton Naval Complex in Puget Sound, WA; and Naval Station Newport in Newport, RI.

Various technologies and data analysis methods identified in this guide were applied at the sites, and results were used to develop a detailed conceptual site model (CSM) that could be used to support the development and selection of the most cost-effective and environmentally sound remediation scenarios for the sites. A case study report for each of these demonstration sites is provided in the appendices. Demonstration site results were used to refine the general approach for characterizing sediment transport presented in this guide.

Many Navy sediment sites are located in areas of relatively low hydrodynamic energy such as rivers, bays, and estuaries, where sediments and contaminants tend to accumulate over time. In some cases, the original source(s) of contamination have been eliminated, reduced, or controlled as environmental management practices have improved over the past 30 years. At some sites, the deposition of newer, relatively clean sediment on top of more contaminated sediment has resulted in burial of contamination.

The most common management questions associated with these sites are as follows:

- Could erosion of the sediment bed lead to the exposure of buried contamination?
- Will sediment transport lead to the redistribution of contamination within the site, or movement of contamination off site?
- Will natural processes lead to the burial and isolation of contamination by relatively clean sediment?
- If a site is actively remediated, could sediment transport lead to the recontamination of the site?

This guide focuses on the collection and analysis of data needed to address these primary questions. A combination of regional and historical data, site-specific measurements, empirical data evaluation methods, and numerical modeling techniques can be used to characterize sediment transport at a given site.

Empirical approaches are particularly useful for characterizing the past and present effects of sediment transport; however, numerical models are more useful for predicting the effects of future events and sediment deposition patterns. The appropriate method(s) and tool(s) should be selected and used on a site-specific basis to qualitatively and/or quantitatively characterize sediment transport, and assess the viability of various remedial options. The approach for a given site depends on the size and complexity of the site, the CSM, the specific site objectives, and the available resources.

This guide presents an overview of sediment transport processes and their relative importance in various site settings. It also describes the sedimentary environments found at most Navy contaminated sediment sites. This background information lays the groundwork for understanding the Tier 1 and Tier 2 evaluation approaches. It discusses the compilation of available data, development of a CSM for sediment transport, and formulation of site-specific sediment management questions and study objectives. Tier 1 data needs and data analysis methods are also presented.

In discussing Tier 2 Evaluation, this guide presents the data needs and data analysis methods for a Tier 2 sediment transport evaluation. It then applies this information to site management and describes how the results of a sediment transport evaluation can be used to support sediment management decisions for a site.

Appendices to the document include a compilation of information on the various tools and technologies that can be used in the Tier 1 and Tier 2 sediment transport evaluations (Appendix A). Supporting information for the available tools and technologies includes a description of the technology, applicability, advantages and limitations, level of development, and relative cost. The case study reports for the site demonstrations are provided in the other appendices.

CONTENTS

EXECUTIVE SUMMARY	iii
1. INTRODUCTION	1
1.1 BACKGROUND.....	1
1.2 OVERALL APPROACH.....	2
1.3 DOCUMENT ORGANIZATION	3
2. SEDIMENT TRANSPORT OVERVIEW	5
2.1 SEDIMENT TRANSPORT PROCESSES	5
2.1.1 Physical Properties of Sediment	5
2.1.2 Hydrodynamic Processes.....	7
2.1.3 Bioturbation	9
2.2 SEDIMENTARY ENVIRONMENTS	10
2.2.1 Rivers	10
2.2.2 Bays	10
2.2.3 Estuaries	12
3. TIER 1 EVALUATION	15
3.1 COMPILE TIER 1 DATA	15
3.1.1 Site Characteristics	15
3.1.2 Sediment Properties.....	20
3.1.3 Hydrodynamic Data.....	20
3.2 DEVELOP SITE DESCRIPTION AND CONCEPTUAL SITE MODEL.....	20
3.3 FORMULATE SEDIMENT MANAGEMENT QUESTIONS AND TIER 1 STUDY OBJECTIVES.....	21
3.4 CONDUCT TIER 1 ANALYSIS.....	22
3.4.1 Erosion/Resuspension	24
3.4.2 Transport.....	28
3.4.3 Deposition	28
3.5 EVALUATE TIER 1 RESULTS.....	31
3.5.1 Could Erosion of the Sediment Bed Lead to Exposure of Buried Contamination?	31
3.5.2 Could Sediment Transport Lead to the Redistribution of Contamination within the Site, or Movement of Contamination Off Site?.....	31
3.5.3 Will Natural Processes Lead to the Burial of Contaminated Sediment by Relatively Clean Sediment?	31
3.5.4 If a Site is Actively Remediated, Could Sediment Transport Lead to the Recontamination of the Site?	32
3.6 DETERMINE NEED FOR TIER 2 ANALYSIS.....	32
4. TIER 2 EVALUATION	33
4.1 COLLECT TIER 2 DATA	33
4.2 CONDUCT TIER 2 ANALYSIS.....	33
4.2.1 Erosion/Resuspension	33
4.2.2 Transport.....	39
4.2.3 Deposition	40
4.2.4 Numerical Modeling.....	44
4.2.5 Model Verification, Calibration, and Validation.....	46

4.3	EVALUATE TIER 2 RESULTS.....	46
4.3.1	Could Erosion of the Sediment Bed Lead to Exposure of Buried Contamination?	46
4.3.2	Could Sediment Transport Lead to the Redistribution of Contamination within the Site, or Movement of Contamination Off Site?	47
4.3.3	Will Natural Processes Lead to the Burial of Contaminated Sediment by Relatively Clean Sediment?.....	47
4.3.4	If a Site is Actively Remediated, Could Sediment Transport Lead to the Recontamination of the Site?	47
5.	APPLICATION TO SITE MANAGEMENT	49
5.1	INTERPRETING SEDIMENT TRANSPORT WITHIN THE CSM.....	49
5.2	DEVELOPING SEDIMENT MANAGEMENT STRATEGIES THAT ACCOUNT FOR SEDIMENT TRANSPORT PROCESSES	49
5.3	INTEGRATING SEDIMENT TRANSPORT INTO THE FEASIBILITY STUDY.....	50
5.3.1	Long-Term Effectiveness and Permanence	50
5.3.2	Short-Term Effectiveness.....	50
5.3.3	Implementability	51
5.3.4	State and Community Acceptance.....	51
6.	REFERENCES	53
	ACRONYMS	59
	GLOSSARY	61
	APPENDICES	
	A: TOOLS, TECHNOLOGIES, AND APPROACHES FOR MEASURING SEDIMENT TRANSPORT PROPERTIES	A-1
	B: HUNTERS POINT SHIPYARD PARCEL F	B-1
	C: BREMERTON NAVAL COMPLEX OPERABLE UNIT B MARINE	C-1
	D: GOULD ISLAND, NAVAL STATION NEWPORT	D-1

Figures

1.	Overall approach for sediment transport evaluation process.....	4
2.	Simplified diagram of sediment transport processes.	7
3.	Boundary layer diagram.....	7
4.	Tube-building worms at 13-cm deep horizontal cross-section and vertical profile of same core (sediment from 0 to 13 cm in cross-section was eroded in SEDflume).	9
5.	Illustration of (A) basic wave anatomy, (B) waves in deep water, and (C) waves in shallow water.	11
6.	Examples of salt wedge, partially mixed, and well-mixed estuaries.	13
7.	Simplified sediment transport CSM.....	23
8.	Mass balance approach.....	29
9.	SEDflume and sediment core.	37
10.	Tidal time-series measurements of suspended sediment concentration (top) and along-channel current velocity (bottom) from the ACE Basin, SC, show that sediments are resuspended during maximum flood and ebb currents.	38
11.	Spatial measurements in San Diego Bay, CA, show evidence of a stormwater plume from a small urban creek.....	38

12. Example of a SPI camera image showing homogeneous clayey silt and RPD (image width, 14 cm).	39
13. Tripod deployed at HPS to measure hydrodynamic parameters.	40
14. Lead-210 profile: ideal and actual from Florida Bay.	41
15. Diver-deployed sediment trap. Photo on right is looking down into a sediment trap, where the brine layer, colored by Rhodamine dye, can clearly be seen.	43

Tables

1. Grain size scale for sediments.	6
2. Online information resources for Tier 1 analysis.	16
3. Data needs for Tier 1 and Tier 2 sediment transport evaluation.	17
4. Common sediment management questions and associated data needs.	19
5. Critical shear stress for particles larger than 200 μm	25
6. Example erosion parameters for cohesive sediments.	26
7. South Basin Tier 2 DQOs.	34
8. Comparison of various sediment stability measurement devices (courtesy of Sandia National Laboratories).	36

1. INTRODUCTION

1.1 BACKGROUND

The Navy has more than 200 contaminated sediment sites, with a projected remediation cost of \$1.3 billion¹. In 2003, Space and Naval Warfare Systems Center San Diego (SSC San Diego) developed a guide for assessing and managing contaminated sediments to ensure that sediment investigations and remedial actions are successful and cost effective (Naval Facilities Engineering Service Center, 2003). This report, which was issued as an interim guide in June 2004, provides the latest guidance on evaluating sediment transport at contaminated sediment sites, and how to use sediment transport information to support sediment management decisions.

When Navy Remedial Project Managers (RPMs) and their technical support staff do not adequately characterize or predict sediment transport at a contaminated site, the range of potential response actions can be limited because technical defensibility is inadequate. As contaminated sediment site investigations move into the Feasibility Study (FS) phase, a lack of accurate and defensible information regarding sediment transport and sediment deposition patterns can potentially lead to selection of unnecessary removal or treatment actions, potentially costing the Navy millions of dollars. Alternatively, the failure to contain or remove contaminated sediments that may be subject to destabilizing hydrodynamic events may lead to larger contamination footprints, movement of contamination off site, and potentially increased future cleanup costs. Sediment stability has been identified by the United States Environmental Protection Agency (USEPA) as a key concern for contaminated sediment sites (see “Principles for Managing Contaminated Sediment Risks at Hazardous Waste Sites,” Office of Solid Waste and Emergency Response [OSWER] Directive 9285.6-08, 12 February 2002, and “USEPA Draft Contaminated Sediments Science Plan,” 13 June 2002).

Little practical guidance has been available for performing a sediment transport assessment at a contaminated sediment site. This guide provides Navy RPMs and their technical support staff with practical guidance on planning and conducting sediment transport evaluations. It identifies and reviews methods and tools that can be used to characterize sediment transport, and provides a framework that can be used to more clearly identify the types of measurements and data analysis methods that can be used at a contaminated sediment site. The final section provides guidance on how the results of a well-designed sediment transport evaluation can be used to develop management decisions for contaminated sediment sites. Regulatory and stakeholder acceptance of sediment management decisions will be facilitated by using sound science and engineering principles and targeted, consensus-based data collection efforts. The framework developed in this guidance document has been applied at three demonstration sites: Hunters Point Shipyard in San Francisco, CA; Bremerton Naval Complex in Puget Sound, WA; and Naval Station Newport in Newport, RI. Various technologies and data analysis methods identified in this guide were applied at the sites, and results were used to develop a detailed conceptual site model (CSM) that could be used to support the development and selection of the most cost-effective and environmentally sound remediation scenarios for the sites. A case study report for each of these demonstration sites is provided in

¹ Navy Environmental Quality Research, Development, Testing and Evaluation (RDT&E) Requirement Improved Characterization and Monitoring Techniques for Sediments, ID No. 1.III.02.n

Appendices B, C, and D of this document. Demonstration site results were used to refine the general approach for characterizing sediment transport presented in this guide.

1.2 OVERALL APPROACH

Contaminant fate and transport in aquatic systems are influenced by a range of physical, chemical, and biological processes. Physical processes significantly affect the fate and transport of hydrophobic organic contaminants (HOCs) such as polychlorinated biphenyls (PCBs) and dioxins, as well as many inorganic contaminants, such as lead and mercury, because they are naturally adsorbed to particles in the sediment bed or suspended in the water column. Often, sediment resuspension, transport, and deposition are the largest components of contaminant transport at a given site. Moreover, the success of many remediation approaches such as in situ capping, dredging, and natural recovery is directly affected by physical sediment transport processes. The effects of physical processes must be evaluated in conjunction with the effects of chemical and biological processes to assess overall fate and transport at a site.

Many Navy sediment sites are located in areas of relatively low hydrodynamic energy such as rivers, bays, and estuaries, where sediments and contaminants tend to accumulate over time. In some cases, the original source(s) of contamination have been eliminated, reduced, or controlled as environmental management practices have improved over the past 30 years. At some sites, the deposition of newer, relatively clean sediment on top of more contaminated sediment has resulted in burial of contamination. The most common management questions associated with these sites are as follows:

- Could erosion of the sediment bed lead to the exposure of buried contamination?
- Will sediment transport lead to the redistribution of contamination within the site, or movement of contamination off site?
- Will natural processes lead to the burial and isolation of contamination by relatively clean sediment?
- If a site is actively remediated, could sediment transport lead to the recontamination of the site?

This guide focuses on the collection and analysis of data needed to address these primary questions. A combination of regional and historical data, site-specific measurements, empirical data evaluation methods, and numerical modeling techniques can be used to characterize sediment transport at a given site. Empirical approaches are particularly useful for characterizing the past and present effects of sediment transport; however, numerical models are more useful for predicting the effects of future events and sediment deposition patterns. The appropriate method(s) and tool(s) should be selected and used on a site-specific basis to qualitatively and/or quantitatively characterize sediment transport, and assess the viability of various remedial options. The approach for a given site will depend on the size and complexity of the site, the CSM, the specific site objectives, and the available resources.

The general approach for a sediment transport evaluation is presented in Figure 1. The tiered approach presented in this guide has been recommended by the United States Environmental Protection Agency (USEPA) (2005) and others (Ziegler, 2002). Initially, the project team will collect all available data, conduct a site inspection, and develop a site-specific CSM for sediment transport. The team also will formulate the preliminary sediment management questions, define the overall study objectives, and identify the most critical data gaps.

After this initial evaluation, the team can conduct a Tier 1 sediment transport evaluation. The goal of the Tier 1 evaluation is to address the most common sediment management questions, using

readily available data from the remedial investigation (RI) and relatively uncomplicated data analysis methods. The Tier 1 evaluation has relatively simple data needs, a lower cost, a shorter time frame, and a higher level of uncertainty than a Tier 2 evaluation. The Tier 1 results can be used to refine the sediment transport CSM and address the relevant site-specific sediment management questions. Depending on the questions asked at a specific site, this level of analysis may be sufficient.

For large or complex sites, a higher degree of certainty may be needed to characterize sediment transport processes and address sediment management questions. In this case, collection of additional site-specific data may be necessary and more detailed and complex data analysis methods may be warranted, including the possible development and use of predictive models. These activities comprise the Tier 2 evaluation. The scope of data collection and analysis for the Tier 2 evaluation will depend on the complexity of the site, the type of data needed to address the most critical data gaps, and the available project budget. Tier 2 results will be used to refine the CSM until the uncertainty associated with the sediment management decision(s) is reduced to an acceptable level.

The sediment transport evaluation can be conducted in conjunction with other sediment site characterization activities, including the evaluation of chemical and biological fate and transport processes. Data collection activities for the Tier 1 and Tier 2 sediment transport evaluations should be coordinated with the RI/FS to maximize data utility and cost efficiency. The Tier 1 evaluation is performed during the RI phase of the investigation, and generally relies on site characterization data collected for the RI. The Tier 2 evaluation, if necessary, should generally take place in the latter stages of the RI or initial stages of the FS, when it becomes apparent that remedial action at the site will most likely be required. Additional site-specific data collection is generally required for a Tier 2 evaluation.

1.3 DOCUMENT ORGANIZATION

This User's Guide is organized as follows:

Section 2, Sediment Transport Overview, presents an overview of sediment transport processes and their relative importance in various site settings. It also describes the sedimentary environments found at most Navy contaminated sediment sites. This background information lays the groundwork for understanding the Tier 1 and Tier 2 evaluation approaches.

Section 3, Tier 1 Evaluation, discusses the compilation of available data, development of a CSM for sediment transport, and formulation of site-specific sediment management questions and study objectives. Tier 1 data needs and data analysis methods are presented.

Section 4, Tier 2 Evaluation, presents the data needs and data analysis methods for a Tier 2 sediment transport evaluation.

Section 5, Application to Site Management, describes how the results of a sediment transport evaluation can be used to support sediment management decisions for a site.

Section 6, References, lists references cited in the text of this report.

Appendices to the document include a compilation of information on the various tools and technologies that can be used in the Tier 1 and Tier 2 sediment transport evaluations (Appendix A). Supporting information for the available tools and technologies includes a description of the technology, applicability, advantages and limitations, level of development, and relative cost. The case study reports for the site demonstrations are provided in Appendices B, C, and D.

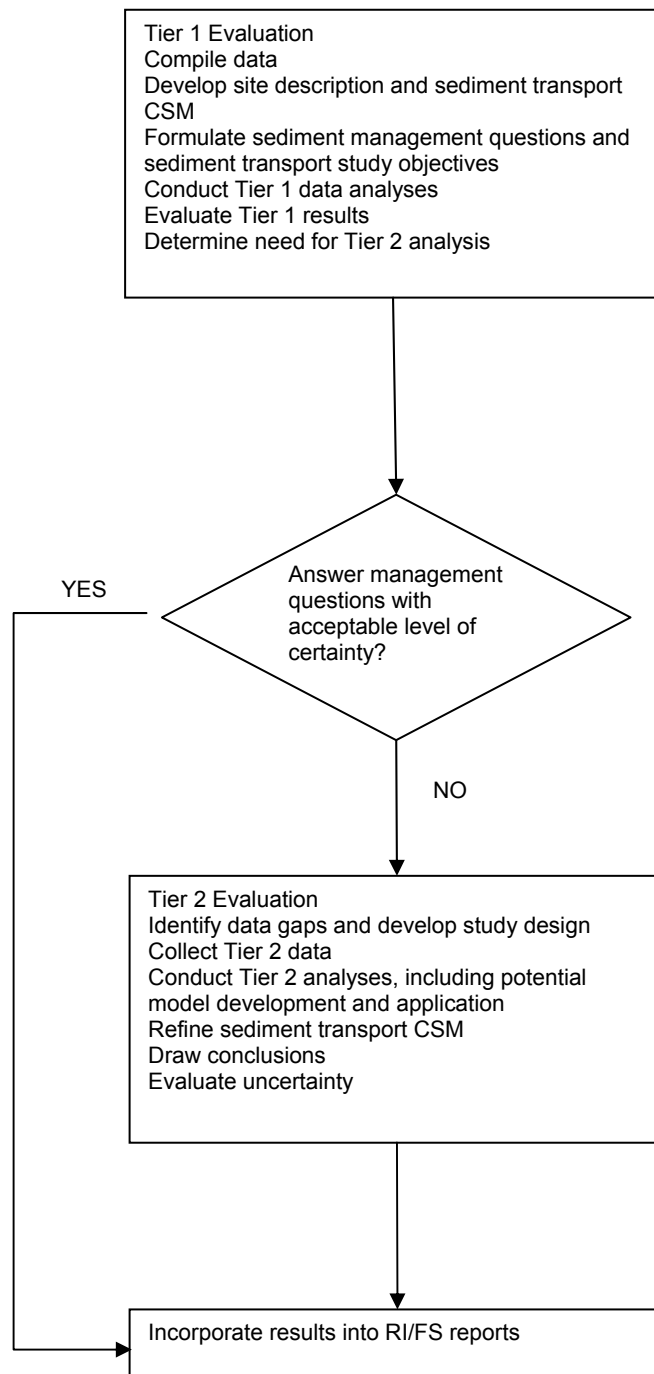


Figure 1. Overall approach for sediment transport evaluation process.

2. SEDIMENT TRANSPORT OVERVIEW

This section provides a general conceptual overview of sediment transport processes and environments, and defines relevant terms so that the discussion of tools and approaches for the Tier 1 and Tier 2 sediment transport evaluations can be more clearly understood. Section 2.1 describes the most important sediment properties and hydrodynamic processes, and Section 2.2 describes the sediment transport environments most commonly associated with contaminated sediment sites. Terms shown in bold are included in the glossary.

2.1 SEDIMENT TRANSPORT PROCESSES

The key to understanding sediment transport is the identification, description, and quantification of the dominant processes involved in moving sediments and understanding how the processes interact at a site. These processes are (1) erosion, (2) movement of sediments in the water column, and (3) deposition. Although other processes can affect sediment transport, an understanding of these fundamental processes is critical. The following sections describe the properties of sediments and sediment beds that have the greatest influence on sediment transport, and the hydrodynamic processes that act on the sediments and sediment beds.

2.1.1 Physical Properties of Sediment

For most systems, knowledge of particle size distribution and bulk density are fundamental to the understanding of local sediment transport processes. Particle size (or grain size) distribution is the most widely used property in engineering and environmental studies for the description of the sediment bed. Sediment particle sizes are classed from very fine clays with a particle diameter of 0.24 μm to boulders larger than 0.25 m in diameter. In the middle of these extremes are particle sizes that make up the sediment beds of common aquatic systems, sands, and silts. Table 1 describes the typical ranges of particle (or grain) size associated with each classification, along with a corresponding phi (Φ) classification that is also used in many engineering and environmental classifications. The classification system shown here is commonly referred to as the Udden–Wentworth classification system. Most often, natural sediments consist of a mixture of sediment grain sizes. These sediments are often described based on the relative proportions of each sediment type. For example, a mixture of a small amount of sand with clay can be called a sandy clay, and a smaller amount of silt with sand might be called a silty sand.

Based on particle size distributions, sediments are generally classed as *cohesive* or *non-cohesive*. Cohesive sediments are sediments in which inter-particle forces are significant, creating an attraction or cohesion between particles. Cohesive sediments are generally defined as those with particle sizes less than 200 μm in diameter. The smaller ranges of cohesive particles (<62 μm) are silts and clays, and the larger sizes (62 to 200 μm) are fine sands. Non-cohesive sediments are those in which inter-particle forces are insignificant, and are generally defined as those with particle diameters larger than 200 μm . These size ranges start with fine to medium sands. Because contaminants are generally associated with finer grained sediments, the focus of this guide is on cohesive sediments. Studies on non-cohesive sediments have shown a strong correlation between sediment bed particle size and sediment transport rates under controlled flow conditions, where transport rates decline as particle size increases. However, this observation does not hold for cohesive sediments, where particle size cannot be used alone to predict transport rates (van Rijn, 1993; Roberts, Jepsen, Gotthard, and Lick, 1998; Mehta and McAnally, 1998; Mehta, Hayter, Parker, Krone, and Teeter, 1989).

Bulk density is another basic property of a sediment bed that is useful for classifying sediments and quantifying transport properties. The bulk density, ρ_b , of a sediment bed describes the overall degree of packing or consolidation of the sediments, and is defined as the total mass of sediment and water in a given volume of bed material. The approximate density of the quartz and clay minerals that make up the majority of sediment particles in the natural world is about 2.65 g/cm^3 . The sediment bed itself is composed of these sediment particles packed into a porous bed. For cohesive sediments, bulk density generally increases with depth into the sediment because the deeper sediments are more consolidated, with less space between individual particles. Cohesive sediment beds also will consolidate over time due to the weight of overlying sediment, which causes an increase in the bulk density with increasing depth into the sediments. As the bulk density increases due to consolidation, the potential for scour or erosion of the sediment generally decreases (Jepsen and Lick, 1997; Mehta and McAnally, 1998).

Table 1. Grain size scale for sediments.

Description	Phi $\Phi = -\log_2(\text{mm})$	Grain Size (mm)	Grain Size (μm)
Boulder	-8	256+	-
Cobble			-
Large	-7	128 to 256	
Small	-6	64 to 128	
Gravel			-
Very coarse	-5	32 to 64	
Coarse	-4	16 to 32	
Medium	-3	8 to 16	
Fine	-2	4 to 8	
Very fine	-1	2 to 4	
Sand			
Very coarse	0	1.000 to 2.000	1000.0 to 2000.0
Coarse	1	0.500 to 1.000	500.0 to 1000.0
Medium	2	0.250 to 0.500	250.0 to 500.0
Fine	3	0.125 to 0.250	125.0 to 250.0
Very fine	4	0.062 to 0.125	62.5 to 125.0
Silt			
Coarse	5	0.031 to 0.062	31.3 to 62.5
Medium	6	0.016 to 0.032	15.6 to 31.3
Fine	7	0.008 to 0.016	7.8 to 15.6
Very fine	8	0.004 to 0.008	3.9 to 7.8
Clay			
Coarse	9	0.002 to 0.004	1.95 to 3.90
Medium	10	0.001 to 0.002	0.98 to 1.95
Fine	11	0.0005 to 0.0010	0.49 to 0.98
Very fine	12	0.00025 to 0.00050	0.24 to 0.49

2.1.2 Hydrodynamic Processes

Sediment transport in aquatic systems occurs because of the action of currents and/or waves on the sediment bed. In river systems, a downstream current is generally responsible for the influence of the fluid on the sediment bed, whereas in coastal regions and estuaries, a combination of waves, currents, and tides are responsible. Erosion, water column transport, and deposition are the major sediment transport processes in aquatic systems (Figure 2). These processes are discussed in more detail below.

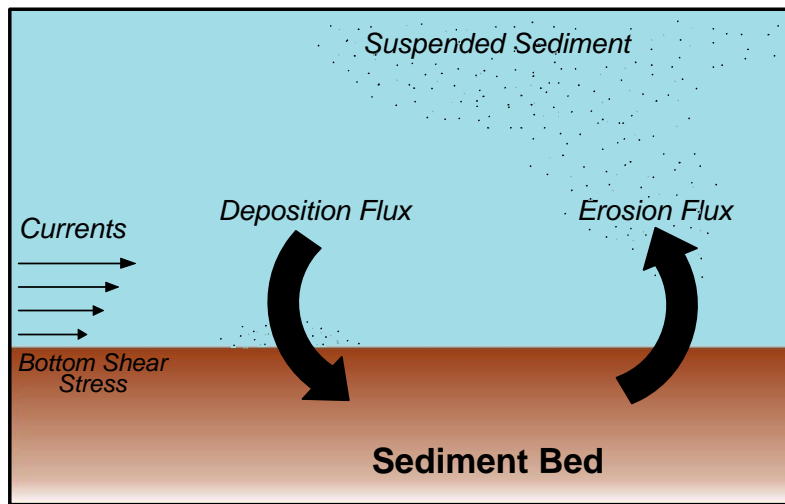


Figure 2. Simplified diagram of sediment transport processes.

2.1.2.1 Erosion

Erosion is the *flux* (i.e., movement) of particles from the sediment bed into the overlying water column. Sediment transport is initiated by erosion at some location, e.g., upstream erosion in a river valley bringing sediments to an estuary, a large storm event in an estuary eroding sediments, coastal waves eroding a shoreline, or any number of scenarios depending on the environmental setting. Erosion is the primary process that can potentially expose contaminated sediments and suspend them in the water column.

Sediment transport (i.e., erosion) is initiated by *shear stress*, τ , which is a force per unit bed area produced at the sediment bed as a result of friction between the flowing water and the solid bottom boundary. As a result, flow velocity decreases as the sediment bed is approached. Velocity increases logarithmically away from the bed until a point is reached where the bottom friction no longer affects the flow. This near-bed layer is called the *boundary layer* (Figure 3). Shear stress is denoted as force per unit area (N/m^2) and can be measured directly in the laboratory and indirectly in the field. It has been studied in detail for currents and waves, and can be defined and quantified mathematically given sufficient information about the hydrodynamics of the system.

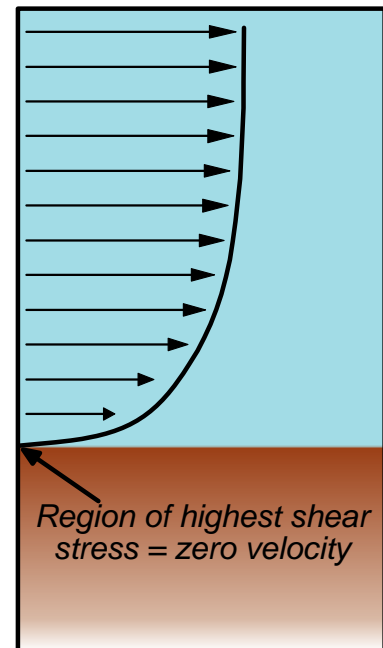


Figure 3. Boundary layer diagram.

Resting sediment particles are in a constant equilibrium between the drag forces from fluid shear, the lift forces from flow over the particles, and the forces exerted by the surrounding particles. At a certain velocity, the combined drag and lift forces on the uppermost particles of the sediment bed are great enough to dislodge them from their equilibrium positions. This velocity is related to the **critical shear stress** for erosion, τ_{ce} , which is defined as the shear stress at which a small but accurately measurable rate of erosion occurs. This initial motion tends to occur only at a few isolated spots. As the shear stress increases with increasing flow velocity, the movement of particles becomes more sustained, causing a net erosive flux from the sediment bed.

2.1.2.2 Movement of Sediments in the Water Column

After sediment movement is initiated, the subsequent transport is divided into two modes: **bedload** transport and **suspended load** transport. Coarser particles move along the bed by rolling and/or saltation (i.e., bouncing) in a thin layer as bedload, whereas finer particles are suspended into the water column and move as suspended load. The mode of transport for a given particle is largely affected by the sediment properties and flow regime of the region.

Bedload can account for a significant amount of sediment transport in systems comprised of coarse-grained sediments (sands and larger), where the flow is high enough to cause motion but not high enough to lift particles off of the sediment bed. Although bedload transport may be dominant in coarse-grained rivers and coastal regions, it may or may not be important in fine-grained (fine sands and smaller) regions such as estuaries and slow-flowing rivers. In fine-grained sediment systems, both individual particles and clumps or small aggregates of particles will erode. The small individual particles move as a suspended load. The clumps and aggregates can move along the bed as bedload, and if the flow is high enough, can be suspended into the water column or broken up into smaller aggregates or individual particles.

Sediment particles transported as suspended load are moving at or very close to the velocity of the fluid. In a steady-state situation, upward turbulent transport of a sediment particle by the fluid is balanced by the gravitational particle settling. This balance keeps the sediments suspended in the water column. As long as the flow remains large enough, sediments will be transported as suspended load. As current velocity decreases, suspended sediment concentrations generally increase near the bed. Vertical profiles of suspended sediment concentrations can be calculated based on particle size, a reference concentration near the sediment bed and fluid velocity (Rouse, 1938; van Rijn, 1993).

Two processes generally dominate the movement and net transport of particles in the water column: **advection** and **turbulent diffusion**. Advection is the transport of particles caused by the motion or velocity of the fluid. Turbulent diffusion is the dispersal of particles in the water column due to random turbulent motion within the fluid. An accurate characterization of these processes in any aquatic system will yield a good quantitative description of local sediment transport.

2.1.2.3 Deposition

Deposition is the process by which sediment particles settle out onto the sediment bed, causing an accretion of particles. As suspended and bedload sediments are transported, they can encounter areas of lower fluid velocity. If the fluid velocity is low enough, turbulent eddies may be insufficient to keep the particles suspended or in motion as bedload. When this happens, the particles will settle to the sediment bed. The shear stress at which settlement begins is termed the critical shear stress for suspension, τ_{cs} , and is also measured in units of force per unit area (N/m^2). As the shear stress decreases, the probability of a particle settling onto the sediment bed and remaining there as

deposited material increases. At a shear stress of zero, the probability of deposition is one. Significant deposition can occur in backwater areas of large rivers, tidal flats, river deltas, etc., where flow is reduced.

As the shear stress fluctuates in a natural system, the sediment bed may be subjected to episodic erosion and resuspension. Net deposition occurs if, over time, the amount of sediment deposited on the bed exceeds the amount that is episodically eroded.

As fine-grained particles interact in the water column, they can attach together, or *flocculate*, to form larger clumps. This process is dependent on sediment type, suspended sediment concentration, fluid velocity and shear, and water chemistry. In general, as sediments flocculate, they form larger particles that tend to deposit faster than smaller individual particles.

2.1.3 Bioturbation

Sediments that remain relatively stable even during large flow events may still undergo active mixing due to biological activity, or *bioturbation*, by benthic macrofauna (i.e., animals) living in the surficial sediments (Figure 4). Bioturbation occurs in the uppermost layers of sediment in which the animals reside, with the most intensive activity in surficial sediments (generally on the order of centimeters), and a decrease in activity with increasing depth (Clarke, Palermo, and Sturgis, 2001). The most common bioturbators in marine/estuarine environments are polychaetes, crustaceans, and mollusks. These animals can have a significant effect on the sediments they inhabit, depending on their modes of feeding and other activities. Bioturbation can affect not only the physical properties of the sediments (i.e., bulk density and cohesion), but can also redistribute contaminated sediments. Biological activity can increase or decrease the ability of the sediment bed to resist erosion. Secretions associated with tube building activities can bind sediment particles and increase sediment strength; burrowing can decrease cohesion and bulk density (Rhoads and Carey, 1997; Boudreau, 1998). The effects of bioturbation are site-specific and can exhibit spatial and seasonal variation.



Figure 4. Tube-building worms at 13-cm deep horizontal cross-section and vertical profile of same core (sediment from 0 to 13 cm in cross-section was eroded in SEDflume).

2.2 SEDIMENTARY ENVIRONMENTS

Sediment transport in natural systems is a function of the physical characteristics of the environments. The driving forces of sediment transport vary from place to place, from lagoons to estuaries and bays to continental shelves. For example, currents on the west coast of the United States are primarily driven by along-shelf winds, whereas currents in the gulf coast and South Atlantic bight are strongly influenced by freshwater input from rivers (National Research Council [NRC], 1993). In other regions, like Puget Sound and San Francisco Bay, tidal motions are a driving force for sediment transport. Most of the Navy's contaminated sediment sites are located in rivers, bays, and estuaries. Sediment transport processes in each of these environments are described in the following sections.

2.2.1 Rivers

Sediment transport in *fluvial* environments (i.e., rivers or streams) is dominated by the interaction between variations in fluid flow and the sediment bed. The critical parameters controlling fluid flow in a river are mean flow characteristics (i.e., discharge), channel shape, sediment size, and bedforms. In rivers, sediments are transported as both bedload and suspended load. Fluvial bedload can be a major factor in forming and changing the character of river channels, and can contribute up to 50 percent of the total sediment yield of a river. Bedload sediments can move along the channel as a series of bedforms (for example, ripples, dunes, and antidunes). Direct measurement of bedload transport is so difficult that no standard procedure is available, despite almost a century of research devoted to this problem. As a result, many researchers have developed equations that can predict the bedload flux using experimental (Meyer-Peter and Muller, 1948), theoretical (Einstein, 1950; Bagnold, 1956; Bagnold, 1966; van Rijn, 1993), and dimensional analysis (Acker and White, 1973; Yalin, 1963) approaches.

The suspended load also contributes significantly to the total sediment load in many rivers. Suspended sediments can be derived from overland flow (runoff), bank erosion, and resuspension from the channel bed. Consequently, changes in suspended sediment load are highly dependent on the land use of the drainage basin (Reid et al., 1997). The suspended sediment load can be measured by direct sampling or calculated using existing data for sediment and water discharge. Sediment and water discharge are most commonly compared using a power law relationship, where sediment discharge increases with water discharge but these relationships rarely capture all of the features of sediment loading (Geyer, Milligan, and Traykouski, 2000; Wheatcroft et al., 1997).

2.2.2 Bays

A bay is a part of the ocean coast that is semi-isolated by land, but not significantly diluted by freshwater drainage. Harbors, gulfs, inlets, sounds, channels, and straits are similar to bays in that they have similar water properties and circulation patterns. Some bays are tide-dominated, and others are wave-dominated. Tides are the rise and fall of the sea around the edge of land due to the gravitational attraction between earth and sun, and earth and moon. A *diurnal* tidal cycle is characterized by one high water and one low water each lunar day (1 lunar day = 24 h, 50 m). A *semidiurnal* tidal cycle has two high and two low water periods each lunar day. A *mixed tide* is a semidiurnal tide where the two highs have unequal height, and two lows have unequal heights. A rising tide is a flood tide, and a falling tide is an ebb tide. A *spring tide* has the greatest difference between high and low tides and occurs during a new moon and a full moon. A *neap tide* has the smallest difference between high and low tides and occurs during the first and last quarter moons. Tidal currents are generated by

the rising (flood) and falling (ebb) tide. Slack water occurs when tidal currents slow down and then reverse direction.

Areas that are always below the lowest water level are *subtidal*. The *intertidal* zone is sometimes but not always covered by water. Intertidal areas are subject to regular flooding and uncovering on a daily basis. On many intertidal flats, the tide rises and falls as a broad sheet of water. Fine-grained sediments are commonly carried into the intertidal area as suspended sediment on the flood tide. These sediments are deposited when the current decreases and reverses at slack tide. The net effect is the transport of fine particles towards the shore, where they accumulate unless resuspended by waves or storms.

Waves are most commonly generated by wind, but can also be caused by landslides, sea bottom movement, ships, etc. Enclosed and semi-enclosed bodies of water are susceptible to wave energy formed from local winds and/or open ocean swell. Wave features are shown in Figure 5A. The portion of the wave that is elevated above the surface is the crest; and the portion depressed below the surface is the trough. The distance between two successive crests or troughs is the *wavelength*. The *wave height* is vertical distance from the crest to the trough. The wave height is controlled by wind speed, wind duration, and *fetch* (the distance over the water that the wind blows in a single direction). Wave height may be limited by any one of these factors (e.g., high-speed winds blowing over a long fetch for a short time will not generate large waves).

As a wave form moves across the surface of the water, particles of water are set in motion. In deep water, the water particles move in a circular path (orbit) as a wave passes (Figure 5B). The diameter of the orbit is equal to the height of the wave. Energy is transferred downward, and the diameters of the orbits become smaller with increasing depth. At a depth of one-half the wavelength, the orbital motion decreases to almost zero. As the wave passes into water that is shallower than one-half its wavelength, the orbits become elliptical (Figure 5C) and the wave begins to “feel” the bottom. In the case of shallow water waves, the orbital motions of the water particles exert a shear stress on the sediment bed, potentially leading to sediment resuspension.

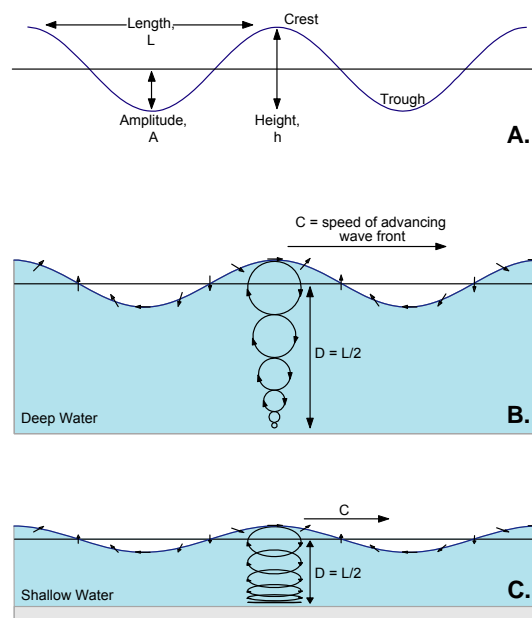


Figure 5. Illustration of (A) basic wave anatomy, (B) waves in deep water, and (C) waves in shallow water.

2.2.3 Estuaries

Estuaries are transition zones between rivers and the ocean, where the mixing of fresh and salt-water occurs. The most common definition of an estuary is from Cameron and Pritchard (1963), who state that “an estuary is a semi-enclosed coastal body of water which has a free connection to the open sea and within which seawater is measurably diluted by land drainage.” The interaction between river discharge, tidal asymmetry, and local bathymetry can lead to large differences in circulation patterns, density stratification, and mixing processes within an estuary.

Three main categories of estuaries have been defined based on their circulation and vertical distribution of salinity in the water column: salt-wedge estuaries, partially mixed estuaries, and well-mixed estuaries. An estuary may not fall cleanly into one category, or may change seasonally or with changes in tidal currents or river flow.

A salt wedge estuary occurs when the mouth of a river flows directly into saltwater. The river water, less dense than seawater, flows outwards over the surface of the denser saline water. Salinity is strongly stratified and the boundary between saltwater and freshwater is sharp (Figure 6A). Highly stratified estuaries generally occur when tides are very small relative to river discharge. As fresh river water flows out over the surface of denser saline water, small parcels of saltwater are entrained into the upper layer due to velocity shearing at the halocline, which is the interface between the freshwater and saltwater. As a result, a residual landward flow of saltwater at the bed compensates for the volume of saltwater passing into the upper layer and exiting the estuary. The strength of residual currents tends to be controlled by horizontal and vertical density gradients between the river and sea (Dyer, 1986). The result is a system where freshwater flows seaward at the surface and saltwater flows landward at the bed, a condition commonly referred to as estuarine circulation. The mouths of the Mississippi, Columbia, Lower Duwamish, Hudson, and Thames Rivers are examples of salt wedge estuaries.

In partially mixed estuaries, the influence of tides is increased and frictional drag at the bed produces turbulent eddies that lead to mixing both upwards and downwards across the halocline (Figure 6B). Because the mixing of saltwater into the upper layer is increased, compensation in the lower layer results in a landward residual flow that generally has a much larger magnitude than in a salt wedge estuary. Partially mixed estuaries are generally deeper than a well-mixed estuary. Puget Sound and San Francisco Bay are examples of partially mixed estuaries.

When the tidal range is very large compared to the water depth in the estuary, the turbulence produced by velocity shear may be enough to mix the entire water column, creating a well-mixed estuary. Salinity is generally vertically uniform and increases from river to ocean (Figure 6C). Lateral circulation may occur in wide estuaries as a result of Coriolis and centrifugal forces, where river water flows down one side of the channel and saltwater enters the other side of the estuary (Dyer, 1997). In narrower estuaries, lateral shear may be great enough to create laterally homogeneous conditions where the salinity increases evenly towards the mouth. Delaware Bay is an example of a well-mixed estuary.

The dynamics of estuarine sediment transport depend on a complex relationship between tidal exchange, *residual circulation*, and the physical properties of the sediments. These sediments form an important link to estuarine processes, including the transport of pollutants that have an affinity for fine, cohesive sediments. As a result, estuarine sediment transport processes must often be described on a site-specific basis.

Suspended-sediment concentrations are generally high, with fine sediment particles that are cohesive and have a tendency to flocculate. The most significant impact of flocculation in terms of sediment transport is that it alters the hydrodynamic properties of the sediment. Aggregation and breakup of flocs essentially alter the particle size, porosity, and surface area with concomitant changes in particle settling velocity.

In many estuaries, particularly those that are partially and well-mixed, a feature known as the turbidity maximum can occur where fine-grained, suspended-sediment concentrations in the upper or middle reaches of the estuary are greater than upstream or downstream concentrations (Nichols and Biggs, 1985; Grabemann and Krause, 1989). A turbidity maximum occurring at the head of a salt intrusion has been observed in the Rappanhannock Estuary, Virginia (Nichols, 1977) and the Tamar Estuary, England (Dyer, 1997).

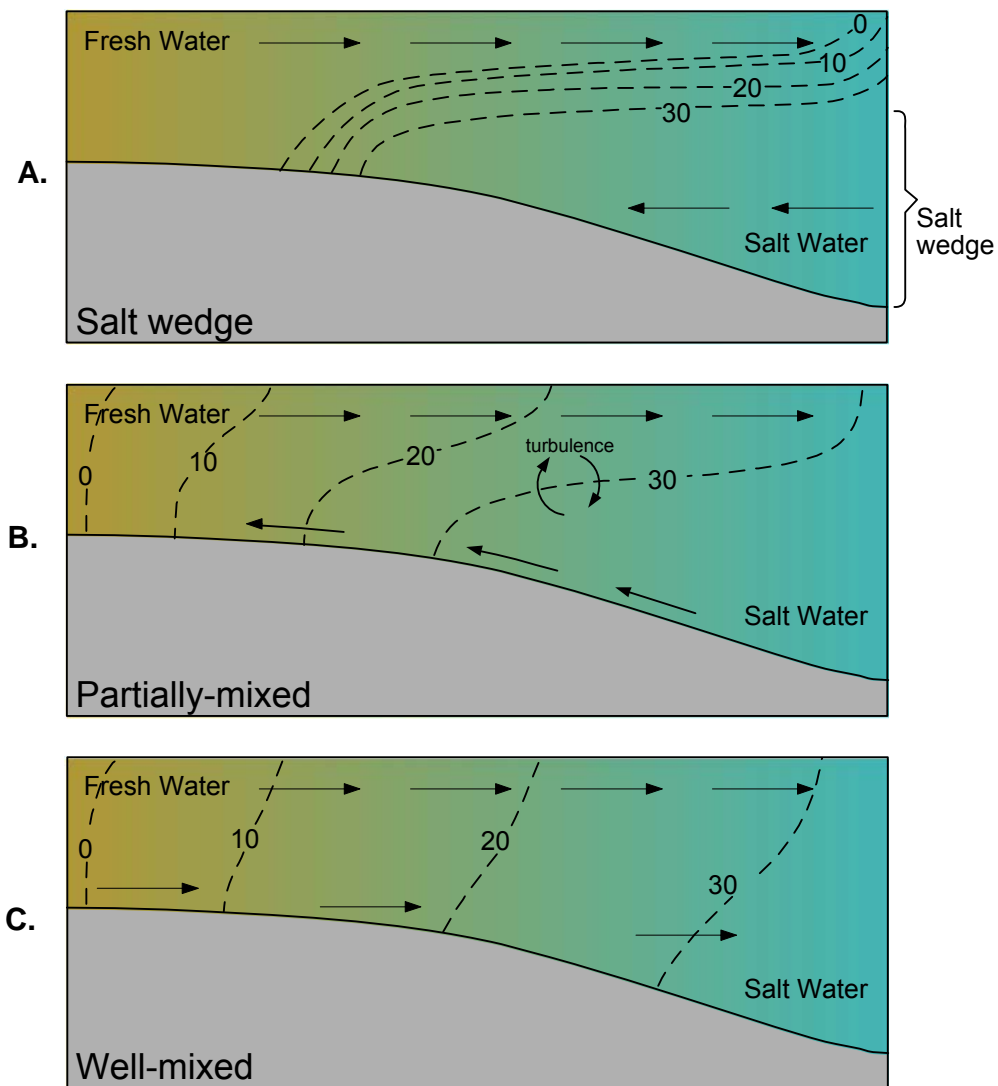


Figure 6. Examples of salt wedge, partially mixed, and well-mixed estuaries.

3. TIER 1 EVALUATION

The goal of the Tier 1 evaluation is to address the most common sediment management questions using readily available data from the RI and relatively uncomplicated data analysis methods. The Tier 1 evaluation has relatively simple data needs, a lower cost, a shorter time frame, and a higher level of uncertainty than a Tier 2 evaluation. Depending on the questions asked at a specific site, the Tier 1 level of analysis may be sufficient. The Tier 1 evaluation is typically conducted after the RI field and lab work are completed and the degree of sediment contamination is generally known. The sediment transport evaluation is conducted concurrently with other fate and transport analyses for the RI and includes the following activities:

- Compile existing data on the physical characteristics of the site
- Develop the sediment transport CSM
- Formulate sediment management questions and Tier 1 sediment transport study objectives
- Perform the Tier 1 analysis
- Evaluate the Tier 1 results and determine whether additional Tier 2 analysis is warranted

Each of these elements is described in the following sections.

3.1 COMPILE TIER 1 DATA

During the initial stages of the sediment transport evaluation, the project team should compile existing data on the site characteristics, sediment properties, and hydrodynamics. Because all of the necessary data should be available from the RI and historical sources, little or no targeted data collection should be needed. These data can be used to develop the initial sediment transport CSM and support the Tier 1 evaluation. Table 2 lists data sources for the Tier 1 evaluation, and Table 3 lists data needs for addressing specific sediment management questions. A summary of the key data categories is provided below.

3.1.1 Site Characteristics

Bathymetric, topographic, and historical information are always needed to characterize a site because physical boundaries often define the extent of a site and its potential influence on the surrounding areas. Historical information can be used to infer past and present sediment transport patterns on the site. Some publicly available sources of information and data are summarized in Table 2.

Bathymetric Data. Bathymetric maps and data may be available from the National Oceanographic and Atmospheric Administration (NOAA) or from Navy records. Dredging records from the Navy or the U.S. Army Corps of Engineers (USACE) may provide information about bathymetric changes, depositional environment, and sediment accumulation rate.

Aerial Photographs and Site Maps. Historical and recent aerial photographs and site maps can provide information on historical changes in the water body configuration, and sources of incoming sediment.

Anthropogenic Activity. Information regarding navigation, dredging, past and future construction activities, and other future use issues should be obtained from various sources including the Navy, USACE, U.S. Coast Guard, and state, regional, or local agencies. Locations, diameters and types of outfalls at or near the site also should be determined.

Existing site conditions should be described as part of the Tier 1 evaluation. If possible, the site should be examined from a boat at high tide and low tide so that shoreline features can be observed. Information that should be noted includes the following:

- Site layout, topography, water body configuration, and identification of features that drain into the water body, including outfalls
- Nature of the shoreline (e.g., presence of riprap, beaches, and intertidal areas; slope, density, and type of vegetation; location of high and low tide lines)
- Dredging and other anthropogenic activity
- Potential sources of sediment to the water body
- Flow directions and estimates of velocities
- Historical land and water body uses

Any features that are not recorded on maps, charts, or in reports should be noted.

Table 2. Online information resources for Tier 1 analysis.

Organization/Type of Information	World Wide Web Address
NOAA National Geophysical Data Center Bathymetry and Topography	http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html
NOAA Office of Coast Survey Nautical charts	http://chartmaker.ncd.noaa.gov/
NOAA CO-OPS Tide and current predictions and real-time observations	http://co-ops.nos.noaa.gov/tide_pred.html
U.S. Geological Survey (USGS) Water Resources Maps and Geographic Information System (GIS) information	http://water.usgs.gov/maps.html
USACE Links to individual divisions and districts	http://www.usace.army.mil/howdoi/where.html#maps
National Weather Service (NWS) Office of Climate, Water and Weather Services Information dissemination services	http://www.nws.noaa.gov/om/disemsys.shtml#FOS

Table 3. Data needs for Tier 1 and Tier 2 sediment transport evaluation.

Parameter	Tier 1 Data Sources	Tier 2 Data Sources	Reason for Measurement
Site Characteristics			
Water body configuration and bathymetry (current and historical)	Maps, NOAA bathymetric charts, aerial photographs, and other available regional and site-specific data (current and historical)	Detailed bathymetric survey - single or multi-beam mapping systems Shoreline surveys Side scan sonar	A basic level of bathymetric, topographic, and historical information is needed to characterize a site because physical boundaries often define the relevant zone of influence. A bathymetric/shoreline change analysis can yield information on long-term depositional or erosional characteristics of the system (sediment sources and sinks) and help quantify rates of change.
Contaminant source identification; horizontal and vertical distribution of sediment contaminants	Sediment chemistry data as collected for the RI	High-resolution horizontal and vertical sediment contaminant distribution data	If contaminant source(s) and loading history are known, then sediment transport patterns can be inferred from the horizontal and vertical contaminant distribution. Sediment contaminants can act as a tracer for the transport of contaminants away from the site, or to identify potential off-site sources contributing to sediment contamination.
Anthropogenic activities (historical, current, and future)	Information on outfalls, dredging, navigation, planned construction activities, future use, anticipated watershed changes	Not applicable	The influence of anthropogenic activities must be taken into account during a sediment transport analysis.
Water Column Properties			
Waves, tides, and currents; salinity and temperature	Available regional or site-specific data	Detailed site-specific current measurements (S4, Acoustic Doppler Velocimeter (ADV), Acoustic Doppler Current Profiler (ADCP), Pulse Coherent Acoustic Doppler Profiler (PC-ADP), velocimeters) Tide and wave measurements (pressure sensors, ADCP wave array, S4) Salinity and temperature profiles (in estuaries)	The dominant hydrodynamic forces should be identified and quantified because they drive sediment transport. When combined with suspended sediment measurements, directions and quantities of sediment transport can be described. Analysis of water column transport properties is necessary for the determination of sediment flux on/off site and for determining settling properties of sediments.
Suspended sediment concentrations	Water quality data from USGS or local regulatory agencies	Site-specific measurement of suspended sediment concentrations (Optical Backscatter Sensor [OBS], Laser In Situ Scattering Transmissometer [LISST], transmissometer, and/or analytic total suspended solids [TSS] samples)	Knowledge of the quantity and character of suspended solids is necessary to calculate the flux of suspended sediments on/off site and to determine sedimentation rates.

Table 3. Data needs for Tier 1 and Tier 2 sediment transport evaluation. (continued)

Parameter	Tier 1 Data Sources	Tier 2 Data Sources	Why do you measure this?
Sediment Bed Properties			
Horizontal and vertical particle size distribution	Grain size data as collected for the RI	Sieve analysis for sediments >63 µm and laser diffraction methods for high resolution <63 µm	Sediment bed property data can be used to infer the sediment transport environment based on distributions of sediment grain sizes and densities; data also are needed for analytic and numeric computations.
Water content/bulk density	Water content data as collected for the RI	Additional data collection if needed	
Total organic carbon content	TOC data as collected for the RI	Additional data collection if needed	
Sediment stratigraphy	Available site data, sediment core descriptions	Sub-bottom profiler and/or multi-beam mapping system	Stratigraphic information can be used to infer depositional environments and historic stability of the sediment bed with depth.
Sediment erosion properties	Calculated estimates or literature values based on sediment properties	Surficial critical shear stress and resuspension potential for cohesive sediments (shaker/annular flume) Sediment erosion profiles with depth for cohesive sediments (SEDflume) Side scan sonar	Some measure of sediment erosion properties must be conducted for cohesive sediments to determine the potential for sediment erosion and potential depths of erosion during extreme events. Non-cohesive sediment behavior can generally be predicted from grain size and density information. An understanding of sediment erosion properties is required to identify erosional sources of contaminated sediment.
Sediment accumulation rate	Historic bathymetric differences Dredging records	Radioisotope analysis Sediment traps Pin/pole survey	Sediment accumulation rates can be used to directly determine rates of burial of on-site sediments.
Bioturbation	Regional and site-specific biological data as available and as collected for the RI	Qualitative or quantitative benthic survey Sediment profile images Push core observations Radioisotope profiling Oxidation-reduction potential measurements	Physical transport of sediments vertically in the zone of bioturbation must be understood and quantified to characterize potential depths to which contaminated sediments may be exposed and/or transported. Oxidized layer of surficial sediment corresponds with most actively mixed sediments.

Table 4. Common sediment management questions and associated data needs.

Question	Site Characteristics ^(a)	Water Column Properties		Sediment Bed Properties			
		Waves, Tides, Currents	Suspended Sediment Concentrations	Sediment Properties ^(b)	Sediment Erosion Properties	Sediment Accumulation Rate	Bioturbation
Could erosion of the sediment bed lead to the exposure of buried contamination?	X	X ^(c)		X	X		
Could sediment transport lead to the redistribution of contamination within the site, or movement of contamination off site?	X	X	X	X	X		
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				

(a) Water body configuration, bathymetry, sediment sources, contaminant sources, horizontal and vertical distribution of sediment contaminants, anthropogenic activities (past, present, future).

(b) Particle size distribution, bulk density, TOC.

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

3.1.2 Sediment Properties

The characteristics of sediment and the sediment bed often provide insight into the sediment transport environment based on distributions of sediment grain sizes, densities, and contaminants. Biological information also is needed to assess the potential effects of bioturbation.

Sediment Particle Size Distribution, Moisture Content, and TOC Content. Sediment type (i.e., particle size distribution) is one of the most important parameters for characterizing sediment transport. Percent moisture data can be used to infer the bulk density of the sediment, which is another critical parameter. If possible, the horizontal and vertical distribution of sediment type (i.e., stratigraphy) should be established.

Sediment Contaminant Distribution Data. If available, data on the horizontal and vertical distribution of contaminants potentially can be used to infer sediment transport patterns, if the contaminant source(s) and source loading history are known.

Biological Activity. Any existing site-specific or regional data on *epibenthic* (near bottom dwelling) and *benthic* (bottom dwelling) biota should be gathered, such as information on organism type and abundance, and seasonal or spatial patterns in biotic activity.

3.1.3 Hydrodynamic Data

Because hydrodynamic processes are always the driving force in sediment transport, these data will often provide a basic level of understanding of the dominant forces in a given site setting. When combined with suspended sediment concentration data, directions and quantities of sediment transport can begin to be determined.

Currents, Tides, Waves, Wind, and Surface Water Runoff. Site-specific or regional data on hydrodynamic forces may be available from various sources, including the U.S. Navy, USACE, NOAA, USGS, NWS, universities, and state, regional, and local agencies (see Figure 7).

Suspended Sediment Concentration Data. Site-specific or regional data on suspended sediment concentrations may be available from the sources listed above. Additionally, available satellite imagery may be used to look at regional trends in relative suspended sediment concentrations.

3.2 DEVELOP SITE DESCRIPTION AND CONCEPTUAL SITE MODEL

The sediment transport CSM should synthesize all available data, describe a mass balance (i.e., a simple representation of all inputs and outputs to a system), and describe inferred sediment transport patterns (areas of deposition and erosion) based on grain size distribution, contaminant distribution, and geomorphology. The following information should be incorporated into the site description and sediment transport CSM:

- Describe the site setting and water body characteristics, including the shoreline configuration and bathymetry. Use geographic and geomorphic features to identify likely areas of erosion and deposition.
- Describe the sediment and sediment bed properties. This description should include the following:
 - Sediment type and distribution. Finer grained sediment (silt and clay) tends to accumulate in depositional areas and coarser grained sediments tend to occur

in higher energy areas, although fine-grained sediment may be found everywhere in areas with high suspended sediment concentrations. Additionally, lower bulk density sediments may indicate ongoing deposition.

- Distribution of contaminants (horizontal and vertical). If a single source is responsible for most of the contamination, then contaminant concentration gradients can be used to infer the direction of sediment transport away from the source. If the loading history is known, then vertical contaminant concentration gradients can be used to infer sediment accumulation rate (i.e., depth of maximum sediment concentration should correspond with period of maximum loading).
- Description of benthic infauna and epifauna.
- Identify and describe the most important hydrodynamic processes, and estimate their magnitude and frequency.
 - In a fluvial setting, this process will be unidirectional currents.
 - In a marine or estuarine setting, it may be a wave-dominated system, tide-dominated system, or a combination.
 - Identify areas where current speeds decrease and are therefore likely to be depositional.
- Identify sources of particulates to the system. Possible sources of particulates include shoreline erosion, stream or river discharge, local resuspension, advection of particulates from other areas of the water body, and outfalls.
- Define the likely hydrodynamic boundaries of the system.
- Describe any anthropogenic activities that may influence sediment transport processes such as dredging, ship activity, or construction.
- Develop an initial assessment of the mass balance (sediment sources and sinks) and sediment transport patterns (areas of erosion and deposition) based on available information.

The CSM can be presented graphically with an accompanying narrative. An example of a sediment transport CSM is presented in Example 3. Once developed, the CSM can be used to identify the dominant sediment transport processes at the site based on available site data. The CSM is refined throughout the Tier 1 and Tier 2 evaluations as more data become available.

3.3 FORMULATE SEDIMENT MANAGEMENT QUESTIONS AND TIER 1 STUDY OBJECTIVES

The sediment management questions associated with a given site should be formulated concurrently with CSM development. The relevant questions should be used to guide the Tier 1 evaluation. The most common contaminated sediment management questions related to sediment transport are as follows:

- Could erosion of the sediment bed lead to the exposure of buried contamination?
 - Under typical conditions?
 - Under extreme conditions?
 - Due to prop scour or other anthropogenic activities?

- In the future (anticipated change in site use or hydrodynamic conditions)?
- Could sediment transport lead to the redistribution of contamination within the site or movement of contamination off site?
- Will natural processes lead to the burial of contaminated sediment by relatively clean sediment?
 - Is the area depositional?
 - What is the sediment accumulation rate?
 - What are the sources of the incoming sediment particles, and are these likely to change in the future?
 - What are the physical and chemical properties of the incoming sediment?
 - At what depth will sediment be unaffected by biological and physical forces?
 - Are there anticipated changes in site use or hydrodynamic conditions?
- If a site is actively remediated, could sediment transport lead to the recontamination of the site?
- Will contaminated sediment be transported into the remediated area from adjacent unremediated areas, or from off-site sources?
- Will remedy implementation result in resuspension of sediment and recontamination of the remediated area?

One must analyze the major sediment transport processes (erosion/resuspension, transport, and deposition) at a site to address any of these questions. Various approaches for characterizing these processes using readily available site data and Tier 1 evaluation methods are described in the following sections. Table 3-2 summarizes the types of data needed to evaluate each question.

3.4 CONDUCT TIER 1 ANALYSIS

When possible, multiple lines of evidence should be developed in the Tier 1 analysis to support the overall interpretation of sediment transport at a site and facilitate regulatory acceptance of study results. Various approaches (i.e., lines of evidence) for characterizing sediment transport processes are provided below, and the application of the Tier 1 results to common sediment management questions is discussed in Section 3.5.

The following section describes basic calculations that may be performed to obtain a quantitative order-of-magnitude estimate of sediment transport processes. These calculations also can be used to identify critical data gaps and guide additional field data collection at the site.

The Tier 1 evaluation relies primarily on *analytical* techniques (i.e., solved using mathematical formulations). The analytical calculations presented below are based on *theoretical* (i.e., derived from basic principles) and *empirical* (i.e., based on measured laboratory or field data) yielding analysis methods useful in describing sediment transport processes. More detail on both *numerical* (i.e., solved using numerical solutions to governing equations) and *analytical* techniques will be presented as part of Tier 2 evaluation, along with details on providing *empirical* data to support these calculations (Section 4.2).

SOUTH BASIN

Figure 1 shows a site map of South Basin, including existing and historical features. South Basin is a shallow embayment in San Francisco Bay, with depths ranging from 6 ft to less than 2 ft. No streams or rivers enter the South Basin except for Yosemite Creek, a shallow, tidally-influenced channel that only flows approximately once per year. Sediments in South Basin are composed primarily of clayey silt, with silty sand along the shoreline. The primary contaminants of concern are PCBs. The highest concentrations of PCBs in surface sediment are found along the northeastern shoreline of South Basin, adjacent to an onshore landfill. PCB concentrations offshore of the landfill decrease with increasing distance from the shoreline. Sediment core data indicate that the highest PCB concentrations are found in subsurface sediments, which suggests that the original source of PCBs to sediment has been reduced or eliminated. Because PCBs strongly adsorb to sediment particles, sediment transport is expected to be the primary mechanism for their movement over time. PCBs appear to have been historically transported to the offshore area primarily via erosion and transport of contaminated soils in and near the surface of the landfill.

Because of its restricted circulation, tidal currents in South Basin are very weak. Waves are likely to be the dominant sediment resuspension mechanism because the basin is shallow and open to the southeast, which is the direction of the prevailing winds during winter storms. The primary source of sediment to the basin appears to be suspended sediment from San Francisco Bay; shoreline erosion may contribute some sediment although the topography adjacent to the basin is relatively flat. Because of the weak circulation in the basin, it is likely to be a net depositional environment with infrequent resuspension events that only act on the surficial sediments (~1-5 cm).

A basic CSM for sediment and contaminant transport in South Basin is shown in Figure 2. The dispersal pattern of PCBs, with higher concentrations near shore and decreasing concentrations offshore, is consistent with wave- and tidally-influenced sediment transport. Storm waves breaking along the shoreline suspend fine, low-density sediments in the near-shore region. A return flow near the bottom of the water column (balancing the shoreward flow due to waves at the surface of the water column) transports the sediments away from the shoreline and into South Basin. Tidally induced currents may facilitate additional transport across the mudflats and extend the influence of waves further offshore during low tide, and potentially carry material further offshore into South Basin. Finally, the deposition of cleaner background sediments transported in from San Francisco Bay and deposited in South Basin results in the dilution and burial of the near-shore and off-shore sediments. Biological activity mixes the newly-deposited surface sediment into the sediment bed.



Figure 1. Site Map

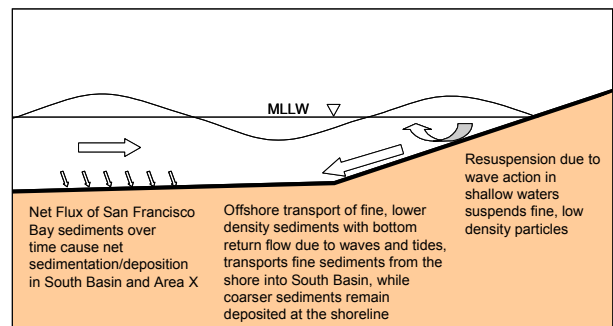


Figure 2. Sediment Transport CSM

Figure 7. Simplified sediment transport CSM.

3.4.1 Erosion/Resuspension

The following lines of evidence can be used to characterize sediment stability through the quantification of potential sediment erosion/resuspension at a site:

- Evaluate qualitative indicators (grain size, bathymetry, chemical profiles, etc.) during CSM development to infer if the sedimentary environment may be erosive (see Section 3.3).
- Calculate the bottom shear stresses and critical shear stress for the system to determine under what conditions erosion is likely.
- Evaluate the likelihood and magnitude of extreme events in the system of interest.
- Estimate the potential depth of scour based on expected shear stress.
- Evaluate the potential for erosion due to vessel traffic.

Methods for developing these lines of evidence are presented below.

3.4.1.1 Estimating Bottom Shear Stress

As described in Section 2.1.2, shear stress is the force produced at the bed as a result of the fluid flow, due to waves and/or currents, applied to an area of sediments. Turbulent shear stress can be simply calculated as

$$\tau = \rho C_f u^2,$$

where ρ is the fluid density (kg/m^3), C_f is the coefficient of friction, and u is the average fluid velocity (m/s). The coefficient of friction can be calculated for a unidirectional flow by

$$c_f = \frac{k^2}{\left(\ln \frac{11h}{k_s}\right)^2},$$

where k is von Karman's constant (0.42), k_s is the effective bottom roughness (m), and h is the water depth (m). A first estimate of the effective bottom roughness is generally chosen as 2 to 3 times the largest 10% of the material in the sediment bed (D_{90}) (Wright and Parker, 2004). Using these values, typical ranges for c_f are between 0.002 and 0.004 in rivers and estuaries. The coefficients of friction for environments where waves play a larger role involve more effort in their computation and are outlined in more detail in van Rijn (1993), Christoffersen and Jonsson (1985), and Grant and Madsen (1979).

The key to estimating shear stress in rivers and estuaries is knowledge of the average velocity over the sediment bed. The average velocity in a river at a given flow rate can generally be obtained through flow rating curves, which give an empirical estimate of velocity from flow rate measurements. The USGS generally has developed flow rating curves on any river or stream it has gauged. These data provide a good resource for a first estimate of the flow magnitudes expected in the region.

NOAA has developed resources for the prediction of tides and associated currents for most of the navigable estuaries and coastal regions in North America. In many navigable locations, NOAA has worked with local agencies to deploy real-time current and wave meters for a region. These data provide an excellent resource for determining order of magnitude waves and currents for sites of interest.

More sophisticated instrumentation for directly measuring velocity and shear stress is discussed in more detail in the Tier 2 evaluation (Section 4). In some cases, current and wave data from more sophisticated instruments may be readily available and should be sought out.

The error associated with these computations of shear stress come from the error of the velocity used to compute the shear stress and the calculation of the coefficient of friction. The more data available for the calculation of shear stress, the lower the level of uncertainty associated with these calculations. Some sites may have sufficient information available for the Tier 1 analysis. If the data are not available for even basic calculations, instruments and methods for collecting site-specific measurements must be used. These instruments and methods are described in Section 4 and summarized in Appendix A.

3.4.1.2 Estimating Critical Shear Stress

To predict whether contaminated sediments will be exposed under various flow conditions, one must determine the stability of the sediments under those conditions. As described in Section 2.1.2, sediment motion is initiated through the shear stress at the bed. The shear stress at which sediment movement begins, the critical shear stress for erosion (τ_{ce}), can be determined from the Shields curve, which gives the critical shear stress for erosion as a function of particle diameter for sediment particles greater than 200 μm .

To help simplify the calculation of critical shear stresses, a dimensionless particle diameter, d^* , is used:

$$d^* = d \left[(\rho_s - 1) \frac{g}{\nu^2} \right]^{1/3},$$

where d is the median particle diameter (cm), ρ_s is the density of the particles that is generally assumed to be about 2.6 g/cm^3 , ν is the kinematic fluid viscosity (which is 0.0117 cm^2/s for saltwater and 0.0112 cm^2/s for freshwater), and g is the acceleration due to gravity (980 cm/s^2). Using the d^* for the sediment bed, the critical shear stress in dynes/cm² for a particle larger than 200 μm may be calculated as shown in Table 5 (van Rijn, 1993). Shear stress can also be expressed as Pascals (Pa) (1 Pascal = 10 dynes/cm²).

Table 5. Critical shear stress for particles larger than 200 μm .

Critical Shear Stress (dynes/cm ²)	Valid d^* Range
$\tau_{ce} = 0.24 d^{*-1} [(\rho_s - 1)gd]$	$1 < d^* \leq 4$
$\tau_{ce} = 0.14 d^{*-0.64} [(\rho_s - 1)gd]$	$4 < d^* \leq 10$
$\tau_{ce} = 0.04 d^{*-0.1} [(\rho_s - 1)gd]$	$10 < d^* \leq 20$
$\tau_{ce} = 0.013 d^{*0.29} [(\rho_s - 1)gd]$	$20 < d^* \leq 150$
$\tau_{ce} = 0.055 [(\rho_s - 1)gd]$	$d^* > 150$

For smaller cohesive sediment particles (i.e., smaller than 200 μm), the determination of τ_{ce} is a function of many more sediment variables than particle size, and no single formulation for its calculation exists. For a conservative estimate, 1 dyne/cm² can be used (Gailani, Ziegler, and Lick, 1991), but this value might vary by almost an order of magnitude for cohesive sediments at various sites (Roberts, Jepsen, Gotthard, and Lick, 1998). For cases requiring a high degree of certainty in

critical shear stress measurements, site-specific measurements such as those outlined in the Tier 2 analysis may be required (see Section 4).

3.4.1.3 Estimating Resuspension and Depth of Scour

With an initial estimate of τ_{ce} , the potential for sediment motion can be calculated. For non-cohesive sediments, van Rijn (1993) has developed formulations to describe the transport rates of sediments in wave- and/or current-dominated environments. Depths of scour around structures in non-cohesive sediments are also well outlined in Sumer and Fredsoe (2002).

Because contaminants of concern are generally associated with cohesive sediments, cohesive sediment sizes are addressed in more detail. The erosion of cohesive sediments is generally described through empirical formulations as no predictive analytical formulation has been developed. One common empirical formulation based on a variation of Partheniades (1965) and refined by Gailani, Ziegler, and Lick (1991) can be used to obtain order-of-magnitude predictions of sediment erosion. Ziegler (2002) modified it further to estimate the maximum sediment erosion, E_{max} (mg/cm²), for a specific site based on a maximum expected shear stress, τ_{max} , where all shear stress values are in dynes/cm²:

$$E_{max} = A \left(\frac{\tau_{max} - \tau_{ce}}{\tau_{ce}} \right)^n,$$

where constant A and exponent n are site-specific parameters. Ziegler (2002) has compiled the average values of A and n for eight cohesive sediment systems (Table 6).

Table 6. Example erosion parameters for cohesive sediments.

Study Site	Constant A (mg/cm ²)	Exponent n
Upper Hudson River (HydroQual, Inc., 1995)	0.027	3.0
Pawtuxet River (Ziegler and Nisbet, 1994)	0.24	2.0
Watts Bar Reservoir (Ziegler and Nisbet, 1995)	0.1	2.7
Upper Mississippi River	0.11	2.6
Fox River (Lick et al., 1995)	0.75	2.3
Green Bay (Lick et al., 1995)	0.34	2.5
Saginaw River (Lick et al., 1995)	0.053	2.7
Buffalo River (Lick et al., 1995)	0.081	3.1
Average values ± 95% confidence interval	0.21 ± 0.20	2.6 ± 0.3

From this estimate of the maximum erosion at a specific location, the depth of potential scour in cm, S_{max} , can be estimated as follows:

$$S_{max} = \frac{E_{max}}{1000\rho_{sed}}.$$

The dry density of the sediments, ρ_{sed} (g/cm³), is determined from site-specific data. If no data are available, Ziegler (2002) recommends 1 g/cm³ as a first-order approximation.

3.4.1.4 Extreme Events

Many contaminated sediment sites are located in areas that are depositional most of the time. The most significant risk of contaminant exposure in these systems occurs during large storm or flood events that create conditions under which significant amounts of sediment can be resuspended. These storm and flood events are termed extreme events and must be considered in any sediment transport evaluation.

At riverine sites, the extreme event will typically be a flood. The average number of years between floods of a certain size is the recurrence interval or return period. Flood designations are based on statistical averages, not on the number of years between big floods (USGS, 1996). The term **100-year flood** indicates that there is a 1-in-100 chance that a flood of this size will occur in any given year. The actual number of years between floods of any given size varies in response to natural climatic fluctuations. USACE has developed a manual titled “Hydrologic Frequency Analysis” (USACE, 1993) that can be used to evaluate hydrographs and determine the frequency and magnitude of flood events. The values from these analyses can be used to determine the order of magnitude of the maximum bottom shear stress that may be anticipated during these events.

For coastal and estuarine sites, storm activity typically will generate the most extreme event potentially affecting sediment transport in the region. USACE has developed the “Coastal Engineering Manual” (USACE, 2002), which outlines how to evaluate the maximum wave and water level conditions at a coastal or estuarine site. These values can be used to predict the order of magnitude bottom shear stress that may be expected during these events. Note also that the river input into an estuary during an extreme event can significantly alter flow patterns in the region, in which case, the analyses for both the riverine and estuarine environments should be combined.

3.4.1.5 Erosion/Resuspension due to Prop Scour

The sediment beds of navigable waterways may be susceptible to scouring action from passing ship traffic, which has presented an engineering challenge in the past and has been studied in some detail. Techniques for determining the maximum depth of scour due to ship propellers include those of Sumer and Fredsoe (2002), Blaauw and van de Kaa (1978), Fredsoe (2002), and Hamill, Johnston, and Stewart (1999). The impacts of ship scour have been investigated by Lindholm, Svartstrom, Spoo, and Meriluoto (2001) and Michelsen (1998). With known vessel characteristics, empirical methods can be used to predict the maximum bottom velocity (Liou and Herbich, 1976; Maynard, 2000; Dargahi, 2003). The maximum bottom velocities generated by the ship traffic can then be used to determine the maximum bottom shear stress over the time of vessel movement. The shear stress can then be used to make estimates of maximum bed scour.

3.4.1.6 Summary

The assessment of sediment stability at a site is achieved by quantifying potential erosion/resuspension of sediments. Once the site has been described in the CSM, typical currents and/or waves at the site can generally be described using the methods outlined above. The range of these values can additionally be determined through an extreme event analysis appropriate for the type of site. With this information, bottom shear stresses typical of the site can be calculated, along with a critical shear stress for the sediments present. This information can be used to determine order of magnitude scour depths in regions of interest. Additionally, the potential for erosion due to ship traffic should also be considered.

For cohesive sediments, a great deal of uncertainty is generally associated with the prediction of an erosion rate and scour depth. Cohesive sediments are highly heterogeneous, not only from site to site, but within a localized area. This uncertainty is in addition to any uncertainty regarding currents and/or wave forces at the site. Therefore, if an accurate estimate of erosion rates and scour depths is required for the site, a Tier 2 analysis should be considered.

3.4.2 Transport

As discussed in Section 2.1.2, the two fundamental processes responsible for moving sediments from one location to another are advection and diffusion. Advection is the primary process in most systems and therefore is the focus of the Tier 1 analysis. The most useful tool in the initial determination of directions and quantities of sediment transport is a mass balance. A mass balance is a simple representation of all of the inputs and outputs of mass in a system. In an ideal well-mixed, steady-state system, a mass balance can be written as

$$\text{Sediment mass inflow} - \text{Sediment mass outflow} + \text{Sediment erosion} - \text{Sediment deposition} = 0.$$

This basic steady-state mass balance can help determine whether the area of interest is net depositional or net erosional. Mathematically, the steady state mass balance can be expressed as

$$Q_{in} C_{in} - Q_{out} C_{out} + A(E - D) = 0.$$

The average suspended sediment concentration of the region in mass per unit volume is C ; t is the time, Q_{in} and Q_{out} are the incoming and outgoing mass flow rate in volume per unit time, C_{in} and C_{out} are the suspended sediment concentrations of the incoming and outgoing water in mass per unit volume, A is the surface area of the system, and E and D are erosion and deposition in mass per unit volume per unit time.

As a first approximation, the region selected for the CSM can be used as the surface area, A . Inflow and outflow from the region, Q , can be estimated for known sources such as rivers and can generally be calculated as $Q = A_c * u_c$, where A_c is the cross-sectional area of the inflow (e.g. river, outfall, etc.) and u_c is the average velocity through the cross section. The suspended sediment concentrations must be taken from measurements of suspended solids in the system. Erosion and deposition can be estimated as shown in Sections 3.5.1 and 3.5.3, respectively. Conversely, if erosion and deposition rates are unknown, the system inputs and outputs can be balanced to determine if the system is net depositional or net erosional. This determination can be extremely useful in characterizing a site, but should be used with care. Schnoor (1995) provides more detail on the application of mass balances.

Although the information to complete the mass balance with any quantitative certainty will generally not be available in a Tier 1 analysis, it is a useful framework for identifying potential inputs and outputs of sediments and refining the CSM. As an example, a simple bay may be approached from the mass balance framework as shown in Figure 8.

3.4.3 Deposition

For a Tier 1 analysis, the following lines of evidence can be used to characterize deposition at a site:

- Estimate sediment supply to the site (Section 3.5.2).
- Use bathymetric change over time to determine deposition rate (surveys, dredging records, etc.).
- Use suspended sediment concentrations if available to determine potential deposition rates.

The system of interest is a bay with two rivers delivering sediments into the system, and a connection to the ocean through an inlet. We know that the water exiting the bay into the ocean has a known concentration of sediment in it (C_o) and a net mass flow rate to the ocean of Q_o . Tides in the area are negligible and the sediments have been shown not to erode for the shear stresses observed. The two river inlets have known mass flow rates of Q_1 and Q_2 with sediment concentrations in the water column of C_1 and C_2 .

The steady state mass balance for the system can be written as follows.

$$Q_1C_1 + Q_2C_2 - Q_oC_o + A(E - D) = 0$$

From our previous knowledge of the system we know that the bay wide erosion is negligible ($E=0$), the input of both of the rivers is Q_1C_1 and Q_2C_2 , and the output to the ocean is Q_oC_o . These values will typically vary with time but can be averaged over a time period of interest (i.e. month, year, decade, etc.) . This allows us to rearrange the above equation to the following form.

$$D = Q_1C_1 + Q_2C_2 - Q_oC_o$$

Because we know all of the values on the right hand side of the equation from measurements, we can directly calculate the deposition rate of sediments in the bay and from that determine rough rates of burial for any substance on the surface of the sediment bed.

The mass balance approach as shown here is a simplification of the sediment transport processes in any system. This approach should be used very carefully, but can yield insight into some of the long-term trends in the system by determining average inputs and outputs over the course of a typical year. Refined versions of this approach (e.g., Schnoor, 1995) can help to quantify in more detail the dominant transport processes in a system. In systems where higher spatial and temporal resolutions are required, a Tier 2 analysis should be considered.

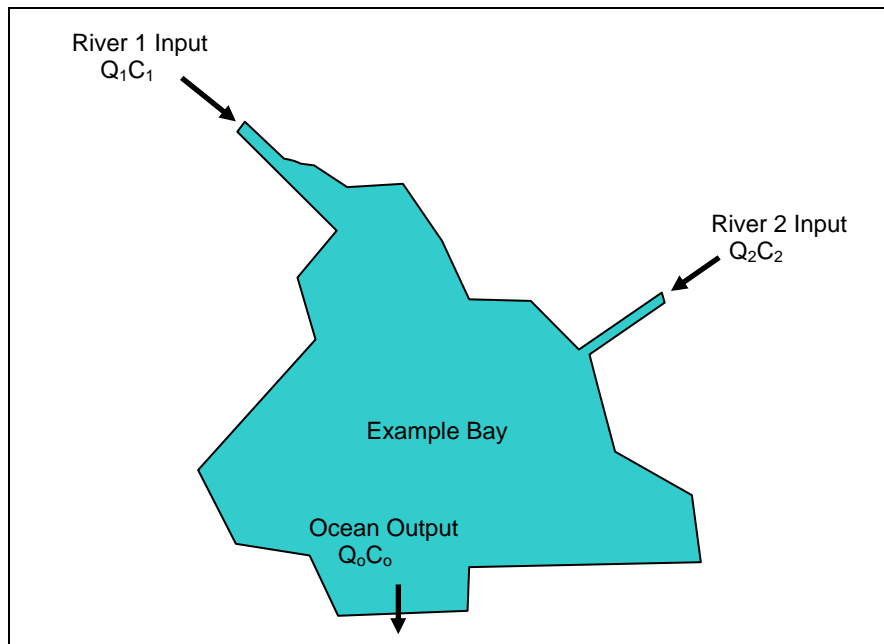


Figure 8. Mass balance approach.

The measurement of specific radioisotopes in sediment cores can yield estimates of sediment deposition rate; this method is discussed further in Section 4 as part of the Tier 2 analysis. At some sites, these data may be available from other research efforts.

For navigable waterways, bathymetry records and/or dredging records are generally maintained by the USACE or the local port authority. Sequential bathymetry records can be analyzed to determine volumetric sediment changes throughout an area of interest and/or to simply determine a net change in sediment depth at a specific location over time (see Byrnes, Baker, and Li, 2002; van der Wal and Pye, 2003). The ability to accurately resolve depth differences between survey dates depends on the type and consistency of the methods used to collect the data (i.e., single-beam versus multi-beam mapping methods; use of same vertical datum and tide correction procedure, etc.). If possible, bathymetric surveys based on the same survey method should be used to ensure data comparability, and the measurement error of the survey method should be noted. Additionally, dredging records can be used to directly determine the volume of sediment deposited in the navigable waterways. All of this information can be used to better characterize the depositional environment (i.e., amount of deposition, type of material, quality of material, and direction of long-term transport).

To more quantitatively determine deposition rates at a specific location, the following methodology can be used with other lines of evidence. In a non-moving fluid where no shear stress is present, the deposition to the sediment bed, D in $\text{g/cm}^2/\text{s}$, can be described as the product of the settling speed of the sediment particles, w_s in cm/s , and the concentration of the sediment in the overlying water, C in mg/L . However, in flowing water, the deposition is affected by the fluid turbulence, which is a function of shear stress. In this case, a probability of deposition, P , can be included in the formulation to account for the effects of the shear stress to yield the following equation:

$$D = P w_s C .$$

The settling speed of a sediment particle can be described by Cheng's (1997) formulation as

$$w_s = \frac{v}{d} \left(\sqrt{25 + 1.2d^{*2}} - 5 \right)^{1.5} ,$$

where d^* is the dimensionless particle diameter calculated in Section 3.4.1. This formula gives a generally accurate settling speed based on the sediment particle diameter.

The probability, P , would be unity (i.e., 1) in the case of zero flow and would decrease as the shear stress increases. The probability accounts for the decreased chance for deposition as the shear stress increases. For sediment particles, Krone (1962) found that the probability of deposition varied approximately as

$$P = \begin{cases} 0 & \text{for } \tau > \tau_{cs} \\ \left(1 - \frac{\tau}{\tau_{cs}} \right) & \text{for } \tau \leq \tau_{cs} \end{cases} .$$

When the shear stress at the sediment bed is lower than the critical shear stress for suspension, τ_{cs} , particles will begin to deposit onto the sediment bed. For a first guess, τ_{cs} can be assumed equivalent to τ_{ce} . With an approximation of shear stress, settling speed, and suspended sediment concentration, the deposition rate at a location can be estimated. Dividing the deposition rate by the bulk density of the deposited sediments, ρ_{sed} , gives the burial velocity, B_v , in cm/s ($B_v = D/\rho_{sed}$). Hakanson and Jansson (2002) can be consulted to find appropriate ranges of bulk densities for depositional sediments.

Deposition calculated using this technique is highly dependent on having accurate time series data of sediment concentrations and velocity, generally at multiple locations, at the site. Any calculations based on relatively short-term measurements of sediment concentration can yield deposition rates much different from the long-term rates at the site. One should never rely on this method alone to quantify deposition; therefore, this method should always be coupled with other lines of evidence. If an accurate determination of deposition rates at a site is required and the requisite water column data, historic bathymetry, and/or dredging records are not available for a quantitative analysis, a Tier 2 analysis should be considered.

3.5 EVALUATE TIER 1 RESULTS

The use of the Tier 1 analysis results to address specific sediment management questions is discussed below. When addressing these questions, the uncertainty associated with the Tier 1 estimates must be carefully evaluated, documented, and considered. The degree of uncertainty will depend on the quantity and quality of data used in the Tier 1 analysis. Confidence in the results will be greater if multiple lines of evidence point to similar conclusions. The Tier 1 results should be used to refine the sediment transport CSM developed as part of the initial site evaluation.

3.5.1 Could Erosion of the Sediment Bed Lead to Exposure of Buried Contamination?

The Tier 1 results should be used to describe the conditions under which bottom shear stresses at the site are likely to exceed the critical shear stress, resulting in sediment resuspension and erosion. The Tier 1 analysis may indicate that erosion will occur under some conditions such as spring tides or seasonal storm events, may occur only in an extreme event, or is unlikely to occur under any meteorological conditions. In many cases, the extreme event predictions are the most important because contamination would not have persisted at the site for decades (assuming that most contamination occurred from the 1940s to the 1980s) if it was subject to significant erosion under typical conditions. The high level of uncertainty associated with this Tier 1 analysis should be acknowledged. If erosion is possible, then the potential depth of scour can be estimated and compared with the vertical distribution of contamination. If unacceptably high contaminant concentrations are within the possible depth of scour, then it should be assumed that exposure could occur.

3.5.2 Could Sediment Transport Lead to the Redistribution of Contamination within the Site, or Movement of Contamination Off Site?

If the Tier 1 analysis indicates that sediment resuspension and erosion may occur, then the direction and magnitude of sediment transport should be estimated. Suspended sediments will advect in the direction of currents until reaching a region of lower shear stress, where they will be deposited back onto sediment bed. In tidally influenced areas, the net direction of transport generally will be in the direction of *residual circulation*. The accurate characterization of transport generally requires a Tier 2 analysis, although estimates can be made based on the mass balance developed in Tier 1. Contaminant distribution data (i.e., concentration gradients) may be useful for inferring whether sediment transport is leading to contaminant migration in cases where a single source of contamination exists.

3.5.3 Will Natural Processes Lead to the Burial of Contaminated Sediment by Relatively Clean Sediment?

All lines of evidence that indicate that an area is depositional should be summarized (i.e., based on geographic location, contaminant distribution, mass balance, and/or bathymetric changes). If

possible, the sediment accumulation rate should be estimated. The following questions should be addressed: Are sediment sources and quantities likely to change in the future? Do contaminant data indicate that surficial sediments are cleaner than subsurface sediments? At what depth are hydrodynamic forces and bioturbation unlikely to disrupt the sediment profile? Are unacceptable levels of contamination below this depth, or likely to be below this depth, in a reasonable amount of time? These questions can be answered with varying degrees of certainty based on the quantity and quality of data available for the Tier 1 analysis.

3.5.4 If a Site is Actively Remediated, Could Sediment Transport Lead to the Recontamination of the Site?

In cases where a sediment site has been remediated, recontamination could occur as a result of off-site sources or from changes in site conditions that would allow on-site contamination to be remobilized (i.e., through changes in site use or hydrodynamic conditions). If potential off-site sources of contamination have been identified, these should be documented in a Watershed Contaminated Source Document (WCSD), which is required as part of Navy sediment policy (Chief of Naval Operations [CNO], 2002). Potential recontamination from off-site sources should be documented in the Record of Decision for the site before the response action is taken.

The mass balance can be used to qualitatively evaluate the effects of changes in future hydrodynamic conditions or site use. For example, construction of a navigational channel near the remediated area could increase current speeds and the potential for erosion. Additionally, the potential effects of the remedial approaches themselves (e.g., construction of a cap) on the site hydrodynamics should be evaluated in the FS.

3.6 DETERMINE NEED FOR TIER 2 ANALYSIS

After the sediment management questions have been addressed, the need for a more refined Tier 2 evaluation must be evaluated. The decision about whether to conduct a Tier 2 analysis must consider the level of uncertainty associated with the Tier 1 analysis, and the potential consequences from a risk and cost perspective of making an incorrect site management decision based on the Tier 1 analysis. Possible scenarios include the following:

- In general, if a site is relatively large and complex and the anticipated costs for remediation are high, then a Tier 2 analysis will be required to refine the sediment transport CSM and reduce the uncertainty associated with site management decisions, particularly if in situ approaches (i.e., monitored natural recovery or capping) are expected to be a component of the remedy.
- If a site is relatively small and the anticipated cost of remediation is relatively low, then a Tier 2 analysis may be unnecessary.
- If the Tier 1 analysis indicates that sediment transport is not likely to be a major factor in contaminant migration, the site risks are relatively low to moderate, and the uncertainty is relatively small, then a Tier 2 analysis may not be warranted. However, if the uncertainty associated with the same analysis is relatively high, then a Tier 2 analysis should be considered.
- If the Tier 1 analysis indicates that a site is stable, then, in the future, the consequences of contaminant dispersal caused by sediment transport should be considered in case the initial conclusion is incorrect. If the consequences are unacceptable, then a Tier 2 analysis should be performed to reduce uncertainty.

4. TIER 2 EVALUATION

When the results of a Tier 1 investigation indicate that remedial action is likely, a more detailed analysis may be needed to support evaluation of alternatives, particularly in situ approaches (i.e., capping and natural recovery). The goal of a Tier 2 evaluation is to address common sediment management questions with a higher degree of certainty using targeted, site-specific data and more sophisticated data analysis methods than for Tier 1 investigations. Tier 2 evaluations generally are conducted in the latter stages of the RI or early stages of the FS. Additional site-specific, focused data collection is generally required to support Tier 2 analyses. Detailed sediment contaminant distribution mapping also may be useful and can be conducted concurrently to better define the area and volume of sediment to be considered in the FS. Appendix B presents a case study for Hunters Point Shipyard (HPS); Appendix C presents a case study for Bremerton Naval Complex (BNC), where many of the Tier 2 data collection and analysis methods were applied; and Appendix D presents a case study for Gould Island Naval Station Newport, where Tier 1 analysis was applied.

4.1 COLLECT TIER 2 DATA

The refined CSM and a sensitivity analysis of the Tier 1 results can be used to identify the greatest sources of uncertainty associated with sediment transport estimates. The Tier 2 data collection effort should be based on the key data gaps identified at the end of the Tier 1 evaluation. The scope of the data collection effort should be developed through application of the seven-step data quality objective (DQO) process (USEPA, 2006). Example DQOs for a Tier 2 sediment transport evaluation are provided in Example 3. Examples of Tier 2 data sources and data collection methods are summarized in Table 7. Appendix A provides more detail on tools and technologies available for Tier 2 data collection, including advantages, limitations, and cost considerations.

4.2 CONDUCT TIER 2 ANALYSIS

The Tier 2 analyses should focus on Tier 1 findings, the refined CSM, and relevant sediment management questions. Tier 2 analyses should describe more complex and site-specific sediment transport processes. When possible, multiple lines of evidence should be used in Tier 2 to support the overall interpretation. Generally, a Tier 2 analysis will focus on site-specific data collection to support modeling efforts. These modeling efforts can be *analytical* and/or *numerical*.

4.2.1 Erosion/Resuspension

If sediment erosion and/or resuspension have been identified in Tier 1 as one of the driving forces for sediment transport, additional data/analyses may be done to more accurately quantify this parameter. One of the key measurements in predicting sediment erosion at a site is to directly measure the critical shear stress and sediment erosion rate with depth. These measurements will allow a quantitative estimation of sediment erosion under both typical and extreme conditions based on site-specific hydrodynamic and sediment strength data. Several types of laboratory and in situ flume techniques exist to measure these parameters, including annular flumes, straight flumes, and shaker flumes. Table 8 summarizes some of the more common research and commercially available methods for the measurement of sediment stability parameters. All of the devices measure parameters associated with the corrosion of cohesive sediments; the primary differences between them are related to whether they can be used in situ, the applicable shear stress range, and the depth to which erosion properties can be measured. Appendix A provides additional information on advantages, limitations, and relative costs for some of the more readily available devices.

Table 7. South Basin Tier 2 DQOs.

<p>STEP 1: State the Problem</p> <p>Sediments in South Basin are contaminated with PCBs and may pose an unacceptable risk to human health and the environment. Additional data are needed to characterize sediment transport, refine the conceptual site model (CSM), and evaluate the feasibility of various remedial alternatives (i.e., removal, monitored natural recovery, and in situ capping).</p>
<p>STEP 2: Identify the Goals of the Study</p> <ol style="list-style-type: none"> 1. Is the sediment bed likely to erode under typical and extreme hydrodynamic conditions, and to what depth? 2. Will natural processes effectively cap contaminated sediments?
<p>STEP 3: Identify Information Inputs</p> <ol style="list-style-type: none"> 1. Existing site-specific data on the horizontal and vertical distribution of PCBs sediment, and current velocities in South Basin in summer and winter. 2. Vertical profiles of bulk density, grain size, and erosion rates for sediment cores obtained from SEDflume sampling to characterize stability of the sediment bed. 3. Sediment accumulation rate (age profile) from radioisotope data (^{210}Pb, ^{137}Cs, ^7Be, ^{237}Th). 4. PCB concentration data for sediment particles settling on the sediment bed as collected in sediment traps. 5. Thickness of the biologically active zone from published literature, and estimation of the mixed depth from site-specific radioisotope data (^{210}Pb, ^{137}Cs, ^7Be, ^{237}Th).
<p>STEP 4: Define the Boundaries of the Study</p> <ul style="list-style-type: none"> • The study area is bounded by the toe of the embankment along the South Basin shoreline. Only soft sediment will be sampled. Sediment cores will be collected in South Basin from Yosemite Creek to Candlestick Point. • The vertical limit of the study area is 1 m, because previously collected core data indicate that PCB concentrations drop significantly below 0.7 m. Cores for radioisotope analysis will be collected to a depth of 1.5 m.
<p>STEP 5: Develop the Analytic Approach</p> <ul style="list-style-type: none"> • SEDflume cores: analysis of SEDflume data, including vertical erosion rates, critical shear stress values, bulk density profiles, and particle size profiles, will determine the likelihood of PCB-contaminated sediment resuspension under typical and extreme hydrodynamic conditions. If the bottom shear stresses associated with typical and extreme hydrodynamic conditions in South Basin are insufficient to erode sediments below a given depth, then sediments below this depth will be considered stable. • Previously published data for biota in South Basin and bioturbation in San Francisco Bay and radioisotope profile data will be used to estimate the depth of the mixing/biologically active layer. If the ^{210}Pb profiles deviate from the ideal profile of exponential decrease with depth, then the thickness of the mixed layer will be inferred from the disrupted profile. If ^7Be or ^{234}Th is measured in subsurface sediments, then the degree of short-term mixing will be inferred from the maximum depth of the occurrence of these short lived isotopes. • Data for vertical profiles of PCB concentrations, sediment accumulation rate from radioisotope cores, depth of the mixing/biologically active layer, sediment bed stability, and chemical quality of sediment particles settling on the sediment bed will be used to evaluate whether natural processes are effectively capping contaminated sediment. The following questions will be addressed: <ol style="list-style-type: none"> 1) Are subsurface sediments containing elevated concentrations of PCBs being covered by more recent, relatively clean sediment, and at what rate? 2) Are contaminated subsurface sediments near or below the depth of the mixing/biologically active layer? 3) Are the contaminated subsurface sediments below the depth where the sediment bed can be considered stable? <p>If these lines of evidence indicate that contaminated subsurface sediments are being effectively isolated from the environment through natural processes, then passive remediation (i.e., monitored natural recovery) may be considered appropriate. Alternatively, if natural processes are not effectively isolating contaminated subsurface sediments from the environment, then active remedial measures may be considered more appropriate. All potential remedial approaches (active and passive) will be evaluated in the Feasibility Study.</p>

Table 7. South Basin Tier 2 DQOs. (continued)

<p>STEP 6: Specify Performance or Acceptance Criteria</p> <p>An erroneous assessment of the depth of the mixing/biologically active layer or stability of the sediment bed could result in incorrect conclusions regarding the mobility and availability of PCBs, which in turn could lead to incorrect conclusions regarding the most optimal risk reduction method. These errors will be minimized by relying on multiple lines of evidence to characterize PCB fate and transport at the site.</p>
<p>STEP 7: Develop the Plan for Obtaining Data</p> <p>Depth of Mixing/Biologically Active Layer, Sediment Erosion Potential, and Natural Capping Processes: These objectives require site-specific data on contaminant fate and transport to support the evaluation of remedial alternatives (removal, capping, monitored natural recovery, and in situ treatment). The sample design for these objectives is based on best professional judgment as described below.</p> <p>SEDflume Cores: Eleven (11) sediment cores will be collected for SEDflume analysis. SEDflume coring locations are located along two transects: one following the PCB concentration gradient from onshore to offshore (NNE to SSW, four cores), and the other transect following the ‘spine’ of South Basin (NW to SE, six cores), including samples at both previous sediment dynamics study tripod locations. One additional core is located at the mouth of Yosemite Creek to help characterize sediment input from the creek. SEDflume cores will be approximately 1 m in length, with examined intervals between 0 and 90 cm (the bottom 10 cm is typically considered disturbed).</p> <p>Radioisotope Cores: Three (3) sediment cores for high-resolution radioisotope profiling will be collocated with SEDflume cores. Radioisotope cores will be sectioned into 2-cm intervals from 0-50 cm, and 5-cm intervals from 50-150 cm. Different intervals will be selected for ^{210}Pb, ^{137}Cs, and $^7\text{Be}/^{234}\text{Th}$ isotope analysis. Profiles of ^{210}Pb and ^{137}Cs data will provide an age profile with depth, allowing plots of PCB concentration vs. time and verification of site-specific sediment accumulation rates (previously estimated at about 1 cm/year). $^7\text{Be}/^{234}\text{Th}$ have relatively short half-lives (53 d/24.1 d); the depth of its activity is an independent measurement of mixing depth on a time scale of weeks to months.</p> <p>Sediment Traps: Two sets of sediment traps will be collocated with two of the radioisotope profile cores to provide complementary data on the quantity and quality of sediment particles settling on the sediment bed. A third set of sediment traps will be deployed at the entrance to South Basin, at the location of the previous sediment dynamics study tripod location. Two sediment traps will be deployed at each location to provide sufficient sample material in the event that one of the traps fails. Sediment from both traps at each location will be combined into a single sample. Sediment traps will be deployed for one year to assess seasonal variability. Each deployment period will be three months in duration, with the initial deployment in October 2003 and turnaround cruises in January, April, and July 2004.</p> <p>Depth of Mixing/Biologically Active Layer: A literature review will be conducted to provide information on a range of bioturbation depths for a number of different species and habitats in San Francisco Bay. Radioisotope profile data from sediment cores will also be used to support an estimation of total mixed depth.</p>

Table 8. Comparison of various sediment stability measurement devices (courtesy of Sandia National Laboratories).

Device	Flow Conditions (over sediment surface)	In Situ	Ex Situ	Transport Measured	τ_{cs}	Erosion Rate	Sediment Type	Depth Measured (m)	Shear Stress Range (PA)
Straight Flume	Unidirectional/Oscillatory	Yes	Yes	Total Load	Yes	Yes	Clay/Silt/Sand	Surficial Layers	0 to 4
Annular Flume / Sea Carousel	Unidirectional	Yes	Yes	Suspended Load Only	Yes	No	Clay/Silt/Sand	Surficial Layers	0 to 1
Shaker	Unknown	No	Yes	Suspended Load Only	Yes	No	Clay/Silt/Sand	Surficial Layers	0 to 1
SEDflume	Unidirectional	No	Yes	Total Load	Yes	Yes	Clay/Silt/Sand	0 to 1	0 to 10+
ASSET Fume	Unidirectional	No	Yes	Suspended And Bedload	Yes	Yes	Clay/Silt/Sand	0 to 1	0 to 10+
SEAWOLF Flume	Unidirectional/Oscillatory	No	Yes	Total Load	Yes	Yes	Clay/Silt/Sand	0 to 1	0 to 10+

Erosion properties of sediments at HPS (Appendix B) and BNC (Appendix C) were measured using SEDflume as part of the site demonstrations. A diagram of SEDflume is provided in Figure 9. SEDflume has a test section with an open bottom through which a circular cross-section coring tube containing sediment is inserted. Other components of the flume are an inlet section for uniform, fully developed, turbulent flow; a flow exit section; a water storage tank; and a pump to force water through the system. The coring tube, test section, inlet section, and exit section are made of clear acrylic so that the sediment–water interactions can be observed. At the start of each test, the coring tube is inserted into the bottom of the test section. An operator moves the sediment upward using a piston located inside the coring tube. By this means, the sediment core is raised and leveled with the bottom of the test section. Water is forced through the test section over the surface of the sediments. The shear produced by this flow causes the sediments to erode. As the sediments in the core erode, they are continually moved upwards by the operator so that the sediment–water interface remains level with the bottom of the test and inlet sections. Test measurements are used to determine erosion rates and critical shear stresses.

In combination with measurements of critical shear stress and erosion rates, the forces driving erosion events must be characterized. This analysis will be site-specific, and can include river discharge, tidal currents, and wave action. At sites where wave action is a driver of sediment transport, wave energy can be determined. Waves contribute to sediment transport by increasing the bed shear stress and by mixing and transporting sediment that is already suspended. Most commonly, these data can be used in conjunction with measurements of critical shear stress and erosion rate to predict the erosion of sediments as a result of current and wave action. These types of field measurements and data analyses were performed as part of the HPS (Appendix B) and BNC (Appendix C) site demonstrations.

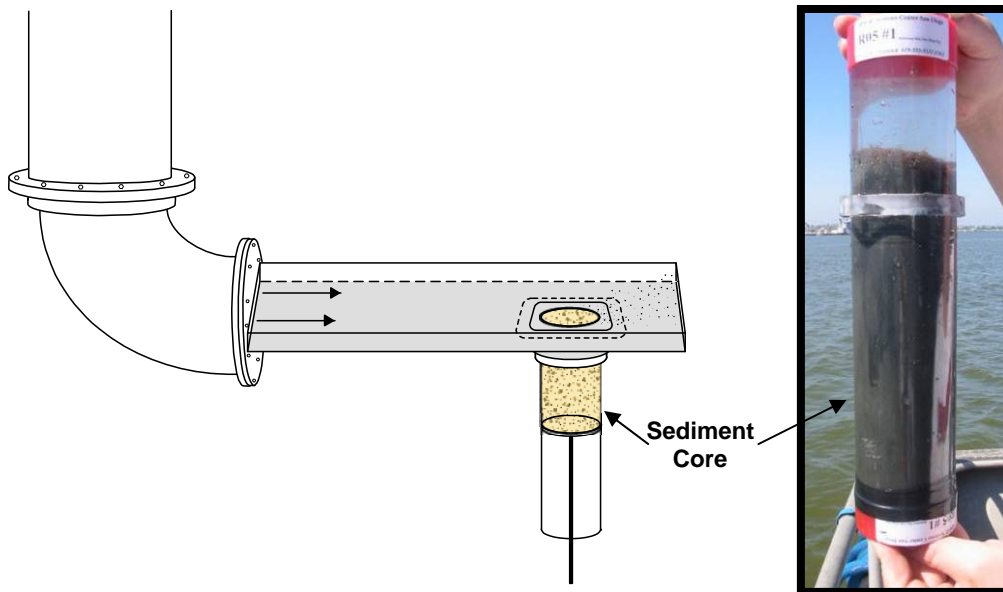


Figure 9. SEDflume and sediment core.

Erosion and resuspension events in riverine and estuarine environments can also be directly measured at a site by collecting spatial and time-series measurements of suspended sediment concentrations and current velocity in the water column. These types of measurements can allow determination of the current velocity at which sediments become resuspended, the concentration of sediment in suspension, and the height in the water column to which sediments are being carried. The signature of the sediment signal may also indicate whether the sediments are being resuspended by tidal currents (Figure 10), advection, or storm events (Figure 11). Suspended sediment concentration data collected at HPS indicated that significant resuspension occurred only during winter storms (Appendix B).

Extreme weather events such as floods and hurricanes may have significant effects on sediment transport at a site. To predict the impact of extreme events, a statistical analysis can be performed to quantify the probability and magnitude of events and their effect on erosion, transport, and deposition at a site. Because extreme conditions are typically difficult to estimate accurately and often have large economic implications, a number of different techniques have been developed to determine the probability and magnitude of extreme events in different systems (USACE, 1993; 2002). An extreme event analysis for HPS indicated that sediments in the embayment south of the facility would erode to a depth of less than 10 cm in a 25-year storm (Appendix B).

Another factor affecting the stability of bed sediments is biological activity in the surface sediments. Biological activity can have a significant effect on the physical properties of the sediments by increasing sediment strength during tube-building activities and decreasing strength and cohesion during burrowing. Changes in sediment stability resulting from biological activity can be estimated from detailed biological assessment, sediment profile images, redox profiles, and measurement of short-lived isotopes. Benthic activity in sediment at HPS was qualitatively evaluated using Sediment Profile Imaging (SPI) technology as part of the site demonstration (Appendix B). The SPI technology was developed as a rapid reconnaissance tool for characterizing physical, chemical, and biological seafloor processes (Figure 12). A wide variety of physical and biological parameters can be measured in the top 20 cm of the sediment bed, including sediment grain size distribution, small-scale

boundary roughness, apparent redox potential discontinuity depth (RPD), presence of methane, infaunal successional stage, and biological mixing depth.

Anthropogenic activities such as ship movement and dredging also may affect the erosional characteristics of a site. The propellers of ships generate a high-intensity current, which can scour marine sediments to significant depths. If the sediments in the region of scour are contaminated, a significant potential exists for contaminant release. The subsequent transport of these sediments in littoral zones and side channels also may adversely affect ecosystems over larger areas.

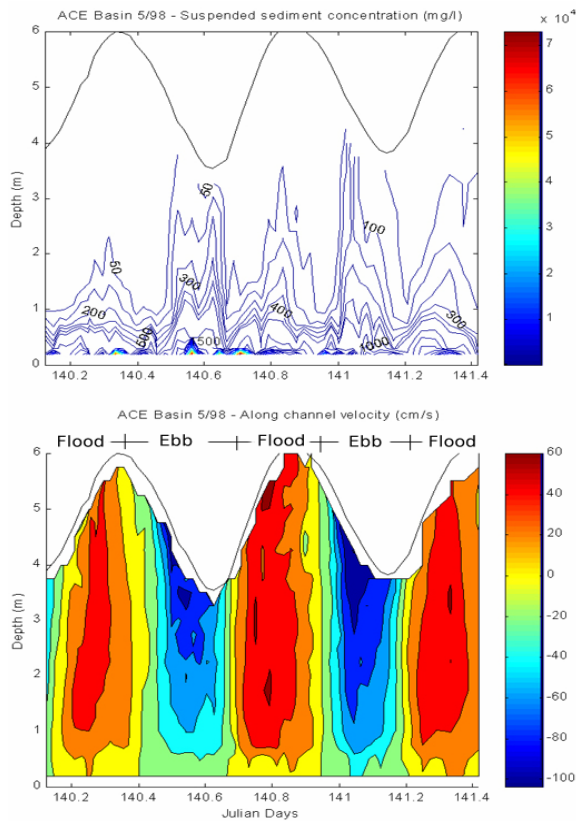


Figure 10. Tidal time-series measurements of suspended sediment concentration (top) and along-channel current velocity (bottom) from the ACE Basin, SC, show that sediments are resuspended during maximum flood and ebb currents.

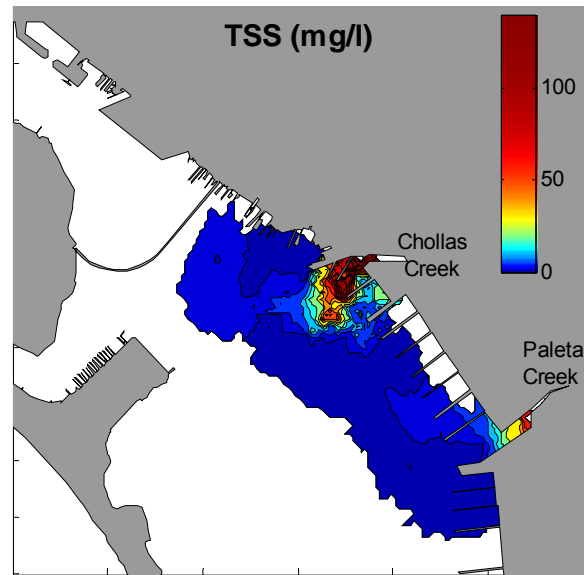


Figure 11. Spatial measurements in San Diego Bay, CA, show evidence of a stormwater plume from a small urban creek.

As stated in Section 3.4.1, the sediment beds of navigable waterways may be susceptible to scouring action from passing ship traffic. Currently available methods for estimating prop scour rely on empirical sediment stability relationships for sands (e.g., non-cohesive sediments), which have limited use in determining the resistance of natural sediments to scour. The SEDflume and related devices are effective tools that may be used to directly measure sediment erosion (or scour) rates under various flow conditions and critical shear stress of the sediment bed. As part of the BNC site demonstration, maximum prop wash velocities predicted for a typical ship movement were used in conjunction with SEDflume erosion rate and critical-shear-stress sediment data to determine potential scour depth (Appendix C). The maximum scour depth was estimated as less than 5 cm.



Figure 12. Example of a SPI camera image showing homogeneous clayey silt and RPD (image width, 14 cm).

4.2.2 Transport

The direct measurement of suspended sediment transport at a site may include additional data on currents, waves, and suspended sediment concentration. These data should be collected over time scales (i.e., tidal time scales, seasonal time scales) that correspond to the hydrodynamic forces of interest. Time-series measurements of current velocity and suspended sediment concentration can be used to determine the net flux of sediments past a given point. Calculating the net flux will provide information on the direction of net sediment movement. The instantaneous sediment flux, F , through a section perpendicular to the mean flow, can be calculated using the equation:

$$F = \int_0^h uc \cdot \Delta z = h \langle uc \rangle ,$$

where u is the along-channel velocity, c is suspended-sediment concentration, Δz is the depth interval between measurements, and h is the total depth (Dyer, 1997). The instantaneous fluxes of sediment can also be evaluated over time (i.e., a tidal cycle), yielding a net mean flux, \bar{Q} (Dyer, 1997). The angle brackets denote averaging over the total depth, and an overbar (i.e., \bar{Q}) denotes an average over time. The calculated value for the net sediment flux can also be used to refine the mass balance for the system (Section 3.4.2).

At HPS, current, wave, and suspended sediment measurements were collected over a full tidal cycle in the winter and summer seasons. The instrumentation was deployed using tripods that were designed for use in shallow water (Figure 13). Results indicated that no appreciable sediment transport occurred during the deployment periods because of the weak currents (Appendix B).



Figure 13. Tripod deployed at HPS to measure hydrodynamic parameters.

If significant non-cohesive sediment transport is suspected, regional bathymetry data may be collected over time to determine the net movement of sediments by tracking bedforms. The direction of sediment movement can sometimes be determined based on the shape of bedforms. Direct measurement of bedload transport is difficult, however, and many different equations have been developed to predict the bedload flux (van Rijn, 1993).

4.2.3 Deposition

In Tier 2, site-specific deposition processes can be characterized in more detail by using radioisotope dating techniques. Sediment traps can be used to evaluate the physical and chemical characteristics of the incoming depositing material. Particle settling characteristics can also be evaluated using various in situ devices.

Radioisotope profiling is a useful tool that can be used to date sediment sections in an undisturbed core and determine the net accumulation rate of sediments (USGS, 1998). The age of sediments is calculated by knowing the original concentration of the isotope and measuring the percentage of the remaining radioactive material after decay has occurred. In an undisturbed sediment core, the activity of the isotope will decrease exponentially with increasing depth until it reaches a background level (Figure 14). However, mixing of sediment by organisms or other processes will disrupt the smooth profile and reduce the accuracy of the estimated dates and sediment accumulation rates. Commonly used radioisotope tracers are ^{210}Pb , ^{137}Cs , ^{14}C , ^7Be , and ^{234}Th . Each isotope has a different half-life and can be used to detect sedimentary accumulation over different timescales. ^{210}Pb , ^{137}Cs , ^7Be , and ^{234}Th were measured in sediment cores from HPS as part of the site demonstration; results are presented in Appendix B. Radioisotope data for BNC were collected as part of the RI and incorporated into the sediment transport site demonstration.

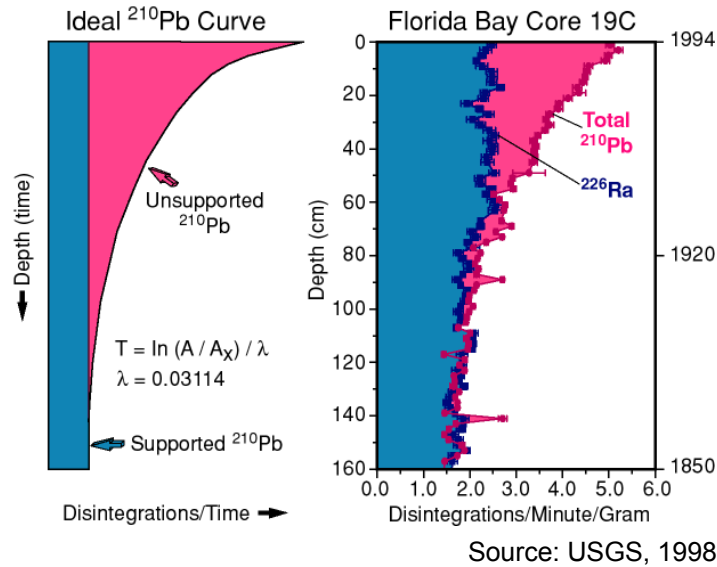


Figure 14. Lead-210 profile: ideal and actual from Florida Bay.

^{210}Pb forms by the radioactive decay of its gaseous parent, ^{222}Rn (^{222}Rn forms from the decay of radium). ^{210}Pb is removed from the atmosphere by precipitation, and is rapidly adsorbed to and deposited with sediment particles. This flux of ^{210}Pb from the atmosphere produces a concentration of “unsupported” ^{210}Pb (i.e., a concentration which exceeds the “supported” concentration resulting from radioactive decay of the sediment itself). The half-life of ^{210}Pb is 22.3 years, and dates of sediment deposition can be estimated by determining decrease of ^{210}Pb activity with depth. In an undisturbed sediment core, “unsupported” ^{210}Pb activity will decrease exponentially with increasing depth until it reaches the supported ^{210}Pb level. The rate of sediment accumulation in centimeters per year can be calculated based on the dated sediment column. The sedimentation rate in grams of dry sediment per year per centimeters squared also can be calculated if the wet and dry densities of the sediment are determined.

^{137}Cs was present in the fallout from atmospheric nuclear tests, and first appeared in sediment cores around 1952 to 1955. Deposition of ^{137}Cs peaked in 1963 to 1964. In an undisturbed sediment core, ^{137}Cs activity levels will reflect ^{137}Cs production during the period of atmospheric nuclear testing, with an initial appearance in the early to mid-1950s, a peak in the early 1960s, and a decrease in the early 1970s after atmospheric testing was halted. ^{14}C was also a byproduct of atmospheric nuclear testing. The amount of bomb-produced ^{14}C can be determined by comparing present activity to the 1950 carbon activity, which is by convention the baseline used for radiocarbon dating (USGS, 1998). Naturally occurring ^{14}C can be used to date organic material between 100 and 70,000 years old.

^7Be and ^{234}Th can be used to date sediments in shorter time frames and provide information about short-term surface sediment mixing. ^7Be is formed by the atmospheric bombardment of atmospheric nitrogen and oxygen. It has a half-life of 53 days, and can be used to date sediments with an age up to 1 year. ^{234}Th forms from the decay of ^{238}U . ^{234}Th has a half-life of 24 days. ^7Be and ^{234}Th were measured in sediments from HPS to evaluate bioturbation depth, but activities were either undetected or very close to the detection limit and therefore not interpretable. The reliability of the ages obtained from radioisotope dating methods depends on the degree to which the assumptions underlying the method are met.

Some of the key assumptions are as follows:

- The sediment accumulation rate is constant (i.e., sedimentation processes are constant). However, natural sedimentation is commonly episodic rather than continuous, and sedimentation rates are likely to fluctuate rapidly over short periods of time in watersheds where rapid development has occurred.
- The sediment bed has not been exposed to major erosion events, by natural (e.g., extreme weather events) or anthropogenic causes (e.g., dredging).
- The grain size of the deposited sediment is uniform. Uncertainty will be introduced if samples are taken from core segments with unequal grain sizes.
- The background (i.e., unsupported) level of activity is known. If this information is not available from regional studies, then an assumption regarding the background activity level must be made.

Because of the inherent uncertainty in the ages obtained from radioisotope analysis, other information (geological, chemical, and historical) should be considered when interpreting the data. Detailed stratigraphic information can be used in conjunction with the radioisotope data to infer the depositional characteristics of the site. Contaminant profiles in the sediment core may also be used as a reference for age-dated core sections. For example, a historical contaminant spill at a site may be evident as a spike at depth in the chemical profile. Dates obtained from one age-dating method (e.g., ^{137}Cs) can be used to validate the dates derived by another method (e.g., ^{210}Pb). Chillrud et al. (2003), Fuller, van Geen, Baskaran, and Anima (1999), and Aller and Cochran (1976) are examples of studies based on radioisotope analysis of sediment cores.

A sediment trap is a device deployed in the water column that collects a representative sample of the material settling through the water column before it passes to a greater depth and is incorporated into the sediment bed (Figure 15). Sediment trap data can be used to characterize the flux of sinking particles in a system. Contaminant chemistry measurements from sediment traps can be useful in determining the source(s) and quality of incoming sediments, although the analysis may be confounded if multiple sources of contamination are present or flow in the water body is tidally influenced (i.e., oscillatory).

Sediment traps were first designed for use in the deep ocean where current velocities are very small (<0.1 m/s). However, recent work has been done to assess the use of sediment traps in shallower, high-energy environments. Many different designs for sediment traps have been used over the last few decades, with most designs falling into the following five broad categories (Gardner, 1980):

- Cylinders
- Funnels
- Wide-mouth jars
- Flasks and Tauber traps (mouth of container $<$ body)
- Basin/tray-like containers (width \gg height)

Studies show that cylinders are the most efficient sediment trap shape (Hargrave and Burns, 1979; Bloesch and Burns, 1980; Blomqvist and Hakanson, 1981; Butman, 1986), whereas funnel- and tray-shaped traps tend to under-collect sediment (Pennington, 1974; Reynolds and Godfrey, 1983) and Tauber traps tend to over-collect sediment (Pennington, 1974).

Additional factors affecting the efficiency of a sediment trap are the aspect ratio (height:diameter ratio) of the trap and the addition of brine. For example, upwelling and resuspension of sediments

in the trap may occur if the height:diameter ratio is too low. In high-energy environments, an aspect ratio between 3 and 5 is recommended (White, 1990). Commonly, traps are partially filled with a brine solution (~50 psu) to prevent sediments resuspension by currents (Nodder and Alexander, 1999). Dye may be added to the brine solution so that the interface can be seen and to determine if the brine layer has been mixed with the overlying water during deployment. Biocides (i.e., formalin or sodium azide) also can be added to deter animals from eating or removing sediment from the trap.

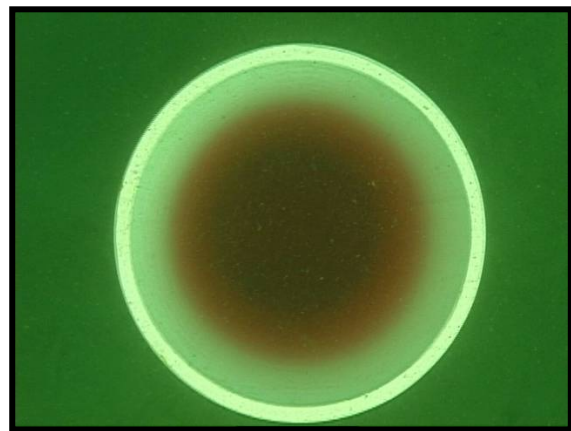


Figure 15. Diver-deployed sediment trap. Photo on right is looking down into a sediment trap, where the brine layer, colored by Rhodamine dye, can clearly be seen.

Sediment traps deployed at HPS and BNC were constructed of 6-inch, schedule 40, polyvinyl chloride (PVC) pipe with a trap height of 30 inches (5:1 aspect ratio), as shown in Figure 4-7. Sediment trap data were used to qualitatively evaluate sediment deposition and characterize chemical concentrations in sediments captured in the traps (Appendices B and C).

Particle size characteristics may also affect the deposition of sediments in an aquatic environment. The settling speed of a disaggregated natural sediment particle can be described by Cheng's (1997) formulation as

$$w_s = \frac{v}{d} \left(\sqrt{25 + 1.2d^{*2}} - 5 \right)^{1.5},$$

where d^* is the dimensionless particle diameter calculated in Section 3.4.1 for estimating critical shear stress. This formula gives a generally accurate settling speed based on the sediment particle diameter.

In estuarine waters in particular, suspended sediments are prone to flocculate, or aggregate, into larger particles. Analysts may underestimate particle settling velocities up to an order of magnitude when they fail to consider particle aggregation in fine-sediment environments (Kineke and Sternberg, 1989). Techniques have been developed to predict flocculation and determine resulting particle sizes (Burban, Xu, McNeil, and Lick, 1990). Additionally, sophisticated in situ settling tubes and optical devices have been developed to measure suspended particle settling speeds and size distribution (LISST instruments).

Post-depositional processes (i.e., bioturbation) may alter sedimentary structures, making the analysis of the depositional history difficult. As noted above, these processes can be characterized through detailed biological assessment, sediment profile imaging, redox profiling, and the measurement of short-lived radioisotopes.

4.2.4 Numerical Modeling

Numerical models are useful tools that can provide a more complete understanding of the transport and fate of sediments than can be provided by empirical data (from field or laboratory) alone. However, they can be expensive to apply at complex sediment sites because they require large quantities of site-specific data and modeling experience. Modeling of contaminated sediments, just as with other modeling, should follow a systematic planning process that involves examination of data quality objectives (or other measures), uncertainty, and specific hypothesis. In most cases, models are expected to complement environmental measurements and address gaps that exist in empirical information. A good discussion of modeling approaches is presented in the USEPA's Contaminated Sediment Remediation Guidance for Hazardous Waste Sites (USEPA, 2005).

Models can be used to assess the historical stability of sediment and the future of sediment stability under various events or conditions. Confidence in a model's predictions is based largely on the amount of site-specific data available, and the error associated with predicting the natural variability in the system. Because predictions are accompanied by uncertainty, validation often must be performed to demonstrate the numerical accuracy of the prediction (e.g., via confidence intervals). Typically, confidence decreases with the degree of extrapolation involved in predicting the design event (e.g., long-range predictions). Once a sediment transport model is calibrated properly and validated, the model can be used as a management tool to quantitatively and objectively evaluate the efficacy of various remedial alternatives.

Specific examples of sediment and contaminant transport model applications identified in the USEPA's Contaminated Sediment Remediation Guidance for Hazardous Waste Sites (USEPA, 2005) include the following:

- Predicting contaminant fate and transport over long periods of time (e.g., decades) or during episodic high-energy events (e.g., tropical storm or low-frequency flood event).
- Predicting future contaminant concentrations in sediment, water, and biota to evaluate relative differences among the proposed remedial alternatives, ranging from monitored natural recovery to extensive removal.
- Comparing modeled results to observed measurements to show convergence of information. Both modeling results and empirical data usually will have a measure of uncertainty, and modeling can help to examine the uncertainties (e.g., through sensitivity analysis) and refine estimates.

A wide range of models has been developed with varying levels of complexity. For application at a site, only peer-reviewed models should be considered. The models described here have been broken down into three types. A few examples of peer-reviewed modeling frameworks are presented below for Types 2 and 3. Characteristics of various hydrodynamic and coupled hydrodynamic/sediment transport models also have been summarized by the USGS (2002); see the following Web site: <http://woodshole.er.usgs.gov/project-pages/sediment-transport/ModelTable.pdf>.

- Type 1: Control volume models (i.e., box models).
- Type 2: Simplified hydrodynamic and sediment transport: one-dimensional (1-D) simulations of flow and sediment transport.
- Type 3: Higher order hydrodynamic and sediment transport models: two-dimensional (2-D) or three-dimensional (3-D) transport models.

4.2.4.1 Type 1

Most Type 1 models are designed to solve the mass continuity equation (advective/dispersive transport) by employing a “well-mixed” controlled volume approach. These models are also commonly referred to as “box models.” Although the number of dimensions and scales of resolution that can be specified with these models is very flexible, the hydrodynamic and sediment transport portions of the model are typically very general (i.e., coarse resolution). Although models of this type are widely available, well-developed, and provide a good descriptive ability, they are generally not suitable for accurate predictions of sediment transport because they do not resolve fine-scale transport processes critical for accurate predictive capability. These relatively simple models are usually used for preliminary screening level analyses at a site and are a common framework for contaminant fate and transport efforts.

4.2.4.2 Type 2

Type 2 models simulate one-dimensional flow and sediment transport using simplistic mechanical descriptions of resuspension and deposition. These models differentiate between non-cohesive and cohesive sediments and take into account bed armoring effects, multiple particle size classes, and spatially variable bed properties. Generally, these models require almost as much site-specific data as Type 3 models, although less modeling experience is needed to apply them. Interpretation requires as much (if not more) knowledge of hydrodynamics and sediment transport as that for multi-dimensional models. Examples of Type 2 models are HEC-6 and the Generalized Stream Tube Model for Alluvial River Simulation (GSTARS) 2.1.

4.2.4.3 Type 3

In general, Type 3 models employ more detailed descriptions of resuspension and deposition processes that are developed from experimental results. Like Type 2 models, Type 3 models can differentiate between non-cohesive and cohesive sediments and include bed armoring effects, particle size classes, and spatially variable bed properties. They are used to assess 2-D or 3-D water column transport and are coupled to sophisticated hydrodynamic models. They also incorporate the effects of currents and waves on bottom shear stress. In general, these models can produce accurate simulations of sediment transport, assuming an adequate amount of site-specific and calibration data are entered into the model. Because they are relatively complicated models, an experienced engineer or scientist needs to be responsible for applying and interpreting these models.

4.2.5 Model Verification, Calibration, and Validation

In any case where a model is selected and used in a site study, calibration and validation should be performed to yield a scientifically defensible modeling study (USEPA, 2005). Model calibration is defined as using site-specific measurements from a specified time period of time to adjust the appropriate model parameters to obtain an agreement between the measured data set and model calculations. Some example model parameters include bottom roughness in the hydrodynamic and shear stress calculations, water column viscosity, and water column diffusivity.

Model validation is defined as demonstrating that the calibrated model accurately reproduces known conditions over a period of time that is different than the calibration period of time. The parameters adjusted during the calibration process are not changed during model validation. If an acceptable level of agreement is achieved between the data and model simulations, then the model can be considered validated for the range of conditions defined by the calibration and validation data sets.

It is important that calibration and validation be conducted during periods of time where the forces driving the dominant processes are occurring. It must be noted that data typically cannot be collected during an extreme event, so the dominant processes during those periods must be evaluated in the modeling effort (e.g., the model must be able to accurately simulate waves coming from the same direction as they do during a storm). A review committee with the appropriate technical background should provide an objective review of any modeling conducted.

4.3 EVALUATE TIER 2 RESULTS

The use of the Tier 2 results to address specific sediment management questions is discussed below. The uncertainties and limitations associated with the Tier 2 analysis should be described and documented, and considered when making site management decisions. As with the Tier 1 evaluation, confidence in the Tier 2 results will be greater if multiple lines of evidence lead to similar conclusions. If different lines of evidence produce conflicting results, then the reasons for the discrepancies should be investigated, and greater weight should be given to the lines of evidence that have less uncertainty. The Tier 2 results should be used to refine the sediment transport CSM, which will be integrated with the overall CSM for the site in the FS (see Section 5).

4.3.1 Could Erosion of the Sediment Bed Lead to Exposure of Buried Contamination?

The expected stability of the sediment bed under typical and extreme conditions based on site-specific hydrodynamic and sediment strength data should be described. The potential effects of extreme events can be predicted with greater certainty using site-specific data on the erosion properties of the sediment bed. Therefore, the probability of exposing subsurface contamination can be more reliably predicted based on site-specific erosion estimates and vertical profiles of contaminant concentrations.

The Tier 2 results for BNC and HPS indicated no significant potential for erosion due to waves and currents under typical hydrodynamic conditions. The potential effects of extreme events at BNC were not evaluated; however, winds and waves are not expected to be significant in an extreme event because the area of concern is in relatively deep, protected waters. Erosion due to propeller scour at BNC was estimated to be on the order of a few centimeters for conventional propellers. The Tier 2 evaluation at HPS indicated that up to about 6 cm of erosion could occur during a 25-year storm, and a stiff clay layer found at 30 to 40 cm throughout the study area is likely to be resistant to erosion, even under very high shear stress conditions.

4.3.2 Could Sediment Transport Lead to the Redistribution of Contamination within the Site, or Movement of Contamination Off Site?

The magnitude and direction of net sediment transport (i.e., net flux) can be calculated based on site-specific information on waves, currents, and suspended sediment concentrations. These data also can be used to refine the mass balance for the site. Tier 2 results for HPS and BNC indicate that current speeds are low, and therefore net sediment transport is negligible. At HPS, contaminated sediments in the nearshore region have the potential to be resuspended by waves, particularly during winter storms, and transported to deeper regions outside the influence of waves. However, once these sediments reach the deeper water outside the influence of waves, tidal currents are insufficient to transport the contaminants offsite.

4.3.3 Will Natural Processes Lead to the Burial of Contaminated Sediment by Relatively Clean Sediment?

Evidence for sediment deposition at the site should be summarized based on flux estimates, radioisotope data, and/or sediment trap data when available. Sources of incoming sediment particles should be described based on the refined mass balance, and the quality of incoming sediment should be evaluated based on sediment trap data or detailed vertical contaminant profile data. Natural recovery may be occurring if the site is depositional and if vertical contaminant profiles indicate that surface sediments are relatively clean compared with subsurface sediments. The depth at which subsurface sediment is unlikely to be affected by physical (i.e., hydrodynamic) or biological processes should be estimated based on site-specific data. Sediment accumulation rates can be used to estimate the time required to bury contaminated sediments below this depth, although post-depositional mixing of surface and subsurface sediments must be considered. Potential changes in any of the processes responsible for natural recovery should be evaluated. For example, are the sources or quality of incoming sediment likely to change in the future? Will dredging or marine construction alter the hydrodynamic conditions at the site? Contingency plans should be considered in the event that recovery ceases to occur.

Multiple lines of evidence indicate that both Sinclair Inlet at BNC and South Basin at HPS are net depositional environments. Limited sediment trap results for BNC suggest that incoming sediments have lower contaminant concentrations than bed sediments. Sediment trap results for HPS were ambiguous; however, the vertical profiles of contaminant concentrations indicate that chemical concentrations in surface sediments have decreased over time. The net sediment deposition rates estimated from radioisotope data were relatively consistent for South Basin (about 1 cm/yr), but rates estimated for Sinclair Inlet were more variable (from approximately 0.3 to 0.9 cm/yr). In both cases, it appears that natural processes will lead to the burial of contaminated sediment by relatively clean sediment over time.

4.3.4 If a Site is Actively Remediated, Could Sediment Transport Lead to the Recontamination of the Site?

The refined mass balance can be used to re-evaluate the potential for recontamination of the site from off-site sources, or the effects of potential changes in hydrodynamic conditions at the site. The potential effects of the most promising remedial approaches also can be re-evaluated using site-specific Tier 2 data.

Various factors could influence the potential recontamination of a remediated site due to sediment transport. Some of these factors are uncontrolled sources of contamination, off-site sources of contamination, resuspension and transport of contaminated sediment due to remedy implementation

(e.g., resuspension due to dredging or cap placement, dredging residuals), and changes in hydrodynamic conditions as a result of the remedy (i.e., increased current speeds in response to deepening). These factors were evaluated for HPS (Appendix B) and BNC (Appendix C).

5. APPLICATION TO SITE MANAGEMENT

5.1 INTERPRETING SEDIMENT TRANSPORT WITHIN THE CSM

The overall CSM for the site identifies known or suspected contaminant sources, release and transport mechanisms, contaminated media, exposure pathways, and potential receptors. The potential ramifications of sediment transport at the site must be interpreted within the CSM. For example, if the sediment transport analysis indicates that natural processes will lead to the burial of contaminated sediment by relatively clean sediment, interpretation within the CSM may indicate that a previously complete exposure pathway may be eliminated over time as a result of deposition. Alternatively, if the sediment transport analysis indicates that erosion of the sediment bed could lead to exposure of previously buried contamination, interpretation within the CSM may indicate that action will be required to prevent the development of a complete exposure pathway in the future.

Sediment transport also should be interpreted in the context of other contaminant transport mechanisms identified in the CSM (e.g., diffusive fluxes, advective fluxes, biodegradation) to evaluate the significance of sediment transport relative to other processes. For example, although burial of contaminants due to transport of clean sediment may reduce direct exposure, it may also limit oxygen penetration, thus inhibiting biodegradation. In general, one should not assume that contaminant transport is insignificant solely based on physical stability of the sediment bed. This interpretation and integration with the CSM should be presented in the FS report and used to help form a technically defensible basis for developing remedial alternatives. The development of remedial alternatives in the FS should consider the most significant contaminant transport pathways.

5.2 DEVELOPING SEDIMENT MANAGEMENT STRATEGIES THAT ACCOUNT FOR SEDIMENT TRANSPORT PROCESSES

Sediment transport analysis and interpretation results should be considered during the development of site sediment management strategies. These results can be particularly critical when the remedial options include in-place management alternatives. A combination of management options is commonly used at sediment sites, particularly at sites that are large and complex. Contaminant hot spots may be dredged, whereas in-place methods such as in situ capping and/or natural recovery may be adopted for other parts of the site. Considerations in accounting for sediment transport processes are described below for the major remedial approaches for sediment, including monitored natural recovery, capping, and dredging. Other factors such as source control and magnitude of risk also must be considered during the development of sediment management strategies.

Monitored natural recovery is most suitable for depositional areas where the sediment bed appears stable and is expected to remain stable for a long time. Sources should be controlled and the sediment deposited on the sediment bed should be relatively clean. If the sediment bed is disturbed and contaminants are released as a consequence, no immediate and substantial risk to potential receptors should be anticipated. Ideally, there should be no changes in site use, adjacent land use, or regional hydrodynamic conditions that would lead to a significant change in the bed stability or the mass balance. Institutional controls to prevent marine construction, navigational dredging, anchoring, and prop scour from ships may be required in conjunction with monitored natural recovery.

The sediment transport characteristics that support a capping alternative are similar to those for monitored natural recovery. In addition, contaminant release and subsequent risk from sediment disturbance during placement of cap materials should be controlled. The cap should be designed to withstand existing and potential future hydrodynamic conditions, and an immediate or substantial risk should not be expected if the cap is disturbed.

For dredging remedies, sediment transport information should be used to select the optimal times for dredging to control sediment resuspension and contaminant dispersion. If dredging significantly deepens an area, then current speeds and circulation patterns may change. Potential changes in hydrodynamic conditions should be analyzed to ensure that they do not adversely affect any other components of a remedy. If near shore, in-water disposal methods are used (i.e., confined disposal or contained aquatic disposal), then the containment structures should be designed to withstand expected hydrodynamic forces.

5.3 INTEGRATING SEDIMENT TRANSPORT INTO THE FEASIBILITY STUDY

The results of the sediment transport studies should be incorporated into the detailed evaluation of remedial alternatives according to the National Contingency Plan (NCP) nine-remedy selection criteria. All remedies must meet the two threshold criteria: overall protectiveness and compliance with applicable or relevant and appropriate requirements (ARARs). Hydrodynamic conditions and sediment transport characteristics are most important when evaluating long-term effectiveness and permanence, short-term effectiveness, implementability, and state and community acceptance, as described below. If monitored natural recovery or capping is incorporated into a remedy, then post-remediation monitoring will be required to verify that sediment transport processes occur as predicted. Sediment transport considerations for the five balancing criteria are summarized below.

5.3.1 Long-Term Effectiveness and Permanence

Sediment transport can directly influence the long-term effectiveness and permanence of a remedial option. The long-term effectiveness of any remedial option can be reduced if sediment transport acts to recontaminate the site. Monitored natural recovery may or may not be a permanent remedy, depending on the efficacy of the recovery processes and the influence of sediment transport processes (e.g., stability of the bed, sediment accumulation rate, depth and degree of bioturbation, and potential for contaminant degradation). The degree of permanence is generally higher and magnitude of residual risk lower for sediment caps because control can be exerted over transport processes during the cap design process. Institutional controls may be needed to improve permanence and manage the residual risks that result from sediment transport at the site. Long-term effectiveness of in-place remedial actions such as capping can also be significantly degraded by extreme events.

5.3.2 Short-Term Effectiveness

Sediment transport can also influence the short-term effectiveness of a remedial option. For example, natural recovery controlled by deposition of clean sediment is unlikely to be effective on a short-term basis due to the low deposition rates that are characteristic of most U.S. Navy harbors. However, for the same reason, other short-term issues such as community and worker protection during the implementation of a monitored natural recovery or capping remedy generally are not an issue. The short-term transport of residual sediments during dredging can reduce the effectiveness of a removal action and lead to the potential contamination of previously

uncontaminated areas. Sediment transport processes should also be taken into account when predicting short-term benthic recolonization rates following capping or dredging actions.

5.3.3 Implementability

With both monitored natural recovery and capping remedies, institutional controls and monitoring may be required for long periods of time to ensure that the sediment bed is not disrupted by anthropogenic activities. However, due to the long implementation period for institutional controls and monitoring, their use may adversely affect the administrative feasibility of in-place sediment management.

5.3.4 State and Community Acceptance

If in situ remedial approaches are used, stakeholders may have concerns about leaving contamination in place and the potential spread of contamination during an extreme event. The need for long-term institutional controls may also be a concern. These concerns are best addressed by collecting high-quality, site-specific data that reduce the uncertainty associated with predicting the long-term fate of the remaining contaminants.

Site demonstration results at HPS are being used to support the development of the FS for near-shore and off-shore sediments. The BNC Tier 2 study results will be used in conjunction with other studies performed as part of the regulatory program that involves planning potential future remedial activities. Applying the Tier 2 sediment transport study results to site management decisions is discussed further in the site demonstration reports Appendices B and C.

6. REFERENCES

- Acker, P. and W. R. White. 1973. "Sediment Transport: New Approach and Analysis." *Journal of Hydraulics Division, American Society of Civil Engineers (ASCE)* 99(HY11): 2041–2060.
- Aller, R. C. and J. K. Cochran. 1976. "234Th/238U Disequilibrium in Near-Shore Sediment: Particle Reworking and Diagenetic Time Scales," *Earth and Planetary Science Letters* 29: 37–50.
- Bagnold, R. A. 1956. "Flow of Cohesionless Grains in Fluids," *Philosophical Transactions Royal Society of London, Series A* 249: 235–297.
- Bagnold, R. A. 1966. "An Approach to the Sediment Transport Problem from General Physics." Professional Paper No. 422. United States Geological Survey (USGS), Reston, VA.
- Blaauw, H. G., and E. J. van de Kaa. 1978. "Erosion of Bottom and Banks Caused by the Screw Race of Maneuvering Ships." Publication No. 202. Delft Hydraulics Laboratory, Delft, Netherlands.
- Bloesch, J. and N. M. Burns. 1980. "A Critical Review of Sediment Trap Technique," *Schweizerisch Zeitschrift fur Hydrologie* 42: 15–55.
- Blomqvist, S. and L. Hakanson. 1981. "A Review of Sediment Traps in Aquatic Environments," *Archiv fuer Hydrobiologie* 91: 101–132.
- Boudreau, B. P. 1998. "Mean Mixed Depth of Sediments: The Wherefore and the Why," *Limnology and Oceanography* 43(3): 524–526.
- Burban, P., Y. Xu, J. McNeil, and W. Lick. 1990. "Settling Speeds of Floes in Fresh and Sea Waters," *Journal of Geophysical Research* 95(C10): 18213–18220.
- Butman, C. A. 1986. "Sediment Trap Biases in Turbulent Flows: Results from a Laboratory Flume Study," *Journal of Marine Research* 44: 645–693.
- Byrnes, M. R., J. L. Baker, and F. Li. 2002. "Quantifying Potential Measurement Errors Associated with Bathymetric Change Analysis." ERDC/CHL Coastal and Hydraulic Engineering Technical Note (CHETN)-IV-50 (September). U.S. Army Engineer Research and Development Center Coastal and Hydraulic Laboratory, Vicksburg, MS.
- Cameron, W. M., and D. W. Pritchard. 1963. "Estuaries." In *The Sea*, Vol. 2, pp. 306–324, Wiley & Sons, New York, NY.
- Cheng, N. S. 1997. "Simplified Settling Velocity Formula for Sediment Particles," *Journal of Hydraulic Engineering* 123(2): 149–152.
- Chief of Naval Operations. 2002. "Policy on Sediment Site Investigation and Response Action." Ser N453E/2U589601 (February 8), Washington, DC.
- Chillrud, S., S. Hemming, E. Shuster, H. Simpson, R. Bopp, J. Ross, D. Pederson, D. Chaky, L. Tolley, and F. Estabrooks. 2003. "Stable Lead Isotopes, Contaminant Metals and Radionuclides in Upper Hudson River Sediment Cores: Implications for Improved Time Stratigraphy and Transport Processes," *Chemical Geology* 199: 53–70.
- Christoffersen, J. and I. Jonsson. 1985. "Bed Friction and Dissipation in a Combined Current and Wave Motion," *Ocean Engineering* 17(4): 479–494.

- Clarke, D., M. Palermo, and T. Sturgis. 2001. "Subaqueous Cap Design: Selection of Bioturbation Profiles, Depths, and Rates." DOER Technical Notes Collection (ERDC TN-DOER-C21), U.S. Army Engineering Research and Development Center, Vicksburg, MS.
- CNO, see Chief of Naval Operations.
- Dargahi, B. 2003. "Three-Dimensional Modeling of Ship-Induced Flow and Erosion." *Proceedings of the Institution of Civil Engineers: Water and Maritime Engineering* 156(2): 193–204.
- Dyer, K. R. 1986. *Coastal and Estuarine Sediment Dynamics*. John Wiley & Sons, Chichester, England.
- Dyer, K. R. 1997. *Estuaries: A Physical Introduction*. 2nd ed. John Wiley & Sons, Chichester, England.
- Einstein, H. A. 1950. "The Bed Load Function for Sediment Transport in Open Channel Flows." Technical Bulletin 1026. U.S. Department of Agriculture, Soil Conservation Service, Washington, DC.
- Fredsoe, J. 2002. *The Mechanics of Scour in the Marine Environment*. World Scientific, River Edge, NJ.
- Fuller, C. C., A. van Geen, M. Baskaran, and R. Anima. 1999. "Sediment Chronology in San Francisco Bay, California, defined by ^{210}Pb , ^{234}Th , ^{137}Cs , and $^{239,240}\text{Pu}$," *Marine Chemistry*, 64: 7–27.
- Gailani, J., C. K. Ziegler, and W. Lick. 1991. "The Transport of Suspended Solids in the Lower Fox River," *Journal of Great Lakes Research* 17(4): 479–494.
- Gardner, W. D. 1980. "Sediment Trap Dynamics and Calibration: A Laboratory Evaluation," *Journal of Marine Research* 38: 17–39.
- Geyer, W. R., P. S. Hill, T. G. Milligan, and P. Traykovski. 2000. "The Structure of the Eel River Plume During Floods," *Continental Shelf Research* 20: 2067–2093.
- Grabemann, I. and G. Krause. 1989. "Transport Processes of Suspended Matter Derived from Time Series in a Tidal Estuary," *Journal of Geophysical Research* 94(C10): 14373–14379.
- Grant, W. D. and O.S. Madsen. 1979. "Combined Wave and Current Interaction with a Rough Bottom," *Journal of Geophysical Research* 84(C4): 1797–1808.
- Hakanson, L. and M. Jansson. 2002. *Principles of Lake Sedimentology*. Blackburn Press, Caldwell, NJ.
- Hamill, G. A., H. T. Johnston, and D. P. Stewart. 1999. "Propeller Wash Scour Near Quay Walls," *Journal of Water, Port and Coastal Engineering* 125(4): 170–175.
- Hargrave, B. T. and N. M. Burns. 1979. "Assessment of Sediment Trap Collection Efficiency," *Limnology and Oceanography* 24: 1124–1136.
- HydroQual, Inc. 1995. "The Erosion Properties of Cohesive Sediments in the Upper Hudson River." Mahwah, NJ.

- Jensen, A., M. Perjup, and J. R. Valeur. 1990. "Accumulation and Resuspension of Sediment and Nutrient in Vejle Fjord." Report #4, pp. 189–193. National Environmental Research Institute, University of Aarhus, Foulum, Denmark.
- Jepsen, R., J. Roberts, and W. Lick. 1997. "Effects of Bulk Density on Sediment Erosion Rates," *Water, Air, and Soil Pollution* 99: 21–31.
- Jones, C. and W. Lick. 2000. "Effects of Bed Coarsening on Sediment Transport," *Estuarine and Coastal Modeling* 6: 915–930.
- Keen, T. R. and S. M. Glenn. 1998. "Resuspension and Advection of Sediment During Hurricane Andrew on the Louisiana Continental Shelf." *Proceedings of the 5th International Conference on Estuarine and Coastal Modeling* (pp. 481–494). 22–24 October 1997, Alexandria, VA. American Society of Civil Engineers.
- Kineke, G. C. and R. W. Sternberg. 1989. "The Effects of Particle Settling Velocity on Computed Suspended-Sediment Concentration Profiles," *Marine Geology* 90: 159–174.
- Krone, R. B. 1962. "Flume Studies of the Transport of Sediment in Estuarial Shoaling Processes." Final Report to San Francisco District, U.S. Army Corps of Engineers, Washington, DC.
- Lee, J. 1992. "An Empirical Relationship Between the Bed-Load Concentration and the Excess Shear Stress in a Wave-Current Boundary Layer." Master's Thesis, Ohio State University, Columbus, OH.
- Lick, W., Y. J. Xu, and J. McNeil. 1995. "Resuspension Properties of Sediments from the Fox, Saginaw, and Buffalo Rivers," *Journal of Great Lakes Research* 21(2): 257–274.
- Lindholm, T., M. Svartstrom, L. Spoof, and J. Meriluoto. 2001. "Effects of Ship Traffic on Archipelago Waters Off the Langnas Harbor in Aland, SW Finland," *Hydrobiologia* 444: 217–225.
- Liou, Y. and J. B. Herbich. 1976. "Sediment Movement Induced by Ships in Restricted Waterways." TAMU-SG-76-209, COE Report No. 188, U.S. Army Corps of Engineers, Washington, DC.
- Maynard, S. T. 2000. "Physical Forces Near Commercial Tows. Interim report for the Upper Mississippi River-Illinois Waterway System Navigation Study." Env Report 19 (Interim Report). U.S. Army Corps of Engineers Research and Development Center, Vicksburg, MS.
- Mehta, A. J., E. Hayter, W. Parker, R. Krone, and A. Teeter. 1989. "Cohesive Sediment Transport, I: Process Description," *Journal of Hydraulic Engineering* 115(80): 1076–1092.
- Mehta, A. J. and W. H. McAnally. 1998. "Fine-Grained Cohesive Sediment Transport." In *Sedimentation Engineering American Society of Civil Engineers Manual 54, Volume 2*, American Society of Civil Engineers, New York, NY.
- Mellor, G. L. and T. Yamada. 1982. "Development of a Turbulence Closure Model for Geophysical Fluid Problems," *Reviews of Geophysics and Space Physics* 20: 851–875.
- Meyer-Peter, E. and R. Müller. 1948. "Formulas for Bed-Load Transport." *Proceedings of the 2nd Meeting of the International Association of Hydraulic Research* (pp. 39–64). 6–7 June, Stockholm, Sweden.

- Michelsen, T. C., C. C. Ebbesmeyer, M. D. Francisco, C. D. Boatman, and D. Norton. 1998. "Transport of Contaminants Along the Seattle Waterfront: Effects of Vessel Traffic and Waterfront Construction Activities," *Water Science and Technology* 37(6-7): 9–15.
- Molinas, A. and C. T. Yang. 1986. "Computer Program User's Manual for GSTARS (Generalized Stream Tube model for Alluvial River Simulation)." U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, CO.
- National Research Council. 1993. "Managing Water in Coastal Urban Areas." National Academy of Sciences, Washington, DC.
- Naval Facilities Engineering Service Center. 2003. "Implementation Guide for Assessing and Managing Contaminated Sediment of Navy Facilities." User's Guide UG-2053-ENV. Port Hueneme, CA.
- Nichols, M. M. 1977. "Response and Recovery of an Estuary Following a River Flood," *Journal of Sedimentary Petrology* 47: 1171–1186.
- Nichols, M. M. and R. B. Biggs. 1985. "Estuaries." In *Coastal Sedimentary Environments*, pp. 77–186, R. A. Davis, Jr., Ed. Springer-Verlag, New York, NY.
- Nodder, S. D. and B. L. Alexander. 1999. "The Effects of Multiple Trap Spacing, Baffles and Brine Volume on Sediment Trap Collection Efficiency," *Journal of Marine Research* 57: 537–559.
- NRC, see National Research Council.
- Partheniades, E. 1965. "Erosion and Deposition of Cohesive Soils," *Journal of Hydraulic Engineering* 91(1): 105–138.
- Pennington, W. 1974. "Seston and Sediment Formation in Five Lake District Lakes," *Journal of Ecology* 62: 215–251.
- Perjup, M., J. R. Valeur, and A. Jensen. 1996. "Fluxes of Particulate Matter in the Arhus Bight," *Continental Shelf Research* 16: 1047–1064.
- Reid, I., J. C. Bathurst, P. A. Carling, D. E. Walling, and B. W. Webb. 1997. "Sediment Erosion, Transport and Deposition." In *Applied Fluvial Geomorphology for River Engineering and Management*. C. R. Thorne, R. D. Hey, and M. D. Newson, Eds. John Wiley & Sons, Chichester, England.
- Reynolds, C. S. and B. M. Godfrey. 1983. "Failure of a Sediment Trapping Device," *Limnology and Oceanography* 28: 172–176.
- Rhoads, D. C. and D. A. Carey. 1997. "Capping Dredged Materials in the New York Bight: Evaluation of the Effects of Bioturbation." SAIC Report No. 374 submitted to New York District U.S. Army Corps of Engineers, New York, NY (Report 39). Science Applications International Corporation, Newport, RI.
- Roberts, J., R. Jepsen, D. Gotthard, and W. Lick. 1998. "Effects of Particle Size and Bulk Density on Erosion of Quartz Particles," *Journal of Hydraulic Engineering* 124(12): 1261–1267.

- Rouse, H. 1938. "Experiments on the Mechanics of Sediment Suspension." Reprint from *Proceedings of the Fifth International Congress for Applied Mechanics* (pp. 550–554). 12–16 September, Harvard University and the Massachusetts Institute of Technology, Cambridge, Massachusetts.
- Schnoor, J. 1995. *Environmental Modeling: Fate and Transport of Pollutants in Water, Air, and Soil*. John Wiley & Sons, Inc., New York, NY.
- Spasojevic, M. and M. J. Holly. 1994. "Three-Dimensional Numerical Simulation of Mobile-Bed Hydrodynamics." Technical Report HL-94-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Sumer, M. and J. Fredsoe. 2002. *The Mechanics of Scour in the Marine Environment*. World Scientific Publishing Co. Pte. Ltd., River Edge, NJ.
- Tetra Tech, Inc. 2000. "A Theoretical Description of Sediment Transport Formulations used in the EFDC Model." Technical Memo TT-EFDC-00-1. Tetra Tech, Inc., Fairfax, VA.
- Tetra Tech, Inc. 2001. EFDC1D—A One-Dimensional Hydrodynamic and Sediment Transport Model for River and Stream Networks: Model Theory and User's Guide." EPA/600/R-01/073. U.S. Environmental Protection Agency, Washington, DC.
- U.S. Army Corps of Engineers. 1990. "Status and New Capabilities of Computer Program HEC-6: Scour and Deposition in Rivers and Reservoirs." Technical Paper No. 129. Hydrologic Engineering Center, Davis, CA.
- U.S. Army Corps of Engineers. 1993. "Hydrologic Frequency Analysis." EM 1110-2-1415. Available online at <http://www.usace.army.mil/publications/eng-manuals/em1110-2-1415/toc.htm>.
- U.S. Army Corps of Engineers. 2002. "Coastal Engineering Manual." EM 1110-2-1100. Available online at <http://chl.erdc.usace.army.mil/chl.aspx?p=s&a=ARTICLES;104>.
- U.S. Environmental Protection Agency. 2005. "Contaminated Sediment Remediation Guidance for Hazardous Waste Sites (December 2005). EPA-540-R-05-012. USEPA National Service Center for Environmental Publications, Washington, DC.
- U.S. Environmental Protection Agency. 2006. "Guidance on Systematic Planning Using the Data Quality Objectives Process (EPA QA/G-4)." EPA/240/B-01/001 (February). USEPA Office of Environmental Information, Washington, DC.
- U.S. Geological Survey. 1996. "The '100-Year Flood.'" Fact Sheet FS-073-98. Available online at <http://water.usgs.gov/pubs/fs/FS-229-96/>.
- U.S. Geological Survey. 1998. "Short-Lived Isotopic Chronometers—A Means of Measuring Decadal Sedimentary Dynamics." Fact Sheet FS-073-98. Available online at <http://sofia.usgs.gov/publications/fs/7398/>.
- U.S. Geological Survey. 2002. "Community Model for Coastal Sediment Transport: Existing Model." Available online at <http://woodshole.er.usgs.gov/project-pages/sediment-transport/ModelTable.pdf>.
- USACE, see U.S. Army Corps of Engineers.
- USEPA, see U.S. Environmental Protection Agency.

USGS, see U.S. Geological Survey.

Van der Wal, K. and K. Pye. 2003. "The Use of Historical Bathymetric Charts in a GIS to Assess Morphological Changes in Estuaries," *Hydrographic Journal*, 110 (October): 3–9. Available online at <http://www.hydrographicsociety.org/PDF/Journal-110-Article1.pdf>.

Van Rijn, L. 1993. *Principles of Sediment Transport in Rivers, Estuaries, and Coastal Seas*. Aqua Publications, Amsterdam, The Netherlands.

Wave Model and Development Implementation (WAMDI) Group. 1988. "The WAM Model—A Third Generation Ocean Wave Prediction Model," *Journal of Physical Oceanography* 18: 1775–1810.

Welsh, D. J. S., K. W. Bedford, R. Wang, and P. Sadayappan. 2000. "A Parallel-Processing Coupled Wave/Current/Sediment Transport Model." ERDC MSRC/PET TR/00-20. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Wheatcroft, R. A., C. K. Sommerfield, D. E. Drake, J. C. Borgeld, and C. A. Nittrouer. 1997. "Rapid and Widespread Dispersal of Flood Sediments on the Northern California Margin," *Geology*, 25: 163–166.

White, J. 1990. "The Use of Sediment Traps in High-Energy Environments," *Marine Geophysical Research* 12: 145–152.

Wright, S. and G. Parker. 2004. "Density Stratification Effects in Sand-Bed Rivers," *Journal of Hydraulic Engineering* 130(8): 783–795.

Yalin, M. S. 1963. "An Expression for Bedload Transportation," *Journal of the Hydraulic Division, American Society of Civil Engineers*, 89(HY3): 221–250.

Ziegler, C. K. and W. Lick. 1986. "A Numerical Model of the Resuspension, Deposition, and Transport of Fine-Grained Sediments in Shallow Water." UCSB Report ME-86-3. University of California, Santa Barbara, CA.

Ziegler, C. K. and B. S. Nisbet. 1994. "Fine-Grained Sediment Transport in Pawtuxet River, Rhode Island," *Journal of Hydraulic Engineering* 120(5): 561–576.

Ziegler, C. K. and B. S. Nisbet. 1995. "Long-Term Simulation of Fine-Grained Sediment Transport in Large Reservoir," *Journal of Hydraulic Engineering* 121(11): 773–781.

Ziegler, K. 2002. "Evaluating Sediment Stability at Sites with Historic Contamination." *Environmental Management* 29(3): 409–427.

ACRONYMS

1-D	One-dimensional
2-D	Two-dimensional
3-D	Three-dimensional
ADCP	Acoustic Doppler Current Profiler
ADV	Acoustic Doppler Velocimeter
ARAR	Applicable or Relevant and Appropriate Requirement
BNC	Bremerton Naval Complex
CNO	Chief of Naval Operations
COMAPS	Coupled Marine Prediction System
CSM	Conceptual Site Model
DQO	Data Quality Objectives
EFDC	Environmental Fluid Dynamics Code
FS	Feasibility Study
GIS	Geographic Information System
GSTARS 2.1	Generalized Stream Tube Model for Alluvial River Simulation, Version 2.1
HEC	Hydraulic Engineering Center
HOC	Hydrophobic Organic Contaminant
HPS	Hunters Point Shipyard
LISST	Laser In Situ Scattering and Transmissometry
NCP	National Contingency Plan
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NWS	National Weather Service
OBS	Optical Backscatter Sensor
PCB	polychlorinated biphenyl
RDT&E	Research, Development, Testing and Evaluation
RI	Remedial Investigation
RPM	Remedial Project Manager
SSC San Diego	Space and Naval Warfare Systems Center San Diego

TOC	Total Organic Carbon
TSS	Total Suspended Solids
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WCSD	Watershed Contaminated Source Document

GLOSSARY

advection	The transport of particles due to the motion or velocity of the fluid.
analytical methods	Using mathematical techniques to solve a problem.
bedload	Sediment particles resting on or near the channel bottom that are pushed or rolled along by the flow of water.
benthic	Of the seafloor, or pertaining to organisms living on or in the seafloor.
bioturbation	Reworking of sediments by organisms that burrow and ingest them.
boundary layer	The thin layer of fluid next to a solid boundary (e.g., bottom of an estuary) where friction is very important.
bulk density	The total mass density of sediment and water in a given volume of sediment bed material.
cohesive	Description of sediments, generally less than 200 μm in diameter, which tend to stick together and resist separation.
critical shear stress	The shear stress at which sediments begin to exhibit a measurable amount of motion.
diurnal tide	Tide with one high water and one low water each tidal day.
epibenthic	Pertaining to organisms living near the seafloor.
empirical	Based on laboratory or field measurements of the process to be described.
fetch	Distance of water over which the wind blows in essentially a constant direction.
flocculate	When suspended sediment particles aggregate to form larger particles called flocs.
fluvial	Pertaining to rivers or streams.
flux	The rate of flow of a physical substance (e.g., water or sediments) through a given area.
intertidal	Area of the shore between mean high water and mean low water; the intertidal zone.
mixed tide	Type of tide in which large inequalities between the two high waters and the two low waters occur in a tidal day.
neap tide	Tides occurring near the times of the first and last quarters of the moon, when the range of the tide is least.
non-cohesive	Description of sediments, generally more than 200 μm in diameter, which exhibit no tendency towards resisting separation.

numerical methods	Using iterative techniques to solve a problem. Generally, the methods that are used in computer modeling.
100-year flood	A flood of a given size that has a 1-in-100 chance of occurring in any given year. The actual number of years between floods of any given size varies in response to natural climatic fluctuations.
residual circulation	The net circulation of a system, generally tidal, left after filtering out any oscillatory processes affecting the circulation.
semidiurnal tide	Tide with two high waters and two low waters each tidal day.
shear stress	The force due to friction exerted on a unit area of the sediment bed due to a moving water mass.
spring tide	Tides occurring near the times of the new and full moon, when the range of the tide is greatest.
subtidal	Benthic zone from the low tide line to the seaward edge of the continental shelf.
suspended load	Sediment particles maintained in the water column by turbulence and carried with the flow of water.
turbulent diffusion	The movement and dispersal of a mass in the water column due to random turbulent motions in the flow.
theoretical methods	Methodology derived from basic physical principles.
wave height	Vertical distance between a wave crest and the adjacent trough.
wavelength	Horizontal distance between two successive wave crests or two successive wave troughs.

APPENDIX A

TOOLS, TECHNOLOGIES AND APPROACHES FOR MEASURING SEDIMENT TRANSPORT PROPERTIES

Table A-1. Tools, Technologies, and Approaches for Measuring Sediment Transport Properties.

Tool, Technology or Approach	Description	Applicability	Advantages	Limitations	Cost Considerations (a)
Site characteristics					
Bathymetric survey – single beam mapping	Single acoustic beam used for point measurement of depth below vessel.	Any aquatic system with vessel access.	Easy to deploy and method is standardized.	Depth limitations due to vessel draft. Horizontal resolution limited to transects run by vessel.	Inexpensive
Bathymetric survey – multi-beam mapping	Multiple acoustic beams used to generate a swath of depth data.	Any aquatic system with vessel access.	Gives 100% coverage in the horizontal with properly laid transects. Can be used to identify large bedforms and geomorphologic features.	Generally needs larger vessel support than single beam surveys.	Moderate – Expensive
Shoreline survey	Identify seasonal changes in shoreline.	Shoreline areas with measurable seasonal variability.	Simple method.	Low resolution and labor intensive.	Inexpensive
Side Scan Sonar	Acoustic sonar for mapping but not bathymetry.	Any aquatic system with vessel access.	Can quickly map geomorphic features. Can be tuned to identify sand and silt differences.	No bathymetry is given.	Moderate
Sediment contaminant mapping	High resolution data on the horizontal and vertical distribution of sediment contaminants.	Systems with traceable contaminant.	Gives a discrete tracer of sediment movement.	Can be influenced by other transport and transformation mechanisms (biota, diffusion, degradation, ...).	Moderate – Expensive
Water column properties					
Currents - S4 current meter	Currents - S4 current meter	Currents - S4 current meter	Currents - S4 current meter	Currents - S4 current meter	Currents - S4 current meter
Currents - ADV current meter	Currents - ADV current meter	Currents - ADV current meter	Currents - ADV current meter	Currents - ADV current meter	Currents - ADV current meter

Table A-1. Tools, Technologies, and Approaches for Measuring Sediment Transport Properties. (continued)

Tool, Technology or Approach	Description	Applicability	Advantages	Limitations	Cost Considerations ^(a)
Water column properties (continued)					
Currents - PC-ADP current meter	Pulse coherent – acoustic doppler profiler provides 3-D velocity profile near the sediment bed.	Any aquatic system of sufficient depth.	High-resolution velocity profile near the bed allows for wave and current shear stresses on the sediment bed to be indirectly determined.	Only provides near-bed measurements which can limit description of stratified systems.	Moderate – Expensive
Currents - upward looking ADCP current meter	Subsurface-deployed acoustic profiler provides 2-D velocity profiles through the entire water column.	Any aquatic system of sufficient depth.	Standardized system provides wave and current information. Can be tailored to specific water depths. Data can be used to determine shear stress. Can also be used to determine suspended sediments.	Only single point profile. Must be carefully calibrated for suspended sediments.	Moderate - Expensive
Currents - boat mounted downward looking ADCP current meter	Vessel-deployed acoustic profiler provides downward looking 2-D current profiles.	Any aquatic system of sufficient depth.	Standardized system provides current information at a point or along transects. Can be used to determine shear stress and suspended solids.	Must be relatively calm water. Only provides relatively short-term snapshot during time of deployment. Must be carefully calibrated for suspended sediments.	Moderate - Expensive
Currents - mechanical current meter	Measures velocity and direction of currents.	Any aquatic system of sufficient depth.	Very simple to deploy.	Low accuracy and only provides single data point. In situ deployments must be short term due to fouling.	Inexpensive
Waves and tides - pressure sensors to measure wave and tide height	Measures subsurface pressure to determine water surface variations due to waves and tides.	Any aquatic system of sufficient depth.	Easily deployable and calibrated. Applicable to any type of aquatic system.	Higher memory sensor required for wave measurements. Only provides single point measurement.	Inexpensive

Table A-1. Tools, Technologies, and Approaches for Measuring Sediment Transport Properties. (continued)

Tool, Technology or Approach	Description	Applicability	Advantages	Limitations	Cost Considerations ^(a)
Water column properties (continued)					
Salinity - conductivity meter	Measurement of salinity.	Any aquatic system of sufficient depth.	Easily deployable and calibrated.	Single point measurement.	Inexpensive
Temperature - temperature recorder	Measurement of temperature.	Any aquatic system of sufficient depth.	Easily deployable and calibrated.	Single point measurement.	Inexpensive
Suspended sediment concentrations - OBS	Uses optical backscatter techniques to determine suspended sediment concentrations.	Any aquatic system of sufficient depth.	Easily deployable and integrated into other systems. Tunable to be very accurate in specific concentration ranges. Good for very large sediment concentrations.	Single point measurement that is only valid for a specific concentration range. Degradation of data quality due to biofouling over time. Must be calibrated to TSS.	Inexpensive – Moderate
Suspended sediment concentrations - transmissometer	Uses an optical measure of light transmission to determine suspended sediment concentrations.	Any aquatic system of sufficient depth.	Easily deployable and integratable into other systems. Very good in low suspended sediment concentrations.	Single point measurement. Not as durable as other systems. Not good for heavy sediment loads. Must be calibrated to TSS.	Inexpensive - Moderate
Suspended sediment concentrations - LISST 100	Optical measurement of light transmission to determine suspended sediment concentrations and particle size.	Any aquatic system of sufficient depth.	Easily deployable and integrated into other systems. Tunable to be accurate for a specific range of particle sizes and concentrations. Strong Navy support.	Generally needs trained technician to calibrate. Single point measurement that is only valid for a specific concentration range.	Expensive
Suspended sediment concentrations - laboratory determination of TSS	Discrete sample filtered and weighed in laboratory to determine total suspended solids concentration.	Any aquatic system.	Generally required for calibration of any other instrumentation. Can be determined for any system at any time. Standardized method available in all aquatic laboratories.	Provides only discrete single point measurement.	Inexpensive

Table A-1. Tools, Technologies, and Approaches for Measuring Sediment Transport Properties. (continued)

Tool, Technology or Approach	Description	Applicability	Advantages	Limitations	Cost Considerations ^(a)
Sediment bed properties					
Sediment properties - particle (grain) size distribution by sieve analysis	Physical determination of particle size distribution by ASTM D244.	All sediment systems.	Standardized method.	Labor-intensive and low-resolution distributions. Large quantities of sediment reqd.	Moderate
Sediment properties - particle (grain) size distribution by laser diffraction analysis	Optical determination of particle size by laser scattering properties.	All sediment systems with particle sizes up to 3,000 µm.	Provides very high resolution distributions down to 1 µm. Small quantities required, so may be subsampled from other cores.	Non-standard technique.	Moderate
Sediment properties - water content/bulk density	Wet and dry weighing of sediments to determine bulk density.	All sediment systems.	Standardized measurement required for most sediment transport analyses.	Point measurement.	Inexpensive
Sediment properties - total organic carbon	Percentage determination by mass of the total organic carbon present in sediments.	All sediment systems.	Can be used for contaminant transport calculations as well.	Point measurement.	Moderate
Stratigraphy - sediment core logging	Geologic description of sediment cores to identify sediment types and map stratigraphy.	All sedimentary systems where changes in sediment types exist.	Can be used to identify erosion/ deposition patterns. Provides ground truth for remote systems. Provides a core that can be subsampled for other purposes.	Disturbs collected core. Relies on generally qualitative description of sediments. Labor-intensive.	Inexpensive – Moderate
Stratigraphy - sub-bottom profiling	Establishes sediment stratigraphy and density.	All aquatic systems with vessel access that have distinct sediment differences.	Tunable to specific sediment environments, large area coverage and high- resolution description of sediment distribution.	Must be ground-truthed. Low penetration in sandy environments. Presence of gas in fine sediments can invalidate results.	Moderate – Expensive
Sediment stability - shaker/annular flume	Establishes critical shear stress and resuspension potential for surficial cohesive sediments.	Any soft sediment systems.	Easily deployable and quick processing of cores. Provides core for epibenthic characterization.	Only provides surficial information.	Moderate

Table A-1. Tools, Technologies, and Approaches for Measuring Sediment Transport Properties. (continued)

Tool, Technology or Approach	Description	Applicability	Advantages	Limitations	Cost Considerations ^(a)
Sediment bed properties (continued)					
Sediment stability - SEDflume	Measures critical shear stress sediment erosion profiles with depth for cohesive sediments.	Any soft sediment systems.	Provides direct measure of sediment erosion and critical shear stress. Provides quantitative and qualitative characterizations of sediments and benthic communities with depths up to 1 m.	Labor intensive and limited area coverage.	Moderate – Expensive
Sediment accumulation rate - radioisotope profiles (Pb-210, Cs-137)	Sedimentation rate, sediment mixing profile and rate.	Best suited for fine-grained depositional sites where the sediment column is undisturbed.	Best method available for estimating sediment accumulation rate over time scales of interest.	Accuracy depends on the validity of the assumptions inherent in the method. Method is ineffective for dating if significant post-depositional disturbance has occurred.	Inexpensive - Moderate
Sediment accumulation rate - sediment traps	Assess quantity and quality of sediment settling on the sediment bed.	Any aquatic system of sufficient depth.	Provides in situ measure of sediments settling to bed. No support required during long-term deployments.	No time series data without retrieval and redeployment. No standardized trap design methodology.	Inexpensive - Moderate
Sediment accumulation rate - erosion pin/pole survey	Determines long-term erosion/sedimentation patterns.	Any sediment system.	Easily deployable. Easy to obtain measurements.	Measurements at discrete intervals only. Large changes in bed height can be biased by presence of pole and/or pole movement.	Inexpensive
Bioturbation - qualitative benthic survey	Visual inspection of epibenthic (surficial) communities.	All aquatic systems.	Quick and efficient method for describing epibenthic communities. Large area coverage easily possible.	Surficial communities are the only ones covered. Not a quantitative measurement.	Moderate
Bioturbation - quantitative benthic survey	Provides an accurate count of epibenthic and infaunal communities.	Systems with observed biotic activity.	Quantitative description of community structure. Can be used to define bioturbation rates and depths throughout a system.	Labor intensive and relies heavily on local expertise of personnel conducting survey.	Expensive

Table A-1. Tools, Technologies, and Approaches for Measuring Sediment Transport Properties. (continued)

Tool, Technology or Approach	Description	Applicability	Advantages	Limitations	Cost Considerations ^(a)
Sediment bed properties (continued)					
Bioturbation - sediment profile imaging	Camera is inserted into the sediments to photograph cross-section of sediment and biotic activity.	Any sedimentary system with vessel access.	Remotely deployed technology. High resolution photography of sediment cross-section. Can provide measure of bioturbation.	Only provides 15 cm of depth. Large vessel requirements for deployment. Relies heavily on local expertise of personnel for the determination of bioturbation.	Moderate
Bioturbation - push cores: visual description and high resolution photography	Clear cores pushed into sediments are collected and photographed.	Any sedimentary system.	Provides cores on the order of 1 m depth in soft sediment systems. Cores can be used for other analysis. Simple equipment requirements.	Labor intensive and techniques must be modified for deeper (>10 m) waters.	Inexpensive – Moderate
Bioturbation – radioisotope profiles (Th-234, Be-7)	Depth to which short-lived isotopes are found in sediment bed can provide information about short-term mixing rates.	Any sedimentary system.	Allows characterization of the surficial, rapidly mixed zone.	Data should be collected and interpreted by a technical expert.	Inexpensive – Moderate
Bioturbation – oxidation-reduction profile measurements	Semi-quantitative measurement of redox potential discontinuity.	Any sedimentary system.	Real time, in situ determination of redox discontinuity	Only provides relative changes in redox potential – not absolute measurements	Inexpensive

APPENDIX B

HUNTERS POINT SHIPYARD PARCEL F

CONTENTS

B.1 BACKGROUND	B-5
B.1.1 PROJECT HISTORY	B-5
B.1.2 SITE DESCRIPTION	B-6
B.1.2.1 Topography and Bathymetry	B-6
B.1.2.2 Meteorology.....	B-7
B.1.2.3 Hydrodynamic Processes.....	B-7
B.1.2.4 Sediment Properties.....	B-7
B.1.3 SEDIMENT TRANSPORT CONCEPTUAL SITE MODEL.....	B-7
B.2 TIER 2 EVALUATION	B-11
B.2.1 STUDY DESIGN.....	B-11
B.2.1.1 Hydrodynamic Measurements.....	B-12
B.2.1.2 SEDflume Cores.....	B-15
B.2.1.3 Radioisotope Cores.....	B-16
B.2.1.4 Sediment Traps.....	B-16
B.2.1.5 Sediment Profile Imaging	B-16
B.2.2 TIER 2 RESULTS.....	B-17
B.2.2.1 Transport.....	B-17
B.2.2.2 Erosion and Resuspension	B-21
B.2.2.3 Deposition	B-24
B.2.2.4 Numerical Modeling.....	B-27
B.2.3 TIER 2 CONCLUSIONS AND RECOMMENDATIONS	B-31
B.2.3.1 Refined Sediment Transport Conceptual Site Model	B-31
B.2.3.2 Sediment Management Questions	B-31
B.2.3.3 Major Data Gaps and Uncertainties	B-33
B.3 REFERENCES.....	B-35

Figures

B-1. HPS site location map	B-6
B-2. PCB concentrations in South Basin sediment.....	B-10
B-3a. PCB concentration profiles offshore of Parcel E-2 shoreline (station locations are shown in Figure B-5).....	B-10
B-3b. PCB concentration profiles at the mouth of Yosemite Creek (station locations are shown in Figure B-5)	B-10
B-4. Sediment transport conceptual site model	B-11
B-5. Parcel F FS Data Gaps Investigation station locations	B-14
B-6. Parcel F FS Data Gaps Investigation station types.....	B-15
B-7. Station S1, winter current speed, bottom orbital velocity, and bed shear stress. The red dashed line indicated the critical shear stress of 0.28 Pa as measured by the SEDflume.....	B-18
B-8. Current velocities measured in spring (T2) and summer (T3) 2004.....	B-19
B-9. Turbidity measured in Spring (T2) and Summer (T3) 2004. The dashed lines indicate data where biofouling is suspected to have altered the data.....	B-19
B-10. Bed shear stresses calculated from the current meter data. The red dashed lines indicate the critical shear stress of 0.28 Pa as measured by the SEDflume.....	B-20

B-11. SEDflume data for Station SB-114.....	B-21
B-12. SEDflume data averaged from 12 South Basin cores in 5-cm depth intervals.....	B-22
B-13. Critical shear stress as a function of depth for the average South Basin sediments.....	B-22
B-14. Depth of erosion as a function of time for the 25-year extreme event.....	B-24
B-15. Gross sediment accumulation rates in sediment traps. The green dotted line represents the net sediment accumulation rate calculated from the radioisotope data.	B-25
B-16. Total PCB concentrations measured from the sediment trap and surface sediment samples	B-26
B-17. Deposit-feeding infaunal assemblages in South Basin sediments. Width of each image is 14.2 cm.....	B-27
B-18. Maximum winter ebb tide bed shear stress and velocity vectors (7 February 2001). Bed shear stress is due to currents only.....	B-28
B-19. Maximum winter ebb tide shear stress and velocity vectors (7 February 2001). Shear stress is due to waves and currents.....	B-28
B-20. Six regions used in PCB flux modeling	B-30
B-21. PCB concentration profile over time for Station SB-094	B-30
B-22. Surface PCB concentrations over time for each of the six areas	B-31

Tables

B-1. Summary of Tier 2 sediment transport study field investigation.....	B-13
B-2. Extreme event analysis with corresponding shear stresses and erosion depths	B-23
B-3. Estimated net sediment accumulation rates.....	B-25

B.1 BACKGROUND

Southwest Division Naval Facilities Engineering Command coordinated a study to evaluate the transport of sediment-bound contaminants at the Hunters Point Shipyard (HPS) Parcel F in conjunction with other studies performed to support the regulatory program. A Tier 2 evaluation of sediment transport was performed following the methodology presented in the Guide for Assessing Sediment Transport at Navy Facilities (June 2004). The results of the Tier 2 evaluation and implications for remedial planning are presented in this site demonstration report.

B.1.1 PROJECT HISTORY

HPS is a former Navy installation located on a peninsula in the southeast corner of San Francisco, CA (Figure 1). From 1945 to 1974, the Navy maintained and repaired ships at HPS. The facility was deactivated in 1974 and remained relatively unused until 1976, when it was leased to Triple A Machine Shop, a private ship repair company. In 1986, the Navy resumed occupancy of HPS. The facility was closed in 1991 under the Defense Base Realignment and Closure Act (BRAC) of 1990 and is in the process of conversion to non-military use.

Past site activities at HPS resulted in the release of chemicals to the environment, including offshore sediments (Parcel F). Various studies have been conducted since 1991 to evaluate shoreline and offshore contamination. The Parcel F Feasibility Study (FS) is currently in progress. The Tier 2 sediment transport evaluation was conducted in conjunction with the Parcel F FS Data Gaps Investigation (Battelle et al., 2005a) to provide data to support the development and evaluation of remedial alternatives. The Tier 2 sediment transport evaluation focuses on South Basin, which is on the south side of HPS. South Basin (also referred to as Area X) is one of the areas being evaluated in the Parcel F FS.

Historical activities associated with a former landfill in adjacent upland Parcel E-2 (Figure B-1) contributed to contamination of sediments in South. Remedial measures that have been implemented in Parcel E-2 include construction of a landfill cap and removal of contaminated soils along the shoreline (shoreline actions are in progress). A Tier 1 sediment transport evaluation of South Basin was not performed because a similar evaluation was completed in 2000 as part of the regulatory program (Battelle and Woods Hole Group, 2000). The initial evaluation was used to develop a site-specific sediment dynamics study that was performed in 2001 (Battelle et al., 2005b); results of that study are incorporated into this report.

This report is organized according to the framework provided in Section 1.1 of the Guide for Assessing Sediment Transport at Navy Facilities (Users Guide). Section 1 presents a site description and conceptual site model for sediment transport based on previous studies. Section 2 describes the Tier 2 sediment transport data collection program, presents the Tier 2 data analyses and refined conceptual model of sediment transport, and discusses the application of the results to sediment management questions. References are provided in Section B-3.

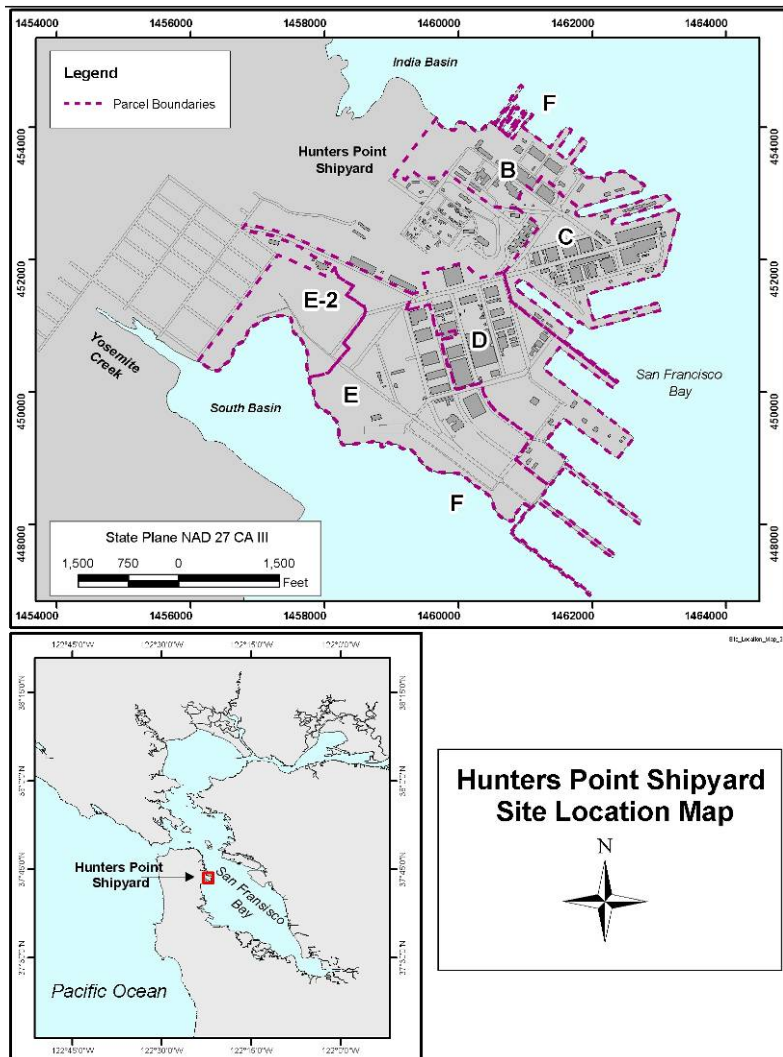


Figure B-1. HPS site location map.

B.1.2 SITE DESCRIPTION

The following site description forms the basis for the sediment transport conceptual site model and Tier 2 sediment transport evaluation.

B.1.2.1 Topography and Bathymetry

South Basin is a shallow embayment on the south side of HPS that trends southeast–northwest (Figure B-1). Water depths in South Basin range from less than 1 to approximately 2 m. South Basin was originally a marshy, wetland area. Its current configuration largely reflects filling activities that took place from the 1940s to the 1970s. The sources of fill material were not documented, and no streams or rivers enter South Basin except for Yosemite Creek, a shallow, tidally influenced channel with no permanent flow. Yosemite Creek is an outlet for a City of San Francisco combined sewer overflow (CSO).

B.1.2.2 Meteorology

During winter in San Francisco Bay, episodic storms typically cause strong southerly winds and local flooding. Winter storms are responsible for approximately 95 percent of the average annual rainfall (54 cm). During summer, persistent northerly to northwesterly winds usually occur, with little to no rainfall.

B.1.2.3 Hydrodynamic Processes

Tides in San Francisco Bay are mixed semidiurnal, with two high and two low tides per day of unequal heights. Tidal amplitudes at spring tide can be as much as twice those at neap tide (Cheng and Gartner, 1985). Circulation in South Basin is restricted and tidal currents are weak. The basin is open to the southeast, which is the direction of the wind during winter storms.

B.1.2.4 Sediment Properties

Subtidal sediments in South Basin consist of uniform clayey silt. Sandy sediments are found along the Parcel E-2 shoreline. TOC content is generally between 1 and 2 percent. The average net sediment accumulation rate determined from radioisotope profiles in three cores collected in South Basin is about 1 cm/yr (Battelle et al., 2005b).

Polychlorinated biphenyls (PCBs) are the primary chemical of concern in South Basin. PCB concentration distributions are described in detail in the *Parcel F FS Data Gaps Technical Memorandum* (Battelle et al., 2005a). PCB concentrations decrease with increasing distance from the Parcel E-2 shoreline; higher concentrations are also found near the mouth of Yosemite Creek (Figure B-2). PCB concentration profiles offshore of the Parcel E-2 shoreline and at the mouth of Yosemite Creek show well-defined subsurface PCB concentration peaks (Figures B-3a and B-3b). Offshore of Parcel E-2, peak subsurface PCB concentrations are found at a depth of approximately 20 to 40 cm below the mudline. Peak subsurface concentrations near the mouth of Yosemite Creek are higher and deeper than those offshore of the Parcel E-2 shoreline. The decrease in PCB concentrations in more recent sediments strongly suggests that the region has experienced net deposition since the largest input of PCBs to the basin.

B.1.3 SEDIMENT TRANSPORT CONCEPTUAL SITE MODEL

Because PCBs tend to adsorb to fine-grained sediment particles and organic matter, sediment transport processes (i.e., resuspension, transport, and deposition) are important contaminant transport pathways in South Basin. A conceptual site model of sediment transport in South Basin is shown in Figure B-4.

Because of its restricted circulation, tidal currents in South Basin are very weak. Waves are likely to be the dominant sediment resuspension mechanism because the basin is shallow and open to the southeast, which is the direction of the prevailing winds during winter storms. The primary source of sediment to the basin appears to be suspended sediment from San Francisco Bay; shoreline erosion may contribute some sediment. The basin appears to be a net depositional environment with a net

accumulation rate of about 1 cm/yr. The dispersal pattern of PCBs, with higher concentrations near shore and decreasing concentrations off shore, is consistent with wave-influenced and tidally influenced sediment transport.

Storm waves breaking along the shoreline suspend fine, low-density sediments in the near-shore region. A return flow near the bottom of the water column (balancing the shoreward flow due to waves at the surface of the water column) transports the sediments away from the shoreline and into South Basin. Tidally induced currents may facilitate additional transport across the mudflats and extend the influence of waves further offshore during low tide, and potentially carry material further offshore into South Basin.

The deposition of cleaner background sediments transported in from San Francisco Bay and deposited in South Basin results in the dilution and burial of the nearshore and offshore sediments. As new sediments are deposited, mixing processes (physical and biological) act to mix surface and subsurface sediments, resulting in the gradual decrease in surface PCB concentrations over time. The smooth vertical PCB profiles in sediment cores (i.e., gradual increase and then decrease in concentration with increasing depth) indicate that overall, the sediment bed in South Basin appears to be relatively stable and undisturbed.

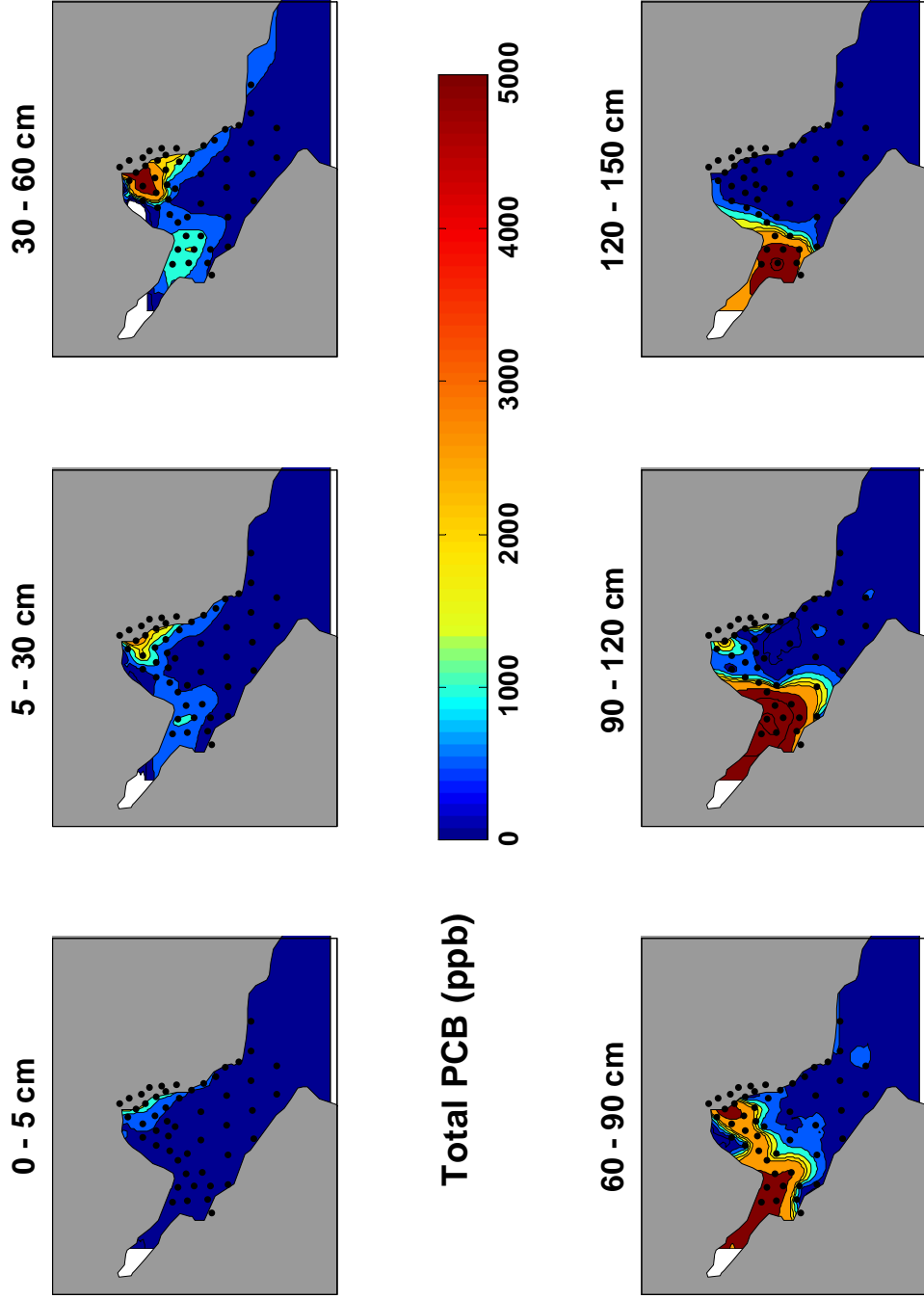


Figure B-2. PCB concentrations in South Basin sediment.

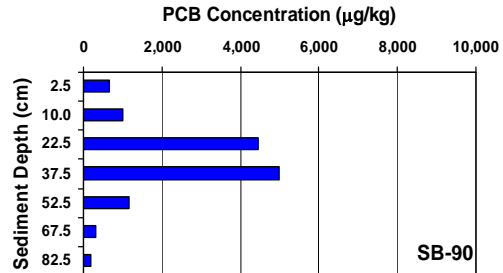
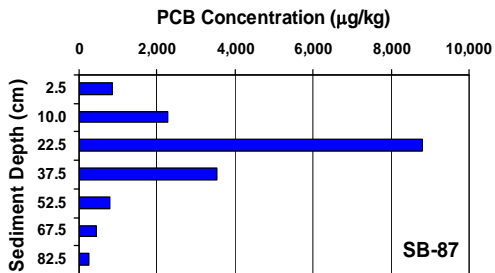
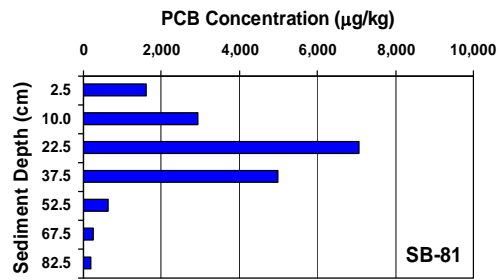
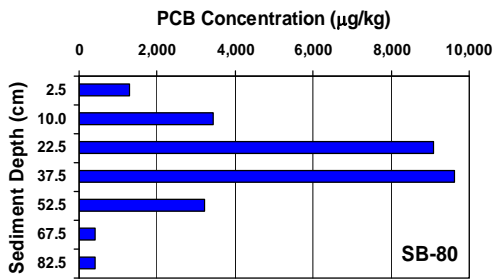


Figure B-3a. PCB concentration profiles offshore of Parcel E-2 shoreline (station locations are shown in Figure B-5).

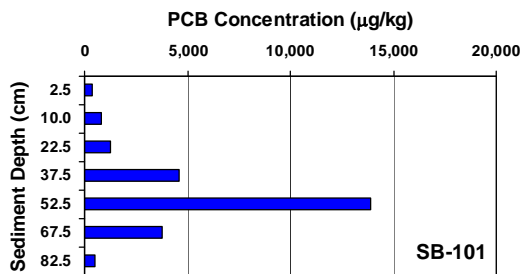
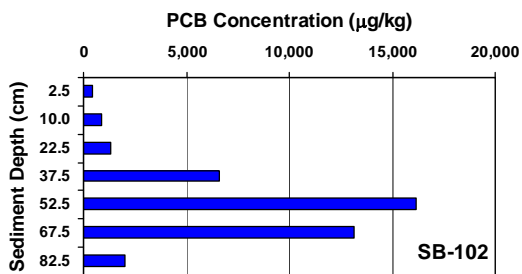
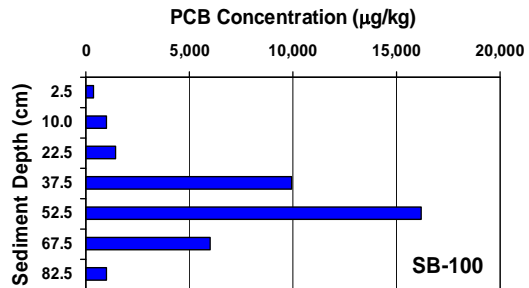
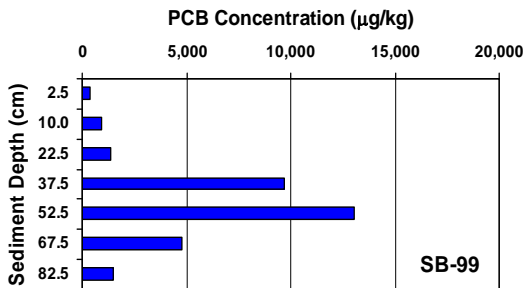


Figure B-3b. PCB concentration profiles at the mouth of Yosemite Creek (station locations are shown in Figure B-5).

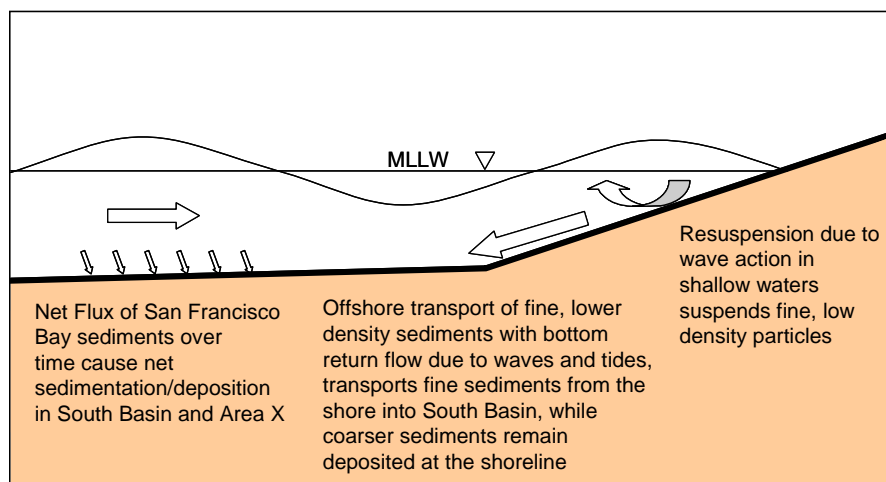


Figure B-4. Sediment transport conceptual site model.

B.2 TIER 2 EVALUATION

The Tier 2 sediment transport study at HPS was designed to fill data gaps associated with completing the Parcel F FS. Specific objectives were to (1) predict the frequency and depth of erosion of the sediment bed under typical and extreme hydrodynamic conditions; (2) characterize the depth of the mixing/biologically active zone; and (3) evaluate whether natural processes will effectively cap PCB-contaminated sediments. The results were used to address the four general sediment management questions posed in Section 3.3 of the Users Guide:

- Could erosion of the bed lead to the exposure of buried contaminants?
- Could sediment transport lead to the redistribution of contaminants within the site or movement of the contaminants off site?
- Will natural processes lead to the burial of contaminated sediment by relatively clean sediment?
- If a site is actively remediated, could sediment transport lead to the recontamination of the site?

Results of the analyses will be used in the Parcel F FS to develop and evaluate remedial alternatives for South Basin sediments.

B.2.1 STUDY DESIGN

The Tier 2 field sampling was conducted in conjunction with the HPS Parcel F FS Data Gaps Investigation and HPS Parcel F Validation Study (Battelle et al., 2005a and 2005b). The scope of the field sampling program is summarized in Table B-1 and described below. Sampling locations for the FS data gaps investigation are shown in Figure B-5.

B.2.1.1 Hydrodynamic Measurements

Two sets of hydrodynamic measurements were collected in 2001 and 2004 in South Basin to characterize currents, waves and suspended sediment concentrations.

B.2.1.1.1 2001 Hydrodynamic Measurements

In 2001, time-series measurements of currents, waves, suspended sediment concentrations, temperature, and salinity were collected at two stations in January–February and July–August using Sediment Transport Measurement Systems (STMS) (Battelle et al., 2005b). The 2001 STMS tripod locations are shown in Figure B-6. The STMS is shown in Figure 4-6 of the Users Guide. The principal objective of the deployments was to characterize seasonal differences in hydrodynamic forces. The STMS data were used to estimate the frequency of sediment resuspension at the two stations during winter and summer. In addition, regional hydrodynamic and sediment transport patterns were characterized using a numerical model.

Table B-1. Summary of Tier 2 sediment transport study field investigation.

Sampling Event	Analysis	Location(s)
STMS tripod deployment: Jan–Feb 2001	Currents, waves, suspended sediment, temperature, conductivity, salinity	~SB120, ~SB110
STMS tripod deployment: Jul–Aug 2001	Currents, waves, suspended sediment, temperature, conductivity, salinity	~SB120, ~SB110
Sediment core collection: October 2003	SEDflume	SB80, SB81, SB89, SB94, SB104, SB110, SB113, SB114, SB118, SB120, SB168
Sediment core collection: October 2003	Radioisotope	SB94, SB110, SB114
T1: Oct–Feb 2004	Sediment traps	SB120, SB110, SB104, SB94
T2: Feb–May 2004	Sediment traps	SB120, SB110, SB104, SB94
	Currents	SB120
	Turbidity	SB120
T3: July–Aug 2004	Sediment traps	SB120, SB110, SB104, SB94
	Currents	SB120, SB110
	Turbidity	SB120, SB110
Sediment profile imaging: Feb 2004	Sediment image Analysis	SB80, SB81, SB89, SB90, SB91, SB94, SB95, SB103, SB104, SB105, SB108, SB109, SB110, SB112, SB113, SB114, SB117, SB118, SB120, SB168
Sediment core collection	Chemical analysis, fine intervals	SB81, SB94, SB110, SB114 (data used in PCB flux model)
Sediment core collection	Chemical analysis	All stations shown in Figure B-5 to support contaminant concentration mapping (Figures B-2 and B-3)

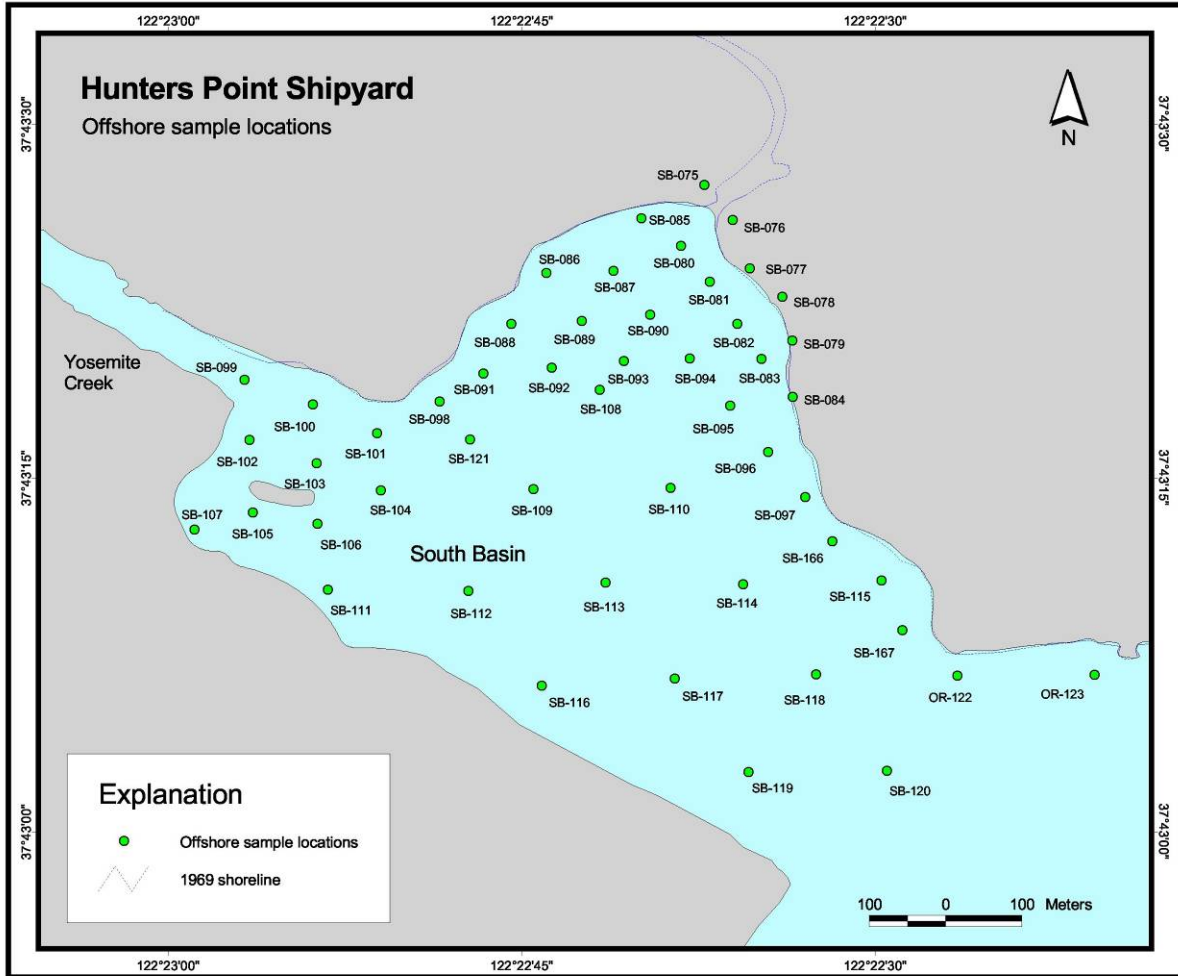


Figure B-5. Parcel F FS Data Gaps Investigation station locations.

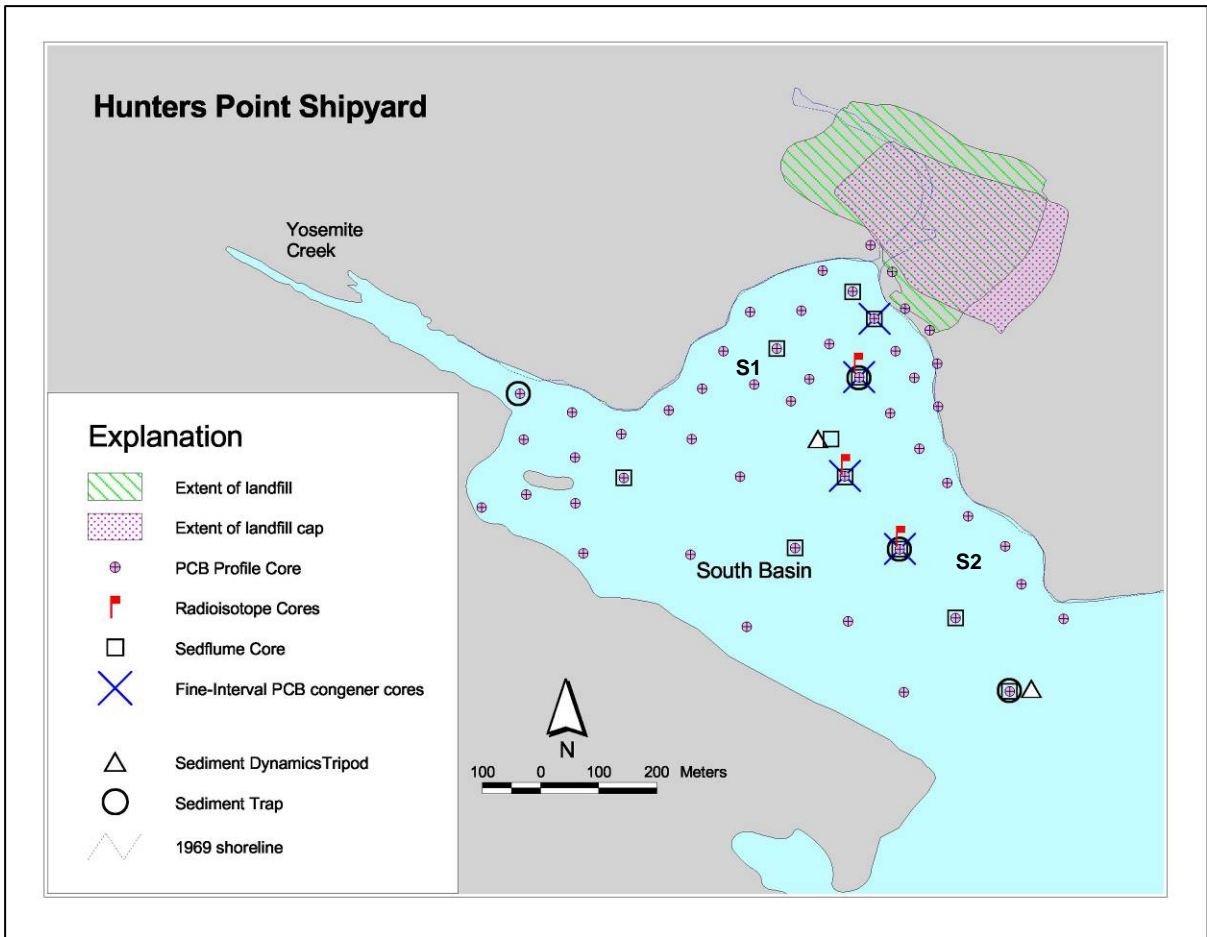


Figure B-6. Parcel F FS Data Gaps Investigation station types.

B.2.1.1.2 2004 Hydrodynamic Measurements

Two instrument deployments were conducted in 2004. The first field event took place in March–April (Spring, T2), and the second event took place in July–August 2004 (Summer, T3). Instrumentation deployed during the 2004 surveys included time-series measurements of currents and suspended sediment concentrations. Near-bottom currents were measured using an InterOcean S4[®] current meter, and turbidity was measured simultaneously using a D&A Instruments OBS[®]-3A. Instruments were deployed at Station SB-120 during the spring and summer deployments, and at Station SB-110 during the summer deployment only, to measure the near-bottom currents responsible for sediment erosion and transport. Figure B-5 shows station locations.

B.2.1.2 SEDflume Cores

SEDflume is a device that is used to estimate erosion properties of sediments. SEDflume has a test section with an open bottom through which a circular cross-section coring tube containing sediment is inserted. Twelve sediment cores, including one replicate, were collected from eleven stations in South Basin and analyzed in a mobile SEDflume laboratory to provide information on

sediment erosion rates. SEDflume core locations are shown in Figure B-6. The SEDflume data were used to characterize erosion rates and sediment stability with depth (i.e., to determine the critical shear stresses needed to cause sediment resuspension). Particle size distribution and bulk density also were determined. This information was used to estimate the potential for resuspension of sediment under typical and extreme hydrodynamic conditions. All cores were successfully analyzed in the SEI SEDflume laboratory using the standard procedures described in McNeil, Talor, and Lick (1996). A diagram of the SEDflume is provided in Figure 4-1 of the Users Guide.

B.2.1.3 Radioisotope Cores

Three sediment cores were subsampled and analyzed for lead-210, cesium-137, beryllium-7, and thorium-234 to provide age data to confirm the previously estimated sediment accumulation rate of approximately 1 cm/yr for South Basin, and provide information on the degree of surface sediment mixing. Radioisotope core locations are shown in Figure B-6.

B.2.1.4 Sediment Traps

Sediment traps were deployed at four locations in South Basin to evaluate the quality of the sediment particles settling on the sediment bed (Figure B-6). Two traps were deployed at each station to ensure data retrieval in the event that one of the traps was unsuccessful (i.e., falls over, colonized by marine organisms). Two sets of sediment traps were collocated with two of the radioisotope profile cores to provide complementary data on the quantity and quality of sediment particles settling on the sediment bed. A third set of sediment traps were deployed at the entrance to South Basin, at the location of the 2001 sediment dynamics tripod location. A fourth set of sediment traps was deployed at the mouth of Yosemite Creek. Sediment traps were deployed for three seasons (November 2003–February 2004, March–April 2004, and July–August 2004) to assess seasonal variability. The traps were constructed of 6-inch, Schedule 40, polyvinyl chloride (PVC) pipe with a trap height of 30 inches (5:1 aspect ratio) and a volume of approximately 14 liters. An example of a sediment trap is shown in Figure 4-8 of the Users Guide.

B.2.1.5 Sediment Profile Imaging

Sediment profile images were obtained at 20 stations in South Basin. The Sediment Profile Imaging (SPI) technology was developed as a rapid reconnaissance tool for characterizing physical, chemical, and biological seafloor processes. Camera penetration depth in South Basin was 8 to 16 cm. A wide variety of physical and biological parameters were measured, including sediment grain size distribution, small-scale boundary roughness, apparent redox potential discontinuity depth (RPD), presence of methane, infaunal successional stage, and biological mixing depth.

B.2.2 TIER 2 RESULTS

Details of the field investigation are provided in the field survey report (Battelle, 2004) and SPI data report (Germano and Associates, Inc., 2004). Results of the Tier 2 data analyses are provided below.

B.2.2.1 Transport

Hydrodynamic data collected in 2001 and 2004 are presented in the following sections.

B.2.2.1.1 2001 Hydrodynamic Data

Hydrodynamic measurements collected in South Basin in 2001 are described in detail in Appendix L of the HPS Parcel F Validation Study Report (Battelle et al., 2005b). Currents and waves at the two stations in South Basin were small at all times, except during winter storms identified by significant wind and rain events in National Weather Service records. Figure B-7 shows water levels, current velocities, suspended sediment concentrations, and wave orbital velocities for Station S1 during the winter.

Bottom stresses due to waves and currents were calculated using the STMS data in a 1-D bottom boundary layer model (Wiberg and Harris, 1994). The results show that the highest bed shear stress (τ_b) occurred at Stations S1 and S2 during the periods of largest waves in winter (Figure B-7). Tidal velocities did not produce significant bed shear stresses during any part of the tidal cycle. During one storm on January 25, 2001, τ_b exceeded 1.0 Pa. The τ_b exceeded the critical shear stress (τ_c) for the sediments (0.28 Pa; see Section B.2.2.2), and likely caused erosion of the sediment bed as evidenced by elevated suspended sediment concentrations. Otherwise, during both winter and summer seasons, wave energy and residual currents were low, and circulation in South Basin was weak. Frequencies of resuspension of bottom sediment during winter and summer (combined) at the two 2001 stations, S1 and S2, were 1 percent and 3 percent of the deployment time, respectively.

The 2001 data suggest that although bottom sediment in South Basin was mobilized by increased wave stresses during storms, no appreciable transport occurred because of the weak currents. Additionally, tidal action did not resuspend a significant amount of sediment. Suspended sediment that entered South Basin during the 2001 deployment periods likely accumulated except during the infrequent, brief but energetic, winter storm events.

B.2.2.1.2 2004 Hydrodynamic Data

Current velocity profiles for Station SB-120 (Spring 2004) and Station SB-110 (Spring and Summer 2004) are presented in Figure B-8. Current velocities were relatively low during each of the deployment periods, with maximum velocities of approximately 15 cm/s at both stations. OBS[®] data show low turbidity during both the spring and summer deployments, with background concentrations ranging from 5 to 10 NTU (Figure B-9). Higher concentrations were seen during storm events, with a maximum of 263 NTU during the spring survey. Increased turbidity

measurements during the summer deployment are suspected of being caused by severe biofouling on the sensor (represented by the dashed line in Figure B-9).

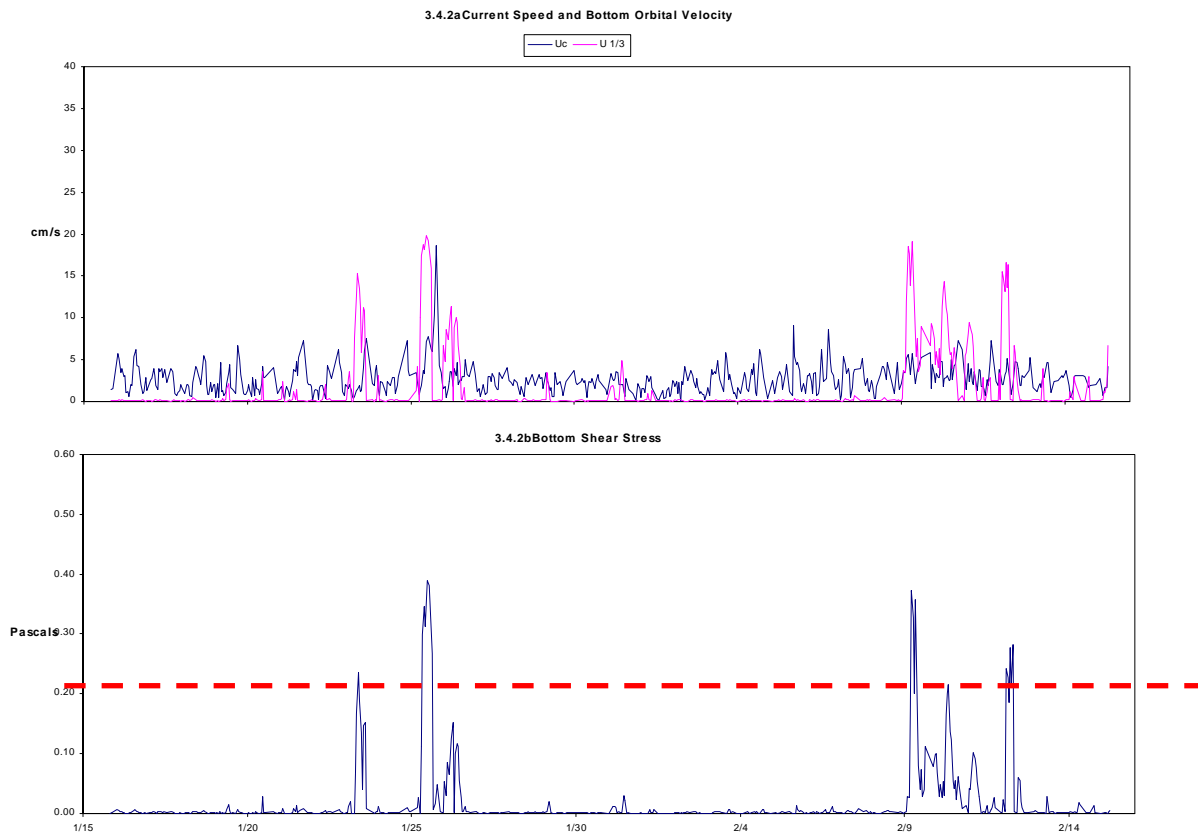


Figure B-7. Station S1, winter current speed, bottom orbital velocity, and bed shear stress. The red dashed line indicated the critical shear stress of 0.28 Pa as measured by the SEDflume.

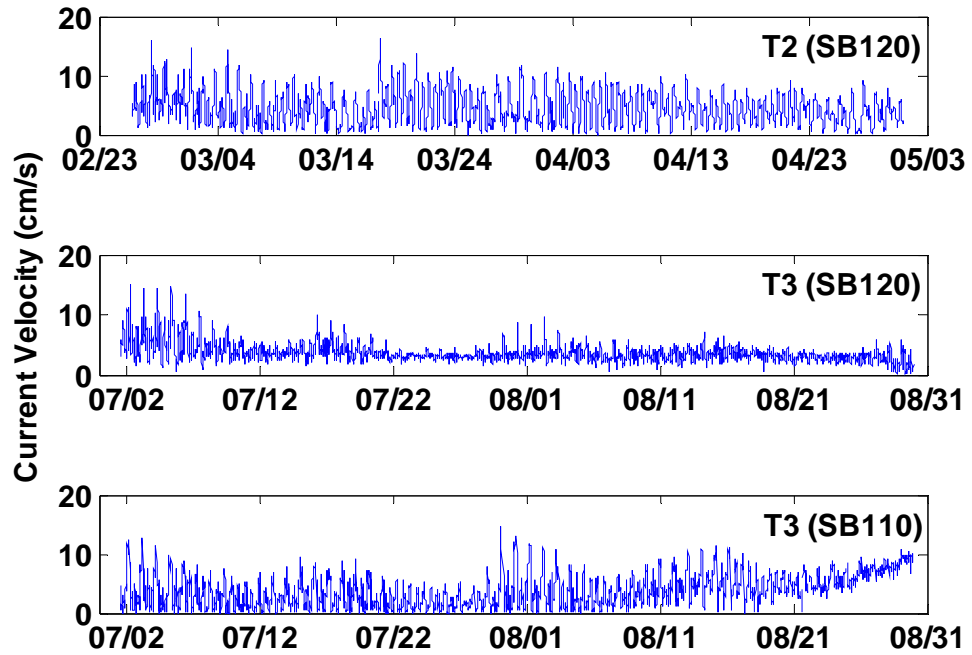


Figure B-8. Current velocities measured in spring (T2) and summer (T3) 2004.

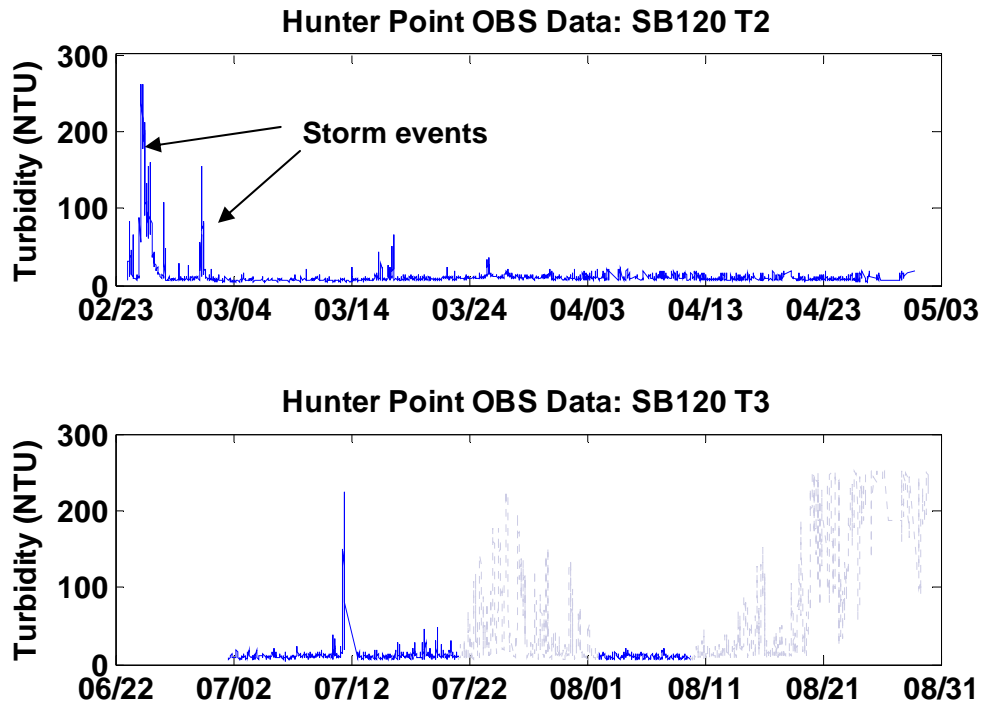


Figure B-9. Turbidity measured in Spring (T2) and Summer (T3) 2004. The dashed lines indicate data where biofouling is suspected to have altered the data.

Bed shear stresses (τ_b) were calculated using the current velocities measured during the survey to determine if erosion of the consolidated bed occurred. The τ_b due to currents was calculated using the formula:

$$\tau_b = \rho_w \cdot c_f \cdot u^2,$$

where ρ_w is the water density (kg/m³), c_f is the coefficient of friction (using an average value of 0.003 [Heathershaw and Simpson, 1978; Sternberg and Lick, 1968]), and u is the near-bed current velocity measured with the current meter. Wave information was not available for the calculation of wave generated component of τ_b . Bed shear stresses due to tidal currents were low during each deployment, ranging from 0 to 0.08 Pa, and never exceeded the critical shear stress for erosion of 0.28 Pa that was measured from the SEDflume analysis (Figure B-10). This implies that shear forces on the bed never reached the threshold for erosion, and that sediment erosion at each of the study sites was not occurring during measurement periods due to tidal action. The data provides additional evidence that wave-generated shear stresses are the only force capable of eroding sediment in South Basin.

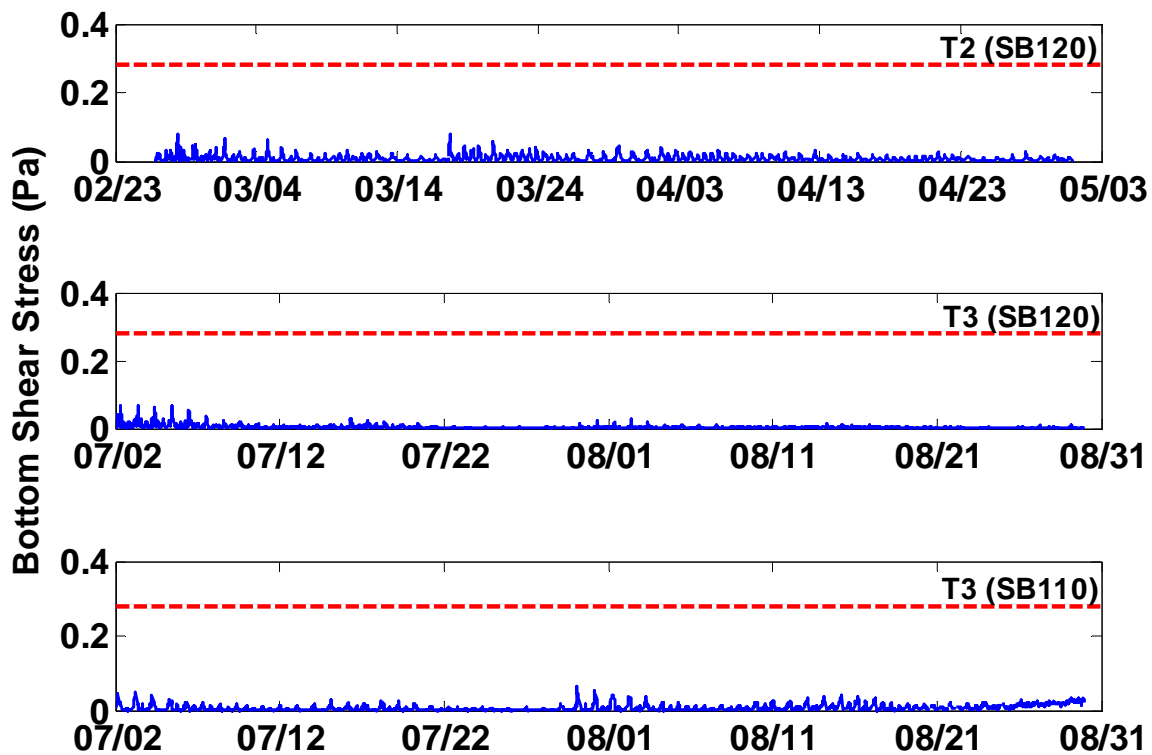


Figure B-10. Bed shear stresses calculated from the current meter data. The red dashed lines indicate the critical shear stress of 0.28 Pa as measured by the SEDflume.

B.2.2.2 Erosion and Resuspension

Sediment erosion and resuspension in South Basin under typical and extreme hydrodynamic conditions are described below. Additional information on methodology is provided in the Parcel F FS Data Gaps Investigation Technical Memorandum (Battelle et al., 2005a).

B.2.2.2.1 SEDflume Data

Figure B-11 shows SEDflume data for Station SB-114. Similar results were obtained for the other South Basin stations. The plot shows erosion rates with increasing shear stress at various depths in the core. Erosion rates increase with increasing shear stress, and show an overall decrease with increasing depth in the core due to sediment consolidation. At the deepest levels in the sediments (30 to 40 cm), stiff clays were encountered that could only be eroded at high shear stresses of 1.6 Pa and over. Many other factors play a role in erosion rate variations and are discussed in more detail in the SEDflume Data Report (SEI, 2004). The SEDflume data provide a quantitative measure of the variability in South Basin sediments as well as providing upper and lower limits to the variation of site wide erosion rates, particle sizes, and bulk density.

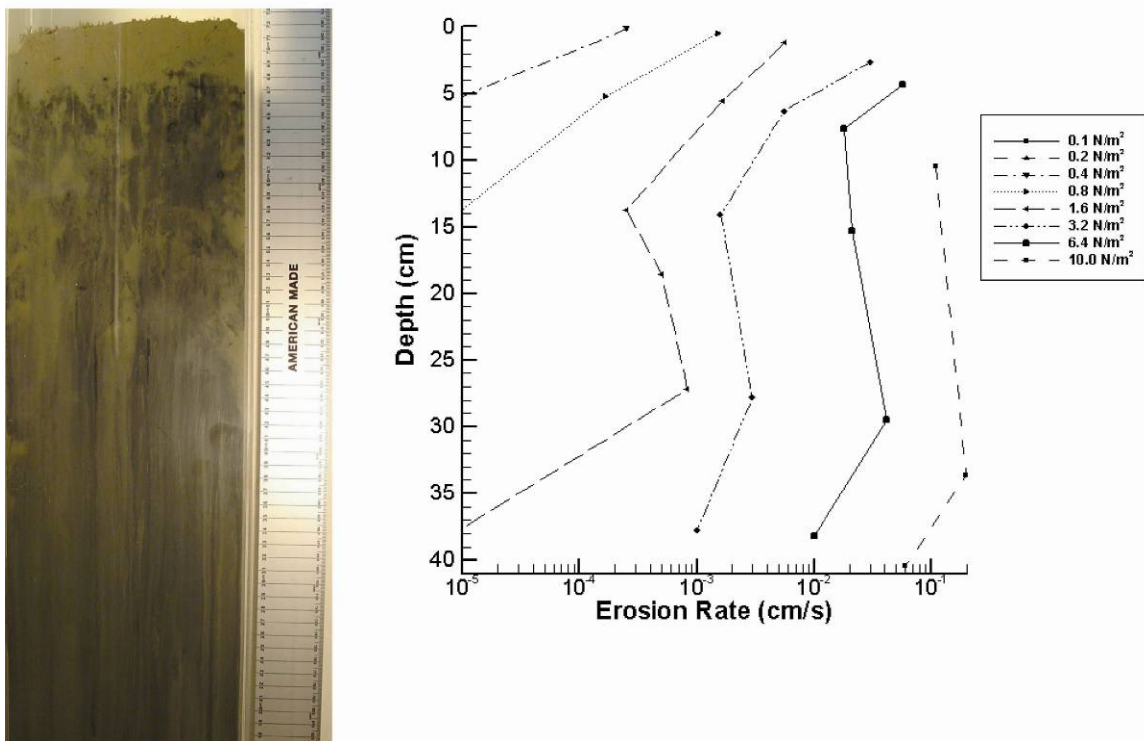


Figure B-11. SEDflume data for Station SB-114.

To evaluate sediment stability, the data for all of the SEDflume cores were combined into 5-cm depth intervals, and the erosion rates were averaged to provide a single dataset that represented typical sediments across South Basin. Figure B-12 is a plot of the depth-averaged erosion rates in 5-cm increments. From these data, the critical shear stress was calculated as a function of depth in the sediments. Figure B-13 shows the critical shear stress as a function of depth based on basin-wide average erosion rates. The critical shear stress shows an overall

increase with depth, until a very stiff layer of sediments denoted by a higher critical shear stress is reached at a depth of 30 to 40 cm.

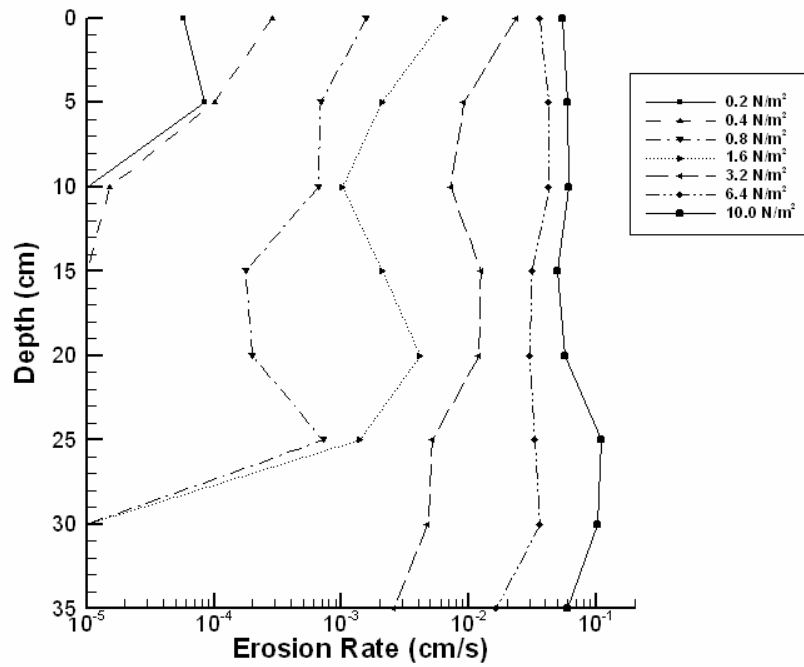


Figure B-12. SEDflume data averaged from 12 South Basin cores in 5-cm depth intervals.

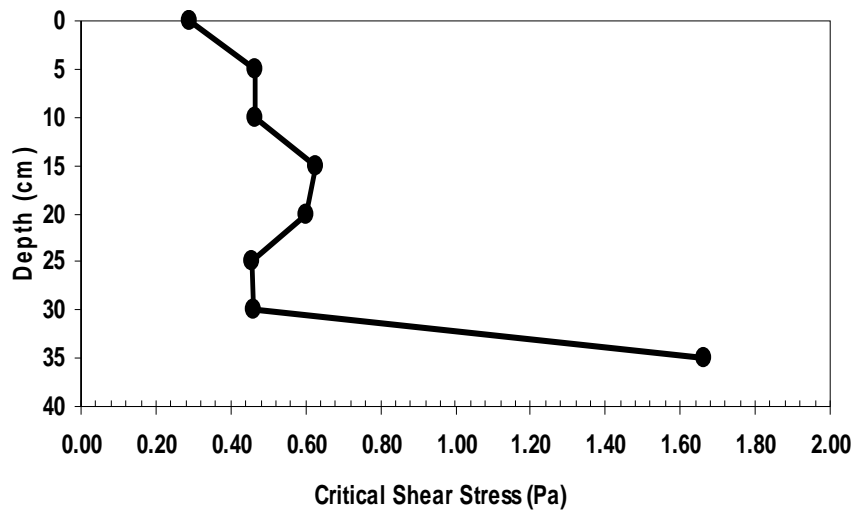


Figure B-13. Critical shear stress as a function of depth for the average South Basin sediments.

B.2.2.2.2 Depth of Erosion Calculations

The predicted depth of sediment erosion during typical and extreme hydrodynamic events was calculated based on the SEDflume data and hydrodynamic measurements described in Section

B.2.1.1. The hydrodynamic data showed that wave events were the only physical force capable of eroding sediments; therefore, the following analysis was performed to characterize the wave events responsible for eroding South Basin sediments.

A nearly 8-year record of continuous wind measurements from National Oceanographic and Atmospheric Administration (NOAA) offshore buoy 46026, located 18 miles west of San Francisco, was obtained and used for an extreme wind event analysis. Using the extreme winds from directions between south and east, the maximum wave height possible in South Basin was calculated (0.91 m). This wave height was used in conjunction with the 2001 hydrodynamics measurements to calculate a maximum sustained bottom shear stress exerted on the South Basin sediments. Table 2 shows the maximum predicted shear stress for events with various return periods. The maximum return period that could be predicted statistically was a 25-year storm. The duration of all extreme events was assumed to be equivalent to the mean event duration of 11.4 hours.

Table B-2. Extreme event analysis with corresponding shear stresses and erosion depths.

Return Period	Shear Stress (Pa)	Duration (hrs)	Maximum Erosion (cm)
1	0.49	11.40	4.2
5	0.57	11.40	5.0
10	0.59	11.40	5.2
25	0.64	11.40	5.7
25	0.64	18.60	6.1

Using the shear stresses, event duration, and measured sediment data, the SEDZLJ model (Jones and Lick, 2000) was used in a simple one-dimensional mode to determine the maximum possible erosion for that event. In the model, the predicted shear stress is applied to the South Basin sediments using erosion rate and critical shear stress information from the SEDflume cores. The model then predicted the maximum depth of erosion under those conditions. During a typical year, up to 4.2 cm of erosion may be expected during a storm event. Potential erosion during the 25-year event was predicted based on the maximum event duration of 18.6 hours. The maximum probable erosion for this event is 6.1 cm. Figure 14 shows erosion depth as a function of time for the 25-year event. The one-dimensional SEDZLJ model only determines maximum scour during discrete storm events; however, the hydrodynamic data indicate that currents in South Basin are weak. Therefore, sediments resuspended by storms are most likely deposited within South Basin.

As described above, the maximum scour depth caused by an annual storm event is about 4 cm. This depth is approximately equivalent to the thickness of the oxidized layer observed in the SEDflume cores and the sediment profile images (Section B.2.2.3). An extreme event, approximated by the 25-year event, is only expected to erode about 6 cm of sediment. Depth of

erosion is also limited by the stiffer clays found at depth. Additionally, the distinct subsurface PCB concentration profile clearly indicates that large sustained transport and erosion events are not present; otherwise, there would be no continuous subsurface PCB concentration peak throughout the site.

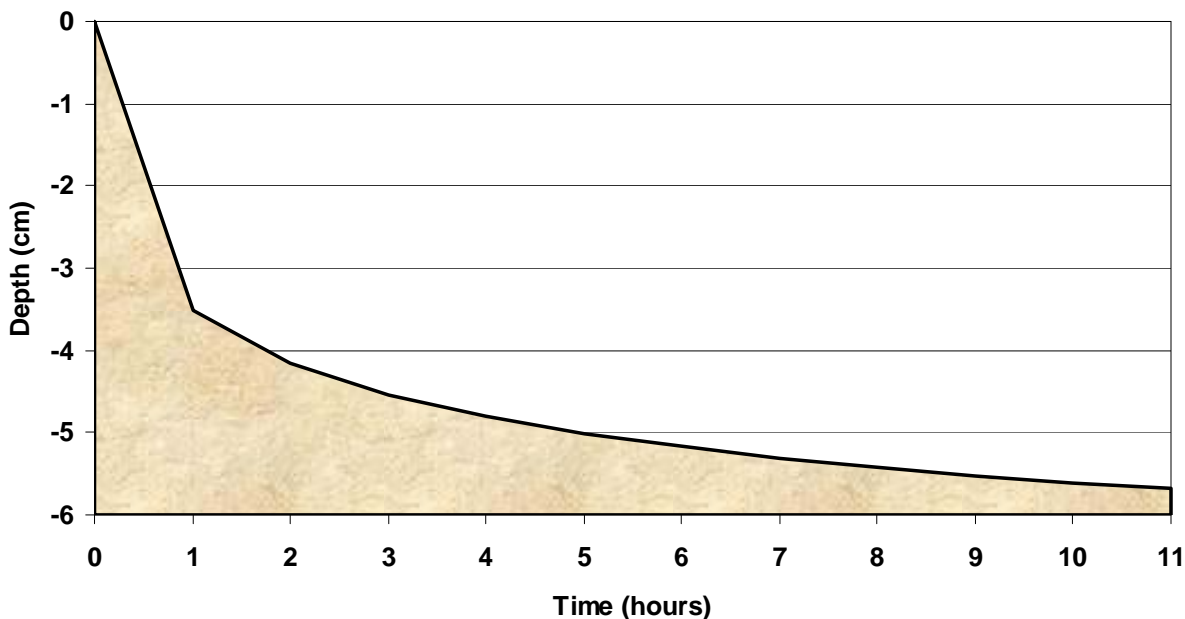


Figure B-14. Depth of erosion as a function of time for the 25-year extreme event.

B.2.2.3 Deposition

B.2.2.3.1 Radioisotope Cores

Radioisotope profile data were obtained for cores from three stations: SB-094, SB-110, and SB-114. Table C-3 summarizes the net sediment accumulation rates based on the first appearance and peak activity of cesium-137, which correspond to approximately 1954 and 1963, respectively. The net sediment accumulation rate also was estimated by analyzing the relationship between excess lead-210 activity (i.e., activity above the supported or background level) and depth in the sediment. These data confirm that the net sediment accumulation rate in much of South Basin is approximately 1 cm/yr. Radioisotope cores previously collected in the vicinity of Yosemite Creek were unsuitable for dating purposes; therefore, the net deposition rate in this area is not known.

The short-lived radioisotope beryllium-7 was not detected in any core. Although thorium-234 was present above detectable concentrations in some core samples, the data were considered as unreliable because the difference between the supported (background) activity and measured activity was relatively small, thereby increasing the uncertainty associated with the determination of excess activity.

B.2.2.3.2 Sediment Traps

Gross sediment accumulation rates for each deployment are shown in Figure B-15. Results of this analysis show that the accumulation rates were seasonally dependent and higher than those calculated from radioisotope data (~ 1 cm/yr), particularly during the winter deployment. Sediment traps capture suspended sediment that advects into South Basin from San Francisco Bay as well as suspended sediment derived from runoff and local resuspension. Because sediment cannot escape the trap once it has entered, the results cannot be used to estimate net sediment accumulation rate. However, the quantity of sediment captured in the trap can be used as an indication of the degree of suspended sediment transport taking place during the given season. These results indicate that the greatest amount of suspended sediment transport occurs in the winter and the least amount occurs during the summer, which is consistent with the suspended sediment concentration data collected in 2001 (Section B.2.1.1).

Table B-3. Estimated net sediment accumulation rates.

Parameter	SB-094		SB-114		SB-110	
	Cs-137 first appearance (range in cm)	38	40	50	55	46
Number of years (2003–1954)	49	49	49	49	49	49
Sedimentation rate (cm/yr)	0.8	0.8	1.0	1.1	0.9	1.0
Cs-137 peak (range in cm)	N/A	N/A	38	44	28	34
Number of years (2003–1963)	40	40	40	40	40	40
Sedimentation rate (cm/yr)	N/A	N/A	1.0	1.1	0.7	0.9
Pb-210 regression R ²	0.78		0.61		0.93	
Pb-210 sedimentation rate (cm/yr)	1.1		1.1		0.9	

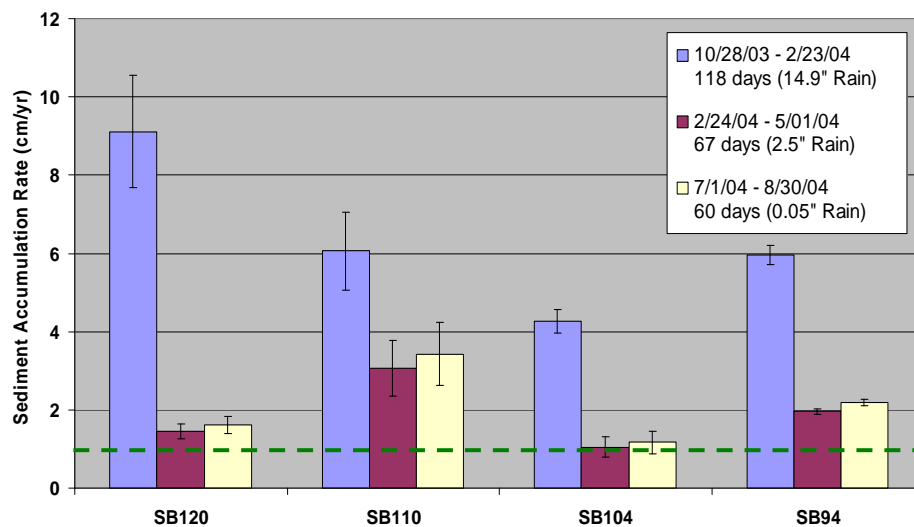


Figure B-15. Gross sediment accumulation rates in sediment traps. The green dotted line represents the net sediment accumulation rate calculated from the radioisotope data.

The total PCB concentrations measured in each sediment trap sample and corresponding surface sediment sample at each station are shown in Figure C-16. In general, total PCB concentrations in bed sediment and trap samples are lower farther out in South Basin (Station SB-120). Otherwise, no clear trends in PCB concentrations are evident in these data, even when potential differences due to TOC content are taken into account. PCB concentrations in the sediment trap samples from the second deployment (Spring 2004) appear to be higher than those from the other deployments. The reason for this apparent increase is not clear.

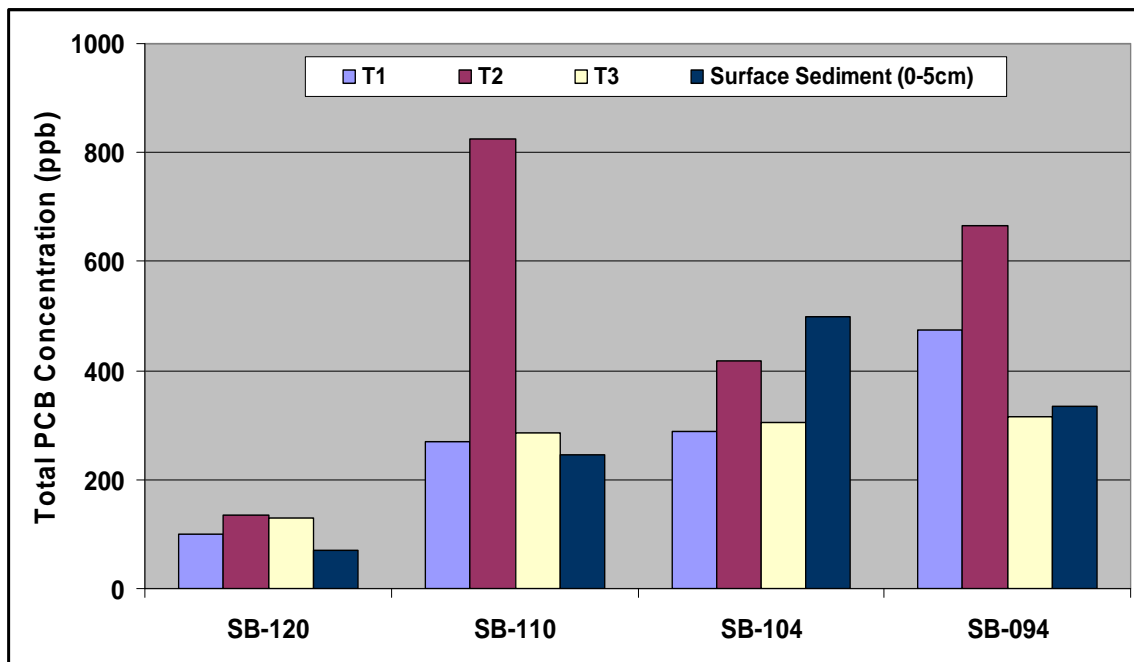


Figure B-16. Total PCB concentrations measured from the sediment trap and surface sediment samples.

B.2.2.3.3 Sediment Profile Imaging

SPI results indicate that the sediments and the biological community in South Basin were extremely homogeneous (Germano and Associates, 2004). Sediments at surveyed stations were all fine-grained muds. Surface boundary roughness ranged from 0.3 to 2.4 cm due primarily to fecal mounds and burrow openings from infaunal activities. No erosional features were seen in any of the images, which were taken in February 2004. The average apparent RPD depth ranged from approximately 2 to 10 cm, indicating active bioturbation by resident infauna. Subsurface sediments at many of the stations had high concentrations of organics and evidence of methane generation.

The infaunal successional stage describes the continuum of change in the benthic community that occurs after a seafloor disturbance, ranging from Stage I communities that initially appear after a disturbance, followed by Stage II and then Stage III assemblages (Germano and Associates, 2004). In South Basin, mature infaunal successional assemblages (i.e., Stage III head-down deposit-feeding taxa) were present at every station. Figure B-17 shows the degree to which

sediments are reworked by the infauna. One variation was the presence of the amphipod *Ampelisca* at about half of the surveyed stations. Despite the relatively shallow water depths, there was no evidence of recent erosion or transport in any of the profile images; most stations showed evidence of a low-energy, stable depositional environment.

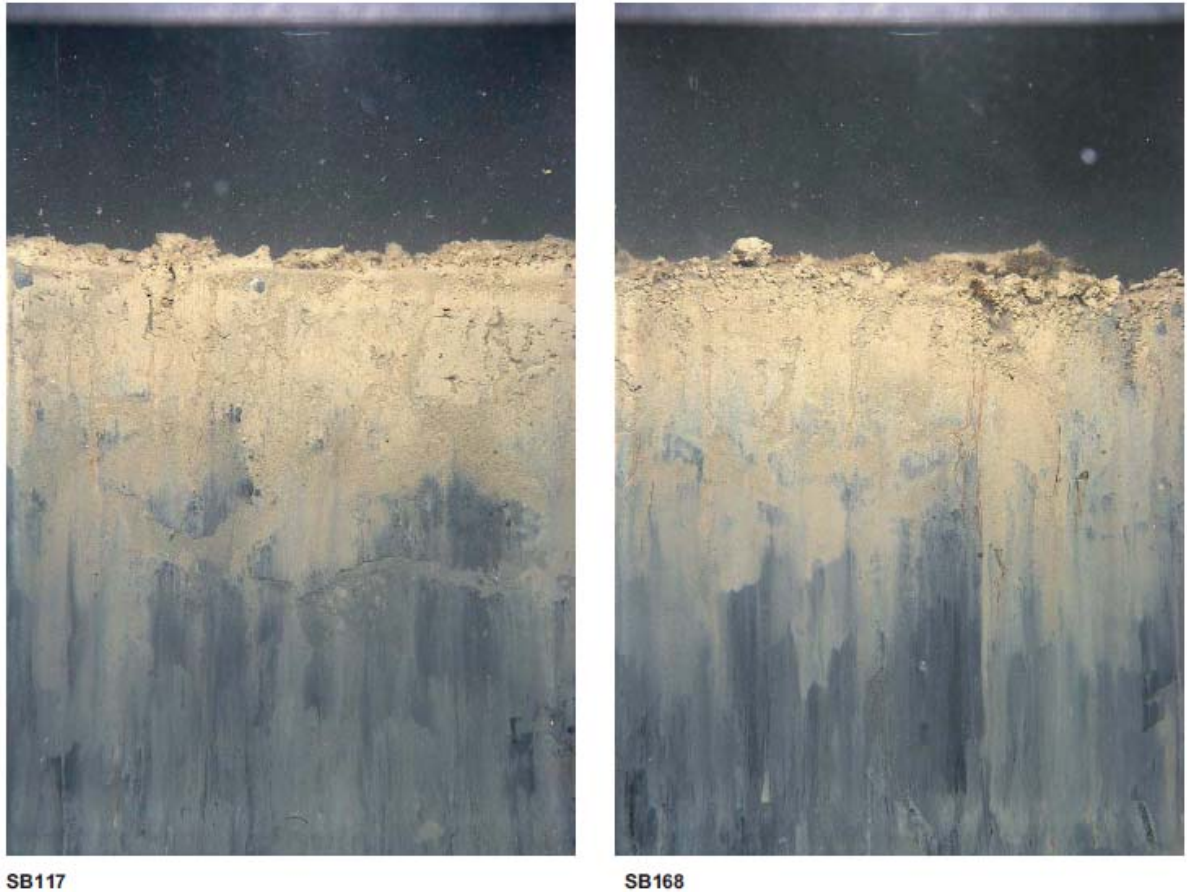


Figure B-17. Deposit-feeding infaunal assemblages in South Basin sediments. Width of each image is 14.2 cm.

B.2.2.4 Numerical Modeling

B.2.2.4.1 Two-Dimensional Hydrodynamic Model

A regional hydrodynamic model was developed to indicate areas of erosion and transport potential based on tidal conditions observed during the 2001 winter and summer deployment, and on a spring tide and wave event. South Basin was specifically studied as a part of the modeling effort. The two-dimensional hydrodynamic model RMA-2 was utilized to simulate the tidal currents in the region (King, 1990). The model application to HPS is detailed in Appendix L of the HPS Parcel F Validation Study Report (Battelle et al., 2005b). Figure 18 shows modeled bed shear stresses due to tidal currents alone during maximum winter ebb conditions. The figure shows bed shear stresses of less than 0.1 Pa in South Basin due to currents alone. These modeled values are consistent with the field measurements. Figure 19

shows the same case with 0.7-m waves from the southeast superimposed. The 0.7-m wave height corresponds to a 1-year storm wave. The combined wave and current shear stress values range up to 0.7 Pa, which is consistent with measurements during winter storm events.

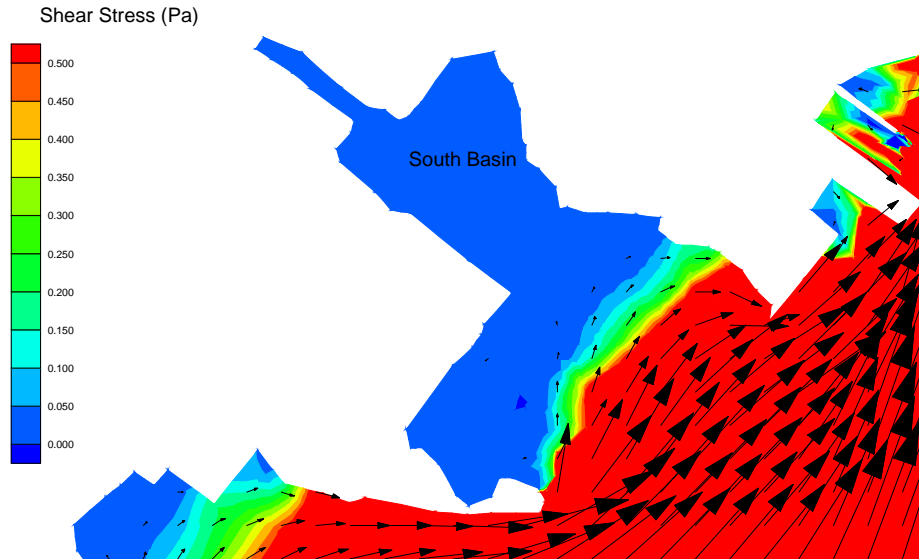


Figure B-18. Maximum winter ebb tide bed shear stress and velocity vectors (7 February 2001). Bed shear stress is due to currents only.

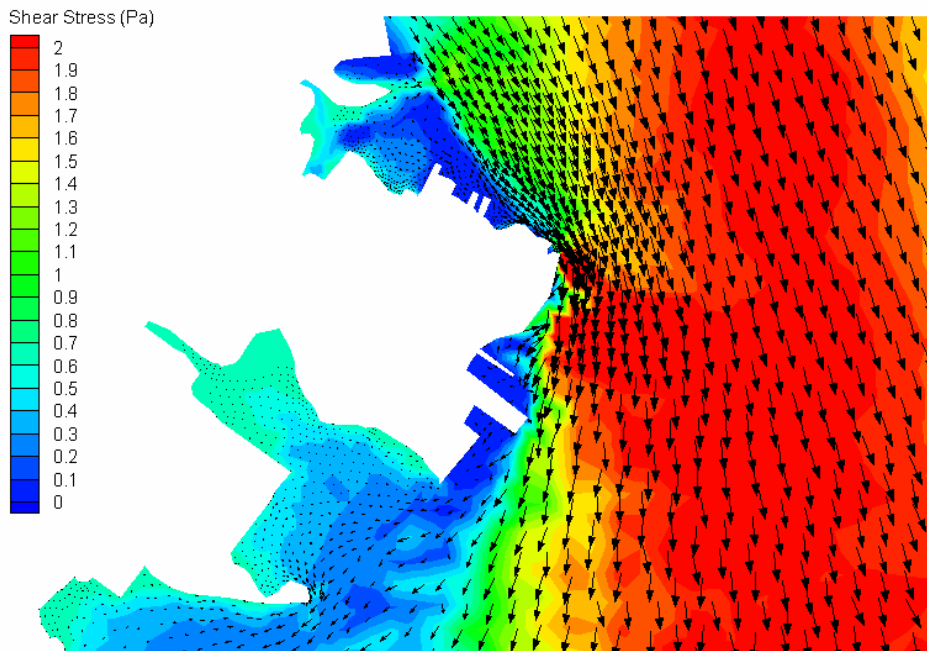


Figure B-19. Maximum winter ebb tide shear stress and velocity vectors (7 February 2001). Shear stress is due to waves and currents.

The modeling effort provides additional verification that the tidal currents throughout South Basin produce only negligible shear stresses, even during spring tides. These low shear stresses provide ideal depositional conditions for sediments entering South Basin. The model additionally verifies that waves must be present to exceed the critical shear stress of sediments (0.28 Pa). Due to the configuration and orientation of South Basin, waves must be approaching from between south and east to impact the Parcel E-2 shoreline with any significant energy. The strong southerly winds required to generate these waves occur during infrequent winter storms.

B.2.2.4.2 PCB Flux Modeling

As part of the HPS Parcel F FS data gaps investigation, a PCB flux model was developed to estimate the flux of dissolved-phase PCBs from the sediment bed into the water column under non-resuspending conditions caused by active and passive mechanisms (e.g., bioturbation, diffusion, and porewater advection). The following information was required to model the flux of PCBs in the sediment bed:

- Net deposition rate based on radioisotope core data
- Initial PCB concentrations based on sediment sampling data
- Sediment-water PCB partition coefficients
- Rates and depths of sediment mixing due to physical and biological mechanisms
- Total organic carbon content from sediment chemistry data.

Details of model development are provided in the Parcel F FS Data Gaps Technical Memorandum (Battelle et al., 2005a). A net deposition rate of 0.5 cm/yr was used in the model as a conservative estimate of future deposition. Sediment mixing due to physical and biological mechanisms was assumed to be at a maximum at the surface, and then to decay logarithmically with a 10-cm length scale. Detailed data on the vertical distribution of PCBs in sediment cores were used to estimate vertical PCB gradients and calculate the PCB flux through the sediment bed and into the water column over time in six areas of South Basin (Figure B-20). The PCB flux model was then used to predict the change in PCB concentrations throughout the sediment bed over time.

Fine-interval core samples were obtained from four stations (SB-081, SB-094, SB-110, and SB-114) and analyzed for PCB congeners. A contaminant flux model developed by Lick, Jones, and Lick (2003) was used to estimate the transport of dissolved-phase PCBs in South Basin sediments over time due to diffusion, bioturbation, and advection. PCB concentrations in bed sediment were simulated for a 100-year period in the absence of any active remediation. Figure B-21 shows an example of the predicted profiles over time at Station SB-094. The burial of the PCB peak is predominantly due to sediment deposition; therefore, accurate measurement of net deposition rate is critical to developing this analysis. Figure B-22 shows a summary of the average surface PCB concentrations for all six areas. The surface concentrations are averaged over the top 10 cm of the sediment bed in order to represent the PCBs that are readily bioavailable. This depth represents the depth above which the majority of bioturbation in South Basin was observed. These types of plots can be used to evaluate the potential effectiveness of monitored natural recovery for achieving remedial goals.

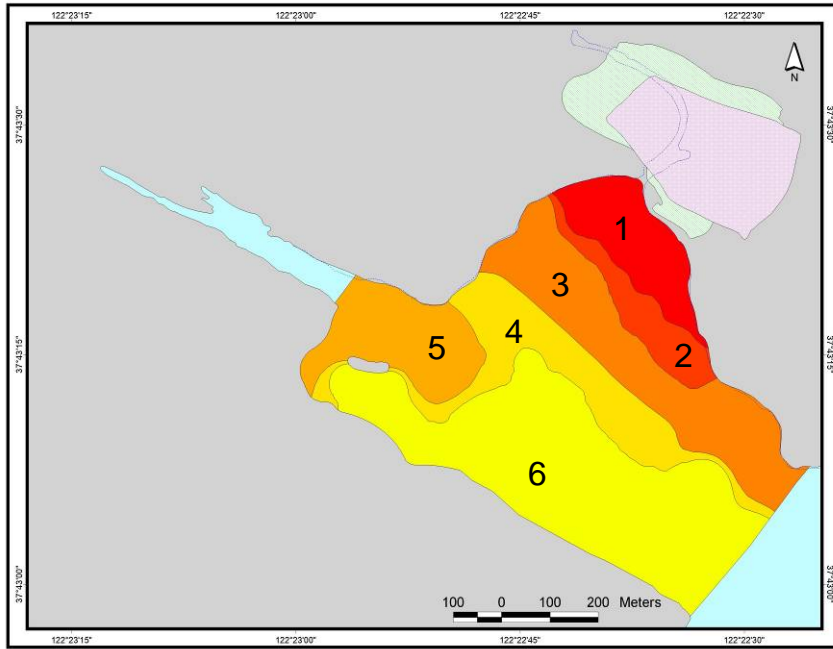


Figure B-20. Six regions used in PCB flux modeling.

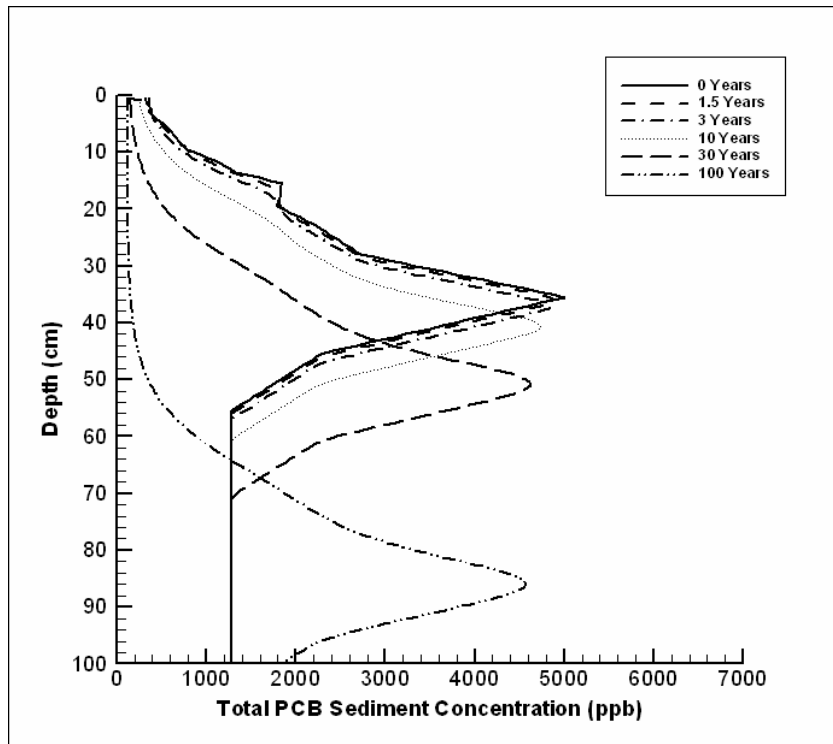


Figure B-21. PCB concentration profile over time for Station SB-094.

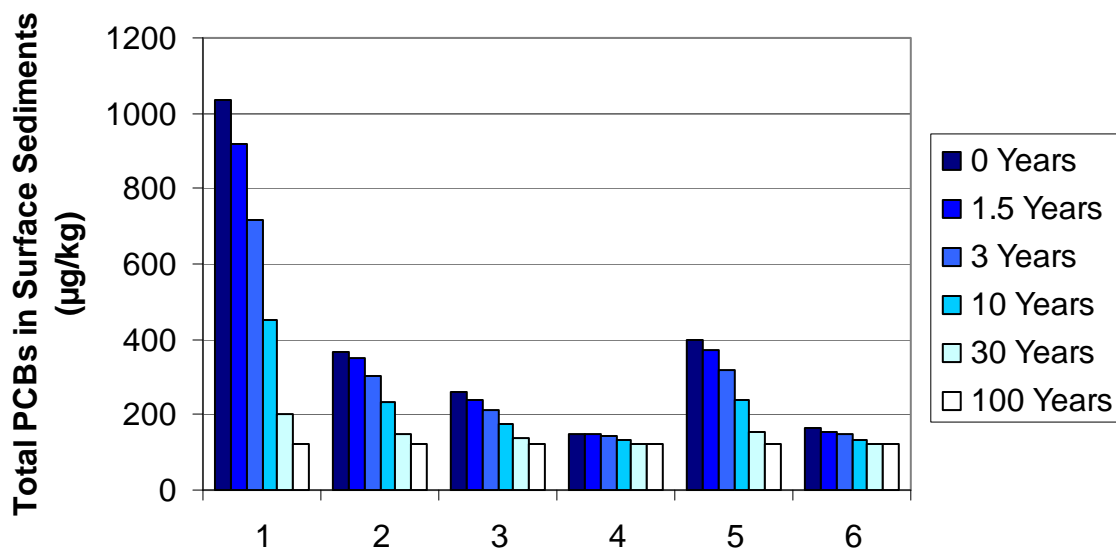


Figure B-22. Surface PCB concentrations over time for each of the six areas.

B.2.3 TIER 2 CONCLUSIONS AND RECOMMENDATIONS

B.2.3.1 Refined Sediment Transport Conceptual Site Model

The Tier 2 sediment transport evaluation confirmed the sediment transport conceptual site model presented in Section B.1.3, and provided data for quantification of sediment transport processes. The site-specific, quantitative data allowed development of a simple model for predicting future contaminant distribution in response to natural recovery processes.

Overall, the sediment bed in South Basin appears to be relatively stable. Hydrodynamic measurements confirmed that tidal currents in South Basin are relatively weak and incapable of eroding bed sediments. Wave activity can resuspend sediments, particularly during winter storms. The maximum depth of erosion is estimated to be 4 cm in a typical year, and 6 cm in a 25-year storm. However, little transport occurs because of the weak tidal circulation. Little evidence of past erosion is apparent in sediment cores or SPI photographs.

The net sediment accumulation rate in much of South Basin is about 1 cm/yr. Biological activity mixes the newly deposited surface sediment into the sediment bed. Most biological activity takes place in the upper 10 cm of sediment, with decreasing biological activity with increasing depth below 10 cm. The mixing of surface and subsurface sediments via bioturbation tends to produce a smooth PCB profile (i.e., gradually increasing concentrations with increasing depth in the sediment to a subsurface peak, and a gradual decrease in concentration below the peak). Head-down deposit feeding worms are found to a depth of 20 to 30 cm.

B.2.3.2 Sediment Management Questions

The results of the Tier 2 analyses were used to address key questions that influence the development of remedial alternatives for South Basin sediments.

B.2.3.2.1 Could Erosion of the Sediment Bed Lead to Exposure of Buried Contamination?

Sediment stability predictions indicate that up to 6 cm would be eroded in a 25-year storm. Additionally, a stiff clay layer is encountered in South Basin at a depth of 30 to 40 cm, which corresponds to the maximum depth of deposit-feeding worms. This stiff clay layer is expected to be resistant to erosion even under very high shear stress conditions. PCB concentrations in subsurface sediment increase with increasing depth to a subsurface peak between 20 and 40 cm near Parcel E-2 and 30 and 60 cm near Yosemite Creek. PCB contamination within the top 5 to 10 cm of sediment could be exposed due to erosion. There is less chance of exposure of sediments between 10 and 30 cm, and it is highly unlikely that erosion would expose sediments below 30 cm.

B.2.3.2.2 Could Sediment Transport Lead to the Redistribution of Contamination within the Site, or Movement of Contamination Offsite?

The sediment stability evaluation showed the potential for up to 6 cm of erosion in the surface sediments due to waves. Contaminated sediments in nearshore regions have the potential to be distributed to deeper regions outside the influence of waves. The decreasing horizontal PCB concentration gradient in an offshore direction in South Basin indicates that offshore transport is occurring. However, once these sediments reach the deeper water outside the influence of waves, tidal currents are insufficient to transport the contaminants offsite.

B.2.3.2.3 Will Natural Processes Lead to the Burial of Contaminated Sediment by Relatively Clean Sediment?

The PCB concentration profiles described in Section B.1.2.4 show a distinct peak in the subsurface, with progressively decreasing concentrations towards the surface. These profiles indicate that the most highly contaminated sediments are being progressively buried throughout South Basin. Radioisotope data confirm that the net sediment accumulation rate in South Basin is approximately 1 cm/yr, although it may be higher near the mouth of Yosemite Creek. Regions above MLLW are only submerged a portion of the time, which may reduce gross sediment deposition, although it will also reduce erosion caused by wave activity. Therefore, net deposition is likely to be comparable in the near-shore and off-shore areas.

B.2.3.2.4 If a Site is Actively Remediated, Could Sediment Transport Lead to the Recontamination of the Site?

Various factors could influence the potential recontamination of a remediated site due to sediment transport. Some of these factors are as follows:

- **Uncontrolled sources of contamination.** PCBs in South Basin appear to be primarily caused by historical releases in two areas: the Parcel E-2 shoreline, and Yosemite Creek. Contaminated sediments in shallow near-shore areas can be resuspended by waves and transported off-shore. If sources in either area are not controlled prior to remediation, then recontamination caused by sediment transport is possible.

- **Off-site sources of contamination.** Suspended sediments are advected into South Basin from San Francisco Bay and deposited on the sediment bed. If PCB concentrations in the incoming suspended sediments have increased for any reason, then recontamination of remediated areas in South Basin is possible.
- **Remedy implementation.** Resuspension and transport of contaminated sediment could occur during remedy implementation (e.g., resuspended sediment from dredging or cap placement; dredging residuals). These factors would be addressed in the remedial design to minimize recontamination potential.
- **Changing hydrodynamic conditions.** Potential changes in hydrodynamic conditions (e.g., increased current speeds caused by increased water depth) associated with the remedial design or future use of South Basin should be evaluated to ensure that bed shear stresses would not be sufficient to remobilize any buried contaminants that are left in place as part of the remedy.
- **Anthropogenic activities.** Dredging, propeller wash, and marine construction activities could remobilize buried contaminants that are left in place as part of a remedy. These factors could be controlled through institutional controls.

The FS should consider these scenarios as appropriate given the remedial alternatives under consideration.

B.2.3.3 Major Data Gaps and Uncertainties

Sediment transport in South Basin has been well characterized using multiple lines of evidence that provide consistent results. Several data gaps remain, although the existing data are expected to be sufficient for completing the Parcel F FS and remedial design. The potential effects of extreme event storms with a return period of greater than 25 years could not be predicted using the data and methods employed in this study. However, uncertainty associated with scour estimates can be taken into account when developing remedial alternatives. Although bioturbation can vary spatially and temporally, the SPI survey was conducted in one season only. However, the infaunal assemblage observed was classified as mature and stable, and significant seasonal variations are unlikely. The net sediment deposition rate near the mouth of Yosemite Creek is not known. This parameter is important for accurately predicting the rate of natural recovery; however, applying a rate of 1 cm/yr or less is likely to be a conservative estimate for the purposes of remedial planning.

B.3 REFERENCES

- Battelle. 2004. "Field Survey Report, Hunters Point Shipyard Parcel F Feasibility Study Data Gaps Investigation, San Francisco Bay, CA." February.
- Battelle, Blasland Bouck & Lee, and Neptune & Company. 2005. "Final Hunters Point Shipyard Parcel F Validation Study, San Francisco Bay, CA." May.
- Battelle, Neptune & Company, and Sea Engineering, Inc. 2005. Draft Technical Memorandum, Hunters Point Shipyard Parcel F Feasibility Study Data Gaps Investigation, San Francisco Bay, CA." February 25.
- Battelle and Woods Hole Group. 2000. "Sediment Resuspension at Hunters Point Shipyard, San Francisco Bay." Draft Technical Memorandum. March 17.
- Cheng, R.T. and J.W. Gartner. 1985. "Harmonic Analysis of Tides and Tidal Currents in South San Francisco Bay, California," *Estuarine, Coastal and Shelf Science*, 21, 57–74.
- Germano and Associates, Inc. 2004. "Sediment Profile Imaging Report: Benthic Macrofaunal Activity at Hunters Point, San Francisco Bay." June.
- Heathershaw, A. D. and J. H. Simpson. 1978. "The Sampling Variability of the Reynolds Stress and its Relation to Boundary Shear Stress and Drag Coefficient Measurements," *Estuarine and Coastal Marine Science*, 6: 263–274.
- Jones, C., and W. Lick. 2000. "Effects of Bed Coarsening on Sediment Transport," *Estuarine and Coastal Modeling*, 6: 915–930.
- King, I. P. 1990. "Program Documentation—RMA2—A Two Dimensional Finite Element Model for Flow in Estuaries and Streams." Resource Management Associates, Lafayette, CA.
- Lick, W., C. Jones, and J. Lick. 2003. "Effects of Finite Sorption Rates on Sediment-Water Fluxes Hydrophobic Organic Chemicals." *Estuarine and Coastal Monitoring VIII*.
- McNeil, J., C. Taylor, and W. Lick. 1996. "Measurements of Erosion of Undisturbed Bottom Sediments with Depth," *Journal of Hydraulic Engineering*, 122(6):316–324.
- Sea Engineering Inc. (SEI). 2004. "Data Report for SEDflume Analysis." Hunters Point Shipyard Parcel F Feasibility Study Data Gaps Investigation. December.
- Sternberg, R. and W. Lick. 1968. "Friction Factor in Tidal Channels with Differing Bed Roughness." *Marine Geology*, 6: 243–260.
- Wiberg, P. L. and C. K. Harris. 1994. "Ripple Geometry in Wave-Dominated Environments," *Journal of Geophysical Research*, 99: 775–789.

APPENDIX C

BREMERTON NAVAL COMPLEX OPERABLE UNIT B MARINE

CONTENTS

C.1 BACKGROUND	C-5
C.1.1 PROJECT HISTORY.....	C-5
C.1.2 SITE DESCRIPTION.....	C-8
C.1.2.1 Topography and Bathymetry	C-8
C.1.2.2 Meteorology.....	C-8
C.1.2.3 Hydrodynamic Processes.....	C-8
C.1.2.4 Sediment Properties.....	C-10
C.1.3 SEDIMENT TRANSPORT CONCEPTUAL SITE MODEL	C-10
C.2 TIER 1 EVALUATION	C-13
C.2.1 TIER 1 RESULTS.....	C-13
C.2.1.1 Erosion and Resuspension	C-13
C.2.1.2 Transport.....	C-15
C.2.1.3 Deposition	C-15
C.2.2 TIER 1 CONCLUSIONS AND RECOMMENDATIONS	C-17
C.3 TIER 2 EVALUATION	C-19
C.3.1 STUDY DESIGN	C-19
C.3.2 TIER 2 RESULTS.....	C-20
C.3.2.1 Transport.....	C-20
C.3.2.2 Erosion and Resuspension	C-20
C.3.2.3 Deposition	C-28
C.3.3 TIER 2 CONCLUSIONS AND RECOMMENDATIONS	C-29
C.3.3.1 Refined Sediment Transport Conceptual Site Model	C-29
C.3.3.2 Sediment Management Questions	C-29
C.3.3.3 Major Data Gaps and Uncertainties	C-31
C.4 REFERENCES	C-33
C.5 ATTACHMENT—TIER 1 FLUX CALCULATIONS	C-35
C.5.1 ATTACHMENT REFERENCES	C-37

Figures

C-1. Site location map.....	C-6
C-2. OUB Marine remedy components and sediment transport study sample locations.....	C-7
C-3. Bathymetry of Sinclair Inlet based on surface mapping survey data (m, MLLW). Source data: Katz et al., 1999.....	C-9
C-4. Preliminary conceptual model of sediment transport for Sinclair Inlet	C-12
C-5. Locations of USGS measurements, RI radioisotope cores, and ENVVEST Radioisotope cores	C-14
C-6. Sources (blue) and sinks (red) of sediment in Sinclair Inlet	C-16
C-7. Current speeds at each sampling station measured with an electromagnetic current meter.....	C-21
C-8. Turbidity measurements at each station, as measured with an OBS [®] . No data were retrieved at Station SI-03 and the dataset at SI-04 did not span the entire deployment period. Increased values at SI-01 and SI-02 were the result of biofouling on the optical sensor.	C-21

C-9. Bed shear stresses (blue line) are well below the critical shear stress values (red-dashed line) that were measured at each station using SEDflume C-22

C-10. Plot of bottom velocity from propeller wash, N = 50 RPM with field measurements C-25

C-11. Plot of bottom velocity from propeller wash, N = 100 RPM with field measurements ... C-25

C-12. Plot of bottom velocity from propeller wash, N = 150 RPM with field measurements ... C-26

Tables

C-1. Parameters for estimating sediment erosion..... C-13

C-2. Critical shear stress values from SEDflume analysis and maximum calculated bed shear stress values for each sampling station C-22

C-3. Physical parameters required C-24

C-4. S4 current meter locations C-24

C-5. Average erosion rates (cm/s) as a function of shear stress and depth for core locations in BNC piers..... C-27

C-6. Propeller wash velocities and resulting scour depths after 30 minutes as Station SI-03 C-27

C-7. Propeller wash velocities and resulting scour depths after 30 minutes as Station SI-04 C-28

C-8. Summary of sediment trap and sediment bed sample results C-29

C.1 BACKGROUND

Naval Facilities Northwest (NAVFAC NW) coordinated a study to evaluate the transport of sediment-bound contaminants at the Bremerton Naval Complex (BNC) in Bremerton, Washington, in conjunction with the regulatory program for Operable Unit (OU) B Marine. A remedial action in OU B Marine was performed in 2000–2001, and long-term monitoring data collected in 2003 and 2005 indicate that remedial goals are unlikely to be met. NAVFAC NW requested a Tier 1 and Tier 2 evaluation of sediment transport at BNC, following the methodology presented in the User's Guide for Assessing Sediment Transport at Navy Facilities (June 2004). The results of the Tier 1 and Tier 2 sediment transport evaluations and the implications for additional remedial planning are presented in this site demonstration report.

C.1.1 PROJECT HISTORY

BNC is located on the northeast shore of Sinclair Inlet in Puget Sound (Figure 1). BNC comprises the Puget Sound Naval Shipyard (PSNS) and Naval Station Bremerton. PSNS provides vessel overhaul, maintenance, conversion, refueling, defueling, and repair services. Naval Station Bremerton is a deep draft home port for aircraft carriers and supply ships. Historical waste disposal practices associated with shipyard operations led to the contamination of sediments in Sinclair Inlet. Inputs from other point and non-point sources such as regional stormwater runoff and sewage treatment plant discharges also contribute to chemical contamination in sediments. The marine portion of BNC is referred to as OU B Marine. OU B Marine includes approximately 230 acres of subtidal land within Sinclair Inlet and extends up to 460 m (1,500 ft) offshore of the terrestrial portions of the BNC to depths of approximately 12 m (40 ft) below mean lower low water (MLLW) (Figure C-1).

The remedial investigation/feasibility study (RI/FS) of OU B Marine identified the presence of polychlorinated biphenyls (PCBs), mercury, and other chemicals at concentrations exceeding Washington State sediment quality standards in approximately the top 2 feet of sediment (URS, 1999a and 1999b). The remedial action objectives (RAOs) for OU B Marine are as follows:

- Reduce the concentration of PCBs in sediments below the minimum cleanup level (MCUL) of 3 mg per kg organic carbon (mg/kg OC) in the biologically active zone (0 to 10 cm) as a measure expected to reduce PCB concentrations in fish tissue.
- Control shoreline erosion of contaminated fill material at adjacent Site 1.
- Selectively remove sediment with high concentrations of mercury that were collocated with PCB-contaminated sediment.

A two-phase remedial action was conducted at OU B Marine in 2000–2001 to remove or contain sediments contaminated with PCBs and mercury. The first phase involved a combination of dredging and capping in areas of highest PCB concentrations. Navigational dredging in other parts of BNC also was performed. Dredged material was placed in an onsite confined aquatic disposal (CAD) pit. The second phase of the remedy relies on monitored natural recovery. Natural recovery modeling conducted prior to the remedial action indicated that area-weighted average total PCB concentrations in OU B Marine sediments would decrease to below the MCUL of 3 mg/kg OC within 10 years (2014) due to the natural deposition of clean sediment (URS, 2000). However, long-term monitoring data collected in 2003 and 2005 indicated that sediment PCB concentrations in dredged areas were higher than expected, and that OU B Marine sediments were not recovering as predicted. Figure C-2 shows the components of the OU B Marine remedy, including the sediment transport study locations.

The overall objective of the Tier 1 and Tier 2 sediment transport study at OU B Marine was to evaluate whether the transport of sediments from adjacent unremediated or offsite areas may be responsible for the higher concentrations observed in the dredged areas. Other questions to be addressed by the site demonstration are as follows:

- Is the conceptual site model of localized sediment transport that was used as the basis for the OU B Marine remedy accurate?
- Can the input parameters used in the natural recovery model be validated or refined to increase confidence in the model results?
- How do sediment transport patterns guide the determination of what, if any, additional remedial actions are necessary?

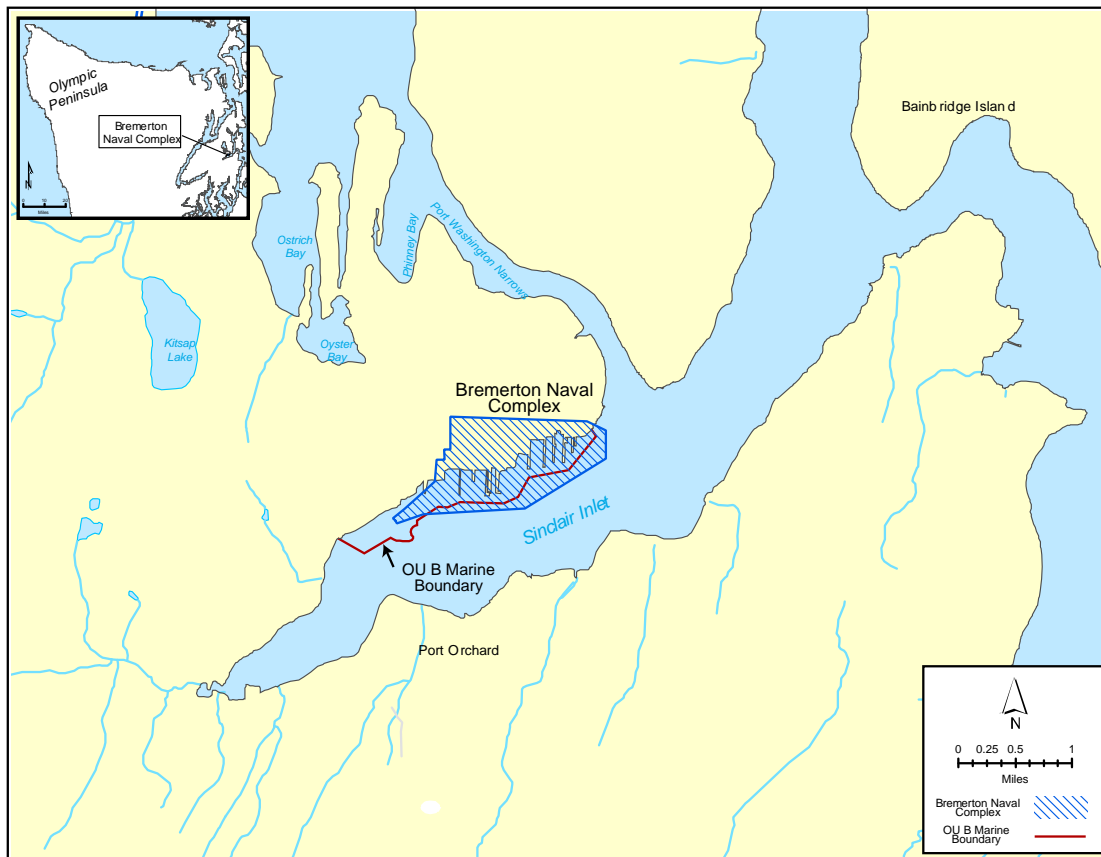


Figure C-1. Site location map

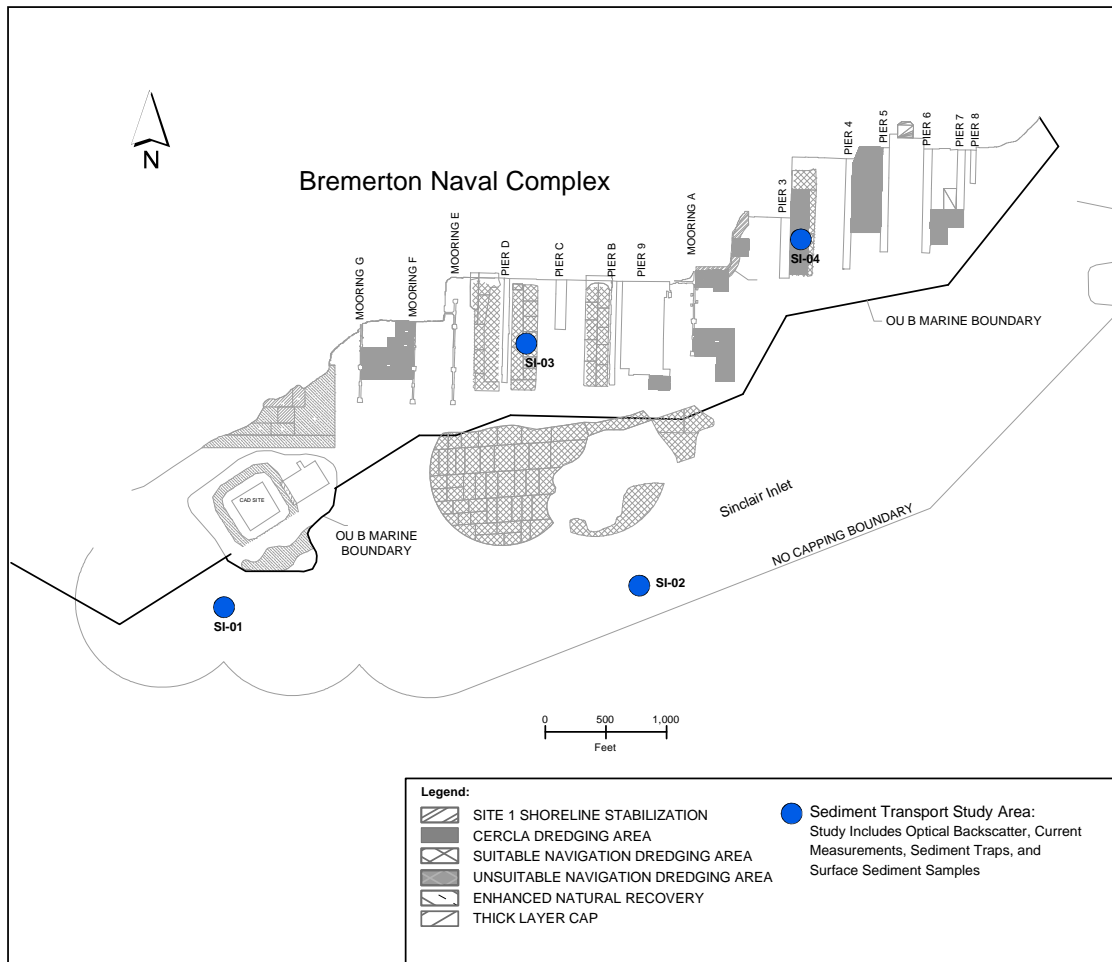


Figure C-2. OUB Marine remedy components and sediment transport study sample locations.

The BNC study also addressed the four general sediment management questions posed in Section 3.3 of the Guide for Assessing Sediment Transport at Navy Facilities (User's Guide):

- Could erosion of the bed lead to the exposure of buried contaminants?
- Could sediment transport lead to the redistribution of contaminants within the site or movement of the contaminants offsite?
- Will natural processes lead to the burial of contaminated sediment by relatively clean sediment?
- If a site is actively remediated, could sediment transport lead to the recontamination of the site?

This report is organized according to the framework provided in Section 1.1 of the User's Guide. Section 1 presents a site description and conceptual site model for sediment transport based on previous studies. Section 2 presents the results of the Tier 1 evaluation and identifies key data gaps for evaluation in the Tier 2 study. Section 3 describes the Tier 2 sediment transport data collection program, presents the Tier 2 data analyses and refined conceptual model of sediment transport, and discusses the application of the results to sediment management questions. Section 4 provides the references.

C.1.2 SITE DESCRIPTION

The first step in the BNC sediment transport study was to compile a site description based on previous investigations (URS, 1999a; U.S. Navy et al., 2000; Gartner et al., 1998; GeoSea Consulting, 1998; Katz et al., 1999; and Wang and Richter, 1999). These studies provided the baseline data for the sediment transport conceptual site model and Tier 1 sediment transport evaluation.

C.1.2.1 Topography and Bathymetry

Sinclair Inlet trends northeast–southwest and is approximately 4 miles long and 1 mile wide. It is connected to Puget Sound by Port Orchard Passage and Rich Passage (Figure 1). The Port Washington Narrows connects Dyes Inlet to the northeast end of Sinclair Inlet and Port Orchard Passage. Bathymetric survey data indicate water depths in Sinclair Inlet generally range from 12.2 to 13.7 m (40 to 45 ft), except in dredged areas near piers and vessel berthing areas where depths increase to 13.7 m to 15.2 m (45 to 50 ft) (Figure 3). Offshore of OU B Marine, water depths are generally 12.2 to 13.7 m (40 to 45 ft). Depths increase to over 15.2 m (50 ft) in two bathymetric depressions located south of BNC in central Sinclair Inlet.

OU B Marine is primarily subtidal. The shoreline is armored with sea walls, riprap, piers, and dry docks. Along the sea walls, water depth drops off more or less vertically to approximately 4.5 m to 6 m (15 to 20 ft) below mean lower low water (MLLW). In rip-rapped areas, depths at the immediate shoreline are typically less than 1.5 m (5 ft) below MLLW, but drop off steeply.

C.1.2.2 Meteorology

BNC is located in a region with a cool, maritime climate due to its proximity of the Pacific Ocean and Puget Sound. Bremerton’s average annual rainfall is 115 cm. Maximum precipitation occurs in December (24 cm), and minimum precipitation occurs in August (1.5 cm). Approximately 85 percent of the precipitation occurs between October and April. Prevailing winds in the fall and winter are from the southwest. Spring and summer prevailing winds are from the north. The U.S. Geological Survey (USGS) collected wind data over a 13-month period in 1994–1995 from three sites in Sinclair Inlet (Gartner et al., 1998). These data indicated that wind speeds are typically low, below 2 m/s 50 percent of the time, and below 5 m/s 90 percent of the time. Wind speeds above 10 m/s were rare. Hills on the north and south sides of Sinclair Inlet are about 100-m high, which, in combination with the prevailing regional southwest–northeast trending winds, cause wind directions to be aligned with the longitudinal axis of the inlet most of the time.

C.1.2.3 Hydrodynamic Processes

Semidiurnal tides in Sinclair Inlet produce two unequal high and low tides daily. The mean tide range (difference between MLLW and mean higher high water [MHHW]) is 3.6 m. Salinity is about 30 psu (practical salinity units), but varies by a few psu both spatially and temporally. The circulation is typical of a two-layer estuarine system, with cold saltier water moving in at the bottom replacing warmer less salty water at the surface. The source of the higher salinity water comes primarily from Rich Passage. The largest two streams that discharge into Sinclair Inlet are Blackjack and Gorst Creeks, on the south side of the inlet and near the inlet’s mouth, respectively (Figure C-4). Two existing and one former publicly owned treatment work (POTW) outfalls discharge into the inlet.

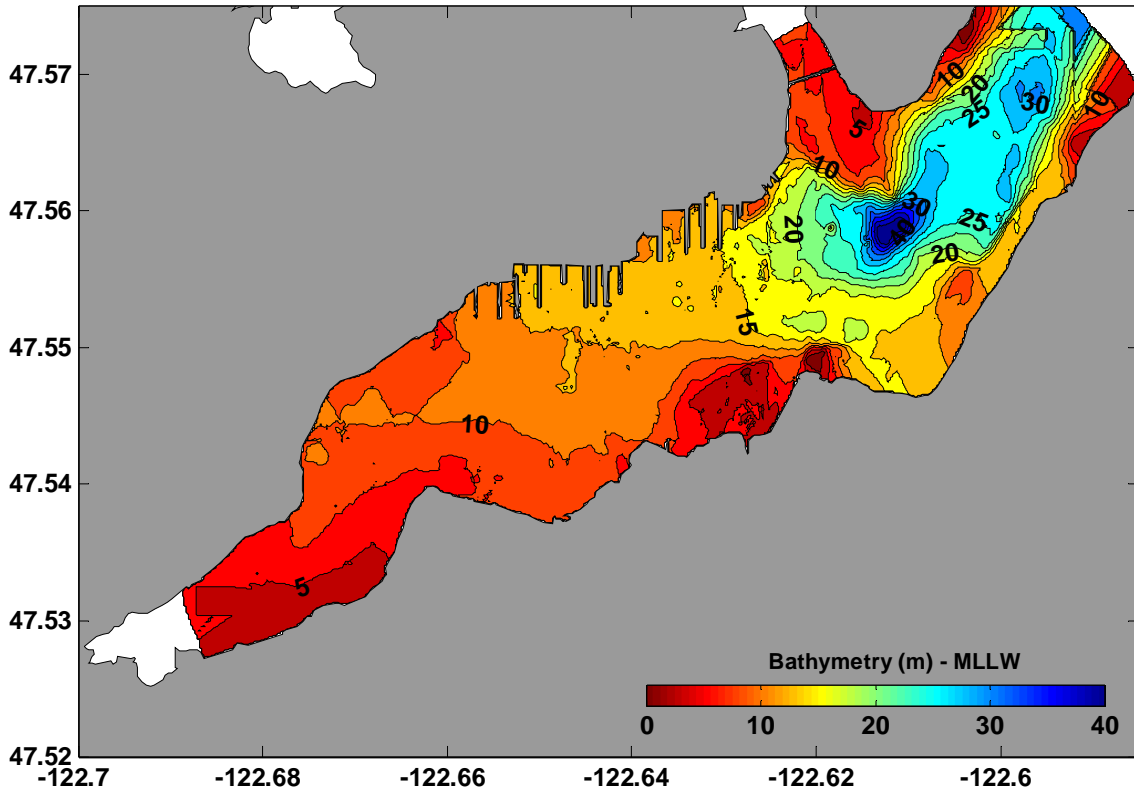


Figure C-3. Bathymetry of Sinclair Inlet based on surface mapping survey data (m, MLLW). Source data: Katz et al., 1999.

Even though the tidal range in Sinclair Inlet usually exceeds 3 m, tidal currents in the inlet are normally less than 10 cm/s due to the inlet’s relatively short length. Water currents measured at the three locations in Sinclair Inlet in the winter and summer of 1994 were relatively weak (Gartner et al., 1998). Typical speeds were 5 to 10 cm/s, and the root mean square (RMS) speeds (i.e., the statistical mean of the current variation) were less than 8 cm/s. The maximum speed observed was 16 cm/s. Tidal and residual (i.e., the long term average) currents were of similar magnitude. Residual currents near the bottom typically were flowing in the opposite direction of the prevailing wind, while surface currents were in the same direction as the prevailing wind.

Suspended sediment concentration data collected by the USGS indicate low to moderate levels of suspended solids (i.e., less than 10 mg/L) (Gartner et al., 1998). Higher concentrations measured at one station corresponded with times of peak tidal currents; however, the amount of material resuspended during each tidal cycle was small. Suspended sediment particles were composed primarily of aggregates, most likely produced by zooplankton feeding activities.

Space and Naval Warfare (SPAWAR) Systems Center San Diego (SSC San Diego) developed a three-dimensional hydrodynamic model, CH3D, using historical tide and current data collected by the National Oceanic and Atmospheric Administration (NOAA) and the USGS prior to 1994, and SSC San Diego during 1997–1998. The model simulates fate and transport of contaminants that originate from the watershed (non-point), the shipyard (point source), and other sources to the receiving water. CH3D was developed to predict tides and currents of the Inlet and was calibrated

against field hydrodynamic data, including water heights and water column currents measured at fixed locations inside the Inlet (Wang and Richter, 1999).

C.1.2.4 Sediment Properties

RI data indicate that bottom sediments in OU B Marine are composed primarily of silt, with the percentage of clay decreasing and percentage of sand increasing from the southwest head of the inlet to the northeast entrance (URS, 1999a). Total organic carbon (TOC) content ranged from 0.5 to 7.9 percent. The USGS described a smooth, soft muddy bottom in Sinclair Inlet, with abundant benthic fauna (Gartner et al., 1998). The activities of these organisms are expected to cause the top 1 to 2 cm of sediment to be porous and loose.

Critical shear velocity, based on particle sizes and density of the bed material, was estimated to be 0.39 cm/s or larger (Gartner et al., 1998). Comparisons of the bottom shear velocities with the critical shear velocity necessary for resuspension of the bed sediments indicated that resuspension occurs only infrequently, usually at times of maximum current during the tidal cycle.

The net deposition rate for Sinclair Inlet has been estimated based on analysis of radioisotope profiles (lead-210 and cesium-137) in sediment cores. Recent net deposition rates based on lead-210 activity in three cores collected for the OU B Marine RI were 0.21 cm/yr, 0.61 cm/yr, and 0.91 cm/yr, although the activity profile in the core with the lowest deposition rate did not appear to meet the assumptions associated with the method (URS, 1999a). The RI radioisotope data were re-evaluated as part of a natural recovery modeling effort, and a net deposition rate of 0.55 to 0.82 cm/yr was estimated (TTEC, 2006). Eight sediment cores were collected from Sinclair and Dyes Inlet as part of the PSNS Project ENVIRONMENTAL InVESTment (ENVVEST) (Crececius et al., 2003). Results for individual cores were not available; however, the average deposition rate for the eight cores was estimated to be 0.25 ± 0.12 cm/yr.

A Sediment Trend Analysis (STA[®]) of Sinclair Inlet/Port Orchard (GeoSea Consulting, 1998) indicated that the muddy sediments in Sinclair Inlet show a dominant clockwise pattern, with flood-directed transport on the south side of the inlet and ebb-directed transport on the north side. The study postulated that resuspension of sediment caused by propeller wash and vessel activity results in mixed trends of contemporaneous erosion and deposition of muddy sediments.

The OU B Marine RI evaluated chemical concentrations in sediment relative to Washington State Sediment Management Standards. Concentrations of PCBs, several inorganic chemicals, and semivolatile organic compounds exceeded sediment quality standards (i.e., no adverse effects levels) or cleanup screening levels (i.e., minor adverse effects levels). The vertical extent of contamination was generally less than 3 ft (U.S. Navy, Department of Ecology, and USEPA, 2000). Elevated mercury levels were found to be ubiquitous throughout the OU B Marine sediment and central Sinclair Inlet.

Sediment cores collected in Sinclair Inlet as part of the ENVVEST program indicate an increase in levels of mercury, copper, polynuclear aromatic hydrocarbons (PAHs), and PCBs beginning around 1900, and peaking between 1940 and 1960. The thickness of the layer of contaminated sediment ranged from 15 to 50 cm. The enforcement of environmental laws is reflected in the core profiles, which shows a significant decline in the later part of the 20th century (Crececius et al., 2003).

C.1.3 SEDIMENT TRANSPORT CONCEPTUAL SITE MODEL

The sediment transport conceptual site model for BNC based upon previous investigations is presented in Figure 4. Sinclair Inlet is an area of low hydrodynamic energy as evidenced by relatively weak currents, a muddy bottom, and absence of current-generated ripples. Bed shear velocities only infrequently exceed the estimated critical shear velocity. Wave effects are minor because of the depth and limited fetch of the inlet. The primary sources of sediment to the inlet include runoff, several streams and POTWs, and tidal exchange. The BNC shoreline is armored, preventing shoreline erosion.

Sinclair Inlet is a net depositional environment. Suspended sediment concentrations are low to moderate (generally less than 10 mg/L), and net deposition rates are relatively low (i.e., less than 1 cm/yr). Contaminant profiles in cores collected for the ENVVEST program show a distinct subsurface peak, indicating that higher levels of contamination associated with historical activities have been progressively buried by relatively cleaner sediment over time. The vertical extent of contamination at BNC is generally less than 0.9 m.

Anthropogenic activities that may affect sediment transport include dredging, ship movements, and nearshore maintenance and construction activities. These conditions suggest that little sediment transport due to waves and tides is likely; however, the potential effects of anthropogenic activities are unknown.

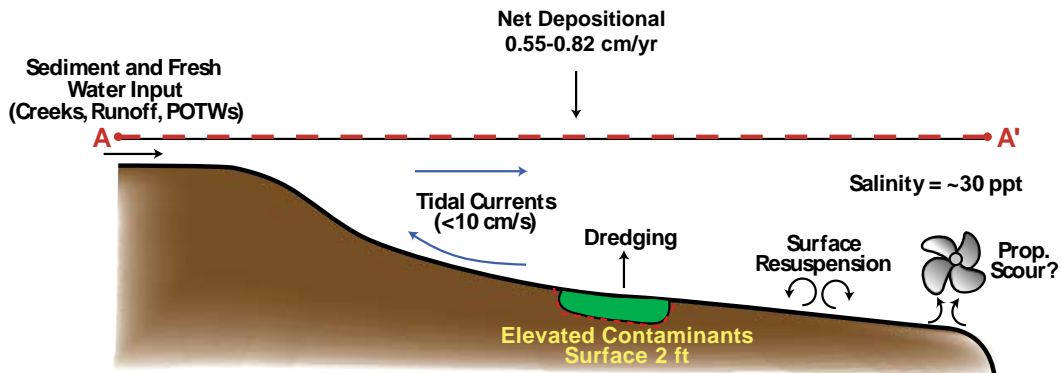
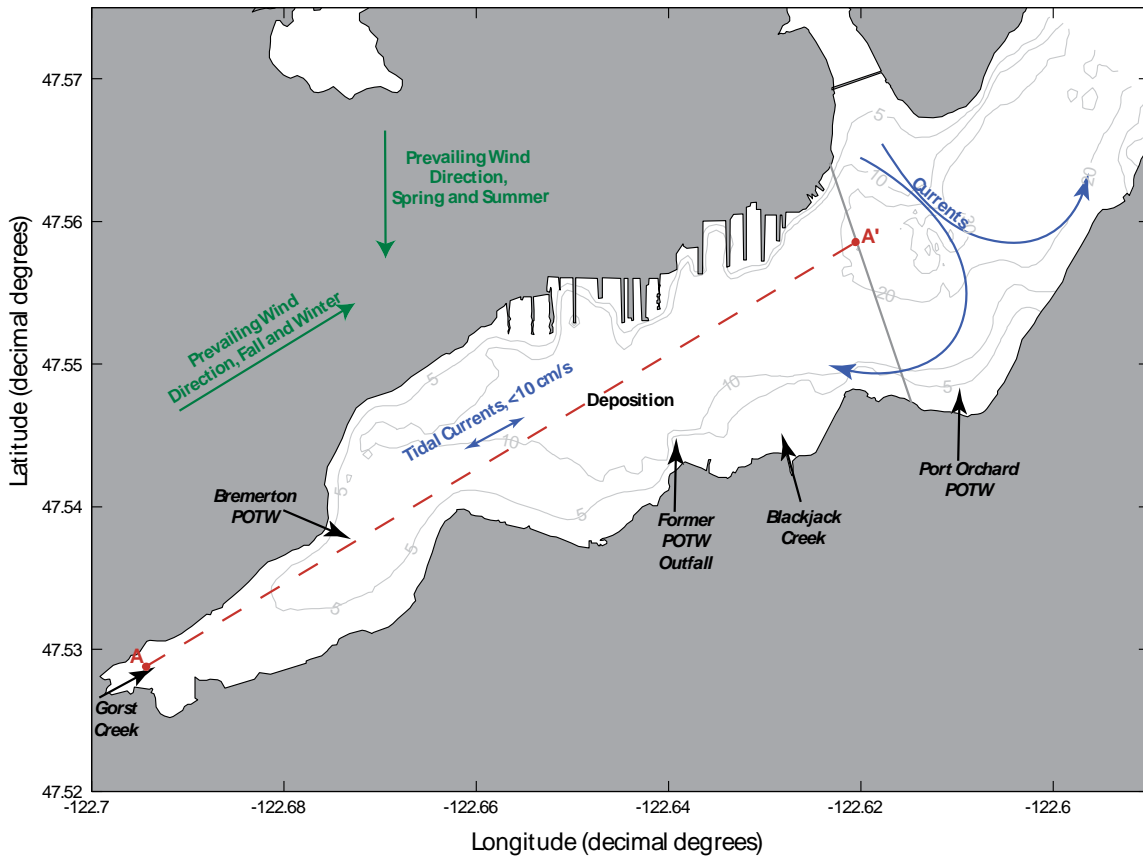


Figure C-4. Preliminary conceptual model of sediment transport for Sinclair Inlet.

C.2 TIER 1 EVALUATION

A Tier 1 evaluation was conducted to address the general sediment management questions identified in Section 1.1 and identify key data gaps for the Tier 2 study. The Tier 1 evaluation is based on existing data.

C.2.1 TIER 1 RESULTS

Existing data were used to characterize sediment erosion and resuspension, transport, and deposition using the methods outlined in Section 3 of the User’s Guide. Tier 1 results are presented below.

C.2.1.1 Erosion and Resuspension

The OU B Marine RI, USGS, and SSC San Diego studies (URS, 1999a; Gartner et al., 1998, and Katz et al., 1999) provide information about the hydrodynamic and sediment properties important for evaluating the potential for erosion in the BNC from currents. The sediment properties include grain size distribution, porosity, and critical shear stress for erosion. The important hydrodynamic properties are current velocities and bottom shear stresses. These parameters and the associated data source are summarized in Table 1.

Table C-1. Parameters for estimating sediment erosion.

Parameter	Value	Data Source
Sediment diameter	silt range for over 90% of cores	URS, 1999a
Porosity	Average 0.80	URS, 1999a
Critical Shear Stress Range τ_{ce}	0.15 dynes/cm ² to 0.63 dynes/cm ²	Gartner et al., 1998
Coefficient of Friction C_f	0.0055 to 0.007	Gartner et al., 1998
Average RMS velocity range	5-10 cm/s at the USGS measurement locations	Gartner et al., 1998
Maximum velocity	16 cm/s at the USGS measurement locations	Gartner et al., 1998

As described in Sections 1.2.3 and 1.2.4, the USGS performed hydrodynamic and sediment transport measurements at three locations in Sinclair Inlet (Gartner et al., 1998). Figure 5 shows the three locations where water column velocities, and suspended sediment concentrations were measured continuously during a summer and winter period in 1994. These measurements provide the range of velocities and bottom shear stresses that can be expected in the vicinity of the BNC. Additionally, SSC San Diego measured currents and water quality constituents throughout Sinclair Inlet during three separate sampling periods. These data were used to verify the circulation patterns observed by the USGS. The USGS scientists also estimated the critical shear stresses for erosion for the surface sediments at the measurement locations based on suspended solids measurements and local bed properties. The particle size information for surficial sediments throughout the BNC provided in the OU B Marine RI showed that the sediments in the pier regions are similar in character to the sediments at the USGS survey locations (URS, 1999a).

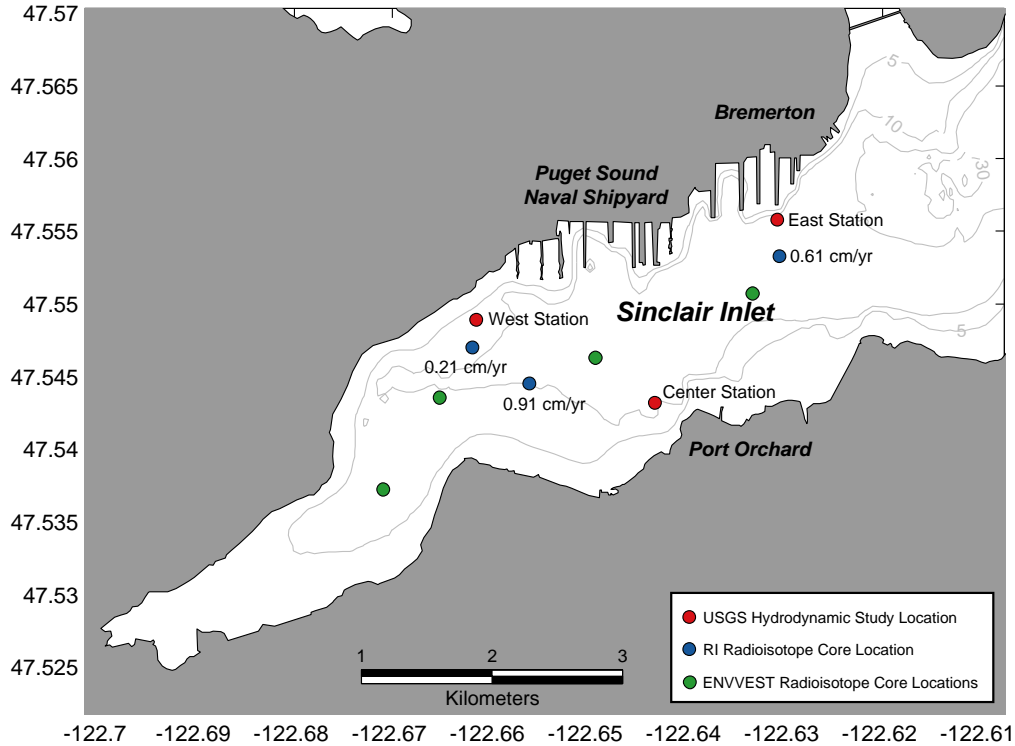


Figure C-5. Locations of USGS measurements, RI radioisotope cores, and ENVVEST Radioisotope cores.

The USGS estimated that current velocities exceeded the critical shear stress range for an average of 1 to 94 minutes per day, usually correlating to times of maximum current in the tidal cycle (Gartner et al., 1998). Current measurements performed by SSC San Diego verified that the maximum currents inside the inlet were 10 to 15 cm/s (Katz et al., 1999). The SSC San Diego current measurements also showed lower current speeds along the shorelines and shipyard relative to the central Sinclair Inlet. The approximate depth of scour in response to current activity was estimated as follows:

Using the maximum measured current of 16 cm/s and maximum $C_f = 0.007$ from the USGS study (Gartner et al., 1998) yields a τ_{max} of 0.18 Pa (1.8 dynes/cm²). Using average values from Table 3-4 of the User's Guide ($A = 0.21$ and $n = 2.6$), assuming a sediment density of 1 g/cm³, and using equations for E_{max} and S_{max} presented in Section 3.4.1 of the guide, we can calculate an order of magnitude depth of scour as

$$E_{max} = A \left(\frac{\tau_{max} - \tau_{ce}}{\tau_{ce}} \right)^n;$$

$$E_{max} = 130 \text{ mg/cm}^2;$$

$$S_{max} = \frac{E_{max}}{1000 \rho_{sed}};$$

$$S_{max} = 0.13 \text{ cm.}$$

From this calculation, it can be concluded that the maximum sediment available for scour at the USGS measurement locations is approximately 1.3 mm. This is consistent with the conceptual model that only the surficial sediments are resuspended by maximum tides. It is important to note that these calculations consider the enhancement of the currents by winds to a maximum velocity of 16 cm/s (Gartner et al., 1998). The CH3D model and currents measured by SSC SAN DIEGO additionally show that the currents (and corresponding shear stresses) decrease shoreward from the USGS East and West tripod locations (Figure 5) to the piers at the shipyard (Wang and Richter, 1999). Therefore, the scour depth presented here is expected to be an upper bound on the scour depths from currents in the shipyard.

C.2.1.2 Transport

A mass balance was constructed in order to initially quantify sediment transport in Sinclair Inlet following the method outlined in Section 3.4.2 of the User's Guide. A basic steady state mass balance of sediments can be expressed as

$$\text{Sediment Mass Inflow} - \text{Sediment Mass Outflow} + \text{Sediment Erosion} - \text{Sediment Deposition} = 0$$

To apply this basic model to Sinclair Inlet, the sources and sinks of sediments in the inlet must be defined. The likely sources include several creeks, two POTWs, runoff, tidal exchange with Puget Sound, and any net erosion. The sediment sinks in the inlet are local net deposition, tidal exchange with Puget Sound, and any loss due to dredging. Figure 6 depicts these sources and sinks of sediment. Flux calculations were performed to determine the amount of sediment moving through the system, and the net direction of movement over a tidal cycle using the method described by Dyer (1997). The calculations are provided in Attachment A to this report. The results indicate that the net flux of sediment per tidal cycle is directed into Sinclair Inlet and out of Dyes Inlet, which supports the conclusion that Sinclair Inlet is a net depositional environment.

C.2.1.3 Deposition

As described in Section 1.2.4, net deposition rates in Sinclair Inlet based on radioisotope data collected for the OU B Marine RI were in the range of 0.55 to 0.82 cm/yr (TTEC, 2006). Using the estimated average suspended particle size of 30 μm , and taking the average near bottom suspended sediment concentration from all USGS measurements of 2.3 mg/L (Table 11, Gartner et al., 1998), we can use the equations from Section 3.4.3 of the User's Guide to calculate settling speed and probability of deposition. These values in turn can be used to estimate the net deposition rate. This provides an alternate approach for estimating net deposition rate if no radioisotope data are available, or can be used to confirm rates determined by other methods.

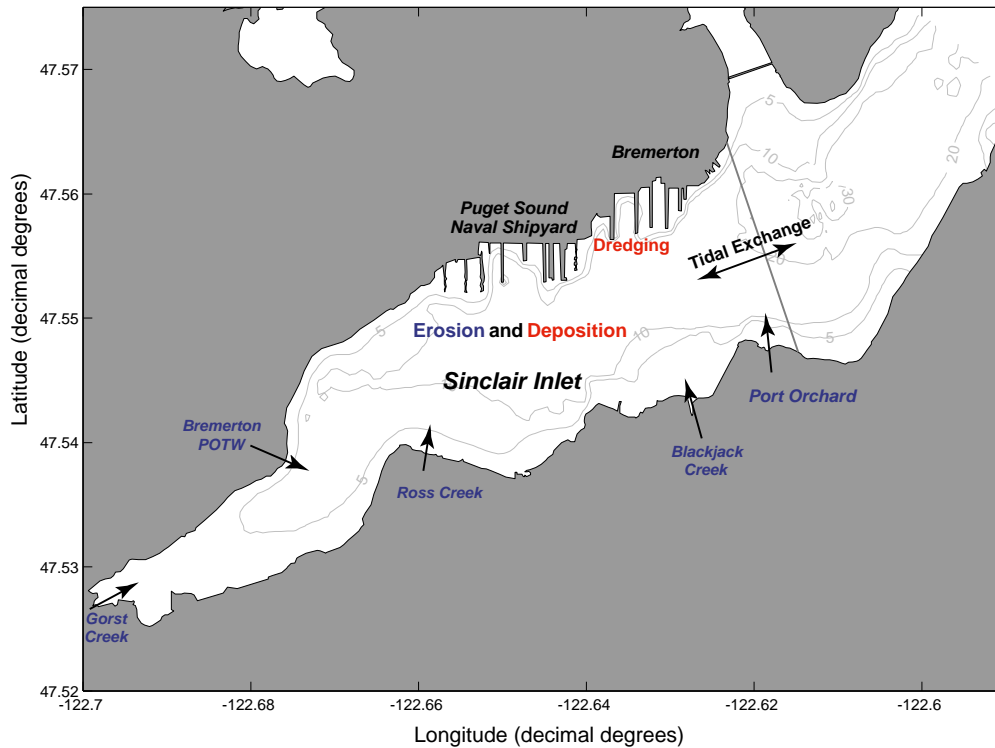


Figure C-6. Sources (blue) and sinks (red) of sediment in Sinclair Inlet.

The average suspended sediment concentration from the three SSC San Diego surveys throughout the entire inlet was 2.27 mg/L, which validates the selection of this value to represent the background concentration of suspended sediments. Settling speed was estimated as follows (Section 3.4.3 of the guide):

$$w_s = \frac{v}{d} \left(\sqrt{25 + 1.2d^{*2}} - 5 \right)^{1.5}$$

$$w_s = 0.051 \text{ cm/s}$$

To calculate the probability of deposition, we can assume the particles begin to settle out at the critical shear stress for suspension. For fine particles, the critical shear stress for suspension is equal to the largest critical shear stress for erosion from Table 1 to provide a conservative estimate, or 0.63 dynes/cm² for this case. With these values the probability of deposition was calculated as

$$P = 1 - \frac{\tau}{\tau_{cs}}$$

$$P = 0.13$$

$$D = P w_s C$$

$$D = 0.13 \times 10^{-7} \text{ g/cm}^2/\text{s}$$

Assuming a sediment density of 1 g/cm³ we can calculate an average deposition rate (Burial Velocity, B_v), assuming no net resuspension, over a given square centimeter as follows:

$$B_v = \frac{D}{\rho_{sed}}$$

$$B_v = 0.4 \text{ cm/yr}$$

The calculated deposition rate from the USGS measurements, assuming no net resuspension, is within 30 percent of the low end of the range estimated from RI data (0.55 cm/s). This estimate is consistent with the measured rates and provides another line of evidence for the conclusion that Sinclair Inlet is a net depositional region.

C.2.2 TIER 1 CONCLUSIONS AND RECOMMENDATIONS

Tier 1 results regarding sediment transport were used to address the four general sediment management questions presented in Section 1.1, and identify the key data gaps that were addressed in the Tier 2 study.

C.2.2.1.1 Sediment Management Questions

The general sediment management questions are discussed below based on Tier 1 results. Specific questions formulated by the BNC project team are addressed as part of the Tier 2 evaluation.

C.2.2.1.2 Could erosion of the sediment bed lead to the exposure of buried contamination?

Based on the Tier 1 analyses for BNC, there appears to be little potential for the exposure of buried contamination due to currents and waves. The data from the RI, USGS, and SSC San Diego studies coupled with a scour analysis show that surficial sediments (i.e., less than 1 cm) are resuspended by tidal currents, and typically only at times of maximum current. Only minimal surficial sediment erosion (0.2 cm) was predicted when the maximum measured shear stress during wind events was used in the scour analysis. The potential for erosion based on anthropogenic activities (e.g., ship movements) was not evaluated based on Tier 1 data.

C.2.2.1.3 Will sediment transport lead to the redistribution of contamination within the site, or movement of contamination offsite?

There is the potential for movement of surficial sediment (i.e., less than top 1 cm) in the BNC. Any ongoing source of contamination to surficial sediment could result in the redistribution of contamination within the site or offsite. However, the RI report indicates that there are no ongoing sources of contamination to sediment related to BNC activities (URS, 1999a). It is unlikely that significant net transport from or within OU B Marine occurs because of the weak tidal currents.

C.2.2.1.4 Will natural processes lead to the burial and isolation of contamination by relatively clean sediment?

Radioisotope cores collected during the RI and ENVVEST studies show that Sinclair Inlet is a net depositional environment. Calculation of the net sediment deposition rate using data obtained by the USGS verifies the magnitude of the sedimentation rates determined from the radioisotope cores. Contaminant profiles in cores collected in the inlet for the ENVVEST program show a clear decline in contaminant concentrations in more recent sediment, indicating that natural recovery by burial is

occurring. The flux analysis shows a net transport of sediment into Sinclair Inlet during a typical tidal cycle. Chemical concentrations in incoming sediments were unknown at the time of the Tier 1 analysis.

C.2.2.1.5 If a site is actively remediated, could sediment transport lead to the recontamination of the site?

OU B Marine was actively remediated in 2000–2001, and dredged areas show evidence of potential recontamination based on 2003 and 2005 long-term monitoring results. Based on the Tier 1 evaluation, it is unlikely that sediment transport due to tides or waves would cause recontamination of dredged areas. However, potential transport due to anthropogenic activities (e.g., the dredging process itself or ship activity) was not evaluated as part of Tier 1.

C.2.2.1.6 Major Data Gaps and Uncertainties

The key data gaps and uncertainties that were identified during the Tier 1 evaluation were as follows:

- **Site-specific sediment erosion rates.** The physical behavior of fine-grained cohesive sediments can be more accurately characterized based on site-specific measurements of erosion properties. This information is needed to quantify the conditions under which BNC sediments are likely to be eroded and resuspended.
- **Currents in the vicinity of the shipyard piers.** Although hydrodynamic data are available for Sinclair Inlet, wave and current measurements were not taken immediately in the vicinity of the BNC piers. Site-specific hydrodynamic data, in conjunction with sediment erosion rate data, will provide more accurate estimates of sediment transport in the immediate vicinity of the piers.
- **Quality of suspended solids.** Characterizing chemical concentrations in sediment particles settling on the sediment bed would support evaluation of the effectiveness of monitored natural recovery.
- **Information about effects of prop scour.** Potential effects of prop scour should be further evaluated to assess the likelihood that this mechanism could be responsible for potential recontamination of remediated areas in OU B Marine.

As noted in the User's Guide, the decision about whether a Tier 2 evaluation is required must consider the level of uncertainty associated with the Tier 1 analysis, and the potential consequences from both a risk and cost perspective of making an incorrect site management decision based on the Tier 1 analysis. Although a great deal of site-specific information was available for the Tier 1 evaluation, the reasons for the higher-than-expected sediment contaminant levels in the remediated area could not be confidently ruled in or out based on the Tier 1 evaluation alone. Given the cost implications of an incorrect decision about the potential need for additional remedial action, a Tier 2 evaluation was warranted. The Tier 2 work plan was developed based on the key data gaps that were identified above.

C.3 TIER 2 EVALUATION

The Tier 2 sediment transport study at BNC had three specific objectives:

- Characterize the direction and magnitude of sediment transport in the immediate vicinity of the BNC piers, where higher than expected PCB concentrations have been detected within the dredged areas.
- Measure the stability of the sediment bed in the vicinity of the piers.
- Evaluate whether incoming (depositing) sediments have lower PCB concentrations than the sediment bed, or if there appears to be a continuing source of PCBs to the bed.
- Evaluate the potential for and magnitude of erosion due to prop scour in the vicinity of the BNC piers.

These data allowed direct quantification of localized sediment transport so that the potential for site recontamination and/or natural recovery could be evaluated. NAVFAC NW used the Tier 2 sediment transport data in conjunction with high resolution multibeam bathymetry data collected as part of the regulatory program to update the natural recovery model, and determine the potential impact of localized sediment transport on the OU B Marine remedy (TTEC, 2006).

C.3.1 STUDY DESIGN

The Tier 2 field study was conducted in the summer of 2005, and included three tasks:

- **Hydrodynamic measurements:** Time-series measurements of currents, waves, suspended sediment concentrations, temperature and salinity were collected at four stations to determine the frequency, direction, and magnitude of sediment transport.
- **SEDflume cores:** Sediment cores were collected from four stations and analyzed in the SSC San Diego SEDflume laboratory. The SEDflume data were used to characterize sediment stability and erosion rates. Particle size distribution and bulk density also were determined. This information was used in conjunction with hydrodynamic data to estimate the potential for erosion and resuspension of sediment under typical hydrodynamic conditions.
- **Sediment traps:** Sediment traps were deployed at four stations to evaluate the quantity and quality of the sediment particles settling on the sediment bed. Sediment trap samples were analyzed for PCB Aroclors, mercury, grain size, and total organic carbon (TOC). In addition, grab samples were collected from the sediment bed at each sediment trap location as part of NAVFAC NW's long-term monitoring study to provide data for comparison to sediment trap samples.

The four sampling stations were designated SI-01, SI-02, SI-03, and SI-04 (Figure 2). Stations SI-01 and SI-02 were reference sites located in Sinclair Inlet outside of the BNC boundary. Station SI-03 was located between BNC Piers C and D, and Station SI-04 was located adjacent to BNC Pier 3. The following instrumentation was deployed at each station: three sediment traps; a current meter to measure current velocities; an optical backscatter sensor (OBS[®]) to measure suspended sediment concentrations; a conductivity, temperature, and depth (CTD) sensor; and a data logger. The sediment traps were constructed of 6-inch, Schedule 40, polyvinyl chloride (PVC) pipe with a trap height of 30 inches and a volume of approximately 14 liters. Five sediment cores for SEDflume analysis were collected at each station. Two cores from each station were tested. A diagram of SEDflume is provided in Figure 4-1 of the Interrin User's Guide.

C.3.2 TIER 2 RESULTS

Details of the Tier 2 field investigation are provided in Appendix A of the Sediment Transport Study and Natural Recovery Model Report (TTEC, 2006). Tier 2 data analyses are presented below.

C.3.2.1 Transport

Time-series plots of current velocity at each station are shown in Figure 7. Current velocities were relatively low during the deployment period, with maximum velocities generally less than 10 cm/s at every station. Bed shear stresses were calculated using the current velocities measured during the survey to determine if erosion of the consolidated bed was occurring. The bed shear stress, τ_b , was calculated using the formula:

$$\tau_b = \rho_w \cdot c_f \cdot u^2,$$

where ρ_w is the water density (kg/m^3), c_f is the coefficient of friction from the USGS study (0.007), and u is the near-bed current velocity (m/s) measured with the current meter. Bed shear stresses were low during each deployment, ranging from 0 to 0.047 Pascals (Pa). These results are compared with critical shear stresses determined from SEDflume tests in the following section.

Suspended sediment concentration data measured with the OBS[®] are shown in Figure 8. These data show low turbidity during the initial phase of the deployment. Stations SI-01 and SI-04 had background levels of ~3 nephelometric turbidity units (NTU), and SI-02 had background levels of ~10 NTU. An increase in the turbidity signal at Stations SI-01 and SI-02 indicates that biofouling of the optical sensor occurred after 1 to 2 weeks of deployment. The OBS[®] at Station SI-03 did not successfully record turbidity data during any part of the deployment. Although the data set is incomplete, the measurements appear to be consistent with suspended sediment data collected by the USGS (Gartner et al., 1998).

C.3.2.2 Erosion and Resuspension

C.3.2.2.1 SEDflume Studies

The average critical shear stress for surface sediment determined from the SEDflume tests on cores from each station is shown in Table 2, along with the bottom shear stresses determined from the hydrodynamic data. Bed shear stresses were up to an order of magnitude lower than the critical shear stress for erosion that was measured at each station from the SEDflume analysis (Figure 9). This implies that shear stresses on the sediment bed never reached the threshold for erosion, and that sediment erosion at each station did not occur during the deployment period.

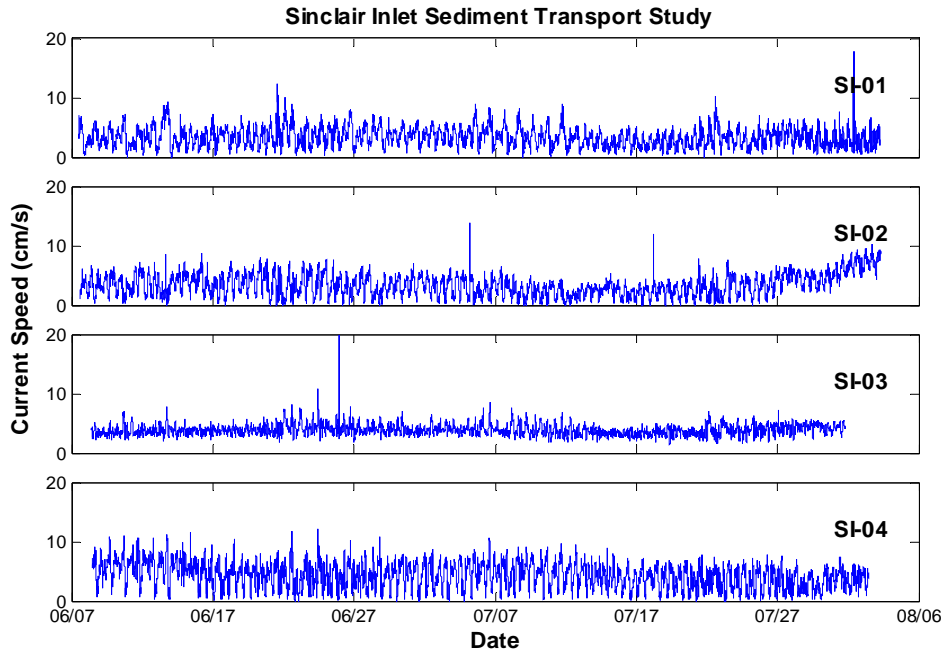


Figure C-7. Current speeds at each sampling station measured with an electromagnetic current meter.

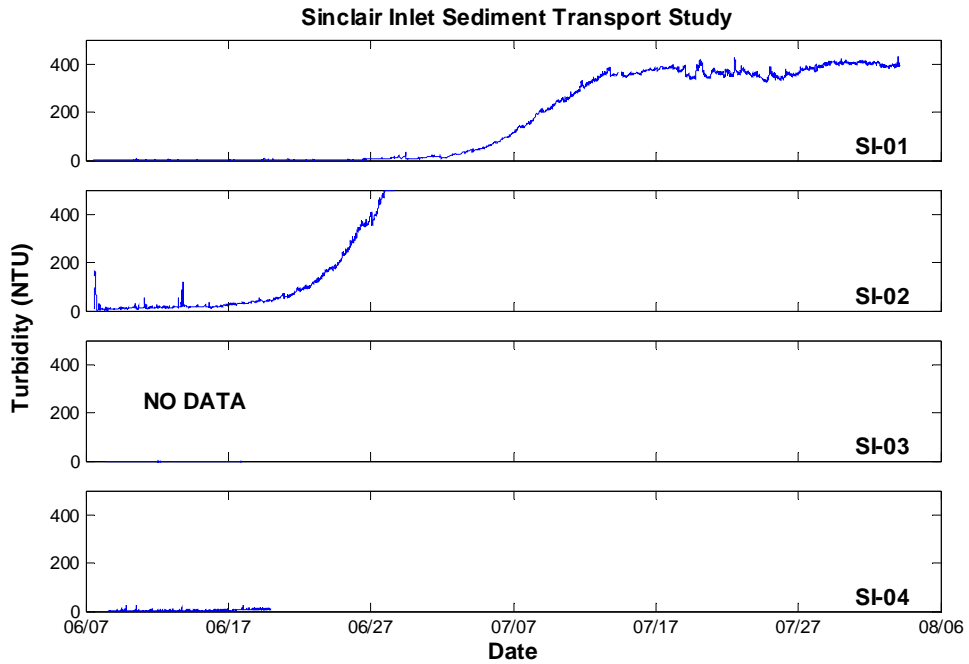


Figure C-8. Turbidity measurements at each station, as measured with an OBS[®]. No data were retrieved at Station SI-03 and the dataset at SI-04 did not span the entire deployment period. Increased values at SI-01 and SI-02 were the result of biofouling on the optical sensor.

Table C-2. Critical shear stress values from SEDflume analysis and maximum calculated bed shear stress values for each sampling station.

Station ID	Critical Shear Stress (Pa)	Maximum Bed Shear Stress (Pa)
SI-01	0.25	0.08
SI-02	0.25	0.05
SI-03	0.40	0.05
SI-04	0.20	0.1

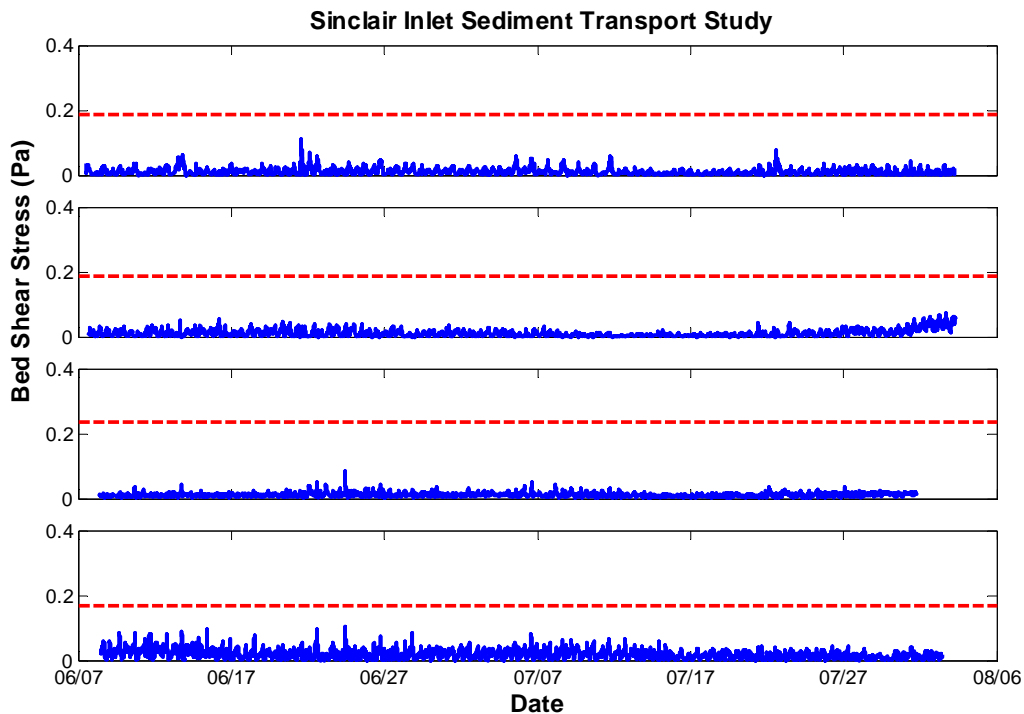


Figure C-9. Bed shear stresses (blue line) are well below the critical shear stress values (red-dashed line) that were measured at each station using SEDflume.

C.3.2.2.2 Prop Scour Evaluation

The goal of this analysis is to investigate the potential effects of propeller wash on sediment resuspension in BNC. The maximum propeller wash velocities predicted for a typical ship movement were used in conjunction with SEDflume erosion rate and critical shear stress data for sediment cores collected from the BNC piers to determine potential depths of scour. The Navy directly measured propeller wash generated by a tugboat during docking operations at BNC (U.S. Navy, 1999). In these field experiments, four current meters at various locations measured current velocities in the propeller jet generated by a stationary tugboat. Predictions of maximum velocities from propeller wash presented below were compared to the Navy's field measurements for validation purposes.

C.3.2.2.3 Propeller Wash Analysis

The bottom velocity due to propeller wash (V_{prop}) was estimated following the formulation outlined in Maynard (2000). Several physical parameters describing the ship, propeller, and operating environment are required for this analysis. Table C-3 includes the parameters, noting which ones were available from the Navy (1999) field experiment and which were determined from other sources. Specifications for a typical Puget Sound commercial tug, *J.T. Quigg*, were used for the parameters that were not readily available from the U.S. Navy (1999) field experiment. *J.T. Quigg* has an open-wheel propeller similar to the vessel used in the field experiment.

The thrust formulation used here includes N as a parameter to account for the varying revolutions per minute (RPMs) in the field experiments. The thrust was calculated from the following equation:

$$T = \rho_w K_t N^2 D_p^4.$$

This formulation is dependant on a propeller thrust coefficient (K_t), which is not specified for the tugboat that was used in the experimental measurements. A value of 0.05 was chosen to give the best fit to the measured values.

The location of each bottom-mounted current meter relative to the tugboat in the U.S. Navy (1999) field experiment is included in Table B-4. In this analysis, X_p is the longitudinal direction, where $X_p = 0$ is at the propeller. z_{cl} is the lateral distance from the ship centerline. The average measured velocity for each RPM value at each current meter is also included in Table C-4. These were calculated from plots of velocity vs. time included in the field experiment report (U.S. Navy, 1999). Figures C-10 through C-12 show spatial plots of modeled velocities with measurement locations noted.

The current meter 1708 always has a higher value than predicted by the propeller wash equations, which suggests that the jet was not symmetric in the experiment. The current meter 1709, which is opposite 1708, compares the best of all four with predicted velocities. The velocity measured at 1678 shows no variation with change in propeller speed, which indicates a potential error in the field measurements or experimental design. Current meter 1851 is located in a region where velocities are expected to change rapidly due to proximity to the propeller; therefore, it is difficult to compare predictions at this location.

The predicted velocities very close to the propeller are very small for reasonable values of the propeller thrust coefficient. Predicted velocities for larger values of K_t (>0.5) agree with measured velocities in this region, but the predictions of velocity in the outer plume (100 cm/s) are significantly higher than those measured; therefore, the presented values are chosen as most representative of the real-world case. Based on these comparisons, the model provides a reasonable prediction of the average range of velocities measured when realistic parameters are used. From this analysis, the maximum predicted propeller wash velocity is 28.6 cm/s. The highest velocity measured during the experiment was 30 cm/s, suggesting that the predictions give a realistic estimate of the magnitude of the propeller wash velocities. The average error of all measurements is approximately 50 percent. Therefore, a 1.5 factor of safety should be applied to these velocity predictions to account for the average error.

Table C-3. Physical parameters required.

Parameter	Description	Value	Source
L_{tb}	Length of ship, m	30.48	Navy, 1999
d_s	Ship draft, m	3.75	<i>J.T. Quigg</i>
L_{set}	Distance from stern to propeller, m	3.05	<i>J.T. Quigg</i>
W_p	Distance between twin prop., m	4.57	<i>J.T. Quigg</i>
D_p	Propeller diameter, m	3.05	Navy, 1999
δ_p	Propeller axis depth, m	2.44	<i>J.T. Quigg</i>
<i>Power</i>	Total ship power, hp (kW)	2000 (1491)	Navy, 1999
H	Water depth, m	12.80	Navy, 1999
V_a	Ambient channel velocity, m/s	0	Assumption
V_g	Ship speed relative to ground, m/s	0	Navy, 1999
N	Propeller speed, rpm	50 to 150	Navy, 1999
ρ_w	Density of seawater, kg/m ³	1026	
K_t	Propeller thrust coefficient	0.05	Calibrated
G	Acceleration of gravity, m/s ²	9.82	

Table C-4. S4 current meter locations.

Current Meter ID	Long. Distance from prop (X_p) (ft)	Lateral distance from prop (Y_c) (ft)	Velocity (cm/s)	Velocity (cm/s)	Velocity (cm/s)
			50 RPM	100 RPM	150 RPM
1678 S4	475	0	15	15	15
1708 S4	270	150	15	20	30
1709 S4	325	100	5	8	10
1851 S4	100	25	5	10	20

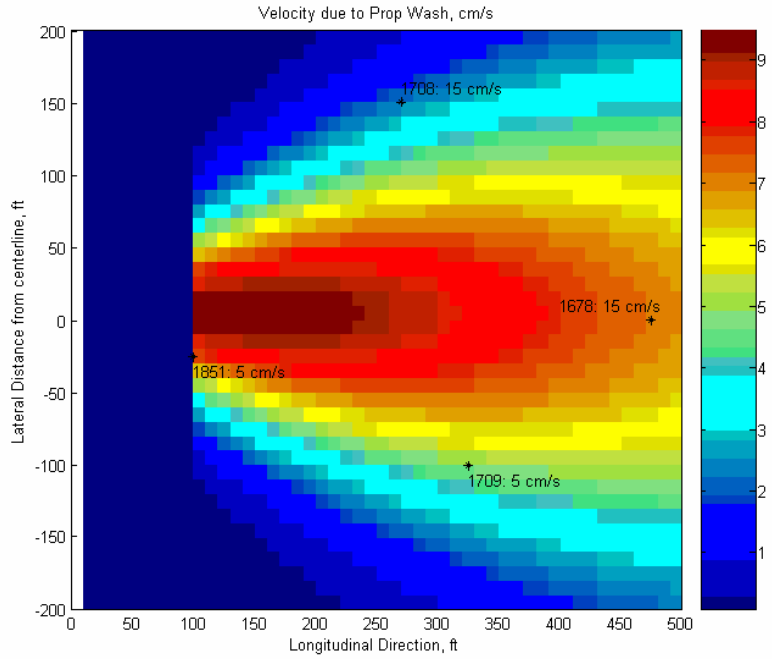


Figure C-10. Plot of bottom velocity from propeller wash, N = 50 RPM with field measurements.

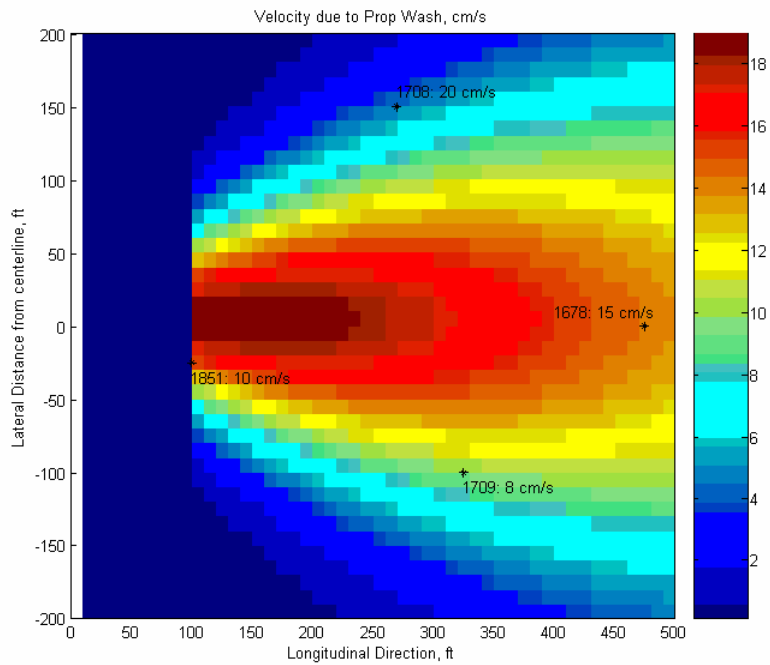


Figure C-11. Plot of bottom velocity from propeller wash, N = 100 RPM with field measurements.

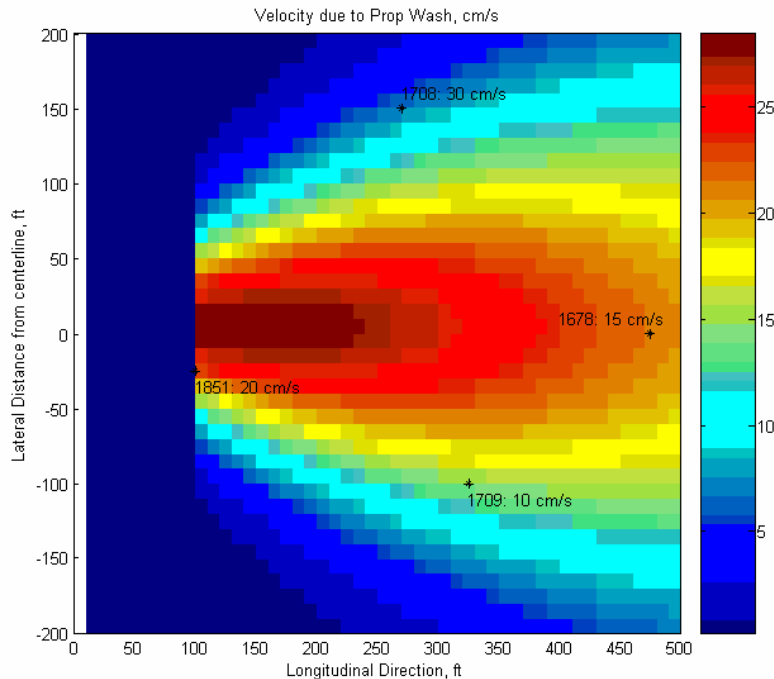


Figure C-12. Plot of bottom velocity from propeller wash, N=150 RPM with field measurements.

Other types of tugboat drives are in common use at BNC (i.e., Z-drive, cycloidal drive, etc.), but measurements of velocities behind these drives are currently unavailable.

C.3.2.2.4 Scour Due to Propeller Wash

SEDflume analysis was conducted on cores from Stations SI-03 and SI-04, which were located in the BNC pier areas most likely impacted by propeller wash during ship operations. Table C-5 shows the average erosion rates for the cores collected at each location as a function of shear stress and depth.

Using the predicted velocities from the propeller wash, the bed shear stress, τ_b , exerted on the sediment bed during ship operations was calculated using the formula presented in Section C.3.2.1. Given that an extended ship movement lasts for up to 30 minutes (U.S. Navy, 1999), the total scour depth can be calculated by multiplying the time period by the erosion rate of the sediment at the applied bed shear stress. Tables C-6 and C-7 summarize a range of propeller jet velocities, corresponding shear stresses, erosion rates, and scour depths after 30 minutes for each core location. Note that erosion does not occur until the critical shear stress of the sediments is exceeded by the propeller wash velocity.

Table C-5. Average erosion rates (cm/s) as a function of shear stress and depth for core locations in BNC piers.

Interval	Core SI-03				
	0.2 Pa	0.4 Pa	0.8 Pa	1.6 Pa	3.2 Pa
0 - 3.75 cm	0.00E+00	7.92E-05	9.29E-04	5.51E-03	1.88E-02
3.75 - cm	0.00E+00	0.00E+00	7.78E-04	2.61E-03	5.61E-03
Interval	Core SI-04				
	0.2 Pa	0.4 Pa	0.8 Pa	1.6 Pa	3.2 Pa
0 - 6 cm	1.38E-04	5.04E-04	1.42E-03	6.90E-03	2.99E-02
6 - cm	0.00E+00	5.42E-05	4.54E-04	2.18E-03	1.13E-02

The tables include velocities to 45 cm/s to account for a 1.5 factor of safety in the calculation of the probable tug velocities. The calculations show that no scour is likely until velocities of 30 cm/s at Station SI-04 and 40 cm/s at Station SI-03 are reached. The scour maximum in 30 minutes is 1.8 cm at location SI-04 at 45 cm/s.

These calculations assume no deposition of sediments to the scour location during tug activity. This assumption is likely accurate because the velocities would remain too high to allow fine sediments to deposit back to the bed. Once tug activity ceases, it is likely that the sediments will deposit back to the bed in the same region due to the low overall tidal velocities at BNC. Therefore, the scour listed in the tables below represents an absolute maximum scour depth that will not likely be sustained after the tug activity ceased.

Table C-6. Propeller wash velocities and resulting scour depths after 30 minutes as Station SI-03.

Velocity (cm/s)	Shear (Pa)	Erosion Rate (cm/s)	Scour (cm)
5	0.0075	0	0.0
10	0.0300	0	0.0
15	0.0675	0	0.0
20	0.1200	0	0.0
25	0.1875	0	0.0
30	0.2700	0	0.0
35	0.3675	0	0.0
40	0.4800	2.49E-04	0.4
45	0.6075	5.20E-04	0.9

Table C-7. Propeller wash velocities and resulting scour depths after 30 minutes as Station SI-04.

Velocity (cm/s)	Shear (Pa)	Erosion Rate (cm/s)	Scour (cm)
5	0.0075	0	0.0
10	0.0300	0	0.0
15	0.0675	0	0.0
20	0.1200	0	0.0
25	0.1875	0	0.0
30	0.2700	2.66E-04	0.5
35	0.3675	4.45E-04	0.8
40	0.4800	6.86E-04	1.2
45	0.6075	9.77E-04	1.8

C.3.2.3 Deposition

Sediment traps were deployed for 57 days at Stations SI-01 and SI-02, and for 55 days at Stations SI-03 and SI-04. Sediments from the three traps at each station were combined after retrieval and analyzed for PCBs, mercury, TOC, and grain size. The quantity and quality of sediment retrieved from each trap is summarized in Table 8. The quantity of material captured in traps at Stations SI-01, SI-02 and SI-03 was similar (~400 g). Note that sediment traps capture locally resuspended sediment as well as incoming sediment from outside Sinclair Inlet. More sediment was captured in the traps at Station SI-04, possibly due to sediment resuspension as a result of construction activities at Pier 3 during the deployment period (as previously noted, the OBS[®] failed to collect suspended sediment concentration data at this station).

Collocated bed sediment samples (0 to 10 cm) were collected by NAVFAC NW in June 2005 as part of their long-term monitoring program. OC-normalized total PCB concentrations in collocated bed sediment samples are shown in Table B-8. PCB concentrations in the sediment traps were below the remediation goal of 3 mg/kg OC and were lower than the bed sediment samples at every station. These data suggest that newly depositing sediments have lower total PCB concentrations than the existing bed sediments. Total mercury concentrations in all sediment trap samples and collocated bed samples are similar. TOC content was approximately 5 percent in sediment trap samples and approximately 3 percent in bed sediment samples. The higher TOC in the sediment trap samples may reflect seasonal variation in water column solids composition as suggested by the USGS (Gartner et al., 1998), whereas bed sediment samples reflect average TOC content over all seasons.

Table C-8. Summary of sediment trap and sediment bed sample results.

Station	SI-01	SI-02	SI-03	SI-04
Total mass captured in sediment traps (g dry wt)	443	397	406	624
Total PCB in sediment trap sample (mg/kg OC dry wt)	1.5	1.0	1.9	2.6
Mercury in sediment trap sample (mg/kg dry wt)	0.506	0.614	0.706	0.732
% TOC in sediment trap sample	4.97	4.88	5.18	4.83
% fines in sediment trap sample (silt + clay)	91.9	90.1	95.7	93.2
Total PCB in bed sediment sample (0-10 cm) (mg/kg OC dry wt)	2.7	1.6	49.2	10.9
Mercury in bed sediment sample (0-10 cm) (mg/kg dry wt)	0.737	0.635	0.551	0.842
% TOC in bed sediment sample (0 to 10 cm)	3.11	3.51	3.05	3.31
% fines in bed sediment sample (silt + clay)	96.5	92.1	85.3	88

C.3.3 TIER 2 CONCLUSIONS AND RECOMMENDATIONS

Tier 2 data were used to refine the conceptual site model for sediment transport. General sediment management questions and project-specific objectives were addressed, and remaining data gaps and uncertainties were identified.

C.3.3.1 Refined Sediment Transport Conceptual Site Model

The Tier 2 evaluation confirmed the conceptual site model for sediment transport presented in Section 1.3, with the following refinements. Site-specific measurements in the OU B Marine pier area indicated that bed shear stresses were an order of magnitude lower than critical shear stresses for erosion during the deployment period, and no resuspension due to waves or tides was observed. Although the suspended sediment concentration data set was incomplete, available data indicated that suspended sediment concentrations were low. Sediment trap data indicate that PCB concentrations in newly deposited sediment are less than the remedial goal of 3 mg/kg OC.

The analysis of potential scour from conventional propeller wash indicated that no scour is likely until velocities of 35 to 40 cm/s are reached. The maximum scour depth after 30 minutes is estimated to be less than 2 cm. Measurements of velocities associated with other types of tugboat drives (e.g., Z-drive or cycloidal) are currently unavailable. Once tug activity ceases, it is likely that the sediments will deposit back to the bed in the same region due to the low overall tidal velocities at BNC.

C.3.3.2 Sediment Management Questions

The answers to the four general sediment management questions developed in the Tier 1 evaluation were reviewed and revised in light of the additional information obtained in Tier 2. In addition, specific questions formulated by the BNC project team also are addressed.

C.3.3.2.1 Could Erosion of the Sediment Bed Lead to the Exposure of Buried Contamination?

The Tier 2 evaluation confirmed that there is no significant potential for erosion of the sediment bed and exposure of buried contamination due to currents. Current velocities were relatively low

during the 2005 deployment period, with maximum velocities generally less than 10 cm/s at every station. Bed shear stresses were up to an order of magnitude lower than the critical shear stress for erosion that was measured at each station from the SEDflume analysis. This measurement implies that shear stresses on the sediment bed never reached the threshold for erosion, and that sediment erosion at each station did not occur during the deployment period. In addition, low turbidity measurements were observed during the deployment period.

C.3.3.2.2 Will Sediment Transport Lead to the Redistribution of Contamination Within the Site, or Movement of Contamination Off Site?

The Tier 2 evaluation indicates that sediment transport within the BNC due to waves and tides is insignificant. The analysis of prop scour based on forces generated by a conventional propeller indicate that scour depths would be on the order of a few centimeters at velocities of 35 to 40 cm/s; however, site-specific information on forces generated by other types of propellers is not available. Any sediment resuspended by anthropogenic forces (e.g., propeller wash or nearshore maintenance and construction) is not expected to be transported any significant distance due to the weak tidal currents.

C.3.3.2.3 Will Natural Processes Lead to the Burial and Isolation of Contamination by Relatively Clean Sediment?

The Tier 1 evaluation indicated that Sinclair Inlet is a net depositional environment as evidenced by radioisotope and contaminant profile data (URS, 1999a; Crecelius et al., 2003). The Tier 1 flux analysis shows a net transport of sediment into Sinclair Inlet during a typical tidal cycle. Tier 2 sediment trap results showed that PCB concentrations in newly deposited sediments are lower than PCB concentration in bed sediments. In addition, the sediment trap PCB concentrations were all below the 3 mg/kg OC remedial goal. These results indicate that natural processes will lead to the progressive burial and isolation of contaminated sediments by relatively cleaner sediment in undisturbed areas.

C.3.3.2.4 If a site is actively remediated, could sediment transport lead to the recontamination of the site?

Possible explanations for apparent recontamination of the dredged area at BNC are identified below, and interpreted in terms of likelihood based on the refined sediment transport conceptual site model.

- **Transport of contaminants from adjacent unremediated areas or offsite sources.** Transport from other areas due to wave and tidal action is unlikely, given the weak currents observed in Sinclair Inlet and relatively low PCB concentrations (i.e., below the 3 mg/kg OC remedial goal) measured in sediment trap samples.
- **Resuspension and transport due to propeller wash.** The initial evaluation based on conventional (open wheel) propellers indicates that this mechanism is unlikely to cause significant resuspension. Information on velocities generated by other types of propeller designs is currently unavailable (e.g., Z-drive and cycloidal); therefore, the potential differences in scour potential are not known.
- **Residual contamination from remedy implementation.** Recontamination of dredged areas can occur due a variety of processes including deposition of sediment resuspended during the dredging or disposal process, incomplete removal of sediment, and slumping of excavation sidewalls. Evaluation of recontamination potential due to these processes was outside the scope of the sediment transport study.

- **Inaccuracies in the site-specific natural recovery model.** A natural recovery model was used to predict post-remediation sediment concentrations in dredged areas, and expected time to achieve remedial goals through monitored natural recovery (URS, 2000). Inaccurate assumptions regarding any of the input parameters in the natural recovery model could have resulted in inaccurate predictions of post-remediation PCB concentrations in sediment, and/or effectiveness of monitored natural recovery. Tier 2 study data were used to help validate and refine the input parameters for the natural recovery model (TTEC, 2006).

The NAVFAC NW project team for the BNC site demonstration provided the following specific questions:

C.3.3.2.5 Is the conceptual model of localized sediment transport at BNC accurate?

The Tier 1 and Tier 2 evaluations confirm the conceptual model of localized sediment transport for BNC. Transport rates due to waves and tides are minimal, and sediments are expected to be stable in the absence of anthropogenic disturbance.

C.3.3.2.6 Can the input parameters used in the natural recovery model be validated or refined to increase confidence in the model results?

As noted above, the Tier 2 study data were used to help refine and validate input parameters for the natural recovery model (TTEC, 2006).

C.3.3.2.7 How do sediment transport patterns guide the determination of what, if any, additional remedial actions are necessary?

Given the lack of active transport in Sinclair Inlet, apparent recontamination of dredged areas does not appear to be caused by uncontrolled onsite or offsite sources of contamination, and additional source control actions do not appear to be necessary. Although propeller wash does not appear to be significant mechanism for sediment transport, additional study regarding potential scour from the types of vessels commonly used in BNC would clarify whether scour interferes with natural recovery processes.

C.3.3.3 Major Data Gaps and Uncertainties

Some of the remaining uncertainties associated with the characterization of sediment transport at BNC are as follows:

- Hydrodynamic measurements within the pier area at BNC were collected in the summer only, and may not represent conditions during other seasons. However, based on measurements collected by the USGS in Sinclair Inlet in winter and summer, conditions are not expected to be significantly different.
- The potential effects of extreme events (e.g., 100-year storm) were not evaluated as part of the Tier 1 or Tier 2 studies, but wind and wave effects are not anticipated as significant in the protected deep water piers during an extreme event. The water depths of 12 m and greater in the area of interest are not impacted by wind waves, and no data or anecdotal evidence indicate currents significantly larger than those measured.
- Net sediment deposition rate is a key parameter for the natural recovery model. All of the available radioisotope data are from cores located south of the pier area in Sinclair Inlet rather than from the pier area itself; therefore, they may not be representative of deposition rates within the piers. Additionally, the estimates of net deposition rates are variable, from 0.25 cm/yr

(average of eight ENVVEST cores from Sinclair Inlet and Dyes Inlet; Crecelius et al., 2003) to 0.91 cm/yr (maximum rate measured in a core collected for the RI; URS, 1999a). However, it could be difficult to collect intact cores for radioisotope analysis from the pier areas because of the potential for disturbance from anthropogenic activities.

- As noted above, additional study regarding the velocities generated by other types of propellers (e.g., Z-drive or cycloidal) would address uncertainty regarding the effects of ship activity within BNC.
- Conclusions regarding the quality of recently deposited sediment are based on a single sediment trap sample at each of four stations. Estimates of PCB and TOC concentrations in incoming sediment would be improved if additional samples were collected over all seasons.

These uncertainties can be considered in conjunction with the sediment transport study results and other information as part of planning potential future remedial activities in OU B Marine.

C.4 REFERENCES

- Crececius, E., R. Johnston, J. Leather, J. Guerrero, M. Miller, and J. Brandenberger. 2003. "Contaminant Mass Balance for Sinclair and Dyes Inlets, Puget Sound, Washington." Proceedings of the 2003 Georgia Basin Puget Sound Research Conference, Vancouver, BC, Canada. April 2.
- Dyer, K. R. 1997. *Estuaries: A Physical Introduction (2nd Edition)*. John Wiley and Sons, Chichester, England. 195 pp.
- Foster Wheeler Environmental Corporation. 2002. "Final Closure Report, OU B Marine Post Construction Report and FY00 MILCON Project P-338 Closure Report, Bremerton Naval Complex, Bremerton, Washington." November 26.
- Gartner, J. W., E. Prych, G. Tate, D. Cacchione, R. Cheng, W. Bidlake, and J. Ferreira. 1998. "Water Velocities and the Potential for the Movement of Bed Sediments in Sinclair Inlet of Puget Sound, Washington." U.S. Geological Survey Open-file Report 98-572.
- GeoSea Consulting Ltd. 1998. "A Sediment Trend Analysis (STA[®]) of Sinclair Inlet/Port Orchard." Prepared for URS Greiner. November.
- Katz, C. N., P. Noble, D. Chadwick, B. Davidson, and R. Gauthier. 1999. "Puget Sound Wastewater Technology Evaluation and Research Project: Sinclair Inlet Water Quality Assessment." SPAWAR Environmental and Applied Sciences Division.
- Maynard, S. T. 2000. "Physical Forces Near Commercial Tows: Report for the Upper Mississippi River-Illinois Waterway System Navigation Study." Env. Report 19, Interim Report. U.S. Army Corps of Engineers Research and Development Center, Vicksburg, MS.
- TetraTech EC Inc. (TTEC). 2006. "Draft Final Sediment Transport Study and Natural Recovery Model Report, Bremerton Naval Complex, Bremerton, Washington." May 24.
- URS Corporation (URS). 2000. "Technical Memorandum: Results of Modeling and Analysis of PCB Concentrations in Marine Sediments at the Bremerton Naval Complex, Bremerton, WA." June 13.
- URS Greiner (URS). 1999a. "Draft Final Remedial Investigation Report, Operable Unit B Marine, Bremerton Naval Complex, Bremerton, Washington." March 16.
- URS Greiner (URS). 1999b. "Draft Feasibility Study Report, Operable Unit B Marine, Bremerton Naval Complex, Bremerton, Washington." April 26.
- U.S. Navy. 1999. "Final EIR for Developing Home Port Facilities for Three NIMITZ-Class Aircraft Carriers in Support of the U.S. Pacific Fleet." Volumes 2-5."
- U.S. Navy, Washington Department of Ecology, and U.S. Environmental Protection Agency. 2000. Final Record of Decision, Bremerton Naval Complex Operable Unit B Marine, Bremerton, Washington." June 6.
- Wang, P. F. and K. Richter. 1999. "A Hydrodynamic Modeling Study Using CH3D for Sinclair Inlet: Final Report Prepared for Puget Sound Naval Shipyard." Marine Environmental Quality Branch, SPAWAR Systems Center San Diego.

C.5 ATTACHMENT—TIER 1 FLUX CALCULATIONS

The Navy conducted a study to assess the net flux of sediments in Sinclair Inlet using their Marine Environmental Survey Capability (MESC) (Katz et al., 1999). Current and suspended sediment data were collected along cross-sections at the mouth of Sinclair and Dyes Inlet over a full tidal cycle (Figure ATT-1). Flux calculations were performed to determine the amount of sediment moving through the system and the net direction of movement over a tidal cycle using the method outlined below, as described by Dyer (1997).

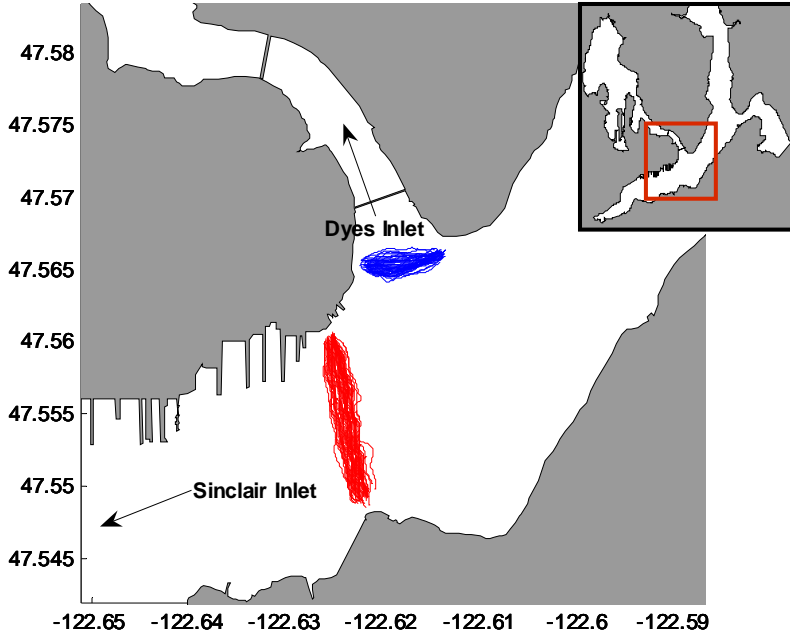


Figure ATT-1. Locations of transects used for the sediment flux calculation.

The instantaneous flux, F , through a section perpendicular to the mean flow is given by the equation:

$$F = \int_0^h uc \cdot dz = h \langle uc \rangle,$$

where u is the velocity, c is suspended-sediment concentration, dz is the depth interval between measurements and h is the depth (Dyer, 1997). The angle brackets denote averaging over the total depth and an overbar (i.e. \bar{u}) denotes an average over time. At any depth, $u = u_z + u'$ and $c = c_z + c'$, where u_z and c_z are the observed values at a given height above the bed, z , and u' and c' are the turbulent variations of these values. The values of u_z and c_z can also be evaluated as:

$$u_z = \langle u \rangle + u_v \text{ and } c_z = \langle c \rangle + c_v,$$

where u_v and c_v are deviations from the depth mean values. Over a tidal cycle, values for velocity and suspended-sediment can be evaluated as

$$\langle u \rangle = \bar{u} + U \text{ and } \langle c \rangle = \bar{c} + C,$$

where

$$\bar{u} = \frac{1}{T} \int_0^T \langle u \rangle \cdot dt \quad \text{and} \quad \bar{c} = \frac{1}{T} \int_0^T \langle c \rangle \cdot dt ,$$

where \bar{u} and \bar{c} are mean values of $\langle u \rangle$ and $\langle c \rangle$, respectively, over the tidal cycle, and U and C represent the deviation from the mean values over the tidal cycle. Thus, the instantaneous fluxes of sediment at evenly spaced intervals through the tidal cycle can be averaged over time, yielding a net mean flux, \bar{Q} , which can be broken down into several components, represented by the equation:

$$\bar{Q} = \bar{h} \cdot \bar{u} \cdot \bar{c} + \frac{1}{T} \int_0^T hUC \cdot dt + \frac{1}{T} \int_0^T h \langle u_v \cdot c_v \rangle dt + \frac{1}{T} \int_0^T h \langle u'c' \rangle dt$$

or

$$\begin{aligned} \bar{Q} &= \bar{h} \bar{u} \bar{c} + \overline{(hUC)} + \overline{h \langle u_v c_v \rangle} + \overline{h \langle u'c' \rangle} \\ &= Q1 + Q2 + Q3 + Q4. \end{aligned}$$

The first term, $Q1$, represents the contribution of the flux due to mean Eulerian flow. The second term, $Q2$, is referred to as tidal pumping, which arises from the phase differences between the mean velocity and suspended-sediment concentration through the tidal cycle. The third term, $Q3$, is the shear effect that arises from the variation of suspended-sediment concentration with velocity over depth. The fourth term, $Q4$, is caused by short period turbulent diffusion as a result of eddy diffusion. The value for this term is generally very small and can often be ignored (Dyer, 1997). For an accurate estimate of flux over a tidal cycle, velocity and suspended-sediment concentration values were determined for every lunar half-hour, or 0.0223 days.

Calculations show that the net \bar{Q} flux of sediment is directed into Sinclair Inlet and out of Dyes Inlet (see table). A breakdown of the flux components shows that the term $Q1$, representing the mean flow, is directed into Sinclair Inlet and out of Dyes Inlet. The tidal pumping term, $Q2$, is controlled by the variation in velocity and suspended sediment from the mean values as well as by changes in depth. $Q2$ is positive (into the inlet) for Sinclair Inlet and negative (out of the inlet) for Dyes Inlet. The tidal pumping effect was much stronger and also in a negative direction at Dyes Inlet as a result of higher suspended-sediment concentrations and stronger current velocities during the ebb tide, relative to the flood. The shear effect, $Q3$, is controlled by vertical variations in suspended-sediment concentration and current velocity. The Dyes Inlet transect has a very low $Q3$ values as a result of little vertical structure in suspended sediment concentration. The Sinclair Inlet transect, on the other hand, shows vertical stratification in both salinity and suspended sediment concentration throughout the tidal cycle resulting in a significant $Q3$ value. The sum of these terms for each anchor station results in the mean flux, \bar{Q} , showing an outward flux of sediments at Dyes Inlet and an inward flux at Sinclair Inlet. Fluxes were calculated at regularly spaced intervals across the transect, and then integrated to determine both the net instantaneous flux and the total flux of sediment over a tidal cycle.

Table ATT-1. Integrated mean fluxes and total flux per tidal cycle for the Sinclair and Dyes Inlets. A negative flux is out of the inlet and a positive flux is into the inlet.

	Sinclair Inlet (g/s)	Dyes Inlet (g/s)
Q1	112.8	3.2
Q2	27.8	-41.3
Q3	-19.3	0.0
\bar{Q}	121.3	-38.1
	Sinclair Inlet (kg)	Dyes Inlet (kg)
Total F	225.8	-70.9

C.5.1 ATTACHMENT REFERENCES

Katz, C. N., P. L. Noble, D. B. Chadwick, B. Davidson, and R. D. Gauthier. 1999. "Puget Sound Wastewater Technology Evaluation and Research Project: Sinclair Inlet Water Quality Assessment." SSC San Diego Environmental and Applied Sciences Division, SSC San Diego.

Dyer, K. R. 1997. *Estuaries: A Physical Introduction (2nd Edition)*. John Wiley and Sons, Chichester, England.

APPENDIX D

GOULD ISLAND, NAVAL STATION NEWPORT

CONTENTS

D.1 BACKGROUND	D-5
D.1.1 PROJECT HISTORY.....	D-5
D.1.2 SITE DESCRIPTION.....	D-6
D.1.2.1 Topography and Bathymetry	D-6
D.1.2.2 Hydrodynamic Processes.....	D-7
D.1.2.3 Sediment Properties	D-7
D.1.2.4 Biological Activity.....	D-9
D.1.3 SEDIMENT TRANSPORT CONCEPTUAL SITE MODEL	D-9
D.2 TIER 1 EVALUATION	D-13
D.2.1 TIER 1 RESULTS.....	D-13
D.2.1.1 Erosion and Resuspension.....	D-13
D.2.1.2 Deposition.....	D-19
D.2.1.3 Sediment Transport.....	D-20
D.2.2 TIER 1 CONCLUSIONS AND RECOMMENDATIONS	D-20
D.2.2.1 Sediment Management Questions	D-20
D.2.2.2 Major Data Gaps and Uncertainties	D-21
D.3 REFERENCES	D-23
ACRONYMS AND ABBREVIATIONS.....	D-29

Figures

D-1. Site location map and aerial photo of Gould Island taken in 1997; Building 32 is visible at the north end of the island.....	D-6
D-2. Site map of Gould Island showing the location of the RI sediment samples.....	D-8
D-3. PCB concentrations in surface sediment samples adjacent to Site 17.	D-10
D-4. PCB concentrations in surface sediment samples throughout the study area.....	D-11
D-5. Sediment Transport Conceptual Site Model for Gould Island.	D-12
D-6. Wind rose diagram for CMAN buoy BUZM3 showing frequency and direction of storm winds greater than 15 m/s. Outside ring shows wind direction in degrees and radial length is frequency of occurrence.	D-15
D-7. STWAVE domain for the study. Contours represent water depth in meters.	D-16
D-8. STWAVE domain in the region north of Gould Island. Contours represent water depth in meters.....	D-16
D-9. Significant wave heights for the 33 m/s north wind case.....	D-18
D-10. Significant wave heights for the 34 m/s north–northeast wind case.....	D-18
D-11. Bottom shear stresses for the 34 m/s north–northeast wind case.	D-19

Tables

D-1. Parameters for estimating erosion potential.....	D-14
D-2. Extreme wind predictions for a 100-year storm.....	D-15
D-3. Model results for wave height, wave period, and shear stress for Station SD312 in Stillwater Basin.....	D-17

D.1 BACKGROUND

Engineering Field Activity Northeast, Naval Facilities Engineering Command (NAVFAC) (now part of Atlantic Division NAVFAC) requested a Tier 1 sediment transport evaluation to support the remedial investigation (RI) of the offsite portion of Site 17 (Building 32), Gould Island, Naval Station Newport, Newport, Rhode Island. The Tier 1 evaluation was performed following the methodology presented in the User's Guide for Assessing Sediment Transport at Navy Facilities (User's Guide). The results of the Tier 1 evaluation and recommendations for additional investigation to address key sediment management questions are presented in this site demonstration report.

The report is organized according to the framework provided in Section 1.1 of the User's Guide. Section D-1 presents a site description and conceptual site model (CSM) for sediment transport. Section D-2 presents the Tier 1 sediment transport evaluation and discusses the application of the results to sediment management questions. References are provided in Section D-3.

D.1.1 PROJECT HISTORY

Gould Island is located in the East Passage of Narragansett Bay, 1.5 miles west of Newport (Figure D-1). The island is 52 acres in size, and Site 17 (the former Building 32 area) occupies 6 acres at the north end of the island. Gould Island also has a formerly used defense site (FUDS) operated by the U.S. Army Corps of Engineers that is being evaluated for the presence of contamination.

Site 17 was developed in the early 1940s. The site was primarily occupied by Building 32, a torpedo overhaul shop that included electroplating, torpedo service and maintenance, machine shops, degreasing shops, and grinding/buffing shops. The facility was operated primarily during World War II and was inactive after the 1950s. Building 32 was demolished in 2001–2002. Site 17 also includes former underground storage tanks, polychlorinated biphenyl (PCB) transformer buildings, and former material storage areas.

Solvent and electroplating wastes were apparently discharged from Building 32 to Narragansett Bay on the east side of Gould Island via a floor drain system. Additionally, a number of sewer, stormwater, and wastewater outfalls discharged to the bay on the east and west sides of the island. Discharge of wastes via the outfall pipes was once likely to be a significant source of contaminants to the nearshore area around Gould Island; however, these sources are no longer active.

Contaminants of potential concern identified for Site 17 include solvents, fuel-related compounds, metals, and PCBs. An RI was performed in 2005–2006 to determine the nature and extent of contamination associated with the past use and disposal of chemicals at Site 17 (TtNUS, 2006).

D.1.2 SITE DESCRIPTION

The first step in the Gould Island sediment transport study was to compile a site description of the offshore area based on previous investigations, including the RI. These studies provided the baseline data for the sediment transport CSM and Tier 1 sediment transport evaluation.

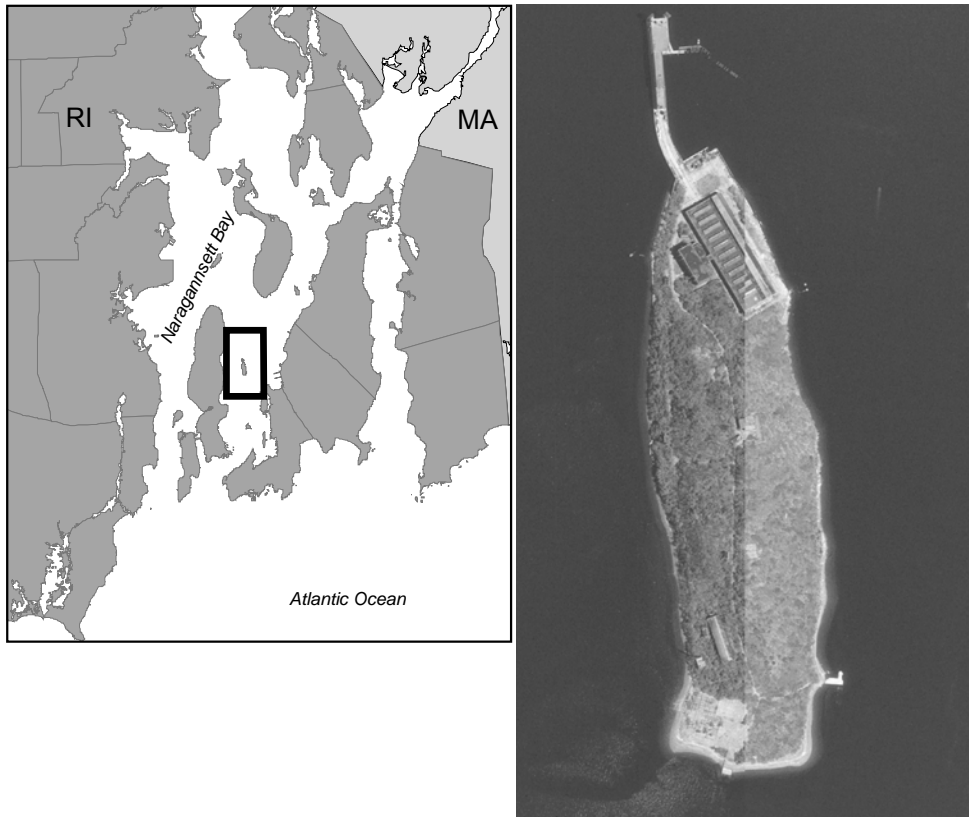


Figure D-1. Site location map and aerial photo of Gould Island taken in 1997; Building 32 is visible at the north end of the island.

D.1.2.1 Topography and Bathymetry

Gould Island is composed of bedrock covered with a thin layer of topsoil. The north end of the island is an exposed point of land, with a breakwater extending to the north and east, forming a partially protected area referred to as the Stillwater Basin (Figure D-1). The water depth in the boat basin is approximately 6 m. The intertidal zone is steep, and the water depth increases to greater than 20 m off the east and west sides of the island.

The intertidal shoreline along the east side of Site 17 consists of a deteriorated steel sheetpile wall backfilled with boulders and broken concrete. The shoreline at the north end of the island in the Stillwater Basin consists of a partially collapsed former rigging platform. The northwest shore of the island consists of a stony beach face. Most of the shoreline is exposed to wave action, except for the partially protected Stillwater Basin at the north end of the island.

D.1.2.2 Hydrodynamic Processes

Narragansett Bay is a partially to well-mixed estuary. Strong tidal motions and highly variable bottom topography result in a well-mixed water column (Kincaid, Ellis, and DeLeo, 1996). Freshwater input is at a maximum in the winter and spring, and at a minimum in the late summer and fall. The salinity gradient in the bay is from north to south.

Narragansett Bay has an average depth of 9 m, with a maximum depth in the East Passage of 57 m. Circulation patterns in Narragansett Bay are oriented north–south and are driven primarily by tides. Residual flow is to the south. Secondary circulation is driven primarily by the wind. Prevailing winds are from the southwest in the summer and the northwest in the winter. It has been reported that wind events can permeate the entire water column and at times provide more force than tidal flow in the bay (Weisberg, 1976).

Gould Island is subject to prevailing wind exposure and currents almost year-round. Based on field observations, maximum tidal current velocities are between 25 and 50 cm/s at the southern end of the island (TtNUS, 2006). The presence of sand deposits in intertidal and subtidal areas at the south end of the island could suggest that there is a net southern transport of sediment along both sides of the island. A 1943 aerial photograph of the island shows sand deposits on the north sides of piers, which also indicates the southward transport of sediment along the shoreline.

Sediment deposition is not evident in the intertidal areas adjacent to Site 17, except in the Stillwater Basin at the north end of the island. Net sediment accumulation rates in Coddington Cove, approximately 3 km to the east, were estimated to be up to 2.2 cm/year (SAIC and URI, 1997). However, deposition rates in the Stillwater Basin are anticipated to be lower, based on its higher energy location in the center of the East Passage.

D.1.2.3 Sediment Properties

A field investigation was conducted as part of the RI between May and September 2005 (TtNUS, 2006). The field effort included an underwater video survey and non-invasive eelgrass survey in addition to sediment sample collection and analysis. The underwater video survey provided information about bottom sediment type, aquatic vegetation, biota, and presence of debris. The eelgrass survey defined a narrow band of eelgrass up to 30 m in width on the east and west sides of the northern end of Gould Island.

Sediment samples were collected from 25 stations located in the subtidal and intertidal zones along the shoreline of Gould Island. Sixteen stations were located proximal to the existing or suspected terminus of each outfall pipeline. Nine additional stations were located downgradient (south) of outfall pipelines and presumed release points. Sample locations are in Figure D-2.

Fifty-seven surficial sediment samples (0 to 15 centimeters [cm]) were collected; 49 from subtidal locations and eight from intertidal locations. Nine additional subsurface samples (15 to 30 cm) were collected from subtidal locations, where substrate conditions permitted. Sediment samples were analyzed for grain size distribution, total organic carbon (TOC), volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), polynuclear aromatic hydrocarbons (PAHs), pesticides and PCBs, metals, cyanide, gasoline-range and diesel-range organics (GRO/DRO), and acid volatile sulfides/simultaneously extractable metals (AVS/SEM). In addition, measurements of the surface water temperature, pH, specific conductivity, dissolved oxygen, and salinity were collected at each sediment sample location.



Figure D-2. Site map of Gould Island showing the location of the RI sediment samples.

Sediment sample results from the RI indicate that grain size distribution varies based on the general location within the study area (TtNUS, 2006). Overall, coarse-grained materials (that is, sand or gravelly sand) are the predominant sediment type. The sand and gravel content in RI samples ranged from 48 to 96 percent. In general, gravel comprises a larger component of the nearshore intertidal sediment, with gravel content decreasing with increasing distance from the shoreline into the subtidal zone.

The only fine-grained samples were collected in the Stillwater Basin, where the fines content (silt and clay) ranged from 25 to 51 percent of sediment. The average values for percent fines were approximately 13 percent for the northeast and northwest sides of the island, 36 percent for the Stillwater Basin, and 9 percent for the samples collected in the south part of the

island. Average TOC content was 0.7 to 0.9 percent in sediment samples from the northeast, northwest, and southern sides of the island, and 1.7 percent in samples from the Stillwater Basin.

Contaminant concentration data indicate that PCBs, PAHs, and several metals were elevated above benchmark values at specific locations along the shoreline and in the subtidal sediment. Samples with elevated contaminant concentrations were located primarily in the Stillwater Basin and along the northeast shoreline. Figures D-3 and D-4 show the distribution of PCBs in surface sediment samples at the north end of the island and the entire island, respectively. Aroclor 1260 was the only PCB detected in sediment. PCB concentrations were highest in samples from the Stillwater Basin, with a maximum of 41,000 micrograms per kilogram ($\mu\text{g}/\text{kg}$) detected in the sample from Station SD312. Concentrations greater than 1,000 $\mu\text{g}/\text{kg}$ were measured in samples from the subtidal area adjacent to the former ferry slip (Stations SD304 and SD305). PCB concentrations were relatively lower in surface sediments between the Stillwater Basin and the former ferry slip, which suggests that a concentration gradient from north to south is not present. PCB concentrations also appear to decrease south of the former ferry slip, although no sample data are available for the area between Stations SD304 and SD303 on the east side of the island (Figure D-4).

The distribution of the PCBs in sediment appears to correlate to upland areas where PCBs were removed from the site in 1999–2002. The presence of PCBs in sediment most likely originated from the former waste discharge system and/or overland runoff from upland release areas. Shoreline erosion of PCB-contaminated soils also may have contributed to offshore contamination, particularly in the area near the former rigging platform at the north end of the site where a release occurred in the past (TtNUS, 2006).

D.1.2.4 Biological Activity

Species observed by the sampling team during the RI included a variety of invertebrate and fish species. Invertebrate species included quahogs (*Mercenaria mercenaria*), mussels (*Mytilus edulis*), a soft shell clam (*Mya arenaria*), hairy sea cucumbers (*Sclerodactyla briareus*), lobsters (*Homarus americanus*), purple sea urchins (*Arbacia punctulata*), and several species of crabs. Fish species included cunner (*Tautogolabrus adspersus*), tautog (*Tautog onitis*), scup (*Stenotomus chrysops*), striped bass (*Morone saxatilis*), summer flounder (*Paralichthys dentatus*), winter flounder (*Pleuronectes americanus*), menhaden (*Brevoortia tyrannus*), and silversides (*Menidia sp.*). In addition, a tropical transcient, snowy grouper (*Epinephelus niveatus*), also was observed at one sediment station (SD303).

D.1.3 SEDIMENT TRANSPORT CONCEPTUAL SITE MODEL

The sediment transport conceptual site model for Gould Island is presented in Figure D-5. Gould Island is subject to prevailing wind exposure and currents almost year-round. Based on field observations, tidal current velocities around the island are a maximum of 25 to 50 cm/s at the southern end of the island. Residual flow in Narragansett Bay is to the south.

Most of the shoreline is exposed to wave action, although the breakwater at the north end of the island partially protects the Stillwater Basin. However, the presence of eelgrass beds on the eastern and western shorelines adjacent to Site 17 suggests that the impacts from waves and currents are being attenuated, and that no net erosion of the near-shore sediments is occurring.

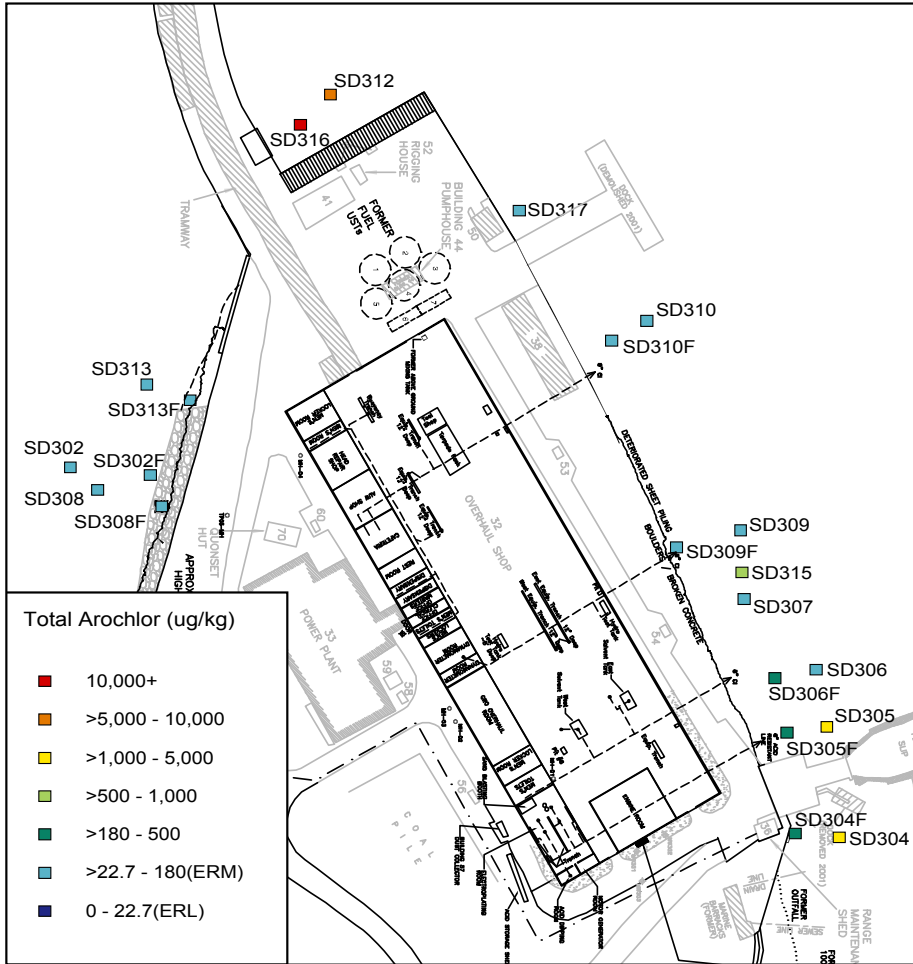


Figure D-3. PCB concentrations in surface sediment samples adjacent to Site 17.

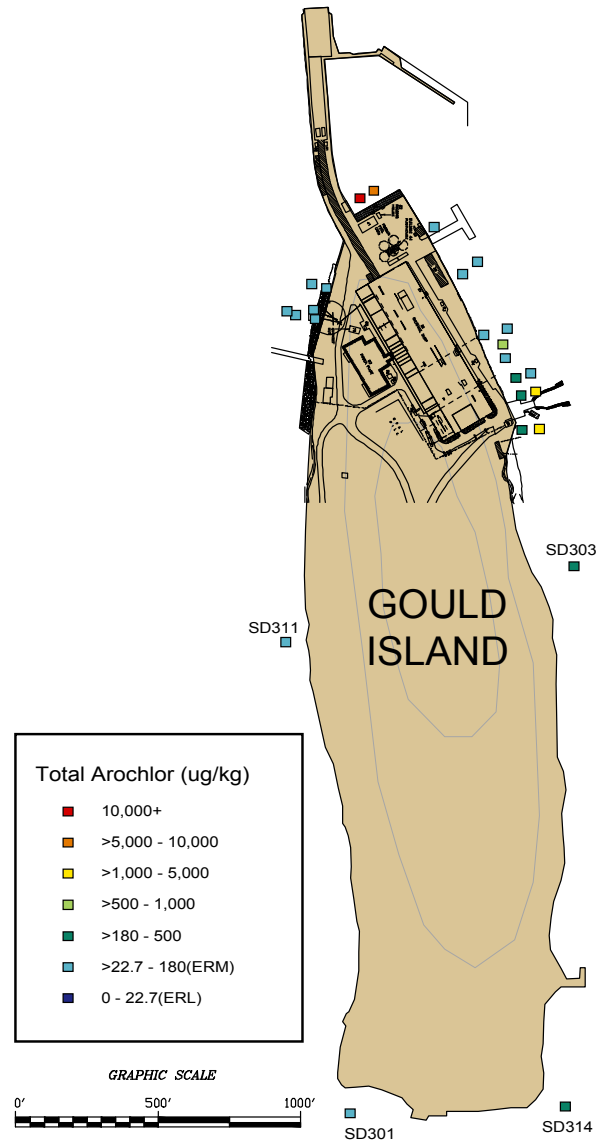


Figure D-4. PCB concentrations in surface sediment samples throughout the study area.

Sediment accumulation is not evident in the intertidal and subtidal areas adjacent to Site 17, except in the Stillwater Basin at the north end of the island. Sediments are generally composed of sand or gravelly sand with less than 15 percent silt and clay, except in the Stillwater Basin where silt and clay content increases to an average of about 36 percent. Along the northeast shoreline, wind waves prevent fine-grained sediments from depositing, resulting in a sandy bottom.

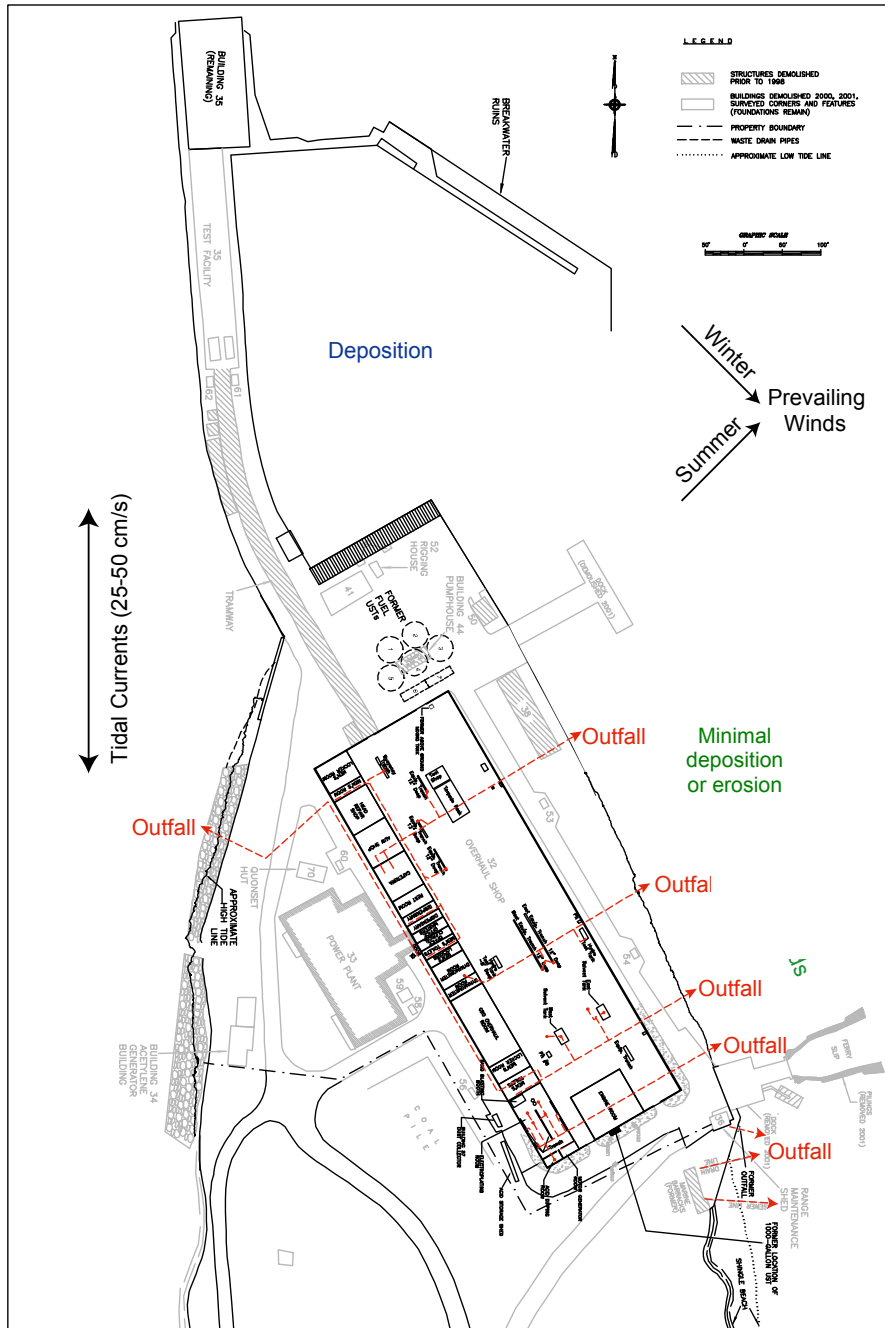


Figure D-5. Sediment Transport Conceptual Site Model for Gould Island.

D.2 TIER 1 EVALUATION

A Tier 1 sediment transport evaluation was conducted to support interpretation of the RI data for sediments adjacent to Site 17 and address sediment management questions that may be relevant for the site.

D.2.1 TIER 1 RESULTS

Existing data were used to characterize sediment erosion and resuspension, transport, and deposition using the methods outlined in Section 3 of the Users Guide. Tier 1 results are presented below.

D.2.1.1 Erosion and Resuspension

The potential for sediment erosion and resuspension due to tidal circulation and wind-generated waves was evaluated. The wave analysis included consideration of extreme storm conditions.

D.2.1.1.1 Erosion Potential Due to Tidal Circulation

The Site 17 RI (TtNUS, 2006) provided information about the hydrodynamic and sediment properties important for evaluating the potential for erosion along the Gould Island shoreline. Erosion potential was evaluated at RI Stations SD304, SD305, SD312, and SD316 because of the relatively higher PCB concentrations that were measured in samples from these stations (Figures D-3 and D-4). Table 1 summarizes the parameters used for estimating the erosion potential at each station due to tidal currents. Current velocities were taken from Spalding, Swanson, and Turner (1990) and represent maximum current speeds during mid-ebb flow. Currents are most likely much lower in the Stillwater Basin; however, no data were available for the basin so the shoreline current estimates were used.

Mean particle diameters show that sediments at Stations SD304 and SD305 are medium-grained sands, and sediments at Stations SD312 and SD316 are very fine-grained sands. Based on these parameters, the bottom shear stress, d^* (dimensionless particle diameter), and critical shear stress were calculated using the methods outlined in Section D.3.4.1 of the User's Guide. Results of these calculations show that the bottom shear stress is the same order of magnitude as the critical shear stresses, which indicates that transport of bed sediments due to tidal currents under typical hydrodynamic conditions is possible. This result is consistent with the coarse grain sizes observed during the RI.

Table D-1. Parameters for estimating erosion potential.

	Station			
	304	305	312	316
Maximum Current velocity (knots)*	0.6	0.6	0.6	0.6
Current velocity (m/s)	0.31	0.31	0.31	0.31
Median particle diameter (μm)	254	308	162	104
Bottom Shear Stress (Pa), τ	0.29	0.29	0.29	0.29
d* (dimensionless particle diameter)	5.79	7.02	3.69	2.37
Critical Shear Stress (Pa), τ_{ce}	0.18	0.19	0.17	0.17

* Spaulding, Swanson and Turner (1990); mid-ebb flow (as quoted in RI field documentation, App. E-2)

D.2.1.1.2 Extreme Event Analysis

The potential for resuspension of sediments in the Stillwater Basin due to wave activity, including under extreme storm conditions, was also evaluated because of concerns about high PCB levels measured in sediment samples from Stations SD312 and SD316 (Figure D-3). Gould Island is subjected to frequent winter storms and occasional hurricanes. The most powerful regional storm is a nor'easter with strong winds blowing out of the north or northeast. This type of storm has the potential to produce large waves in the vicinity of Gould Island because of the large fetches (the unsheltered distance over which the wind is blowing) in those directions (10 to 12 km). Strong winds blowing from other directions have less of an impact on Gould Island because the fetch lengths in those directions are much smaller. The potential impacts of winds from the north and north-northeast on sediments in the Stillwater Basin were evaluated in this analysis.

An analysis was conducted of local winds to determine the frequency and direction of winds in the region. Wind data from the National Oceanographic and Atmospheric Administration (NOAA) National Data Buoy Center C-MAN buoy BUZM3 located south of Buzzard's Bay, MA (southeast of Narragansett Bay, RI) were used because this buoy provides the longest nearly-continuous record for the region. The record length used was from 1986 to 2005, with a data gap for 1995 and 1996. These results show dominant storm winds from the north-northeast and the west-northwest (Figure D-6). Because the north and northeast shores of Gould Island are protected from westward wind-waves, only the effect of wind-waves from the north and north-northeast were considered.

The extreme wind event for the region was assumed to be the 100-year return period wind. A statistical analysis was conducted on the C-MAN wind record to predict the 100-year wind magnitudes for the north and northeast direction following the methods outlined in Goda (2000). The corresponding extreme wind predictions are provided in Table D-2.

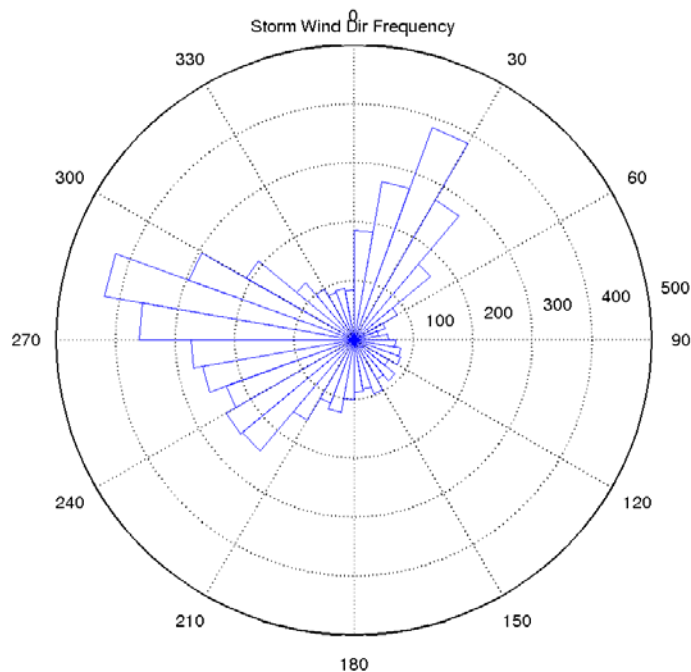


Figure D-6. Wind rose diagram for CMAN buoy BUZM3 showing frequency and direction of storm winds greater than 15 m/s. Outside ring shows wind direction in degrees and radial length is frequency of occurrence.

Wind-wave propagation from each direction was modeled with STWAVE (STeady state spectral WAVE), an extensively validated wind-wave generation and wave propagation model developed by the U.S. Army Corps of Engineers (USACE) (Smith, 1999). For the present study, a 15-m x 15-m rectangular grid was generated to encompass most of Narragansett Bay. Due to the enclosed nature of the bay, swell from the Atlantic Ocean is considered negligible; therefore, wind was used as the primary driving force behind wave generation.

Table D-2. Extreme wind predictions for a 100-year storm.

Wind Direction	Predicted Wind Speed (m/s)	90% Confidence Intervals
North	33	±4 m/s
North-northeast	34	±4 m/s

Two cases were modeled for each specified direction: (1) A typical storm case (15 m/s wind), and (2) a 100-year wind storm case (33-34 m/s wind, Table 2). The bathymetry for the model was obtained from a public Narragansett Bay database (<http://www.narrbay.org/>) and interpolated onto the model grid. Figures D-7 and D-8 show the final model domain with bathymetric contours. The north end of Gould Island is denoted at the bottom of the domain. For each modeled scenario, the wind was applied from the two directions of interest for the typical storm and extreme storm cases. STWAVE was used to calculate the significant wave heights for each set of parameters. The following section describes the results for each case.

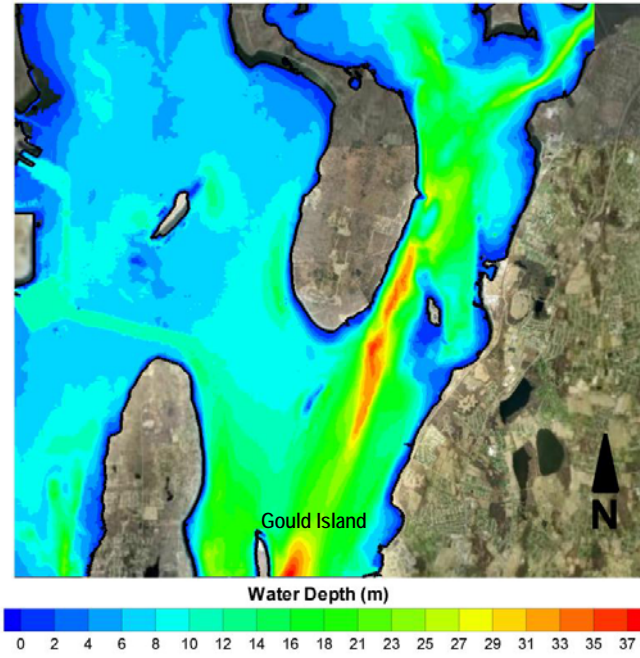


Figure D-7. STWAVE domain for the study. Contours represent water depth in meters.

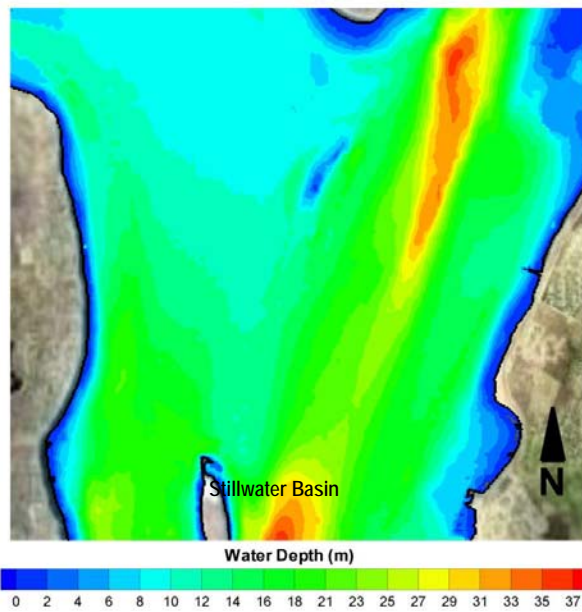


Figure D-8. STWAVE domain in the region north of Gould Island. Contours represent water depth in meters.

The potential for resuspension of sediments in Stillwater Basin was evaluated for Station SD312, which is offshore of the bulkhead in about 2.1 m of water. Table D-3 lists the wave height and period results from the STWAVE model at Station SD312. The shear stresses in Table 3 were calculated using the Christoffersen and Jonsson (1985) wave-generated shear stress model using a roughness generated by particles in the very fine sand range. The sediment roughness range was chosen from measurements of the particle size distribution in sediment samples from SD312.

Table D-3. Model results for wave height, wave period, and shear stress for Station SD312 in Stillwater Basin.

Case	Wind Direction	Wind Magnitude (m/s)	Wave Height (m)	Wave Period (s)	Shear Stress (dynes/cm ²)
1	North	15	0.3	3.4	10.0
2	North	33	0.9	4.8	47.0
3	North-Northeast	15	0.3	3.3	9.8
4	North-Northeast	34	1.2	5.0	65.0

The significant wave height predictions resulting from the 100-year estimated wind speeds are shown in Figures D-9 and D-10. The largest significant wave heights at Gould Island are predicted to reach approximately 2 m during a north wind in water depths of greater than 10 m. In the Stillwater Basin, which is shallower and partially protected by the pier structure to the north, the wave heights are significantly smaller.

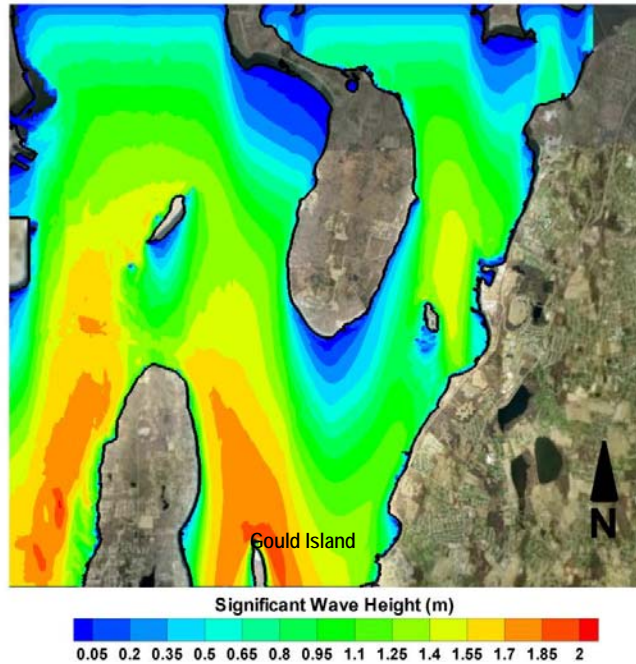


Figure D-9. Significant wave heights for the 33 m/s north wind case.

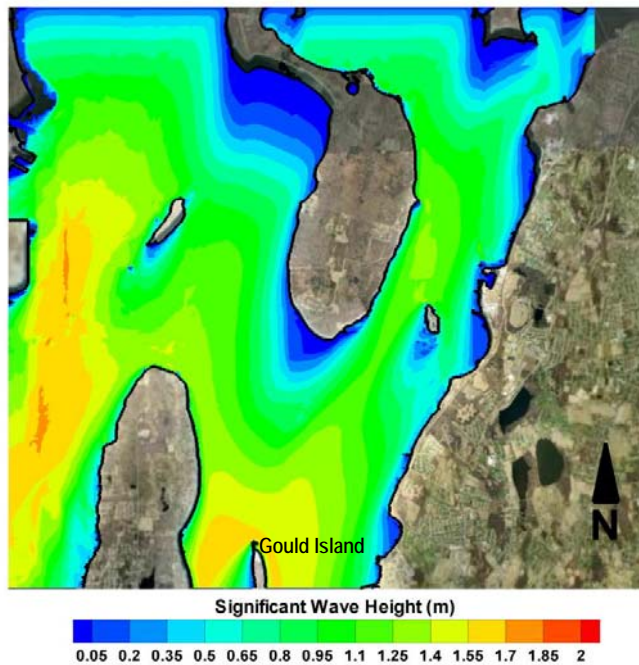


Figure D-10. Significant wave heights for the 34 m/s north–northeast wind case.

Although the north wind produces the largest wave heights in Narragansett Bay, the extreme north–northeast winds generate waves that propagate more wave energy into Stillwater Basin. Figure D-11 shows the shear stresses for the north–northeast wind. The highest shear stresses occur in the shallow regions of the bay where waves begin to shoal and eventually break. The shoreline in Stillwater Basin experiences higher shear stresses due to this shoaling and breaking

of waves from the north–northeast. Note that the entire northeast portion of the island experiences high shear stresses during storm events.

Based on the summary of conditions at Stations SD312 and SD316 in Stillwater Basin (Table D-1), the waves are expected to produce shear stresses high enough during all of the storm cases to initiate sediment erosion. Although the potential depth of erosion cannot be calculated with the available data, the STWAVE modeling effort demonstrates the likelihood for periodic sediment erosion during storm events. The potential for periodic sediment erosion does not necessarily indicate net long-term erosion at the site. Based on other lines of evidence such as the presence of silt and clay particle sizes and the very low tidal circulation, it still appears that Stillwater Basin has been a net depositional environment over the long-term.

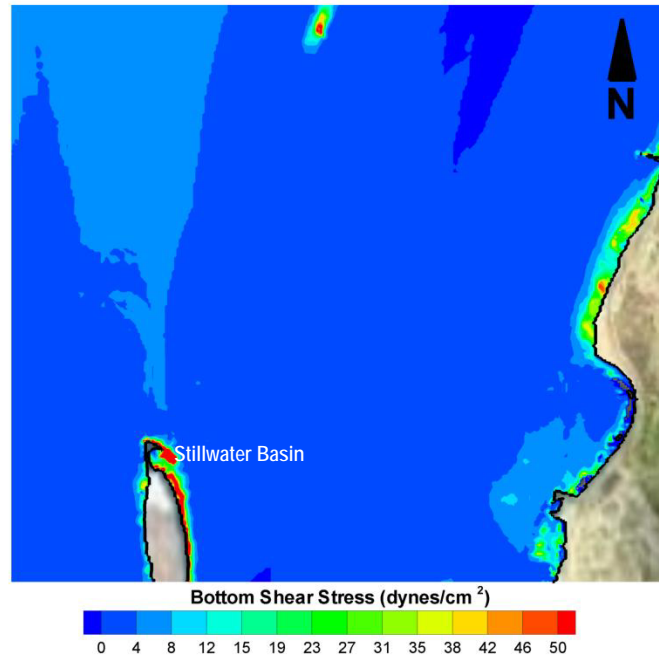


Figure D-11. Bottom shear stresses for the 34 m/s north–northeast wind case.

D.2.1.2 Deposition

Based on underwater video surveys, no depositional areas were observed along the eastern and western shorelines of Site 17. The relatively coarse grain sizes observed on the sediment bed suggest that deposition is not occurring in these areas. Evidence exists, however, of some deposition at the north end of the island in the Stillwater Basin. Grain sizes are finer in samples from the basin, and the protected environment would facilitate sediment trapping. Sources of sediments to the basin include suspended sediments advected in from Narragansett Bay, runoff from Gould Island, and shoreline slumping.

Suspended sediment concentrations in Narragansett Bay are relatively low (1 to 5 mg/L; Morton, 1972). The highest probability for deposition is in the Stillwater Basin, where currents are expected to decrease. The deposition rate can be estimated using the methods outlined in Section 3.4.3 of the Users Guide, although the grain size of suspended material is not known. Using the mean particle diameters measured at the stations in the basin (Table D-1), deposition

rates of 36 and 16 cm/year at Stations SD312 and SD316 were calculated. These rates are extremely high and not likely to be accurate. It is likely that suspended sediment particles are finer than those found on the sediment bed, which would result in lower deposition rates. As previously noted, net deposition rates in Coddington Cove approximately 3 km to the east are on the order of 2 cm/year.

D.2.1.3 Sediment Transport

Visual field observations made during the RI indicated that suspended sediment concentrations are low. Morton (1972) supports this observation, reporting concentrations of 1 to 5 mg/L. Therefore, sediment transport appears to be negligible, and it appears that neither appreciable erosion nor deposition of sediments is occurring along the shoreline. PCB concentrations do not show a clear gradient and do not appear to indicate that the transport of contaminated materials is taking place. Moreover, the comparison of estimated bottom shear stresses with critical shear stress indicates that resuspension and subsequent transport is unlikely to occur under typical hydrodynamic conditions.

D.2.2 TIER 1 CONCLUSIONS AND RECOMMENDATIONS

Tier 1 results regarding sediment transport were used to address the four general sediment management questions presented in Section 1.1 of the Users Guide and identify any key data gaps that could be addressed in future sampling efforts.

D.2.2.1 Sediment Management Questions

The general sediment management questions are discussed below based on Tier 1 results.

D.2.2.1.1 Could Erosion of the Sediment Bed Lead to the Exposure of Buried Contamination?

Subsurface sediment data were not collected as part of the RI; therefore, the existence of buried contamination has not been established. However, based on the Tier 1 analyses for Gould Island, it does not appear that significant erosion of the sediment is occurring at the site in response to tidal circulation. Calculations show that under maximum tidal conditions, the critical shear stress for erosion is just exceeded, but not likely to sustain widespread erosion.

The extreme event analysis indicates that storm-generated waves may produce shear stresses high enough to initiate sediment erosion in the Stillwater Basin. The potential depth of erosion cannot be calculated with the available data. However, the potential for periodic sediment resuspension does not necessarily indicate that net long-term erosion occurs. The Stillwater Basin appears to be a net depositional environment based on the presence of finer-grained sediment relative to the rest of the study area, and the low current speeds within the basin. The potential for erosion based on anthropogenic activities (such as ship movements) was not evaluated due to lack of data.

D.2.2.1.2 Will Sediment Transport Lead to the Redistribution of Contamination within the Site or Movement of Contamination Off Site?

It does not appear that the active transport of sediments is occurring under typical hydrodynamic conditions. Currents along the Gould Island shoreline do not appear to be high

enough to resuspend and transport sediments. Although sediments in the Stillwater Basin may be resuspended by waves during storms, most of the sediments are probably re-deposited within the basin due to the low tidal currents. However, the breakwater that protects the basin is in a deteriorated state, and its failure could increase the probability for sediments to be eroded and redistributed both within the site and offsite.

D.2.2.1.3 Will Natural Processes Lead to the Burial and Isolation of Contamination by Relatively Clean Sediment?

No depositional areas (areas of fine sediment deposits) were observed during the underwater video survey, with the exception of the Stillwater Basin. The sediment deposition rate in the Stillwater Basin is unknown, as is the quality of sediments that may be depositing on the sediment bed. However, PCB concentrations in surface sediment adjacent to the former rigging platform are extremely high (that is, up to 41,000 $\mu\text{g}/\text{kg}$); therefore, natural recovery does not appear to be occurring.

D.2.2.1.4 If a Site is Actively Remediated, Could Sediment Transport Lead to the Recontamination of the Site?

At the current time, it does not appear that a significant amount of sediment transport is occurring at the site. No evidence of either significant erosion or deposition was seen in the subtidal areas of Gould Island. Deposition does appear to be occurring in the Stillwater Basin; however, the absence of suspended particle data prevents determination of whether particles available for deposition are clean or if there may be an active source of contaminants to sediment.

D.2.2.2 Major Data Gaps and Uncertainties

The key data gaps and uncertainties that were identified during the Tier 1 evaluation are as follows:

- **More extensive vertical and spatial delineation of contaminant concentrations.** Higher resolution vertical and horizontal contaminant concentration gradients could provide information to infer sediment transport patterns. Areas of particular interest based on the RI data are the Stillwater Basin and the area adjacent to the former ferry slip along the northeast shoreline.
- **Currents and waves along the northeast shoreline and in the Stillwater Basin.** Although some hydrodynamic data are available for Narragansett Bay, wave and current measurements have not been taken in the immediate vicinity of the Gould Island shoreline and in the Stillwater Basin. Site-specific hydrodynamic data, in conjunction with sediment erosion rate (that is, Sedflume) data, could provide more accurate estimates of sediment transport in the immediate vicinity of the site.

Radioisotope analysis of sediment cores to establish sediment accumulation rates is not likely to be successful at Gould Island because the sediments along the northeast shoreline are sandy, and sediments within the Stillwater Basin have most likely been disturbed by construction and boat activity.

As discussed in the User's Guide, the decision about whether a Tier 2 evaluation is required must consider the level of uncertainty associated with the Tier 1 analysis, and the potential

consequences from a risk and cost perspective of making an incorrect site management decision based on the Tier 1 analysis. Because the extent of contamination and associated level of risk have not been established for Gould Island sediments, it is not clear whether additional site-specific sediment transport data are needed to refine the answers to the sediment management questions discussed above. For example, if the extent of contamination in sediment is limited to relatively small and well-defined hot spots, then additional sediment transport data are probably not needed to support management decisions. However, if the sediments within the Stillwater Basin are more extensively contaminated, then additional site-specific sediment transport data could be collected to evaluate potential remobilization in the event that the breakwater is breached or removed. Consequently, the need for a focused Tier 2 evaluation should be evaluated after additional information on the nature and extent of sediment contamination and associated risk is available.

D.3 REFERENCES

- Christoffersen, J., and I. Jonsson. 1985. "Bed Friction and Dissipation in a Combined Current and Wave Motion," *Ocean Engr.*, 17(4): 479–494.
- Goda, Y. 2000. "Random Seas and Design of Maritime Structures," World Scientific. Advanced Series on Ocean Engineering. Volume 15.
- Kincaid, C., W. Ellis, and W. DeLeo. 1996. "Hydrographic Survey for the Offshore Ecological Risk Assessment at Derecktor Shipyard/Coddington Cove, Newport, Rhode Island." Derecktor Shipyard Marine Ecological Risk Assessment, Department of the Navy (Northern Division). Technical Report, Vol. III, Appendix D.
- Morton, R. W. 1972. "Spatial and Temporal Distribution of Suspended Sediment in Narragansett Bay and Rhode Island Sound." *Geological Society of America Memoirs*, 133:131–141.
- SAIC and The University of Rhode Island (URI). 1997. "Final Derecktor Shipyard Marine Ecological Risk Assessment Report." Comprehensive Long-Term Environmental Action Navy Contract. May.
- Smith, J. M., D. T. Resio, and A. K. Zundel. 1999. "STWAVE: Steady-State Spectral Wave Model; Report 1: User's Manual for STWAVE Version 2.0," Instructional Report CHL-99-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS.
- Spaulding, M., C. Swanson, and C. Turner. 1990. "The New Tides & Currents of Narragansett Bay." University of Rhode Island Marine Technical Report No. 35. Second Revision. Rhode Island Sea Grant, Narragansett, RI.
- TetraTech (TtNUS). 2006. "Remedial Investigation for Site 17: Building 32, Gould Island." Naval Station Newport, Newport, Rhode Island. Comprehensive Long-Term Environmental Action Navy Contract.
- Weisberg, R. H. 1976. "The Nontidal Flow in the Providence River of Narragansett Bay: A Stochastic Approach to Estuarine Circulation," *J. Phys. Oceanogr.*, 6, 721–73.

ACRONYMS AND ABBREVIATIONS

µg/kg	micrograms per kilogram
µm	micrometer
AVS/SEM	acid volatile sulfides/simultaneously extractable metals
cm	centimeter
cm/s	centimeters per second
cm/year	centimeters per year
CSM	conceptual site model
d*	dimensionless particle diameter
DRO	diesel-range organic
FUDS	formerly used defense site
GRO	gasoline-range organic
km	kilometer
m/s	meters per second
mg/L	milligrams per liter
NAVFAC	Naval Facilities Engineering Command
PAH	polynuclear aromatic hydrocarbon
PCB	polychlorinated biphenyl
RI	remedial investigation
SVOC	semivolatile organic compound
TOC	total organic carbon
VOC	volatile organic compound

Approved for public release; distribution is unlimited.