Review

Assessing and Managing Contaminated Sediments: Part I, Developing an Effective Investigation and Risk Evaluation Strategy

Sabine E. Apitz,† John W. Davis,‡ Ken Finkelstein,§ David W. Hohreiter,‖ Robert Hoke,# Richard H. Jensen,†† Joe Jersak,‡‡ Victoria J. Kirtay,§§ E. Erin Mack,†† Victor S. Magar,‖‖ David Moore,## Danny Reible,††† and Ralph G. Stahl, Jr.††*

†SEA Environmental Decisions, 1 South Cottages, The Ford, Little Hadham, Hertfordshire, SG11 2AT, United Kingdom
‡Toxicology & Environmental Research Laboratory, The Dow Chemical Company, 1803 Building, Midland, Michigan 48674, USA
§NOAA, c/o U.S. Environmental Protection Agency Office of Site Remediation & Restoration (HI0), 1 Congress Street – Suite 1100, Boston, Massachusetts 02114-2023
‖BBL Sciences, 6723 Towpath Road, P.O. Box 66, Syracuse, New York 13214, USA
#E.I. du Pont de Nemours, Haskell Laboratory for Health and Environmental Sciences, P.O. Box 50, 1090 Elkton Road, Newark, Delaware 19714, USA
††E.I. du Pont de Nemours, Corporate Remediation Group, Barley Mill Plaza #27, Route 141 and Lancaster Pike, Wilmington, Delaware 19805, USA
‡‡Hull & Associates, 3401 Glendale Avenue – Suite 300, Toledo, Ohio 43614, USA
§§Space and Naval Warfare Systems Center, San Diego, Div 2361, 53475 Strothe Road, Rm 267D, San Diego, California 92152, USA
‖‖Battelle Memorial Institute, 505 King Ave. Room 10-1-27, Columbus, Ohio 43201-2693, USA
##MEC Analytical Systems, 2433 Impala Drive, Carlsbad, California 92009, USA
†††Hazardous Substance Research Center, Louisiana State University, 3221 CEBA, Baton Rouge, Louisiana 70803, USA

(Received 10 December 2003; Accepted 19 July 2004)

EDITOR'S NOTE:

This is the first of a two-part review article on the assessment and management of contaminated sediments. Part II, "Evaluating Risk and Monitoring Sediment Remedy Effectiveness," is available in the online edition of IEAM Volume (1), Number (1).

ABSTRACT

This is the first of a two-part review of the current state-of-the-science pertaining to the assessment and management of contaminated sediments. The goal of this review is to introduce some of the major technical and policy issues stemming from the assessment and management of contaminated sediments, highlight a number of aspects of contaminated sediment assessment and management found to be successful, and, when appropriate, address the barriers that still exist for improving contaminated sediment management. In this paper, Part I, the many key elements of an effective investigation and risk evaluation strategy are reviewed, beginning with the development of a conceptual site model (CSM) and including a discussion of some of the key factors influencing the design of sediment investigations and ecological risk assessment of sediment-bound chemicals on aquatic biota. In Part II of this paper (Apitz et al. 2005), various approaches are reviewed for evaluating sediment risk and monitoring sediment remedy effectiveness. While many of the technical and policy issues described in this review are relevant to dredged material management, the focus of this paper is on sediment assessment for environmental management.

Keywords: Sediment assessment   Sediment management   Ecological risk assessment   Sediment quality

INTRODUCTION

Sediments are the ultimate reservoir for the numerous potential chemical and biological contaminants that may be contained in effluents originating from urban, agricultural, and industrial lands and recreational activities. Contaminated sediments in rivers and streams, lakes, coastal harbors, and estuaries have the potential to pose ecological and human health risks. It has been shown in numerous studies in which water quality criteria are not exceeded that adverse effects are possible in aquatic organisms that reside or forage in or near sediment (Chapman 1989). It is widely understood that sediment contamination can have many detrimental effects on an aquatic ecosystem, some of which may be readily evident and others more subtle or unknown. In most receiving waters, however, the effects are difficult to observe and require the use of a variety of investigation and risk assessment tools, such as benthic macroinvertebrate community analyses, chemical testing, hydrodynamic and sediment transport modeling, habitat analysis, and toxicity testing (Wenning and Ingersoll 2002).

Contaminated sediment investigations have features that make them more complex than water evaluations and, to a lesser degree, soil or terrestrial investigations (NRC 2001). The simple fact that sediments lie under water makes measurement, observation, and mapping of contaminant and ecosystem characteristics technically challenging and expensive. Sediments integrate contaminant input from multiple sources within a watershed or coastal region, creating difficulties in tracking the potential sources of contamination. This can

* To whom correspondence may be addressed drsea@cvrl.org

Table 1. Definitions of key terms used in assessment and management of contaminated sediments[a]

Contaminated sediments	Defined by the U.S. EPA as "soils, sand and organic matter or minerals that accumulate on the bottom of a water body and contain toxic or hazardous materials that may adversely affect human health or the environment" (USEPA 1998).
Sediment assessment	The process used to characterize sediment for a given purpose (e.g., evaluations-for risks to environmental health, dredged material disposal, land farming, habitat enhancement, creation, and construction).
Sediment management	The process of making decisions and taking actions on sediments (including no action), taking into consideration a wide range of factors.
Contaminated sediment management strategies, or options	The range of actions that can be taken once the potential risks have been assessed and risk managers balance those risks against various objectives and goals. Objectives and goals may range from no action (either because risks do not exist, or because the risks are not controllable), to institutional controls, to more aggressive in situ containment strategies and ex situ treatment and removal actions.

[a] From Apitz and Power (2002), with the exception of the first term.

lead to ubiquitous, regional "background" levels of anthropogenic contaminants that are difficult to separate from site-specific sources (Crommentuijn et al. 2000). For the same reasons, sediments are often contaminated with multiple chemicals (Long et al. 1995), making risk assessment and management decision-making difficult and complex. The hydrodynamics and geochemistry of aquatic ecosystems are also quite different than those of terrestrial ecosystems. While soils and groundwater can often be isolated from receptors during remediation, similar isolation or removal approaches for contaminated sediments are more difficult to implement successfully; sensitive aquatic biota are more likely, and at times unavoidably, directly affected during the implementation of the remedy (USEPA 2002a). Because the benthic community in direct contact with sediments is often near the base of the aquatic food chain, cleanup targets can be orders of magnitude lower than those at most contaminated land sites.

Together, these and other factors often push the limits of assessment methods and cleanup technologies for sediment and can increase costs significantly over what may be needed to address similar contaminant conditions in soil and groundwater. In addition, while the benefits of ownership and cleanup of contaminated land, which can subsequently be sold or developed (or both) to offset the costs of remediation, are clear, such benefits are less obvious in aquatic ecosystems. However, the management of sediments cannot be completely separated from that of soil and water, as these systems are interrelated and linked, hydrodynamically, if not always in regulatory terms (Apitz and White 2003).

Much of the current discussion among scientists focuses on the need for a framework to guide sediment management (Apitz and Power 2002; Wenning and Ingersoll 2002; Apitz and White 2003). Several of the components inherent in any such framework are discussed throughout this review. For example, the final report of a Pellston Workshop on sediment quality included recommendations for sediment assessment frameworks addressing different management purposes (Wenning and Ingersoll 2002). The different frameworks should be flexible and guided by specific questions that address toxicity to, and bioaccumulation by, sediment-dwelling organisms or risks to wildlife or human health. Sediment assessment frameworks should also be driven by site-specific questions, which may require a tiered evaluation involving a suite of assessment tools chosen to appropriately answer the questions established a priori and to generate specific biological or chemical lines of evidence. Workshop participants concluded that the development of a relevant set of site-specific questions is best done in conjunction with a site-specific model, such as a conceptual site model (CSM), and that a scientifically defensible weight of evidence approach is the appropriate framework in which to place the results from multiple lines of evidence to provide a meaningful interpretation of ecological significance and to make sound management decisions (Wenning and Ingersoll 2002).

While it is entirely feasible to develop decision frameworks based on goals other than risk, this paper focuses on the development of contaminated sediment management approaches within a risk-based framework; namely the assessment and management of sediments based on their potential risk to human health and the environment.

From a risk-based perspective, a range of sediment management options exist on a continuum, beginning with those requiring no containment or engineering controls, through more aggressive in situ treatment and containment technologies, to options that typically involve short-term ecological damages such as dredging and ex situ disposal or treatment technologies (USEPA 2002a). In general, risk management for in-place sediments typically consists of exposure pathway interdiction, while ex situ approaches often involve mass removal. If contaminants are to be left in place, it is critical to evaluate the potential exposure pathways by which contaminants might pose ecological or human health risks. For in situ approaches, it is important to monitor and to minimize or eliminate potential exposure pathways, while at the same time assessing the potential for various natural processes or engineered attenuation approaches to reduce the potential threats posed by the contamination (USEPA 2002a; Brenner et al. 2004). On the other hand, if sediments are to be removed, it is essential to understand sediment characteristics as a function of depth, determine the volume of sediment or mass of contaminants to be removed, and evaluate the treatability of the dredge material and the potential consequences of any disturbance or disposal activities (NRC 1997; USEPA 2002a).

In this two-part paper, the current state-of-the-science pertaining to the assessment and management of contaminated sediments is reviewed, including the various sediment

Table 2. Lines of evidence useful in ecological risk assessment of contaminated sediments

Nature and extent of the contamination
Expected or acceptable indices of benthic diversity and abundance in the absence of contamination
Estimates of the potential for bioavailability, bioaccumulation, and adverse effects posed by chemicals and mixtures of chemicals (the potential for chronic and acute effects) on aquatic organisms
Stability (fate and transport) of the sediments and contaminants
Estimates of the potential risks posed by contamination to aquatic biota and associated resources

assessment approaches that support remedy design such as CSM development; contaminant distribution, fate, and behavior, including the use of novel screening tools; linking sediment chemistry with biology, including toxicological and bioaccumulation studies; assessing the natural recovery potential for contaminated sediments; and predicting and monitoring remedy effectiveness. In Part I, the many key elements of an effective investigation and risk evaluation strategy are reviewed, beginning with the development of a CSM through the evaluation of environmental fate and the factors influencing the effects of sediment-bound chemicals on aquatic biota. In Part II of this paper (Apitz et al. 2005), various approaches are reviewed for evaluating ecological risk and monitoring sediment remedy effectiveness.

For clarity, several of the key terms used throughout this review are defined in Table 1, because these terms can have different engineering and regulatory connotations. The goal of this review is to introduce some of the major technical and policy issues stemming from the assessment and management of contaminated sediments, highlight a number of aspects of contaminated sediment assessment and management found to be successful, and address the barriers that still exist for streamlining contaminated sediment management. While many of the technical and policy issues described in this review are relevant to dredged material management, the focus of this paper is on sediment assessment for environmental management.

KEY ELEMENTS OF AN EFFECTIVE SEDIMENT ASSESSMENT STRATEGY

A common approach to achieving the explicit management goals inherent in different sediment assessment frameworks in the United States and elsewhere is the use of ecological risk assessment (ERA) (USEPA 1997). An ERA is defined as "the practice of determining the nature and likelihood of effects of our actions on animals, plants, and the environment" (SETAC 1997). An ERA provides information relevant to the management decision-making process (Stahl et al. 2001). It should be performed in a scientifically based, defensible manner that is cost-effective and protective of human health and the environment (CNO 1999).

Data collection at sediment sites can be difficult and resource intensive, and requires extensive sampling and subsequent laboratory analyses for specific contaminants. Data collection within the ERA process should be tiered to minimize costs and improve efficiency.

Tiered ERA frameworks such as that proposed by the U.S. Environmental Protection Agency (U.S. EPA) (USEPA 1997) are used by environmental agencies to design ecological investigations, define sampling objectives, and direct how data will be utilized in the decision-making process. Tannenbaum (2002, 2003) cautions that, in some cases, traditional ERAs performed at terrestrial sites should be viewed with caution or replaced with "impact assessments," because, at many of these sites in the USA, impacts are rarely, if ever, observed in wildlife receptors, despite the predictions based on predictive exposure models and the use of hazard quotients based on comparisons to ecotoxicological benchmarks. Increasingly, sediment assessments address this concern through the use of multiple lines of scientific and site-specific evidence as the basis for decision-making.

Sediment sites have a number of features that differentiate them from the typical terrestrial assessment, and a number of sediment-specific guidance documents are referenced throughout this paper. The U.S. EPA is in the process of developing sediment-specific guidance for Superfund sites, and has published a set of principles to guide the Agency's management of contaminated sediment risks at hazardous waste sites (USEPA 2002b). Several tiered sediment frameworks for various sediment assessment and management needs have been proposed or continue to be developed in the U.S. and other countries (ANZECC–ARMCANZ 2000; MacDonald and Ingersoll 2002; den Besten et al. 2003).

While the various tiered approaches may differ in detail, they generally are designed to specify an appropriate de minimis level of information required for decision-making. A de minimis approach initially applies conservative tools (and criteria) that screen out the majority of sites that pose negligible risks to ecological receptors and human health, with a minimum of false negatives and only a slight bias towards false positives. At sites where uncertainty remains, tools, or suites of tools, are applied in later tiers to reduce the uncertainties in such a manner that the bias towards false positives also is reduced. A tiered framework provides several decision levels such as no further action, immediate management, or, if uncertainty remains, more detailed analyses. A well-designed, tiered framework is an explicit statement about how regulatory policy, scientific methods, and mathematical models will be combined.

Whereas there is strong evidence of anthropogenic impacts on the benthic community at many sediment sites, the degree of toxicity (or even its presence or absence) cannot be predicted by contaminant concentrations alone. According to Wenning and Ingersoll (2002), a sediment ERA should include lines of evidence derived from several different investigations (Table 2). Many of the tools available to carry out these investigations are described in this paper.

One common approach to developing several of these lines of evidence in a decision framework is the triad approach. Triad-based assessment frameworks require evidence of hazard and exposure (generally based on sediment chemistry, toxicity, benthic community structure, and, perhaps, evidence of bioaccumulation) to designate sediment as toxic or requiring management (Chapman 1996).

Among the key elements of an effective sediment assessment strategy that guide the technical development of a sediment assessment, whether based on a triad approach or some other set of biological and chemical measures (USEPA 2001), are a well-designed and site-specific CSM; transparent and well-thought-out data collection, processing and communication; explicit discussion of heterogeneity, uncertainty, and scaling issues; and carefully selected reference sites and decision criteria.

The importance of a conceptual site model

A CSM is a three-dimensional description of a site representing what is known (or suspected) about the contaminant source areas, as well as the physical, chemical, and biological processes that affect contaminant transport from the sources through environmental media to potential environmental receptors (ASTM 1995). The CSM identifies exposure pathways, provides a template upon which to base an exposure assessment, and identifies relevant receptors, habitats, and a suite of potential response actions. Inasmuch as it describes the major exposure pathways of concern, and how those pathways may be examined and managed, it also serves as an important communication tool between scientists, regulators, and stakeholders across several technical disciplines and through several phases of an investigation.

Construction of the CSM begins with a thorough literature review and evaluation of the regional geology, hydrogeology, and atmospheric conditions, including maps and aerial photos, if available. The CSM should describe the region and associated geomorphology, hydrogeology, and surface water bodies. This helps in evaluating past and current contaminant fate and transport, and in defining and prioritizing investigation and remedial objectives. The CSM helps identify the movement of surface and groundwater (and associated contaminants) that result from large-scale processes (e.g., structural geology, hydrodynamics, depositional history, geomorphology, water body locations, and other sinks or sources, and atmospheric conditions). Surface water, sediment porewater, and groundwater transport are also influenced by small-scale processes that must be considered such as matrix porosity, consolidation, grain size, angularity, degree of fracturing, groundwater–surface water interaction, bioturbation, bioirrigation, and wave activity (NRC 2003; Reible et al. 2004).

Recognized as an important communication tool to facilitate stakeholder discussions and the decision-making process, CSMs are being used with greater frequency by state and federal agencies in the United States to aid in making sediment assessments a more focused effort, requiring only those data necessary to meet the goals of the assessment strategy and objectives (USEPA 2001; Wenning and Ingersoll 2002). The CSM should be continuously evaluated and refined as data become available, and, as the level of uncertainty associated with the CSM decreases, it should help identify data gaps and target additional investigations.

Heterogeneity, uncertainty, and scale issues

In sediment systems, contaminant distribution, behavior, and effects are usually heterogeneous and uncertain in time and space (Levin 1992). When possible, assessment and management should address, quantify, and communicate this uncertainty at every level of the decision process.

Uncertainty can be divided into two categories: (1) that which can be reduced by further data collection (e.g., higher density sampling may better elucidate contaminant distributions), and (2) that which is based on "ignorance," which may or may not be reduced over time with further research (e.g., insufficient understanding of the fundamental mechanisms driving ecosystem response to a given stressor). According to Levin (1992), heterogeneity is a fundamental and necessary component of ecosystem functioning, and no description of variability and predictability makes sense without reference to the particular range of scales that are relevant to the organisms or processes being examined. Thus, care must be taken to ensure that studies are designed with an understanding of the mechanisms linking measurements and the biological communities that may be the focus of protection, as well as the relevant spatial, temporal, trophic, and organizational scales.

Spatial and temporal heterogeneity of various parameters (including, for example, contaminant distribution, toxicity, and current velocity) can, to a certain extent, be addressed in sampling design. An examination of available data and CSMs may help guide sampling design. In some cases, phased sampling, with some range-finding analyses followed by further sampling, the use of low-cost screening tools to fill data gaps between sample locations, and acoustic tools to map sediment stratigraphy can be cost-effective activities that help to reduce uncertainty in the assessment.

Uncertainty, and how it is handled, can be communicated in a number of quantitative and qualitative ways, including various statistical treatments and the use of models such as Monte Carlo simulations or weighted decision criteria analysis (Coates and Delfino 1993; Johnston et al. 2002). Sampling design and data interpretation should be done with care. For instance, insufficient sample replication or sampling over too short a period can make it difficult to differentiate spatial heterogeneity and seasonality, possibly leading to incorrect remedy decisions.

It is widely recognized, however, that no amount of data collection and assessment will completely remove uncertainty in complex natural systems (Chapman et al. 2001). According to Levin (1992), to develop the predictive models that are needed for sediment management, scientists must learn how to interface the disparate scales of focus inherent in biological, ecological, and chemical studies, which are typically conducted at different levels. Germano (1999) observed that because the public views scientists as providing the facts upon which decisions are made with absolute certainty and based on known outcomes, it is increasingly necessary for scientists to acknowledge and clearly communicate the uncertainties associated with their conclusions to the public, and to carefully balance conservatism in the assessment with the potential costs of decision-making based on inaccurate or incomplete information.

Maximizing data utility for sediment assessment and management

Explicitly identified by U.S. EPA (USEPA 1993), a significant stumbling block in environmental assessments continues to be the inability to compile and integrate or synthesize environmental data, especially data derived from multiple studies. The data quality objectives (DQO) process promoted by U.S. EPA as part of the Superfund Program is intended to help overcome this challenge (USEPA 2000).

While there are many reasons to collect environmental data at a site, a critical assessment of all currently available data should be carried out prior to the initiation of any ad-

Table 3. Critical questions in the preparation of data quality objectives for sediment assessments

Do the proposed biological, chemical, and physical parameters to be measured fill important data gaps?
Are these data relevant to the decision criteria identified in the conceptual site model as the basis for decision-making?
How will the data be used in the assessment and in any remedial decision?
Have all stakeholders or decision-makers agreed upon the need for, and the use of, these data?

ditional sampling (Table 3). Once collected, it is critical that data are summarized and communicated in a manner that can address the concerns and priorities of all stakeholders who will be part of the decision process, including the public, regulators, risk assessors, and engineers designing different remedy options.

The definition of DQOs and the point in a tiered framework at which they are applied can influence the choice of appropriate sediment benchmarks. Throughout an assessment framework, a range of generic or site-specific SQGs may be appropriate, depending on the sophistication of the assessment, the degree of conservatism desired in the analysis of the potential risks, or even the tiers or specific questions to which benchmarks are being applied. If the objective is a determination of the potential risk of a contaminant of concern (COC) in the sediments, then comparisons between bulk chemistry measurements and one or more sediment quality guidelines (SQGs), or benchmarks, describing the likelihood for adverse biological responses may be most important. According to Wenning and Ingersoll (2002), however, SQGs based on empirical or mechanistic approaches (e.g., effects range-low [ER-L], effects range-median [ER-M], threshold-effects levels [TEL], probable-effects levels [PEL], and apparent effects thresholds [AET]) are intended for different purposes, and should be selected carefully. A thorough review of sediment quality benchmarks is provided in Wenning and Ingersoll (2002).

In turn, the appropriate SQGs to use in a sediment assessment framework may change depending on the sophistication of the assessment and the degree of conservatism desired in the analysis of the potential risks. For example, if the objective is to determine whether, for a given COC, the contaminant conditions in the sediment differ from those in sediments from comparable reference areas, then comparisons of bulk chemistry values to background, regional, or reference values may be most appropriate. Chapman et al. (2001) addresses a number of the challenges and complexities of this issue.

Although the concentrations of COCs in sediment are an important part of assessing sediment conditions, contaminant chemistry alone does not provide a full understanding of the potential ecological and human health risks (Apitz 1998). Because most contaminants have a tendency to associate with fine-grained materials (De Bartolomeo et al. 2004), sediments are often categorized by grain size to distinguish fine- and relatively coarse-grained sediments. Total organic carbon (TOC) content and acid volatile sulfide (AVS) levels both play a role in contaminant bioavailability (Boothman et al. 2001; Simpson 2001). An understanding of ambient background contaminant levels is important because, in some cases, it is possible for natural background COC concentrations to exceed SQG screening levels or risk-based concentration limits (Hunt et al. 2001). In other cases, anthropogenic COCs such as PAHs and certain metals also may be present at elevated background levels due to proximity of the water body to urban and heavily industrialized areas (Crawford et al. 1995). Regardless, it may be technically impracticable to remove COCs to ambient or background concentration levels on a site-specific basis. The costs and engineering logistics make it prohibitively expensive to remediate an entire region; furthermore, if COCs at specific sediment sites are remedied to below local or regional ambient levels, those sediments are likely subject to recontamination.

In addition to evaluating risk, several statistical and analytical tools are available to differentiate COCs among multiple sources (Barabas et al. 2004; De Bartolomeo et al. 2004). These tools include the use of multivariate statistics and factor analysis to examine contaminant profiles in sediment, determine the isotopic signature of metals or organic compounds, or test for the presence or absence of unique chemical markers (Barabas et al. 2004). For instance, PAH fingerprinting can provide information on source, background, weathering patterns, potential toxicity, and the potential for natural attenuation (Page et al. 1995; Brenner et al. 2001; Stout et al. 2001). While the field of environmental forensics has primarily focused on terrestrial sites (Morrison 2000; Stout et al. 2003), work in aquatic systems and sediments have advanced rapidly, and methods should be adapted and standardized for aquatic systems.

SUMMARY

In this paper, Part I of a two-part paper on the current state-of-the-science pertaining to the assessment and management of contaminated sediments, the many key elements of an effective sediment investigation and risk evaluation strategy have been reviewed, beginning with the development of a CSM and including a discussion of some of the key factors influencing sediment investigations and ecological risk assessment of sediment-bound chemicals on aquatic biota. Throughout the process of developing a CSM, identifying DQOs, and planning for investigations, the involvement of stakeholders in the sediment assessment and management process is viewed by many as critical (USEPA 2002b). According to the NRC (1997), the most successful sediment management case studies involved the broadest range of stakeholders early and often. Stakeholder groups can include representatives from local communities and governments, fishermen, industries, ports, environmental and public interest groups, and regulatory and trustee organizations from local, state, and national organizations and tribes. This broad representation allows all interested parties to be involved with and understand the problems, and their investigation and resolution, fostering trust and the development of a consensus, if possible (NRC 2001; USEPA 2002b).

In Part II of this paper (Apitz et al. 2005), various approaches are reviewed for evaluating the potential for adverse effects to aquatic biota and monitoring the effectiveness of sediment remedies that are intended to reduce those effects.

Acknowledgement—The authors gratefully acknowledge two anonymous reviewers, Mark Hendershot, and the IEAM editorial office for substantial editorial input. Several of the authors are currently, or were previously, members of the U.S. EPA's Remediation Technology Development Forum (RTDF) Sediment Action Team that conceived many of the concepts presented in the original RTDF report (MESO-02-TM-01; http://meso.spawar.navy.mil/docs/MESO-02-TM-01.pdf) prepared in 2002 by the Marine Environmental Support Office, SPAWAR Systems Center, San Diego, California, USA.

Disclaimer—This paper does not necessarily represent the views of the U.S. EPA, U.S. Navy, or any of the project sponsors or affiliations represented by each of the authors. References to brand names and trademarks in this document are for information purposes only and do not constitute endorsements by the U.S. EPA, U.S. Navy, project sponsors, or the authors. This work was funded, in part, by the Naval Facilities Shoreside Environmental RDT&E (Y0817) Program and by the U.S. Navy, Office of Naval Research, Environmental Quality Applied Research Program.

REFERENCES

[ANZECC–ARMCANZ] Australian and New Zealand Environment and Conservation Council–Agriculture and Resource Management Council of Australia and New Zealand. 2000. Australian and New Zealand guidelines for fresh and marine water quality: Volume 1: The guidelines. Canberra, Australia: ANZECC–ARMCANZ.

Apitz SE. 1998. Streamlining contaminated sediment management: The use of advanced sediment characterization: Preliminary results. *Water Sci Technol* 37:435–442.

Apitz SE, Power B. 2002. From risk assessment to sediment management: An international perspective. *J Soils Sediments* 2:61-66.

Apitz SE, White S. 2003. A conceptual framework for river-basin-scale sediment management. *J Soils Sediments* 3:132–138.

Apitz SE, Davis JW, Finkelstein K, Hohreiter DW, Hoke R, Jensen RH, Jersak J, Kirtay VJ, Mack EE, Magar V, Moore DW, Reible D, Stahl RG, Jr. 2005. Assessing and managing contaminated sediments: Part II: Evaluating risk and monitoring sediment remedy effectiveness. *Integ Environ Assess Manag* 1 (online only):e1–e14.

[ASTM] American Society for Testing and Materials. 1995. Standard guide for developing conceptual site models for contaminated sites. In: Annual book of ASTM standards, Vol. 04.08. West Conshohocken (PA): ASTM. E 1689-95.

Barabas N, Goovaerts P, Adriaens P. 2004. Modified polytopic vector analysis to identify and quantify a dioxin dechlorination signature in sediments. 1. Theory. *Environ Sci Technol* 15;38(6):1813–1820.

Boothman WS, Hansen DJ, Berry WJ, Robson DL, Helmstetter A, Corbin JM, Pratt SD. 2001 Biological response to variation of acid-volatile sulfides and metals in field-exposed spiked sediments. *Environ Toxicol Chem* 20:264–72.

Brenner RC, Magar VS, Ickes JA, Abbott JE, Stout SA, Crecelius EA, Bingler L. 2001. monitored natural recovery of PAH-contaminated sediments at the Wyckoff/Eagle Harbor superfund site. *Environ Sci Technol* 36:2605–2613.

Brenner RC, Magar VS, Ickes JA, Foote EA, Abbott JE, Bingler LS, Crecelius EA. 2004. Long-term recovery of PCB-contaminated surface sediments at the Sangamo-Weston Twelve-mile Creek/Lake Hartwell superfund site. *Environ Sci Technol* 38:2328–2337.

Chapman PM. 1989. Current approaches to developing sediment quality criteria. *Environ Toxicol Chem* 8:589–599.

Chapman PM. 1996. Presentation and interpretation of sediment quality triad data. *Ecotoxicology* 5:327–339.

Chapman PM, Birge WJ, Adams WJ, Barrick R, Bott TL, Burton A, Collier TK, Cumberland HL, Douglas WS, Johnson LL, Luther GW, O'Connor T, Page DS, Sibly P, Standley LL, Wenning RJ. 2001. Learned discourse: Sediment quality values (SQVs): Challenges and recommendations. *SETAC Globe* 2:24–26.

[CNO] Chief of Naval Operations. 1999. Letter 5090 Ser N453E/9U595355 dated 5 Apr 1999; Navy Policy for Conducting Ecological Risk Assessments.

Coates JA, Delfino JJ. 1993. Sources of uncertainty in the application of the equilibrium partitioning approach to sediment quality assessment. *Water Sci Technol* 28:317–328.

Crawford DW, Bonnievie NL, Wenning RJ. 1995. Sources of pollution and sediment contamination in Newark Bay, New Jersey. *Ecotoxicol Environ Saf* 30:85–100.

Crommentuijn T, Sijm D, de Bruijn J, van den Hoop M, van Leeuwen K, van de Plassche E. 2000. Maximum permissible and negligible concentrations for metals and metalloids in the Netherlands, taking into account background concentrations. *J Environ Manag* 60:121–143.

De Bartolomeo A, Poletti L, Sanchini G, Sebastiani B, Morozzi G. 2004. Relationship among parameters of lake polluted sediments evaluated by multivariate statistical analysis. *Chemosphere* 55:1323–1329.

den Besten PJ, de Deckere E, Babut MP, Power B, DelValls TA, Zago C, Oen AMP, Heise S. 2003. Biological effects-based sediment quality in ecological risk assessment for European waters. *J Soils Sediments* 3:144–162.

Germano JD. 1999. Ecology, statistics and the art of misdiagnosis: The need for a paradigm shift. *Environ Rev* 7:167–190.

Hunt JW, Anderson BS, Phillips BM, Newman J, Tjeerdema RS, Fairey R, Puckett HM, Stephenson M, Smith RW, Wilson CJ, Taberski KM. 2001. Evaluation and use of sediment toxicity reference sites for statistical comparisons in regional assessments. *Environ Toxicol Chem* 20:1266–1275.

Johnston RK, Munns WR Jr, Tyler PL, Marajh-Whittemore P, Finkelstein K, Munny K, Short FT, Melville A, Hahn SP. 2002. Weighing the evidence of ecological risk from chemical contamination in the estuarine environment adjacent to the Portsmouth Naval Shipyard, Kittery, Maine, USA. *Environ Toxicol Chem* 21:182–194.

Levin SA. 1992. The problem of pattern and scale in ecology. *Ecology* 73:1943–1967.

Long ER, MacDonald DD, Smith SL, Calder FD. 1995. Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. *J Environ Manag* 19:81–97.

MacDonald DD, Ingersoll CG. 2002. A guidance manual to support the assessment of contaminated sediments in freshwater ecosystems. Volume I: An ecosystem-based framework for assessing and managing contaminated sediments. Chicago (IL): U.S. Environmental Protection Agency Great Lakes National Program Office.

Morrison RD. 2000. Environmental forensics, principles and applications. Boca Raton (FL), USA: CRC.

[NRC] National Research Council. 1997. Contaminated sediments in ports and waterways: Cleanup strategies and technologies. Washington DC: National Academy.

[NRC] National Research Council. 2001. A risk-management strategy for PCB-contaminated sediments. Washington DC: National Academy.

[NRC] National Research Council. 2003. Bioavailability of contaminants in soils and sediments: Processes, tools and applications. Washington DC: National Academy.

Page DS, Boehm PD, Douglas GS, Bence AE. 1995. Identification of hydrocarbon sources in the benthic sediments of Prince William Sound and the Gulf of Alaska following the *Exxon Valdez* Oil Spill. In: Wells PG, Butler JN, Hughes JS, editors. *Exxon Valdez* oil spill: Fate and effects in Alaskan waters. West Conshohocken (PA): American Society for Testing and Materials. STP 1219. p 41–83.

Reible DD, Jensen RH, Bentley SJ, Dannel MB, DePinto JV, Dyer JA, Farley KJ, Garcia MH, Glaser D, Hamrick JM, Lick WJ, Pastorok RA, Schwer RF, Ziegler CK. 2004. The role of modeling in managing contaminated sediments. In: Chien CC, Medina MA, Pinder GF, Reible DD, Sleep BE, Zheng C, editors. Contaminated groundwater and sediment. Boca Raton (FL), USA: Lewis. p 61–106.

Simpson SL. 2001. A rapid screening method for acid-volatile sulfide in sediments. *Environ Toxicol Chem* 20:2657–2661.

[SETAC] Society of Environmental Toxicology and Chemistry. 1997. Technical issue paper: Ecological risk assessment. Pensacola (FL), USA: SETAC. 4 p.

Stahl RG, Bachman R, Barton AL, Clark JR, de Fur PL, Ells SJ, Pittinger CA, Slimak MW, Wentsel RS. 2001. Risk management: Ecological risk-based decision making. Pensacola (FL), USA: SETAC. 192 p.

Stout SA, Magar VS, Uhler RM, Ickes J, Abbott J, Brenner R. 2001. Characterization of naturally-occurring and anthropogenic PAHs in urban sediments—Wycoff/Eagle Harbor superfund site. *J Env Forensics* 2:287–300.

Stout SA, Leather JM, Corl WE III. 2003. A user's guide for determining the sources of Contaminants in sediments: A demonstration study: Sources of PAH in sediments in the vicinity of the Norfolk Naval Shipyard, Elizabeth River, Norfolk, Virginia. U.S. Navy–Space and Naval Warfare Systems Center. Technical report

1907. http://www.spawar.navy.mil/sti/publications/pubs/tr/1907/tr1907cond.pdf. Accessed 20 Jul 2004.

Tannenbaum LV. 2002. Learned discourses: Terrestrial ecological risk assessment: Are we missing the forest for the trees? *SETAC Globe* 1:38–39.

Tannenbaum LV. 2003. Can ecological receptors really be at risk? *Hum Ecol Risk Assess* 9:5–13.

[USEPA] U.S. Environmental Protection Agency. 1993. Data quality objectives for superfund, interim final guidance. Washington DC: USEPA. EPA 540-R-93-071.

[USEPA] U.S. Environmental Protection Agency. 1997. Ecological risk assessment guidance for superfund: Process for designing and conducting ecological risk assessments. Washington DC: USEPA. EPA 540-R-97-006.

[USEPA] U.S. Environmental Protection Agency. 2000. Data quality objectives process for hazardous waste site investigations, EPA QA/G-4HW, Final. Washington DC: USEPA. EPA/600/R-00/007.

[USEPA] U.S. Environmental Protection Agency. 2001. Draft report on the incidence and severity of sediment contamination in surface waters of the United States, national sediment quality survey. Washington DC: USEPA. EPA-823-F-01-031.

[USEPA] U.S. Environmental Protection Agency. 2002a. Contaminated sediment remediation guidance for hazardous waste sites. Washington DC: USEPA, Office of Solid Waste and Emergency Response. OSWER 9355.0-85.

[USEPA] U.S. Environmental Protection Agency. 2002b. Principles for managing contaminated sediment risks at hazardous waste sites. Washington DC: USEPA, Office of Solid Waste and Emergency Response. OSWER 9285.6-08.

Wenning RJ, Ingersoll CG. 2002. Summary of the SETAC Pellston Workshop on use of sediment quality guidelines and related tools for the assessment of contaminated sediments: Executive summary booklet. Pensacola (FL),