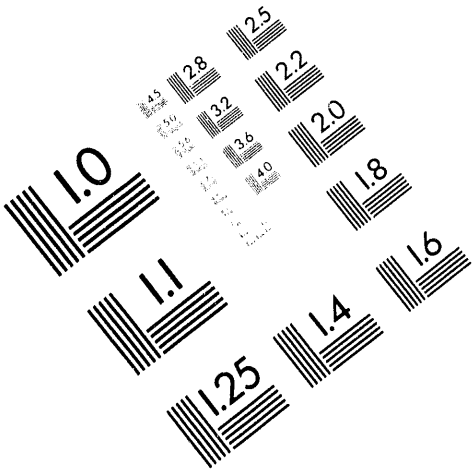

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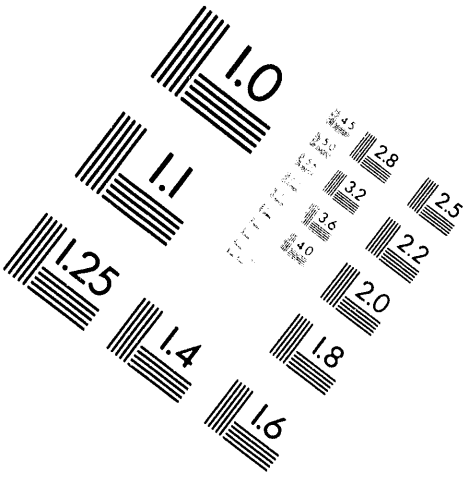

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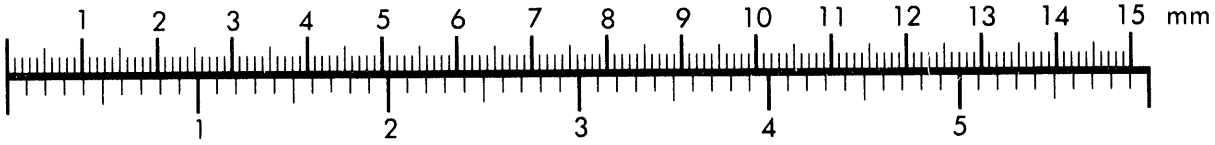

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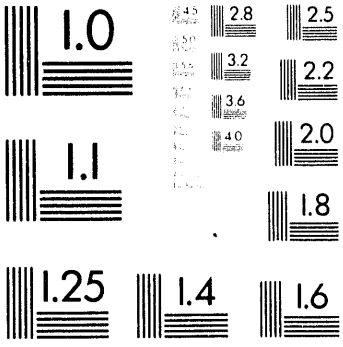

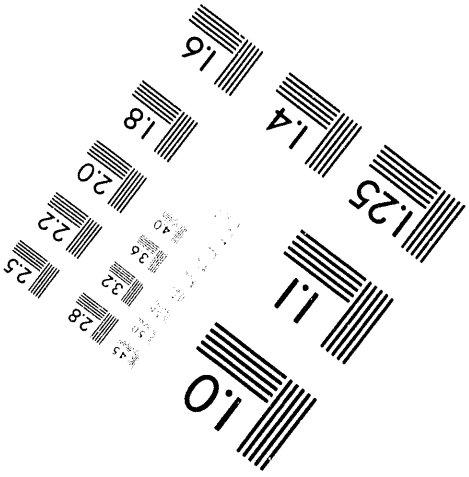

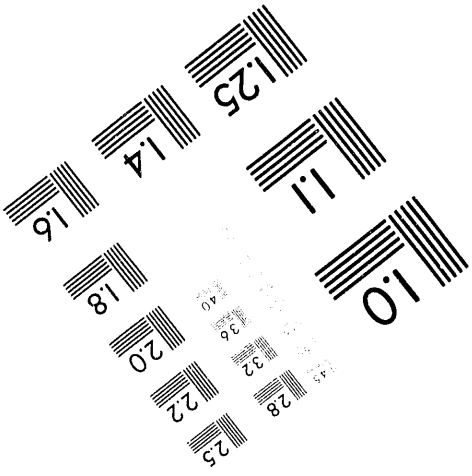

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Sediment Quality Criteria: A Review with Recommendations for Developing Criteria for the Hanford Site

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May 1994

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Summary

Criteria for determining the quality of river sediment are necessary to ensure that concentrations of contaminants in aquatic systems are within acceptable limits for the protection of aquatic and human life. Such criteria should facilitate decision-making about remediation, handling, and disposal of contaminants. Several approaches to the development of sediment quality criteria (SQC) have been described and include both descriptive and numerical methods. However, no single method measures all impacts at all times to all organisms (U.S. EPA 1992b). The U.S. EPA's interest is primarily in establishing chemically based, numerical SQC that are applicable nation-wide (Shea 1988). Of the approaches proposed for SQC development, only three are being considered for numerical SQC on a national level. These approaches include an Equilibrium Partitioning Approach, a site-specific method using bioassays (the Apparent Effects Threshold Approach), and an approach similar to EPA's water quality criteria (Pavlou and Weston 1984). Although national (or even regional) criteria address a number of political, litigative, and engineering needs, some researchers feel that protection of benthic communities require site-specific, biologically based criteria (Baudo et al. 1990). This is particularly true for areas where complex mixtures of contaminants are present in sediments. Other scientifically valid and accepted procedures for freshwater SQC include a background concentration approach, methods using field or spiked bioassays, a screening level concentration approach, the Apparent Effects Threshold Approach, the Sediment Quality Triad, the International Joint Commission Sediment Assessment Strategy, and the National Status and Trends Program Approach. The various sediment assessment approaches are evaluated for application to the Hanford Reach and recommendations for Hanford Site sediment quality criteria are discussed. It appears that application of several complementary methods will better assess the nature and degree of sediment contamination at Hanford than can be achieved by a single approach. An important benefit of complementary method use is the independent verification of sediment contamination afforded by the different tests, if the conclusions of the tests are the same. If they differ, important insight can be obtained relative to site-specific circumstances that may come into play (U.S. EPA 1992b). In addition, an assessment strategy that involves several approaches more easily affords the use of a tiered progression of testing, which reduces cost and focuses directly on site-specific conditions.

Contents

Summary iii

1.0 Introduction 1
- 1.1 Sediments 1
- 1.2 Contaminated Sediments 1
- 1.3 Hanford Sediments 2
- 1.4 Sediment Quality Criteria 2

2.0 Approaches for Determining Sediment Quality 3
- 2.1 Numeric Approaches Under Consideration for Application at the National or Regional Level 3
  - 2.1.1 Equilibrium Partitioning Approach 4
  - 2.1.2 Water Quality Criteria Approach 6
  - 2.1.3 Apparent Effects Threshold Approach 7
- 2.2 Other Important Approaches to Sediment Quality Assessment 10
  - 2.2.1 Background Concentration Approach 10
  - 2.2.2 Screening Level Concentration Approach 11
  - 2.2.3 Site-Specific Sediment Quality Assessment (Field Bioassays Approach) 12
  - 2.2.4 Spiked Bioassay Approach 16
  - 2.2.5 Sediment Quality Triad Approach 17
  - 2.2.6 International Joint Commission Approach 18
  - 2.2.7 National Status and Trends Program Approach 19

3.0 Recommendations for Hanford Site Sediment Quality Criteria 23
- 3.1 Hydrologic Constraints on Establishing Sediment Quality Criteria 23
  - 3.1.1 The Hydrologic Boundaries 23
  - 3.1.2 Spatial Variability within the Depositional Environment 24
  - 3.1.3 Impact of Hydrologic Events 24
- 3.2 Applicability of Existing Sediment Quality Approaches to Hanford Site Sediments 25
  - 3.2.1 Chemical-Specific Approaches 25
  - 3.2.2 Biological-Effects-Based Approaches 26
  - 3.2.3 Overall Approach to Exploratory Sediment Quality Assessment on the Hanford Site 28

4.0 References 31

Tables

2.1 Sediment Protperties that Influence Site-Specific Bioassays 13

2.2 Relative Ranking of Sediment Toxicity Screening Bioassays 14

3.1 Ranking of Sediment Quality Criteria Approaches Relative to Suitability for Hanford Site Use 25

1.0 Introduction

This document compiles and summarizes the dominant approaches for assessing sediment quality currently in use and those being developed in the United States and Canada. Westinghouse Hanford Company (WHC) requested Pacific Northwest Laboratory (PNL)[a] to prepare this document in response to requirements set forth in the Tri-Party Agreement milesone document "Columbia River Impact Evaluation Plan" (U.S. DOE/RL 1993). Specifically, the plan identifies the need to develop recommendations on approaches for developing sediment quality criteria (Activity 3-1 and Activity 4-1). This plan identifies the need for several tasks to provide information for human health and ecological risk assessments. The compilation and summary is intended to provide a background source of information for CERCLA unit managers and technical coordinators. This background information compilation is the first step in working with regulatory agencies in choosing appropriate methodology for the Columbia River sediment quality criteria.

1.1 Sediments

Sediments are accumulations of mineral and organic particles found at the bottom of rivers, lakes, bays, estuaries, and oceans. Bioactive sediments may also be located in non-submerged areas within the hydrologic zone of the water body (See Section 3.2). The composition of aquatic sediments can vary widely within a small area. Among the constituents commonly found in aquatic sediments are detritus, carbonate precipitates, plant material, clays, inorganic and organic erosional materials, fumic acids, iron and manganese oxides, crystalline and amorphous sulfides, and calcarious organism remains. This chemically complex and dynamic matrix is an important component of the aquatic ecosystem, providing habitat for a wide variety of benthic organisms, and feeding and rearing areas for water-column dwellers. Many of these species are important components of food chains that include wildlife and human consumers.

1.2 Contaminated Sediments

Sediments receive chemical and particulate input from ground water, surface water and atmospheric sources. Chemicals from these sources can sorb to particulate matter and become concentrated in the sediments and sediment porewater (Tessier and Campbell 1987). Because sediments tend to accumulate both inorganic and organic chemicals, they can become a source of direct contaminant exposure to benthic organisms (Tessier and Camplell 1987) or affect other aquatic species by becoming bioavailable through leaching, resuspension, or food chain accumulation (Malueg et al. 1983; Allan 1986; Belton et al. 1986). However, site-specific factors can influence the bioavailablity and potential exposure of sediment contaminants to aquatic life. For example, the organic carbon content of the sediment is a key factor influencing the bioavailability of nonpolar contaminants. Metal availability is influenced by metal oxides (Fe and Mn) and sulfides in addition to organic content in the sediment. Grain size, hydrodynamic factors, and residence time also influence the exposure of aquatic organisms to sediment pollutants (Zarba 1988). Although sediments accumulate pollutants and contaminated sediments have resulted in adverse impacts to aquatic systems (U.S. EPA 1990), there is no generally accepted definition of a

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contaminated sediment (U.S. EPA 1992a; NRC 1989). Working definitions include the presence of pollutants above levels expected in the absence of human influence (U.S. EPA 1992a) and the presence of contaminants at concentrations that pose a known or suspected environmental or human health threat (NRC 1989). These definitions differ significantly relative to the potential levels of contaminant in sediment that would trigger consideration of remedial action. In practice, the former definition considers the absolute concentration of the contaminant in the sediment regardless of its availability to aquatic organisms, whereas the latter definition focuses on the bioavailable fraction. Different strategies for assessing and interpreting sediment contamination have been developed in response to these different definitions.

1.3 Hanford Sediments

The strong currents and frequently fluctuating water levels of the Columbia River as it passes through the Hanford Site result in a scouring hydrologic environment. Sediments do accumulate in slack-water areas such as the White Bluffs Slough, the slough area downstream of the 100-F Area, the Hanford Slough and several deep holes in the channel. Other important areas of sediment accumulation occur below Coyote Rapids and 100-D Area as a result of the daily fluctuation in the river level and the spring freshet. Radionuclide and trace metal contamination have been documented in the shoreline soils and sediments of the Hanford Reach (Cooper and Woodruff 1993).

Sediments of the Columbia River support representatives of all major freshwater taxa. The dominant benthic organisms in the Hanford Reach are insect larvae of the Trichoptera (caddisflies), Chironomidae (midge flies), and Simuliidae (black flies) families. Numerous fish species inhabit the Hanford Reach, all of which rely on the benthic biota as an important food source. Of particular economic importance are the salmonid species (chinook salmon, sockeye salmon, coho salmon, and steelhead trout) that migrate through or spawn in the area (Cushing 1990).

1.4 Sediment Quality Criteria

Management of contaminated sediments requires criteria for interpreting the significance of contaminant levels in sediment as they relate to ecosystem and human health protection and to remediation choices (e.g., the risk of disturbing sediment for remediation activities weighed against the risks of leaving it in place). Interpretation of the degree of contamination must take into account technical results, societal values, the potentially exposed food webs and populations, and the current use and proposed uses of the contaminated area. Unfortunately, acceptable contamination limits that establish the extent of sediment cleanup necessary to protect the environment and public health have not been determined for most toxic substances. Initially, the U.S. Environmental Protection Agency's (EPA's) well documented water-quality criteria were thought to be capable of protecting aquatic systems in themselves. However, ecosystem degradation has been observed in aquatic systems where the water quality criteria have not been exceeded (Lyman 1987). It is now generally accepted that water quality criteria must be augmented with sediment quality criteria (SQC) to protect epibenthic and benthic infaunal organisms and their associated food webs. Ideally, sediment criteria would produce guidelines that provide threshold effect levels for sensitive and ecologically important benthic and epibenthic organisms and take into account site-specific factors including the hydrologic environment, physicochemical conditions of the sediment, the potential for human exposure, and subsequent land or water uses.

2.0 Approaches for Determining Sediment Quality

Sediment quality assessment is a relatively young science. One of the first efforts by the scientific community to address sediment assessment issues was the Pellston workshop on the "Fate and Effects of Sediment-Bound Chemicals in Aquatic Systems" in 1984, the proceedings of which were published in 1987 (Dickson et al. 1987). Assessment techniques have progressed significantly since this first effort and several approaches to evaluate sediment quality have been published. In recent years, a number of programs have been initiated in the United States and Canada to specifically develop SQC for the protection of aquatic environments and human health. Of particular importance to the identification, development, and evaluation of SQC methods has been the Puget Sound Estuary Program and the Puget Sound Dredged Disposal Analysis initiative supported by the State of Washington Departments of Ecology and Natural Resources, the U.S. EPA, and the U.S. Army Corps of Engineers (PTI 1988), the Canada-Ontario Agreement for the protection of Ontario aquatic systems supported by Environment Canada and the Ontario Ministry of the Environment, and the large effort by the Criteria and Standards Division of the U.S. EPA, as authorized by the Clean Water Act (CWA, 1972, Sections 104 and 304), to develop and implement SQC analogous to EPA water quality criteria. Generally, the approaches identified and evaluated as a result of these programs fall into one or a combination of the following categories: 1) background approaches, 2) porewater approaches, 3) equilibrium partitioning approaches, and 4) biological sampling approaches. Several of these approaches are being considered for inclusion in regulatory programs. An equilibrium partitioning approach, a method using bioassays, and an approach similar to EPA's water quality criteria are currently being evaluated by U.S. EPA for use on a national level. Other scientifically valid and accepted procedures for freshwater SQC include a Background Concentration Approach, a Screening Level Concentration Approach, the Site-Specific Sediment Quality Assessment Approach, the Spiked Bioassay Approach, the Sediment Quality Triad, the International Joint Commission Sediment Assessment Strategy, and the National Status and Trends Program Approach. Each of these SQC approaches are summarized in the following sections. The advantages and disadvantages to the application of the procedures to Hanford Site sediments are discussed in Section 3.0.

2.1 Numeric Approaches Under Consideration for Application at the National or Regional Level

Three approaches to sediment quality assessment are being considered for application at the national or regional level by the U.S. EPA and local regulatory agencies. These approaches have been designed to provide generic criteria that ideally can be applied to all sediments to provide realistic (or at least conservative) assessments of ecosystem health and adequate protection of benthic species and human health. Two of these approaches, the Water Quality Criteria Approach and the Equilibrium Partitioning Approach, make use of the large data base incorporated in ambient water quality criteria to assess sediment toxicity. The use of water quality criteria for sediment assessment is based on the strong correlation between concentrations of contaminants in porewater (the interstital water of the sediment) and both the observed exposure of benthic organisms to sediment contaminants and the observed toxicity to aquatic organisms. The correlation between contaminant concentrations in sediment particles and toxicity is low (Luoma 1983; Di Toro 1989). The equilibrium partitioning approach is a predictive method that estimates the bioavailable contaminant concentration (i.e., contaminant concentration in porewater) from bulk sediment contaminant levels and compares these to existing water quality criteria. In the water quality criteria approach, direct measures of porewater contamination are made and these values compared to the water quality criteria. The third numeric approach, the Apparent Effects Threshold method, uses field

data on sediment contamiant concentration and at least one indicator of biological-effects/bioavailability to determine the contaminant concentration in sediment above which statistically significant biological effects always occur. The threshold values are empirically derived from field data of biological effects paired with sediment chemistry. More detailed descriptions of these methods are provided in the following sections.

2.1.1 Equilibrium Partitioning Approach

The Equilibrium Partitioning (EP) Approach uses existing water quality criteria together with estimated bioavailable concentrations of the chemical to predict toxicity to benthic organisms. It is based on the observation that, for the most part, concentrations of contaminants in porewater correlate closely with toxicity, whereas concentrations in sediment do not (Luoma 1983; Di Toro 1989; Adams et al. 1985; Kemp and Swartz 1986; Swartz et al. 1990). Indeed, the toxicity of different sediments can differ by factors of 50 or more for the same total concentration of chemical. Several equilibrium partitioning approaches have been proposed to quantify the bioavailability of chemicals in aquatic systems. Each method attempts to model the tendency of a chemical to move from the solid phase of the sediment to the porewater. The equilibrium partitioning approach assumes toxicants in the solid phase of sediments will reach an equilibrium with the porewater, that equilibrium has been reached at the time of sampling, and that equilibrium concentrations can be predicted from the chemical and physical properties of the sediment.

The partitioning of a contaminant between sediment and water is expressed mathematically as a sum of the surface interactions that associate a contaminant (C) with a sediment (S). The total surface concentration of the contaminant ([CS]T) is expressed as:

$$[CT]T = \sum \sum KCi\ Sj\ [Ci][Sj] \text{ with } C_i + S_j <=> C_iS_j \text{ with } K_{CiSj} = [CiSj]/[CiSj] \qquad (1)$$

where Ci represents the different forms of the contaminant and Sj the components of the sediment capable of binding the contaminant. CiSj is the number of surface sites of component j associated with the contaminant form Ci and where K CiSj is the equilibrium constant (i.e., the intrinsic adsorption constant for the reaction). For nonpolar hydrophobic organic chemicals, bioavailability is largely controlled by the amount of organic carbon in the sediment. Metal bioavailability is not only influenced by organic carbon, but by the large sorptive capacity of oxides of Fe and Mn, which coat sediment particles (Jeanne 1968, 1977; Luoma and Bryan 1981; Oakley et al. 1980).

Substituting the appropriate chronic water quality criteria values for [Ci] and measuring all [Sj] with known values for KCiSj will give the SQC for the contaminant. The appropriate water quality criteria are used to estimate the potential biological effects of the contaminant concentration in the sediment. Thus, the SQC generated by this method is a sediment concentration of a particular contaminant that corresponds to a porewater concentration equivalent to the U.S. EPA water quality criterion.

General Advantages

The EP Approach is useful for establishing general sediment criteria and provides a standard basis for comparison within and among sites. It incorporates a large toxicity data base by making use of the water quality criteria effects data. By using simple chemical parameters of the sediment, such as organic carbon content and the sediment-water partition coefficient, the method accounts for contaminant bioavailability and can be used to evaluate most sediments. This method provides better prediction of biological impact than do bulk sediment concentrations and could be used to predict bioaccumulation potential from the bioconcentration factor once the concentration in

porewater has been predicted from the bioavailable iron normalization coefficient (Tessier 1984) and/or the carbon-normalized partition coefficient (Swindoll and Applehans 1987).

General Disadvantages

The EP method cannot be used for chemicals for which there is no toxicity data. It is further limited to contaminants for which both water quality criteria and sediment-water partitioning coefficients have been determined. Also, direct application of the water quality criteria to this sediment method is valid only if there is a single dominant toxicant in the sediment. This approach does not account for unmeasured toxicants, complex mixtures, or chemical interactions. Exposure of benthic organisms to sediment contaminants by ingestion of particles or direct absorption/adsorption from sediment is also unaddressed.

Because each environmental compartment (sediment, porewater, biota) is made up of a number of components that influence the partitioning of chemicals between compartments (see equation 1) or for which little or no partitioning information exists, it is difficult to accurately describe the partitioning in a generic aquatic system. However, this problem may be minimized by site-specific information. The complicating factors of the biotic compartment include the number of species and individuals present and the various growth stages of the organisms. Sediment components of concern are the presence of oxides or hydrous oxides of Fe, Mn, Al, and Si, metal carbonates, metal sulfides, reactive particulate organic carbon, and the clay types. Although the technical approaches for developing SQC for nonpolar organics are available and have been evaluated, the methods for metal contaminants are still under development.

The assumption that porewater is the source of contaminant uptake in benthic biota can be challenged because, in many sediments, the porewater is a hostile environment to aquatic biota in that it is devoid of oxygen and contains high levels of toxic sulfides and ammonia (Lee et al. 1992). It can be reasonably argued that the organisms must be obtaining contaminant burdens from some source other than the sediment porewater.

Although equilibrium is assumed, in the aquatic system of interest, sediment and water concentrations of the contaminant may actually not be at equilibrium (Lee et al. 1992).

Extent of Use

This method is widely accepted and will be adopted by U.S. EPA for developing national SQC (U.S. EPA 1992b). Five criteria for nonionic organic contaminants have been developed for protection of benthic organisms and will be proposed for public comment in 1994. A total of 12 interim and draft SQC are available at this time. The Science Advisory Board is currently reviewing methodology for developing SQC for metal contaminants using this approach.

Reliability of Results

Reliability of the data generated by the EP Approach has only been evaluated for nonionic chemicals. This approach is applicable to sediments only if the organic carbon content of the sediment is $\geq 0.2\%$ (Kemp and Swartz 1986; Swartz et al. 1990). The uncertainty associated with the partition coefficients and the water quality criteria are the principal uncertainties associated with the EP Approach. For nonpolar, organic chemicals, the $\log_{10}$ standard error of the partitioning coefficient is 0.38 (DiToro 1985). The draft and interim SQC developed thus far are bracketed with uncertainty values. The water quality criteria are used for effect levels and the level of uncertainty of each of these criteria are established. (The water quality criteria are considered to be protective of 95% of the organisms.) However, Krueger et al. (1987) report that uncertatinty for

individual contaminants vary from less that one order of magnitude to six orders of magnitude. Field validation of the EP Approach appears to be consistent with the SQC being tested at this time.

Level of Effort

No biological data are required from the site. Effort is related to the collection of representative sediment samples and chemical analyses. If the sediment concentration of a particular contaminant is within the degrees of uncertainty that bracket the water quality criterian, then additional testing may be needed to clarify the risk.

Relative Cost

Costs are largely associated with the collection of site-specific chemistry data.

2.1.2 Water Quality Criteria Approach

In the Water Quality Criteria Approach, sediment porewater is analyzed for individual contaminants and the concentrations compared to existing water quality criteria. The basis for using this approach to assess sediment toxicity is the same as that for the EP Approach, i.e., the strong correlation between concentrations of the contaminants in the porewater and both the observed exposure of benthic organisms to sediment contaminants and the observed toxicity to aquatic organisms.

This approach is best used in combination with the Toxicity Identification Evaluation (TIE) methods developed by the U.S. EPA (Mount and Anderson-Carnahan 1988a, 1988b; Mount 1988; U.S. EPA 1991) to identify and quantify contaminants responsible for sediment toxicity. These procedures involve chemical and physical manipulations of the porewater that, in conjunction with toxicity tests, separate the toxic fractions from nontoxic fractions and further distinguish the generic class of toxic compounds present (e.g., oxidants, volatiles, cationic metals, nonpolar organics, polar organics, substances with pH-dependent toxicity). Chemical analyses are performed on the isolated toxicants for identification of potential toxic components, then a series of toxicant confirmation tests are conducted to confirm the suspected chemicals or elements are the actual toxicants, followed by standard analyses of the concentrations of the toxins in the samples.

General Advantages

There is an extensive data base on the toxicity of many chemicals and their effect on a number of aquatic species. There are more water quality criteria established than there arc for sediment quality. In addition, this method can be used to predict acute and chronic (growth and reproduction) effects of the sediment on aquatic organisms. In combination with the TIE procedure, this approach can identify contaminants responsible for the observed effects and evaluate interactive effects (synergistic, additive, antagonistic) among various toxicants present in porewater. However, the TIE procedures are applicable to acutely toxic samples only. The Water Quality Criteria/TIE approach is the only approach currently available that allows for the identification of specific toxicants. The method is suitable for evaluating nonpolar organics, ammonia, and cationic metals (Adams et al. 1985; Swartz et al. 1985, 1988, 1990; Knezovich and Harrison 1988; Connell et al. 1988; US. EPA 1989a; Ankley et al. 1990, 1991; DiToro et al. 1990).

General Disadvantages

Because few studies have evaluated porewater toxicity, no standard methods for porewater preparation are available. This approach is further limited by the criteria available for water quality; thus far, there are water criteria for only 50 chemicals. Even fewer have been established for sediment quality. Another limitation of this method is the reliance on nectonic organism response for water quality criteria, whereas sediment quality is based on the response of benthic organisms. SQC developed from this approach will likely be overprotective in that the water quality criteria were established in sediment-free systems. This is because many contaminants bind to sediments such that their bioavailability is greatly reduced. On the other hand, this approach probably greatly underestimates the risk to benthic organisms that ingest particles or are in direct contact with contaminated sediments. Also, the compounds identified as being toxic to test organisms in the laboratory must be verified as the ones causing toxicity to organisms in the field. The Water Quality Criteria Approach cannot be used to address bioconcentratable toxicants. TIE procedures have only recently been developed for aqueous samples and have not yet been widely used for sediment toxicity assessment. Because TIE procedures rely on acute toxicity tests, this method cannot be used to identify sediment contaminants that result in chronic toxicity.

Extent of Use

The Water Quality Criteria Approach has been used for sediment toxicity assessment (Adams et al. 1985; Swartz et al. 1985, 1988, 1990; Giesy et al. 1988; U.S. EPA 1989; Hoke et al. 1990; Schubauer-Berigan and Ankley 1991). The TIE procedures have also been successfully applied to sediment toxicity evaluation (Ankley et al. 1990, 1991b; Schubauer-Berigan et al. 1990; Schubauer-Berigan and Ankley 1991).

Reliability of Results

Accuracy and precision are usually high for this laboratory approach. The complexity of the sample and the number of contaminants contributing to sediment toxicity may complicate interpretation of the results of the TIE methods; however, results of the Water Quality Criteria Approach itself are straightforward. TIE procedures have successfully identified acutely toxic contaminants in over 90% of the sediments tested. Little field validation has been conducted for this procedure.

Level of Effort

Field sampling, porewater preparation, toxicity tests and TIE procedures, including chemical analyses, are required to generate results. The level of effort is largely dependent on the TIE procedures needed.

Relative Cost

Cost of conducting the Water Quality Criteria Approach procedures is relatively low. However, costs will escalate with application of TIE and increasing complexity of the toxicant mixture and chemical identification and quantification methods.

2.1.3 Apparent Effects Threshold Approach

The apparent effects threshold criteria are based on observed relationships between sediment contaminant concentration and biological effects (Barrick et al. 1989). Biological effects may be determined by bioassays or evaluation of benthic infaunal community structure. Specifically, for

each chemical of concern the concentration of the chemical above which a statistically significant biological effect (relative to reference conditions) is observed (the apparent effects threshold concentration) is used as the criterion (Tetra Tech 1986). The criterion is established on a defined species using a defined endpoint. The information needed to establish the criterion is obtained from field and reference samples. First, matched chemical and biological-effects data on sub-samples of the same field sample are obtained. These data are then compared to those obtained from reference sediments (uncontaminated sediments). The apparent effects threshold value is determined to be the highest detected concentration among the sediment samples that did not exhibit statitisically significant effects for a given bioindicator, but above which significant effects occur. The assumptions on which this method is based are: 1) if the threshold concentration of a chemical or element is exceeded, any observed effects are caused by that chemical or element, 2) effects observed at concentrations below the threshold concentration are attributable to other toxicants, 3) all the observed adverse effects are caused by a single toxicant (i.e., the most toxic chemical or element in a mixture), 4) the most toxic contaminant in a mixture of contaminants can be identified and its concentration determined without error.

This approach has been used for management decisions concerning marine dredging, superfund cleanup, pollution control efforts, and classifying marine sediments by both the U.S. EPA and the Washington State Department of Ecology (Albright and Malek 1990). There is a strong impetus by North American governments to use the Apparent Effects Threshold Approach for establishing marine SQC.

General Advantages

Criteria are field based using both chemical and biological data. The method is applicable to any quantifiable chemical and sediment type and can be used to predict effects on any life stage for which there is a measurable response assay. It does not assume a specific route of uptake and effectively uses existing data (e.g., data from TRIAD studies). There is historical precedence for its use for establishing SQC.

General Disadvantages

The Apparent Effects Threshold Approach is similar to the screening level concentration approach and/or the field bioassay approaches, and suffers from the same limitations (see Sections 2.2.2 and 2.2.3). The criteria are developed on a toxicant by toxicant basis, not accounting for multiple chemical effects. It is unlikely that the assumption that all the observed adverse effects are caused by a single toxicant is often met in the field. This approach is limited to sediments that do not contain contaminants with similar modes of toxicity, a condition that is not met, for example, in sediments containing several metals or radionuclides. Gillam (1990) showed that sediments predicted to be toxic by Apparent Effects Threshold Approach criteria for several metals and PAHs were not toxic to aquatic invertebrates when tested, indicating that assumption that sediment toxicity could be attributed to individual contaminants in a complex mixture was not valid. In addition, a large data base is required preferably for the same species, endpoint and collection protocol. This data base does not currently exist for many benthic species, or for many toxicants. Normalization of the data to eliminate variation caused by local sediment parameters is difficult. Indeed, the indicator species are not independent of the sediment and are known to covary with several parameters including grain size and organic carbon content of the sediment. Choice of the biological effects indicator also greatly influences the Apparent Effects Threshold value.

Extent of Use

The Apparent Effects Threshold Approach is accepted by federal and state agencies to provide guidelines for regulatory decisions. It has wide application in sediment management programs in the Pacific Northwest. This approach has be used in several projects to generate SQC for the protection of Puget Sound aquatic biota. Washington State has promulgated over 60 SQC from this approach, which have been approved by EPA, Region X. These standards include values for PCBs and 10 metals in the Puget Sound area.

Reliability of Results

In practice, two sets of values are usually generated from the Apparent Effects Threshold Approach. One set identifies low contaminant concentrations below which no biological effects are likely to occur; the other set describes concentrations above which multiple effects are likely. Direct biological testing of concentrations between these two values serve as a means accounting for the uncertainty of chemical predictions.

The accuracy with which the Apparent Effects Threshold Approach predicted the presence or absence of adverse biological effects in field samples from the Puget Sound ranged between 85 to 96% (Mount and Anderson-Carnahan 1988a). Barrick et al. (1988) evaluated the reliability of this approach using Puget Sound data. These researchers found that 68 to 83% of all the stations predicted to have adverse effects were found to be impacted. The magnitude of the uncertainty associated with SQC generated by this method is typically less than one-third to one-half of the value of the SQC. Field validation in the Puget Sound has been extensive (Barrick et al. 1989). However, threshold values determined by this method have been found to be confounded by correlated distributions of other contaminants within the same sediment. Therefore, application of SQC determined by the Apparent Effects Threshold Approach must be restricted to areas where the co-occurence/correclation relationships among contaminants are similar.

This approach is most accurate when developed from a very large data base that includes a diverse group of measured contaminants and a wide range of contaminant concentrations. Small data sets with large concentration gaps or narrow contaminant conconcentration ranges will increase the uncertainty of the threshold levels.

Level of Effort

Generation of SQC by this method is labor-intensive. To ensure adequate predictive capabilities a minimum of 50 stations should be sampled for chemical and biological effects (Barrick et al. 1989). In addition, suitable reference areas must also be sampled. Chemical tests over a wide range of chemicals most also be conducted.

Relative Cost

Costs can be very high for this method. However, limiting the range of chemicals tested (if contaminants are known) and the number of biological indicators for each station greatly reduces the cost.

2.2 Other Important Approaches to Sediment Quality Assessment

In addition to the three methods that are being considered by the U.S. EPA and other regulators for establishing numeric SQC, several other assessment strategies have been or are being used for sediment management and remediation criteria. Two of these methods use bioassay techniques to determine dose-response relationships between surrogate aquatic species and contaminated sediments. In the Site-Specific Sediment Assay Approach, field-collected sediments with known concentrations of contaminants are used. The Spiked Bioassay method uses sediments spiked with known amounts of contaminants. A third strategy, the Screening Level Concentration Approach, uses field data to delineate the relationship between the occurrence of endemic benthic species and specific levels of sediment contamination. The Background Approach has been used to set concentrations standards based on existing concentrations in local unimpacted sediments or on concentrations in pristine sediments. The three remaining approaches integrate sediment chemistry data with toxicity bioassays, and benthic infauna assessments to establish SQC. More detailed descriptions of these assessment strategies are provided in the following sections.

2.2.1 Background Concentration Approach

In this approach the concentrations of contaminants in a suspect sediment are compared to "background" concentrations in reference sediments determined to be unimpacted (Mudroch et al. 1986). The suitability of a reference or "background" sediment is determined by the presence of indicator organisms and is often obtained from a remote site (Persaud et al. 1989). However, historic concentrations, as determined from sediment cores, must be used for metal backgrounds because of the geographic variability of natural concentrations of heavy metals.

General Advantages

The background concentration approach has little application to synthetic organic contaminants but is advantageous in that it requires little information and provides benchmark values for evaluating heavy metal accumulations.

General Disadvantages

This approach is generally not useful because its lacks a strong biological base, cannot be applied to synthetic organic compounds, and pivots around the use of an acceptable reference background sediment that is often difficult to establish. The approach also suffers from inconsistent definition of background and lacks explicit rationale for environmental protection goals (Fitchko 1989). Note: the Background Concentration Approach can be applied to naturally occurring organic compounds such as polycyclic aromatic hydrocarbons (PAH)).

Extent of Use

Sediment criteria established by regulatory agencies typically is based on this approach (Fitchko 1989).

Reliability of Results

Because this approach is based on comparisons to a reference sediment, adequacy and acceptibility of the reference standard greatly influences the reliability of the results. Because the method is not based on biological data and does not account for bioavailability of the contaminants, its ability to predict biological impact is limited.

Level of Effort

The level of effort is minimal, requiring only chemical analysis of suspect and reference sediments.

Relative Cost

Because of the minimal amount of information required compared to most of the other approaches, the relative cost of the Background Concentration Approach is minimal.

2.2.2 Screening Level Concentration Approach

The Screening Level Concentration approach is based on the comparison of contaminant concentrations with the benthic organism distributions in the same sediment (Neff et al. 1988). It attempts to estimate the greatest concentration of a toxicant that will be tolerated by about 95% of the benthic infaunal species (i.e., the threshold concentration). To accomplish this, the frequency distribution of toxicant concentrations at a minimum of twenty locations and for a minimum of ten species is determined (Neff et al. 1988). The concentation below which 90% of the samples contain a particular individual species is determined. This value is the Species Screening Level Concentration (SSLC). The SSLC for at least ten species are then compared to determine the contaminant concentration above which 95% of the SSLCs occur (i.e., the Screening Level Concentration). Because a threshold concentration is being determined, the sampling locations must encompass the full range of concentrations for each contaminant tolerated by the organisms. Calculations are based on a graphic plot and cumulative frequency distribution of species occurrence versus concentration of specific contaminants.

General Advantages

The Screening Level Concentration Approach provides threshold toxicity data and, because synergisms and responses to unidentified or unquantified contaminants are not considered, this approach results in SQC that are conservative. Because it is based on direct measurements of benthic organisms, this method is directly applicable to the protection of aquatic biota. It provides an accurate picture of the health of the system being assessed. Being a correlation method, little bias in the results is obtained from sediment parameters or simultaneous exposure to multiple contaminants. (This can also be a negative attribute; see below.)

Normalization of the data (e.g., to the total organic carbon content of the sediment) to correct for contaminant availability, allows for the derivation of more global SQC if the specific toxicants are known.

General Disadvantages

The SQC developed by the Screening Level Concentration Approach must be developed on a chemical by chemical basis. Exposures to multiple toxicants are not accounted for in this procedure. If several contaminants occur in the sediments at concentrations near the threshold of effects, the accuracy and precision of criteria developed by this method would be adversely

affected. In addition, differences among benthic populations and/or endpoint responses cannot be concluded to result from, or be solely due to, contaminants in the sediments. This is because a wide range of natural physicochemical parameters (e.g., grain size, temperature, ammonia, pH) that are usually not fully quantified for the test sediments can alter, even eradicate, invertebrate populations. Other uncertainties involve extraction and analysis efficiency, and bioavailability of the toxicants *in situ*. (Bellar et al. 1980; Hoke and Prater 1980; Samoiloff et al. 1983). Therefore, the predictive power of this approach is low and threshold values determined by this method may either have little potential for protecting local populations or could be too protective. Criteria established by this method would have to be verified by a bioassay approach.

This approach is data-intensive and involves a number of uncertainties that render this method less useful compared to other methods for establishing SQC.

Extent of Use

The Screening Level Concetration Approach on its own has received little use in sediment quality assessments. However, it has been used to verify results of the Sediment Quality Triad Approach.

Reliability of Results

If several contaminants occur in the sediments at concentrations near the threshold of effects, the accuracy and precision of criteria developed by this method are adversely affected. No comparability studies have been conducted to determine accuracy and precision of the method.

Level of Effort

This method is relatively labor-intensive. The separation, sorting, preparation and identification of benthic macroinvertebrates typically takes about 11 hours per station after sample collection. Depending on the potential number of contaminants in the sediment, the chemical analyses can also be extensive.

Relative Cost

Chemical analyses can be costly, unless relatively few toxicants are present in the sediment. Combined with the number of labor hours necessary to establish species occurrence, this method is moderately costly.

2.2.3 Site-Specific Sediment Quality Assessment

Site-specific SQC are based on a multiphase chemical and biological assessment of the site. The first phase determines the general suitability of the site for colonization by benthic organisms by measuring simple chemical and physical properties of the sediments. For example, the presence of sulfides or ammonia will restrict benthic invertebrates from colonizing sediments and may mask the effect of other contaminants (Ankley et al. 1990). Indeed, as a common contaminant of sediments, the effects of ammonia should be accounted for before other causes of toxicity can be determined (Baudo et al. 1990). Those properties to be measured or obtained from historical data should, at a minimum, include dissolved oxygen, pH, total ammonia, total sulfides, and particle size of the sediments (U.S. EPA 1988). Values of these sediment properties that may influence site-specific bioassays are listed in Table 2.1.

Table 2.1 Sediment Properties that Influence Site-Specific Bioassays

Ammonia (LD50)[a]	Acid Volatile Sulfides (AVS)	Particle Size
Species		
Fathead minnows (*Pimephales promelas*) 1.04 mg/L	Concentration of metal ≤AVS = no toxicity Molar sum of all metals in sediment ≤ molar acid AVS concentration = no toxicity[b]	Concentration of contaminants decrease with increasing particle size.
Ceriodaphnia dubia 0.288 mg/Lc		Toxicity associated with particles particles < 63 μ and > 300 μ[c]

(a) Values are for 48-hour and 96-hour exposures. Ammonia is more toxic at high pH values than at low values (e.g., at levels causing 50% mortality in minnows and *C. dubia* when the pH was 8.5, no mortality was seen at pH 6.5; Ankley et al. 1990).

(b) DiToro et al. 1992.

(c) Contaminants associated with particles > 300 μ are retained longest in given location because they are less affected by scour and transport (Wilber and Hunter 1970).

The second phase involves a battery of bioassays to determine the toxicity of the field-collected sediments (not laboratory-spiked sediments) and is referred to as the "field bioassay" approach. Surrogate species are used in the tests and the response of these species to the field-collected sediments are then compared to their response to reference sediments. The test battery includes bioassays to determine direct toxicity of the sediments, long-term effects, such as teratogenicity and mutagenesis, bioaccumulation potential, and biochemical effects. Table 2.1 provides a relative ranking of the usefulness of currently used and proposed sediment toxicity screening bioassays as adapted from Giesy and Hoke (1989).

Because no single assay has been shown to adequately project the impact of contaminants in an aquatic system, a battery of bioassays is usually recommended to maximize the predictive capability of the Field Bioassay Approach (Williams et al. 1986). Table 2.2 provides a relative ranking of the characteristics of currently used and proposed sediment toxicity screening bioassays.

General Advantages

Because of its ability to identify sediments of toxicological concern, the Field Bioassay Approach by itself can be used to direct cleanup efforts. Screening bioassays have been found to be useful, cost-effective tools for mapping sediment toxicity, both horizontally and vertically, for identifying and prioritizing toxic sites for additional tests or remedial action, and for monitoring remediation efforts (Prater and Anderson 1977; Hoke and Prater 1980; Malueg et al. 1984a,b; Chapman et al. 1987; Giesy et al. 1988).

In general, sediment bioassays for screening purposes are simple, rapid, and inexpensive. In addition to the screening assays, definitive tests that evaluate sublethal effects (e.g., growth and reproduction), can provide predictive information for ecological impacts such as altered species distribution and community structure. The discriminatory power of the assays can be increased by

Table 2.2 Relative Ranking of Sediment Toxicity Screening Bioassays (adapted from Giesy and Hoke 1989).

Assay	Characteristic								References
	Cost	Rapid	Simple	Replicable	Sensitive	Ecologically Relevant	Correlatable Field Effect	Relatable to Regulatory Stds	
MICROBIAL									
Polytox®	4[a]	4[b]	4	2	2	1	1	1	Elnabarawy et al. 1988
Mirotox®	4	4	4	4	3	1	1	1	Bulich 1984 Giesy et al. 1988b
Protozoan Assay	2	3	2	2	3	4	2	1	Cairns 1979
Algal Flask Assay	3	3	3	3	3	2	2	2	U.S. EPA 1978
Algal Microplate Assay	3	4	3	3	3	2	2	2	Blaise et al. 1986
Algal Flow Cytometry	1	4	2	3	3	2	2	2	Berglund et al. 1988
Algal ETS Assay	4	4	4	2	3	2	2	2	Rawson et al. 1987
INVERTEBRATES									
Oligochaete Assay	3	3	3	2	2	4	4	2	Horning 1980 Keilty et al. 1988a Chapman & Brinkhurst 1984
Mollusk Assay	2	1	2	2	2	4	4	2	Dauble et al. 1985
Amphipod Assay	2	2	2	2	2	4	4	2	Nebeker et al 1986
Daphnia Magna Assay	3	3	3	4	3	3	3	4	Schuytema et al 1984 Nebeker et al. 1984
Ceriodaphnia dubia Assay	3	3	2	3	4	3	3	3	Hoke et al. 1990
Hexagenia Assay	1	2	1	2	4	4	4	2	Prater & Anderson 1977 Malueg et al. 1983 Giesy et al. 1990
BENTHIC INSECTS									
Chironomus tentans Assay	2	2	2	3	2	4	4	2	Wentsel et al. 1977 Adams et al. 1985 Giesy et al. 1988a
FISH									
Pimephales promelas Assay	2	2	2	3	3	3	3	4	Hoke et al. 1990 Dawson et al. 1988

(a) 1 = very expensive, 2 = expensive, 3 = moderate cost, 4 = inexpensive
(b) 1 = poor, 2 = fair, 3 = good, 4 = excellent

using a continuous response variable (e.g., weight gain) instead of a quantal response variable (e.g., mortality) (Giesy et al. 1988a).

The ability to test the actual sediments in question allows for more reliable prediction of impact to the extant aquatic system and is a direct measure of the integrated toxicity of the contaminants. This approach can be used for any chemical contaminant and all classes of sediments. Use of sediment porewater would enable direct comparisons with existing water quality criteria.

Data can be normalized to factors such as acid-volatile sulfides and organic carbon (Note: these normalization procedures are still in the development stage.)

Theoretically, any organism can be used in the site-specific bioassay approach. Surrogate species are often used in screening tests to reduce the uncertainty and variability observed in endemic organism response because surrogates, generally, are of a more defined and similar genetic stock, nutritional status, and toxicant exposure history. However, surrogate species response may not accurately reflect impacts on endemic species. Whenever possible, the most sensitive benthic species in the community being evaluated should be used as the test organism to protect the structure and function of the entire ecosystem (Becker et al. 1990). In addition to the

choice of test species, the selection of the biological endpoint allows the tests to be made as sensitive or protective as needed. There are established bioassay procedures already in use for dredged material characterization.

General Disadvantages

The site-specific bioassays cannot be used by themselves to generate SQC. Identification of the toxic agent or agents is not direct by this method and requires additional chemical and physical fractionation information. However, SQC can be established when the bioassay approach is combined with the TRIAD or the Apparent Effects Threshold Approach (see below). Also, use of the tiered TIE guidelines developed by the U.S. EPA for characterizing and identifying sources of acute toxicity in complex effluents (Mount and Anderson 1988a,b) show promise as a method for determining causes of toxicity in sediment porewater assays (Baudo et al. 1990).

Extent of Use

Site-specific bioassays are widely used by both research and regulatory communities and have been tested in court. Because of their wide acceptance, standard procedures have been developed for bioassay testing (ASTM 1990a, 1990b, 1990c). It is the basis for dredged material disposal regulatory programs, effluent testing, and discharge monitoring (PSEP 1991; Reish and LeMay 1988; U.S.EPA/USACE 1991). Field bioassays find particular use when the effects of chemical interactions are of interest.

Reliability of Results

As a laboratory-controlled method, the accuracy and repeatability of the test are high. More than one type of organism should be used to ensure a range of sensitivity to various contaminants that may be in the sediment. Some field validation of the Site-Specific Bioassay Approach have been reported (Chapman 1986b; Plesha et al. 1988; Swatz et al. 1982, 1986, 1989). Using multivariate principal components analysis to compare data from several bioassays of sediments from the Detroit River, Giesy et al. (1988a) showed that any combination of two of the assays used (Microtox®, *Daphnia magna*, and *Chironomus tentans*) accounted for greater than 95% of the explained variance, whereas each separate test accounted for only 60 to 70% of the explained variance. Therefore, conducting more than two sediment bioassays appears to increase the cost of a screening program without providing significant additional information. Baudo et al. (1990) suggest that the minimum set of assays for screening sediments include Microtox® and *Daphnia magna* tests. These tests are suggested because the responses of algal assays have been found to be highly correlated with the responses of the Microtox assay, indicating that both assays are not needed (Baudo et al. 1990). The fish assays are not included because of the high correlation ($r = 0.98$, Maki 1979) between the no observable effect level (NOEL) of *D. magna* and the fathead minnow (*Pimephales promelas*) for chemicals of similar structure. A chronic, whole-sediment assay that may be substituted for one of Microtox® or *D. magna* tests is the *C. tentans* assay, which is a sensitive assay with good predictive power (Table 2.2). The more expensive 7-day fathead minnow,*Ceriodaphnia dubia* tests and chemical analysis can then be judiciously used to potential causes and ecological effects of the sediments identified as toxic in the screening tests.

Level of Effort

Lacking extensive chemical analysis or benthic community surveys, the level of effort is small, involving field sampling and laboratory toxicity tests. Effort levels increase when this approach is combined with other methods to identify and quantify contaminants responsible for the observed effects.

Relative Cost

This method is comparatively inexpensive and cost-effective because laboratory tests are relatively simple, do not require chemical measurements or analysis of benthic community structure, and integrate the effects of all toxic contaminants. Only readily available equipment and standard procedures are needed for field sampling (ASTM 1990b).

2.2.4 Spiked Bioassay Approach

In the Spiked Bioassay Approach, dose-response relationships are determined by exposing organisms to sediments that have been spiked with known amounts of contaminants. Results are compared with results from reference sediments. These laboratory concentration-response values are then used to predict harmful levels to resident biota under field conditions.

General Advantages

The effects of both single toxicants and multiple toxicants in sediments can be assessed by this method. It is the only method that can directly quantify the interactive effects of combinations of contaminants. Bioaccumulation and therefore uptake into food webs that ultimately affect human health can also be predicted by this method. If the most sensitive species within the benthic community can be determined and used in the tests, the criterion developed would then be protective of the structure and function of the entire ecosystem (Hansen and Tagatz 1980). A species with comparable sensitivity could provide equivalent information. The Spiked Bioassay Approach can be applied to all classes of sediments and any chemical contaminant. This method can be used to determine the bioavailable component of the contaminants and can be used to validate other SQC generated by other approaches if the normalization factor is known.

General Disadvantages

If the normalizing factor for bioavailability is unknown, the data produced by the Spiked Bioassay Approach can be difficult to interpret. The assumptions that chemical behavior in the laboratory test system is the same as that found in the natural sediments of interest and laboratory results for a given sediment are representative of biological effects of similar sediments in the field may, in some cases, be incorrect. Also, laboratory-spiked sediments often have different sorption properties than aged field samples.

Extent of Use

Procedures for standardizing the Spiked Bioassay Approach method are being developed in several laboratories by ASTM's sediment toxicology subcommittee (ASTM 1990b). This method can be used to validate SQC generated by other approaches.

Reliability of Results

Because of the laboratory control, Spiked Bioassay Approach criteria have a high degree of accuracy. However, laboratory bioassays, particularly short-term assays, are limited in their ability to represent field conditions; therefore, SQC generated by this approach should be field validated.

Level of Effort

Although the laboratory toxicity tests required by this approach are straightforward, the laboratory effort to generate SQC by this method ranges from moderate to considerable. The effort increases with the number of sediment types, chemicals, and combinations of chemicals.

Relative Cost

Cost of the individual toxicity tests are low because of the minimal effort and inexpensive equipment needed. However, the chemical analyses needed can substantially raise the cost of the overall testing program. The cost to generate a global criterion is high; however, criteria for specific sites could be substantially less if sediment types do not vary greatly.

2.2.5 Sediment Quality Triad Approach

The Sediment Quality Triad Approach is a combination approach consisting of three components: 1) a measure of chemical contamination (sediment chemistry), 2) a measure of toxicity (sediment bioassays), and 3) a measure of *in situ* biological alteration. Chemistry and bioassay estimates are based on laboratory tests with field-collected sediments. Sediment toxicity tests generally include four bioassays covering measures of mortality, reproductive impairment, sublethal behavioral impacts, and mutagenic effects. *In situ* measures generally include studies of resident benthic community structure in the same sediment. Complete taxonomic analysis of benthos are commonly conducted in quintriplicate at each of several stations. As a minimum, species richness, total abundance, abundance of individual species, and community similarity indices are evaluated. Each component is weighted equally and, taken together, provide a preponderance of empirical data (burden of evidence) of both contamination and effects. The chemical and biological response data are then integrated and three criteria established for each contaminant. The criteria define chemical concentrations below which biological effects are "minimal," and above which major biological effects would be expected. The third level incorporates the concentration range between the minimal and severe effects levels in which the occurance and magnitude of the biolgocial response is uncertain.

General Advantages

The Sediment Quality Triad Approach provides empirical evidence of sediment quality and allows interpretation of biological, chemical, and physical properties at the ecological level. This comprehensive approach to sediment quality evaluation usually precludes the need for additional follow-up studies. Indeed, the Triad method provides sufficient objective information on which to judge the extent of contaminant-induced degradation. The size of degraded and nondegraded areas can be estimated with the Sediment Quality Triad Approach. It can be used to describe the ecological relationships between sediment properties and organisms at risk from sediment contamination. All sediment types can be tested by this method and physicochemical characteristics of the sediments that influence interpretation of the results are measured. This approach takes into account all routes of uptake of contaminants by benthic organisms and is applicable to complex mixtures.

General Disadvantages

Field surveys may be confounded by organism motility and spatial variablity (e.g., bioavailablity from site to site is not considered). Because of the large data set required and the nature of the samples needed, sample collection, analysis and data interpretation are labor-intensive. A study team with broad expertise (analytical chemistry, toxicology, and benthic ecology) is

required. The presence of unmeasured toxicants may or may not covary with measured contaminants. This can potentially bias single-chemical criteria generated by the Sediment Quality Triad Approach. In addition, statistical criteria for use with this approach have yet to be fully developed and selection of an adequate reference site can be difficult. Bioconcentration is not measured; therefore, food chain effects and human health impacts are not addressed by this method.

Extent of Use

Although development of the formalized Sediment Quality Triad Approach concept is recent, it is gaining a high degree of acceptance (Forstner et al. 1987; U.S.EPA 1992). A number of assessments performed in various regions in the United States have used this approach. Over 400 stations have been studied and measured thus far. The approach has been used to establish SQC and Apparent Effects Threshold values (Tetra Tech 1986; PTI 1988a, 1988b).

Reliability of Results

No quantitative assessment of the accuracy and precision of the Sediment Quality Triad Approach has been conducted. Field validation is built into the framework of the approach. Available data from studies using this Triad approach show a relatively large degree of uncertainty and variation in the relationship between chemical contamination and biological effect on a station-to-station basis. There is often a wide range in contaminant concentration at stations with similar toxicity and benthos alterations.

Level of Effort

Sampling, chemical analysis, toxicity testing, taxonomic identification, and data interpretation are all labor-intensive activities, making this approach one of the most labor-intensive. Data evaluation is also difficult and new approaches for treating and evaluating the data are needed.

Relative Cost

Because of the large amount of data needed and the high level of chemical and biological expertise required to obtain the data, the Sediment Quality Triad Approach is very expensive in terms of both time and money. However, a tiered use approach of the Triad components is possible and would reduce costs. While cost-effective on a large scale (e.g., regional projects) relative to environmental remediation efforts, it is not used for smaller projects because of the cost and expertise required.

2.2.6 International Joint Commission Approach

This approach is an integrated strategy proposed by the International Joint Commission for assessing contaminated sediment problems in the Great Lakes (IJC 1988). It is composed of two phases. The first phase consists of gathering sufficient data to determine if further study (i.e., progression to Phase II) is needed. The determiners for proceeding to Phase II include above background levels of metal in sediments, detectable concentrations of hazardous persistent organic compounds in sediments, fish, or benthos, the absence of a healthy benthic community, or presence of external abnormalities in fish. Existing data may preclude the need for Phase I testing. Phase II is the detailed assessment and consists of four steps. Step 1 defines the areas of homogeneity within a study area by obtaining data on the physical composition of the sediments. In Step 2, benthic community structure is determined along with the surfical sediment chemistry (e.g., total organic carbon, pH, redox potential, metals, extractable organic compounds). A battery of laboratory bioassays are conducted on sediments collected from the area in Step 3.

Also in Step 3, stratified chemical analyses and bioassays are performed on sediment core sections and histopathological examinations for internal tumors on adult fish. The final step (Step 4) sediment dynamics (resuspension, accumulation) are quantified to aid in selection of remediation options.

General Advantages

The International Joint Committee approach provides direct measures of benthic infaunal and fish effects. *In situ* community analysis and use of site-relevant species in the bioassays provide a high degree of environmental relevance. Tissue residue data may aid in the preliminary evaluation of contaminant exposure to wildlife and humans. The approach is suitable for any sediment type or chemical class. It is a flexible strategy, relying on the expertise of the investigating organization.

General Disadvantages

This comprehensive method is costly and labor-intensive. Although an integrated approach, the component protocols (bioassays, chemical analyses, benthic community structure, etc.) suffer from the limitation described in the above approaches. It is an approach best applied to only major projects.

Extent of Use

Although component protocols are in wide use, this comprehensive approach has only been applied to the ARCS program. It will likely have widespread use in the Great Lakes basin.

Reliability of Results

Accuracy and precision are difficult to define in an approach that is comprised of many optional procedures and design possibilities. This was a concern of the joint committee and the recommended methods were selected for their relevance to the Great Lakes ecosystem. Field validation of the approach was conducted in 1989 to 1991. Results are not yet available.

Level of Effort

The level of effort required to complete this approach is very high and not recommend for other than major evaluation projects.

Relative Cost

Costs for detailed assessments are high for both Phase I and Phase II. However, the tiered approach allows for cost minimization if data gathered in Phase I indicates that no further testing is needed. Phase I may be omitted if existing data is available to indicate if a sediment contamination problem does or does not exist.

2.2.7 National Status and Trends Program

The National Status and Trends Program was initiated in 1984 by the Ocean Assessments Division of the National Oceanic and Atmospheric Adminstrations's (NOAA) Office of Oceanography and Marine Assessment to evaluate the status and trends of chemical contaminants and their effects in estuarine and coastal waters. Although most of the data collected thus far are for marine waters, the approach is easily adaptable to freshwater systems. In general, the approach evaluates

existing data from many studies (burden of evidence) to identify three concentration ranges associated with biological effects. Data are gathered from acute and chronic toxicity tests and from analyses of benthic community structure. The three ranges identified for each chemical are: the no-effects range, the range in concentrations for which toxic effects are rarely observed; the possible-effects range, the range for which toxic effects are occasionally observed; and the probable-effects range, the range in concentrations that frequently or always show toxic effects. The guideline provide a means of numerically estimating the frequency of biological effects over the three concentration ranges. The National Status and Trends Program Approach is structured around a three-tiered design. The first tier establishes a monitoring program or collects data from existing monitoring programs to establish baseline data of contaminant concentrations and associated biological effects to which subsequent measurements at the same sites will be compared. Tier 2 synthesizes available literature to evaluate extent (spatial and temporal) of degradation in environmental quality (i.e., proposes current status). The third tier tests uses bioassays to confirm proposed status and trends.

General Advantages

The National Status and Trends Approach is applicable to all sediment types and chemical species for which sufficient information is available. Although sufficient data is not available currently, the guidelines can be normalized to account for bioavailability when that information becomes available. Much of the labor-intensive assembling of the database, called BEDS, had been completed. Therefore, expansions of the database are anticipated to be relatively rapid, and inexpensive. The guidelines are easily used and interpreted and provide an estimation of the probability of biological effects for each chemical.

General Disadvantages

This method assumes that data from all the studies from which data are taken are equal in weight and credibility, which is unlikely given the many different methods and end points used in the individual studies. This approach provides no information for protection of wildlife or human health at this time because sufficient data on bioaccumulation are not available.

Extent of Use

The National Status and Trends approach has received extensive peer review. The approach has been used by the State of Florida and California and by Environment Canada. NOAA routinely uses the guidelines for ecological risk assessments of National Priority List hazardous waste sites. The method has also been used for data interpretation in court cases.

Reliability of Results

The degree of certainty in the data is reported along with the data from the studies. It has been determined (McDonald 1992) that if a minimum of 40 data sets were obtained, the variability of the guidelines becomes minimal. The accuracy of the guidelines in predicting toxicity has not been quantified. No field validations of the method have been conducted.

Level of Effort

Little effort is required to use the guidelines for any of the over 200 chemicals or chemical classes documented in the data base. If additional data must be entered, the labor required is still relatively small, generally requiring only a few days. (The original effort and subsequent expansion of the data base each required a man-year of labor.)

Relative Cost

If appropriate data are available in the data base, this method is extremely inexpensive. However, if data must reviewed and entered into the data base, the costs increase. If *de novo* studies are needed for a chemical or to fill a data gap, additional costs are accrued.

3.0 Recommendations for Hanford Site Sediment Quality Criteria

The fundamental goals of sediment quality assessment at Hanford will focus on determining whether sediment contaminants are exerting biological stress in benthic biota, if the toxicants are being bioaccumulated, where "unsafe" sediments are located and their horizontal and vertical distribution in these areas (i.e., the spatial zone of impact), and whether remediation efforts are necessary and successful. No single SQC approach appears to provide all the information needed to attain these goals. However, a combination of approaches and methods should provide a defensible, site-specific assessment. The assessment strategy selected must account for the constraints on sediment quality procedures imposed by the hyrologic environment of the Hanford Reach.

3.1 Hydrologic Constraints on Establishing Sediment Quality Criteria

The hydrologic environment is an important, but often ignored, factor in the implementation of sediment quality assessment techniques and in the interpretation of their results. Important hydrologic issues relative to sediment hazard assessment strategies include defining the boundaries of the aquatic environment, accounting for the depositional environment (i.e., heterogenous sediment types and contaminant levels within even small areas), and obtaining representative samples relative to hydrologic events (e.g, low water or high water). These issues should be considered when selecting and implementing any, or any combination of, sediment assessment strategies.

3.1.1 The Hydrologic Boundaries

For river sediments such as those of the Columbia River, the boundaries of the hydrologic environment should include the islands, sloughs, and floodplain to ensure that all *in situ*, potentially bioactive sediments are evaluated. Floodplain sediments are important to sediment hazard assessments because they are deposited by aquatic processes, are important biotic zones (terrestrial and aquatic), receive much of their contamination from fluvial sources, and often contain sediments with contaminant concentrations an order of magnitude higher than channel sediments. These sediments also release slug-like injections of contaminated sediments into active channel sediments by ground water percolation and/or erosion (Marcus 1989). Therefore, applying SQC to these sporadically flooded sediments would reduce pollutant input to the permanently inundated system via erosion, groundwater, and biological routes. Determining the distance from the perennial water body that includes the floodplain can be difficult; however, delineation of the aquatic environment can be made on a frequency rather than spatial basis. The 100-year floodplain has been suggested as a boundary because it would include most of the sediments that have been deposited or reworked since the agricultural and industrial settlement of the United States (Marcus 1989). Considering the history of the Hanford Site, a 50-year floodplain of the river should account for "aquatic" sediments associated with the Columbia River in the vicinity of the Hanford Site that may have been contaminated from site activities and contribute, through leaching, run-off or erosion, to the contaminated environment of the benthic biota. As a minimum, those shoreline sediments of the Hanford Reach that are inundated from the daily fluctuations in river level and from the spring freshet should be included within the hydrologic boundary within which sediment quality is assessed.

Because no water or organisms are available for sampling much of the time in floodplain areas, SQC approaches based on porewater concentrations (Water Quality Criteria Approach) and benthic organism assessments are not feasible for sporadically inundated sediments. However, the Background Concentration Approach or EP Approach could be applied as they do not rely on water analysis or benthic community structure. Procedures using bioassays could be applicable; however, questions relating to the length of time to rehydrate the sediments and to allow chemical transfer between the sediment and water would have to be addressed.

3.1.2 Spatial Variability within the Depositional Environment

Another hydrologic constraint on SQC in river sediments is the variation within the depositional environment and the difficulty of representing that variablity by sampling. The composition of sediments relative to density, size, and contaminant loading can vary greatly within very small distances. How a given depositional environment is sampled (i.e., the number, depth, and location of the samples) will greatly influence the assessment of the hazard of those sediments. For example, most of the channel sediments of the Hanford Reach tend to be mobile and sampling only from these sediments is likely to miss "hot spots" of accumulated chemicals that are potentially more environmentally damaging. However, sampling from only accumulated sediments does not portray the overall conditions in the river sediments. Therefore, probably the most important physical assessment that should be made of the suspect environment is a three-dimensional mapping of sediment zones to provide for sample-site selection and, later, delineation of contaminated areas. Mapping data should include location, areal extent, thickness, sediment volume, and depths of overlying water. Spatial resolution of the sediment zones and bottom features should be obtained by applying cluster analysis to these data. Used in conjuction with benthic population effects-based SQC, this spatial information will be important to the application of remedial technologies. However, for those sediment quality methods that rely solely on sediment contaminant concentrations (i.e., the Background Concentration Approach, and the EP Approach), it is unclear how sample data should be interpreted. For example, allowing any individual sample whose concentration exceeds background to trigger remedial action would potentially be overly restrictive by allowing a very small amount of sediment (i.e., "hot spots") to cause the total sediment to exceed the criterion, whereas calculating a weighted average concentation for an area would potentially mask "hot spot" effects.

3.1.3 Impact of Hydrologic Events

In addition to spatial variablility in depostional zones, the timing and frequency of sample collection also affects whether or not sediment quality assessments are representative. The impact on sediment assessments by hydrologic events is largely because of the predominant sorption of contaminants to fine-grained clays and colloids. These small particles are more mobile than coarser sediments. Thus, sampling during low-water periods could yield sediments with high chemical burden compared to sediments collected during high-flow periods when fine-grained materials are in suspension in the water-column. As with the problems associated with spatial variability, temporal changes in contaminant concentrations in the sediments make use of reference or partioning methods for SQC problematic. However, benthic population sampling approaches and, to some extent, the Water Quality Criteria Approach using porewater, integrate environmental effects through space and time and appear to be better able to provide acceptable SQC. Time-integrated effects could also be conservatively represented by sampling only during periods of stable low-flow conditions (Bradford and Horowitz 1988).

3.2 Applicability of Existing Sediment Quality Approaches to the Hanford Site

To aid in the development of an assessment strategy appropriate to the Hanford Site, approaches to sediment quality criteria described in Section 2.0 are ranked in Table 3.1 according to the reliability of results, relative cost, ability to predict contaminant-specific effects, integrate multiple chemicals, protect benthic organisms, and predict food chain transfer of contaminants. The higher the total accumulated score, the more reliable, informative and/or cost-effective the approach is for setting SQC at contaminated areas such as the Hanford Reach.

3.2.1 Chemical-Specific Approaches

The chemical-specific approaches (the Background Concentration, the EP, and the Water Quality Critera) have limited applicability to the Hanford Reach sediments. These sediments have been analyzed for specific chemicals (but have not undergone exhaustive analysis for all aquatic toxins) and have been found to contain multiple contaminants. The chemical-specific methods do not account for the toxicity of unmeasured contaminants or for synergistic, antagonistic or additive interactions of multiple contaminants (e.g., the additive effects of several chemicals may be harmful to benthic organisms although, individually, the chemicals are below concentrations that are toxic). Not only can using chemical-specific rather than effects-based criteria result in inaccurate sediment quality assessments, but ecological damage can be attributed to the wrong chemical(s). Implicating the wrong chemical could greatly impact selection of cleanup methods and the subsequent quality of the remediated sediment to benthic biota. However, the chemical-specific approaches may be used for first-cut screening of sediment contaminants, thus reducing subsequent use of the more expensive biological-effects approaches to sediment quality assessment.

Table 3.1 Ranking of Sediment Quality Criteria Approaches Relative to Suitability for Hanford Site Use

Criteria	Relative Cost	Site Specific	Chemical Specific	Integrates Chemicals	Predicts Bioaccum.	Protects Benthos	Reliability of Results: Uncertainty	Reliability of Results: Field Validated	Total
Equilibrium Partitioning	4[a]	0[b]	1[b]	0[c]	1[d]	0[e]	1[f]	1[g]	8
Water Quality Criteria	3	1	1	1	0	1	2	1	10
Apparent Effects Threshold	1	1	1	0	0	1	3	2	9
Site-Specific Bioassays	4	1	0	1	2	1	3	1	13
Spiked Bioassay	3	1	1	2	2	1	2	1	13
Screening Level Conc.	2	1	1	0	0	1	1	0	6
Sediment Quality Triad	1	1	1	0	1	1	0	1	6
Int. Joint Commission	1	1	1	1	1	1	0	1	7
Nat. Status and Trends Pgm	4	0	1	0	1	1	2	0	9
Background Conc.	3	1	1	0	0	0	0	0	5

(a) 1 = very high, 2 = high, 3 = moderate, 4 = low.
(b) 0 = no, 1 = yes
(c) 0 = no, 1 = potentially, 2 = yes
(d) 0 = no, 1 = potentially, 2 = yes
(e) 0 = no, 1 = yes
(f) 0 = unknown, 1 = large, 2 = moderate, 3 = low
(g) 0 = no, 1 = partially, 2 = yes

Background Concentration Approach

Applied at the regional or national level, criteria established by the Background Concentration Approach would face serious legal and environmental questions relative to their applicability to local sediments. This approach is difficult to defend legally or technically because it has no foundation in biological effects, does not account for bioavailability, and relies on the relatively subjective selection of a reference standard. Selection of the reference sediment is critical to the outcome of any evaluation made using the Background Concentration Approach. For example, grossly over-restrictive criteria can be developed from the use of remote pristine sediments that differ in natural mineral, metal, and organic carbon content from the suspect sediments at the Hanford Site, resulting in unnecessary remediation efforts. However, this method, when applied at the local level using site-specific reference sediments (i.e., sediments of the same natural physicochemical composition as suspect sediments and that support unimpacted benthic populations) can provide a simple and relatively inexpensive means of screening suspect sediments for certain pollutants such as radionuclides. Those sediments with contaminant concentrations at or below levels found in the reference standard would not need to undergo further study and resources could be more effectively applied toward assessing the biological and ecological hazards associated with the contaminated sediments. To the extent that sediments on the Hanford Site have been previously analyzed for contaminant content, the expense of this procedure would be further reduced. The major drawback to this approach is that no biologically defensible conclusion can be drawn about the hazard or safety of sediments deemed "contaminated" by comparison to the reference sediment.

Equilibrium Partitioning Approach

It is unlikely that even a screening function for Hanford sediments could be adequately obtained from the EP Approach. Few criteria have been developed for chemicals of concern to the area and normalization methods for metal and radionuclide contaminants (contaminants of greatest concern in the Columbia River sediments) have not been validated. Moreover, conclusions about sediment toxicity using this method would be extrapolated from data not derived from local sediments and, therefore, may not provide a true measure of *in situ* biological effects in the Hanford Reach.

Water Quality Criteria Approach

The Water Quality Criteria Approach suffers from limitations similar to those of the EP Approach. In addition, this method does not account for the bioavailability of contaminants and fundamentally ignores the organisms of greatest concern relative to sediment contaminant exposure and aquatic food chain importance at Hanford, i.e., benthic biota.

3.2.2. Biological-Effects-Based Approaches

Generally, effects-based SQC approaches (i.e., methods requiring bioassays and/or monitoring of benthic infaunal populations) are more defensible from an environmental protection standpoint. These approaches (Sediment Quality Triad, Site-Specific Sediment Assessment, Screening Level Concentration Approach, Apparent Effects Threshold Approach, Spiked Bioassay Approach, the International Joint Commission Approach, and the National Status and Trends Program Approach) integrate the complex nature of sediment composition and contamination, potentially account for all possible routes of uptake by aquatic and benthic organisms, and provide direct information on the biotic significance of sediment-associated contaminants. Unlike the pass/fail information obtained from chemical-specific approaches, biological effects measurements

can allow for relative comparisons of impact and, thus, prioritization for cleanup/mitigation. However, they do not establish the cause(s) of any observed biological effects and are usually relatively expensive to perform.

Bioassays

The two sediment quality assessment methods based solely on bioassay procedures are the Site-Specific Sediment Assessment Approach and the Spiked Bioassay Approach. As bioassay procedures, both approaches provide information on the biological significance of contaminants in the sediment but suffer from being artificial systems that may not accurately reflect the biotic responses that would be observed in the natural environment. The Site-Specific Sediment Assessment Approach, which uses the suspect sediments and well-established bioassay methods, would probably provide the most expedient and defensible approach to screening sediments in the Hanford Reach for ones of toxicological concern (Table 3.1). Data from this approach, however, will not provide cause-effect data needed for remediation. The Spiked Bioassay procedure can provide cause-effect data and is the only method that can directly quantify interactive effects of multiple contaminant situations as may be found in Hanford sediments.

Alternatively, use of appropriate sequences in the TIE procedure could be used to resolve the identification of the harmful chemical class(s) present in the sediments. The tiered nature of the TIE procedure minimizes the tests necessary for identifying potential causative agents in the sediments. Once the suspect chemical classes are identified, the sediments or the porewater can be analyzed for specific contaminants within these classes as indicated by historic information. This greatly reduces the otherwise broad range of chemicals that would have to be investigated. The concentration of the contaminants suspected from the TIE procedure could then be compared to the National Status and Trends (NST) guidelines or water quality criteria (after appropriate normalization), if values have been established for the toxicants in question to determine the potential culpability of the contaminant. The NST guidelines provide no-effects, possible effects, and effects levels. Other standards can be used by determining the ratio between the sediment concentration and the guideline value. If it is 10 or greater (a safety margin) then that contaminant is no longer suspect. If, however, the ratio is less than 10, then that chemical would proceed to further confirmatory testing with relevant aquatic organisms. When no guidelines are available for comparison, the toxicity may be established by using spiked-bioassay methods. For both bioassay methods, selection of representative sediment can be both difficult and controversial. Significant cost can be associated with attempting to establish a representative sediment for reference or testing (see Section 3.2).

Because bioassay methods cannot assure that *in situ* benthic infaunal communities are affected, a more complete assessment of sediment quality can be made when combined with approaches that collect benthic infaunal data (e.g., the Sediment Quality Triad Approach, The Apparent Effects Threshold Approach, the Screening Level Concentration Approach).

In situ Benthic Community Assessments

Benthic infaunal assessment approaches (e.g., the Screening Level Concentration Approach, the Apparent Effects Threshold Approach, and the Sediment Quality Triad) can directly indicate whether sediments in the Hanford Reach detrimentally impact benthic communities. However, they really can serve only a screening function and define sediments of poor enough quality to merit further studies. This limitation is because of the inability of *in situ* assessments to sort out community responses to pollutants introduced by human activities from those induced by environmental conditions (sediment type, local flow rates, slope gradients, etc.) and contaminants of natural origin (e.g., ammonia, sulfides, oxygen, and other gasses). When used in combination

with bioassay procedures this deficiency can be overcome. The Apparent Effects Threshold Approach and Sediment Quality Triad Approach are similar methodologies that incorporate the use of field bioassays and sediment chemistry to enhance the interpretation of results from benthic population studies. The two approaches differ in that the Apparent Effects Threshold Approach defines a threshold criterion above which harm will always occur and uses bioassays and benthic infaunal studies independently to determine the criterion, whereas the Sediment Quality Triad Approach establishes chemical concentrations of minimal harm and severe harm using bioassays and population studies together in a burden of evidence manner. The International Joint Commission Approach also uses a combination of field bioassays and benthic community structure to evaluate sediment quality, but approaches the evaluation in a tiered fashion to reduce cost. Spiked bioassays are still needed to delineate and confirm that any environmental damage determined by these three approaches is, indeed, caused by the suspect contaminant and to address the problem of potential multicontaminant interactions. The problem of selecting reference sediments and adequately sampling suspect sediments is as difficult and important as it is for site-specific bioassays. Because of the data base magnitude (multiple stations, multiple samples per station, and multiple species assessments) required to establish a criterion or indicate damage, studies of benthic community structure are labor-intensive and can be very expensive to conduct. This cost issue argues strongly for the judicial use of *in situ* population studies to augment other screening efforts.

The National Status and Trends Program is another approach based on biological-effects data but, because it is not site-specific, has less applicability to the Hanford Site. It can be useful to compare sediment contaminant concentrations to these guidelines if the suspect toxicant is one of the 200 or so chemicals for which criteria have been established.

3.2.3 Overall Approach to Exploratory Sediment Quality Assessment on the Hanford Site

No single approach to sediment quality assessment appears to be able to adequately discriminate sediments of poor quality, assign the causative agent(s), and provide criteria for clean-up goals and strategies for the Hanford Reach. The more comprehensive procedures that incorporate both bioassay and benthic infaunal assessments are very costly without providing sufficient information to make remediation decisions. This would suggest that a combination of methods that capitalize on available site-specific sediment chemistry data, the integrative nature of biological systems to screen for sediments of poor quality, and the cost-effectiveness of a tiered approach to identifying toxicants should be used. Although a very conservative approach, the use of existing sediment chemistry data with the Background Concentration Procedure could significantly reduce the area(s) of sediments needing further study. The remaining area could be screened more accurately by use of field bioassays and/or benthic infaunal surveys. The Site-Specific Bioassay Approach or Screening Level Approach would provide a more economical means of screening than the more comprehensive Apparent Effects Threshold or Sediment Quality Triad Approaches. These comprehensive procedures could be used for areas not passing the initial biological-effects screening. However, because matched sediment samples for bioassays, chemistry, and benthos assessments are needed and a wide range of contaminant concentrations are required to observe concentration-related effects, it may be more economical, in the long run, to design the screening efforts after one of the comprehensive approaches to avoid re-sampling or to conduct the screening with the Triad or Apparent Effects Threshold methods. Subsequently, tiered toxicological studies (e.g., Spiked Bioassays), extensive chemical surveys, and source identification investigations could be conducted using TIE guidelines or the philosophy and design of the International Joint

Commission Approach to delineate the causative toxic agents and their distribution in the Hanford Reach. All of these studies should be conducted against a background of hydrologic concerns that ensure all bioactive sediments are evaluated and necessary sampling is designed in a manner that will provide a truly representative assessment.

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