Metals Bioavailability in the Navy's Tiered Ecological Risk Assessment Process

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Abstract

Bioavailability is the extent to which a substance can be absorbed by a living organism and can cause an adverse physiological or toxicological response. For environmental risk assessments involving soil and sediment, this definition implicitly includes the extent to which a substance can desorb, dissolve, or otherwise dissociate from the environmental medium in which it occurs to become available for absorption. For incorporation into a risk assessment, bioavailability must be quantified much like any other parameter in a risk calculation. Thus, it is also useful to define bioavailability in the context of how it is measured.

Components of the Tiered Ecological Risk Assessment Process

The first step in an ecological risk assessment (Tier 1) is performing a Screening Risk Assessment (SRA). This step is a conservative, worst-case evaluation of the potential risks at the site being evaluated. Therefore, all chemicals are assumed to be 100 percent bioavailable. All pathways are identified, and exposure point concentrations (EPCs) are determined for all relevant environmental media. Toxicity benchmarks are identified on the basis of available water, sediment, and soil criteria. If the EPCs do not exceed the selected toxicity benchmarks, the site passes the SRA and the site is closed out for ecological concerns. If the EPCs exceed the selected toxicity benchmarks, the site either undergoes interim cleanup or proceeds to the second tier.

Tier 2, or the Baseline Ecological Risk Assessment (BERA), entails a more detailed, less conservative approach incorporating site-specific exposure factors. Bioavailability considerations may be incorporated into this tier in a number of ways, depending on the data, funding, and time available. For example, as a first effort, chemical and physical parameters such as sediment and soil pH, total organic carbon (TOC), redox potential (Eh), specific form of the metal, simultaneously extracted metals/acid volatile sulfides (SEM/AVS), etc. can be evaluated. Evaluation of each of these factors provides qualitative information for use in a line-of-evidence approach to eliminating individual metals or the entire site from future consideration. Similarly, application of literature-based bioaccumulation factors or absorption fractions, if appropriate, can provide evidence demonstrating a lack of bioavailability. If, on the basis of these refinements, there is evidence indicating that the site poses acceptable risks, the site exits the

ecological risk assessment process (step 3a). Otherwise, the assessment proceeds to Step 3b, which involves a more extensive evaluation of site-specific information.

In Step 3b, additional site-specific data may be collected, such as concentrations of metals in tissues of organisms from the site, or measurement of the bioavailable fraction in sediment or soil through sequential extraction techniques. In addition, site-specific bioassays, such as bioaccumulation tests or relative bioavailability, are considered. It is important to note that site-specific information collected previously should be carefully evaluated to determine the potential cost-effectiveness of proceeding with these more expensive and time-consuming bioassays. If determined to be appropriate, the results of these tests, combined with the data previously collected, can be evaluated to determine if the site poses acceptable risks. If the risks are determined to be acceptable, no further evaluation or remediation from an ecological perspective is required. If the risks are determined to be unacceptable, and additional evaluation in the form of remedy development is appropriate, the process proceeds to the third tier.

The focus of the Tier 3, Evaluation of Remedial Alternatives is to develop site-specific, risk-based cleanup goals and to determine the appropriate remedial strategy. All site information collected during the assessment, including that pertaining to the potential for bioavailability, should be evaluated when considering the various remedial alternatives.

Role of Bioavailability in Ecological Risk Assessment

The uptake by plants and animals of metals from soils, sediments, and water is a complex, dynamic process that involves all levels of the ecological food web. Thus, ecological risk assessment is somewhat more complicated than human health risk assessment. Plants and animals take up bioavailable metals from soils, sediments, and water through contact with external surfaces; ingestion of contaminated soil, sediment, or water; and inhalation of vapor-phase metals or airborne particles (Brown and Neff, 1993). In addition, animals may take up bioavailable metals from their food. Metal intake may occur through only one of these routes of exposure, or through multiple routes functioning either simultaneously or intermittently. A fish, for example, can take up a metal directly from environmental media through its gills, its skin, or through incidental ingestion of sediment; however, it may also ingest and ultimately absorb contaminants through consumption of food (Campbell et al., 1988). Each of these processes involves a different mechanism and, therefore, a different measure of bioavailability.

For ecological evaluations three different approaches can be used to address bioavailability:

- Evaluating direct exposures to the available fraction of metals present in the environmental media (i.e., sediment or soil),

- Estimating or measuring bioaccumulation directly from the environmental media, or

- Estimating uptake from ingestion of food.

Evaluating Direct Exposures to the Available Fraction in Environmental Media

Metals present in sediments or soils can be toxic to organisms directly exposed to them. However, site-specific chemical and physical conditions greatly influence the form in which metals occur in the environment and thus the degree to which they are sorbed to sediments and soils. Therefore, the total metal concentrations alone does not accurately measure the fraction biologically available to aquatic and terrestrial organisms. Use of total concentrations as exposure point concentrations (EPCs) in an ecological risk assessment may overestimate actual exposures. Consideration of qualitative and quantitative evidence related to the physical and chemical conditions of a site can assist in determining what portion of the total measured concentration is actually available to organisms exposed. This information provides a better indication of the actual acute and chronic toxicity associated with metals at the site and may help determine which chemicals and/or sampling locations should be included for evaluation in the assessment.

Bioaccumulation from Environmental Media

Another method of evaluating the bioavailability of metals present in soil and sediment is to determine the bioaccumulation of these compounds. This approach provides an estimate of the potential for trophic transfer (i.e., movement of chemicals through the food chain) rather than simply evaluating the potential for direct toxicity to exposed organisms. Bioaccumulation is the uptake and retention of a bioavailable chemical from any one or a combination of possible external sources. Bioavailable metals bioaccumulate by passive diffusion or active transport down a concentration or activity gradient across the outer membranes of the organism (Newman and Jagoe, 1994). As the concentration of the chemical in the tissues increases, the gradient decreases and there is a tendency for the rate of loss of the chemical from the tissues to increase by either passive diffusion or active transport.

Equilibrium is reached when the rates of uptake and passive or active excretion of the metal are equal. It is necessary to consider bioaccumulation when exposures to upper trophic level species (e.g., birds, and mammals) occur.

Uptake from Food.

Terrestrial, freshwater, and marine animals are able to accumulate most bioavailable forms of metals from their food. When an animal consumes a lower trophic organism, any metals that have accumulated in the tissues of that organism can be transferred to the animal (i.e., through trophic transfer). This process occurs primarily or exclusively in the unique environment of the gut of the consumer. Metals that are sorbed or bound to the tissues of a food item and are introduced into the gut of the consumer may be desorbed from the food, dissolved in the gut fluids during digestion, and then partitioned from the gut fluids across the gut lining into the tissues of the consumer. As with uptake directly from soils or sediment, the amount of metal desorbed from the food (i.e., the bioavailable fraction) dependent on several chemical and physiological factors (e.g., redox potential, pH). Physiological factors within the receptor organism, such as acidic gastric juices in

the gastrointestinal tract, may also increase the availability of a soil- or sediment-bound contaminant that would otherwise have limited availability under ambient environmental conditions. Consideration of qualitative and quantitative evidence related to the physical and chemical conditions associated with ingestion and absorption can assist in determining what portion of the total measured concentration is actually available to the exposed organisms. This information may help determine which chemicals and/or sampling locations should be included for evaluation in the assessment

Environmental Factors Controlling the Bioavailability of Metals

The bioavailability of an environmental contaminant is largely a function of environmental processes that act on the contaminant to increase or decrease its mobility, thereby making it more or less accessible to the receptor organism. Thus, it is relevant to review the processes that affect the fate of a metal in soil and sediment systems

Factors Affecting the Mobility of Metals in Terrestrial (Soil) Environments

Metals can occur in the soil environment in both the solid phase and the aqueous (i.e., soil solution) phase. In solution, metals can exist either as free ions or as various complexes associated with organic (e.g., functional groups such as carboxyl and phenolic) or inorganic (e.g., anions such as OH^-, CO_3^{-2}, SO_4^{-2}, NO_3^-, or Cl^-) ligands. In the solid phase, metal ions can be retained on organic and inorganic soil components by various sorption mechanisms (e.g., ion exchange or surface complexation); or they can exist as minerals or be co-precipitated with other minerals (e.g., carbonates) in the soil. Ions in solution generally are more available for a variety of processes, including plant uptake and transport; however, metal ions in the solid phase may become available if environmental conditions change.

Dissolution and ***precipitation*** are the chemical reactions that determine the availability of inorganic *mineral* components of soils. Because most soils are undersaturated with respect to their inorganic mineral components, the minerals undergo continuous dissolution and dissolution kinetics is the major factor controlling the availability of mineral-derived metal ions.

Sorption is an important process because it retains ions on the soil and limits their availability in the soil solution. Sorbed compounds can occur as *surface complexed* (i.e., adsorbed); or, if the density of surface complexes is great enough, as a *surface precipitate* or *cluster* (i.e., a three-dimensional growth on the surface of a soil particle).

Ion Exchange is another type of sorption reaction; however, it is distinguished from the other reactions because it occurs mainly at "fixed charge" sites (i.e., the charge is permanent, not pH dependent) of clay minerals that have undergone isomorphic substitution (i.e., replacement of cations in the clay mineral lattice with other cations of lower charge). Soils with significant negative charge have a high cation exchange

capacity (CEC) and low cation mobility. Soils high in clay typically have the highest CEC.

Oxidation-Reduction Reactions involve the transfer of electrons from one compound to another, resulting in a change in the oxidation state of the compounds involved. The ability of metals to exist in multiple oxidation states is an important property that affects their form and distribution in soils.

In summary, soil conditions that tend to promote precipitation or sorption also tend to reduce the mobility and bioavailability of metals. Thus, the metals that tend to be the most mobile and bioavailable are those that form weak outer sphere complexes with organic or inorganic (clay, metal oxides) soil components, or those that complex with ligands in solution and are not sorbed. Conversely, metals that form inner-sphere complexes are much less likely to desorb and thus are less mobile and bioavailable. However, in the presence of dissolved organic carbon, the mobility and bioavailability of metals that form inner-sphere complexes may be higher than expected based on sorption behavior, because these metals tend to also form strong soluble complexes.

Factors Affecting the Mobility of Metals in Aquatic Environment

Metals are found in all sediments; however, a large amount of the total metals in most sediments is in a residual fraction as part of the natural minerals that make up the sediment particles. These residual metals are not bioavailable. The remaining metals in sediments are adsorbed to or complexed with various sediment components and may be bioavailable. In oxidized sediments, metals may be adsorbed to clay particles, iron, manganese, and aluminum oxide coatings on clay particles, or dissolved and particulate organic matter. As the concentration of oxygen in sediment decreases, usually because of microbial degradation of organic matter, the metal oxide coatings begin to dissolve, releasing adsorbed metals. In oxygen-deficient sediments, many metals react with sulfide produced by bacteria and fungi to form insoluble metal sulfides. Metals may be released from sorbed or complexed phases into sediment pore water in ionic, bioavailable forms during changes in oxidation/reduction potential. Microbial degradation of organic matter may also release adsorbed metals to pore water. Certain bacteria are able to methylate some metals, such as mercury, arsenic, and lead, to organic species that are more bioavailable than the inorganic forms.

Bioavailability Approaches for Ecological Risk Assessments

Three general approaches can be used to evaluate bioavailability to ecological receptors. This section explains the methods for including each of these approaches in an ecological assessment.

Evaluating Direct Exposures to the Available Fraction

In the initial stages of the tiered risk assessment process, estimates of the available fraction of metals in sediment or soil may be limited to qualitative evaluation of the site-specific chemical and physical parameters that control bioavailability. These data may provide a line of evidence argument for inclusion or exclusion of individual chemicals or

sampling locations in the risk assessment. As the investigation progresses through the tiered evaluation, more complex, quantitative approaches, such as specific analytical techniques or bioassays, may be considered.

For example, analytical techniques may be applied to quantify the specific concentrations of metals in sediments or soils, defined as the simultaneously extracted metals (SEM), that are bioavailable. Concentrations determined from these analytical techniques can be used as adjusted EPCs. For sediments, the estimates of the bioavailable concentration can be further modified by evaluation of acid volatile sulfides (AVS). In the presence of AVS in sediments, certain metals, including copper, cadmium, lead, nickel, zinc (Ankley, 1996; Ankley et al., 1996), possibly arsenic, and mercury (Luoma, 1989; Allen et al., 1993; Ankley et al., 1996; Neff, 1997a; Berry et al., 1999), precipitate as their respective metal sulfides, which are not bioavailable (Di Toro et al., 1990). If the molar concentration of AVS in sediments is higher than the sum of the molar concentrations of these metals in the 1 Normal hydrochloric acid (N HCl) extract (the SEM of the sediment), all of the metals are in nonbioavailable forms in the sediments. This relationship can be summarized in the following manner:

SEM:AVS > 1, metals are present in bioavailable forms

SEM:AVS < 1, metals are not likely to be bioavailable.

If the SEM:AVS>1, then these data can be used to calculate an EPC as discussed below. It is important to note that each of the metals evaluated has a different binding affinity for sulfides (U.S. EPA, 1994). Currently there is considerable debate regarding the relative affinities of each of the metals; however, typically it is assumed that at equilibrium, copper will preferentially react with AVS, displacing all other metals. If the available AVS is not completely saturated by copper, then the remaining metals will react in the following order: lead, cadmium, zinc, and nickel. In this model, the amount of copper in the sediment that is potentially bioavailable and toxic is considered to be defined as follows:

$$Cu_b = (Cu_{SEM} - AVS)*(MW_{cu})$$

where,

Cu_b	=	concentration of copper that is bioavailable (mg/kg),
Cu_{SEM}	=	molar concentration of Cu as defined by simultaneous extraction (moles/kg),
AVS	=	molar concentration of AVS (moles/kg), and
MW_{cu}	=	molecular weight of copper (mg/moles).

The bioavailable concentration of the other metals in sediment may be determined in the same manner, following the order described above. For each successive metal, the molar concentration of AVS applied should be decreased according to the molar concentration of the preceding chemical; when the concentration of AVS is zero, all remaining metals

are assumed to be bioavailable. The metal concentrations derived in this manner can be used as EPCs.

Bioaccumulation from Environmental Media

Uptake of sediment or soil-bound metals by organisms (i.e., bioaccumulation) may either be measured directly by collecting and analyzing the tissues of representative organisms, or it may be estimated (BJC, 1998). In the initial stages of a risk assessment, estimates are typically derived according to the following equation:

$$C_t = C_s \times BAF$$

where,

C_t = concentration in tissue (mg/kg),
C_s = concentration in sediment or soil (mg/kg), and
BAF = bioaccumulation factor ([mg/kg$_{tissue}$] / [mg/kg$_{sed/soil}$]).

In the event that tissue-based toxicity reference values (TRVs) are available, C_t can be used to derive a hazard quotient (HQ) as defined by the equation:

$$HQ = \frac{C_t}{TRV}$$

In addition, C_t can be used to represent the exposure point concentration for estimating ingested doses for upper trophic level species. For example:

$$Dose_{ingested} = \frac{C_t \times IR}{BW}$$

where,

IR = ingestion rate of receptor species (kg/day) and
BW = body weight of receptor species (kg).

Bioaccumulation factors (BAFs), defined as the ratio of the concentration of the chemical in the tissues of the organism to the concentration of the chemical in sediment or soil, have been derived for various chemicals and species and are available in the literature. In the event that BAF values for relevant chemicals or species are not available, they may be derived from tissue and soil or sediment data available in the literature or determined experimentally at the site. This relationship may not be valid for those metals that are essential trace nutrients for plants and animals.

Uptake from Food

For upper tropic level species, quantitative data can also be used to modify ingested doses for use in calculating risk estimates. For example, when evaluating exposures resulting

from the ingestion of contaminated prey items, the following simplified equation can be used to determine the risk from food ingested by the ecological receptor:

$$HQ = \frac{Dose_{ingested} \times AF}{TRV}$$

where,

$Dose_{ingested}$	=	ingested dose (mg/kg/day),
AF	=	absorption factor (unitless), and
TRV	=	toxicity reference value (mg/kg/day).

For screening-level evaluations, the AF is typically assumed to be 1 (i.e., absorption is 100 percent). However, as the investigation progresses through the ecological risk assessment process, it may be possible to refine this value to reflect actual conditions through either a review of the relevant literature or through bioassays.

Test Methods for Ecological Receptors

A variety of approaches may be used to incorporate bioavailability into ecological risk assessments. For each of these approaches, several specific test methods may be used to provide a quantitative or qualitative measure of the bioavailable metals, depending on the complexity of the site and the current phase of the risk assessment process (i.e., Tier 1 or Tier 2). In general, the more qualitative methods are typically used in the initial stages of the baseline ecological risk assessment, while site-specific bioassays or complex analytical techniques are reserved for consideration as the risk assessment process progresses. Table 1 summarizes the test methods associated with each of the approaches discussed.

Evaluate Direct Exposures to the Available Fraction

Estimates of the available fraction in sediment or soil can be determined analytically, by a variety of sequential extraction techniques (Tessier and Campbell, 1987; Campbell et al., 1988). Although no single extraction method can completely quantify the available fraction, use of a 1-N HCl extraction technique provides the best estimate (Luoma, 1989). Use of the metal concentration derived from this analytical technique as the EPC provides a more accurate estimate of the actual exposures to ecological receptors than the use of the total metal concentration. In sediment these concentrations can be further refined to reflect consideration of AVS, which are operationally defined as the sulfide liberated from wet sediment by treatment with 1 N HCl (Ankley et al., 1996).

In addition to the analytical determination of the bioavailable fraction, it is possible to qualitatively determine the potential for bioavailability on the basis of certain chemical and physical parameters (e.g., pH, fraction organic carbon [f_{oc}], TOC, Eh). For example,

adsorption of inorganic cations (e.g., Pb^{2+}) to soil increases with pH, with a resulting decrease in bioavailability, while the reverse is true for inorganic anions (e.g., $H_2AsO_4^{1-}$). Similarly, metals in sediments tend to be more bioavailable in acidic freshwater bodies than in neutral or basic waters. Sea water is naturally buffered at a pH of about 8.0 (alkaline), so most metals in marine sediments are less bioavailable than those in most freshwater systems. The basis of this information, evaluation of soil pH can provide a quick, qualitative indication of whether measured metals are likely to be bioavailable. In addition, bioavailability and toxicity may vary depending on the form of the metal (U.S. EPA, 1992). Therefore, an understanding of the specific forms of the metal present can also assist in determinations regarding their potential bioavailability.

Toxicity tests of environmental media such as sediment and soil also can be used to evaluate the potential for bioavailability from environmental media. Typically, these tests are used to confirm assumptions made based on qualitative evaluations of chemical and physical parameters at the site. Although such tests do not provide a numerical estimate of the bioavailable fraction, the presence or absence of toxicity in organisms exposed to site materials versus reference materials provides an additional line-of-evidence argument for or against bioavailability. The combination of qualitative evidence indicating limited bioavailability and bioassays exhibiting low toxicity have been used successfully to demonstrate that metals at a site are not bioavailable.

Evaluate Bioaccumulation from Environmental Media

Uptake and retention of metals by organisms (i.e., bioaccumulation) may either be measured directly by collecting and analyzing the tissues of representative organisms, or it may be estimated (BJC, 1998). As previously discussed, estimates of tissue concentration are derived by multiplying the concentration in environmental media (i.e., soil, sediment, or water) by a chemical-specific BAF typically found in the literature. Alternatively, BAF values can be derived from tissue and soil or sediment data available in the literature or even determined experimentally at the site. Determination of site-specific BAF values requires correlated concentrations in sediment or soil and tissues to provide an accurate representation.

Bioaccumulation of metals may also be evaluated through the use of bioaccumulation assays. These studies involve exposure of relevant species not previously exposed to metals to sediments or soils collected from the site. At the end of the test, the concentrations of metals in the tissues of the organism are determined. For the purpose of the bioassay, lower accumulation of metals from site soils or sediments relative to a reference material would indicate limited bioavailability at the site. Similar to toxicity studies, these bioassays may be used in the latter stages of an ecological risk assessment to provide an additional line of evidence regarding assumptions based on more qualitative approaches earlier in the process.

Evaluate Uptake from Food

Estimates of the uptake of metals by ecological receptors from their food may be made by using absorption factor (AF). However, identifying the appropriate AF for use in an ecological assessment can be a complicated process. The concept of relative bioavailability, which is used to derive a relative absorption factor (RAF) for human

health assessments, is another approach. Although not typically considered for ecological assessments, this approach could be applied in the same manner to estimate the fraction of metal in food available to ecological receptors. To apply this approach to ecological assessments, it is suggested that the tests be designed to incorporate species representative of the key receptors identified at the site.

Time and Costs Associated with Determining Bioavailability in Ecological Risk Assessments

Table 2 summarizes the estimated cost and time for each of the different tests and analyses proposed for measuring bioavailability in ecological risk assessments. These cost estimates are intended to provide an indication of the analytical level of effort necessary to address these issues and may not reflect actual total costs associated with each task. In general, all of the tests proposed are standard laboratory protocols for which specific methods have been developed. For example, the American Society for Testing and Materials (ASTM) publishes guidance on the appropriate methodologies for evaluating the toxicity of metals to aquatic and terrestrial invertebrates. Similarly, the analytical methods discussed rely on standard techniques. As a result, these tests can be performed by any qualified laboratory. The cost estimates provided are averages for contract laboratories; other laboratory facilities (e.g., universities) may offer lower costs for some of these analyses.

It is important to note that the exact cost of a bioavailability study will vary from site to site, depending on the existing data and the complexity of the site. For example, if all necessary chemical and physical parameters are available from existing data, it may not be necessary to collect additional samples. In addition, costs could not be estimated for qualitative evaluations (e.g., incorporation of a literature-based BAF) or for interpretation of results or negotiations with agencies. It is impossible to accurately predict the costs associated with these tasks because their scope is entirely dependent on site-specific factors including the size of the site, tests selected for inclusion, as well as the technical expertise available to the Navy. In some instances, the Navy may require additional technical expertise for assistance in data interpretation, while at other sites, such assistance may not be required. Therefore, the costs in Table 2 are offered to provide a general background on the relative costs of the various tests proposed.

Table 1. Test Methods for Assessing Bioavailability in Ecological Risk Assessments

	Approach	Methodology	Purpose	Limitation
Evaluate Direct Exposures to the Available Fraction in the Media	When evaluating direct exposures/toxicity associated with sediments or soils	Extraction Techniques (e.g., 1 N HCl).	Provides numerical estimate of bioavailable fraction (i.e., concentration).	No single extraction technique has been demonstrated to completely characterize the bioavailable fraction
		Comparison of AVS/SEM (sediment only)	Provides additional modification to bioavailable fraction estimate.	Recent data indicate that the AVS/SEM model is not always a good predictor.
		Evaluation of chemical and physical parameters	Provides qualitative evidence for line of evidence argument.	Evidence is only qualitative.
		Toxicity tests.	Absence of toxicity provides line of evidence support for lack of bioavailability.	Results of toxicity tests can be difficult to interpret, nd test may be costly and time consuming to conduct.
Evaluate Bioacumulation from Environmental Media	When estimating tissue concentrations to evaluate trophic transfers	Collect and analyze site specific tissue data	Provides a measure of amount of chemical that is taken up by resident species.	Measured concentrations may be affected by sources other than those at the site.
		Estimate tissue concentrations using BAF	Estimates amount of chemical that is taken up by resident species in the absence of site-specific data.	BAF values are empirically derived and may not reflect actual conditions at the site.
		Conduct bioaccumulation studies	Demonstrates whether metals in site soils / sediments are available for biological uptake.	Bioaccumulation tests may be costly and more time consuming.
Evaluate Uptake from Food	When evaluating absorption of metals from contaminated food	Perform laboratory bioassay to determine relative bioavailability	Provides measure of actual absorption of site-specific dose.	Bioassays may be costly and time consuming.

Table 2. Time and Cost Associated with Test Methods for Assessing Bioavailability in Ecological Risk Assessments

	Test Type	Description	Estimated Cost per Sample[(a)]	Time per Test
Evaluate Direct Exposures to the Available Fraction	Extraction Techniques	1 N HCl	$120	Allow 3-4 weeks for sample analysis
	Comparison of AVS/SEM	Compare ratio of measured SEM to AVS	$250	Allow 3-4 weeks for sample analysis
	Evaluation of chemical and physical parameters	Chemical form, pH, TOC, Eh, f_{oc}, etc.	$200	Allow 3-4 weeks for sample analysis
	Toxicity Tests	Standard test methods for aquatic or terrestrial invertebrates	$500-1,200	Test lengths can vary from 10 to 28 days
Evaluate Bioaccumulation from Environmental Media	Collect and analyze site-specific tissue data	Metals in fish, invertebrates, birds, mammals, etc.	$300-400[(b)]	Allow 3-4 weeks for sample analysis
	Estimate using BAF	Literature-based (reported or derived); site-specific	Level of effort will vary depending on number of chemicals and species evaluated	Level of effort will vary depending on number of chemicals and species evaluated
	Conduct bioaccumulation studies	Standard test methods for aquatic or terrestrial invertebrates	$1,900 per species (includes cost of 5 replicates and chemical analyses)	Test lengths can vary from 10 to 28 days
Evaluate Uptake from Food	Relative Bioavailability study	As described in Test Methods for Ecological Receptors		

(a) Costs provided are estimated based on the basis of standard procedures. Total may vary depending on specifics of project protocol, number of chemicals analyzed, and other factors.
(b) Costs provided assume analysis of whole-body concentrations.

Chemical-Specific Considerations for Assessing Bioavailability to Ecological Receptors in Aquatic (Sediment) Settings

All sediments contain metals. The metals in freshwater and marine sediments originate from several natural and human sources and are present in the sediments in several different physical and chemical forms (Goldberg, 1954). The chemical species and forms of complexed, adsorbed, and solid metals in sediments have profound effects on the bioavailability and toxicity of the metals to aquatic/marine plants and animals (Nelson and Donkin, 1985). Each metal has unique physical and chemical properties that determine the forms of the metal in sediments and pore water and its relative bioavailability to aquatic receptors. Metals in highly insoluble solid forms are not bioavailable to sediment-dwelling organisms. Metals in solution or colloidal suspension in sediment pore water or in adsorbed forms that are readily desorbed (leached) into the dissolved phase by small changes in oxygen concentration, pH, and Eh are bioavailable. Therefore, it is important to understand the chemical forms of metals in sediments if bioavailability is going to be evaluated in ecological risk assessment.

Table 3 summarizes information on background concentrations and effects levels for seected metals. In addition, "high" concentrations developed by Daskalakis and O'Connor (1995) based on data from the National Status and Trends Program are included. Daskalakis and O'Connor (1995) examined chemical residue data for large numbers of marine sediment samples collected as part of the National Status and Trends Program and several other monitoring programs in coastal marine environments in the United States. They defined a "high" concentration of chemicals in sediments as the geometric mean concentration plus one standard deviation of the National Status and Trends site means.

Table 3. Typical Background Concentrations and "High" Concentrations of Metals in Coastal Sediments. (Effects range low (ERL) and effects range median (ERM) screening levels for marine sediments and acute/chronic marine water quality criteria are included.)

Metal	Background Concentration (µg/g dry wt)	High Concentration (µg/g)	ERL (µg/g)	ERM (µg/g)	Acute/Chronic Water Quality Criteria (µg/L)
Arsenic (As)	5 – 15	13	8.2	70	69/36
Cadmium (Cd)	0.1 – 0.6	0.54	1.2	9.6	43/9.3
Chromium (Cr)	50 – 100	125	81	370	1,100/50
Copper (Cu)	10 – 50	42	34	270	4.8/3.1
Lead (Pb)	5 – 30	45	46.7	218	220/8.5
Mercury[a] (Hg)	≤ 0.2	0.22	0.15	0.71	2.1/1.11[(a)]
Nickel (Ni)	≤ 50	42	20.9	51.6	75/8.3
Zinc (Zn)	1.2 - >100	135	150	410	95/86

[a] Marine water quality values are for inorganic mercury. The chronic value of methylmercury is 0.025 µg/L.

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Acronyms

AF	absorption fraction
ASTM	American Society for Testing and Materials
ATSDR	Agency for Toxic Substances and Disease Registry
AVS	acid volatile sulfides
BAF	bioaccumulation Factor
BERA	baseline ecological risk Assessment
CEC	cation exchange capacity
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
Eh	redox potential
EPC	Exposure Point Concentration
ERL	Effects Range Low
ERM	Effects Range Median
HCl	Hydrochloric Acid
N	normal
RAF	Relative Absorption Factor
SEM	Simultaneously Extracted Metals
SRA	Screening Risk Assessment
TOC	Total Organic Carbon
TRV	Toxicity Reference Value
U.S. EPA	U.S. Environmental Protection Agency

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