A Guidance Manual to Support the Assessment of Contaminated Sediments in Freshwater, Estuarine, and Marine Ecosystems in British Columbia

Volume IV - Supplemental Guidance on the Design and Implementation of Detailed Site Investigations in Marine and Estuarine Ecosystems

Submitted to:

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Executive Summary

Traditionally, concerns relative to the management of aquatic resources in freshwater, estuarine, and marine ecosystems have focussed primarily on water quality. As such, early aquatic resource management efforts were often directed at assuring the potability of surface water or groundwater sources. Subsequently, the scope of these management initiatives expanded to include protection of instream (i.e., fish and aquatic life), agricultural, industrial, and recreational water uses. While initiatives undertaken in the past twenty years have unquestionably improved water quality conditions, a growing body of evidence indicates that management efforts directed solely at the attainment of surface water quality criteria may not provide an adequate basis for protecting the designated uses of aquatic ecosystems.

In recent years, concerns relative to the health and vitality of aquatic ecosystems have begun to reemerge in North America. One of the principal reasons for this is that many toxic and bioaccumulative chemicals [such as metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), chlorophenols, organochlorine pesticides (OC pesticides), and polybrominated diphenyl ethers]; which are found in only trace amounts in water, can accumulate to elevated levels in sediments. Some of these pollutants, such as OC pesticides and PCBs, were released into the environment long ago. The use of many of these substances has been banned in North America for more than 30 years; nevertheless, these chemicals continue to persist in the environment. Other contaminants enter our waters every day from industrial and municipal discharges, urban and agricultural runoff, and atmospheric deposition from remote sources. Due to their physical and chemical properties, many of these substances tend to accumulate in sediments. In addition to providing sinks for many chemicals, sediments can also serve as potential sources of pollutants to the water column when conditions change in the receiving water system (e.g., during periods of anoxia, after severe storms).

Information from a variety of sources indicates that sediments in aquatic ecosystems throughout North America are contaminated by a wide range of toxic and bioaccumulative substances, including metals, PAHs, PCBs, OC pesticides, a variety of semi-volatile organic chemicals (SVOCs), and polychlorinated dibenzo-*p*-dioxins and furans (PCDDs and PCDFs). For example, contaminated sediments pose a major risk to the beneficial uses of aquatic ecosystems throughout Canada and the United States. The imposition of fish consumption advisories has adversely affected commercial, sport, and food fisheries in many areas. In addition, degradation of the benthic community and other factors have adversely affected fish and wildlife populations. Furthermore, fish in many of these areas often have

higher levels of tumours and other abnormalities than fish from reference areas. Contaminated sediments have also threatened the viability of many commercial ports through the imposition of restrictions on dredging of navigational channels and disposal of dredged materials. Such use impairments have been observed at numerous sites in British Columbia, particularly in the Fraser River basin, Columbia River basin, and nearshore areas in the vicinity of industrial developments.

In response to concerns raised regarding contaminated sediments, responsible authorities throughout North America have launched programs to support the assessment, management, and remediation of contaminated sediments. The information generated under these programs provide important guidance for designing and implementing investigations at sites with contaminated sediments. In addition, guidance has been developed under various sediment-related programs to support the collection and interpretation of sediment quality data. While such guidance has unquestionably advanced the field of sediment quality assessments, the users of the individual guidance documents have expressed a need to consolidate this information into an integrated ecosystem-based framework for assessing and managing sediment quality in freshwater, estuarine, and marine ecosystems. Practitioners in this field have also indicated the need for additional guidance on the applications of the various tools that support sediment quality assessments. Furthermore, the need for additional guidance on the design of sediment quality monitoring programs and on the interpretation of the resultant data has been identified.

This guidance manual, which comprises a four-volume series and was developed for the British Columbia Ministry of Water, Land and Air Protection, based on guidance prepared for the United States Environmental Protection Agency and the Florida Department of Environmental Protection, is not intended to supplant the existing guidance on sediment quality assessment. Rather, this guidance manual is intended to further support the design and implementation of assessments of sediment quality conditions by:

- Presenting an ecosystem-based framework for assessing and managing contaminated sediments (Volume I);
- Describing the recommended procedures for designing and implementing sediment quality investigations in freshwater ecosystems (Volume II);
- Describing the recommended procedures for interpreting the results of sediment quality investigations (Volume III); and,

- Providing supplemental guidance on the design and implementation of detailed site investigations in marine and estuarine ecosystems (Volume IV).

The first volume of the guidance manual, ***An Ecosystem-Based Framework for Assessing and Managing Contaminated Sediments***, describes the five step process that is recommended to support the assessment and management of sediment quality conditions (i.e., relative to sediment-dwelling organisms, aquatic-dependent wildlife, and human health). Importantly, the document provides an overview of the framework for ecosystem-based sediment quality assessment and management (Chapter 2). In addition, the recommended procedures for identifying sediment quality issues and concerns and compiling the existing knowledge base are described (Chapter 3). Furthermore, the recommended procedures for establishing ecosystem goals, ecosystem health objectives, and sediment management objectives are presented (Chapter 4). Finally, methods for selecting ecosystem health indicators, metrics, and targets for assessing contaminated sediments are described (Chapter 5). Together, this guidance is intended to support planning activities related to contaminated sediment assessments, such that the resultant data are likely to support sediment management decisions at the site under investigation. More detailed information on these and other topics related to the assessment and management of contaminated sediments can be found in the publications that are listed in the Bibliography of Relevant Publications (Appendix 2).

The second volume of the series, ***Design and Implementation of Sediment Quality Investigations in Freshwater Ecosystems***, describes the recommended procedures for designing and implementing sediment quality assessment programs. More specifically an overview of the recommended framework for assessing and managing sediment quality conditions is presented in this document (Chapter 2). In addition, this volume describes the recommended procedures for conducting preliminary and detailed site investigations to assess sediment quality conditions (Chapters 3 and 4). Furthermore, the factors that need to be considered in the development of sampling and analysis plans for assessing contaminated sediments are described (Chapter 5). Supplemental guidance on the design of sediment sampling programs and on the evaluation of sediment quality data is provided in the Appendix to Volume II.

The third volume in the series, ***Interpretation of the Results of Sediment Quality Investigations***, describes the four types of information that are commonly used to assess contaminated sediments, including sediment and pore-water chemistry data (Chapter 2),

sediment toxicity data (Chapter 3), benthic invertebrate community structure data (Chapter 4), and bioaccumulation data (Chapter 5). Some of the other tools that can be used to support assessments of sediment quality conditions are also briefly described (e.g., fish health assessments; Chapter 6). The information compiled on each of the tools includes: descriptions of its applications, advantages, and limitations; discussions on the availability of standard methods, the evaluation of data quality, methodological uncertainty, and the interpretation of associated data; and, recommendations to guide the use of each of these individual indicators of sediment quality conditions. Furthermore, guidance is provided on the interpretation of data on multiple indicators of sediment quality conditions (Chapter 7). Together, the information provided in the three-volume series is intended to further support the design and implementation of focussed sediment quality assessment programs.

The final volume of the series, ***Supplemental Guidance on the Design and Implementation of Detailed Site Investigations in Marine and Estuarine Ecosystems***, is intended to complement the guidance that is provided in the other three volumes by supporting the design and implementation of assessments of sediment quality conditions in marine and estuarine ecosystems. Accordingly, the document describes the objectives of a detailed investigation for marine and estuarine sites (Chapter 2). In addition, guidance is provided on the collection of physical, chemical, and biological data and information to support such a detailed site investigation (Chapter 3). Furthermore, guidance is provided on the interpretation of the data collected in the detailed site investigation (Chapter 4). Together, this guidance is intended to provide readers with some of the information needed to design and implement detailed investigations of marine and estuarine sites with contaminated sediments.

List of Acronyms

%	percent
µg	microgram
µg/kg	micrograms per kilogram
µg/L	micrograms per litre
µmol/g	micromoles per gram
AET	apparent effects threshold
AETA	apparent effects threshold approach
Al	aluminum
ANOVA	analysis of variance
AOC	area of concern
APHA	American Public Health Association
ARCS Program	Assessment and Remediation of Contaminated Sediments Program
ASTM	American Society for Testing and Materials
AVS	acid volatile sulfides
BCE	British Columbia Environment
BCWMA	British Columbia Waste Management Act
BEST	biomonitoring of environmental status and trends
BSAF	biota-sediment bioaccumulation factor
CA	consensus approach
CAC	Citizens Advisory Committee
CCME	Canadian Council of Ministers of the Environment
CCREM	Canadian Council of Resource and Environment Ministers
CDF	confined disposal facility
CEPA	Canadian Environmental Protection Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act (United States)
CERCLIS	Comprehensive Environmental Response, Compensation, and Liability Information System (United States)
CI	confidence interval
CLP	Contract Laboratory Program
COC	contaminant of concern
COPC	chemical of potential concern
CRLD	contract required detection limit
CSO	combined sewer overflow
CSR	Contaminated Sites Regulation
CWA	Clean Water Act (United States)
-d	- days
DDT	dichlorodiphenyl-trichloroethane
DDTs	*p,p*'-DDT, *o,p*'-DDT, *p,p*'-DDE, *o,p*'-DDE, *p,p*'-DDD, *o,p*'-DDD, and any metabolite or degradation product
DELT	deformities, fin erosion, lesions, and tumours

DL	detection limit
DM	dredged material
DO	dissolved oxygen
DOE	Department of the Environment
DOI	Department of the Interior (United States)
DQO	data quality objective
DSI	detailed site investigation
DW	dry weight
EC	Environment Canada
EC_{50}	median effective concentration affecting 50 percent of the test organisms
EEC	European Economic Community
ELA	effects level approach
EMAP	Environmental Monitoring and Assessment Program (United States)
EPT	ephemeroptera, plecoptera, trichoptera (i.e., mayflies, stoneflies, caddisflies)
EqPA	equilibrium partitioning approach
ERL	effects range low
ERM	effects range median
EROD	ethoxyresorufin-*O*-deethylase
ESB	equilibrium partitioning-derived sediment benchmarks
FCV	final chronic values
FD	factual determinations
FIFRA	Federal Insecticide, Rodenticide and Fungicide Act (United States)
gamma-BHC	gamma-hexachlorocyclohexane (lindane)
GFAA	graphite furnace atomic absorption
GIS	geographic information system
-h	- hours
H_2S	hydrogen sulfide
HC	Health Canada
HCl	hydrochloric acid
IBI	index of biotic integrity
IC_{50}	median inhibition concentration affecting 50 percent of test organisms
ICP	inductively coupled plasma-atomic emission spectrometry
ID	insufficient data
IDEM	Indiana Department of Environmental Management
IJC	International Joint Commission
IWB	index of well-being
K_{oc}	organic carbon partition coefficients
K_{ow}	octanol-water partition coefficients
Kp	sediment/water partition coefficients
LC_{50}	median lethal concentration affecting 50 percent of the test organism
LCS/LCSDs	laboratory control sample/laboratory control sample duplicates
Li	lithium
LMP	lakewide management plan

LOD	limit of detection
LOEC	lowest observed effect concentration
LRMA	logistic regression modelling approach
mean PEC-Q	mean probable effect concentration quotient
MESL	MacDonald Environmental Sciences Ltd.
MET	minimal effect threshold
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
mIBI	macroinvertebrate index of biotic integrity
-min	- minutes
mm	millimeter
MPRSA	Marine Protection, Research, and Sanctuaries Act (United States)
MS/MSDs	matrix spike/matrix spike duplicates
MSD	minimum significant difference
n	number of samples
NAWQA	National Water Quality Assessment (United States)
NEPA	National Environmental Policy Act (United States)
NG	no guideline available
NH_3	unionized ammonia
NH_4^+	ionized ammonia
NOAA	National Oceanic and Atmospheric Administration (United States)
NOEC	no observed effect concentration
NPDES	National Pollutant Discharge and Elimination System (United States)
NPL	National Priorities List (United States)
NPO	nonpolar organics
NR	not reported
NRDAR	natural resource damage assessment and restoration
NSQS	National Sediment Quality Survey (United States)
NSTP	National Status and Trends Program (United States)
NT	not toxic
NYSDEC	New York State Department of Environmental Conservation
OC	organic carbon
OC pesticides	organochlorine pesticides
OECD	Organization of Economic Cooperation and Development
OEPA	Ohio Environmental Protection Agency
OERR	Office of Emergency and Remedial Response (United States)
OPA	Oil Pollution Act (United States)
OPTTS	Office of Prevention, Pesticides, and Toxic Substances (United States)
OSW	Office of Solid Waste (United States)
OW	Office of Water (United States)
PAET	probable apparent effects threshold
PAHs	polycyclic aromatic hydrocarbons
PARCC	precision, accuracy, representativeness, completeness, and comparability
PCBs	polychlorinated biphenyls

PCDDs	polychlorinated dibenzo-*p*-dioxins
PCDFs	polychlorinated dibenzofurans
PCS	permit compliance system
PEC	probable effect concentration (consensus-based)
PEC-Q	probable effect concentration quotient
PEL	probable effect level
PEL-HA28	probable effect level for *Hyalella azteca*; 28-day test
PQL	protection quantification limit
PRGs	preliminary remedial goals
PSDDA	Puget Sound Dredged Disposal Analysis
PSEP	Puget Sound Estuary Program
PSI	preliminary site investigation
QA/QC	quality assurance/quality control
QAPP	quality assurance project plan
QHEI	qualitative habitat evaluation index
RAP	remedial action plan
RCRA	Resource Conservation and Recovery Act (United States)
REF	reference sediment
RPD	relative percent difference
RRH	rapidly rendered harmless
RSD	relative standard deviation
SAB	Science Advisory Board
SAG	Science Advisory Group
SAP	sampling and analysis plan
SEC	sediment effect concentration
SEL	severe effect level
SEM	simultaneously extracted metals
SEM - AVS	simultaneously extracted metal minus acid volatile sulfides
SETAC	Society of Environmental Toxicology and Chemistry
SLCA	screening level concentration approach
SMS	sediment management standards
SOD	sediment oxygen demand
SPMD	semipermeable membrane device
SQAL	sediment quality advisory levels
SQC	sediment quality criteria
SQG	sediment quality guideline
SQRO	sediment quality remediation objectives
SQS	sediment quality standard
SSLC	species screening level concentration
SSZ	sediment sampling zone
STP	sewage treatment plant
SVOC	semi-volatile organic chemical
T	toxic
TEC	threshold effect concentration

TEL	threshold effect level
TEL-HA28	threshold effect level for *Hyalella azteca*; 28-day test
TET	toxic effect threshold
TIE	toxicity identification evaluation
TMDL	total maximum daily load
TOC	total organic carbon
tPAH	total polycyclic aromatic hydrocarbons
TRA	tissue residue approach
TRG	tissue residue guideline
TRV	toxicity reference values
TSCA	Toxic Substances Control Act (United States)
USACE	United States Army Corps of Engineers
USDOI	United States Department of the Interior
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
VOC	volatile organic compound
WDOE	Washington Department of Ecology
WMA	Waste Management Act
WQC	water quality criteria
WQS	water quality standards
WW	wet weight

Glossary of Terms

Acute toxicity – The response of an organism to short-term exposure to a chemical substance. Lethality is the response that is most commonly measured in acute toxicity tests.

Acute toxicity threshold – The concentration of a substance above which adverse effects are likely to be observed in short-term toxicity tests.

Altered benthic invertebrate community – An assemblage of benthic invertebrates that has characteristics (i.e., mIBI score, abundance of EPT taxa) that are outside the normal range that has been observed at uncontaminated reference sites.

Aquatic ecosystem – All the living and nonliving material interacting within an aquatic system (e.g., pond, lake, river, ocean).

Acute toxicity – The response of an organism to short-term exposure to a chemical substance. Lethality is the response that is most commonly measured in acute toxicity tests.

Acute toxicity threshold – The concentration of a substance above which adverse effects are likely to be observed in short-term toxicity tests.

Altered benthic invertebrate community – An assemblage of benthic invertebrates that has characteristics (i.e., mIBI score, abundance of EPT taxa) that are outside the normal range that has been observed at uncontaminated reference sites.

Aquatic ecosystem – All the living and nonliving material interacting within an aquatic system (e.g., pond, lake, river, ocean).

Aquatic invertebrates – Animals without backbones that utilize habitats in freshwater, estuaries, or marine systems.

Aquatic organisms – The species that utilize habitats within aquatic ecosystems (e.g., aquatic plants, invertebrates, fish, amphibians and reptiles).

Benthic invertebrate community – The assemblage of various species of sediment-dwelling organisms that are found within an aquatic ecosystem.

Bioaccumulation – The net accumulation of a substance by an organism as a result of uptake from all environmental sources.

Bioaccumulation-based sediment quality guidelines (SQGs) – Sediment quality guidelines that are established to protect fish, aquatic-dependent wildlife, and human health against effects that are associated with the bioaccumulation of contaminants in sediment-dwelling organisms and subsequent food web transfer.

Bioaccumulative substances – The chemicals that tend to accumulate in the tissues of aquatic and terrestrial organisms.

Bioavailability – Degree to which a chemical can be absorbed by and/or interact with an organism.

Bioconcentration – The accumulation of a chemical in the tissues of an organism as a result of direct exposure to the surrounding medium (e.g., water; i.e., it does not include food web transfer).

Biomagnification – The accumulation of a chemical in the tissues of an organism as a result of food web transfer.

Chemical benchmark – Guidelines for water or sediment quality which define the concentration of contaminants that are associated with low or high probabilities of observing harmful biological effects, depending on the narrative intent.

Chemical of potential concern – A substance that has the potential to adversely affect surface water or biological resources.

Chronic toxicity – The response of an organism to long-term exposure to a chemical substance. Among others, the responses that are often measured in chronic toxicity tests include lethality, decreased growth, and impaired reproduction.

Chronic toxicity threshold – The concentration of a substance above which adverse effects are likely to be observed in long-term toxicity tests.

Congener – A member of a group of chemicals with similar chemical structures (e.g., PCDDs generally refers to a group of 75 congeners that consist of two benzene rings connected to each other by two oxygen bridges).

Consensus-based probable effect concentrations (PECs) – The PECs that were developed from published sediment quality guidelines and identify contaminant concentrations above which adverse biological effects are likely to occur.

Consensus-based threshold effect concentrations (TECs) – The TECs that were developed from published sediment quality guidelines and identify contaminant concentrations below which adverse biological effects are unlikely to occur.

Contaminants of concern (COC) –The toxic or bioaccumulative substances that occur at concentrations that are sufficient to cause or substantially contribute to adverse effects on microbial, benthic invertebrate, plant, fish, avian or mammalian communities.

Contaminated sediment – Sediment that contains chemical substances at concentrations that could potentially harm sediment-dwelling organisms, wildlife, or human health.

Conventional variables – A number of variables that are commonly measured in water and/or sediment quality assessments, including water hardness, conductivity, total organic carbon (TOC), sediment oxygen demand (SOD), unionized ammonia (NH_3), temperature, dissolved oxygen (DO), pH, alkalinity

Core sampler – A device that is used to collect both surficial and sub-surface sediment samples by driving a hollow corer into the sediments.

Degradation – A breakdown of a molecule into smaller molecules or atoms.

DELT abnormalities – A number of variables that are measured to assess fish health, including deformities, fin erosion, lesions, and tumours.

Diagenesis – The sum of the physical and chemical changes that take place in sediments after its initial deposition (before they become consolidated into rocks, excluding all metamorphic changes).

Ecosystem – All the living (e.g., plants, animals, and humans) and nonliving (rocks, sediments, soil, water, and air) material interacting within a specified location in time and space.

Ecosystem-based management – An approach that integrates the management of natural landscapes, ecological processes, physical and biological components, and human activities to maintain or enhance the integrity of an ecosystem. This approach places equal emphasis on concerns related to the environment, the economy, and the community (also called the ecosystem approach).

Ecosystem goals – Are broad management goals which describe the long-term vision that has been established for the ecosystem.

Ecosystem metrics – Identify quantifiable attributes of the indicators and defines acceptable ranges, or targets, for these variables.

Ecosystem objectives – Are developed for the various components of the ecosystem to clarify the scope and intent of the ecosystem goals. These objectives should include target schedules for being achieved.

Endpoint – A measured response of a receptor to a stressor. An endpoint can be measured in a toxicity test or in a field survey.

Epibenthic organisms – The organisms that live on the surface of sediments.

Exposure – Co-occurrence of or contact between a stressor (e.g., chemical substance) and an ecological component (e.g., aquatic organism).

Grab (Dredge) samplers – A device that is used to collect surficial sediments through a scooping mechanism (e.g. petite ponar dredge).

Index of biotic integrity (IBI) – An index that is used to evaluate the status of fish communities. The IBI integrates information on species composition (i.e., total number of species, types of species, percent sensitive species, and percent tolerant species), on trophic composition (i.e., percent omnivores, percent insectivores, and percent pioneer species), and on fish condition.

Infaunal organisms – The organisms that live in sediments.

Injury – A measurable adverse change, either long or short-term, in the chemical or physical quality or the viability of a natural resource resulting either directly or indirectly from exposure to a discharge of oil or release of a hazardous substance, or exposure to a product of reactions resulting from the discharge to oil or release of a hazardous substance. As used in this part, injury encompasses the phrases "injury", "destruction", and "loss". Injury definitions applicable to specific resources are provided in Section 11.62 of this part (this definition is from the United States Department of the Interior Natural Resource Damage Assessment Regulations).

Macroinvertebrate index of biotic integrity (mIBI) – A multimetric index that is used to evaluate the health of benthic invertebrate communities. The mIBI integrates information on a number of metrics, such as number of taxa, percent dominant taxa, and relative abundance of selected taxa, into a single value that provides a measure of the condition of the community as a whole.

Mean probable effect concentration-quotient (PEC-Q) – A measure of the overall level of chemical contamination in a sediment, which is calculated by averaging the individual quotients for select chemicals of interest.

Natural resources – Land, fish, wildlife, biota, air, water, ground water, drinking water supplies, and other such resources belonging to, managed by, held in trust by, appertaining to, or otherwise controlled by the federal government, provincial government, local government, or First Nation.

Natural resources damage assessment and restoration – The process of collecting, compiling, and analysing information, statistics, or data through prescribed methodologies to determine damages for injuries to natural resources.

Neoplastic – Refers to abnormal new growth.

Piscivorus wildlife species – The wildlife species that consume fish as part or all of their diets (e.g., herons, kingfishers, otter, osprey, and mink).

Population – An aggregate of individual of a species within a specified location in time and space.

Pore water – The water that occupies the spaces between sediment particles.

Probable effect concentration (PEC) – Concentration of a chemical in sediment above which adverse biological effects are likely to occur.

Probable effect concentration-quotient (PEC-Q) – A PEC-Q is a measure of the level of chemical contamination in sediment relative to a sediment quality guideline, and is calculated by dividing the measured concentration of a substance in a sediment sample by the corresponding PEC.

Receptor – A plant or animal that may be exposed to a stressor.

Sediment – Particulate material that usually lies below water.

Sediment-associated contaminants – Contaminants that are present in sediments, including whole sediments or pore water.

Sediment chemistry data – Information on the concentrations of chemical substances in whole sediments or pore water.

Sediment-dwelling organisms – The organisms that live in, on, or near bottom sediments, including both epibenthic and infaunal species.

Sediment injury – The presence of conditions that have injured or are sufficient to injure sediment-dwelling organisms, wildlife, or human health.

Sediment quality guideline – Chemical benchmark that is intended to define the concentration of sediment-associated contaminants that is associated with a high or a low probability of observing harmful biological effects or unacceptable levels of bioaccumulation, depending on its purpose and narrative intent.

Sediment quality targets – Chemical or biological benchmarks for assessing the status of each metric.

Simultaneously extracted metals (SEM) – Divalent metals - commonly cadmium, copper, lead, mercury, nickel, and zinc - that form less soluble sulfides than does iron or manganese and are solubilized during the acidification step (0.5m HCl for 1 hour) used in the determination of acid volatile sulfides in sediments.

Stressor – Physical, chemical, or biological entities that can induce adverse effects on ecological receptors or human health.

Threshold effect concentration (TEC) – Concentration of a chemical in sediment below which adverse biological effects are unlikely to occur.

Tissue – A group of cells, along with the associated intercellular substances, which perform the same function within a multicellular organism.

Tissue residue guideline (TRG) – Chemical benchmark that is intended to define the concentration of a substance in the tissues of fish or invertebrates that will protect fish-eating wildlife against effects that are associated with dietary exposure to hazardous substances.

Trophic level – A portion of the food web at which groups of animals have similar feeding strategies.

Wildlife – The fish, reptiles, amphibians, birds, and mammals that are associated with aquatic ecosystems.

Whole sediment – Sediment and associated pore water.

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Chapter 1. Introduction

In response to concerns raised regarding contaminated sediments, a number of programs have been established or expanded to support the assessment and management of contaminated sediments in Canada and the United States. The information generated under these programs provides important guidance for designing and implementing investigations at sites with contaminated sediments (see USEPA 1994a; MacDonald 1994a; 1994b; Reynoldson *et al.* 2000; Ingersoll *et al.* 1997; USEPA and USACE 1998; ASTM 2002a; USEPA 2000a; Krantzberg *et al.* 2001). While these guidance documents have unquestionably advanced the field of sediment quality assessment, the users of these individual guidance documents have expressed a need to consolidate this information into an integrated ecosystem-based framework for assessing and managing sediment quality in freshwater, estuarine, and marine ecosystems.

This guidance manual ***"A Guidance Manual to Support the Assessment of Contaminated Sediments in Freshwater, Estuarine, and Marine Ecosystems in British Columbia. Volume IV - Supplemental Guidance on the Design and Implementation of Detailed Site Investigations in Marine and Estuarine Ecosystems"*** is intended to complement the three-volume series that was jointly developed for the United States Environmental Protection Agency, British Columbia Ministry of Water, Land and Air Protection, and Florida Department of Environmental Protection (MacDonald and Ingersoll 2003a; 2003b; Ingersoll and MacDonald 2003). As was the case for the previous three volumes, this supplemental guidance is not intended to supplant the existing guidance documents on sediment quality assessment (e.g., USEPA 1994a; USEPA and USACE 1998; Environment Canada 1998; USEPA 2000a; Environment Canada 2001; ASTM 2002b; 2002c; 2002d; 2003a). Rather, it is intended to further support the design and implementation of assessments of sediment quality conditions in marine and estuarine ecosystems. More specifically, this document is intended to provide more detailed guidance on the design and implementation of detailed site investigations for sites that are located in nearshore marine and estuarine areas, by:

- Describing the objectives of a detailed site investigation (Chapter 2);
- Describing the collection of sediment quality data (Chapter 3); and,
- Describing the interpretation of the data collected in a DSI (Chapter 4).

Whenever possible, the guidance presented in this document was obtained directly from other authoritative sources (e.g., ASTM 2002a; 2002b; 2002c ; 2002d; 2002e; 2002f; 2002g; 2003a; 2003b; USEPA and USACE 2001; Environment Canada 1992; 1998; 2001). In this way, it was possible to highlight standardized and commonly used methods for assessing sediment quality conditions. The key references that were used to assemble this guidance manual are cited in Section 5.0 of this document. Additional references that may be relevant to the assessment of sediment quality conditions in marine and estuarine ecosystems are provided in Appendix 2 of MacDonald and Ingersoll (2003a).

Chapter 2. Goals and Objectives of a Detailed Site Investigation

2.0 Introduction

A detailed site investigation (DSI) is required at marine or estuarine sites if the results of the preliminary site investigation (PSI; which is conducted using sediment chemistry data) indicate that sediments are sufficiently contaminated to impair the beneficial uses of the aquatic ecosystem (i.e., pose unacceptable risks to sediment-dwelling organisms, aquatic-dependent wildlife, and/or human health). The information collected and compiled during the PSI should be used to design the DSI. As the PSI was conducted to evaluate the nature, magnitude, and extent of sediment contamination at the site, the results of the investigation should provide the information needed to identify which substances occur in sediments at potentially harmful levels [e.g., in excess of sediment quality criteria (SQC) or similar values), describe the range of concentrations of priority substances, and identify the locations that contain elevated levels of sediment-associated chemicals of potential concern (COPCs). Importantly, the PSI should also provide essential background information on the site, such as the location of contaminant discharges and spills, historic activities, and land uses at the site. As such, the PSI provides critical information for designing a well-focussed DSI.

2.1 Objectives of a Detailed Site Investigation

A DSI should be conducted when the results of the PSI indicate that a site contains or is likely to contain concentrations of COPCs in sediments that are likely to adversely affect sediment-dwelling organisms, wildlife, and/or human health. The DSI is designed to provide the information needed to assess risks to sediment-dwelling organisms, wildlife, and human health associated with exposure to contaminated sediments. In addition, the DSI should provide the necessary and sufficient information to support the evaluation of remedial alternatives and the development of a remedial action plan (RAP). Because the results of the DSI will be used directly to support sediment management decisions, the scope of this

investigation will necessarily be broader than that of a PSI. More specifically, the DSI should be designed to answer four main questions, including:

- Does the presence of COPCs in whole sediments and/or pore water pose an unacceptable risk to the receptors under consideration (i.e., sediment-dwelling organisms, aquatic-dependent wildlife, or human health)?
- What is the nature, severity, and areal extent of the risk to each receptor group under consideration?
- Which COPCs are causing or substantially contributing to the risk to the receptor under consideration (i.e., the contaminants of concern; COCs)?
- What are the concentrations of COPCs, by media type, that are associated with negligible risk to the receptor under consideration?

By fulfilling these objectives, the DSI provides the information needed for developing a remedial action plan (RAP) for the site, if required (Figure 1). In many ways, the DSI is an extension of the Stage II PSI (see Volume II for more details; MacDonald and Ingersoll 2003b). Therefore, combining these two types of investigations may be cost-effective under certain circumstances (i.e., following the completion of a Stage I PSI, which primarily involves compilation and evaluation of existing sediment quality data and related information; see MacDonald and Ingersoll 2003b for more details).

2.2 Considerations for Designing a Detailed Site Investigation

A number of important and potentially costly decisions are dependent on the results of the DSI. For this reason, it is essential that the DSI be based on a detailed study design, as articulated in the sampling and analysis plan (SAP) and the associated quality assurance project plan (QAPP). More specifically, the study should be designed to confirm or refute the presence of COPCs, to determine the spatial extent of chemical contamination (both in surficial and in deeper sediments), to identify chemical gradients (which can be used to identify possible sources of contamination), and to identify the location of sediment hot

spots. While whole-sediment chemistry, sediment toxicity, and benthic invertebrate community structure are a primary focus of this investigation, the DSI should also provide data for assessing the nature, severity, and extent of contamination in surface water, pore water, and biological tissues (including sediment-dwelling organisms, fish, and wildlife, as appropriate) and for assessing the status of fish communities inhabiting the area. Such information on the levels of COPCs can then be evaluated relative to the SQC (see Macfarlane *et al.* 2003), water quality criteria (WQC), or tissue residue guidelines (TRGs; Volume III; Ingersoll and MacDonald 2003). In this way, it is possible to identify the COCs at the site.

While the results of chemical analyses of environmental samples provide important information for assessing the risks that contaminated sediments pose to human health and environmental receptors, other types of data should also be collected during the DSI to confirm the results of such assessments and to provide multiple lines of evidence for assessing risks to ecological receptors. Specifically, data from toxicity tests (including whole-sediment and pore-water tests), benthic invertebrate community assessments, and fish community assessments can provide important information for evaluating the effects of contaminated sediments on aquatic organisms. In addition, bioaccumulation assessments can be used to assess the potential effects of COPCs that tend to bioaccumulate in the food web and, in so doing, pose risks to aquatic-dependent wildlife and/or human health. In designing the DSI, it is important to remember that the weight-of-evidence required needs to be proportional to the weight of the decisions that are likely to be made at the site (Wenning and Ingersoll 2002). More detailed guidance on the design and implementation of DSIs for marine and estuarine sites is presented in Chapter 3 of this document, while additional guidance for designing sampling programs is provided in Chapter 5 of MacDonald and Ingersoll (2003b).

Chapter 3. Collection of Data and Information to Support a Detailed Site Investigation at Marine and Estuarine Sites

3.0 Introduction

A DSI should be conducted when the results of the PSI indicate that a site contains or is likely to contain concentrations of COPCs in sediments that are likely to adversely affect sediment-dwelling organisms, wildlife, or human health. In this context, the term DSI is used to describe various types of detailed investigations that are conducted under specific programs [e.g., baseline ecological risk assessment (BERA) or human health risk assessment (HHRA); USEPA 1997]. The DSI is intended to provide detailed information on the site, including:

- The identity of the substances that are causing or substantially contributing to adverse effects on ecological receptors and/or human health (i.e., COCs);
- The magnitude and areal extent of sediment contamination at the site; and,
- The potential for and/or actual effects of contaminated sediments on ecological receptors and/or human health.

By fulfilling these objectives, the DSI provides the information needed for assessing the risks to ecological receptors and/or human health posed by contaminated sediments and for developing a remedial action plan (RAP) for the site, if required (Figure 1). In many ways, the DSI is an extension of the Stage II PSI (see Volume II for more details; MacDonald and Ingersoll 2003b).

3.1 Considerations for Conducting a Detailed Site Investigation

The development of a DSI SAP and associated QAPP represent essential steps in the overall data collection process. Some of the key steps involved in developing an SAP for the DSI include (see Chapter 5 of Volume II for more information):

- Map and describe the area to be sampled (i.e., sediment sampling zone; SSZ);
- Determine the data requirements for ecological and human health risk assessments;
- Map and describe the proposed sampling sites (including latitude and longitude; both primary and alternate sampling sites should be identified at this stage of the process, with criteria specified for when alternate sites should be sampled);
- Describe the sediment sampling, handling, and storage procedures that will be used for obtaining sediment samples for chemical analysis;
- List the chemical analytes that will be measured in sediment samples and associated data quality objectives (DQOs);
- Describe the sediment sampling, handling, and storage procedures that will be used for obtaining sediment samples for toxicity and bioaccumulation testing;
- Describe the toxicity tests that will be conducted on the sediment samples, including the associated description of the selected metrics (e.g., survival and growth);
- Describe the procedures that will be used to assess bioaccumulation;
- Describe the procedures that will be used for sampling the benthic invertebrate community, including associated descriptions of the selected metrics (e.g., benthic index);
- Describe the procedures that will be used to assess sediment transport at the site (see Appendix 1); and,
- Describe the quality assurance procedures that will be used in the field and the laboratory to assure that the resultant data meet project DQOs (i.e., which should be included as an appendix to the sampling plan).

Definition of the SSZ is the first step in the development of a sampling plan for the DSI. As the DSI is designed to provide further information on the areal extent of sediment contamination, including the extent to which COPCs have been transported to adjoining properties, the SSZ may be larger than that identified in the PSI. For example, if significant contamination was found near the boundaries of the SSZ for the PSI, then the SSZ for the DSI should be expanded substantially to support characterization of the areal extent of contamination. Information on sediment transport at the site should be considered in defining the SSZ as it provides a basis for evaluating the potential for off-site movement of sediment. While near-term sampling costs are likely to be less if the SSZ for the DSI is relatively small, additional sampling may be required if the results of the DSI indicate that contaminated sediments occur at or near the boundaries of the SSZ. Therefore, it may be more cost-effective to err on the side of inclusiveness when defining the SSZ for the DSI (i.e., making it larger than what seems absolutely necessary). As was the case for the PSI, the size of the SSZ does not, in any way, indicate the limit of responsibility or liability for contaminated sediments. Instead it provides an operational definition of the area that is most likely to be contaminated by activities at the site.

The second step in the design of a DSI sampling plan is to develop a sampling grid (i.e., identify the location of sampling sites). As the DSI needs to provide information on the specific areas, depths, and magnitude of contamination at the site and in nearby areas, it is important to review the results of the PSI to identify potential hot spots with respect to sediment contamination. In general, a biassed sampling design is preferred for the DSI because it can be used to focus sampling effort on the areas that are most likely to be contaminated (i.e., by conducting targeted sampling to delineate the location and extent of hot spot areas). Within the original SSZ (i.e., the area sampled during the PSI), intensive sampling should be conducted in the vicinity of the sediment hot spots that were identified to confirm the results of the PSI, to determine the areal extent of contamination at each hot spot, and to identify gradients in contaminant concentrations. Outside the original SSZ, biassed sampling should be used to target potential hot spots (i.e., near the contaminated areas within the original SSZ) and random sampling should be used to investigate the potential for contamination in other areas.

Importantly, the DSI sampling program should be designed to determine the concentrations of COPCs in both surficial (i.e., 0 to 10 cm) and deeper sediments. Sampling of deeper

sediments is essential in order to characterize sediment quality conditions within the biologically-active zone (0 to 100 cm) and in areas that could become more biologically active if surficial sediments were removed. The sampling plan should identify the location and depths of each site that will be sampled, with decision criteria also provided in the event that sampling certain sites is not feasible. As the mobilization/demobilization costs associated with sediment sampling can be substantial, it may be prudent to collect and archive samples from additional locations during the DSI. This makes it possible to, for example, analyse samples collected 10 m from a hot spot if the samples collected 5 m from that hot spot show significant contamination. In this way, the costs associated with chemical analyses can be minimized. However, attention needs to be paid to acceptable holding times to ensure that only high quality data are generated (ASTM 2002a; 2003a).

The sampling plan should include descriptions of the methods that will be used to collect, handle, and store sediment samples. These instructions are particularly important for the DSI because sediment samples are likely to be collected for several purposes, including chemical analysis, toxicity testing, bioaccumulation assessment, and/or benthic invertebrate community analyses. As one of the objectives of the DSI is to confirm that the contaminated sediments are actually toxic to sediment-dwelling organisms, it is critical that sediments be collected in a manner that facilitates the generation of matching sediment chemistry and biological effects data (i.e., by preparing splits of homogenized sediment samples). The collection, handling, and storage of sediment samples needs to follow established protocols (ASTM 2002a; 2002e; 2002f; USEPA 2000a; 2001). To achieve this objective, everyone involved in the sampling program should receive specialized training on these methods before starting the sampling program.

In addition to the foregoing considerations, development of the DSI sampling program should consider additional factors that apply to each of the key indicators of sediment quality conditions, including sediment chemistry data, sediment toxicity data, benthic invertebrate community assessments, and bioaccumulation assessments (MacDonald and Ingersoll 2003a; 2003b). Some additional considerations that should be taken into account in designing the DSI sampling program are discussed in the following sections. Additional guidance on each of these indicators is provided in Volume III.

3.2 Sediment Chemistry

The procedures that will be used to identify and quantify the chemical substances in the sediment samples should be described in the sampling and analysis plan (see Chapter 2 of Ingersoll and MacDonald 2003 for more information). As a first step, a list of substances for chemical analysis should be compiled using the results of the PSI and other considerations (e.g., substances used to calculate mean SQC-quotients). This list should also include the sediment quality variables that provide ancillary information for interpreting the resultant sediment chemistry data (e.g., TOC, AVS, Al, Li). In addition, the water quality variables that need to be measured to support interpretation of the sediment quality data should be identified [e.g., bottom water dissolved oxygen (DO) and salinity, pore water salinity, hydrogen sulphide, pH, and total ammonia]. The preferred analytical method for each analyte can also be specified in the sampling plan; however, it may be more prudent to let the analytical laboratory select the methods based on the DQOs for the project. Clearly, articulating the data quality requirements (i.e., accuracy, precision, and detection limits) to the laboratory personnel at the outset of the project is likely to minimize the potential for problems later.

3.3 Biological Investigations

The procedures that will be used to assess the biological effects that are associated with exposure to contaminated sediments should also be included in the sampling and analysis plan. Biological assessment is an essential tool for evaluating sediment quality conditions at contaminated sites because it provides important information for interpreting sediment chemistry data. The five types of biological assessments that are commonly conducted at sites with contaminated sediments include toxicity testing, benthic invertebrate community assessments, bioaccumulation testing, fish health assessments, and fish community structure assessments. More detailed information on each of these indicators is presented in Volume III of this guidance manual.

3.3.1 Toxicity Testing

Laboratory sediment toxicity tests can provide rapid and highly relevant information on the potential toxicity of contaminated sediments to benthic organisms. Acute (10- to 14-d exposures) and chronic (21- to 60-d exposures) toxicity tests have been developed to evaluate the biological significance of sediment contamination. Tests have been designed to assess the toxicity of whole sediments (solid phase), suspended sediments, elutriates, sediment extracts, or pore water. The organisms that can be tested with these methods include microorganisms, algae, invertebrates, and fish. This section of the report is intended to provide general guidance on the selection of toxicity tests to support assessments of sediment quality conditions of contaminated sites.

The objective of a sediment toxicity test is to determine whether contaminated sediments are harmful to benthic organisms (ASTM 2002a; USEPA 2000a). These tests can be used to measure the interactive toxic effects of complex chemical mixtures in sediment. Furthermore, knowledge of specific pathways of interactions among sediments and test organisms is not necessary to conduct the tests. Sediment toxicity tests can be used to: (1) determine the relationship between toxic effects and bioavailability; (2) investigate interactions among chemicals; (3) compare the sensitivities of different organisms; (4) determine spatial and temporal distribution of contamination; (5) evaluate hazards of dredged material; (6) measure toxicity as part of product licensing or safety testing; (7) rank areas for clean up; and, (8) estimate the effectiveness of remediation or management practices.

The results of sediment toxicity tests can be used to assess the bioavailability of contaminants in field-collected sediments. The responses of organisms exposed to field-collected sediments are often compared to the response of organisms exposed to a control and/or a reference sediment. The results of toxicity tests on sediments spiked with one or more chemicals can also be used to help establish cause and effect relationships between chemicals and biological responses. The results of toxicity tests with test materials spiked into sediments at different concentrations are often reported in terms of a median lethal concentration (LC_{50}), a median inhibition concentration (IC_{50}), a no observed effect concentration (NOEC), or a lowest observed effect concentration (LOEC; ASTM 2002a; USEPA 2000a). The advantages and disadvantages of sediment toxicity tests are presented in Table 1.

The choice of a test organism has a major influence on the relevance, success, and interpretation of a test. In marine and estuarine toxicity testing, the test species that are commonly used include amphipods, polychaetes, echinoderms, and molluscs. As no one organism is best suited for all applications, considering the intended uses of the resultant data is important in the selection of toxicity tests. Criteria for selecting toxicity testing methods and species are described in USEPA (1994a) and ASTM (2003a), and presented in Table 2.

Currently, there are a variety of standardized acute (i.e., short-term tests; duration of $\leq$10-d) and chronic (i.e., longer-term tests; duration of >10-d) toxicity tests available for determining the adverse effects that are associated with exposure of benthic organisms to marine and estuarine sediments. USEPA (1994a), ASTM (2003a), and Environment Canada (1992a; 1998) have described procedures for testing estuarine or marine amphipods in 10-d laboratory exposures to evaluate the toxicity of COPCs associated with whole sediments. In total, methods have been described for four species of estuarine or marine sediment-burrowing amphipods, including:

- *Ampelisca abdita*, a marine species that inhabits marine and estuarine portions of the Atlantic coast, the Gulf of Mexico, and San Francisco Bay;
- *Eohaustorius estuarius*, a Pacific coast marine and estuarine species;
- *Leptocheirus plumulosus*, an Atlantic coast estuarine species; and,
- *Rhepoxynius abronius*, a Pacific coast marine species.

The habitat characteristics and other life history parameters of these four amphipod species are summarized in Table 3.

Generally, the methods described may be applied to all four species, although acclimation procedures and some test conditions (i.e., temperature and salinity) are species-specific (ASTM 2003a). The toxicity test is conducted in 1-L glass chambers containing 175 mL of sediment and 800 mL of overlying seawater. Exposure is static (i.e., water is not renewed), and the animals are not fed over the 10-d exposure period. The endpoint in the toxicity test is survival and reburial of surviving amphipods is an additional measurement that can be used as an endpoint (i.e., for *Rhepoxynius abronius* and *Eohaustaurius estuarius*). Performance criteria established for this test state that the average survival of amphipods in

negative control treatment must be greater than or equal to 90%. Procedures are described for use with sediments with pore-water salinity ranging from >0 ‰ to fully marine. The recommended test conditions for conducting reference toxicity tests with four species of marine and estuarine amphipods are presented in Table 4. Additionally, the test conditions for conducting 10-d toxicity tests with these species are summarized in Table 5, while the associated application limits are presented in Table 6.

While 10-d toxicity tests with marine and estuarine amphipods is the gold standard for acute toxicity testing, standardized methods have also been established for testing other species. For example, acute sediment toxicity tests may be conducted with the Pacific oyster (*Crassostrea gigas*), the blue mussel (*Mytilus edulis*), the purple sea urchin (*Strongylocentrotus purpuratus*), and the sand dollar (*Dendraster excentricus*; Environment Canada 1992b; WDOE 1995; ASTM 2002c). For each of these species, mortality and/or abnormality of larvae are the endpoints that are measured in elutriate or pore-water toxicity tests, depending on the species used. Additionally, whole-sediment toxicity tests may be conducted using bivalve molluscs, copepods, crabs, mysids, polychaetes, fish and other organisms (ASTM 2002e; 2002c; 2002d). Procedures for conducting whole-sediment, elutriate, and saline-extract toxicity tests with microorganisms (i.e., *Vibrio fisheri*) are also available (WDOE 1995). However, the procedures for conducting such tests are not as well-established as they are for marine and estuarine amphipods (i.e., the procedures for testing most species have not been standardized).

Because sediment-dwelling organisms are exposed to contaminated sediments for extended periods, at least one chronic (i.e., longer-term) toxicity test on a sensitive sediment-dwelling organism, in which sub-lethal endpoints are measured, should be included in the DSI. Although several longer-term toxicity tests have been described, USEPA and USACE (2001) and ASTM (2003a) recently described a procedure for determining the chronic toxicity of COPCs associated with whole sediments with the amphipod *Leptocheirus plumulosus* in laboratory exposures. The toxicity test is conducted for 28 d in 1-L glass chambers containing 175 mL of sediment and about 725 mL of overlying water. Test temperature is 25 ± 2^{o}C, and the recommended overlying water salinity is 5‰$\pm$2‰ (for test sediment with pore water at 1‰ to 10‰) or 20‰$\pm$2‰ (for test sediment with pore water >10‰). However, a range of salinity between 1 and 39‰ can be tested (ASTM 2003a) . Four hundred millilitres of overlying water is renewed three times per week, at which times test

organisms are fed. The endpoints in the toxicity test are survival, growth, and reproduction of amphipods. Performance criteria established for this test include: the average survival of amphipods in negative control treatments must be ≥80%; and, there must measurable growth and reproduction in all replicates of the negative control treatment. This test is applicable for use with sediments from oligohaline to fully marine environments, with a silt content greater than 5% and a clay content less than 85%. The test conditions that are recommended for conducting such chronic toxicity tests are summarized in Table 7.

In addition to the 28-d test with marine amphipods, methods for conducting chronic toxicity tests with other marine and estuarine species have been developed. For example, ASTM (2002b) described standard methods for conducting 20- to 28-d chronic toxicity tests with marine and estuarine polychaetes (*Neanthes arenaceodentata*). The endpoints measured in these whole-sediment toxicity tests include survival and growth. It is important to note, however, that these tests may not be as sensitive as 10-d toxicity tests with marine amphipods (MacDonald *et al.* 1994). Therefore, the use of polychaetes in chronic toxicity testing should be discouraged.

3.3.2 Benthic Invertebrate Community Assessments

The structure of benthic invertebrate communities represents an important indicator of sediment quality conditions in marine and estuarine ecosystems. Such assessments are based on comparisons of community structure metrics, such as species richness, diversity, and the abundance of key taxa at test stations and appropriate reference stations (i.e., stations with similar depth, salinity, flow, substrate type, sediment grain size, and TOC), and provide a means of assessing the COPC-related effects associated with exposure to sediments in the assessment area (USEPA 1992; 1994a). Numerous studies have documented changes in the composition of benthic invertebrate communities resulting from sediment contamination (i.e., Hyland *et al.* 2003; MacDonald *et al.* 2003). This section of the report is intended to briefly describe the existing procedures for assessing benthic invertebrate data as part of an overall assessment of sediment quality in marine and estuarine habitats.

Benthic communities are assemblages of organisms that live in or on the bottom sediment. In most benthic community assessments, the primary objective is to determine the identity, abundance, and distribution of the species that are present (USEPA 1992; 1994b). Because most benthic macroinvertebrates are relatively sedentary and are closely associated with the sedimentary environment, they tend to be sensitive to both short-term and long-term changes in habitat, sediment, and water quality conditions (Davis and Lathrop 1992). Therefore, data on the distribution and abundance of these species provide important information on the health of the aquatic ecosystem. As such, benthic invertebrate community structure represents an important ecosystem health indicator.

Assessments of benthic community structure have been used to describe reference conditions, to establish baseline conditions, and to evaluate the effects of natural and anthropogenic disturbances (Striplin *et al.* 1992). A wide variety of techniques have been used to evaluate the effects of contaminated sediments on benthic invertebrate communities (see Ingersoll *et al.* 1997). These techniques can be classified into four general categories based on the level of organization considered. The assessments are reliant on measurements of endpoints that are relevant to the following organizational scales:

- Individual (e.g., morphological changes, biomarkers);
- Population (e.g., abundance of keystone species; population age/size structure);
- Community structure (e.g., benthic index, multivariate analyses); and,
- Community function (e.g., energy transfer, functional groups).

All of the various measurement endpoints are evaluated based on departure from an expected or predicted condition (such as observations made at appropriate reference sites). Uncertainty in the application of these techniques stems from incomplete knowledge of the system (i.e., what represents normal conditions); systematic error in the method being used; and, the sampling scale selected (Ingersoll *et al.* 1997). Of the organization scales evaluated, the measurement endpoints which provide information on the status of invertebrate populations and community structure were considered to be the most reliable (Reynoldson *et al.* 1995; Ingersoll *et al.* 1997). Such assessments usually require identification of benthic macroinvertebrates to the species level.

In terms of evaluating sediment quality conditions, such assessments are focussed on establishing relationships between various community structure metrics (e.g., species richness, total abundance, relative abundance of various taxonomic groups, macroinvertebrate index of biotic integrity; mIBI) and measures of sediment quality (e.g., chemical concentrations and organic content; MacDonald *et al.* 2002). Data from benthic community assessments have the potential to provide relevant information for identifying impacted sites and, with appropriate supporting data, the factors that are contributing to any adverse effects that are observed (USEPA 1992; 1994b).

It is important to note that there are a number of important limitations of benthic invertebrate community assessments. First, the absence of benthic organisms in sediment does not necessarily indicate that sediment contamination caused the observed response. Benthic invertebrate distributions may exhibit high spatial or temporal variability. Furthermore, short-term exposure to chemical (e.g., ammonia, DO) or physical (e.g., temperature, abrasion) factors can influence the distribution and abundance of benthic invertebrates, even in the absence of measurable levels of COPCs in sediment. Therefore, information on the distribution of benthic invertebrates alone is not always indicative of ambient sediment quality conditions and is certainly not diagnostic of sediment contamination or sediment toxicity (USEPA 1992; 1994b).

3.3.3 Bioaccumulation Assessments

In aquatic ecosystems, many substances that occur at only trace levels in overlying water can accumulate to elevated levels in sediments. The same physical-chemical properties that cause these substances to accumulate in sediments (e.g., low aqueous solubilities, high K_{ow}), make chemicals such as PCBs, organochlorine pesticides, and mercury prone to bioaccumulation in marine and estuarine ecosystems. The accumulation of such substances in the tissues of sediment-dwelling organisms and subsequent biomagnification in aquatic food webs can pose risks to a variety of ecological receptors, particularly those organisms that consume aquatic species (i.e., aquatic-dependent wildlife). Bioaccumulation assessments are conducted to provide the information needed to assess the risks to aquatic-dependent wildlife and human health associated with exposure to bioaccumulative substances. This section of the report is intended to describe the procedures for

bioaccumulation assessments as part of integrated assessments of sediment quality conditions in marine and estuarine ecosystems.

Contaminated sediments represent important sources of the substances that accumulate in aquatic food webs (Ingersoll *et al.* 1997). Because these contaminants can adversely affect aquatic-dependent wildlife species and/or human health, tissue chemistry represents an important ecosystem health indicator in sediment quality assessments (ASTM 2002e; 2002f). In general, the concentrations of COPCs in the tissues of sediment-dwelling organisms represent the primary metrics for tissue chemistry. As wildlife species typically consume the entire prey organism, whole-body COPC levels in prey species are the most relevant for assessing risks to wildlife. In contrast, the levels of COPCs in edible tissues represents the most important metrics for human health assessments. Assessments that are directed at evaluating COPC residues in the tissues of benthic macroinvertebrates should focus on the bioaccumulative COPCs that are known or suspected to occur in sediments at the site under investigation. Typically, the COPCs that are considered in such assessments include: metals, methyl mercury, PAHs, PCBs, organochlorine pesticides, chlorophenols, and/or PCDDs/PCDFs. However, this list should be refined based on the land and water use activities that have been documented in the vicinity of the site. Representative concentrations of selected COPCs in uncontaminated sediments (i.e., control sediments) and in the tissues of control organisms used in bioaccumulation tests are presented in Tables 8 and 9, respectively. These values can be used to assess the adequacy of control materials selected for use in bioaccumulation assessments.

The selection of species for inclusion in assessments of bioaccumulation requires an understanding of the predator-prey relationships in the ecosystem under investigation. For example, the levels of COPCs in benthic macroinvertebrates are likely to be relevant when evaluating risks associated with dietary uptake of COPCs by bottom-feeding fish or sediment-probing birds. The characteristics of various species of marine invertebrates are presented in Table 10. This information is useful for selecting test organisms for use in tests to assess bioaccumulation in benthic invertebrates. In cases where fish-eating birds and mammals represent the wildlife species of special concern, fish would be the primary species targeted in sampling and analytical programs. In this way, sampling programs can be tailored to answer the key risk questions that are being posed by the investigators. Bioaccumulation

is not an appropriate assessment approach for COPCs that are rapidly metabolized or otherwise not accumulated in the tissues of the organism(s) being evaluated.

Ingersoll *et al.* (1997) identified four general approaches for conducting bioaccumulation assessments, including:

- A laboratory approach, which involves exposing organisms to sediment under controlled conditions;
- A field approach, which involves collecting organisms from a study area;
- Assessment of food web transfer; and,
- Models to predict bioaccumulation processes.

The following sections briefly describe each of these approaches. The types of information gained and the requirements of each approach are summarized in Table 11.

In the laboratory approach, individuals of a single species are exposed under controlled laboratory conditions to sediments collected from the study area being assessed (ASTM 2002f; USEPA 2000a). After an established period of exposure, the tissues of the organisms are analysed for the COPCs. Bioaccumulation has occurred if the final concentration in tissues exceeds concentrations that were present before the exposure began. This requires that individuals representative of initial conditions also be analysed. Table 12 provides estimates of the percent of steady state concentrations that are achieved after 10 and 28 days of exposure to whole sediments. These results demonstrate that longer term tests are needed to estimate steady state concentrations of COPCs in invertebrate tissues for most COPCs. This approach has been routinely applied in the assessment of contaminated sediments (ASTM 2002f; USEPA 2000a).

In the field approach, concentrations of COPCs in tissues are determined by collecting one or more species exposed to sediments at the study area being assessed. In addition, organisms representing various trophic levels may be collected and analysed to determine tissue residue levels. These concentrations are compared to those that have been measured in the tissues of organisms collected from appropriately selected reference area(s). Two methods have been used to determine bioaccumulation in the field:

- Organisms resident at the area are collected *in situ* for analysis; or,
- Organisms are transplanted from another location (presumably with a history of little contaminant exposure) to the area of concern then re-collected, and tissues are analysed after an established period of exposure.

These approaches have not been used routinely in the assessment of contaminated sediments (ASTM 2002f), although the use of caged mussels has expanded in recent years (Salazar and Salazar 2002; ASTM 2002g). In some cases, semipermeable membrane devices (SPMDs) are deployed in the field for specified time periods to simulate exposures of aquatic organisms to COPCs (Williamson *et al.* 2002).

Models which describe bioaccumulation are relatively well developed for both organic and inorganic contaminants (Thomann 1989; Luoma and Fisher 1997; ASTM 2002f). Toxicokinetic models have a long history, as do simpler models of bioaccumulation processes. Site-specific models predict bioaccumulation on the basis of laboratory-determined characterization of biological processes in the species of interest and field-determined chemical measurements at the area of concern. Some uncertainties remain unresolved in most models and consensus does not exist about the appropriate model to apply for some (if not all) COPCs (Luoma and Fisher 1997).

Equilibrium models are commonly employed in risk assessment of bioaccumulation and are available for both organic and inorganic COPCs (Di Toro *et al.* 1991; Ankley *et al.* 1996). The models assume that the concentrations of COPCs among all compartments of the environment are controlled by thermodynamics and at least approach equilibrium conditions. If thermodynamic equilibrium exists and if one route of uptake is known or can be predicted, overall bioaccumulation is inferred. Recent applications use an extension of the equilibrium models, termed kinetic or pathway models (ASTM 2002f). These models incorporate geochemical principles and also address uncertainties in the assumptions of equilibrium. Kinetic models assume that routes of bioaccumulation are additive and must be determined independently. Kinetic models and equilibrium models may yield similar results if COPC distributions and concentrations in an environment are at equilibrium (although not always), but can yield very different results where environmental compartments are not at equilibrium

(e.g., if biological processes control concentrations, speciation, or phase partitioning of COPCs; Ingersoll *et al.* 1997).

An expert panel evaluated the uncertainty associated with all four of the procedures established for conducting bioaccumulation assessments (Ingersoll *et al.* 1997). The results of this evaluation indicate that bioaccumulation is a highly variable endpoint that primarily provides information on exposure to contaminants. It is particularly useful for determining the bioavailability of sediment-associated contaminants. Of the four approaches evaluated, laboratory assessments were considered to be the most reliable and are recommended for assessing bioaccumulation potential at contaminated sites.

The choice of test species can greatly influence the success, ecological significance, and interpretability of a bioaccumulation test (ASTM 2002f). While it is not possible to recommend a single species of test organisms that can be used in assessments of bioaccumulation in marine and estuarine ecosystems (i.e., due to the potential range of environmental conditions), two essential characteristics of test species are chemical resistance and sediment ingestion. Accordingly, polychaetes, such as *Nereis virens* or molluscs (*Macoma nasuta*) often represent the best choice for use in such sediments. However, many other species may be used in this application (see ASTM 2002f). It should be noted that such data do not necessarily provide a direct means of estimating tissue residues in the field. For this reason, it is also recommended that the tissues of resident species also be collected and analysed to provide a basis for assessing hazards to human health and aquatic-dependent wildlife species (i.e., by comparing measured tissue concentrations to TRGs).

Tissue residue guidelines for the protection of piscivorus wildlife species and/or human health represent the principal targets that are used to interpret the results of bioaccumulation assessments (e.g., CCME 1999). Thus far, such TRGs have been established for methyl mercury, PCBs, and PCDDs/PCDFs. However, a variety of risk-based procedures have also been developed to evaluate the results of such assessments. These tools can also be used to back-calculate to the concentrations of COPCs in sediment that will protect human health and ecological receptors.

3.3.4 Other Tools for Assessing Sediment Quality Conditions

While sediment chemistry, sediment toxicity, benthic invertebrate community structure, and bioaccumulation data represent the primary tools for assessing sediment quality conditions in marine and estuarine ecosystems, there are a number of other tools that can be used to support the sediment quality assessment process. For example, in certain circumstances it may be necessary to identify the substances that are causing or substantially contributing to the effects observed in the investigation (i.e., COCs). In these cases, spiked sediment toxicity tests and/or toxicity identification evaluation (TIE) procedures can be used to help identify the putative causal agents. In addition, numerical SQGs can be used to assist in the identification of the substances that are causing or substantially contributing to sediment toxicity (Wenning and Ingersoll 2002). Furthermore, various data analytical approaches, such as multiple regression analysis and principal components analysis, can be applied to identify the substances that are most directly linked to the toxic effects observed in field collected samples. Some of these tools and their applications are described in Chapter 7 of Volume III.

3.4. Quality Assurance Project Plan (QAPP)

The sampling and analysis plan for the DSI should include a QAPP that applies to both the field and laboratory components of the program. Some of the important elements that need to be contained in a QAPP for a DSI include:

- Project organization and responsibility;
- Personnel training and instruction;
- Quality assurance objectives and methods for assessing precision, accuracy, completeness, representativeness, and comparability of the data generated (a list of low level detection limits for sediment and biological tissues is provided in Table 13; these should be considered in the development of target detection limits for DSIs conducted at marine and estuarine sites);

- Sampling procedures, including sampling equipment, decontamination of equipment, collection of field duplicates, generation of field blanks, collection of positional data, sample containers, sample identification and labelling, sample preservation and holding times, field documentation, and field data sheets;
- Sample handling and preparation procedures for each media type and purpose (i.e., chemistry, toxicity testing, etc.);
- Sample custody and transportation, including field custody procedures, chain-of-custody documentation, sample packaging and transport, and laboratory log-in procedures and documentation;
- Analytical methods, including target DQOs;
- Toxicity testing procedures, including descriptions of negative controls, positive controls, and reference samples, and associated criteria for data acceptance;
- Bioaccumulation testing procedures and associated criteria for data acceptance;
- Benthic invertebrate identification and counting procedures and associated criteria for data acceptance;
- Data management, validation, analysis, and reporting procedures; and,
- Quality assurance report preparation.

Implementation of a well-designed sampling program is likely to provide the data needed to conduct a comprehensive assessment of sediment quality conditions at the site. More information on the design of sediment quality sampling programs is provided in Chapter 5 of Volume II, while the elements of sampling and analysis plans are described in Appendix 1 of Volume II.

Chapter 4. Interpretation of Data and Information Collected to Support a Detailed Site Investigation at Marine and Estuarine Sites

4.0 Introduction

A variety of indicators are commonly used to assess sediment quality conditions at marine and estuarine sites. Of these, sediment and pore-water chemistry data, sediment toxicity data, benthic invertebrate community structure data, and bioaccumulation data provide the most relevant information for assessing the risks posed by sediment-associated COPCs to aquatic organisms, aquatic-dependent wildlife, and human health. Detailed guidance on the interpretation of these and other data types is provided in Ingersoll and MacDonald (2003; i.e., Volume III of this series). Therefore, only an overview of that process is provided in this document.

4.1 Interpretation of Data and Information on Sediment Quality Conditions

Interpretation of the data collected in the DSI is more involved than the interpretation of Stage II PSI data. As was the case for the PSI, the review and evaluation of the quality assurance information (i.e., in light of the acceptance criteria that were established in the QAPP) represents the first stage of the data interpretation process. This initial evaluation provides a basis for assessing the validity of the resultant data and determining if additional sampling is required.

In the second step of the data analysis process, the data collected in the DSI are compiled and used to assess exposures to contaminated sediments, the effects of contaminated sediments

on ecological receptors and human health, and the risks posed by contaminated sediments to beneficial uses of the aquatic ecosystem. The objectives of the exposure assessment are to identify the receptors at risk, describe the relevant exposure pathways, and determine intensity and areal extent of the exposure to COPCs. Sediment chemistry data and/or pore-water chemistry data may be used, in conjunction with applicable benchmarks (e.g., SQC, water quality criteria, background levels), to identify the areas, depths, and degree of contamination at the site and in nearby areas. If significant contamination (i.e., > SQC) is observed at or nearby the boundaries of the SSZ (either in surficial sediments or at depth), then additional sampling may be required to fully characterize the spatial extent of contamination.

The primary objective of the effects assessment is to describe the nature and severity of effects that are being caused by contaminated sediments. Sediment chemistry data can be used in the effects assessment to estimate the probability that specific types of effects would be associated with exposure to contaminated sediments (i.e., using the dose-response relationships established for individual COPCs or groups of COPCs; e.g., Swartz 1999; MacDonald *et al.* 2000; USEPA 2000b; Wenning and Ingersoll 2002). Additionally, the results of the toxicity tests can be used to determine if sediments with elevated concentrations of COPCs (i.e., relative to the SQGs) are toxic to aquatic organisms. Contaminants may be present in relatively unavailable forms or other factors may be mitigating toxicity at the sites that have elevated chemical concentrations but are not toxic to sediment-dwelling organisms. The results of benthic invertebrate community assessments can also be used to evaluate the effects of contaminated sediments on sediment-dwelling organisms. Agreement among the three measures of adverse biological effects (i.e., the SQGs, toxicity tests, and benthic assessments) provides strong evidence for identifying the specific areas and sediment depths that are contaminated to levels that are adversely affecting or have the potential to adversely affect sediment-dwelling organisms (Chapter 7 of Volume III).

The data collected in the DSI can also be used to assess the hazards associated with exposure to bioaccumulative substances at the site. In this assessment, the results of laboratory bioaccumulation tests provide a basis for identifying which substances are bioavailable and have the potential to bioaccumulate in the food web. The results of chemical analyses of biological tissues collected at the site can then be used to confirm the results of the laboratory

bioaccumulation tests. To evaluate the potential effects associated with exposure to bioaccumulative substances, the tissue residue data can be compared to the TRGs that have been established for the protection of wildlife and human health. In this way, the chemicals and the locations that pose the greatest hazards to human health and wildlife can be identified. Integration of the results of the exposure and the effects assessments provides a basis for estimating risks to ecological receptors associated with exposure to contaminated sediments. More specific guidance on ecological and human health risk assessments of contaminated sediment is provided in Ingersoll *et al.* (1997), Landis *et al.* (1997), USEPA (1998) and Suter *et al.* (2000).

The results of the investigations that are conducted during this phase of the project should be compiled and collated into a comprehensive DSI report. This report should include the objectives of the investigation, a summary of the background information on the site, a description of the study approach, a summary of the existing information on sediment quality conditions at the site, a description of the methods that were used to generate the new data, a summary of the results of the investigations, and a discussion of the interpretation of the resultant data. All of the data collected during the investigation should be compiled in appendices that facilitate access to and/or re-analysis of the information. The reader is directed to Volume III of this guidance manual for more information on the interpretation of data on individual and multiple indicators of sediment quality conditions generated during the DSI.

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Tables

Table 1. Advantages and disadvantages of sediment toxicity tests (modified from ASTM 2003a).

Advantages
Measure bioavailable fraction of contaminant(s).
Provide a direct measure of benthic effects, assuming no field adaptation or amelioration of effects.
Limited special equipment is required.
Methods are rapid and inexpensive.
Legal and scientific precedence exist for use; ASTM and Environment Canada standards are available.
Measure unique information relative to chemical analyses or benthic community analyses.
Tests with spiked chemicals provide data on cause-effect relationships.
Sediment-toxicity tests can be applied to all chemicals of concern.
Tests applied to field samples reflect cumulative effects of contaminants and contaminant interactions.
Toxicity tests are amenable to confirmation with natural benthos populations.
Disadvantages
Sediment collection, handling, and storage may alter bioavailability.
Spiked sediment may not be representative of field contaminated sediment.
Natural geochemical characteristics of sediment may affect the response of test organisms.
Indigenous animals may be present in field-collected sediments.
Route of exposure may be uncertain and data generated in sediment toxicity tests may be difficult to interpret if factors controlling the bioavailability of contaminants in sediment are unknown.
Tests applied to field samples may not discriminate effects of individual chemicals.
Few comparisons have been made of methods or species.
Only a few chronic methods for measuring sublethal effects have been developed or extensively evaluated.
Laboratory tests have inherent limitations in predicting ecological effects.
Tests do not directly address human health effects.

Table 2. Rating of selection criteria for estuarine or marine amphipod sediment toxicity testing (ASTM 2003a).

Criterion	Species			
	Ampelisca abdita	***Eohaustorius estuarius***	***Leptocheirus plumulosus***	***Rhepoxynius abronius***
Relative sensitivity toxicity data base	+	+	+	+
Round-robin studies conducted	+	+	+	+
Contact with sediment	+	+	+	+
Laboratory culture	+/-	-	+	-
Taxonomic identification	+	+	+	+
Ecological importance	+	+	+	+
Geographical distribution*	Atlantic Coast, Pacific Coast and Gulf of Mexico	Pacific Coast	Atlantic Coast	Pacific Coast
Sediment physicochemical tolerance	+	+	+	+
Response confirmed with benthos	+	-	-	+
Populations peer reviewed	+	+	+	+
Endpoints monitored	Survival	Survival, reburial	Survival	Survival, reburial

"+" = postive attribute; "-" = negative attribute.

Table 3. Comparison of habitat characteristics and other life history parameters of four estuarine or marine amphipod species used in sediment toxicity tests (ASTM 2003a).

Criterion	Species			
	Ampelisca abdita	***Eohaustorius estuarius***	***Leptocheirus plumulosus***	***Rhepoxynius abronius***
Substrate Relation	Tube dwelling, closed and well developed[1]	Free burrowing[2]	Tube dwelling, open and less developed[1]	Free burrowing[3]
Zoogeography	Atlantic-Gulf[1] San Francisco[4,5]	Pacific[2,6]	Atlantic[1]	Pacific[3]
Habitat	Poly-upper mesohaline[1]	Oligo-mesohaline[2,6]	Oligo-mesohaline[1]	Polyhaline[3,7]
Life cycle	40 to 80 days[8]	Annual[2]	30 to 40 days[9,11,12]	Annual[10]
Availability	Field or potential laboratory culture[1]	Field[2]	Field and laboratory culture[9,11,12]	Field[7]
Ecological importance	High	High	High	High[9]

[1]Bousfield (1973).
[2]DeWitt *et al.* (1989).
[3]Barnard and Barnard (1982).
[4]Nichols *et al.* (1985).
[5]Hopkins (1986).
[6]Environment Canada (1992).
[7]Swartz *et al.* (1985).
[8]Scott and Redmond (1989).
[9]DeWitt *et al.* (1992).
[10]Kemp *et al.* (1985).
[11]Schlekat *et al.* (1992).
[12]McGee *et al* . (1993).

Table 4. Recommended test conditions for conducting reference-toxicity tests with marine and estuarine amphipods (USEPA 1994b).

Parameter	Conditions	Species			
		Ampelisca abdita	***Eohaustorius estuarius***	***Leptocheirus plumulosus***	***Rhepoxynius abronius***
Test Type	Water-only test.				
Dilution series	Control and at least 5 test concentrations (0.5 dilution factor).				
Toxicant	Cd, Cu, ammonia, Sodium dodecyl sulfate (SDS).				
Temperature		20°C	15°C	25°C	15°C
Light quality[1]	Chambers should be kept in the dark over covered with opaque material.				
Photoperiod	24 h dark.				
Salinity[2]		28‰	20‰	5 or 20‰	28‰
Renewal of water	None.				
Age of organisms[3]		3 to 5 mm (no mature males or females)	3 to 5 mm	2 to 4 mm (no mature males or females)	3 to 5 mm
Test chamber:	250- to 1-L glass beaker or jar.				
Volume of water	80% of chamber volume.				
Number of organisms/chamber	n = 20 if 1 replicate; n = 10 (minimum) if >1 per replicate.				
Number of replicate chambers/treatment	1 minimum; 2 recommended.				
Aeration[4]	Recommended; but not necessary if >90% dissolved oxygen saturation can be achieved without aeration.				

Table 4. Recommended test conditions for conducting reference-toxicity tests with marine and estuarine amphipods (USEPA 1994b).

Parameter	Conditions	Species			
		Ampelisca abdita	***Eohaustorius estuarius***	***Leptocheirus plumulosus***	***Rhepoxynius abronius***
Dilution water	Culture water, surface water, site water, or reconstituted water.				
Water quality	Salinity, pH, and dissolved oxygen, at the beginning and end of a test. Temperature daily.				
Test duration	96 h.				
Endpoint	Survival (LC_{50}); Reburial (EC_{50}) optional for *Eohaustorius estuarius* and *Rhepoxynius abronius.*				
Test acceptability	90% control survival.				

[1] USEPA and USACE (2001) recommends 500 to 1000 lux intensity at a 16:8 light:dark cycle for Leptocheirus plumulosus in long-term tests.

[2] Alternatively, the salinity of the overlying water can be adjusted to the salinity of the pore water at the site of interest in tests with *Eohaustorius estuarius* or *Leptocheirus plumulosus.* If tests are conducted at different salinities, additional tests are required to determine comparability of results (ASTM 2003a). Test organisms should be acclimiated to the selected salinity prior to testing, with salinity maintained within the species-specific application limits.

[3] USEPA and USACE (2001) recommends testing Leptocheirus plumulosus in a range of 0.25 to 0.60 mm in length in long-term tests.

[4] USEPA and USACE (2001) recommends that dissolved oxygen should be maintained at >60% saturation (>4.4 mg/L).

Table 5. Test conditions for conducting a 10-d sediment toxicity test with *Ampelisca abdita, Eohaustorius estuarius, Leptocheirus plumulosus,* or *Rhepoxynius abronius* (USEPA 1994b and ASTM 2003a).

Parameter	Conditions
Test type	Whole sediment toxicity test, static.
Temperature	15°C: *Eohaustorius estuarius* and *Rhepoxynius abronius.* 20°C: *Ampelisca abdita.* 25°C: *Leptocheirus plumulosus.*
Salinity	28‰: *Ampelisca abdita* and *Rhepoxynius abronius.* 20‰: *Eohaustorius estuarius* and *Leptocheirus plumulosus.* Alternatively, the salinity of the overlying water can be adjusted to the salinity of the pore water at the site of interest for tests with *E. estaurius* (2 to 35‰) or *L. plumulosus* (1 to 35‰; USEPA and USACE 2001). If tests are conducted with a different salinity, additional tests are required to determine comparability of results.
Light quality	Wide-spectrum fluorescent lights.
Illuminance	500 - 1000 lux.
Photoperiod	24 light.
Test chamber	1-L glass beaker or jar with 10-cm inner diameter.
Sediment volume	175 mL (about 2-cm depth).
Overlying water volume	775 mL.
Renewal of overlying water	None.
Size and life stage of amphipods	*Ampelisca abdita:* 3 - 5 mm (no mature males or females). *Eohaustorius estuarius:* 3 - 5 mm. *Leptocheirus plumulosus:* 2 - 4 mm (no mature males or females). *Rhepoxynius abronius:* 3 - 5 mm.
Number of organisms/chamber	20 per test chamber
Number of replicate chambers/treatment	Depends on objective of test. At a minimum, four replicates should be used.
Feeding	None.

Table 5. Test conditions for conducting a 10-d sediment toxicity test with *Ampelisca abdita, Eohaustorius estuarius, Leptocheirus plumulosus,* or *Rhepoxynius abronius* (USEPA 1994b and ASTM 2003a).

Parameter	Conditions
Aeration	Water in each test chamber should be aerated overnight before start of test and throughout the test; aeration at rate that maintains ≥90% saturation of dissolved oxygen concentration.
Overlying water	Clean sea water, natural or reconstituted water.
Overlying water quality	Temperature daily. pH, ammonia, salinity, and DO of overlying water at least at test start and end. Salinity, ammonia, and pH of pore water.
Test duration	10 d.
Endpoints	Survival (reburial optional for *Eohaustorius estuarius, Leptocheirus plumulosus,* and *Rhepoxynius abronius).*
Test acceptability	Minimum mean control survival of 90% and satisfaction of performance-based criteria specifications outlined in ASTM 2003a.

Table 6. Application limits for 10-d sediment toxicity tests with *Ampelisca abdita, Eohaustorius estuarius, Leptocheirus plumulosus,* or Rhepoxynius abronius (USEPA 1994b).

Parameter	Units	Species			
		Ampelisca abdita	***Eohaustorius estuarius***	***Leptocheirus plumulosus***	***Rhepoxynius abronius***
Temperature	°C	20	15	25	15
Overlying water salinity	‰	>10	1 to 34	1.5 to 32	>25
Grain size	% silt/clay	>10	0 to 100 (<70 clay)[a]	Full range	<90 (<40 clay)[a]
Ammonia (total, pH 7.7)	mg/L	<30	<60	<60	<30
Ammonia (unionized, pH 7.7)	mg/L	<0.4	<0.8	<0.8	<0.4

[a]Environment Canada (1998).

Table 7. Test conditions for conducting a 28-d sediment toxicity test with *Leptocheirus plumulosus* (USEPA and USACE 2001 and ASTM 2003a).

Parameter	Conditions
Test type	Whole sediment toxicity test, static-renewal.
Test sediment grain size	>5% silt and clay to <85% clay.
Test sediment pore-water salinity	1 to 35‰.
Overlying water salinity	5‰ if pore water is 1‰ to 10‰ 20‰ if pore water is >10‰ to 35‰ Alternatively, the salinity of the overlying water can be adjusted to a selected target salinity (e.g., one representative of the salinity regime at the site of interest). If tests are conducted at a different salinity, additional tets are required to determine comparability of results.
Test sediment pore-water ammonia	$\leq$60mg/L (total mg/L, pH 7.7); $\leq$0.8 mg/L (unionized mg/L, ph 7.7).
Test sediment pore-water sulfides	Not established.
Temperature	Daily limits: 25°C ($\pm$3°C); 28-d mean: 25°C ($\pm$2°C).
Light quality	Wide-spectrum fluorescent lights.
Illuminance	500 - 1000 lux.
Photoperiod	16 h light: 8 h dark
Test chamber	1-L glass beaker or jar with 10 cm inner diameter.
Sediment volume	175 mL (about 2 cm depth).
Sediment preparation	Press-sieved through 0.25 mm sieve.
Overlying water volume	Fill to 950 mL mark in test chamber (775 mL of water).
Renewal of overlying water	3 times per week: siphon off and replace 400 mL.
Source	Laboratory cultures.
Life stage and size	Neonates: age-selected (<48-h old) or size-selected: retained between 0.25 mm and 0.6 mm mesh screens.
Number test organisms/chamber	20

Table 7. Test conditions for conducting a 28-d sediment toxicity test with *Leptocheirus plumulosus* (USEPA and USACE 2001 and ASTM 2003a).

Parameter	Conditions
Number of replicate chambers	5 for toxicity test; ≥2 additional replicate chambers for pore-water treatment: ammonia (Day 0 and Day 28).
Diet	Days 0 to13, 20 mg Tetramarine® per test chamber; Days 14 to 28, 40 mg Tetramarine® per test chamber.
Feeding schedule	3 times per week (M-W-F) after water renewal.
Aeration and dissolved oxygen	Aerate constantly with trickle flow of bubbles. Daily limits: ≥3.6 mg/L (50% saturation). 28-d mean: ≥4.4 mg/L (60% saturation).
Overlying water	Clean seawater, natural or reconstituted water; same source as used for culturing.
Overlying water quality and monitoring	Daily temperature in water bath or in an additional replicate chamber, daily frequency: minimum/maximum recommended; salinity, temperature, DO, and pH at test initiation and termination, and in one replicate per sediment treatment preceding water renewal during the test (three times per week); aeration rate daily in all containers; total ammonia on Days 0 and 28 in one replicate per treatment.
pH	7.0 to 9.0 pH units.
Pore-water quality	Total ammonia, salinity, temperature, and pH of pore water from surrogate containers on Days 0 and 28; recommended in whole sediment before testing.
Test duration	28 d.
Test organism observations	Observe condition and activity in each test chamber preceding water renewal (3 times per week).
Endpoints	Survival, growth rate, and reproduction.
Test acceptability	Minimum mean control survival of 80%, growth and reproduction measurable in all control replicates, and satisfaction of performance-based criteria outlined in ASTM 2003a.

Table 8. Representative control sediment concentrations (from ASTM 2002f).

Compound	Puget Sound[a]	Oregon[b]	Fresh Water[c]
Organics (µg/kg dry weight)			
Benzo(a)pyrene	7 - 30	10 - 66	<10
Benzo(i,b,k)-fluoranthene	7 - 80	26.2	25
DDT	0.03 - 0.6	<6.0	
Napthalene	3 - 30[d]	37[e]	16
Polycyclic aromatic hydrocarbons	2 - 60	<0.01	
Polychlorinated biphenyls	<0.02 - 1.0	<2.0	27
Metals (mg/kg dry weight)			
Arsenic	3 - 15		<47
Cadmium	3.1 - 18.3	0.47	0.32
Copper	20.9	19.3	23.5
Chromium	10 - 50	6.3	10.4
Mercury	0.02 - 0.12		0.06
Nickel	13	14.5	21.2
Lead	8	5.5	<32
Zinc		26.3	45

[a] Puget Sound, Washington (Konasewich *et al.* 1982).

[b]Yaquina and Alsea Bays, Newport and Waldport, Oregon (unpublished data).

[c]An undisturbed agricultural soil collected from Florissant, Mussori (Ingersoll and Nelson 1990).

[d]Brown *et al.* (1984).

[e]Schults, unpublished data, United States Environmental Protection Agency, Newport, Oregon.

Table 9. Representative control organism tissue residues (from ASTM 2002f).

Substance	Various East Coast Sites[a]	Puget Sound[b]	Yaquina Bay, Oregon[c]
Organics (µg/kg wet weight)			
Chlorinated benzenes	<1.0 - 70		
Benzo(i,b,k)fluoranthene		<10	
Benzo(a)pyrene	0.3 - 6.0[a,b]	2.3 - <10[a,b]	1.9
DDT	<0.08 - 3.8	<1.0 - <5.0	3.9
Hexachlorobenzene	0.02 - 0.17	<130	
Naphthalene	<1.0 - 9.1	<0.05	
Polycyclic aromatic hydrocarbons	0.02 - 7.2	<2 - 17[a,b]	
Polychlorinated biphenyls	10 - 70	<2.0 - 10	
Pesticides	<0.03 - 0.6		
Metals (mg/kg wet weight)			
Silver	0.2 - 2.6		
Arsenic	1.5 - 3.9		
Cadmium	<0.06 - 4.0		<0.005
Chromium	0.26 - 2.5		
Copper	0.1 - 7.2		<1.5
Mercury	<0.05 - 1.2	1.0	
Nickel	<0.4 - 7.0		
Lead	<0.6 - 2.6		
Zinc	2.4 - 30		<2.0

[a]Tetra Tech, Inc. (1985).

[b]Konasewich *et al.* (1982).

[c]Unpublished data.

Table 10. Test species characteristics[a] (from ASTM 2002f).

Marine Species	Feeding Type	Biomass[a]	Salinity Tolerance, %	Pollution Tolerance	Culture Potential	Commercial Availability	Information on Bioaccumulation and Toxicity
Polychaetes							
Abarenicola sp.	FUN	+ +	>15	+	-	-	+
Arenicola sp.	FUN	+ +	>15	+	-	+	+
Capitella sp.	SSDF	-	>10	+ +	+	+	+ +
Nephtys incisa	SSDF	+	>25	+	-	-	+
Neanthes arenaceodentata	SDF/O	+ ?	>28	+	+ +	+	+ +
*Nereis virens**	SDF/O	+ +	>10	+ +	-	+	+ +
*Nereis diversicolor**	SDF/O	+ +	>10	+ +	-	+	+ +
Crustaceans							
Callianassa sp.	SSDF	+ +	>10	-?	-	+	-
Palaemonetes pugio	SDF	+ ?	>10	-	+	+	+ +
Bivalves							
*Macoma balthica**	SDF	+	>10	+	-	-	+ +
*Macoma nasuta**	SDF	+ +	>10	+	-	-	+ +
Nucula sp.	SSDF	+	?	+	-	-	+
*Yoldia limatula**	SSDF	+	>25	+	-	-	+

[a]+ + = very good; + = good; - = poor or insufficient; * = recommended species.

FUN = funnel feeder; SSDF = subsurface deposit-feeder; SDF = surface deposit-feeder; O = omnivore; FF = filter feeder.

Table 11. Information gained and requirements of different approaches to estimating benthic tissue residues (ASTM 2002f).

Method	Bioaccumulation Potential	False Negative Bioaccumulation Potential	Estimates Equilibrium Residue	Additional Requirements
Accumulation factors	Yes	No	Yes?	Sediment concentration, TOC, lipids
10-day test	Yes	Yes	No	10 days laboratory time, tissue concentration
28-day test	Yes	No	Approximate to yes	18 days additional laboratory time
Kinetic models	Yes	No	Yes	Additional tissue concentration, additional laboratory time? Development of techniques
Long-term exposures	Yes	No	Yes	28 to 70 days additional laboratory time, additional tissue concentration

Bioaccumulation potential = qualitative ability to detect uptake.
False negative bioaccumulation potential = amount accumulated is so low that it is concluded incorrectly that no uptake will occur.
Estimates equilibrium residue = tissue residue data sufficiently accurate for use in quantitative risk assessments.
Experiment techniques = resources devoted to determining the correct uptake and depuration periods for specific compounds and organisms.
Laboratory time = laboratory time required for biological exposure.
Lipids = tissue samples analyzed for lipid content.
Sediment concentration = sediment samples analyzed for contaminants.
Tissue concentration = tissue samples analyzed for contaminants.
TOC = sediment samples analyzed for total organic carbon.

Table 12. Percent of steady-state tissue residues of neutral organics and metals obtained after 10 and 28-day exposures to whole sediment (from ASTM 2002f).

Organic Compound	Percent of Steady-State[a] Concentration at day 10	Percent of Steady-State Concentration at day 28	Species	Estimate by	Reference
Polychlorinated biphenyls (PCBs)					
Aroclor 1242	18	87	*Nereis virens*	G	Langston (1978)
Aroclor 1242	29	82	*Cerastodema edule*	G	Langston (1978)
Aroclor 1254	12	82	*Macoma balthica*	G	Langston (1978)
Aroclor 1254	25	56	*Nereis virens*	K	McLeese *et al.* (1980)
Aroclor 1254	27	100	*Cerastodema edule*	G	Langston (1978)
Aroclor 1260	27	100	*Cerastodema edule*	G	Langston (1978)
Aroclor 1260	53	100	*Macoma balthica*	G	Langston (1978)
Total PCBs	21	54	*Nereis virens*	G	Pruell *et al.* (1990)
Total PCBs	48	80	*Macoma nasuta*	G	Pruell *et al.* (1990)
Total PCBs	23	71	*Macoma nasuta*	G	Boese *et al.* (1995)
Polycyclic aromatic hydrocarbons (PAHs)					
Benzo(a)pyrene	43	75	*Macoma inquinata*	G	Augenfeld *et al.* (1982)
Benzo(bk)fluoranthene	71	100	*Macoma nasuta*	G	Lee (unknown)
Chrysene	43	87	*Macoma inquinata*	G	Augenfeld *et al.* (1982)
Fluoranthene	100	100	*Macoma nasuta*	G	Lee (unknown)
Phenanthrene	100	100	*Macoma inquinata*	G	Augenfeld *et al.* (1982)
Phenanthrene	100	100	*Macoma nasuta*	G	Lee (unknown)
Pryene	84	97	*Macoma nasuta*	G	Lee (unknown)
Polychlorinated dibenzo-p-dioxins / polychlorinated dibenzofurans (PCDD/PCDF)					
2,3,7,8-TCDD	6	22	*Nereis virens*	G	Pruell *et al.* (1990)
2,3,7,8-TCDD	63	80	*Macoma nasuta*	G	Pruell *et al.* (1990)
2,3,7,8-TCDF	43	62	*Nereis virens*	G	Pruell *et al.* (1990)
2,3,7,8-TCDF	92	100	*Macoma nasuta*	G	Pruell *et al.* (1990)

Table 12. Percent of steady-state tissue residues of neutral organics and metals obtained after 10 and 28-day exposures to whole sediment (from ASTM 2002f).

Organic Compound	Percent of Steady-State[a] Concentration at day 10	Percent of Steady-State Concentration at day 28	Species	Estimate by	Reference
Miscellaneous					
Dieldrin	27	65	*Macoma nasuta*	G	Lee and Lincoff (1993)
4,4 DDT	17	10	*Macoma nasuta*	G	Lee and Lincoff (1993)
4,4 DDD	31	60	*Macoma nasuta*	G	Lee and Lincoff (1993)
2,4 DDD	31	56	*Macoma nasuta*	G	Lee and Lincoff (1993)
4,4 DDE	20	50	*Macoma nasuta*	G	Lee and Lincoff (1993)
Hexachlorobenzene	35	70	*Macoma nasuta*	K	Boese et al. (1990)
Hexachlorobenzene	36	98	*Macoma nasuta*	G	Boese *et al.* (1995)
Metals					
Americium	36	47	*Nereis diversicolor*	G	Beasley and Fowler (1976)
Americium	50	95	*Venerupis decussata*	G	Vangenechten *et al.* (1983)
Americium	32	67	*Hermione hystrix*	G	Vangenechten *et al.* (1983)
Cadmium	17	50	*Callinassa australiensis*	G	Jennett *et al.* (1980)
Copper	75	100	*Macoma nasuta*	G	Lee (unknown)
Iron	11	59	*Nereis diversicolor*	G	Jennings and Fowler (1980)
Lead	81	100	*Macoma nasuta*	G	Lee (unknown)
Plutonium	43	83	*Nereis diversicolor*	G	Beasley and Fowler (1976)

[a]All steady-state values are estimates since steady state was not documented rigorously (see Section 12.2; ASTM 2002f) in any of these studies.

K = steady-state tissue residue estimated from the kinetic uptake model.

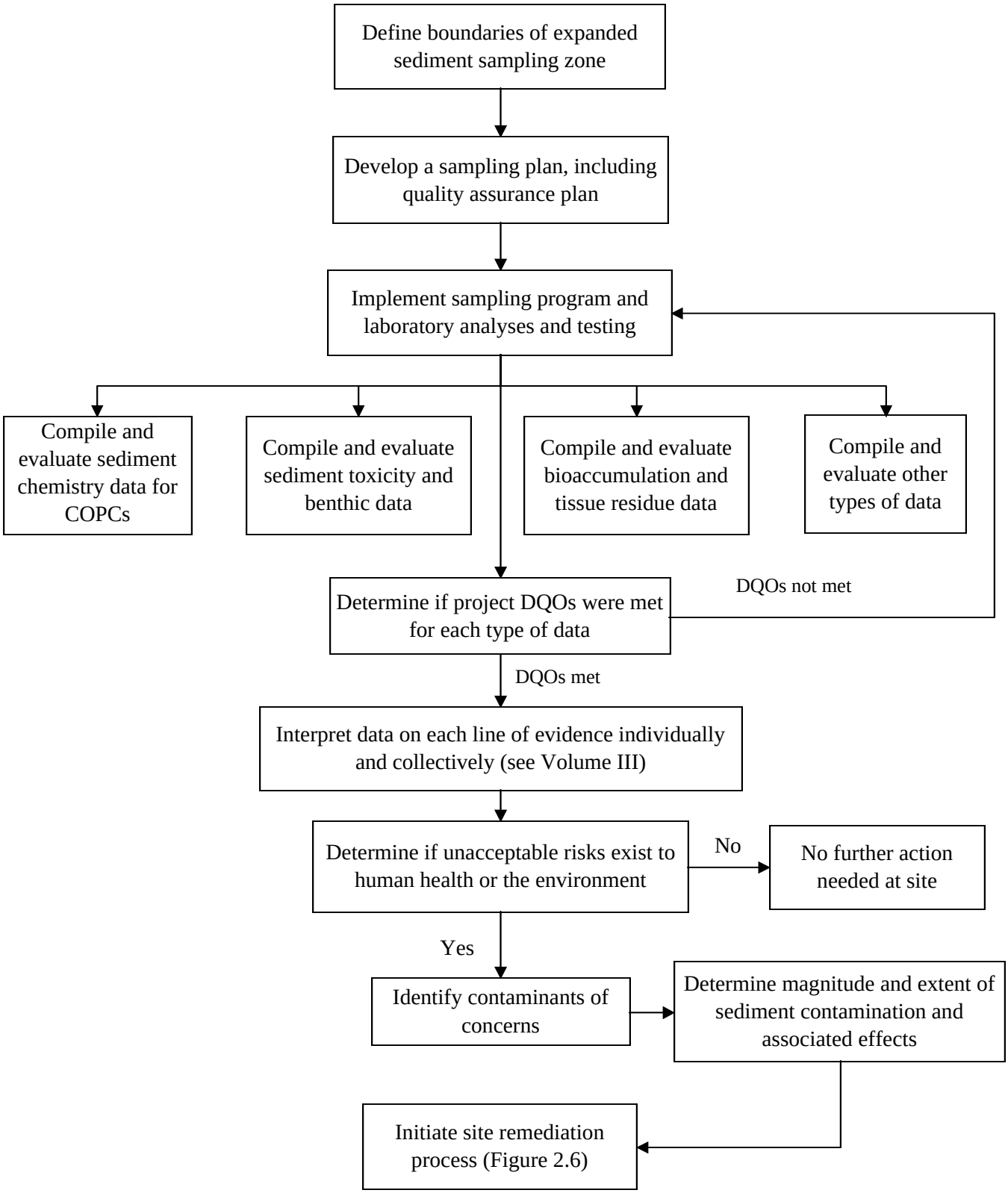
G = steady-state tissue residue estimated by visual inspection of graphs of tissue residue versus time.

Table 13. Low limits of detection for sediment, and tissue matrices recommended in the Puget Sound Dredge Disposal Analysis Program (ASTM 2002f).

Compound	Sediment (dry weight)	Tissue (wet weight)
Organics (µg/kg)		
Volatiles	10 - 20	5 - 10
Semivolatiles	1 - 50	10 - 20
Pesticides/Polychlorinated biphenyls	0.1 - 15	0.1 - 20
Metals (mg/kg)		
Antimony	0.1	0.02
Arsenic	0.1	0.02
Cadmium	0.1	0.01
Copper	0.1	0.01
Lead	0.1	0.03
Mercury	0.01	0.01
Nickel	0.1	0.02
Silver	0.1	0.01
Zinc	0.2	0.2

Figures

Figure 1. An overview of the detailed site investigation (DSI).



Appendices

Appendix 1. Sediment Trend Analysis (STA7) and its Application to Contaminated Sediment Studies

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A1.0 Introduction

The use of relative changes in grain-size distributions to determine patterns of net sediment transport and the dynamic behaviour of bottom sediments has become common in environmental studies (e.g., Teeter *et al.* 2001; Pascoe *et al.* 2002). The premise of the theory is that sediments are not deposited randomly. Their textural properties (defined principally by the mean, variance, and skewness of the full grain-size distribution) are the combined result of the characteristics of their source and the effects of transport. Although an original source for any particular sediment may or may not be known (e.g., in some cases a source may represent a complex integration of all sediment types available over an entire drainage basin, and in others may be traced to a locally eroding cliff or bluff), the changes in distributions due to transport may still be interpreted in the resulting deposits. The aim of the technique, therefore, is to use the particle-size distributions of the sediments to determine the net transport pathways, and in so doing establish sources and sinks and their dynamic behaviour. A strength in this approach is that no *a priori* assumptions about the processes that may be responsible for the erosion, transport and deposition of sediments are necessary. Because the derived patterns of transport are, in effect, an integration of all processes responsible for the transport and deposition of the bottom sediments, the results tend to provide a clear understanding of the nature of the relevant processes. Such information is also useful for the calibration and validation of numerical models, should they be found necessary.

A1.1 Theory

The theoretical background for the use of grain-size distributions to determine net sediment transport directions was first published by McLaren and Bowles (1985) and is briefly summarized here.

Suppose two sediment samples (d_1 and d_2)[1] are taken sequentially in a known transport direction (for example from a river bed where d_1 is the up-current sample and d_2 is the down-current sample). It may be shown mathematically that the sediment distribution of d_2 may become finer (Case B) or coarser (Case C) than d_1; if it becomes finer, the skewness of the distribution must become more negative. Conversely, if d_2 is coarser than d_1, the skewness must become more positive. The sorting will become better (i.e., the value for variance will become less) for both Case B and C. If either of these two trends is observed, sediment transport from d_1 to d_2 can be inferred. If the trend is different from the two acceptable trends (e.g. if d_2 is finer, better sorted and more positively skewed than d_1), the trend is unacceptable and it cannot be supposed that transport between the two samples has taken place.

In the above example, where the transport direction is unequivocally known, $d_2(s)$ can be related to $d_1(s)$ by a function X(s) where 's' is the grain size. The distribution of X(s) may be determined by:

$$X(s)= d_2(s)/d_1(s)$$

X(s) provides the statistical relationship between the two deposits and its distribution defines the relative probability of each particular grain size being eroded, transported and deposited from d_1 to d_2.

[1] A sample is considered to provide a representation of a sediment type (or facies). There is no direct time connotation, nor does the depth to which the sample was taken contain any significance (provided, of course, that the sample does, in fact, accurately represent the facies). For example, d_1 may be a sample of a facies that represents an accumulation over several tidal cycles, and d_2 represents several years of deposition. The trend analysis simply provides the sedimentological relationship between the two. It is unable to determine the rate of deposition at either locality, but frequently the derived patterns of transport do provide an indication of the probable processes that are responsible in producing the observed sediment types.

The shape of the X-distribution, relative to the d_1 and d_2 distributions, enables an interpretation of the dynamic behaviour of bottom sediments, which in turn relates to the fate and behaviour of particle-associated contaminants (see McLaren *et al.* 1993). The types of dynamic behaviour and the associated implications for contaminants are as follows:

1. Dynamic Equilibrium: The shape of the X-distribution closely resembles the d_1 and d_2 distributions. The relative probability of grains being transported, therefore, is a similar distribution to the actual deposits. This finding suggests that the probability of finding a particular grain in the deposit is equal to the probability of its transport and redeposition (i.e., there is a grain by grain replacement along the transport path). The bed is neither accreting nor eroding and is, therefore, in dynamic equilibrium. Sediments in dynamic equilibrium transport show no relationship between contaminant concentrations and distance along a transport path. If a contaminant hotspot is found in such an environment, it will tend to progress down the transport path.

2. Net Accretion: The shapes of the three distributions are similar, but the mode of X is finer than the modes of d_1 and d_2. Sediment must fine in the direction of transport; however, more fine grains are deposited along the transport path than are eroded, with the result that the bed, though mobile, is accreting. In environments undergoing Net Accretion there is a general linear increase of contaminant concentrations along the transport path.

3. Net Erosion: Again the shapes of the three distributions are similar, but the mode of X is coarser than the d_1 and d_2 modes. Sediment coarsens along the transport path, more grains are eroded than deposited, and the bed is undergoing net erosion. Contaminant loadings decrease rapidly with Net Erosion.

4. Total Deposition-Type I: Regardless of the shapes of d_1 and d_2, the X-distribution more or less increases monotonically over the complete size range of the deposits. Sediment must fine in the direction of transport; however, the bed is no longer mobile. Rather, it is accreting under a “rain” of sediment that fines with distance from the source. Once deposited, there is no further transport. In environments of

Total Deposition-Type I contaminants are found as localized "highs" that can often be associated with a specific source and will maintain long-term stability.

5. Total Deposition-Type II: Occurring only in extremely fine sediments when the mean grain-size is very fine silt or clay, the X-distribution may be essentially horizontal. Such sediments are usually found far from their source, compared with Total Deposition-Type I sediments in which size-sorting of the fine particles is taking place, and therefore the source is relatively close. The horizontal nature of the X-distribution suggests that there is now an equal probability of all sizes being deposited. In the case of Total Deposition-Type II, all particles, whether contaminated or not, have an equal probability of deposition. There is not, therefore, any preferred area for the deposition of contaminants and more or less equal concentrations are to be expected throughout such an environment.

A1.2 Derivation of Trends

Several techniques, based on the original theory of McLaren and Bowles (1985), are available to establish patterns of net sediment transport from grain-size distributions. An examination of maps contouring the mean grain size, variance (sorting), and skewness is helpful to establish probable sources and derive an understanding of the data. Asselman (1997) extended this approach further by utilizing a GIS method to establish transport paths from grain size trends. Gao and Collins (1992; 1994) defined a grid of "trend vectors". The method assumes that the grain size trends have a higher frequency of occurring in sediment transport directions than in the opposite directions, but such dominance does not exist if there is no exchange of material between sampling sites. The vectors are filtered and transformed into an ordered pattern of transport vectors representing transport paths. The orderliness of the derived pattern is examined on the basis of a significance test, using the average length of the transport vectors as a criterion. Le Roux (1994a; b) modified the vector approach by extending the number of samples used to define a vector. He also scaled the grain-size parameters in an attempt to eliminate any bias towards any one of them. Specific programs that have been developed to obtain transport pathways are found in Le Roux (1994c), Shu (1996), Pedreros *et al.* (1996) and Chang *et al.* (2001).

Although all of the above methods are helpful, best results appear to be achieved when separate sequences of samples are explored for statistically acceptable trends (e.g., Mohd-Lokman *et al.* 1998). Initially, a trend is easily determined using a statistical approach whereby, instead of searching for "perfect" changes in a sample sequence, all possible pairs contained in the sequence are assessed for possible transport direction. When one of the trends exceeds random probability within the sample sequence, the direction of transport may be inferred, and the dynamic behaviour along the derived pathway as defined by the positions of the samples may be derived following the calculation of X(s). A complete pattern of transport over the entire study area may be obtained as follows: (i) assume the direction of sediment transport over an area containing many sample sites; (ii) from this assumption, predict the sediment trend that should appear along a particular sequence of samples; (iii) compare the prediction with the actual trend that is derived from the selected samples; and (iv) modify the assumed transport direction and repeat the comparison until the best fit is achieved. In addition to the academic research on sediment trend analysis, several engineering and environmental consulting companies offer the technique, incorporating many of the above concepts together with their own specific innovations (e.g., GeoSea 2001).

A1.3 Summary

Sediment trend analysis (STA7), is a technique whereby a statistical examination of the changes in grain-size characteristics between samples is undertaken to infer: first, if transport is occurring between the selected deposits; second, in which direction; and finally, in what manner (e.g. erosion, dynamic equilibrium or deposition). The results of this kind of analysis can include (i) detailed sediment-type maps, (ii) maps showing net sediment transport pathways and the dynamic behaviour of the bottom sediments, (iii) an indication of the dominant processes responsible for sediment movement, (iv) a qualitative understanding of how particle-associated contaminants are likely to behave, and (v) a determination of those regions that will most probably provide the maximum contaminant information in coring and monitoring programs. This information may be important for the site characterization process, and can aid in the continuing development of the conceptual model. In addition, the derived understanding of the transport processes and dynamic behaviour will help focus the

planning for further site investigations, including modelling, and provide an assessment of remedial options.

The technique requires a detailed sediment sampling field program encompassing a sufficiently large area to represent all of the environments that may be affecting transport of sediments and contaminants within the site under investigation. This approach is most effective for rivers, lakes, estuaries and marine environments, but should probably not be used in environments where the organic content of the sediments exceeds the mineralogical component (e.g., wetland deposits and many floodplain environments).

A1.4 References

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