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Guidance on Assessment of Sediment Quality

Global Investigation of Pollution in the Marine Environment

GIPME

GLOBAL INVESTIGATION OF POLLUTION
IN THE MARINE ENVIRONMENT (GIPME)
(IOC–UNEP–IMO)

GUIDANCE ON ASSESSMENT OF SEDIMENT QUALITY

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Foreword

A workshop was held at IMO Headquarters, London, from 11 to 15 October 1999 to consider the development of guidance on sediment quality guidelines. This workshop was held under the auspices of the Programme of Global Investigation of Pollution in the Marine Environment (GIPME), which is co-sponsored by the Intergovernmental Oceanographic Commission (IOC), the United Nations Environment Programme (UNEP) and the International Maritime Organization (IMO).

The workshop had been requested to prepare guidance on the assessment of sediment quality that would assist in both harmonizing national and international mechanisms for environmental protection, and discriminating between sediments that warrant special management attention and those that do not.

A list of experts involved in the preparation of this report is shown in annex 4.

Executive summary

Several attempts have been made to develop approaches for evaluating the degree to which contaminated marine sediments could adversely affect marine resources. None of these approaches have been widely accepted, largely because they lack the practicality and consistency that managers are seeking.

This report examines various approaches to assessing anthropogenic impacts on marine sediments, and associated risks to marine life and human health. It is concluded that numerical sediment quality criteria are unsuitable for widespread application. The scientific basis for assessing sediment quality must incorporate biological, chemical and physical considerations.

In addition to considering new approaches to the assessment of sediment quality, the contributing scientists were asked to address three specific questions. These questions, and concise answers to them, are:

- *Can the concept of sediment quality guidelines be used to derive simple and uniform procedures for marine environmental protection?*

  Answer: Yes uniform and relatively simple procedures can be developed to distinguish serious contamination from that which is trivial. Test protocols can be developed based on biological and/or chemical testing for guiding management decisions in local and possibly national situations.

- *Can such procedures be applied in a manner that provides the benefits expected by managers while still being based on sound scientific principles and methods?*

  Answer: Yes.

- *Can the toxicity of sediments to marine life be predicted by chemical measurements alone?*

  Answer: No – at present no chemical measurements exist that can reliably predict sediment toxicity.

This report does not provide a rigid framework for assessment of sediment quality but does identify empirical procedures that can be used to distinguish among natural sedimentary conditions, anthropogenically disturbed (e.g., contaminated) sediments, and sediment conditions causing adverse effects (i.e., pollution). In essence, it defines possible approaches that meet the criteria of scientific validity and regulatory utility. Most importantly, it offers simple guidance to managers who require rules, regulations, criteria and standards for use in the assessment and management of the marine environment. It may also be helpful to those responsible for licensing waste discharges and dredging operations, implementing environmental regulations and interpreting the results of monitoring programmes.

1 Preface

Marine environmental managers need pragmatic and scientifically based guidance for evaluating the condition of marine sediments in relation to ecological requirements. A number of agencies and international forums have attempted to develop methods for evaluating the degree to which contaminants in marine sediments adversely affect marine life. Marine sediment quality guidelines are numerical limits or narrative statements designed to support and maintain designated uses of the marine environment. Although there is a wide variety of methods and guidelines for determining sediment quality for general application, most of these methods have been criticized by managers as being insufficiently simple and more commonly by scientists questioning their scientific validity. There are still doubts about the practicality of standardized approaches and their ability to provide the simplicity and uniformity that managers are seeking.

The agencies sponsoring this report collaborated in bringing together a small, multidisciplinary group of scientists, familiar with the problems of assessing and managing contaminated marine sediments. The group was asked to explore the possibilities of developing simpler and clearer guidance that would enable discrimination between sediments that give rise to adverse effects and those that do not. Such guidance, if broadly applicable and offering the benefit of reduced dependence on complex technical procedures, might both encourage and facilitate the rational management of contaminated sediments in countries where approaches for dealing with such problems have so far been lacking.

This guidance is intended for managers who develop rules, regulations, standards or criteria for use in the assessment and management of the marine environment. It may also be helpful to personnel responsible for licensing waste discharges and dredging operations, implementing environmental regulations, and interpreting the results of marine monitoring programmes.

2 Purpose and scope

The main purpose of this report is to address the following questions:

- *Can the concept of sediment quality guidelines be used to develop simple and uniform procedures for marine environmental protection?*
- *Can such procedures be applied in a manner that provides the benefits expected by managers while still being based on sound scientific principles and methods?*
- *Can sediment toxicity be predicted solely on the basis of chemical measurements?*

This report responds to these questions and examines approaches that might fulfil the requirements of environmental managers. It also examines the scientific concepts relevant to assessing the condition of marine sediments in relation to contamination and associated risks to marine life and human health. Finally, it specifies empirical procedures that may be used to distinguish among natural sedimentary conditions, anthropogenically disturbed (e.g., contaminated) sediments and sediment conditions causing adverse effects (i.e., pollution).

The guidance does not provide a rigid framework for the assessment of sediment quality. In essence, it defines approaches that meet the criteria of scientific validity and regulatory utility. Further development of these approaches could provide a basis for management.

It should be noted that the scope of the guidance is confined to the effects of chemicals on biota. Thus, it deals with the risks posed by chemicals (both natural and anthropogenic) in marine sediments, the biological properties of marine sediments, and associated interactions and effects. Physical impacts, such as those associated with the dredging and disposal of sediments, shipping and fishing are not addressed.

3 The management framework

Any approach to the assessment of sediment quality should be consistent with prevailing policies for marine environmental protection. For example, a number of countries are committed to reducing contamination of marine media, including sediments, even where there is no discernible damage from existing levels of contaminants. In such circumstances, contamination alone may be a suitable criterion of sediment condition meriting management attention. Other users of sediment quality criteria require procedures that indicate the extent of damage or threat to the marine environment, its resources and amenities, rather than merely a measure of contamination.

Policy aside, other factors that will influence the selection of approaches to sediment quality assessment are the availability of relevant technical expertise and the capacity for surveying, sampling and testing of sediments. In this context, it is recognized that many administrations do not have immediate access to the personnel and facilities needed for the employment of some of the more complex techniques that exist for the investigation of sediment properties. As a result, there is a need for pragmatic, interim approaches that should, in a majority of cases and when properly applied, facilitate rational judgements about the need for management intervention – even with limited data.

Management inputs

Any approach to the assessment of sediment quality will require supporting information that should generally be available from those agencies responsible for environmental protection and management. Most essential is knowledge of land-based sources of contaminants, including direct discharges (sewage and industrial effluents) and diffuse inputs arising from agricultural and industrial activities entering the sea through runoff and atmospheric transport and deposition. Additional information concerning anthropogenic activities in the subject area, including estimates of the quantities of contaminants released, will help in locating coastal areas most vulnerable to sediment contamination.

The choice of appropriate measures for assessing sedimentary conditions will be influenced, in part, by ecological considerations, human uses of the area and associated management objectives. For example, the reasons for conducting an assessment of contamination might include one or more of the following:

- To map spatial patterns;
- To measure temporal trends;
- To determine the condition of marine organisms, populations and communities;
- To estimate risks to human health, and/or to biological production and diversity;
- To evaluate the suitability of a proposed use or development; and
- To assess the impacts of sediment dredging and/or disposal.

In each case, the assessment will guide the selection of management options such as taking no action, imposing strict source controls, or mitigation of impacts. Rigorous definition of the issue of concern will help in developing assessment procedures that yield the most relevant and beneficial information.

Managing risks associated with contaminated sediment

As with many forms of environmental investigation, assessing contaminants in sediments involves the assessment of risk, i.e., the probability that a particular adverse effect will, or will not, occur. These risks can involve harm to human health, marine life and ecosystem function as well as the risk of reducing the value of economically important resources and amenities. In most cases, managers will not have all the information needed to assess risk in statistical terms. They will therefore often be required to make judgements of risk by comparing the most likely consequences arising from observed conditions and various future scenarios. Sediment quality assessments will provide information on *exposure* to contaminants, one of the two principal components of risk assessment. The other component, *hazard*, is an intrinsic function of a substance's physical and chemical properties.

The sediment screening procedures outlined in chapter 6 of this report take into account the hazards and exposures associated with varying degrees of contamination of marine sediments by both organic and inorganic substances.

4 The scientific context

4.1 *Introduction*

There are no chemical measurements that reliably predict sediment toxicity. There are sets of chemical concentrations in sediments that correspond to an absence of acute toxicity. A more useful set, one corresponding to toxicity, does not exist. The likelihood of sediment toxicity increases as chemical concentrations increase, but there are so many mitigating processes (O'Connor and Paul, 2000) that none of the proposed chemically-based methods consistently and reliably predict toxicity. This is why a scientific basis for any broadly applicable guidance on the assessment of sediment quality must inevitably incorporate biological, chemical and physical considerations.

In addition to its use in assessing sediment quality for practical purposes such as dredging, generic guidance might also be applicable to monitoring programmes used both for confirming predicted impacts of regulated activities and for assessing the effectiveness of pollution prevention measures. There is considerable value in adopting a broad approach that takes into account implications for human health and the environment.

Numerical sediment quality criteria are not achievable for global or large-scale application. In developed countries, where substantial resources have been committed to research and development, no single, satisfactory, numerical regime has been established for management applications. The applicability of single numerical values as surrogates for sediment quality is limited. This is partly due to their inability to take account of contaminant interactions but, more importantly, to an inadequate understanding of biological responses to chemical conditions. In addition, fixed standards are often disincentives to the development of innovative approaches based on new scientific findings that might lead to progressive improvements in such assessments.

In summary, a certain number of conclusions can be drawn on the basis of scientific tenets that should underlie the approach to assessing sediment quality. In the context of prevailing management practice, these tenets can be expressed as follows:

- The environmental and human health implications of contaminants in sediments depend on the specific substances and levels present, the natural properties of the sediments, the indigenous flora and fauna and the extent to which local species are used for human consumption. It is clear that, for any area of the marine environment, this combination of conditions is unique. It is therefore essential that assessments of sediment quality take account of the prevailing physical, chemical and biological conditions.
- Comprehensive assessments of sediment quality entail the identification of hazards, the evaluation of exposures and the estimation of effects and risks with due attention to the associated uncertainties.
- Sediment quality assessments must recognize that in any region there will be natural occurrences of substances such as metals and hydrocarbons. Their levels and distribution within the region must be characterized as a basis for identifying additions from anthropogenic sources and activities. Furthermore, a proportion of anthropogenic additions will consist of widespread ambient contamination due to large-scale atmospheric and hydrographic transport. This component of contamination must be characterized before the nature and extent of contamination from local anthropogenic sources can be determined.
- The assessment of sediment quality begins with consideration of existing scientific knowledge. The assessment process should be revised continuously, through an iterative process, expanding the base of scientific knowledge and adjusting the information base as new knowledge and understanding is acquired.
- Attempts to express all appropriate considerations in numerical terms require numerous assumptions and simplifications. Accordingly, numerical levels should not be used as inflexible standards.

4.2 *Physical assessment*

To reach any conclusion regarding sediment quality it is necessary to know the physical characteristics of the local environment and the physical composition of the sediment. It must first be established whether or not the subject area is dispersive or depositional in nature. A dispersive site, generally one in a high-energy hydrodynamic environment, is unlikely to contain fine-grained sediments and is therefore unlikely to be contaminated with, or retain, particle-reactive contaminants. A depositional site, which generally reflects a low energy hydrodynamic environment, is likely to contain fine-grained sediments and is therefore more prone to contamination and the retention of chemicals from anthropogenic sources. In each case, the indigenous biological assemblages will reflect the structure and texture of the sediment and associated hydrodynamic conditions. There are also locations that change from depositional to dispersive as a result of hydrodynamic variability. Sediments at such locations can contain a range of particle sizes. This emphasizes the need to consider the role of non-equilibrium conditions when assessing the mobility and biological availability of sediment associated contaminants. The physical composition of the sediment must be assessed in relation to particle-size distributions. Naturally derived sediments comprising only particles of dimensions greater than 2 mm do not retain any significant quantities of contaminants and should be of little concern to environmental managers. Sands (comprising particles >63 µm diameter) are also unlikely to retain contaminants due to the minimal specific surface area for sorbing chemicals. If the subject sediments have particle sizes exceeding 63 µm and are devoid of large particles of anthropogenic origin (e.g., paint particles), they too should not be of concern to managers. In contrast, sediments comprising silts and clays (<63 µm in particle size) are prone to sequestering chemicals including those of anthropogenic origin. As sediment particle size decreases from 63 µm (silts) to 2 µm (clays) the ratio of particle surface area to mass increases exponentially. The increase in specific surface area and susceptibility to increased surface exchanges enhances the sediment's ability to accumulate ionic and hydrophobic substances. It is sediments containing finer grain-size fractions that warrant more detailed evaluation.

4.3 *Chemical assessment*

Background metals

Chemical investigations can be used to determine if a particular sediment contains elevated levels of contaminants relative to natural or ambient conditions. Entirely natural sediments would not contain synthetic organo-metallic compounds, but would contain metals and other elements consistent with natural mineralogical components of sediments. The abundance of these constituents and any differences from natural conditions can be evaluated using several geochemical normalization procedures.

Elemental, including metal, concentrations can be compared with reported natural abundances of the metals in soils and/or crustal rocks, by normalizing against geochemical markers (e.g., Al, Li) of the predominant natural mineralogical phases (Loring, 1990, 1991; Daskalakis and O'Connor, 1995). These markers can also compensate for constituent variability in sediments resulting from granulometric variations. If the element:normalizer ratios in sediments are similar to natural abundance ratios, there is no reason to believe the sediment is significantly contaminated with elemental constituents.

This concept can be expressed in the following form:

If

$$EF = \frac{(M/N)_{\text{Obs}}}{(M/N)_{\text{Nat}}} \leq 2$$

where: EF is the metal enrichment factor for the sediment,
$(M/N)_{\text{Obs}}$ is the metal : normalizer ratio observed for the sediment, and
$(M/N)_{\text{Nat}}$ is the natural metal : normalizer ratio.
In hemipelagic marine sediments, elemental constituents should be of no management concern.

Given the natural variability of metals in soils and sediments, an enrichment factor of less than 2 would reflect insignificant contamination. If regional sediment data are available from uncontaminated areas, the same approach can be taken by substituting the regional metal:normalizer ratios for such sediments as the denominator of the above equation. Estimates of ambient contaminant levels are often an essential prerequisite to detecting and quantifying recent contamination from local sources. These ambient levels may be inferred by the levels of metals in nearby sediments not prone to contamination from local sources. Where sediments have been uniformly contaminated over large areas by emissions from dispersive sources and associated large-scale transport mechanisms, ambient conditions can be established on the basis of the analysis of sediment layers from cores reflecting past conditions (i.e., in strata representing deposition prior to contaminant introduction or the inception of the activity of concern). This latter approach must, however, include consideration of the effects of post-depositional geochemical processes on the chemical composition of sediments.

Background and baseline organic constituents

The presence of organic compounds at trace levels can be addressed in a somewhat similar manner. Both natural and artificial organic compounds will be present in marine sediments as a result of marine biological processes and geochemical transport from diverse sources or activities such as forest fires, mineral weathering, agriculture, soil erosion, fossil fuel combustion, mining and smelting, etc. Background levels created in this way are beyond national control as they are the legacy of natural processes and previous anthropogenic activities. Clearly, there will be cases and areas in which the levels of organic compounds will be further augmented by nearby anthropogenic activities and these increases may be of concern. Consequently, a method is needed for defining baseline levels that largely represent natural conditions or a legacy of previous human activities and are therefore beyond local control. This, of course, does not rule out the adoption of action at international levels to reduce the dissemination of substances globally such as the development of an international convention on persistent organic pollutants (POPs).

There are two options for approaching the definition of baseline levels of organic compounds in marine sediments. The first is based on an examination of offshore/shelf sediments in regional areas; the second is based on an examination of inshore sediments in areas not prone to contamination from local human and industrial activities. Each of these approaches has advantages and disadvantages. While offshore sediments offer the advantage of being used to define baselines for large coastal areas, and are more likely to reflect the regional level of baseline contamination, they do pose some analytical difficulties because of their normally low organic carbon content. These analytical difficulties can be overcome by the use of increased sample sizes to ensure the analysis of a larger quantity of organic matter. Coastal inshore sediments are more prone to local contamination over and above background but may provide a more appropriate reflection of local background conditions in specific inshore areas. Carefully selected coastal sites (i.e., in the context of remoteness from local anthropogenic activities) pose fewer sampling and analytical difficulties but are unlikely to be a true reflection of conditions on regional scales. In either approach, there will be a need for normalization to take account of variations in grain-size distribution and organic matter content.

The procedure consists of obtaining a few representative samples of the closest reference sediments in which a range of commonly-occurring synthetic organic compounds and total organic carbon are determined. The selection of the specific synthetic compounds should be made primarily on the basis of local and regional sources of such materials. Ideally, it should include some petroleum hydrocarbons, some polycyclic aromatic hydrocarbons (PAHs) and a number of synthetic compounds or congeners of compound groups such as polychlorobiphenyls (PCBs). The baseline would then be represented by the relationship between each of the selected organic compounds and total organic carbon.

A comparison of the ratios of organic compounds to total organic carbon in the subject and reference sediments then provides a basis for assessing the degree of local contamination above the baseline. If the ratios are similar, say within a factor of 2, the subject sediments would be of little concern in terms of damage or risks resulting from the organic chemicals present.

Above-background chemical concentrations consistent with non-toxicity

Most sediments warranting management action contain higher-than-background levels of chemicals. This does not mean that they are toxic. There is merit in compilations such as those of Long *et al* (1995), who empirically defined no-effect concentrations after extensive literature reviews that identified concentrations rarely associated with toxic sediments. It cannot be concluded that sediments with concentrations above these no-effect levels are toxic. However, those with chemical concentrations at or below these no-effect levels may be assumed to be non-toxic without further testing. A cautionary note is, however, needed here: no-effect levels have not been defined for all chemicals; thus it is possible, depending on the species and chemicals involved, that some organisms could still be affected. Evidence of abnormalities such as tumours or reproductive impairment should prompt managers to initiate further investigations.

4.4 *Biological assessment*

Regulatory authorities must determine the limits of acceptable biological responses to chemical contamination. This will vary according to the location and spatial scale of contamination, and on local management objectives and socio-economic judgements. If the objective is to avoid alterations to biochemical processes in individual organisms, less contamination can be accepted than in the case of an objective that aims to sustain populations of commercial species. Once the range of acceptable response is determined, there are suites of field and laboratory tests that can be incorporated into biological assessments.

Many ecotoxicological methods are described in the scientific literature that may be used for determining if an observed impact on benthic organisms is due to chemical contamination. These range from acute and chronic sediment toxicity tests, including sublethal effects measurements performed in the field or in the laboratory, to biochemical assays at a subcellular level (e.g., biochemical biomarkers). Together, these techniques provide a variety of end-points and exposure pathways at different levels of biological organization. The extrapolation of the results to higher levels of biological organization (e.g., population, community) remains very difficult. Simple biological effects tools are being developed (e.g., lysosomal neutral red assay, cardiac monitoring in crustaceans, cholinesterase inhibition assays, etc.) that offer the potential of detecting contaminant gradients and impaired organismal health. These are valuable for environmental assessment. There are standard protocols for some biomarkers and inter-laboratory ring tests for enhancing biomarker utility. Unfortunately, many of these techniques still lack ecological relevance and some suffer from the absence of appropriate interpretative guidance or adequate standardization.

More ecologically relevant studies involve measurements of population variables and analysis of communities. The drawback of these approaches is that it is often difficult to distinguish contaminant-induced changes from natural variability, or to identify cause and effect mechanisms (i.e., which environmental contaminants and in what amounts gave rise to changes in population dynamics or community structure).

The selection of an appropriate suite of biological test methods depends on the particular questions being addressed by managers, the level of contamination at the site and the degree to which the available methods have been standardized and validated. For instance, for ranking and classifying the acute toxicity of harbour sediments prior to maintenance dredging, short-term bioassays may often suffice.

Until recently, efforts to determine the toxicity of contaminants in sediments have focused on measurements of acute toxicity. Often, laboratory tests have been unrealistic, with exposure not to sediment *per se*, but to some kind of aqueous phase extraction that does not simulate natural processes.

Biomarkers (e.g., the induction of metal binding proteins in marine organisms that signal metal exposures, cholinesterase inhibition that signals exposure to organophosphorous and carbamate pesticides) may be used to provide early warning of subtle effects at low and sustained levels of contamination and may also provide insight into the nature of the contaminants present. Long-term effects in specific species (e.g., flatfish) can be evaluated using histopathological endpoints. However, interpreting the results of such studies may be difficult and depend on underlying factors including the requirement that appropriate species were employed.

Decisions about when to apply ecotoxicological techniques and the choice of methods appropriate to the situation are never easy. Wrong decisions may be costly both in time and resources. For this reason, it is always advisable to learn as much as possible from field evidence before laboratory testing is considered.

Contrary to popular belief, *in situ* biological measurements may be carried out quite readily and at low cost. Important clues to the condition of marine sediments can often be found by simple observation of existing biological communities. For example, for each particular climatic regime (e.g., latitude, temperature) water depth and sediment texture will largely determine the natural assemblages of organisms living on or in sediments of continental shelves. As a result, knowledge of assemblages that typically occur at adjacent unperturbed sites may be used to extrapolate the ''normal'' or ''baseline'' assemblages at sites that may have been altered through contamination or other human influences.

The simplest observations of sediment assemblages will involve grab sampling, diver surveys or underwater photography to estimate the relative occurrences of different kinds of organisms. Even simple techniques will indicate major differences that exist between comparable sites. Wherever possible, such observations should be supplemented by more frequent and detailed investigations to determine seasonal patterns in the age and/or size structure of populations of the more common local species. Evidence of sustained reproduction and recruitment of a number of different organism types will provide reassurance that critical physiological functions are not significantly impaired. It is particularly important to establish the reproductive success of those species that, by virtue of their feeding and behaviour, strongly influence the local ecology (i.e., ''key'' species).

Examinations can also be undertaken for the presence of lesions, tumours and developmental abnormalities (including imposex in gastropods) indicative of contaminant influences.

It should be appreciated that, where an effect is observed or suspected, field observations seldom give insight into which particular contaminants are involved and whether their effects have been enhanced through interaction with natural stressors. Some studies have revealed marked seasonal differences in the susceptibility of benthic invertebrates to a given degree of sediment contamination. Moreover, benthic communities in nature are subject to many perturbations, the majority of which are of natural origin. Establishing cause and effect relationships based on such highly variable descriptive information ranges from very difficult to impossible. Conditions in one location may differ markedly from another because of a single past event (e.g., a storm) that cannot be inferred from observations of present conditions.

Where assemblages are clearly unrepresentative of those that might reasonably be expected to occur, the next question is whether the differences can be explained by contamination or by other human activities such as fishing (e.g., bottom trawling) or by natural events (e.g., storms, freshwater influxes, etc.). If a satisfactory explanation can be found, the principal management consideration will be whether or not the observed biological changes are sufficiently severe to justify the imposition of restrictions on human activities. This will depend, in part, on the spatial extent of the affected area in relation to the overall distribution of similar habitats in the region. If there is no immediately obvious explanation, further examination of the sediments will probably be necessary, including laboratory-based measurements of sediment properties and associated biological responses.

Laboratory tests to measure the survival of test organisms often fail to take into account the complexity of the sedimentary environment. For example, the diversity and sustainability of benthic communities are largely dependent on the success of recruitment processes. Early life stages of organisms are not only vulnerable to direct chemical toxicity but also to chemical interferences with sensory mechanisms needed for the detection of food and for larval settlement. This may occur at chemical contaminant concentrations well below thresholds of lethality, and is a phenomenon not considered in contemporary sediment bioassays. The stimulation of growth by exposure to low-level chemical contamination (i.e., hormesis) is another phenomenon shown to give rise to subtle ecological disturbances that can have important consequences for benthic populations and communities. While these effects of low-level exposure to chemicals are of scientific interest, it would be premature to infer that they warrant regulatory concern.

When sediment-associated contaminants affect benthic biota it is usually at a sublethal level rather than causing acute mortality. Thus, there may be differential effects on growth rates, reproductive output and viability of offspring in benthic communities that ultimately give rise to alterations in community structure. It may be difficult to identify the most important chemicals involved because these are not always those discharged into the environment but are instead the intermediates or end products of the metabolism of synthetic organic substances. Contaminants sometimes exert an intense selective pressure resulting in ‘‘resistant’’ populations. This may further confound interpretation and limit the relevance of investigations designed to evaluate sediment toxicity.

It may often be difficult to select appropriate test organisms and routes of exposure for laboratory-based test systems. Animals that feed by ingesting sediment are perhaps more suitable subjects than benthic filter-feeders. Some test systems rely on the use of pore water as an exposure medium. However, there is growing evidence that many organic contaminants (e.g., PAHs) and metals are taken up predominantly from ingested particles rather than from pore water. In most benthic habitats, the in-fauna influence the chemical conditions in sediments through reworking. They make a marked change to surficial sediment redox (oxidation-reduction potential) distributions. The amount of sediment that is re-worked and the degradation of synthetic organic substances are influenced by the number of organisms present, and by organismal growth rates and reproductive output (and recruitment). These population characteristics are themselves influenced by the degree of toxicity of the sediment making it therefore apparent that there is a complex balance between the extent of chemical contamination in sediments and the dynamics of biotic communities.

As sediments can act as sinks for persistent contaminants, the transfer of sediment-associated compounds through the food chain is also a matter of concern. This may have implications for human health through the consumption of seafood (e.g., fish, crustaceans, molluscs). Information on tissue residues can be compared with food standards for particular substances recommended by agencies such as the World Health Organization (WHO), or with chemical residue criteria designed to protect top predators such as fish-eating birds. In order to estimate the likely levels of exposure of humans, measures of bioaccumulation can be combined with data on the consumption of known components of diet. However, care must be taken to ensure that the matrix analyzed is a real and substantive component of the relevant food chain, otherwise the prediction can be misleading and of little value because other routes of uptake are of greater importance.

This account shows there is a wide range of biological test methods for detecting sediment toxicity in individuals, populations and communities of benthic marine organisms. The methods that should be employed in particular assessments will depend on the nature of the managerial concerns. Chapter 5 identifies key questions for managers to consider. Finally, experience gained from the application of one particular test method is provided in annex 2 to this report.

5 Scientific evaluation

Contemporary scientific understanding underscores the complexity of any detailed assessment of contaminated sediments. A majority of oceanic areas are remote from emissions and inputs of material from coastal human activities. They are, nevertheless, contaminated by widely dispersed contaminants from human activities of recent centuries. Recognizing that the majority of marine sedimentary areas are contaminated only to a nominal degree, the most important and immediate task is to provide a basis for identifying coastal sediments that warrant regulatory concern.

Some preliminary tenets based on scientific considerations relevant to sediment management are:

.1 It is unwarranted, except in exceptional circumstances, to consider the following situations to be of regulatory concern:

- the presence and distribution of natural chemicals stemming from natural processes;
- the presence or baseline of natural and other chemicals derived from diverse human activities* that are distributed by global transport mechanisms.

.2 Contaminant concentrations and properties alone cannot predict the toxicity of marine sediments to marine life.

Nevertheless, there may be merit in using available data sets on simultaneously measured chemical concentrations and biological conditions/responses to infer no-effect concentrations for a range of benthic species provided that due consideration is given to differing sensitivities among phyla. See annex 2 to this report for an example.

These tenets are used in chapter 6 to develop an initial screening and evaluation procedure that should greatly simplify the identification of marine sediments not warranting management concern and, thus, further investigation. In the case of sediments not exempted from further consideration by the initial screening, it includes proposals for subsequent assessments and tests to determine the extent of associated biological effects.

6 Recommended management approaches to assessment of sediment quality

It is recommended that sediment quality be assessed by means of a "weight of evidence" approach. This is a sequential process beginning with simple screening and progressing to more detailed assessments in cases where any initial management concerns cannot be discounted.

Initial screening

As a first step, the possibility of significant contamination of sediments within the defined area should be judged by considering answers to the following questions:

* There may be reasons to exclude a proportion of the natural chemicals mobilized by widespread human activities and practices intrinsic to society, e.g., agriculture, forestry and energy conversion.

- *What are the particle size characteristics of the sediment?* If the grain-size of the sediment is almost exclusively >63μm, there are unlikely to be significant amounts of contaminants unless contaminant particles from industrial sources are present, e.g., TBT paint flakes.*
- *What are the current uses and management objectives for the area?* For example, does the area currently support aquaculture, shellfish harvesting, important feeding grounds for birds or young fish dependent on clean sediments?
- *Are there local sources of contamination, either past or present,* e.g., industrial/municipal discharges, riverine inputs containing inputs from industrial, municipal or agricultural sources, and urban surface runoff? Due consideration should be given to the presence of minerals and other materials of natural origin.
- *Is there a basis for concern about risks to human health related to sediment-derived contaminants in seafood?*
- *Is the sedimentary area of management concern defined, or definable, in ecological, resource or other socio-economic terms?*
- *Are the benthic assemblages (including bottom dwelling fish) typical of those expected for similar areas, allowing for the effects of any physical perturbation?*
- *Do benthic species in the area show obvious abnormalities (e.g., lesions and tumours that may be linked to contaminant exposures)?*

Having considered these questions, if the weight of evidence reveals no significant cause for concern, no further assessment of chemical contamination or biological effects is required.

Primary assessment

If, following the initial screening, there remain reasonable doubts as to whether or not the contamination status of the area is consistent with current uses and management objectives, the following questions should be addressed:

- *Are metal concentrations in the sediments enriched significantly above natural background or ambient levels?* (defined in section 4.3)
- *Do organic contaminants in the sediments exceed baseline concentrations?* (defined in section 4.3)

Toxicity assessment

If management decisions regarding sediment quality cannot be made on the basis of the initial screening and the primary assessment described above, sediment toxicity must be investigated through direct measurement. Using guidance such as that in section 4.4 of this report, regulatory authorities should select biological tests to define toxicity for their particular circumstances and management objectives. Sediment assessments can be based directly on such tests. Alternatively, if no-effect concentrations can be established for the substances present, chemical data can be used as surrogate indicators of non-toxicity (see annex 2 to this report). However, as emphasized in this report, chemical data alone cannot predict toxicity. Where estimated no-effect concentrations are exceeded, it should not be presumed that the sediment is toxic; it is only an indication that direct biological testing is required.

The development of a universally accepted definition of sediment toxicity indicative of unacceptable biological effects presents the greatest difficulty from scientific perspectives. Nevertheless, it may be possible to define a protocol for universal application, based primarily on biological testing, that could be used to define levels for local, and possibly national, applications.

Any further work on this topic within the framework of the GIPME Programme would be based on a request from managers to develop appropriate biological testing protocols.

* If the response to this question provides no basis for management concern, addressing the remaining questions of the initial screening procedure should be unnecessary and the conclusion may be reached that the sediments do not warrant any further management concern.

Annex 1

Limitations of chemical-specific numerical sediment quality guidelines

1 Scope

This annex addresses quality guidelines that have been derived according to certain methodologies and using ecotoxicological data. At present, there is still substantial scientific debate on the validity of such quality guidelines and their use for marine environmental management. Quality guidelines encounter one generic limitation that applies to all matrices whether sediments, water or biota. They only address concerns regarding those chemicals for which guidelines have been developed. A sediment, for example, could be below all existing guidelines yet still pose environmental risks due to additional chemicals for which guidelines have not been developed. Existing guidelines provide no means of evaluating such constituents. Moreover, the derivation of sediment quality guidelines (SQG) is hampered by the uncertainties surrounding estimations of the biological availability of sediment-associated contaminants. The actual availability and consequent ecotoxicological effects are strongly influenced by factors such as grain-size distribution, composition of organic matter, occurrence of sulphides and the time period over which the contaminants are present in the sediment. Therefore, in the process of identifying adverse effects of certain sediment compounds, SQGs should merely be used as a first screening tool.

2 Limitations of specific derivation methods for sediment quality guidelines

2.1 *Equilibrium partitioning (EqP)*

Equilibrium partitioning is usually understood to refer to (1) the partitioning of non-ionic organic chemicals between sedimentary organic carbon and porewater (Di Toro *et al*., 1991); and (2) the partitioning of ionic metals between sulphides and porewater, as described by the acid volatile sulphides/simultaneously extracted metals (AVS/SEM) process (Di Toro *et al*., 1992). They are limited by the assumption of equilibrium between sediment and porewater which is questionable in the case of estuarine and coastal sediments (USACE, 1998). Moreover, even if equilibrium between abiotic phases does exist, benthic organisms do not equilibrate with the porewater because they develop strategies to obtain oxygen and waterborne nourishment from the overlying water.

2.2 *Co-occurrence Analysis*

SQGs have been derived on the basis of co-occurrence analyses, i.e., from collections of data on bulk sediment chemical concentrations that were measured along with some measure of biological response. Responses could be results from various bioassays performed in the laboratory, benthic community changes or various sediment quality guidelines from other sources. Examples of such SQGs are the apparent effects threshold (AET), the effects range-low and effects range-medium (ERL/ERM) and the threshold effects level and probable effects level (TEL/PEL). There are potential sources of uncertainty in all co-occurrence approaches, e.g.,:

- AET, ERL/ERM or TEL/PEL do not demonstrate cause and effect (O'Connor *et al*., 1998; USACE, 1998).
- AET, ERL/ERM or TEL/PEL provide inconsistent results. Because these types of SQGs are based on statistical correspondence methods and not on mechanistically based descriptions of the process by

which effects are caused, the results are inconsistent from one geographical area to another (Becker *et al.*, 1990). It is difficult to see how such processes could be used to derive numerical action levels for international application.

– AET, ERM or PEL have a high probability of being false. Some inconsistencies may be caused by correlations among contaminant distributions resulting in false values. It is not uncommon for several contaminants to originate from the same source and for their concentrations in sediment to be closely correlated. When this occurs, the nature of the AET, ERM or PEL process is such that the effects of chemical A cannot be distinguished from the effects of chemical B. Therefore, the value for chemical B reflects combined effects of A and B, resulting in a false effect threshold value (Alden and Rule, 1992).

– Uncertainties in AET, ERL/ERM or TEL/PEL are not adequately described. All the potentially important sources of uncertainty in the derivation and use of the values have not been adequately described and evaluated (USACE, 1998). Until this is done, it is not possible to know the confidence that can be placed in evaluations based on such values.

Annex 2

An example of national experience with a site-specific assessment

During a period of over 10 years of development in the United States, it has been found that amphipod survival during ten-day laboratory exposures to whole sediment varies in proportion to sediment proximity to chemical sources. Other tests with other species have shown ambiguous results in relation to sources or require unrealistic exposures to sediment extracts. Therefore, in the United States, the amphipod test has been chosen for classifying sediments as toxic. This same test could apply in other regions. Other choices are possible on the basis of national experience with tests, particularly in respect to their practicality, reproducibility and sensitivity to gradients in chemical contamination.

In the United States, sediments are classified as toxic if they allow less than 80% survival of amphipods in 10-day laboratory tests. This sensitive test has found that less than 10% of the United States coastal area has toxic sediments (Long *et al.*, 1996). While no chemical measurements can identify toxic sediments, there is some value in listing sets of chemical concentrations that are rarely found in toxic sediments. These have limited value because higher concentrations co-occur with the very common condition of non-toxicity. However, if a sediment sample has no chemical concentration above the no-effect level, biological tests of toxicity are unnecessary. Long *et al.* (1995) provided a set of 25 no-effect concentrations that are all higher than background for metals and above global deposition levels for organic compounds.

In a set of 2,500 samples of sediment chemical data paired with amphipod toxicity measurements, O'Connor and Paul (2000) found only 33 toxic samples among 730 samples where all 25 concentrations were below the no-effect range. This less-than-5% occurrence of toxicity in the no-effect range as calculated by Long and Morgan (1990) may be due to chemicals not included among the 25 with no-effect levels but may also be an irreducible minimum rate of error. In the same dataset 1,370 (80%) of the 1,725 sediment samples with concentrations above the no-effect levels were also non-toxic. Exceedance of a no-effect concentration means only that biological considerations are necessary.

Annex 3

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Annex 4

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