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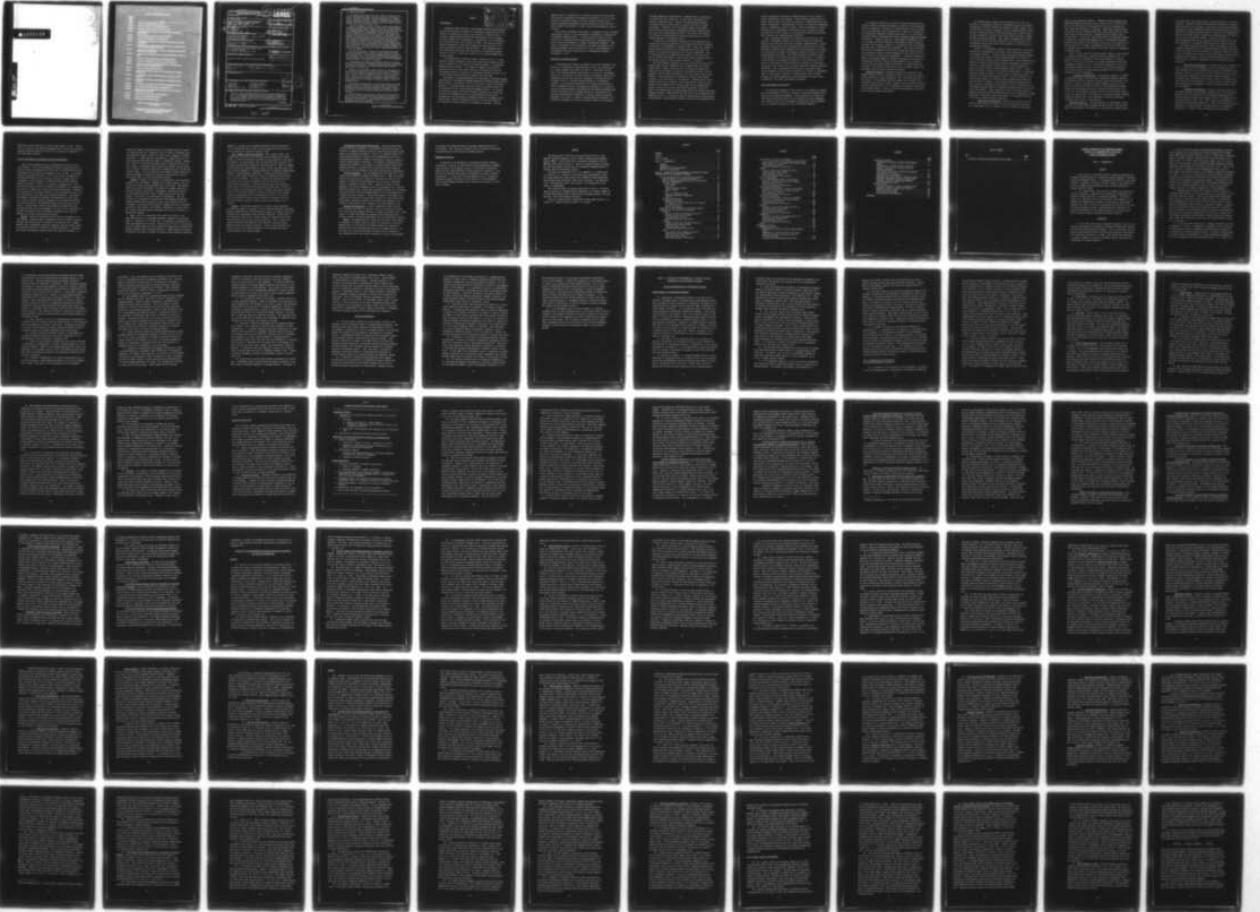
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This report is a guidelines manual to assist in selecting disposal alternatives for contaminated dredged material to minimize adverse environmental effects. It is directed to the small percentage of contaminated sediments that are believed to present a high potential for environmental harm, rather than the great majority of dredging projects that involve uncontaminated or slightly contaminated sediments.

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## 20. ABSTRACT (Continued).

The contaminants and potentially nuisance substances considered in this report include: mercury, cadmium, lead, zinc, copper, nickel, chromium, arsenic, chlorinated hydrocarbons, petroleum hydrocarbons, iron, manganese, nitrogen, phosphorus, and sulfur. Individual contaminants, and in some cases groups of contaminants that behave similarly, are discussed under separate headings. Many of the contaminants respond differently to physical, chemical, and biological conditions at a disposal site.

This report includes a synthesis of research findings of the mobility of contaminants in sediment-water systems, the properties of dredged sediments that affect contaminant release potential, and the short- and long-term physical and chemical environments of dredged material at disposal sites that influence contaminant mobility. Physicochemical (oxidation-reduction, pH, and salinity) conditions of dredged material at a disposal site influence the mobility and bioavailability of most contaminants to a large degree. Typical maintenance dredged sediments are anoxic (reducing) and near neutral in pH. Depending on the disposal methods selected and properties of the dredged sediments, changes in the physicochemical conditions at the disposal site may result in substantial mobilization of certain potentially toxic materials. Understanding the interaction between contaminants, dredged sediment properties, and physical, chemical, and biological conditions at a proposed disposal site permits selection of disposal methods that will minimize contaminant release in many cases. These topics are presented as factors that should be considered in evaluating the environmental risk of a proposed disposal method for a contaminated sediment.

The three major disposal alternatives include subaqueous (open-water), intertidal, and upland methods. A number of variations exist for each of these major alternatives, each having some influence on the fate of contaminants at disposal sites. In many cases, environmentally sound disposal of contaminated dredged material can be achieved by any of the major alternatives if certain variations of each alternative are available and additional management practices discussed in this report are employed.

It was generally concluded that most subaqueous disposal in low-energy aquatic environments where stable mounding will occur will favor containment of potentially toxic materials. A high-energy subaqueous site may result in long-term dispersion and transport of contaminated particulates and possibly greater release to soluble forms.

Effluent from initial dewatering and consolidation at intertidal and upland contaminated dredged material disposal sites may contain contaminants at levels that exceed applicable surface water quality criteria for receiving waters. Practices to maximize suspended particulate removal from these effluents will usually result in a substantial reduction in total contaminant levels. Plant uptake and leaching of contaminants are additional potential long-term problems with these disposal alternatives. However, in many cases, these processes either will not occur to a significant extent or will be manageable problems.

Certain types of dredged material that may become moderately to strongly acid upon drainage and the subsequent oxidation present a high potential for contaminant mobilization under upland conditions. This is potentially one of the greatest problems associated with dredged material disposal. Several potentially toxic metals, cadmium in particular, may be mobilized to biologically available forms or may leach into groundwater under acid, oxidized conditions.

The approach taken in this report is to point out the relative environmental risks of different disposal methods by identifying the possible disposal alternatives and discussing the problems associated with specific contaminants and disposal methods. Certain management practices that may be applicable to some disposal alternatives that will further reduce the environmental risk are also presented.

SUMMARY

Introduction

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During the 1960's and 1970's, environmental concerns and regulatory actions associated with disposal of contaminated dredged materials were directed to protection of surface water quality at disposal sites. As a result, upland disposal methods were increasingly used for dredged materials thought to be contaminated. Comparatively little information was available at that time to assess the short- and long-term environmental consequences of open-water disposal and less was known of the potential adverse effects of upland disposal. Thus implementation of early guidelines and criteria for evaluation of contaminated dredged material to protect surface water quality did not ensure minimal environmental impact.

The Dredged Material Research Program conducted by the U. S. Army Engineer Waterways Experiment Station has supplied much needed information on evaluation of the physical and chemical impacts of contaminated dredged material disposal. The scientific community and regulatory agencies are now in a much better position to evaluate the potential environmental impacts of disposal of contaminated dredged material by the various disposal methods than was possible a few years ago.

This report is a guidelines manual for assisting in selecting disposal alternatives for contaminated dredged materials to minimize adverse environmental effects. The state of the art is such that a step-by-step matrix approach or a decision-making flow chart cannot be developed which will be applicable for all or most proposed dredging projects. The reasons are varied but include the lack of suitable procedures for quantifying the level of contamination and often establishing the presence of contamination, the interaction of numerous properties of sediment-water systems which influence contaminant mobility, and the unavailability of acceptable criteria testing for all methods of disposal. Thus the

approach taken in this manual is to identify problem areas associated with specific contaminants and disposal alternatives, to point out the relative environmental risks of different disposal methods, and to discuss supplemental management practices which may be used with the major disposal alternatives to further reduce the environmental risk of disposal.

Upon initial screening of this report, it appears to take a strongly conservative position on the environmental acceptability of disposal of contaminated dredged material. It should be kept in mind that this report is not concerned with the great majority of dredging projects which involve uncontaminated or slightly contaminated sediments. This report is designed to offer guidance for the small percentage of contaminated sediments which are believed to offer a high potential for environmental harm (See Identification of Contaminated Sediments, Paragraphs 31 to 39).

#### Approach in developing manual.

In developing this manual, a synthesis of research findings of the mobility of contaminants in sediment-water systems, the properties of the dredged sediment that affect the fate of contaminants, and the short- and long-term physical and chemical environment of the dredged material at the disposal site which influence contaminant mobility are presented as factors that should be considered in evaluating the environmental risk of a proposed disposal method for contaminated sediment. The processes involved with the release or immobilization of most sediment-associated contaminants are regulated to a large extent by the physicochemical environment and the related microbiological activity associated with the dredged material at the disposal site. Important physicochemical parameters include pH, oxidation-reduction conditions, and salinity. Where the physicochemical environment of a contaminated sediment is altered by disposal, chemical and biological

processes important to mobilization or immobilization of potentially toxic materials may be affected. In some cases, substantial contaminant release may occur. However, an altered physicochemical environment does not always result in greater mobility of a given contaminant. Frequently, an altered physicochemical environment which results in the release of contaminants from one chemical form will favor other immobilizing reactions. This report will identify the influence of physicochemical conditions associated with various disposal methods on contaminant release.

In addition to the chemical properties of the contaminant, the chemical and physical properties of the dredged material can influence the mobility of contaminants at disposal sites. There are a number of readily identified properties of dredged materials that affect the mobility and biological availability of various contaminants. Some of these properties can change when the sediment is moved from one type of disposal environment to another while other properties are not affected by changes in water content, aeration, or salinity.

The major sediment properties that will influence the reaction of dredged material with contaminants are the amount and type of clay, organic matter content, amount and type of cations and anions associated with the sediment, the amount of potentially reactive iron and manganese, and the oxidation-reduction, pH, and salinity status of the sediment. These properties are discussed in terms of their general influence on the mobilization of contaminants. Although each of these sediment properties is important, much concerning the release of contaminants from sediments can be implied from clay and organic matter content, initial and final pH, and oxidation-reduction conditions. Much of the dredged material removed during harbor and channel maintenance dredging is high in organic matter and clay and is both biologically and chemically active. It is usually devoid of oxygen and may contain appreciable sulfide. These sediment conditions favor effective immobilization

of many contaminants provided the dredged materials are not subject to mixing, resuspension, and transport. Coarse-textured sediments low in organic matter content are much less effective in immobilizing metal and organic contaminants. These materials tend not to accumulate contaminants unless a contamination source is nearby. Should contamination of these sediments occur, potentially toxic substances may be readily released upon mixing in a water column, or by leaching and possibly plant uptake under intertidal or upland disposal conditions.

Many contaminated sediments are reducing and near neutral in pH initially. Subaqueous disposal into quiescent waters will generally maintain these conditions and favor contaminant immobilization. Certain sediments (noncalcareous and containing appreciable reactive iron and particularly reduced sulfur compounds) may become moderately to strongly acid upon gradual drainage and subsequent oxidation as may occur under upland disposal conditions. This altered disposal environment offers a high potential for mobilizing potentially toxic metals. In addition to the effects of pH changes, the mobility of most potentially toxic metals is influenced by oxidation-reduction conditions to some extent, and certain of the metals can be strongly affected by oxidation-reduction conditions. Thus, contaminated coarse-textured, low organic matter content sediments pose the greatest potential for release of contaminants under all conditions of disposal. Sediments which tend to become strongly acid upon drainage and long-term oxidation also pose a high environmental risk under some disposal conditions.

#### Selecting disposal alternatives

The following paragraphs in this section of the Summary are adapted from the discussion of factors to consider in selecting disposal alternatives for contaminated sediments. The discussion in the report for selecting disposal alternatives is not identical for each contaminant since rigorous efforts for containment of potentially toxic substances are not considered necessary for all contaminated sediments.

For sediments determined to represent a high environmental risk, disposal methods stressing containment of potentially toxic substances should be considered. Placement of dredged materials heavily contaminated with potentially toxic substances in or adjacent to ecologically and economically important biological populations, or in areas where productive habitat development will occur, represents high risk disposal alternatives. Likewise, disposal in high-energy environments may not be a desirable alternative because of the greater probable long-term dispersion and subsequent transport of contaminants and the subsequent increased risk of concentration by organisms. Also, this alternative, which favors resuspension in oxic water columns and possible eventual thin spreading in surface oxidized sediment horizons, may result in enhanced release of several metal contaminants. Contaminated sediments placed in low-energy regimes to minimize resuspension and transport of contaminated solids will reduce the environmental risk of disposal. The most effective physicochemical environment for immobilizing most potentially toxic metals is near neutral in pH, strongly reduced, and nonsaline, especially where sulfides are present.

Subaqueous disposal. Subaqueous disposal of potentially toxic dredged materials within or adjacent to especially productive aquatic systems represents a high environmental risk. Unconfined disposal in any moderate- to high-energy hydraulic regime also increases the environmental risk because of likely transport from the disposal site and chemical transformations of the contaminant to potentially more mobile and available forms as a result of altered physicochemical conditions in the receiving aquatic environment.

Unconfined disposal (where stable mounding will not occur) in moderate- to high-energy subaqueous environments also has the inherent disadvantage of greater surface area exposure to water columns. This may contribute to greater transport across the sediment-water interface because of resulting shorter diffusion distances for the small amount of some contaminants that may be mobilized within the reduced dredged material as soluble complexes. Also, greater spreading will increase the surface area and thus the proportion of the total volume of the contaminated material which may become oxidized as a thin horizon at a sediment-water interface.

Certain of the subaqueous disposal alternatives offer the greatest potential for containment of potentially toxic substances associated with dredged materials. Confined (stable mounding) subaqueous disposal of typically fine-textured, reduced dredged material will result in little long-term transport from the disposal site. This alternative will maintain a strongly reduced physicochemical environment and favors the stability of metal sulfide precipitates and insoluble complexes of metals with large molecular weight sediment organic matter. Confinement by mounding in areas of low biological productivity in a low-energy hydraulic regime not subject to storm currents should pose a very low potential for adverse environmental effects. For most purposes, this implies ocean disposal or other deep water placement where depths are about 30 meters or greater. The optimum subaqueous disposal alternative, though not available for most projects, will be confinement in a low-energy depression where the contaminated sediment may be covered with clean, wet material. These alternatives result in the maintenance of reducing conditions favoring immobilization of most contaminants, minimum dispersion, and minimal surface area exposure of contaminated material to the water column and benthic organisms.

Short-term considerations. Elutriate test results and monitoring of water quality at disposal sites have generally shown that most contaminants are not released or are only released in negligible

amounts during subaqueous disposal. Exceptions include manganese and ammonium-nitrogen for which short-term release in toxic concentrations may occur in the absence of mixing and dilution with receiving site water (which should rarely be a problem). Where small elevated levels of potentially toxic substances have been found in receiving site water, these levels usually decrease to predisposal levels quickly, often within minutes. Little short-term adverse impact of subaqueous disposal is expected for contaminated sediments out of a designated subaqueous disposal area because of dilution which will occur at the disposal site, the association of "released" contaminants with the solid phase, and the transient nature of any increase in the total levels of contaminants at disposal sites.

Little, if any, short-term adverse chemical impact on water quality or biological populations is expected within the disposal site. An exception would be contaminated, very coarse-textured, low organic matter, low reactive iron sediments from which substantial short-term contaminant release may occur. As previously mentioned, this type of contaminated sediment may occur only under very localized conditions near a waste outfall as coarse-textured sediments are not effective scavengers of most contaminants.

Long-term considerations. The greatest potential for adverse environmental impacts associated with contaminated sediments disposed of subaqueously will be long-term, gradual release and biological accumulation. Typical fine-grained, reduced sediments placed in a low-energy subaqueous environment should give stable mounding and immobilization of contaminants such that no long-term adverse effects will occur out of the designated disposal area nor to surface water quality within the disposal area. The potential for uptake by benthic organisms within the disposal area can be minimized by covering contaminated sediments with a layer of clean material.

Intertidal disposal. Intertidal disposal of contaminated, coarse-textured, low organic matter dredged material may pose a high environmental risk because of the potential for leaching into adjacent ground

or surface waters and probable greater plant availability of many contaminants. Intertidal disposal near especially productive or sensitive aquatic habitats also represents a high risk as does extensive habitat development on some contaminated dredged material deposited intertidally. Covering the contaminated material with a clean layer of dredged sediments or soil should reduce the potential long-term impact of toxic material uptake by plants and animals. Physical confinement of the bulk dredged solids may be required to prevent erosion and subsequent dispersion of contaminated particulates into nearshore waters.

Intertidal disposal may present a higher environmental risk than subaqueous disposal because of the greater hydraulic energy conditions at some intertidal sites contributing to erosion and dispersion of bulk solids, the important and sensitive benthic and aquatic habitats usually associated with nearshore areas, and the demonstrated potential of plants to take up certain contaminants and cycle them into wetland ecosystems.

Short-term considerations. Unconfined intertidal disposal may result in elevated total contaminant levels in effluents associated with suspended solids during dewatering from initial consolidation and settling. Because of the proximity of most intertidal sites to important biological populations, such discharge should be minimized. It is anticipated that suspended solids levels in effluent from many intertidal sites will be more difficult to control than for upland containment facilities where management to enhance suspended solids removal is more feasible.

Long-term considerations. Potential long-term problems of intertidal disposal of contaminated sediments will be associated with gradual erosion and dispersion of contaminated dredged material in nearshore areas and uptake and possible cycling by organisms which become established on these sites. These risks can be minimized by covering the contaminated sediments by a layer of clean material and by precautions to prevent gradual, long-term erosion of contaminated particulates. Leaching of most contaminants into groundwater or

adjacent surface waters may be a long-term risk only if the contaminated sediments are coarse textured and contain relatively low organic matter content.

Upland disposal. Upland confinement of contaminated sediments for disposal purposes can be done in an environmentally safe manner, though in many cases it may offer little or no benefit over certain subaqueous disposal methods. Sediments heavily contaminated with potentially toxic materials should not be applied upland for the purposes of agricultural soil amendment or habitat development because of the potential for plant uptake, subsequent introduction into food chains, and possible human exposure from crop plants. In some cases, sediments slightly to moderately contaminated with certain potentially toxic substances may be used for many upland purposes.

Ponded, upland containment where leaching and biological colonization can be controlled on a long-term basis can be an effective disposal method for highly contaminated sediments as the maintenance of strongly reducing conditions favors immobilization of most potentially toxic substances. However, the long-term management problems and the relatively low capacity implied by ponded (dewatering permitted only by evaporation) containment makes this alternative feasible only for certain low volume projects. Leaching control and the maintenance of long-term flooded conditions will favor immobilization of most metals as sulfide precipitates in sediments containing appreciable sulfur. Confined upland disposal with management to maximize suspended solids in initial dewatering effluents should be about as effective in containing most potentially toxic substances. Unconfined upland disposal not specifically intended for habitat development represents a moderate environmental risk because of the natural colonization and the implied greater initial spreading and resulting greater exposed surface area of contaminated sediment than will occur with confined disposal.

Except for very coarse-textured, low organic matter sediments with low reactive iron content, leaching of most contaminants into groundwater or adjacent surface waters is not expected to be significant if the dredged material does not become strongly acid upon oxidation. Short-term leaching of iron and manganese and long-term leaching of some nitrogen forms may be exceptions. Upland disposal of toxic metal contaminated in noncalcareous sediments containing large amounts of reactive iron and especially total or pyritic sulfide represents a high potential for long-term leaching. The strongly acid conditions associated with sulfide and pyrite oxidation will almost certainly result in substantial long-term mobilization and leaching of potentially toxic metals.

The use of contaminated dredged material for fill and other engineering purposes will present a low environmental risk: 1) if extensive surface colonization by natural or managed biological populations is not permitted or the fill is covered with a layer of clean material greater than the expected rooting and burrowing depths of organisms, 2) if organic matter, reactive iron, and silt and clay contents are moderate to high, and, 3) if development of excessive acidity upon dredged material oxidation will not occur.

Short-term considerations. Short-term problems with upland disposal will be associated with elevated levels of contaminants associated with suspended particulates in initial dewatering effluents from the confinement sites if applicable criteria for receiving surface waters are exceeded. Management to maximize suspended solids removal will be effective in reducing potential short-term release.

Long-term considerations. Potential long-term problems are associated with uptake and cycling by organisms and leaching into subsurface aquifers. Groundwater contamination may be a problem if strong acidity development is expected upon long-term oxidation of the dredged material. A dredged sediment containing appreciable sulfide or pyrite represents a high, long-term risk for leaching and contaminating groundwater with potentially toxic metals.

Liming the entire depth of an upland confinement facility for pH control may not be feasible for economic reasons and because of the

additional capacity required to contain large amounts of lime. Liming may be an effective and feasible management tool for certain contaminated sediment materials applied as thin lifts for some land reclamation or soil improvement purposes.

#### Role of contaminants in selecting disposal alternatives

Most problem sediments will be contaminated with more than one toxic material. Thus the environmental evaluation associated with the various disposal alternatives will often have to consider more than one contaminant and the relative environmental threat of each. An assigned ranking of environmental risks to each of the various contaminants is not possible because of their varying toxicities, varying levels of contamination, and differences in chemical behavior under different methods of disposal. However, it is prudent to suggest that a very high priority should be given to sediments determined to be contaminated with mercury, cadmium, and certain chlorinated hydrocarbons. Sediments with high levels of nitrogen, phosphorus, and iron generally pose a very low environmental threat under most disposal conditions. Anticipated environmental problems with sediments contaminated with lead, copper, zinc, nickel, chromium, arsenic, manganese, and petroleum hydrocarbons can range from high to low depending on many factors discussed in the report. In many cases, potential environmental problems with these contaminants tend to be more manageable and there is more flexibility in disposal alternatives than for sediments contaminated with mercury, cadmium, and certain chlorinated hydrocarbons.

Mercury. Mercury is potentially one of the most hazardous of the toxic metals. Sediments highly contaminated with this element should be confined such that mercury is isolated at the disposal site. Dredged materials with considerable levels of naturally occurring organic matter and especially sulfide can effectively immobilize mercury. A reducing, near neutral pH disposal condition favors the long-term stability of

sulfide and organic complexes and will thus minimize mercury release. For sediments with low to moderate levels of mercury, oxidizing conditions generally enhance release to a small extent compared to reduced conditions. At high levels of contamination, a moderately acid, oxidized disposal environment may result in substantial release. Hydrous iron oxides can effectively scavenge traces of dissolved mercury in a water column. Increasing chloride levels may, however, reduce adsorption of mercury by hydrous oxides while increasing pH can overcome the chloride effect. Of the potentially toxic metals, mercury losses from upland confinement sites may be especially associated with the fine particulate phase in initial dewatering effluents.

Cadmium. Cadmium, like mercury, is potentially a very hazardous element in the environment. Cadmium can be readily taken up and concentrated by plants and subsequently enter food chains. The chemical mobility and plant availability of cadmium are strongly affected by oxidation-reduction conditions. Furthermore, oxidizing conditions can substantially increase soluble cadmium levels and plant availability. This effect is accentuated by decreasing pH. Thus the potential for environmental contamination from cadmium-contaminated dredged sediments may be enhanced at many upland disposal sites as a consequence of expected pH and oxidation changes which favor increased solubility, plant uptake, and leaching. Maintenance of a near neutral pH, strongly reducing disposal environment will be most effective in immobilizing cadmium.

Lead. Lead is a potentially toxic metal often found in very high concentrations in contaminated sediments compared to mercury and cadmium. Fortunately, it is less toxic in equivalent concentrations in soils and sediment-water systems. Excess levels of lead in fine-textured soils and dredged materials can be effectively immobilized by sulfide and sediment organics under reducing conditions. Immobilization by organics and hydrous iron oxides is almost as effective under oxidized conditions.

Moderate to strongly acid, oxidizing conditions which may develop in certain dredged materials placed in upland disposal facilities may result in substantial long-term release of lead.

Zinc, copper, nickel, and chromium. Zinc, copper, nickel, and chromium are potentially toxic metals at high concentrations, though certain of these are essential nutrients in trace amounts to both plants and animals. Of these metals, zinc and nickel may pose a greater risk of excess accumulation by marsh and cultivated plants. There is evidence of some increase in mobilization of copper, nickel, and especially zinc under oxidized compared to reducing conditions in quiescent sediment-water systems or upland disposal conditions. Substantial mobilization may occur for some dredged materials if disposal conditions favor development of acid conditions. In typical fine-textured dredged materials, a reducing, near neutral pH condition will be most effective in immobilizing these metals. Oxidized conditions may also immobilize these metals if near neutral pH conditions are maintained. Because of the relatively low environmental risk of sediments containing elevated levels of these metals compared to mercury and cadmium, many dredged sediments contaminated with low to moderate amounts of these metals may be considered for marsh creation, habitat development, and other soils improvement purposes if long-term acidity development is not a problem.

Arsenic. The chemical speciation of arsenic affecting mobility is especially subject to changes in pH and oxidation-reduction conditions. Reducing conditions favor the more mobile organic and arsenite forms over arsenate which predominates under oxidized conditions. Unlike most of the potentially toxic metals, arsenic release is apparently less under acid conditions and increases with increasing pH. Thus a mildly acid, oxidized disposal environment may favor greatest long-term arsenic immobilization under upland conditions. However, under quiescent conditions, release from reduced sediments to an overlying oxic water column should not be a problem either.

Chlorinated and petroleum hydrocarbons. Disposal methods which include long-term confinement of contaminated particulates should be effective in immobilizing chlorinated and petroleum hydrocarbon contaminants in contaminated sediments. There is no consistent effect of a given oxidation-reduction condition on the degradation rate of all chlorinated hydrocarbons, though the persistence of some do respond to altered physicochemical conditions. For sediments contaminated with petroleum hydrocarbons of low toxicity, disposal methods which permit gradual dispersion in oxidized water columns and surface sediments should pose a low environmental risk while enhancing their degradation.

Iron and manganese. Iron and manganese are not expected to cause long-term environmental problems at disposal sites. Under rare circumstances where dilution and mixing with receiving site water is very limited, localized short-term manganese toxicity may be a potential problem at subaqueous disposal sites. Leaching of excess iron and manganese from upland confinement sites into groundwater is a potential short-term problem until upland applied sediments oxidize and a potential long-term problem where the dredged sediments will become moderately to strongly acid upon oxidation. Except where moderate to strongly acid conditions may develop at upland sites, hydrous iron oxide particulates formed under oxidizing conditions are an effective scavenger for potentially toxic metals at both subaqueous and upland disposal sites.

Nitrogen and phosphorus. In rare circumstances where dilution with receiving site water is limiting, there is a potential for short-term, very localized ammonia toxicity at subaqueous disposal sites. High levels of nitrogen and phosphorus generally make dredged materials a valuable resource for habitat development and soils improvement purposes.

Sulfur. In dredged materials containing potentially toxic metals, the presence of reduced sulfur as sulfide can contribute to effective immobilization of toxic metals if disposal methods are selected to maintain the initial reducing conditions of the dredged material. On the other hand, long-term oxidation of reduced sulfur compounds in some dredged material under upland conditions can result in development

of strongly acid conditions which can release substantial levels of toxic metals. This condition represents one of the greatest potentials for mobilization of toxic metals in dredged materials.

#### Management practices

In addition to the discussion on selecting acceptable disposal alternatives, a section is included identifying supplemental management practices which can be applied to many of the disposal alternatives. These practices, when applicable, provide additional flexibility to the process of selecting and managing environmentally acceptable disposal alternatives. In some cases, the environmental risk of a marginally acceptable disposal alternative can be reduced by proper management where optimum disposal methods are not feasible for economic or technological reasons.

## PREFACE

The preparation of this report was authorized by the U.S. Army Engineer Waterways Experiment Station (WES), Dredged Material Research Program (DMRP). The objective was to synthesize information from the DMRP and other selected sources to develop a guidelines manual to assist in selecting disposal alternatives for contaminated dredged material to minimize adverse environmental effects.

The report was prepared by Drs. R. P. Gambrell, R. A. Khalid, and W. H. Patrick, Jr., Laboratory for Wetland Soils and Sediments, Center for Wetland Resources, under Contract No. DACW39-77-C-0054 between WES and Louisiana State University, Baton Rouge, Louisiana. The assistance of Ms. Judy Henderson and Ms. Rita Strate in the preparation of this report is acknowledged.

This study was under the general supervision of Drs. R. T. Saucier, Special Assistant for Dredged Material Research, R. M. Engler, Manager of the DMRP Environmental Impacts and Criteria Development Project, and John Harrison, Chief, Environmental Laboratory.

Director of WES during the preparation of this report was COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

## CONTENTS

	<u>Page</u>
SUMMARY . . . . .	1
PREFACE . . . . .	1
LIST OF TABLES . . . . .	5
PART I: INTRODUCTION . . . . .	6
Purpose . . . . .	6
Background . . . . .	6
Approach in Developing Manual . . . . .	8
Scope and Limitations . . . . .	13
PART II: SELECTION OF ENVIRONMENTALLY ACCEPTABLE DISPOSAL ALTERNATIVES FOR CONTAMINATED SEDIMENTS . . . . .	16
Initial Considerations of the Selection Process . . . . .	16
Identification of contaminated sediments . . . . .	16
Role of dredged material properties in selecting disposal alternatives . . . . .	18
Clay content . . . . .	20
Clay type . . . . .	20
Cation exchange capacity . . . . .	20
Organic matter . . . . .	21
pH . . . . .	21
Iron and manganese oxides . . . . .	22
Oxidation-reduction conditions . . . . .	23
Salinity . . . . .	25
Disposal alternatives . . . . .	26
Subaqueous disposal . . . . .	26
Application to intertidal sites for disposal or productive use . . . . .	32
Upland application . . . . .	36
Selection of Environmentally Acceptable Disposal Alternatives for Specific Contaminants . . . . .	40
Mercury . . . . .	40
Mercury release from dredged material in laboratory and field studies . . . . .	41
Physicochemical effects . . . . .	43
Selecting disposal alternatives . . . . .	48
Cadmium . . . . .	55
Cadmium release from dredged material in laboratory and field studies . . . . .	55
Physicochemical effects . . . . .	57
Selecting disposal alternatives . . . . .	61
Lead . . . . .	65
Lead release from dredged material in laboratory and field studies . . . . .	67
Physicochemical effects . . . . .	69
Selecting disposal alternatives . . . . .	72

## CONTENTS

	<u>Page</u>
Zinc, copper, nickel, and chromium . . . . .	73
Zinc, copper, nickel, and chromium release from dredged material in laboratory and field studies . .	75
Physicochemical effects . . . . .	76
Selecting disposal alternatives . . . . .	79
Arsenic . . . . .	84
Arsenic release from dredged material in laboratory and field studies . . . . .	86
Physicochemical effects . . . . .	86
Selecting disposal alternatives . . . . .	87
Iron and manganese . . . . .	91
Iron and manganese release from dredged material in laboratory and field studies . . . . .	93
Physicochemical effects . . . . .	93
Selecting disposal alternatives . . . . .	95
Chlorinated hydrocarbons . . . . .	99
Chlorinated hydrocarbon release from dredged material in laboratory and field studies . . . . .	100
Physicochemical effects . . . . .	102
Selecting disposal alternatives . . . . .	102
Petroleum hydrocarbons . . . . .	106
Petroleum hydrocarbon release from dredged material in laboratory and field studies . . . . .	107
Physicochemical effects . . . . .	108
Selecting disposal alternatives . . . . .	109
Nitrogen . . . . .	114
Nitrogen release from dredged material in laboratory and field studies . . . . .	115
Physicochemical effects . . . . .	116
Selecting disposal alternatives . . . . .	118
Phosphorus . . . . .	121
Phosphorus release from dredged material in laboratory and field studies . . . . .	121
Physicochemical effects . . . . .	122
Selecting disposal alternatives . . . . .	122
Sulfur . . . . .	125
Management Practices . . . . .	129
Subaqueous disposal . . . . .	129
Scheduling to minimize nuisance phytoplankton growth . . . . .	129
Scheduling to coincide project with least sensitive portions of the life cycles of affected organisms . . . . .	130
Covering with uncontaminated material . . . . .	130

CONTENTS

	<u>Page</u>
Intertidal disposal . . . . .	131
Scheduling to minimize nuisance phytoplankton growth . . . . .	131
Scheduling to coincide project with least sensitive portions of the life cycles of affected organisms . . . . .	131
Confinement structures to minimize dispersion and transport by erosion . . . . .	131
Covering with clean material . . . . .	131
Managing plant populations to minimize uptake . . . . .	132
Reducing contaminant losses associated with suspended solids in dewatering effluents . . . . .	132
Reducing leaching losses . . . . .	132
Upland disposal . . . . .	133
Reducing contaminant losses associated with suspended solids in dewatering effluents . . . . .	133
Reducing leaching losses . . . . .	133
Minimizing plant uptake . . . . .	135
Covering with clean material . . . . .	136
REFERENCES . . . . .	138

LIST OF TABLES

<u>No.</u>	<u>Page</u>
1 Disposal Alternatives Considered in This Report . . . . .	27

DISPOSAL ALTERNATIVES FOR CONTAMINATED DREDGED  
MATERIAL AS A MANAGEMENT TOOL TO MINIMIZE  
ADVERSE ENVIRONMENTAL EFFECTS

PART I: INTRODUCTION

Purpose

1. This report is a guidelines manual to assist in selecting and managing disposal methods for contaminated dredged sediments to minimize adverse environmental effects. To accomplish this objective, this report includes a synthesis of published research findings on the chemical mobility of sediment-bound contaminants under various conditions of dredged material disposal.

2. In a simple format, this manual will examine the factors that should be evaluated to determine the environmental acceptability of a proposed disposal method for a contaminated sediment. The subject areas to be considered include a brief review of the chemistry of contaminants in sediment-water systems; the properties of the dredged sediment that affect the fate of contaminants; and the short- and long-term physicochemical (acidity, oxidation-reduction conditions, and salinity) environments of the dredged material at the disposal site which influence processes regulating contaminant mobility.

Background

3. In the 1960's there was an increasing awareness in the U.S. and abroad of the potential environmental problems associated with dredging and especially dredged material disposal. Prior to the 1970's, the only control of dredging and related activities was authorized under Section 10 of the River and Harbor Act of 1899. This law was never intended to regulate dredging to control environmental impacts associated with contaminants in dredged sediments.

4. One of the first actions resulting from environmental concerns about dredging was by the Federal Water Quality Administration (FWQA) which asked that the Buffalo District of the U.S. Army Corps of Engineers report on sediment chemical characteristics of selected harbors in the Great Lakes. As a result of the Great Lakes studies, the U.S. Environmental Protection Agency, which succeeded the FWQA, implemented disposal guidelines commonly known as the "Jenson Criteria" in 1971. Also in that year, the Corps of Engineers issued Engineering Circular 1165-2-97, which applied the Jenson Criteria to all sediments dredged from navigable U.S. waters. If the total concentration of selected chemical parameters exceeded levels specified by the Criteria, the sediment was considered polluted and unacceptable for open-water disposal. Limitations of this Criteria were eventually recognized since the procedure inventories the amount of a contaminant present but does not indicate the potential chemical mobility or biological availability of the contaminant.

5. Implementation of these early criteria resulted in polluted sediments being disposed of by land application as an alternative to the prohibited open-water method. In many cases insufficient information was available to determine potential adverse effects of land disposal. Thus, implementation of early criteria did not ensure limited or even minimal environmental impact relative to open-water disposal. Frequently, the only feasible alternative to open-water disposal is land disposal on marshes or other wetlands which are among the most biologically productive and ecologically significant areas on earth. Wetlands are also fragile ecosystems, and the possible adverse effects from contaminants could have an additional impact over the obvious physical disruption of wetlands.

6. In the 1970 River and Harbor Act, Congress authorized the Corps of Engineers to initiate a comprehensive, nationwide study to determine the environmental impact of dredging and dredged material disposal and to develop new or improved disposal methods. The task of identification of research needs and development of a research program was assigned to the U.S. Army Engineer Waterways Experiment Station. As a result, the

5-year Dredged Material Research Program (DMRP) was initiated at the Waterways Experiment Station.

7. Research of the DMRP has supplied much needed information on criteria testing and evaluation of the physical and chemical impacts of contaminated dredged material at a disposal site as well as information on many other aspects of dredging and dredged material disposal. Several European nations, Japan, and other governmental units in the U.S. have also pursued extensive research into environmental problems associated with contaminated sediments during the same time frame.

8. Criteria development and associated testing procedures for open-water disposal have been updated and revised by the U.S. Environmental Protection Agency and the Corps of Engineers during the DMRP such that more meaningful evaluative procedures are available now for open-water disposal than 5 years ago. However, criteria and testing procedures for possible land disposal of contaminated sediments are still in their infancy. The need for this type of testing has been recognized, and preliminary efforts are under way to provide information to develop criteria for land disposal.

9. A result of the DMRP studies and other research on the environmental effects of dredging is that the scientific community and regulatory agencies are now in a much better position to evaluate the environmental impacts of disposal of contaminated sediments by various disposal methods than they were a few years ago. This report is an attempt to synthesize the information gained from environmental studies of dredging and dredged material disposal into a manual which will be useful in selecting disposal methods for contaminated dredged sediments to minimize adverse environmental effects.

#### Approach in Developing Manual

10. Technological and economic considerations are major factors in selecting feasible disposal alternatives for any proposed dredging project. When a chemically contaminated sediment is involved, the potential environmental impact of the contaminants at the disposal site

must also be considered. This report deals only with selecting environmentally acceptable disposal methods for chemically contaminated sediments from all possible disposal alternatives.

11. The environmental impact of uncontaminated sediments must also be considered. With "clean" sediments, however, the evaluation is much simpler as the physical impact of site modification or biological impact of habitat destruction is usually the problem, and the acceptability or unacceptability of these changes is usually easier to establish.

12. Because the most environmentally sound alternative may often not be feasible for technological or economic reasons, this report will try to identify relative environmental risks of various disposal methods for a given contaminant problem. For some disposal alternatives, management practices which may be applied subsequent to actual disposal will be presented. These practices, where applicable, will further minimize adverse environmental impacts or reduce this impact for second-choice alternatives where the optimum environmental disposal method is not feasible for other reasons.

13. Early environmental concerns of dredging focused on aquatic ecosystems which might be harmed by subaqueous disposal of contaminated sediments. Upland disposal was advocated in many instances to minimize possible adverse environmental effects. Little attention was given to the chemical mobility and biological availability of contaminants in land-applied dredged sediments until recently. If minimizing release and potential biological availability of contaminants is an important consideration, then one type of disposal will not always be best. Indeed, it is likely that some upland disposal methods may release more toxic materials to the surrounding terrestrial ecosystem and possibly to adjacent surface waters than will subaqueous disposal directly into these waters. Shallow estuarine systems which might receive discharge from upland confinement facilities and ecologically sensitive freshwater or intertidal marshes are important breeding grounds and nurseries for many important aquatic fauna.

14. Several processes are involved with the release or immobilization of sediment-associated contaminants. These processes are regulated

to a large extent by the physicochemical environment and the related microbiological activity associated with the dredged material at the disposal site. Important physicochemical parameters include pH, oxidation-reduction conditions, and salinity. Where the physicochemical environment of a contaminated sediment is altered by disposal, chemical and biological processes important to mobilization or immobilization of potentially toxic materials may be affected. In some cases, substantial contaminant release may occur. However, an altered physicochemical environment does not always result in greater mobility of a given contaminant. Many complex and interacting physical, chemical, and biological processes are involved in regulating contaminant availability. Frequently, an altered physicochemical environment which results in release of contaminants from one chemical form will favor other immobilizing reactions. This report will attempt to identify the influence of physicochemical conditions associated with various disposal methods on contaminant release.

15. Also important to the fate of sediment-bound contaminants at a disposal site is biological activity which may play a role in mobilization of contaminants by uptake or other means. Biological populations of interest include aquatic and benthic plants and animals as well as terrestrial plants and consumer organisms of all these systems.

16. Physical processes affecting transport of contaminants and contaminated sediment particulates also play an important role in determining the fate of materials at disposal sites.

17. There are three primary considerations that must be evaluated in selecting an environmentally acceptable disposal method for a contaminated sediment. These are the contaminating materials present, the properties of the sediment, and the fate of the sediment-bound contaminant under the physical, geochemical, and biological conditions of the disposal alternatives.

18. Different contaminants do not always respond similarly to an altered biological or physicochemical condition of a soil or sediment-water system. Thus, most of the contaminants must be considered

individually. Also, the properties of the sediment will influence the fate of a contaminant at both the dredging and disposal site. The most complex of the three considerations is the influence of the physico-chemical conditions associated with the selected disposal alternative on controlling release or immobilization processes. These variables and how they interact to affect the fate of contaminants at disposal sites will be discussed in paragraphs 77 to 228.

19. Environmental impacts of contaminated dredged material disposal must be considered with time. There may be initial, intermediate, and long-term effects. Initial release and uptake of contaminants have received the most research attention. Short-term impact is usually thought of in terms of acute toxicity or stress occurring concurrent and shortly after disposal operations. There is less information available on intermediate and long-term effects. Intermediate effects, if any, represent a transitional impact that is difficult to define and evaluate. Long-term effects tend to be chronic except where there is gradual toxic material accumulation in food chains to excessive levels. It is unlikely that a significant environmental impact would be overlooked if initial and long-term contaminant releases are considered. This report will focus on initial and long-term impacts.

20. Another important question in selecting environmentally sound disposal methods for contaminated sediments is whether the goal should be: (a) to contain contaminants to minimize any possible adverse influence outside of the disposal area or (b) to encourage maximum dispersion of contaminants to hopefully dilute all toxic materials to harmless levels in all compartments of the environment.

21. Scientists concerned with environmental contamination differ on the desirability of containment versus dispersion for contaminated sediments. For example, some argue that trace levels of all potentially toxic metals occur naturally in every terrestrial or aquatic ecosystem and that the small increase in levels associated with wide dispersion of polluted dredged materials will result in an insignificant increase in levels and no adverse impact. Others argue that any increase,

regardless of how small, may exert stress on biological communities which have developed at some lower pollution level and ultimately result in some alteration of that community. It should be noted that disposal methods to encourage maximum dispersion and dilution of contaminated sediments are being employed. The rationale is that dispersion and transport of these contaminated sediments by natural currents in high-energy surface waters will result in their gradual dispersion where dilution to background levels will occur.

22. It is beyond the scope of this report to evaluate the merits of these opposing viewpoints. Indeed, environmental and ecological research methods have not developed to the point to answer these questions definitively for the majority of biological communities. However, in developing a guidelines manual to assist in selecting environmentally sound disposal methods for contaminated dredged sediments, a decision must be made regarding these opposing viewpoints. This guidelines manual was developed with the premise that containment to immobilize toxic substances at the disposal site should be the goal.

23. Electing to contain contaminants bound to dredged sediments is not meant to be a rejection of the idea that dispersion is always inappropriate. It is simply recognition that toxic substances can cause chronic and acute effects on organisms; threshold levels resulting in no ecological stress are not known with certainty for most ecosystems; and containment is a more cautious approach to managing potential environmental threats until such time that more information is available. This approach is compatible with the rather strict environmental protection policies of most state, Federal, and international regulatory agencies. It should be noted that regulatory criteria do not specify that no adverse impact may occur at designated disposal sites. Present criteria are designed to protect the environment outside of the disposal site.

24. A distinction should be made between containment and confinement. Confinement refers to maintaining the physical integrity of the bulk solids to minimize dispersion of dredged material. An example is

subaqueous disposal from barges into a low-energy hydraulic regime where stable mounds of dredged material will result. Another example is upland disposal in diked enclosures. Although confined, it is possible for some quantity of contaminants to move in aqueous form from the disposal site by diffusion and bioturbation from the subaqueous site or by dewatering effluents or leaching in the case of upland-applied material. Containment refers to a more rigorous method of confinement where contaminant movement subsequent to confined solids deposition is restrained. With few exceptions, absolute containment is usually not possible. Thus, at best, efforts at containment usually result in some release of a small proportion of the total contaminants present which will disperse in the environment, but within levels which can be safely assimilated or immobilized by natural regulatory processes. Presumably, this type of minimal release will be environmentally acceptable.

#### Scope and Limitations

25. The most obvious restriction of this manual is that it only pertains to the environmental aspects of dredged material disposal. Any disposal project must include economic and technological as well as environmental considerations. While the dredging industry can accurately assess the economical and technological requirements of a proposed project, a comprehensive method for evaluating the environmental impact of all possible disposal alternatives has not been available. Only recently, primarily as a result of the DMRP studies, has sufficient information become available to understand processes affecting sediment-bound contaminants under different disposal methods and to estimate potential environmental impacts. Thus, this manual is designed to supplement traditional methods for determining the feasibility of various disposal methods by evaluating possible environmental impacts.

26. A limitation in selecting environmentally sound disposal alternatives is the availability of standardized criteria testing and mixing zone calculations for some disposal methods and the lack of suitable evaluative procedures for other methods. Although criteria

for determining the environmental acceptability of dredged material disposal by either ocean or freshwater subaqueous disposal have been developed, implemented, and are being updated periodically, no such criteria have been developed for evaluating the potential environmental impact of land disposal. As a consequence, there are no standardized quantitative methods for evaluating the potential environmental impact of upland disposal. Sufficient information is available, however, to identify interactions between contaminants, sediment properties, and long-term physicochemical conditions associated with upland disposal methods which likely result in contaminant release.

27. Existing criteria testing procedures are based on an "action level" approach rather than on an estimate of the degree of impact expected. In developing this guidelines manual, it was also impossible to quantify the parameters that must be considered in order to estimate the degree of adverse impact associated with each disposal alternative. Thus, the approach taken in this manual is to bring to the attention of a project manager the important parameters that should be considered in selecting environmentally acceptable alternatives and to qualitatively discuss how these parameters should be considered. Each alternative in a list of potential disposal alternatives, therefore, cannot be individually ranked with respect to other alternatives. Instead, the various alternatives will be discussed according to relative risk levels.

28. In addition to the sections on selecting acceptable disposal alternatives, a section is included on supplemental management practices which can be applied to many of the disposal alternatives. These practices, when applicable, provide additional flexibility to the process of selecting and managing environmentally acceptable disposal alternatives. In some cases, the environmental risk of a marginally acceptable disposal alternative can be reduced by proper management where optimum disposal methods are not feasible for economic or technological reasons.

29. The approach described above in developing recommendations for selecting and managing environmentally acceptable disposal methods for contaminated sediments provides considerable flexibility to the

decision-making process. It also places considerable responsibility on the project manager to evaluate the parameters of the proposed project in terms of the suggestions in this guidelines manual. Due to site-specific differences associated with each project and all the various parameters affecting the fate of contaminants, a series of parameter levels cannot be incorporated into a mathematical model to estimate the degree of impact associated with each disposal alternative. It is therefore believed that this flexible approach is of more value than a rigid, uncompromising set of recommended disposal alternatives based on some numerical consideration of limited parameters of typical dredging and dredged material disposal projects.

30. It is recommended that the project manager of a proposed dredging project use this guidelines manual in conjunction with technical, biological, and perhaps environmental specialists familiar with the site-specific aspects of the proposed project when considering the recommendations of this manual. This is especially important for the supplemental management practices section which briefly describes management designed to further reduce the environmental impact of some disposal methods.

PART II: SELECTION OF ENVIRONMENTALLY ACCEPTABLE DISPOSAL  
ALTERNATIVES FOR CONTAMINATED SEDIMENTS

Initial Considerations of the Selection Process

Identification of contaminated sediments

31. Identifying a contaminated sediment is the first step in planning a dredging project to minimize adverse environmental impacts. Once a sediment has been identified as contaminated, the degree of contamination must be evaluated and the potential impact estimated for a given disposal alternative. It is beyond the scope of this manual to present methods for identifying contaminated sediments. Other guides are available for this purpose. Also, it is beyond the scope of this manual to indicate the levels of contamination which warrant consideration in estimating the degree of potential chemical impact of a proposed disposal alternative. Disposal of a dredged material containing high levels of toxic substances such as mercury or cadmium is clearly a greater risk than disposal of a material which has accumulated a low to moderate excess of these materials. However, procedures are not currently available for quantifying the level of contamination as a means of evaluating risk.

32. The purpose of this guidelines manual is to indicate the relative environmental risk associated with the various possible disposal methods for contaminated sediments. Determination of the presence and degree of contamination is to be established by appropriate methods prior to turning to this manual for guidance in selecting environmentally safe disposal methods.

33. Because the sediment of a proposed dredging project has been identified as contaminated does not necessarily mean that the disposal alternative and management practices giving the most rigorous containment of contaminants must be selected. In many cases, the extra expense and technical problems associated with an optimum disposal

alternative may not be justified for the additional environmental protection given over another less rigorous but still environmentally acceptable alternative.

34. There are standardized procedures for determining contaminant release, the probable impact on selected biological populations, and the expected dilution of released contaminants at an open-water disposal site (Environmental Effects Laboratory, 1976; USEPA/CE, 1977). These procedures are useful for identifying potential problems with contaminants at subaqueous disposal sites. With some modification or appropriate interpretation, some of these procedures may offer guidance for dealing with potentially toxic materials in initial dewatering effluents from intertidal and upland confinement sites.

35. Also, there are several state and Federal water quality criteria for both marine and fresh waters used for biological purposes as well as groundwater and drinking water standards. These criteria specify acceptable total levels of many contaminants in surface waters. Many of these criteria must be met for wastes and dredged material to be legally dumped in open water. Most of these criteria specify total concentrations and are based on bioassays using soluble levels of toxic substances to determine acceptable safe concentrations. Unfortunately, their scientific applicability to dredged material disposal is not clear as most of the contaminants in surface water from dredged material disposal are associated with the solid suspended particulate phase. It is difficult to compare the availability of contaminants bound to the solid phase with soluble levels.

36. The above-mentioned procedures are practical only for identifying short-term impacts on water quality at a dredged material disposal site. At present, there are no such standardized methods for evaluating long-term potential impacts of either subaqueous, intertidal, or upland disposal methods.

37. It is especially important to note that results of standardized criteria testing for subaqueous disposal cannot be applied to all disposal methods. For example, environmental interpretation of a

negative (no release) elutriate test result should not be used to predict long-term release under upland disposal conditions. Serious adverse environmental impacts could result from misapplication of existing criteria tests.

38. The permit applicant and appropriate regulatory agencies are ultimately responsible for determining the contamination status of the sediment of a proposed dredging project and deciding how best to minimize adverse environmental impacts associated with contaminated sediments. Site-specific information about the waterway and potential sources of contamination should be utilized to anticipate the presence and extent of contamination problems expected. The total concentrations of commonly encountered potentially toxic or nuisance substances should also be determined. With proper interpretation, this can be used as an inventory to determine what potential toxic substances are present above background or ambient levels. Appropriate criteria testing must be used to get an estimate of contaminant release for alternatives where this testing is applicable.

39. In summary, the applicant and regulatory agencies are responsible for: 1) determining if the sediments of a proposed project are contaminated, 2) determining the presence of an environmental threat associated with disposal of the dredged material, 3) conforming with environmental discharge guidelines and criteria, and 4) selecting disposal methods and implementing management practices which will minimize adverse environmental impacts. This guidelines manual addresses the last responsibility listed above. It is designed to point out problem areas and the relative environmental risk associated with the various possible disposal alternatives to assist in selecting environmentally acceptable disposal methods.

#### Role of dredged material properties in selecting disposal alternatives

40. In addition to the properties of the contaminant, the properties of the dredged material containing the contaminant are important

in determining acceptable disposal methods. Optimum disposal of dredged material depends on a knowledge of the chemical and physical properties of the dredged material. Dredged materials that are high in potentially toxic substances or which contain low amounts of these substances that may be bioconcentrated or bioaccumulated should be disposed of in such a way that contact with the environment is minimized. On the other hand, some dredged material, because of its chemical or physical properties, may have valuable uses for landfill, habitat development, or for other purposes. Some dredged materials react very little with the contaminant, and the major consideration in selecting a disposal method is the properties of the contaminant itself. Such an example would be in the disposal of contaminated sandy material in which there is little reaction between inert quartz surfaces and the contaminant. Some dredged materials are very reactive with the contaminant, and the nature of the reaction should be considered in choosing a disposal method. There are a number of readily identifiable properties of dredged material that affect the reactions and availability of various contaminants, and this section deals with these properties. Some of these properties can change when the sediment is moved from one type of environment to another, while other properties are not affected by changes in water content, aeration, or salinity.

41. The major sediment properties that will influence the interaction between dredged material and contaminants are type and amount of clay, cation exchange capacity, organic matter content, pH status of the sediment, the amount of active iron and manganese, oxidation-reduction conditions, and salinity. Much of the dredged material removed during harbor and channel maintenance dredging is high in organic matter and clay and is both biologically and chemically active. It is usually devoid of oxygen and may contain appreciable sulfide. Potentially toxic metals and organic chemicals are more likely to accumulate in harbor and channel sediments in urban areas and near industrial sites. The behavior of contaminants in sediment removed from such sites

is more difficult to predict than is the case for materials that are less active biologically and chemically. The following discussion deals with the specific properties of dredged materials that affect contaminant behavior and the general nature of the reaction with the major types of contaminants.

42. Clay content. The higher the clay content and the more finely divided the clay particles, the higher is the adsorptive capacity of the sediment for potentially toxic metals and organic chemicals. The exposed surface area of the particles is directly related to the fineness of the particles, and much of the bonding of contaminants to sediment is a surface reaction.

43. Clay type. Certain types of clay are much more reactive with both metal and organic contaminants than others. The shrinking and swelling montmorillonite type clays have a high net negative charge and a large amount of internal adsorptive surfaces that make them especially reactive with metals. The more inert nonswelling kaolinite type clays do not have as great a net negative charge nor as large an adsorptive surface area as the montmorillonite clays. Clays usually react with metal ions by adsorbing them onto these negatively charged surfaces as discussed in the next section. Metals can also be fixed in a more nonreplaceable form by moving within the lattice structure of the clays.

44. Cation exchange capacity. The net negative charge that is a property of all clays gives rise to the capacity of clay surfaces to adsorb or fix in an exchangeable form all positively charged ions or cations. Since most potentially toxic metals occur in a cationic form, this is an important property in removing these metals from solution. Cations held in this form can be displaced by other cations. Thus adsorbed toxic metal cations may be moved into solution by an excess of another cation, such as the sodium ion in salt water, or by an increase in acidity of the sediment caused by sulfur oxidation or other causes. A high cation exchange capacity material will thus remove potentially toxic metal cations from solution and decrease their

chemical and biological availability, but can also cause a long-term release of adsorbed toxic metals from this exchange reservoir to the interstitial water.

45. Organic matter. Organic matter in the dredged material is one of the major components determining the chemical behavior and biological toxicity of metals and organic compounds. The amount and form of organic matter largely determine its effect. Relatively undecomposed plant material is not very reactive, while humus, the residue or organic materials in sediment after it undergoes decomposition, can bind both metal and organic compounds into forms that are not readily released. The higher the content of humus, the higher is the capacity to remove toxic materials from a biologically active form.

46. In addition to the large molecular weight humus fraction, part of the organic matter in many sediments is in a low molecular weight fulvic acid form. Fulvic acid has a much greater solubility in water than does humus, and toxic metals that have reacted with this fraction are likely to be in solution in concentrations much higher than they would be in the absence of this material. Soluble potentially toxic metals complexed with fulvic acid, however, may not be as toxic to organisms as the soluble inorganic forms of the element.

47. The reactivity of organic matter with metal cations is due to two major types of reactions. Humus has a net negative charge similar to that of clays, and the positively charged cations are adsorbed in an exchangeable form at the site of the negative charge. Also, both the humic acid and fulvic acid fractions are able to bind or complex cations in a more permanent bond because of the presence of complexing chemical groups in the organic matter. In the humic acid fraction, the complexed cation is insoluble and not very reactive; in the fulvic acid fraction, the complexed cation is soluble and very mobile.

48. pH. The pH of dredged material has both direct and indirect effects on the way plants and animals are affected by disposed dredged material. A direct effect is that the dredged material can be too

acid or too alkaline to favor good plant growth. The indirect effect of pH is seen largely through an increase in concentration and activity of potentially toxic metals at low pH values and through an increase in free ammonia at high pH values. In addition to this largely chemical effect, the pH of sediment also influences microbiological activity such that reduced activity occurs if the sediment is either too acid or too alkaline. Microbial degradation of toxic organic compounds can also be affected by pH.

49. The pH becomes a problem when the dredged material has values below about 5 or above 8.5. High pH is normally due to an excess of alkali, either sodium or potassium hydroxide and carbonate. Some sediments, especially those with high clay content and high cation exchange capacity, can neutralize large amounts of alkali without a very high pH rise, while low-clay sediments respond to small additions of alkali. High pH from alkali makes the sediment unsuitable for most plants and makes the sediment very slow to dry and wet because of a decrease in water movement caused by a deterioration in the structure of the sediment.

50. Acid conditions below pH 4 are generally caused by the oxidation of sulfide and pyrite (reduced sulfur materials) to sulfuric acid. This process is discussed in detail in paragraphs 222 to 228. Most anaerobic sediments, even those containing appreciable sulfide, are nonacid until exposed to oxygen. Depending on the buffering capacity of the sediment and the amount of oxidizable sulfide, exposing the dredged material to oxygen can result in the development of extremely acid conditions.

51. Iron and manganese oxides. Another important chemical property of dredged material that will affect its behavior after dredging and disposal is the content of reactive iron and manganese oxides. Iron oxides in particular react with toxic metal cations to remove them from soluble forms, although under certain conditions, the metals can be released again to the interstitial water. In sediments where the oxygen supply has been depleted, a large fraction of the

iron oxides may be reduced to ferrous hydroxide form by specialized bacteria, a much more soluble form of iron. Such a reduction reaction releases potentially toxic metals that are bound by the insoluble oxidized iron oxide (ferric oxide). When the sediment is reoxidized, part of the toxic metals in the sediment can be coprecipitated with the insoluble iron oxide and removed from solution. Freshly precipitated iron oxides are reported to be especially effective in immobilizing potentially toxic metals compared to aged iron oxides. The greater activity of freshly formed oxides may be particularly important when reduced sediments are mixed with oxygenated surface waters.

52. Alternating reduced and oxidized conditions also make the iron oxide surfaces more reactive and metal ions as well as other components are more readily adsorbed on these reactive surfaces. In general, however, the greater the content of active iron oxide in the sediment, the greater is the immobilizing capacity for potentially toxic metals.

53. Oxidation-reduction conditions. One of the most important properties of sediment that controls the behavior of contaminants is its oxidation-reduction status. Oxidation-reduction conditions can be defined chemically or microbiologically. Chemically, oxidizing conditions are characterized by the presence of oxygen and other oxidized inorganic components of the sediment such as nitrate, ferric iron, manganic manganese, sulfate, and carbon dioxide. Reduced conditions occur when oxygen and the other oxidized materials are absent and their reduced counterparts are present. These include ammonium, manganous manganese, ferrous iron, sulfide, and methane. Microbiological processes are responsible for conversion of most soil components from oxidized to reduced forms. The reduction reactions never take place as long as oxygen is present, but the absence of oxygen causes microorganisms to reduce the other oxidized components of the soil. When oxygen reenters the sediment, the reactions are reversed and the reduced forms are converted to oxidized forms. Both chemical and microbial reactions are involved.

54. Both chemical and microbiological oxidation-reduction conditions can be characterized by the oxidation-reduction or redox potential of the sediment. Redox potentials of +500 millivolts or higher represent oxidizing conditions, while redox potential values of -200 millivolts or lower represent very reducing conditions. These are near extreme conditions and sediments can be found that have values over the entire redox range. The sequence of reduction of oxidized compounds follows the order of nitrate, manganic manganese, ferric iron, sulfate, and carbon dioxide as the redox potential decreases from +500 millivolts to -200 millivolts or lower resulting in the formation of reduced components such as molecular nitrogen, manganous manganese, ferrous iron, sulfide and methane, respectively. A knowledge of critical redox potentials at which these compounds become unstable is useful for characterizing the intensity of reducing or anaerobic conditions in soils. A detailed account of these redox potential boundaries is given elsewhere (DeLaune, Patrick, and Brannon, 1976).

55. The fixation of potentially toxic substances from dredged material as well as their release will be affected by oxidation-reduction status of the material after disposal. If the disposed sediment is oxygen free and chemically reducing, reactions of the potentially toxic metals and some pesticides will be different than under oxygenated conditions. For example, metals bound by sulfide in oxygen-free, high sulfide sediments will very likely be mobilized to some extent if the sediment is placed into an oxidized environment where oxidation of sulfide occurs. A few potentially toxic materials may be mobilized under certain conditions when a reduced dredged material is oxidized by processes other than sulfide oxidation. Often, the different processes immobilizing potentially toxic metals under reducing and oxidizing conditions tend to be complementary. For example, oxidation of reduced sediments containing appreciable sulfide may release metals from the insoluble sulfide forms, but these metals may then be immobilized by reaction with iron oxides. Depending on the amount of sulfide

present and other sediment properties, a significant acidification of the sediment may occur if the sediment is oxidized. Thus, in order to properly predict whether a sediment will release contaminants following oxidation or reduction, information will be needed on the chemical properties of the sediment as well as on the aeration status of the material after disposal.

56. The persistence of pesticides in sediment may also be affected by the aeration status after disposal. As will be discussed later, research has shown that degradation of several pesticides is greater under anaerobic conditions than under aerobic conditions.

57. Most fine-grained maintenance dredged sediments are reducing. When subjected to dredging and open-water disposal, the bulk of the dredged solids, which contain most of the contaminants, will remain reducing during dredging and subsequent to disposal if the dredged material remains undisturbed at the disposal site. Chemically reactive components of contaminated particulates which are resuspended in oxidized water columns may oxidize affecting contaminant mobility. Disposal of reduced sediments in a high-energy hydraulic regime may result in substantial, long-term resuspension and transport of contaminated particulates in an oxidized water column. The bulk solids of reduced sediments deposited upland where drainage will occur may gradually become well oxidized, affecting the mobility of sediment-bound contaminants.

58. Salinity. The salinity of dredged sediments has an influence on the flocculation of the material and on the behavior of heavy metal contaminants in the material. Clay and organic colloids (fine particulates) are flocculated when they come in contact with a solution of a neutral salt such as sodium chloride in sea water. Removal of suspended particulates from the water column improves the quality of the water since many of the contaminants are associated with the colloids.

59. The sodium ion ( $\text{Na}^+$ ) in salt water also has a specific effect of displacing other cations from the exchange complex on the colloids into the solution or interstitial water. Movement of metal cations

from an adsorbed form to a solution form increases their chemical activity, although experiments have shown that the toxic effect of some heavy metals is greater in a freshwater system than in a saltwater system.

#### Disposal alternatives

60. The major disposal alternatives included in this report are subaqueous (open-water) disposal, application to intertidal sites, and upland application. These categories differ primarily in the biological populations exposed to the contaminated sediments, oxidation-reduction conditions as a consequence of submergence and duration of submergence, and transport processes potentially capable of removing contaminants from dredged material at the disposal site. Both intertidal and upland application may be for disposal or productive use purposes.

61. Several subcategories will be included for each major disposal alternative. These subcategories represent the majority of disposal methods available, and each has some specific influence on the environmental fate of contaminants in dredged sediments. Each of the disposal methods will be described in terms of general processes affecting contaminants. This will provide background information on how evaluations are made on the potential environmental risks of various disposal methods for each contaminant (Paragraphs 77 to 228). The disposal alternatives considered in this report are given in Table 1 and are discussed in the following paragraphs.

62. Subaqueous disposal. Subaqueous disposal is the deposition of dredged material at an open-water site where the material will not become emergent. Dredging can be by hydraulic or mechanical methods. A possible short-term fate of sediment-bound contaminants is the release of these materials to surface waters in either dissolved or suspended particulate forms during transport through the water column and initial settling. Intermediate and long-term release of contaminants from stable bottom deposits of dredged material may occur as a

Table 1

Disposal Alternatives Considered in This Report

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Subaqueous Disposal

- A. Disposal not in conflict with important economic or ecological productivity
  - 1. Confined
    - a. Mounded (isolated) in a stable fashion
    - b. Confined in a depression and covered with a layer of un-contaminated material.
  - 2. Unconfined - wide dispersal with apparent loss from disposal area
- B. Application to especially productive aquatic systems

Application to Intertidal Sites for Disposal or Productive Use

- A. Habitat development
  - 1. Confined by boundary structure - resistant to erosion
  - 2. Unconfined - some erosion and some consolidation (i.e., mudflat, marsh-island complexes)
- B. Nonbiological purpose
  - 1. Shoreline stabilized/modification (to include subaquatic discharge with fastland development)
  - 2. Confined by boundary structure

Upland Application

- A. Long-term confinement for disposal purposes only
    - 1. Poned (no drainage)
    - 2. Nonponed (managed to enhance dewatering)
  - B. Interim confinement for contaminated sediments for dewatering, consolidation, and possibly treatment prior to transport and reuse for productive purposes
  - C. Unconfined upland - not specifically intended for habitat development, but will be subject to biotic colonization with time
  - D. Habitat development - application for specific biological purposes
  - E. Agricultural soil amendment and land reclamation
  - F. Use for fill and other construction/engineering purposes
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result of diffusion from interstitial water (pore water) to surface waters and direct uptake by benthic organisms or vascular rooted plants in the case of very shallow disposal sites.

63. The physicochemical conditions (pH, oxidation-reduction conditions, and salinity) of the contaminated sediments at the dredging and disposal site are important to the mobility and bioavailability of most contaminating substances. Many contaminated sediments will be moderately to strongly reduced with pH levels ranging from 6.5 to 8.5. Organic matter and clay content are often appreciable. These factors contribute to sediments being effective sinks for contaminants initially. Many potentially toxic metal contaminants tend to be slightly more mobile under oxidizing conditions than reducing conditions. Although pH may change, greatly affecting mobility of contaminants when some dredged materials are oxidized under upland conditions, little change in pH occurs upon oxidation of suspended particulates or surface sediment horizons under subaqueous conditions because of the usual high buffering capacity of sediment-water systems.

64. Salinity is an important physicochemical parameter affecting both mobilization and apparently the biological availability of metal contaminants. Though not all studies show this, the deposition of freshwater sediments at saline disposal sites often results in increased solubilization of many metals. This is due to mass action of the abundant sodium, magnesium, and calcium ions of the seawater in displacing the metals adsorbed to mineral and organic cation exchange sites and to greater formation of soluble inorganic complexes due to the high inorganic anionic ligand content of the seawater. On the other hand, increased salinity should favor flocculation of suspended particulates minimizing contact with surface waters. Observations at some disposal sites suggest that benthic organisms are more selective and restrictive in metal accumulation as salinity increases such that there is an inverse relationship between salinity levels and toxic metal uptake. These points will be documented elsewhere. Thus the effects of

increasing salinity on mobility and biological availability differ depending on a number of interacting factors.

65. When fine-textured dredged sediments are initially reduced and near neutral in pH as is commonly the case, deposition of the dredged material in quiescent waters will result in stable mounding and favor maintenance of initial physicochemical conditions. Where bulk sediments maintain initial physicochemical conditions, there may be relatively little change in chemical transformations of contaminants, and they will remain relatively immobile.

66. Unstable bottom deposits may result in an additional transport mode and changes in physicochemical conditions of dredged material. Bottom deposits of dredged material may be unstable due to natural currents, ship wakes, or storm currents. These currents may result in bulk transport or in gradual dispersion of the deposited sediments by sediment resuspension. Wide dispersion of contaminated sediments may impact the environment out of the designated disposal site. In many cases, this may be undesirable. In some cases, dispersion and mixing with uncontaminated sediments may effectively dilute the contaminated material to safe levels. For contaminants that are especially hazardous and subject to potential bioconcentration and accumulation, disposal methods which maximize dispersion may represent a high environmental risk. Long-term resuspension of initially reduced sediments in oxidized water columns or dispersion and resettling as thin layers on surface sediments of areas adjacent to the disposal site may result in a change in physicochemical conditions of the contaminated material, release, and possibly transformations of potentially toxic metals to more bioavailable forms. Bioturbation may also cause mixing of surface sediments possibly affecting the near-surface physicochemical conditions. Thus the energy regime of a subaqueous disposal site may influence both the transport of contaminated solids and chemical transformations affecting the release of contaminants from the solid phase.

67. Holliday (1978) discusses research on the transport of dredged sediments at subaqueous disposal sites. Four distinct zones in both

oceans and estuaries were identified which vary in their energy regimes. Consideration of the expected hydraulic energy regime of potential disposal sites can be useful in selecting sites where stable mounding and minimal dispersion will occur.

68. To limit a potential or expected adverse impact to a designated disposal site, heavily contaminated sediments should be confined and potentially toxic materials contained within the sediment. Although this may require subaqueous confinement structures, disposal in quiescent waters also constitutes confined disposal as stable mounding will occur. If sediment confinement and toxic material containment are achieved, impacts, if any, would be limited to initial effects during settling and reconsolidation within the designated disposal site. These potential short-term effects can be estimated with the standard elutriate test and elutriate concentrations compared with appropriate surface water quality criteria after considering results of initial mixing zone calculations (Environmental Effects Laboratory, 1976). Bioassay procedures are also available to help estimate the potential impact of subaqueous disposal on benthic organisms (Environmental Effects Laboratory, 1976; USEPA/CE, 1977).

Mounded subaqueous disposal not in conflict with important economic or ecological productivity. In a low-energy hydraulic regime unaffected by tidal or storm currents, stable mounds of dredged material may form which will effectively confine contaminated particulates. Transport by diffusion from interstitial waters to surface waters from a typically reduced dredged material should be minimal. If the overlying water column is oxidized, chemically adsorptive hydrous oxides of iron may form in thin oxidized surface layers of many dredged material mounds to further minimize transport by diffusion. The laboratory work of Chen et al. (1976) suggests that most trace metals (with the exception of iron and manganese) are released across a sediment-water interface to a slightly greater extent under an oxic water column compared to an anoxic water column. It is likely this release would be greater if it were not for the metal scavenging effects of oxidized iron particulates. This configuration of an oxidized

sediment horizon comprising the surface of a stable dredged material mound where the bulk sediments remain reduced will be most effective in immobilizing contaminants at the disposal site. Dredging the most contaminated sediments of a project first (usually inner harbor material) and covering them with cleaner dredged materials (i.e. from outer harbor maintenance dredging) will help in isolating highly contaminated sediments (See Paragraph 233).

In a high-energy hydraulic regime, stable mounding may not occur, and contaminants are likely to be transported out of the original site by mass movement of resuspended solids and possibly transformed to more mobile and bioavailable forms.

Confined disposal in subaqueous depression not in conflict with important economic or ecological productivity. Where deep subaqueous depressions are available, such as ocean or inland lake depressions, borrow pits resulting from dike construction for flood protection (Broughton, 1977), or deep lakes resulting from sand dredging, disposal of contaminated sediment into these depressions may be the most effective confinement method available. If the depression is isolated from currents and the contaminated dredged material covered with a layer of clean material (See Paragraph 233), this method will effectively contain potentially toxic materials, isolating them from the environment. Other than incapsulation within impermeable manufactured barriers, this method is probably the most effective containment procedure available. Suitable depressions will likely not be available for most dredging projects. For sediments heavily contaminated with certain toxic materials, however, the environmental advantages of this alternative may justify additional economic and engineering efforts to transport the material to such sites.

Mechanical dredging may offer both short- and long-term advantages over hydraulic dredging in confining contaminated sediments. Upon release at the disposal site, mechanically dredged sediments tend to be more cohesive, mixing less with the water column and resulting in more rapid consolidation on the bottom.

Unconfined subaqueous disposal not in conflict with important economic or ecological productivity. Unconfined subaqueous disposal implies the material is not physically restrained and that dispersal with loss from disposal areas will occur. This alternative differs from confined subaqueous disposal only in that the energy regime at the disposal site is sufficiently great to transport or rework the sediments. This method of disposal should be avoided for sediments contaminated with high levels of especially toxic materials. For sediments with high levels of nontoxic contaminants such as nitrogen, this method may be acceptable for many dredging projects.

It should be mentioned that unconfined disposal has been used for contaminated sediments where environmental priorities have placed recontamination of bays and estuaries over the movement of toxic materials into the open ocean. In San Francisco Bay, contaminated sediments are often intentionally dumped into high-energy zones where predominating currents will move the material away from the bay toward the open ocean.\* Presumably, dilution of contaminants by the ocean is considered acceptable and more environmentally sound than possible recontamination of the dredging area or other biologically productive nearshore regions of the bay.

Disposal to especially productive aquatic systems. The application of sediments contaminated with toxic materials to especially productive aquatic and benthic systems should be avoided.

69. Application to intertidal sites for disposal or productive use. The usual high nutrient content of fine-grained sediments and their desirable physical properties for establishing plant populations essential for habitat development make many dredged sediments a potentially valuable resource. However, some intertidal sites are high-energy systems. At these sites, the potential is great for reworking and transport of deposited sediment materials by normal wave or tidal

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\*Personal communication: John Sustar, CE, San Francisco District.

currents and especially by storm currents (Vincent, 1978). If confinement of dredged sediments contaminated by highly toxic materials is the disposal goal from an environmental perspective, intertidal deposition at especially high-energy sites for either disposal or productive uses should be examined carefully. The environmental risk of intertidal disposal of contaminated sediments would be minimized where stringent mechanical confinement methods are used (See Paragraph 236), where the contaminating substances are nutrients which can be managed or for which dilution is acceptable, or where low-energy intertidal sites are found such that intertidally placed dredged material is expected to remain in place. For example, certain intertidal areas of San Francisco Bay are reported to be low-energy areas as evidenced by the continuous accumulation of sediments by natural processes (U.S. Army Engineer District, San Francisco, 1977). Even in these cases where long-term physical confinement of contaminated solids may be possible, it is important that the potentially toxic substances not be released to interact with biological populations.

70. Contaminants are subject to several modes of transport from intertidal sites. Unless confined disposal and control of suspended solids in dewatering effluents are used for a contaminated sediment, there may be extensive initial loss of contaminated suspended particulates into adjacent surface waters, especially where hydraulic dredging is used, which is the normal practice. Though the biological availability of particulate bound contaminants is difficult to evaluate but thought to be low, many surface water quality criteria are based on total content rather than soluble contaminant concentration making suspended solids control important. Nearshore waters are often important spawning, nursery, and habitat areas for aquatic and benthic organisms, and contamination of these areas should be avoided. In high-energy zones, there may also be extensive long-term erosion of contaminated solids from intertidally applied dredged material. Leaching by gravitational flow of water into subsurface aquifers and eventually into adjacent surface waters is also a potential problem. Entry into food

webs by plant uptake is another transport mode which may prevent containment of toxic substances though mechanical confinement may be accomplished. Except where effective confinement is used, the high-energy regime of some intertidal sites and the potential for erosion of contaminated particulates, leaching, or uptake and detrital transport of plant-bound contaminants into adjacent surface waters may result in similar exposure of the nearshore aquatic and benthic organisms to contaminants as would occur with open-water disposal in the area. Fortunately, habitat development or marsh creation projects are usually not planned for high-energy areas for reasons other than the potential adverse impact associated with mobilization of contaminants.

71. The initial and long-term physicochemical environment of dredged materials at upland or low-energy subaqueous disposal sites can be predicted reasonably well from knowledge of the dredged material properties and the properties of the original soil or sediment at the disposal site. The physicochemical environment of dredged material at an intertidal site can be more complex. Frequent flooding of typical fine-textured high-organic sediments will probably result in a thin surface oxidized layer overlying a deep anaerobic subsurface sediment layer. The depth and possibly the presence of the surface oxidized layer may vary with the frequency and duration of flooding cycles. An intertidal site subject to infrequent flooding may develop a much deeper oxidized layer. The oxidation-reduction conditions of a contaminated dredged material may have a profound influence on processes affecting the mobilization and immobilization of many contaminants. Plant populations, which are influenced by floodwater salinity, climate, sediment types, and flooding regime, may also influence oxidation-reduction conditions within the rooting zone and thus affect availability of contaminants.

Habitat development at intertidal disposal sites. Where a dredged sediment is highly contaminated with potentially toxic materials, especially those known to be relatively mobile and/or readily accumulated by organisms, intertidal disposal for habitat development should usually be avoided.

Dredged material confinement by a boundary structure at intertidal disposal sites. Where it is desirable to minimize movement of potentially toxic substances into adjacent waters and leaching and plant uptake are manageable problems (See Paragraphs 239 and 241), confined intertidal disposal may be an effective method for isolating contaminated sediments. In some cases, a contaminated sediment may be capped with a layer of clean material such that managed shallow-rooted plant populations will not mobilize plant available toxic substances. The effluent from dewatering a confined intertidal disposal site can be controlled to maximize suspended solids removal to prevent contaminated suspended particulates from moving back into adjacent surface waters (See Paragraph 240).

Unconfined application to intertidal disposal sites. This alternative presents a moderate to high risk for contaminated sediments at high-energy sites because of the great potential for physical transport and wide dispersion of contaminants in productive nearshore waters as previously discussed.

Intertidal disposal for nonbiological purposes--shoreline stabilization/modification. Although extensive biological colonization may not be planned for this type disposal alternative, there is a large potential for transport and release of contaminants in particulate or soluble form from the disposal site into adjacent surface waters unless retaining structures are constructed to minimize physical loss of contaminated solids during and subsequent to disposal. Unless this is done, sediments which pose an environmental risk for subaqueous disposal would present a similar risk if disposed of by intertidal methods in moderate- to high-energy systems. The immediate and long-term erosion of contaminated solids subsequent to this disposal method may result in mixing and contaminant release into surface water comparable to nearshore subaqueous disposal.

Intertidal disposal for nonbiological purposes, confined by boundary structure. This alternative is similar to contained disposal for intertidal habitat development except that habitat development is

not intended. Although habitat development may not be planned, it should be noted that intense biological colonization will likely occur by natural processes, making this alternative unsuitable for disposal of heavily contaminated dredged materials.

72. Upland application. As with subaqueous and intertidal disposal, the goal for upland applied contaminated sediments should be containment of potentially toxic materials to control or minimize potential environmental impacts. The possible transport mechanisms for contaminants from upland disposal sites include: (a) leaching into groundwater, (b) surface runoff of contaminants in either dissolved or suspended particulate form, (c) plant uptake and subsequent cycling through food webs, and (d) direct uptake by animal populations living in close association with soil and possibly by grazing animals which may ingest substantial quantities of soil solids.

73. Contaminants from upland applied dredged material can potentially affect more types of organisms than other major disposal alternatives. On the other hand, upland confined disposal sites can be designed and managed to effectively contain many contaminants. Man can be directly affected if subsurface aquifers or surface waters used for drinking purposes are contaminated and possibly by consumption of aquatic organisms from surface waters receiving input from upland disposal sites. Plants may accumulate excessive levels of some contaminants from upland disposal sites and thus contaminate food webs, affecting human consumers either directly or indirectly.

74. The physicochemical conditions of the dredged material at an upland disposal site may be altered substantially as a consequence of drainage of excess water. For some contaminants, this may result in marked changes in chemical mobility and biological availability. If a disposal site is managed to enhance dewatering or if drainage occurs readily, most excess salts associated with saline sediments may be removed within a reasonably short period in moderate to high rainfall areas. In addition to the usual succession sequence of plants which may colonize the site, salinity levels may have a short- to

intermediate-term effect in influencing plant populations. Saline dredged sediments may initially enhance leaching of metals from upland applied dredged material. Although salinity level may be an important short-term consideration, it will have no long-term effect as excess salts will eventually be removed by leaching.

75. At the molecular level, the oxidation-reduction processes associated with upland disposal are the same as those occurring at subaqueous and intertidal sites. An important difference is that the bulk dredged material solids may become well oxidized at upland sites, whereas only thin surface horizons and resuspended particulates may be subjected to oxidized conditions with most subaqueous and intertidal disposal methods. Except for long-term ponded facilities, most upland sites will be subject to gravitational drainage allowing atmospheric oxygen to penetrate deep into the material by gaseous diffusion. The rate of dewatering will vary depending on climate, dredged material properties, and design and management of the confinement facility. The rate, intensity, and eventual depth of oxidation of an initially reduced sediment will depend not only on the rate of dewatering, but also on the chemical, physical, and biological properties of the material. Because of the interacting factors affecting oxidation rates, it is difficult to predict short- and intermediate-term physicochemical conditions at an upland disposal site and the subsequent effects on mobility and availability of contaminants. However, that the initially reduced dredged material will ultimately oxidize at an upland disposal site will certainly affect the long-term mobility and biological availability of several contaminants.

76. In addition to changes in oxidation conditions, there may be substantial changes in the pH of upland applied dredged material as a result of redox potential mediated changes in certain chemical components such as iron and sulfur. The pH of calcareous sediments may change little or even increase as a reduced dredged material becomes oxidized. Noncalcareous sediments with considerable levels of chemically active iron may become moderately to strongly acid under oxidized

conditions. Sediments with high levels of total sulfide may become extremely acid. These pH changes are also important in regulating mobility and availability of many potentially toxic substances as well as the biological communities which may colonize the disposal site.

Ponded long-term upland confinement. This alternative should be considered only where mobile and very toxic contaminants are present at very high levels, subaqueous disposal giving stable mounding is not feasible, and dissolved forms of the contaminants are especially favored under oxidized conditions. This alternative would also be suitable where difficulty is encountered in removing contaminated suspended solids from the effluent of an upland confined facility to meet surface water quality criteria of receiving waters. Unless lined with an impermeable barrier, leaching of excess water may occur, and the acceptability of this method would depend on the mobility of the contaminants in the leachate. Obviously, this procedure can be considered only for comparatively small volumes of highly contaminated dredged sediments. Except for highly contaminated sediments, this alternative would be unattractive because of the extra capacity required to retain the large volumes of water associated with hydraulically dredged sediments. Although management problems are often encountered, this alternative does offer the advantage of an upland disposal method where initial physicochemical conditions of the dredged sediment will not change if leaching is controlled and ponding is maintained. This could be effectively used to immobilize some toxic materials within the disposal site where reducing conditions favor immobilization, but upland methods must be used. This method is also useful where upland disposal must be used, but oxidizing conditions would result in development of strongly acid conditions which would mobilize potentially toxic metals.

Nonponded, long-term upland confinement. Where upland disposal is being considered, this alternative is suitable for a larger total volume of dredged material and perhaps for more frequent applications. Since contaminants tend to be associated with the finer particle size fractions, it is important to employ the best available technology

to minimize suspended solid loads of initial dewatering effluents (See Paragraph 243). Uptake of toxic materials by organisms inhabiting this site must also be evaluated.

As a result of eventual drainage and subsequent oxidation of the bulk solids, long-term release of some contaminants to mobile and plant available forms may occur. In addition, noncalcareous dredged material with high levels of iron and sulfide may become strongly acid which can be detrimental to plant growth and subsequently enhance mobility of most metal contaminants.

Interim upland confinement. The short-term environmental concerns of this alternative are similar to those described above for ponded long-term confinement. Potential long-term environmental effects make this alternative more suitable for uncontaminated dredged materials. Reuse for many productive purposes would present an elevated environmental risk for many contaminated sediments compared to other disposal alternatives, except where excess nutrients can be managed for beneficial purposes.

Unconfined upland disposal, habitat development, or agricultural soils amendment. These alternatives will generally be less desirable for dredged materials heavily contaminated with toxic substances because of the implied wide dispersion of the sediments. Also, the expected change in physicochemical conditions may result in increased mobility and availability of many contaminants. The probable intense colonization by either managed or natural biological populations which may take up, concentrate, and recycle contaminants may also make these alternatives undesirable where toxic materials are involved.

Use for fill and other construction/engineering purposes. An advantage of this alternative is that intense biological colonization will not occur in most cases, limiting biological uptake and environmental cycling of toxic substances. For reasons discussed previously, leaching into groundwaters is a potential problem which must be evaluated before determining the acceptability of this alternative. If leaching of contaminating substances can be controlled or a nonleaching

contaminant is present, the dredged material may be covered with a layer of clean material effectively isolating the contaminants (See Paragraph 252).

Selection of Environmentally Acceptable Disposal Alternatives  
for Specific Contaminants

Mercury

77. Mercury is one of the most hazardous of the heavy metals. It is known to be toxic at relatively low concentrations. Uptake and accumulation resulting from mercury contamination have been documented for aquatic and benthic organisms, terrestrial plants, and mammals consuming contaminated food supplies. It is believed that uptake by aquatic organisms is predominately from water rather than from bio-accumulation in food chains. Although direct uptake from sediments may occur in benthic organisms (especially filter and deposit feeders), uptake from dissolved mercury may be the predominant mechanism for many benthos as well. Of particular relevance to contaminated dredged material, mercury accumulation from polluted sediments has been recorded for benthic organisms in some studies, while other studies have shown no such accumulation. Conflicting conclusions result from differences in experimental parameters, but there is no question about the potential threat of mercury-contaminated materials in the environment. Because of its demonstrated toxicity and potential accumulation by organisms, disposal alternatives for sediments contaminated with potentially hazardous levels of mercury should emphasize containment to isolate this toxic metal at the disposal site.

78. Mercury exists as many specific compounds in the environment and especially in sediment-water systems. Ionic mercury and many of its various compounds also exist adsorbed or complexed to mineral and organic solids of varying composition. Much of the total mercury is in these nonspecific chemical forms and is subject to transformations

affecting chemical mobility and availability. In addition to numerous inorganic compounds, methylmercury is an organic form that is especially hazardous. The short- and long-term mobilization of adsorbed and complexed forms of mercury will be affected by physicochemical conditions at a disposal site.

79. Mercury release from dredged material in laboratory and field studies. Baumgartner, Schults, and Carkin (1978) noted elevated mercury levels in the water column associated with dumping at a Puget Sound disposal site, but the release was transient and measured only at the point of dumping. Postdisposal testing showed reductions in interstitial mercury content compared to predumping levels and reference sites.

80. Elutriate tests on a number of sediments have shown substantial mercury release from very few sediments - most sediments did not release significant amounts (Brannon et al., 1976; Brannon, Plumb and Smith, 1978; G. F. Lee et al., 1975). Monitoring of subaqueous disposal operations at offshore sites in Texas showed occasional increases in water column mercury levels at various depths as the turbidity plume passed. Where these increases occurred, they were highly transient as the levels returned to ambient within minutes (G. F. Lee et al., 1975). In a laboratory study of 32 sediments representing a wide range of properties and pollution conditions, a very small mercury release was found for most sediments (Brannon et al., 1978). In related studies simulating long-term subaqueous disposal conditions, the elutriate test was related to net mass mercury release after 4 months while interstitial water analyses were related to mercury release after 4 and 8 months of leaching. In this work, it was concluded that the sediment-bound mercury was not released to water from the solid phase of any sediment material. The small releases observed were mercury from interstitial water. Disposal actually lowered mercury concentration in overlying water in all cases in long-term exposure studies.

81. Yoshida and Ikegaki (1977) concluded that even with high total mercury levels (greater than 200 mg/kg) in Minamata Bay sediments there may be no problem concerning mercury release from dredged material particles into the sea.

82. Lu, Eichenberger, and Chen (1978) studied loss of mercury and other metals from upland confinement sites. The total concentration of mercury in effluents from two sites was significantly higher than several regulatory criteria. The concentration of dissolved mercury was well below these criteria, and it was concluded the water quality impact would be negligible since most of the mercury was in the solid form. However, many regulatory criteria are based on total levels and do not consider biologically available forms. Mercury removal efficiency in particular was very closely related to suspended solids removal at both sites. Thus, it was suggested that increased detention times or treatment to enhance settling of suspended solids would be effective in reducing effluent mercury levels and that such treatments may be required to meet applicable water quality criteria.

83. In a study of influent and effluent levels of a number of water parameters at nine dredged material containment facilities representing upland, lowland, and island sites and a wide range of salinity conditions, Hoepfel, Myers, and Engler (1978) reported the average removal efficiency of total mercury was 46 percent. This was low compared to other metals studied. Effluent mercury in particular was thought to be associated with very fine ( $<0.45\text{-}\mu\text{m}$ ) particulate matter.

84. In laboratory leaching studies simulating vertical transport at upland confinement facilities, there was some release of particulate mercury and subsequent transport from the dredged material to the underlying soil interface attributed to physical scouring during the gravitational flow of water (Mang et al., 1978). Any soluble mercury detected was thought to be complexed as the elution of measurable dissolved inorganic mercury was thought to be impossible because of the efficiency of retention by sulfide solids and other adsorbent particulates present. Although a low-level mercury transport from dredged material into the underlying soil was noted, it was concluded that the impact of mercury leaching from upland confinement sites would be negligible in these studies. It should be noted that sediments in these column studies did not become well oxidized during the study period.

Substantial oxidation would eventually occur at many upland disposal sites.

85. Physicochemical effects. Mercury is strongly bound to particulates in sediment-water systems. As with most other contaminants, it tends to be associated with the finest particle size fraction. Coarse-textured, low organic matter sediments tend not to accumulate mercury. However, should such sediments become contaminated because of local waste discharge, this mercury may be more readily mobilized during dredging and dredged material disposal than would occur in more typical fine-textured sediments containing one to several percent organic matter.

86. Naturally occurring sediment humic materials are very effective in binding mercury (Gambrell et al., 1977a; Serne and Mercer, 1975; Feick, Johanson, and Yeaple, 1972a). In typical fine-textured materials containing one to several percent organic matter, this may be the predominant regulatory mechanism except in strongly reduced materials containing appreciable sulfide. Feick et al. (1972a) reported that sediments containing high levels of organic matter removed mercury from freshwater much more effectively than low organic matter sediments, and that mercury partitioning between sediments and water was  $10^4$  times greater for the high organic matter sediment.

87. Mercury forms extremely insoluble particulates with sulfide. In strongly reduced sediments containing sulfide, this regulatory process should be very effective in immobilizing mercury. However, many studies have shown that soluble interstitial mercury levels in sulfide-containing sediments, though very low, often exceed the predicted dissolved levels based on the solubility of mercuric sulfide. This may be due to the presence of relatively stable complexes with soluble organics and perhaps soluble polysulfides (Feick et al., 1972a; Mang et al., 1978; Lindberg and Harriss, 1974). Nevertheless, disposal environments where the presence of appreciable organic matter and sulfides are favored should result in the most effective containment of mercury such that minimal mercury will be released and transported if the dredged material is not subject to physical dispersion. This regulatory process should

be utilized to the fullest in selecting and managing disposal alternatives for dredged sediments highly contaminated with mercury.

88. Mercury adsorption by colloidal hydrous oxides is known to be an effective sink for soluble mercury. This regulatory process is most active in weakly acid to alkaline oxidized environments and may be especially effective for soluble mercury at the time reduced sediments containing appreciable reduced (ferrous) iron are mixed with oxygenated surface waters.

89. There is some conflicting information on the effectiveness of hydrous oxides in binding mercury under all physicochemical conditions. Serne and Mercer (1975) suggest this may be due to pH and chloride effects on inorganic mercury speciation. Although it is not appropriate to elaborate on the chemistry involved at this point, it should be mentioned that increasing pH probably favors hydrous oxide immobilization of mercury under oxic conditions. Also, increasing chloride (salinity) levels may decrease the effectiveness of hydrous oxide immobilization of mercury. Increasing pH will tend to compensate for the chloride effect.

90. In studies designed to look at pH and oxidation effects on selected chemical forms of mercury using low-level mercury-203 tracer additions, Gambrell et al. (1977a) reported a tendency for acid reducing and alkaline oxidized conditions to increase dissolved and exchangeable mercury in Mobile Bay sediment-water suspensions. These changes were small, though moderately acid, strongly reducing conditions and mildly alkaline, oxidized conditions did enhance levels of dissolved, complexed (nonionic) mercury in several of the materials. In sequential addition studies where up to several hundred  $\mu\text{g}$  mercury/g sediments were added, soluble and exchangeable mercury measured 24 hours after each addition was greatly affected by incremental changes in both pH and redox potential. At high-level additions, there was a sequential increase in soluble and exchangeable mercury levels with decreasing pH and increasing oxidation-reduction conditions. Greatest release occurred under acid, oxidized conditions.

91. The above studies were conducted between pH 5 and 8. The Japanese have reported that as pH increased above 8, mercury was released from contaminated sediments which had been solidified with cement and lime and then crushed (Murakami and Takeishi, 1977). The pH effect was thought to be due to mercury association with pH dependent suspended colloids.

92. Organic matter (organics + sulfide in the most reducing treatments) was thought to be the primary binding agent for mercury in the sediments studied by Gambrell et al. (1977a). In high level mercury addition studies of four sediment materials, dissolved and exchangeable mercury levels tended to be inversely related to sediment organic matter content. When the initially anaerobic sediments were subjected to aerobic conditions, there was evidence that the mercury binding effectiveness of insoluble, large molecular weight humic materials was reduced.

93. In studies designed specifically to determine the effects of oxidation-reduction conditions on the transport of mercury and other metals from quiescent, not especially contaminated, sediments into an overlying water column, Chen et al. (1976) reported only small changes in mercury levels in the overlying water. However, the following mercury release pattern was noted: Oxidizing conditions > slightly oxidizing > reducing. Feick et al. (1972a) also reported that oxidation of freshwater sediments decreased their ability to adsorb mercury in subsequent laboratory experiments and as suggested by Gambrell et al. (1977a), the decreased binding capacity was attributed in part to some oxidation of sediment organics. In laboratory simulation studies of toxic metal transport in upland confinement facilities, Mang et al. (1978) suggested that, while soluble levels were controlled by complexation (mainly organic), redox potential mediated processes were important in regulating the transport of mercury. Chen et al. (1976) and Brannon et al. (1978) also concluded that redox changes are important factors in regulating mercury mobilization.

94. In studies by Gambrell et al. (1977a), it should be noted that physicochemical effects on mobile forms of mercury were especially

strong at high total sediment mercury levels. Thus physicochemical effects on mercury mobilization and availability may be most important in the more heavily contaminated sediments.

95. It is generally believed that the effect of salinity changes on trace metal desorption would be greatest when freshwater sediment is disposed of at a saline site. Specific chloride complexes may form which tend to be relatively soluble. Freshwater sediments transported to saline environments may tend to release mercury (Brannon et al., 1978). Mercury forms several relatively soluble chloride compounds depending on chloride levels, and these chloride complexes tend to be more mobile than for any other trace metals. Feick, Hoyne, and Yeaple (1972) reported that increasing chloride may cause a release of mercury. As previously mentioned, Serne and Mercer (1975) reported that increasing chloride levels may cause desorption of mercury from hydrous oxides or at least decrease the effectiveness of hydrous oxide binding for mercury unless pH is increased to favor hydroxide forms instead of chloride forms.

96. Salinity effects on solubilization from contaminated solids and uptake by aquatic and benthic organisms apparently differ. Uptake of mercury as well as many other trace metals has been recorded to be reduced as salinity levels increase (Neff, Foster, and Slowey, 1978; Anderlini et al., 1975b). The above salinity effects are concerned with mercury desorption from particulates. It should be mentioned that increasing salinity may sometimes decrease total mercury transport by enhancing flocculation and settling of suspended solids moving from fresh waters into saline waters.

97. Methylmercury is more mobile and more readily accumulated by many organisms, and is toxic in lower concentrations than inorganic mercury. It may be produced microbially or abiotically in the environment. Methylmercury production is thought to be greater under reducing conditions but formation of this compound has been documented under a wide range of oxidation-reduction conditions. Wollast, Billen, and Mackenzie (1975) suggested methylmercury formation may not occur in the

presence of sulfide. Bacterial production may be greatest under reducing conditions, but in the redox potential range just above that favoring production and stability of sulfide. This may account for some observations where methylmercury accumulation has been reported to be greater under oxidizing than reducing conditions. Obviously, there is much yet to learn about the geochemical and biological factors affecting production and mineralization of methylmercury.

98. Feick et al. (1972a) reported that mercury released from sediments and dredged materials may be greater under oxidizing conditions than under reducing conditions. Mobility and loss of mercury (inorganic and methyl forms) from contaminated sediments was thought to be less where sulfides are present as the insoluble sulfide form is favored over the methyl form. Based on the somewhat limited information about methylmercury, it is suggested in this guidelines manual that where sulfides are present in sediments heavily contaminated with mercury, strongly reducing conditions should be maintained to minimize mobility and availability of mercury, and that this management practice may also reduce the potential threat from the especially hazardous methylmercury form.

99. In Japan where very high levels of mercury contamination in sediments have been a problem, methylmercury which accumulates in organisms was found to be derived from water. Exposed organisms accumulated little methylmercury from spiked food sources and essentially none resulted from contact with sediment containing up to 600 ppm mercury in some areas of Minimata Bay (Fujiki, Hirota, and Yamaguchi, 1977).

100. Plant uptake of mercury from contaminated sediments is a potential route for mercury entry into wetland and terrestrial food chains. Organic mercury may be taken up more rapidly than inorganic mercury (C. R. Lee et al., 1976). Plants grown on mercury-contaminated intertidal dredged material may accumulate more mercury as a result of the probable anaerobic rhizosphere. In studies of the effect of oxidation-reduction conditions on mercury uptake by marsh plants, Gambrell et al. (1977b) and C. R. Lee et al. (1978) reported occasional

significant treatment effects, but certainly no general redox effect for the species and rooting mediums studied.

101. In a review of the literature, C. R. Lee et al. (1978) reported that Spartina alterniflora may transfer sediment-bound mercury in the marsh environment. Remobilization of mercury was thought to be an effective way of transferring mercury into food webs. Windom (1973a) estimated total mercury uptake by Spartina alterniflora in Georgia estuaries to be  $0.7 \text{ mg/m}^2/\text{yr}$  and found that much of this was released to surrounding water from the plant leaves. Sampling of marsh plants growing on a number of dredged materials showed that plant mercury content from a majority of sites was not greater than from natural marshes indicating that plants will not accumulate excess mercury from most dredged material (C. R. Lee et al., 1978). Nevertheless, C. R. Lee et al. suggested that use of vegetation should be restricted where dredged materials contain high levels of mercury and that use of such materials for habitat development should be avoided.

102. Selecting disposal alternatives. Because of its toxicity at low levels and its tendency to accumulate from water in aquatic organisms and perhaps by bioaccumulation in food chains of terrestrial organisms, sediments determined to be contaminated with mercury represent a potentially high environmental risk--the degree of risk increasing with the level of contamination. For such high risk dredged materials, disposal methods stressing containment (the most rigorous form of confinement) should be considered to reduce potential adverse environmental effects. Placement of dredged materials heavily contaminated with mercury in or adjacent to ecologically and economically important biological populations, or in areas where productive habitat development will occur represent high risk disposal alternatives. Likewise disposal in high-energy environments is not a desirable alternative because of the probable greater long-term dispersion and subsequent transport of inorganic mercury and its possible uptake by organisms. Also, this alternative which favors resuspension in oxic water columns and possible eventual thin spreading in surface oxidized sediment horizons, does not

ensure that considerable methylmercury will not be produced as released mercury may move into anaerobic environments or may be methylated to some extent in predominately aerobic environments. Mercury-contaminated sediments placed in low-energy regimes to minimize transport of contaminated solids and dispersion of sediment-bound mercury will reduce the environmental risk of disposal. The physicochemical environment most effective in immobilizing inorganic mercury is near neutral in pH, strongly reduced, and nonsaline. However, these may also be the conditions favoring production of methylmercury, a highly mobile, available, and especially toxic form of mercury. In sulfur-bearing dredged materials, maintaining strongly reduced conditions favoring sulfide stability may limit methylmercury production. Because definitive information of factors favoring methylmercury production and mobilization under all conditions in the environment are not known, confinement of mercury-contaminated sediments in strongly reducing environments at disposal sites is suggested as the preferred method of disposal to limit mobility and release of both inorganic and probably organic mercury forms.

Subaqueous disposal. Subaqueous disposal of dredged materials highly contaminated with mercury within or adjacent to especially productive aquatic systems represents a high environmental risk. Unconfined disposal in any moderate- to high-energy hydraulic regime is also a high risk disposal method because of likely transport from the disposal site and chemical transformations of the mercury to potentially more available forms as a result of altered physicochemical conditions in the receiving aquatic environments. Transport and transformations out of the disposal site may result in greater biological exposure and uptake.

Unconfined disposal (where stable mounding will not occur) in moderate- to high-energy subaqueous environments also has the inherent disadvantage of greater surface area exposure to water columns. This may contribute to greater transport across the sediment-water interface because of resulting shorter diffusion distances for the small

amount of mercury that will be mobilized within the dredged material as soluble humic complexes, methylmercury, polysulfides, etc. Also, greater spreading will increase the surface area and thus the proportion of the total volume of the deposited material which may become oxidized as a thin horizon at the sediment-water interface. Certain other of the subaqueous disposal alternatives offer the greatest potential for containment of excess mercury associated with contaminated dredged material. Confined subaqueous disposal of typically fine-textured, reduced dredged material will result in little long-term transport from the disposal site and maintenance of strongly reduced physicochemical environments favoring the stability of mercury sulfide precipitates and mercury complex formation with insoluble, large molecular weight humic materials. Confinement by mounding in a low-energy hydraulic regime not subject to storm currents in areas of low biological productivity should be a desirable disposal method giving a very low potential for adverse environmental effects. For most purposes, this implies ocean disposal or other waters where depths are about 30 meters or greater. The optimum subaqueous disposal alternative will be confinement in a low-energy depression where the contaminated sediment may be covered with clean, wet material. Both of these alternatives result in maintenance of reducing conditions favoring mercury immobilization, minimum dispersion and transport, and minimal surface area exposure of contaminated material to the water column and benthic organisms.

i. Short-term considerations. Elutriate test results and monitoring of water quality at disposal sites have generally shown that mercury release during subaqueous disposal should not be a problem. These tests have indicated that small to negligible amounts of mercury may occasionally be released at a disposal site. Released levels would significantly exceed background levels only if no dilution occurs which is not the case. Field studies have shown that any increase in mercury levels is very transient and associated with the turbidity plume. Mercury levels in water columns will tend to drop to predisposal levels quickly, often within minutes. It is concluded that no short-term

impact of subaqueous disposal will occur out of the designated disposal site because of dilution which will occur at disposal sites; the association of "released" mercury with a solid phase, and the transient nature of increased total mercury levels at the disposal site. Little, if any, short-term adverse chemical impact on biological populations is expected within the disposal site. An exception would be a very coarse-textured, low organic matter, low reactive iron sediment heavily contaminated with mercury from which substantial short-term release could be expected. As previously mentioned, this condition may occur only under very localized conditions near a mercury outfall as coarse-textured sediments are not effective scavengers of low levels of waste mercury in the environment. Also, short-term release may be enhanced when a contaminated freshwater sediment is deposited in a saline environment.

ii. Long-term considerations. The greatest potential for adverse environmental impacts with mercury-contaminated sediments will be long-term effects associated with gradual release and biological uptake possibly resulting in chronic or perhaps undetected stresses in aquatic and benthic populations and subsequent consumer organisms. The relative risks of the various subaqueous disposal methods are based on these potential long-term impacts.

Intertidal disposal. Intertidal disposal of mercury-contaminated, coarse-textured, low organic matter dredged material poses a high environmental risk because of the possibility of movement into adjacent ground or surface waters and possibly greater plant availability. Intertidal disposal near especially productive or sensitive aquatic habitats also represents a high risk as does extensive habitat development on mercury-contaminated dredged material deposited intertidally. Covering the contaminated material with a clean layer of dredged sediments or soil should reduce the potential long-term impact of mercury uptake by plants and animals; however, efforts at physical confinement of the bulk dredged solids would be required to prevent erosion and subsequent dispersion of contaminated particulates into nearshore waters (See Paragraph 236).

Intertidal disposal may present a higher risk than subaqueous disposal because of the greater hydraulic energy conditions at some intertidal sites contributing to erosion and dispersion of bulk solids, the important and sensitive benthic and aquatic habitats usually associated with nearshore areas, and the demonstrated potential of plants to take up mercury and cycle this element into wetland ecosystems. With regard to plant uptake, organic mercury forms are thought to be most available, and the subsurface anaerobic rhizosphere of typical intertidally placed dredged material may favor production of specific organic compounds or soluble fulvic acid complexes.

i. Short-term considerations. Unconfined intertidal disposal may result in elevated total mercury levels in effluents associated with suspended solids during dewatering from initial consolidation and settling. Because of the proximity of most intertidal sites to important biological populations, such discharge should be minimized. It is anticipated that suspended solids in effluent for many intertidal sites will be higher and more difficult to control than for upland containment facilities where management to enhance solids removal is more feasible. This is a particularly important consideration for mercury-contaminated sediments as this metal is strongly associated with the particulate phase and especially with the very fine particulates which are most subject to transport with effluents.

ii. Long-term considerations. Potential long-term problems of intertidal disposal of mercury-contaminated sediments will be associated with gradual dredged material erosion and dispersion in nearshore areas and uptake and possible cycling by organisms which become established on these sites. These risks can be minimized by covering the contaminated sediments by a layer of clean material and by precautions to prevent gradual, long-term erosion of contaminated particulates. Leaching of mercury into groundwater or adjacent surface waters may be a long-term risk only if the contaminated sediments are coarse textured and contain relatively low organic matter content.

Upland disposal. Upland confinement for disposal purposes can be done in an environmentally safe manner, though it may offer little or no benefit over certain subaqueous disposal methods. Sediments heavily contaminated with mercury should not be applied upland for the purposes of agricultural soil amendment or habitat development because of the potential for plant uptake, subsequent introduction into food chains, and possible human accumulation from crop plants. It should be mentioned that this represents a cautious approach to disposal of mercury-contaminated sediments. While there is no doubt of the potential environmental and health hazards associated with mercury toxicity, substantial uptake and accumulation by crop plants has not been documented. Where a mercury-contaminated strongly reduced dredged material contains appreciable sulfide and suitable subaqueous disposal methods are not available, upland ponded disposal may be considered. Leaching control and the maintenance of long-term flooded conditions will favor immobilization as sulfide precipitates. Unconfined upland disposal not specifically intended for habitat development represents a moderate environmental risk because of the eventual natural colonization and the implied greater initial spreading and resulting greater exposed surface area than will occur with confined disposal.

Except for very coarse-textured, low organic matter sediments and perhaps medium-textured sediments with low reactive iron contents, leaching of mercury into groundwater or adjacent surface waters is not expected to be significant if the dredged material does not get strongly acid upon oxidation. Upland disposal of mercury-contaminated sediments containing large amounts reactive iron and especially total or pyritic sulfide represents a very high potential for long-term mercury leaching. Although effects of pH changes in the weakly acid to moderately alkaline range on mercury mobility are not as simple and easy to predict as for many other metals, the strongly acid conditions associated with sulfide and pyrite oxidation will almost certainly result in substantial long-term mobilization and leaching of mercury. It is possible that a very high pH (greater than 8.5) may also increase levels of dissolved mercury.

Use of mercury-contaminated dredged material for fill and other engineering purposes will not pose an environmental risk if extensive surface colonization by natural or managed biological populations is not permitted. Covering the contaminated material with a layer of clean material greater than the expected rooting and burrowing depths of organisms will also reduce the risk of uptake. Leaching and groundwater contamination will not be a problem if organic matter, reactive iron, and silt and clay contents are moderate to high, and if development of excessive acidity, upon dredged material oxidation, will not occur.

i. Short-term considerations. Potential short-term problems with upland disposal will be associated with elevated particulate mercury levels in initial dewatering effluents from the confinement sites. Because much of this mercury is expected to be associated with the solid phase, management to maximize suspended solids removal will be effective in reducing potential short-term release (See Paragraph 243), though particular attention should be directed to remove very fine particulates (Hoeppe et al., 1978).

ii. Long-term considerations. Potential long-term problems are associated with uptake and cycling by organisms and leaching into subsurface aquifers. If excessive acidity is expected upon oxidation of the dredged material, mercury leaching may be a problem. A dredged sediment containing sulfides or pyrites represents a high risk for leaching. Liming to reduce the acidity may not be feasible because of economic reasons or because of the additional capacity required to contain large amounts of lime (See Paragraph 248). For contaminated dredged material where excessive acidity development is expected upon dewatering and oxidation, confined subaqueous disposal may be a better alternative for environmental as well as economic reasons.

See Paragraphs 242 to 253 for methods which can be applied to certain upland disposal alternatives to further minimize mercury release from disposal sites.

## Cadmium

103. Cadmium is toxic to man and other living organisms in all of its chemical forms. Contamination of the terrestrial and aquatic environment with high levels of cadmium is cause for concern since uptake by higher plants and accumulation by aquatic and benthic organisms may cycle cadmium into the food chain and cause acute or chronic toxicity in animals and humans. Geochemical phase partitioning studies conducted under the DMRP and for the San Francisco District indicate that up to 97 percent of sediment-bound cadmium exists in the nonresidual fraction and is susceptible to chemical and biological transformations affecting availability under different geochemical conditions. Dredging and subsequent disposal of cadmium-contaminated sediments under open-water or upland conditions may increase concentrations of potentially available cadmium due to altered physicochemical conditions.

104. Cadmium release from dredged material in laboratory and field studies. Elutriate tests and similar release studies have been extensively employed to determine the potential release of cadmium and other elements from sediments from various locations in the U.S. and Canada (G. F. Lee et al., 1975, 1977; Brannon et al., 1976, 1978; Baumgartner et al., 1978; Wyeth and Sweeney, 1978; Marine Sciences Research Center, 1978; Cheam et al., 1976; Chen et al., 1976). The results of most of these studies indicated either no cadmium release or insufficient release to have any adverse effect on water quality at the disposal site. Although the 1.5 criterion was exceeded in some of the dredged materials, the concentration of cadmium released was below the water quality criteria for drinking water, fresh water, and marine water aquatic life (USEPA, 1973). Monitoring of actual open-water disposal in the studies cited above indicated that slightly elevated concentrations of cadmium in the surface water at the disposal site would persist for only a short time and then decrease to predisposal levels within minutes to a few hours. Results of interstitial water analysis showed that cadmium concentrations in the pore waters increased only

for a short time as a result of reestablishment of equilibria within the sediment-interstitial water systems. The cadmium concentrations returned to predisposal interstitial water levels in a few months after disposal. Thus, cadmium-contaminated sediments disposed of by subaqueous methods in quiescent waters pose a relatively low risk to the aquatic environment within the disposal site and a very low risk in adjacent waters.

105. Cadmium-contaminated sediments may be a greater threat to benthic organisms within the disposal site. Benthic organisms have been reported to accumulate high concentrations of cadmium from some contaminated bottom sediments such that they may cause a serious health hazard if consumed. In some cases, a direct relationship between accumulation and sediment concentration has been established (Ayling, 1974; Wier and Walter, 1976).

106. Removal efficiency of cadmium in effluents from upland confined disposal facilities from both freshwater and brackish water sediments is reported to be related to total solids removal. Hoeppe et al. (1978) and Lu et al. (1978) reported that up to 99 percent of total cadmium was removed at land disposal sites. No change in the concentration of soluble cadmium occurred during confinement and the concentration of total cadmium in effluents was slightly less than levels in influents. The cadmium remaining in the effluent solids was transformed from organic and sulfide complexes to more readily available carbonate, easily reducible and exchangeable forms due to oxidized conditions. This shift of cadmium from relatively unavailable to more available chemical forms suggests that effluent solids-bound cadmium may be more available to organisms. Also, the total cadmium concentrations in the effluents from some disposal sites were significantly higher than the EPA marine and freshwater criteria requirements.

107. In a simulated upland disposal leachate study, Mang et al. (1978) found that essentially all of "the soluble and particulate cadmium leached was retained" by the underlying soils. They attributed this essentially complete removal of cadmium to sulfide precipitation

under reduced soil conditions. However, most upland disposal sites would eventually develop oxidized conditions due to drainage and cadmium levels in the leachates may be substantially increased as will be discussed under Physicochemical effects.

108. Physicochemical effects. Oxidation-reduction potential, pH, and salinity are important parameters influencing cadmium distribution in sediment-water systems. Cadmium mobility and bioavailability tend to respond more to altered physicochemical conditions than the other commonly studied potentially toxic metals. Laboratory studies sponsored by DMRP (Gambrell et al., 1977a; Chen et al., 1976) have demonstrated that most of the cadmium present under reduced sediment conditions is immobilized as insoluble organic and sulfide forms. A change from reduced to oxidized sediment conditions was accompanied by a transformation of unavailable inorganic and sulfide complexes to more mobile and potentially available forms. This effect was noticed in Los Angeles Harbor, Mobile Bay, Mississippi River, and Barataria Bay dredged sediments. A similar shift in cadmium mobility was observed when sediment pH was lowered from alkaline (pH 8.0) to acidic conditions. The effect of oxidation in increasing the concentrations of cadmium in the more mobile exchangeable and soluble forms was more pronounced at pH values of 6.5 or less where cadmium is present in the divalent cationic form or as chloride complexes and does not form less soluble hydroxide complexes. Unlike mercury, the effect of pH on cadmium mobility was similar at both indigenous and added high levels of cadmium in the sediments (Gambrell et al., 1977a).

109. Numerous studies have indicated that the association of cadmium with hydrous oxides of iron and manganese is not as strong as for many other potentially toxic metals (Gambrell et al., 1977a; Brannon et al., 1976; Marine Sciences Research Center, 1978; Kinniburgh, Sridhar, and Jackson, 1977) and that this weak association exists over a wide range of pH and oxidation-reduction conditions (Gambrell et al., 1977a). This may contribute to the relatively greater mobilization

observed for cadmium under oxidizing conditions than is found for many other potentially toxic metals.

110. The studies conducted under controlled pH-redox potential conditions and discussed earlier suggest considerable cadmium release to relatively mobile forms may occur as cadmium-contaminated sediment is transported from an alkaline pH, reducing environment to a moderately acid, oxidizing environment. Most open-water disposal methods probably result in minimal oxidation of the bulk dredged solids during the relatively short settling period through an oxidized water column. However, upland disposal usually results in gradual drainage and subsequent long-term oxidation of dredged materials. Dredged material oxidation may be accompanied by substantial reductions in pH in noncalcareous materials. This will be especially true in dredged sediments containing appreciable sulfide. Under these conditions, cadmium may be transformed from very immobile organic and sulfide forms to more mobile and potentially bio-available forms. This striking effect of decreased sediment pH on cadmium mobility in Inner Oakland Harbor dredged sediments was reported by Brannon et al. (1978). Constant agitation of a sediment-water mixture open to the atmosphere for 4 months resulted in a reduction of suspension pH from 8.0 to 3.6. A net mass release of 1.1 mg of cadmium (a substantial release for the experimental conditions) at the 4-month sampling and 1.6 mg of cadmium at the 8-month sampling was attributed to this low pH. Khalid, Patrick, and Gambrell (1978) attributed a gradual increase in soluble cadmium in Barataria Bay sediment suspensions purged with molecular oxygen to oxidation effects accompanied by a decrease in pH from 7.7 to 5.7.

111. Chen et al. (1976) conducted numerous column studies of metals transport from sediments to overlying water columns which were maintained under various oxidation conditions. More cadmium was released from the sediment phase as the oxidation conditions of the water column increased, but it should be noted that though cadmium was released, the actual increase in concentration was small and thought to be insignificant considering the very low initial levels of dissolved

cadmium. Brannon et al. (1978) also reported a very low net mass release at 4 months in long-term quiescent column studies of 32 dredged sediments with disposal site water maintained under oxidized conditions. The concentration after 8 months decreased to less than the initial disposal site water concentrations resulting in a net mass release of essentially zero for the entire study period.

112. The greater mobility of sediment-bound cadmium under acidic, oxidized conditions is reflected in enhanced plant uptake. Ito and Iimura (1975) and Reddy and Patrick (1976) reported significantly greater cadmium uptake by rice plants under oxidized conditions as compared to reduced conditions. Cadmium uptake increased with decreasing pH and the effect of pH was greatly accentuated in an oxidized soil environment compared to a reducing soil. In controlled laboratory and greenhouse experiments, Gambrell et al. (1977b) observed a substantial increase in the cadmium content of marsh plants under oxidized conditions compared to reduced conditions. Also, more cadmium was taken up at higher salinity levels which contrasts with generally observed salinity effects on benthic animal availability of cadmium. Folsom and Lee (1978) studied the uptake of metals by Cyperus esculentus grown under flooded (reduced) and upland (oxidized) conditions in freshwater sediments collected from various dredging sites. Their results demonstrate a significantly higher cadmium uptake under upland conditions than under flooded conditions.

113. The topic of significant or substantial cadmium release under oxidizing conditions reported for some studies and minimal release from other studies requires discussion. Substantial mobilization and/or uptake is usually reported in studies of well-mixed sediment-water systems or from unsaturated soils or sediments used as rooting mediums in plant uptake studies. These studies permit oxidation of the bulk solids. Undisturbed sediment-water column studies may be characterized by a thin oxidized sediment horizon overlying a reduced horizon containing most of the sediment. Most of the cadmium remains in a strongly reduced environment. Thus, the proportion of the

total sediment mass actually subject to oxidation, pH changes, and chemical transformations affecting mobilization may be greatly different under the two experimental conditions. This suggests that subaqueous stable mounding of dredged sediments should result in greater immobilization of cadmium than upland disposal where dewatering will occur, or disposal in a high energy hydraulic regime where substantial long-term resuspension and transport of contaminated particulates may occur in an oxidized water column.

114. The effect of salinity as a major control mechanism in regulating cadmium mobility is related to the formation of cadmium chloride, sulfate, and carbonate complexes with a greater solubility than those of sulfides and to cation exchange reactions. Several research studies report cadmium release with increased salinity in dredged and suspended sediments (Serne and Mercer, 1975; DeGroot, 1973; DeGroot and Allersma, 1975). It is evident from these studies that the effect of salinity on cadmium desorption from dredged material may be most pronounced when dredged material from a freshwater area is disposed of in a saline disposal site. This cadmium release, however, may be counteracted by an increase in pH of freshwater dredged material dumped in saline environments since alkaline pH conditions enhance cadmium immobilization.

115. Salinity variations in sediment-water systems are reported to affect cadmium accumulations in the benthic and aquatic organisms. Jackim et al. (1977) reported that reduction in salinity from 31.5‰ to 0‰ resulted in enhanced <sup>115</sup>Cd accumulation by 30 orders of magnitude by Fundulus heteroclitis after an 8-day exposure. Controlled laboratory studies on San Francisco Bay dredged sediments indicate that accumulation of cadmium by M. balthica (clams) increased significantly as water salinity was lowered from 25‰ to 4.8‰ (Anderlini et al., 1975a). The tendency of organisms to accumulate more cadmium at lower salinities is in contrast to the effect of salinity on chemical mobility of cadmium.

116. Selecting disposal alternatives. Because of their demonstrated toxicity at low levels and their relatively high mobility and bioavailability, cadmium-contaminated sediments represent a high potential environmental risk. Disposal alternatives for dredged sediments contaminated with high levels of cadmium should minimize interaction with ecologically and economically important terrestrial, aquatic, and benthic populations. Disposal alternatives for cadmium-contaminated sediments should emphasize confinement to reduce dispersion of this element in the environment. Disposal alternatives which result in long-term maintenance of near neutral pH and strongly reducing conditions favor immobilization of cadmium and thus containment within the disposal site. Disposal alternatives discussed in the following paragraphs address some of these concerns.

Subaqueous disposal. Disposal of contaminated materials in high-energy, commercially and ecological productive nearshore areas, estuaries, and inlet zones should be avoided due to a greater potential of uptake by organisms. Disposal of sediments in a high-energy, subaqueous site may result in greater transport and interaction with oxic surface waters and possible conversion to more mobile and available forms. Disposal in shallow waters and near lake shores make the material subject to dispersal by natural currents, waves, and storms. The most desirable disposal alternatives for cadmium-contaminated dredged sediments would be confinement (stable mounding) in low-energy hydraulic regimes where maintenance of reducing, near neutral pH conditions is favored. High concentration of sulfides and/or organic material in reducing bottom sediments will precipitate and complex cadmium in immobile forms with little or no diffusion of soluble cadmium to the overlying waters. Favorable sites may include the deep ocean, low-energy subaqueous depressions, and possibly deep areas of lakes. Capping the contaminated sediments with a layer of relatively clean sediments can be used to further isolate cadmium in contaminated sediments (See Paragraph 233).

i. Short-term considerations. Cadmium-contaminated sediments dredged from freshwater and estuarine harbors and disposed in ocean waters present a potential for short-term release in high salinity surface waters during disposal operations. Cadmium release of several orders of magnitude greater than the background ocean waters has been observed in some laboratory studies, but this should be considered relative to the very low dissolved levels of cadmium in ocean waters. Elutriate test results and monitoring of water quality at disposal sites indicate little or no release in most cases. The short contact time with surface waters during settling and mixing of contaminated water with receiving site water will usually result in no short-term adverse chemical impact.

ii. Long-term considerations. Cadmium-contaminated sediments deposited in a high-energy hydraulic regime represent a high risk for mobilization and potential long-term adverse environmental impact. Cadmium subjected to frequent resuspension in a water column may be transformed to more mobile and potentially bioavailable forms in addition to being transported out of the disposal area. Disposal methods which give stable mounding in quiescent waters should substantially reduce the risk of transport. With stable mounding, the risk of a long-term adverse impact on surface water quality is low both within and out of the designated disposal site. Certain benthic organisms recolonizing a disposal site may accumulate excess cadmium. This risk can be substantially reduced by capping the contaminated material with a layer of clean dredged sediments (See Paragraph 233).

Intertidal disposal. Disposal of cadmium-contaminated dredged sediments in an intertidal zone represents a potentially high environmental risk because of the possibility of cadmium leaching or transport of contaminated particulates to adjacent surface waters during initial dewatering and long-term erosion, the usual proximity of intertidal areas to productive aquatic ecosystems, and the additional risk of increased cadmium exposure to marsh and wetland plant and animal populations.

Use of dredged materials highly contaminated with cadmium specifically for habitat development or where extensive natural colonization will occur represents a high environmental risk, especially in high-energy intertidal sites. Fortunately, these sites rarely pose a contamination problem as marsh creation or habitat development projects with dredged material are usually not planned for high-energy areas regardless of the contamination status of the sediments.

Though the potential exists for a high environmental risk with intertidal disposal of cadmium-contaminated sediments, this risk may be substantially reduced by selection of certain management practices (See Paragraphs 234 to 241).

i. Short-term considerations. Possible short-term problems with intertidal disposal of cadmium-contaminated sediments include leaching from a coarse-textured, low organic content material, or transport of contaminated particulates from the disposal area in initial dewatering effluents resulting in total effluent cadmium levels exceeding some surface water quality criteria. Methods to minimize transport of suspended particulates should be effective in reducing this risk. Intertidal disposal of a coarse-textured, low organic content dredged material highly contaminated with cadmium represents a very high environmental risk and should be avoided.

ii. Long-term considerations. Especially coarse-textured, low organic content sediments highly contaminated with cadmium present a risk of long- and short-term leaching. Such sediments should probably be disposed of at other than intertidal sites. Possible plant and benthic uptake also represent a potential problem. However, the expected reducing, near neutral pH conditions of all but a very thin surface oxidized horizon should minimize plant availability in typical fine-textured maintenance dredged materials unless flooding is infrequent, permitting development of an oxidized rooting zone. Capping with a layer of relatively clean soil or sediment should also be effective in reducing biological uptake. For typical reducing, fine-grained sediments containing considerable organic matter, vertical leaching or

surface drainage should not transport significant cadmium in dissolved forms. Methods to minimize long-term loss of contaminated particulates by surface erosion should be implemented.

Upland disposal. Land disposal of cadmium-contaminated dredged sediments offers the greatest potential of releasing large amounts of cadmium into the environment compared to intertidal and sub-aqueous methods. Eventual oxidation of dredged sediments can substantially increase the chemical mobility and biological availability of cadmium. This is especially true if increased oxidation is accompanied by a reduction in pH which is often the case in noncalcareous dredged materials applied upland. This combination of altered physicochemical conditions often associated with upland disposal results in a very high potential for cadmium mobilization. Because of the relatively high potential chemical mobility and biological availability (especially plant uptake and translocation) documented for this toxic metal, the use of sediments highly contaminated with cadmium specifically for upland habitat development or agricultural soils amendment poses a very high environmental risk as would disposal near important groundwater supplies. The eventual natural colonization of most upland sites by animals and plants which may accumulate dredged material-derived cadmium presents a moderate to high environmental risk with most upland disposal methods.

i. Short-term considerations. The greatest potential short-term impact would be contamination of receiving waters from initial dewatering effluents from upland confinement sites. Total cadmium concentrations in the effluents may exceed surface water quality criteria, though it should be mentioned that studies show that soluble cadmium is usually below these criteria. Practices which maximize suspended solids removal will be helpful in reducing cadmium in initial dewatering effluents. In addition to meeting applicable water quality criteria, removal of cadmium-contaminated particulates is important as some studies have shown that though dissolved levels

are little affected, particulate cadmium in effluents may be in potentially more mobile forms in dewatering effluents than influents.

ii. Long-term considerations. Oxidation of the bulk of dredged sediments applied upland may significantly increase the chemical mobility and biological availability of cadmium. If oxidation is accompanied by an increase in acidity, the increase in cadmium mobility may be substantial. Moderate decreases in pH may be common in noncalcareous dredged sediments containing appreciable reactive iron. Sediments containing elevated levels of pyrite or total sulfides may become strongly acid upon long-term oxidation. This altered physicochemical condition greatly increases the potential for cadmium leaching into groundwater and plant uptake with possible cycling into food chains. Physical confinement of the contaminated bulk solids should be accomplished to minimize transport of cadmium as eroded particulates. Dredged material pH control to minimize release can be effective, but may not be practical in many cases (See Paragraph 248). Capping with a layer of uncontaminated soil or dredged sediments can effectively minimize plant and animal uptake, but will not be effective for leaching control. For typical reduced, fine-textured dredged materials containing appreciable organic matter, subaqueous disposal where stable mounding will occur will usually result in less environmental risk from cadmium-contaminated sediments than most upland disposal methods. Where subaqueous disposal is not feasible, and the sediment cadmium levels warrant extensive efforts to achieve immobilization, long-term upland ponded disposal should effectively contain cadmium. Though the reduced conditions associated with a ponded facility should minimize cadmium leaching, the site should be selected and managed to limit vertical infiltration of water as an added precaution.

#### Lead

117. Lead is a toxic metal commonly encountered in contaminated sediments at levels ranging from 50 to several hundred parts per

million. Lead levels in contaminated sediments usually exceed cultural accumulation of mercury and cadmium by one or two orders of magnitude. Fortunately, lead tends to be very immobile and unavailable to organisms under most conditions and to be less toxic than many other metals. In Britain, where lead from mine tailings and smelters has contaminated large areas, environmental problems are thought to be relatively minor in many soils at lead levels of 300 to 500 parts per million.\* These levels of mercury or cadmium would be cause for the greatest concern in soils or sediments. Thus the environmental threat from lead-contaminated sediments is somewhat low compared to sediments containing equivalent total levels of mercury or cadmium. The relatively low toxicity of lead compared to mercury and cadmium is often countered by its much greater levels in contaminated sediments.

118. Harmful accumulations of lead by aquatic organisms from dissolved lead in surface waters may not be a problem even where the underlying sediment or dredged material is highly contaminated by lead. This is because chemical regulatory processes immobilizing excess lead in sediment-water systems are very effective. A few studies have shown occasional small accumulations of lead by benthic organisms exposed to contaminated sediments. Many studies have not shown lead uptake by benthic organisms exposed to contaminated sediments. Similarly, though high levels of lead are often found associated with roots (Jones, Jarvis, and Cowling, 1973; Reddy and Patrick, 1976), lead is known to be difficultly translocated in plants (Alloway and Davies, 1971; Broyer, Johnson, and Paull, 1972), resulting in safe lead levels in aboveground tissue even in most plants grown on contaminated soils and sediments. However, there are numerous exceptions in the literature where elevated lead levels have been reported in aboveground plant tissues (Gupta et al., 1978; C. R. Lee et al., 1978). Because of its

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demonstrated toxicity and its potential biological accumulation from contaminated habitats, evaluations for environmentally sound disposal alternatives for lead-contaminated sediments will be based on immobilizing this metal within the disposal site. However, because of effective chemical immobilization processes for lead in sediments and its lower environmental toxicity, efforts at containment for sediments contaminated with lead may not need be as rigorous for all but the most highly contaminated sediments.

119. Dissolved lead is potentially the most bioavailable form. Most dissolved lead in sediment-water systems exists as uncharged inorganic compounds or organic complexes.

120. Although many solid inorganic lead compounds may play important roles in regulating dissolved lead levels in a water column, it is likely that sulfide precipitation (in reducing systems), complex formation within insoluble large molecular weight humic materials, adsorption by hydrous oxides, and perhaps the presence of carbonates in calcareous sediments are the major regulating processes immobilizing excess lead in sediment-water systems. The effectiveness of these regulatory processes can be influenced by physicochemical conditions at a dredged material disposal site.

121. Lead release from dredged material in laboratory and field studies. Some elutriate tests and monitoring of water quality at dredging and disposal sites have shown short-term increases in lead levels of simulated or actual water columns (Anderlini et al., 1975b; Wakeman, 1974). Other studies have shown no significant increase. The evidence indicates that, in many cases where these increases are observed, it may be particulate lead that is being measured instead of dissolved lead. Where increases in water lead levels are noted, it is usually concluded that the increases are too small and of too short duration to impact surface water quality, especially out of the designated disposal area (G. F. Lee et al., 1975, 1977).

122. Lead losses from upland confinement facilities are strongly correlated with total suspended solids in effluents (Lu et al., 1978).

Thus, managing effluents to reduce lead losses to meet surface fresh-water or marine water quality criteria can best be accomplished by minimizing suspended solids (See Paragraph 243). Lu et al. (1978) did observe that dissolved lead increased by 15 percent in effluent from one of two upland confinement sites studied, though the dissolved concentration was still less than 10  $\mu\text{g}/\text{l}$ , well below most water quality criteria.

123. Hoeppe et al. (1978) found good removal efficiency of total lead by the nine land confinement facilities studied. Comparison of influent and effluent levels showed a 92-percent removal rate for total lead and no change in soluble phase ( $<0.45 \mu\text{m}$ ) lead. Total effluent lead was well above levels in surface background water, but soluble lead levels in effluents were about the same. They also concluded that suspended solids retention is important in maximizing effluent water quality at land confinement sites.

124. In laboratory studies of lead leaching from simulated upland confinement sites, Mang et al. (1978) reported that soluble lead is not expected to cause problems in leachates. Total lead did exceed several water quality criteria in this study and could cause some problems in the absence of dilution. Lead levels in leachates were reported to be increasing with time, thus, there was some concern over potential long-term problems. It should be pointed out that the dredged materials in these column leaching studies did not attain the well-oxidized conditions which would eventually develop in many upland confinement sites.

125. As previously discussed, lead is relatively unavailable for plant uptake and translocation. However, a sufficient number of cases of substantial plant lead accumulation in aboveground tissues has been documented (Gupta et al., 1978; C. R. Lee et al., 1978; Banus, Valiela, and Teal, 1975) such that this must be considered a potential source for excess lead input into food chains. C. R. Lee et al. (1978) studied metal uptake on marsh plants grown on a number of dredged materials and natural marsh soils. Although plants from a majority of the dredged materials and marsh soils showed no metal accumulation relative to the

natural marsh populations, a few dredged materials resulted in metal levels (including lead) an order of magnitude greater. This was concluded to be a potential environmental hazard. It was recommended that the use of vegetation should be restricted when the dredged material contained high levels of lead and other metals and that this would negate the use of some disposal areas as habitat for wildlife.

126. Physicochemical effects. Studies have shown that pH and redox conditions are more important in regulating lead release than sediment physical properties (Chen et al., 1976). However, should a coarse-textured dredged material with low levels of organic matter and reactive iron be encountered with lead contamination, it is expected such a sediment may be less effective in immobilizing lead than more typical fine-textured materials. Except possibly for sediments near point sources of waste discharge, coarse-textured, low organic matter materials will rarely be contaminated with excessive lead as these sediments are not effective sinks for metals. Lead will be predominately associated with the fine particle size fraction such that reducing turbidity in suspended solids at dredging and disposal sites will effectively reduce lead mobility.

127. Increasing water salinity may substantially increase dissolved lead in surface waters (G. F. Lee et al., 1975; Marine Science Research Center, 1978). A greater release of dissolved lead is expected when contaminated freshwater sediments are disposed of in saline environments than for other sediment-disposal site salinity combinations (Chen et al., 1976). In leaching studies simulating upland confinement sites, soluble lead levels were much higher in interstitial waters of ocean sediments compared to freshwater sediments (Mang et al., 1978). In the saline water, it was suggested that formation of lead carbonates after some oxidation of sulfides contributed to the increase of soluble lead. An increase in salinity may have the opposite effect on actual lead uptake by benthic organisms (Anderlini et al., 1975a).

128. The chemical availability of lead will respond to changes in pH. In long-term release studies using stirred suspensions of a

number of sediment materials ranging widely in properties, large amounts of trace metals (including lead) were released from Oakland Inner Harbor sediments compared to other materials tested (Brannon et al., 1978). In this material, pH decreased to a very acid condition of 3.6. With all of the sediments, it was concluded that release of iron and lead was directly related to pH. In a review of the literature on factors affecting metal mobility in dredged materials, Khalid et al. (1977) concluded that increasing acidity would increase the mobility of lead. Gambrell et al. (1977a) also reported substantial pH effects on exchangeable lead in Mobile Bay sediment suspensions at both indigenous levels and where high level lead additions had been made. Exchangeable lead levels were much greater at pH 5 than at pH 6.5 or 8. Plants are also reported to accumulate more lead from an acid rooting medium (John and VanLaerhoven, 1972; Cox and Rains, 1972; Reddy and Patrick, 1976).

129. Oxidation-reduction conditions of a sediment-water system are important in regulating the availability of lead. Numerous laboratory studies have shown that lead is usually released from soil and sediment under aerobic conditions compared to anaerobic conditions (Serne and Mercer, 1975; Reddy and Patrick, 1976; Mang et al., 1978; Chen et al., 1976), but often the release is relatively small. Gambrell et al. (1977a) have shown that lead immobilized with the organic phase (organic plus sulfide in strongly reduced sediments) tends to be bound less tightly as oxidation conditions are increased. Most lead released from the organic plus sulfide phase as the sediment became oxidized was bound by hydrous iron oxides. Cadmium interacted less with hydrous oxides than lead. This may contribute to the relatively small release of lead compared to cadmium when reduced sediments are subjected to long-term oxidation.

130. In strongly reduced sediments containing appreciable sulfide, lead will tend to be immobilized. The increased levels and structural complexity of naturally occurring organics will also favor immobilization of lead under reducing conditions. Thus, typical fine-grained

reduced sediments containing considerable organics and sulfides should effectively immobilize excess lead in contaminated sediments.

131. Under oxidizing conditions in sediment-water systems containing substantial reactive iron, hydrous ferric oxides will also effectively scavenge dissolved lead (G. F. Lee et al., 1975; Windom, 1972), especially as a reduced dredged material is mixed in an aerobic water column. The result of organic plus sulfide immobilization under reducing conditions and hydrous oxide adsorption of lead under oxidized conditions is that the change in dissolved or plant available lead levels as a result of changes in redox conditions is moderated substantially. If reactive iron levels are high and near neutral or slightly alkaline pH levels are maintained, there may not be a large net change in available lead levels as a result of oxidation, even in sediments with large amounts of potentially available lead. Dissolved lead is often reported to increase slightly as a result of sediment oxidation. Apparently, immobilizing processes associated with organics, hydrous oxides, and specific inorganic lead compounds under oxidized conditions are slightly less effective than organics and sulfide which immobilize lead under reducing conditions.

132. Most soils and sediments will undergo a redox potential mediated change in pH as oxidation-reduction conditions are altered. A very real danger in contaminated noncalcareous reduced sediments containing appreciable reactive iron and especially sulfide is that long-term oxidation can result in development of strongly acid conditions which can greatly increase the mobility of lead probably by decreasing the scavenging action of hydrous iron oxides. Disposal of such sediments contaminated with lead and other trace metals by upland application should be evaluated very carefully.

133. In summary, the disposal conditions favoring minimum lead release from contaminated sediments are low salinity, near neutral pH, and strongly reducing redox conditions. In fine-textured materials containing large amounts of reactive iron, lead should be immobilized almost as effectively under oxidizing conditions provided that pH does not decrease below about 6.0.

134. Selecting disposal alternatives. Because of the toxicity of lead and its tendency to accumulate in some organisms, confinement of sediments determined to be contaminated with potentially harmful levels of lead should be considered to reduce potential adverse environmental effects to very low levels. Because of effective chemical immobilization processes for lead in sediments and its comparatively lower environmental toxicity than for mercury and cadmium, efforts to isolate and confine lead-contaminated sediments need not be as rigorous for all but the most highly contaminated sediments.

135. For dredged sediments in which lead is determined to be a serious environmental threat, disposal in areas where productive wild-life habitat development will occur, on soils to be used for agricultural purposes, or on other upland areas over groundwater aquifers used for water supplies represents a moderate to high potential environmental threat. Lead-contaminated sediments placed in a low-energy regime to minimize long-term release and transport by dispersive forces and placed away from especially sensitive and productive biological populations poses a very low environmental risk.

136. Dredged material properties which favor immobilization of lead include fine texture, high organic matter content, the presence and maintenance of appreciable sulfide content, high reactive iron content, and low salinity. Typical maintenance dredging of lead-contaminated sediments will involve reduced fine-textured materials with considerable organic matter and often sulfide. Maximum immobilization should occur if these dredged sediments are maintained in an environment which is anaerobic, near neutral in pH, and low in salinity in the case of freshwater sediments. If pH can be maintained above about 6, only negligible to small lead release may occur under oxidized conditions if sufficient reactive iron is present in the original material to favor formation of hydrous oxides. It is important to remember that in noncalcareous sediments, the presence of large amounts of reactive iron and especially sulfide will favor development of moderately to

strongly acid conditions upon long-term oxidation which can mobilize substantial lead.

137. In sediments contaminated with high levels of mercury, cadmium, and/or certain chlorinated hydrocarbons which are thought to be a serious environmental threat, evaluations of possible disposal methods to minimize adverse impacts for these contaminants should receive a higher priority than alternatives suggested for lead. In many cases, however, the optimum methods will not differ.

138. The discussion given previously for selecting disposal alternatives for mercury-contaminated sediments is generally applicable to lead-contaminated sediments since the regulatory processes for these two toxins respond similarly to changes in physicochemical conditions. An important difference is that an especially hazardous organic equivalent of methylmercury is not a problem with lead. The reader is referred to the corresponding mercury discussion for additional information on short and long-term considerations in selecting environmentally acceptable disposal methods for lead-contaminated sediments (See Paragraph 102).

#### Zinc, copper, nickel, and chromium

139. Zinc, copper, nickel, and chromium, though toxic at high concentrations (CAST, 1976), can be accumulated by benthic organisms, plants, and animals in large concentrations compared to mercury and cadmium without showing toxic effects. Zinc and copper are essential to plant growth. Zinc is essential to animals and is a component of a number of enzyme systems. Chromium and nickel are required by humans and certain animals, respectively. These four metals are discussed together because their relative toxicity and sediment chemistry are similar. Hence, environmentally sound dredged material disposal alternatives will be similar for these metals.

140. Benthic organisms have been shown to accumulate elevated concentrations of zinc, copper, nickel, and chromium that may be harmful

if consumed (Neff et al., 1978). A direct relationship between heavy metals accumulation by some soil and benthic organisms and total metal concentration in soil and sediments has been demonstrated in several studies (Ayling, 1974; Mathis and Cummings, 1971) while others report conflicting results. Copper, zinc, and chromium are essential or beneficial micronutrients to animals and for this reason benthic invertebrates may have a mechanism for rapid accumulation resulting in toxic levels. The potential for uptake varies with organisms and metals and may be significantly affected by the exposure concentration, duration of exposure, temperature, salinity, chemical form of metals and many other factors. Excessive uptake of copper, zinc, nickel, and chromium is toxic to plants and may reduce growth. Contaminated dredged material applied on agricultural land may also result in excessive accumulation of metal ions in crop plants reducing yields or possibly affecting human health. As with animals, the mode of uptake and the toxicity levels vary with plant species, chemical form and concentrations in soils or dredged sediments, and physicochemical factors such as pH and oxidation-reduction conditions.

141. Crop plants have certain mechanisms to accumulate large concentrations of zinc without showing toxic effects. When zinc toxicity does occur, the tissue of most crops will contain zinc at concentrations of several hundred parts per million. Like zinc, nickel is a mobile element and can accumulate in high concentrations (above 50 ppm) in plant tissues (CAST, 1976). Chromium and copper tend to accumulate in the roots and very little is translocated to the aerial portion of the plant. The normal range of copper concentrations in plant tissue is from 5 to 20 ppm and the concentration at which copper may be toxic varies with plant species. Very little chromium is adsorbed by crop plants, but some species can contain levels up to 10 ppm without yield reductions. It is known that there are large species differences in the tendency of plants to take up and translocate potentially toxic metals to aboveground tissue. Unfortunately for those interested in marsh or habitat development projects, most of this information is for cultivated plants.

142. Zinc, copper, nickel, and chromium release from dredged material in laboratory and field studies. Elutriate tests and monitoring of water quality at actual open-water disposal sites have generally shown little to no release of these metals. Where release has been documented, the increase in metal levels in the water column has been small and elevated levels usually return to background quickly. Interstitial water concentrations may remain elevated for long periods (on the order of days to a few months), but again these observed increases are relatively small and are not permanent. These findings are based on the work of Brannon et al., 1978; Hoeppel et al., 1978; G. F. Lee et al., 1977; Wyeth and Sweeney, 1978.

143. Monitoring of initial dewatering effluents from confined land disposal areas in different geographical areas showed that the removal of particulate-bound metals was correlated with the solids removal (Hoeppel et al., 1978). Total metal analysis of effluent solids indicated removal efficiencies of 95 to 100 percent. However, soluble metal concentrations in the effluents increased 16, 11, and 13 percent for zinc, copper, and chromium, respectively. Compared to influent samples, nickel showed a decrease of 14 percent. Also, concentrations of soluble zinc, copper, and chromium in the discharge effluent were higher than the background water whereas no change in nickel levels were observed. If dredged sediments highly contaminated with these metals were disposed under upland conditions, the soluble concentrations in initial dewatering effluents may exceed certain water quality criteria for drinking water and freshwater and marine water organisms. Land confinement of dredged materials results in chemical phase changes from less soluble to more mobile and bioavailable forms as a result of oxidation. Insoluble organic plus sulfide bound zinc and copper in the influent were transformed to potentially more available carbonate and exchangeable, and easily reducible and carbonate forms, respectively, in the effluent solids as a result of passage through the disposal site. Chromium and nickel did not show any significant phase changes

in the effluents and 85 to 95 percent of the total metals were still present in the organic, sulfide, and residual forms. The results of leaching studies simulating upland disposal indicated that essentially all of zinc and copper released from the dredged material was absorbed by the interfacing soil and the concentrations in the leachates were very low (Mang et al., 1978).

144. In a study of chromium, cadmium, lead, nickel, and zinc uptake by marsh plants from natural and experimental (dredged material) marshes, Lunz (1978) reported nickel was the only metal studied which was found in marsh plant tissue at higher levels from experimental than natural marshes. It was observed that higher levels of nickel were in the easily reducible (hydrous oxide) form in the experimental marsh compared to the natural marsh and the experimental marsh soil was slightly better oxidized, though there was no implied relationship between this observation and plant availability. Both root uptake and translocation as well as transfer to aboveground tissue by water were suggested as contributing to nickel accumulation by plant tissue. It was concluded that the physical and chemical properties of the marsh soils were effective in immobilizing these metals. Though chromium, cadmium, and lead were higher in the experimental marsh and nickel and zinc in the natural marsh, none of these marsh soils were excessively high in any of these metals.

145. Physicochemical effects. Geochemical phase partitioning studies (Serne and Mercer, 1975; Chen et al., 1976; Brannon et al., 1976, 1978) indicate that most of the potentially available sediment-bound copper and zinc in various dredged materials was associated with organic and sulfide complexes with the remainder associated with the crystalline structure of the clay minerals in an unavailable form. Maintenance of strongly reducing conditions will contribute to immobilization of these metals in organic plus sulfide forms. The concentrations of copper and zinc in the interstitial waters of reduced bottom sediments were generally very low.

146. Gambrell et al. (1977a) reported studies of controlled pH and oxidation-reduction conditions on soluble and exchangeable zinc. Under moderately acid conditions (pH 5.0), dissolved and exchangeable zinc increased substantially as oxidation conditions increased. At near neutral to mildly alkaline pH levels, there was less effect of oxidation conditions on soluble and exchangeable zinc and perhaps a slight reduction in concentration at the highest oxidation level. These results were obtained at indigenous zinc levels and in similar studies where several hundred parts per million of zinc salts were added to the sediments.

147. Chen et al. (1976) reported results of controlled laboratory experiments simulating long-term metal ion release from open-water disposal which indicated that the concentration of copper and nickel in the interfacial waters followed the order:

oxidizing > slightly oxidizing > reducing

More copper and nickel were released from sandy-type sediments than from the clay-type sediments. Chromium concentrations did not show any significant change under any redox conditions. An extremely slow rate of oxidation of chromium (III) to chromium (VI) in the aerated sea water may be responsible for the lack of redox effect. In contrast to the three metal ions discussed above, a sharp release of zinc occurred under oxidizing and slightly oxidizing conditions and clay sediments released more zinc than sandy sediments. Even under reduced conditions, more zinc was released than adsorbed in the long-term equilibration studies. However, it should be mentioned that the concentrations of most elements released were at a few parts per billion level, and were thought not to present any potential hazard to aquatic organisms.

148. Brannon et al. (1976) reported that zinc was released in elutriate tests of highly contaminated sediments where oxygen depletion probably occurred. Results from other elutriate tests were cited where

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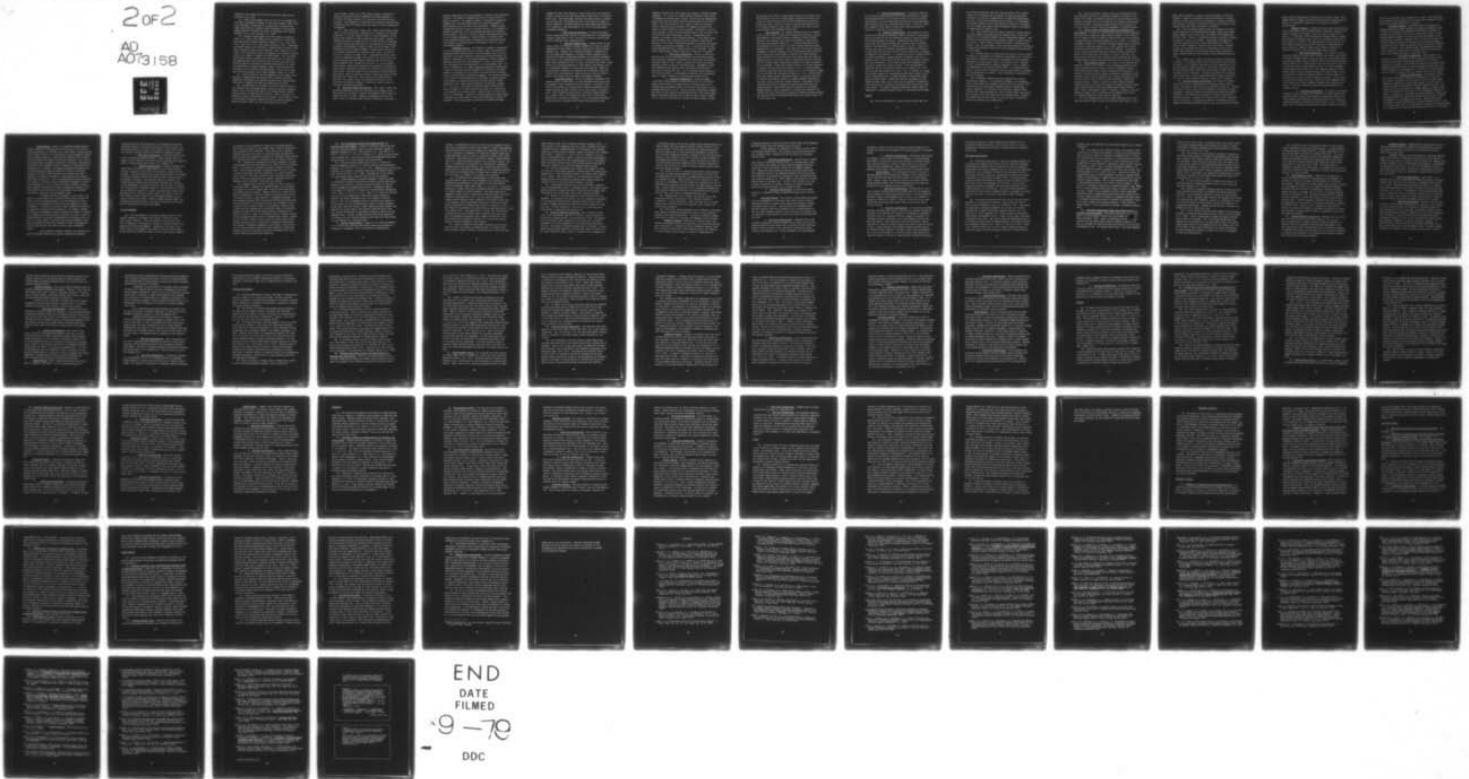
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substantial zinc release was not noted if dissolved oxygen was not permitted to go to zero.

149. These results suggest that zinc will not be released from even highly contaminated sediments in oxic water columns. Where a disposal environment is moderately to strongly acid (a condition more likely associated with long-term upland confinement of noncalcareous dredged materials) oxidation may result in substantial zinc release (Gambrell et al., 1977a; Brannon et al., 1978).

150. Numerous studies suggest that where present, sulfides of copper, zinc, nickel, and chromium control solubility of these metal ions under reduced sediment conditions (Gambrell et al., 1977a; Chen et al., 1976; Blom et al., 1976; Serne and Mercer, 1975). Large molecular weight organics also contribute to immobilization of many of these metals, especially under reduced conditions. Upon oxidation, an increase in the more mobile soluble, exchangeable, and carbonate fractions occurs at the expense of organic and sulfide phases. The controlling solids under oxidized conditions for these metal ions are carbonates and hydroxides which are more soluble than sulfides, resulting in potentially greater concentrations of mobile forms (Chen et al., 1976). The concentration of soluble chromium, copper, and nickel generally increased with an increase in dissolved oxygen. In the case of zinc, this effect was observed only in sandy sediments (Chen et al., 1976).

151. Hydrous oxides of iron and manganese are also thought to be effective in immobilizing these metals under oxidizing conditions, though their precipitation as insoluble sulfides under reducing conditions may be a somewhat more effective immobilization process.

152. Available data on the effect of salinity (Serne and Mercer, 1975) indicate that increasing salinity resulted in greater concentrations of zinc in the elutriate tests of all dredged material studied while the effect on copper was site specific. Data on the effect of salinity on nickel and chromium are not available. The biological uptake of toxic metals is generally inversely related to salinity (Huggett, Bender, and Slone, 1973), but this relationship does not hold

for all metals. Neff et al. (1978) reported higher accumulation of copper and chromium by benthic organisms from dredged sediment at 15 than at 20 percent salinity, but the pattern for nickel and zinc was mixed. The differences in speciation and solubility characteristics of metals in fresh and saline waters may account for their differential accumulation.

153. Plant toxicity of copper, zinc, nickel, and chromium is more likely to occur in an acidic, oxidized soil or sediment due to greater solubility of colloidal hydrous oxides of iron and manganese and subsequent less retention of other potentially toxic metals. However, a substantial fraction of copper and zinc is chelated with and complexed to organic material which may have an overriding effect in increasing solubility and subsequently uptake by plants (Ellis and Knezek, 1972). Published literature contains examples of severe plant toxicity due to excessive concentrations of available zinc, copper, or nickel in the soil at pH below 5.5 (Page, 1974). Jugsujinda and Patrick (1977) reported a significantly higher zinc uptake by rice plants under oxidized conditions than under reduced conditions and this effect was greatly magnified with a change in pH from 8 to 5. Low zinc uptake under alkaline, reduced soil conditions was attributed to sulfide and organic matter complexation reducing zinc solubility and subsequently plant uptake. Research studies on the accumulation of heavy metals by agricultural crops as a result of excessive sludge applications seldom show phytotoxic conditions. Plant toxicity due to high levels of available zinc, copper, nickel, and chromium in acid soils can be effectively alleviated by liming to convert more soluble cations to relatively unavailable hydroxides.

154. Selecting disposal alternatives. Zinc, copper, nickel, and chromium are generally less toxic than mercury and cadmium, though these metals can contribute to adverse environmental effects where contamination levels are high. Sediments contaminated only with zinc, copper, nickel, or chromium permit greater flexibility in selecting a

disposal method that will be environmentally acceptable and economically favorable. The degree of contamination will be a crucial factor in making a selection. For example, slightly or moderately contaminated sediments may be used for agricultural use, habitat development or marsh creation with a low risk to the environment. Sediments highly contaminated with one or more of the metals may have to be isolated to minimize contamination of the surrounding environment and subsequent adverse effects. For all of the major disposal alternatives discussed in the following paragraphs, a coarse-textured, low organic matter content dredged material highly contaminated with these metals should be considered a potentially greater environmental risk than typical fine-grained sediments.

Subaqueous disposal. The disposal of sediments contaminated with low to moderate levels of zinc, copper, nickel, and chromium by subaqueous methods should present a low environmental risk if the disposal site is not near sensitive or especially productive benthic ecosystems. Confinement in a low-energy depression or stable mounding in deep water will give the lowest potential for release and transport from the disposal site and subsequently a low environmental risk. Disposal in depressions or by stable subaqueous mounding and capping with a layer of clean material (See Paragraph 233) represents the optimum methods of confinement, but this level of precaution may be necessary only for the most highly contaminated sediments. The reduced conditions in most stable bottom sediments and the abundance of organic material would maintain or transform potentially available metals to highly unavailable forms. Water quality monitoring of open-water disposal (G. F. Lee et al., 1977; Wyeth and Sweeney, 1978) has demonstrated either no change or a slight increase in the metal ion concentration at the disposal site that returned to ambient levels in a very short time (5 to 90 minutes). Dilution of released metals with large volumes of disposal site water should preclude any possibility of toxicity to organisms. Unconfined disposal of moderately contaminated dredged

sediments in inlet zones adjacent to river inlets, bays, and estuaries directly flowing into the open waters should present only a low environmental risk. This high-energy erosional zone should result in substantial dilution with the flowing water with little impact on aquatic or benthic organisms. Unconfined disposal in high-energy areas would present a moderate to high environmental risk only for the most highly contaminated sediments.

i. Short-term considerations. No short-term adverse effects during open-water disposal are anticipated due to insignificant release of these metals, their relatively low toxicity, and the large dilution expected in most receiving waters.

ii. Long-term considerations. Elevated levels of zinc, copper, nickel, or chromium in dredged sediments may result in greater accumulation of these metals in benthic populations in the designated disposal site. Although low to moderate biological accumulations of zinc and copper should present no problems, benthic organisms can be protected from highly contaminated sediments by covering the sediments with clean or less contaminated material if stable mounding will occur. Where stable mounding will occur in large, well-mixed water bodies, there should be no long-term problem out of the disposal area whether or not the contaminated sediment is covered with clean material. Where confined disposal is achieved, the expected low to negligible long-term release to the overlying water column should pose a very low risk to aquatic water quality from even highly contaminated sediments.

Intertidal disposal. The use of sediments contaminated with moderate levels of these metals to create marshlands should pose a low environmental risk if planned and managed properly. Intertidal areas such as salt marshes are characterized by reduced environments rich in organic material and often sulfide, and are near neutral to alkaline in pH. These conditions should result in effective immobilization of zinc, copper, nickel, and chromium such that little of the soluble metals will be released to floodwater. It is also unlikely that marsh plant species will accumulate these metals from typically reduced

sediments to levels that would reduce plant growth or threaten consumer organisms. C. R. Lee et al. (1978) analysed potentially toxic metals in sediments and standing plant species collected from 28 dredging disposal sites along the Atlantic and Gulf Coastal region of the United States. The concentrations of zinc, copper, nickel, and chromium found in the marsh species growing at the disposal sites were very similar to those reported for natural marshes. There were a few locations, however, in which elevated concentrations of zinc and copper were found that may cause environmental concern. Contaminated coarse-textured, low organic content dredged materials or very highly contaminated sediments will increase the risk of uptake of excess metals. Therefore, use of highly contaminated sediments for habitat development may present a moderate environmental risk. In typical reduced, fine-grained dredged materials, leaching should not be a problem. Contaminated coarse-textured sediments would pose a high risk of leaching.

i. Short-term considerations. There is a moderate to high risk that initial dewatering effluents from intertidal disposal sites receiving contaminated sediments may contain total (and possible dissolved) levels of zinc, copper, chromium, and nickel that exceed applicable quality criteria of receiving waters. Management to maximize suspended solids removal within the disposal site should be effective in reducing this risk. If the receiving surface waters are well mixed and result in a high degree of dilution, the environmental threat to aquatic organisms in receiving waters should be low.

ii. Long-term considerations. In all but highly contaminated dredged sediments having fine-textured and considerable organic matter content, the long-term risk of adverse effects from leaching, plant and animal uptake, or of erosion and transport of contaminated particulates is low. Coarse-textured, contaminated sediments may result in some long-term leaching and possibly excess plant uptake. Highly contaminated sediments pose a moderate risk of excess accumulation of certain of these metals by plants and benthic animals, though

the reducing, near neutral pH environment expected at intertidal sites should minimize this risk. Capping highly contaminated sediments with a layer of cleaner materials and possibly managing plant populations should effectively reduce the potential long-term environmental risk of intertidal disposal of zinc, copper, chromium, and nickel contaminated sediments (See Paragraphs 238 and 239).

Upland disposal. For dredged sediments with low to moderate levels of zinc, copper, nickel, and/or chromium contamination, several environmentally sound upland disposal alternatives may be feasible because of the relatively low toxicity and mobility of these metals under many environmental conditions. It has been previously stated that maintenance of near neutral, strongly reducing conditions favors immobilization of these metals. Only long-term, ponded facilities with management to minimize leaching of water and maintain ponded conditions could provide these physicochemical conditions for upland disposal. Except possibly for a relatively low volume project with very high contamination levels, this rather rigorous alternative should be reserved only for the most highly contaminated sediments when other alternatives are not available. Except where dredged material will become moderately to strongly acid upon long-term oxidation, effective long-term immobilization of these metals may be achieved for many upland disposal methods for low and moderately contaminated dredged materials. Acidity development under upland disposal conditions presents the greatest potential for adverse environmental effects for dredged sediments contaminated with zinc, copper, nickel and possibly chromium. Development of acid conditions may result in substantial long-term leaching losses and enhanced uptake by plants which become established on the oxidized dredged material. Where development of strongly acid conditions are expected upon upland application, appropriate subaqueous disposal methods may offer less risk of contaminant mobilization and possible impact out of the disposal area.

i. Short-term considerations. The greatest potential for short-term problems associated with upland application of contaminated dredged material will be elevated levels of total and possibly soluble metals in initial dewatering effluents which exceed applicable water quality criteria for receiving surface waters. Practices to maximize suspended solids removal during initial dewatering should be effective in reducing this potential loss.

ii. Long-term considerations. The potential for mobilization and subsequent environmental impact is greater for many upland disposal alternatives than for subaqueous disposal in quiescent waters where stable mounding is achieved. Dredged materials which tend to become acid upon long-term drainage and oxidation offer the greatest potential for mobilization by leaching and plant uptake. Selection of disposal sites away from important groundwater supplies and selection of sites which have fine-textured soils will be beneficial in reducing contamination of groundwater. If leaching will not be a problem because of acidity development, dredged sediments contaminated with low to moderate levels of these metals may be safely used for habitat development, land reclamation, and even agricultural soils amendment with a low risk of uptake and cycling by plants. If the rooting depth is limed such that the final pH will be within the range 6.5 to 7.5 the risk of excess plant uptake will be low. Also, if leaching is a manageable problem, capping the contaminated material with a layer of clean or less contaminated soil or dredged material can effectively reduce plant and animal uptake. Adding lime uniformly throughout the bulk dredged material where lifts of many feet are planned in confined disposal sites may not be feasible for leaching control where acid conditions develop. For highly contaminated materials, efforts should be implemented to minimize long-term erosion of contaminated particulates.

#### Arsenic

155. The toxic properties of arsenic have been known longer and

utilized more extensively than most other potentially toxic elements. Arsenic has been manufactured in hundreds of organic and inorganic compounds for industrial, pharmaceutical, and pesticide applications, and many of these find considerable use even today. As a consequence, some dredged sediments may be contaminated with arsenic to the extent that this element may present some environmental threat at or adjacent to dredged material disposal sites.

156. Less is known about the chemical behavior of arsenic associated with dredging and dredged material disposal than for most other potentially toxic elements commonly found contaminating sediments. Less interest in anticipated adverse environmental impacts of arsenic may be due in part to fewer reported problems with arsenic in sediment-water systems. Also, the requirement of more specialized analytical procedures for arsenic has probably contributed to less information being available on this element.

157. Elevated levels of arsenic have been found in various tissues of shellfish, crustaceans, and freshwater and saltwater fish. Arsenic is also known to accumulate from aquatic environments by some organisms, especially by certain plants (Lunde, 1973; Woolson, 1975). Although arsenic is bioconcentrated by aquatic organisms, it is not thought to be biomagnified up food chains (Woolson, 1975). At sufficiently high levels, it may be toxic to sensitive vascular plant species as evidenced from the agricultural literature. Little information is available for marsh plant species.

158. Groundwater supplies have been contaminated by arsenic leaching from landfills. In contaminated sediments, the predominant arsenic forms present are inorganic arsenate ( $\text{As}^{5+}$ ) and arsenite ( $\text{As}^{3+}$ ) compounds and several methylated compounds which are formed under natural conditions. In a review of the literature, Johnston (1978) reported that, unlike methylmercury, there is some evidence that methylated arsenicals tend to be less toxic than inorganic forms. Arsenite, the reduced form, has been found to be far more toxic to plants and animals than arsenate, the oxidized form.

159. Thus the potential certainly exists for environmental problems associated with arsenic-contaminated sediments at disposal sites. However, only highly contaminated sediments will warrant rigorous environmental safeguards and it is believed that the potential environmental threat from arsenic contaminated dredged materials can be reduced to low level risks by proper selection and management of disposal methods.

160. Arsenic release from dredged material in laboratory and field studies. In studies of toxic material uptake by benthic organisms associated with dredging and dredged material disposal in San Francisco Bay, no changes in arsenic levels were detected that could be attributed to dredging-related activities (Anderlini et al., 1975a). In studies of contaminant release from 32 sediment materials ranging widely in physical and chemical properties, Brannon et al. (1978) reported that arsenic and mercury showed the greatest affinity for sediments. In long-term release studies, simulated subaqueous disposal actually improved the quality of overlying water with respect to arsenic. Elutriate test results and interstitial water levels were most predictive for arsenic exchange between sediments and overlying water after a period of 4 months.

161. Physicochemical effects. In a review of the literature and laboratory studies of the effects of pH and oxidation-reduction conditions on dissolved arsenic levels in soils and sediments, Johnston (1978) reported that arsenic release increased with increasing pH. In laboratory studies under both aerobic and anaerobic conditions, soluble arsenate, arsenite, methyl arsenate, and cacodylate were greater at pH 8.0 than at pH 5.0 and 6.5 after a 15-day incubation of Mobile Bay sediment material. Arsenic is subject to redox potential mediated changes in valence state within the range of oxidation-reduction conditions normally found in soils and sediment-water systems (Johnston, 1978). These transformations affect its mobility. Arsenite is the predominant inorganic form in reduced soils and sediment-water systems, but arsenate predominates under oxidized conditions.

162. The transformations between readily mobilized forms of oxidized and reduced arsenic species are relatively rapid (days to a few

weeks) when subjected to a change in redox environment in soils and sediments. Because of the greater toxicity and mobility of arsenite compared to other forms and the transformation of arsenate to arsenite under anaerobic conditions, problems with arsenic may be greater under reducing conditions unless the arsenic is confined.

163. Iron and aluminum hydrous oxides are reported to be an important regulatory process immobilizing inorganic arsenic and perhaps several organic forms (Jacobs, Syers, and Keeney, 1970; Johnson and Hiltbold, 1969). Removal of these hydrous oxides has greatly decreased the capacity of soil to fix arsenic. Development of strongly acid conditions apparently does not release large amounts of arsenic in soluble forms as commonly is found for most trace metals. Although strongly acid conditions may result in dissolution of hydrous iron oxides, which effectively retain arsenic under oxidized conditions, arsenic released tends to form sparingly soluble undisassociated acid forms.

164. Brannon et al. (1978) concluded that arsenic released from a sediment to an oxidized surface water column would not be a problem. For arsenic, as for numerous other metals, pH was identified as an important parameter regulating release. Unlike most toxic metals which are mobilized more under acidic conditions, arsenic release tended to be greater with increasing pH. Although large amounts of most metals were released when a stirred Oakland Inner Harbor sediment became very acid (pH 3.6) under oxidized conditions, arsenic was not released.

165. Selecting disposal alternatives. The release of sediment-bound arsenic and its transformations to chemical forms of varying toxicity are strongly influenced by physicochemical conditions. Arsenite is the most likely to cause toxicity problems to both plant and animal populations. Arsenite formation and stability are favored by reducing conditions. The formation and stability of arsenate are favored by oxidized conditions. Increase in pH tends to favor greater solubilization of both forms. In oxidized near neutral to moderately acid environments containing appreciable reactive iron, most potentially available

arsenic should be immobilized by adsorption with hydrous oxides. Thus, dredged material disposal conditions favoring greatest immobilization of arsenic in contaminated sediments will be oxidized and slightly to moderately acid.

Subaqueous disposal. Subaqueous disposal where stable mounding occurs will usually result in physicochemical conditions (reducing, near neutral) favoring the relatively toxic and soluble arsenite form of arsenic. In laboratory studies simulating low-energy hydraulic regimes where quiescent oxygenated water overlies the sediment, release has not been found to be a problem. The oxygenated water column and thin surface oxidized sediment horizon may be resulting in transformation of mobile arsenite to immobile arsenate with subsequent adsorption to hydrous iron oxides at the oxidized sediment-water interface.

i. Short-term considerations. The release of typically anaerobic sediments in surface water columns could release some soluble and readily available arsenic during settling and reconsolidation based on anticipated higher levels of soluble arsenic under reduced conditions. However, Brannon et al. (1978) reported that the elutriate test as well as long-term release studies showed that only 3 or 4 of 32 sediments tested released arsenic while all of the remaining sediments actually removed arsenic from the simulated disposal site water column. It was not possible to explain the observed behavior of the few samples releasing arsenic by other sediment parameters measured. The net removal of arsenic from disposal site water observed for most sediments may be due to hydrous iron oxide scavenging or perhaps other regulatory processes. In any case, substantial short-term arsenic release is not expected to occur.

ii. Long-term considerations. The reports and processes discussed previously indicate most sediments will remove arsenic from quiescent aerobic surface waters despite the probability that the interior sediment physicochemical conditions probably favor elevated interstitial inorganic and methylated arsenic levels. Only 1 of 32 sediments tested in long-term release studies showed a release at 8 months,

and this was relatively small (Brannon et al., 1978). Thus, long-term arsenic release is not expected to be a problem with subaqueous disposal where stable sediment deposition is achieved.

Intertidal disposal. Intertidal disposal may present the greatest problem with arsenic mobility and uptake by organisms, though it should be mentioned that insufficient information is available to document this at present. The bulk of reducing near neutral or mildly alkaline sediments deposited in intertidal sites will remain in this physicochemical condition. Enhanced levels of arsenic as arsenite and possible methylated arsenicals associated with these physicochemical conditions may favor uptake and cycling by plants and possibly enhanced toxicity to plants. Thus, sediments highly contaminated with arsenic offer a moderate to high risk for increased uptake and mobilization by plants which become established on intertidal sites.

i. Short-term considerations. Possible short-term problems would be from arsenic in initial effluents exceeding surface water quality standards during disposal operations as a result of soluble or, more likely, total arsenic associated with suspended solids. Implementing optimum methods for removing suspended solids should control this problem (See Paragraph 240). Elutriate test results indicate arsenic bound to suspended solids in effluents would not be released.

ii. Long-term considerations. Plant uptake of arsenic from typical fine-textured reduced bulk sediments at an intertidal site could be a problem as well as arsenite toxicity to marsh plants. Although the potential for these adverse impacts is greater than for a long-term impact associated with confined subaqueous disposal, such impacts have not been documented on dredged sediments, possibly because of lack of research into this aspect of the environmental behavior of arsenic. Selection of a low-energy site and precautions to confine the bulk solids within the disposal site should reduce the risk of erosion and dispersion of contaminated particulates. Because near neutral to alkaline, reducing conditions favor increased dissolved levels of several arsenic forms, there is some potential for gradual, long-term leaching if the disposal site favors net gravitational flow of interstitial water.

Upland disposal. Arsenic in contaminated dredged material applied upland may be transported from the disposal site by initial dewatering effluents, by leaching, or by plant uptake. Arsenic-contaminated sediments should not be placed above or near groundwater aquifers used for human consumption. There have been numerous cases of groundwater contamination by arsenic leaching from landfills. Also, the use of material highly contaminated with arsenic for habitat development or agricultural soils amendment presents a moderate to high potential environmental risk. However, the oxidizing conditions associated with most long-term upland disposal methods will do much to transform arsenite to the less soluble and less toxic arsenate form, and to immobilize the arsenate, especially in oxidized material containing appreciable reactive iron. Thus, the immobilizing processes associated with oxidized materials and certain supplemental management practices (See Paragraphs 143, 145, and 150) may be used to minimize potential adverse impacts associated with arsenic-contaminated sediments at upland disposal sites such that all but agricultural soils amendment may present a relatively low environmental threat.

For many other metal contaminants in this report, the effects of acid conditions on increasing soluble levels has been discussed. Selecting disposal methods to avoid development of acidic conditions or supplemental pH control have been suggested for these contaminants. It should be noted that arsenic solubility and mobility are apparently increased with increasing pH. For example, disposal alternatives and management practices favoring near neutral or alkaline pH to immobilize lead may increase the mobility of arsenic. Thus if a dredged material is seriously contaminated by both arsenic and one or more of the toxic metals, the relative potential environmental threat must be evaluated for each toxic substance to select environmentally sound disposal methods for arsenic as well as other contaminants present.

Where important subsurface aquifers are located near an upland confinement disposal site, arsenic leaching and subsequent

contamination may be best described as an intermediate-term problem. Substantial amounts of the relatively mobile and toxic arsenite form may possibly leach for a period of many weeks to several years before well-oxidized conditions develop and effectively immobilize arsenic.

i. Short-term considerations. Short-term problems with arsenic-contaminated sediments applied to upland disposal sites, if present, will be elevated total arsenic levels associated with suspended solids of initial dewatering effluents (See Paragraph 143).

ii. Long-term considerations. Potential long-term adverse effects of arsenic at upland disposal sites include leaching, toxicity to plants, or plant uptake and subsequent cycling in the environment. Long-term leaching into surface aquifers should be considered the greatest potential problem, and disposal sites should be selected and managed accordingly. Well-oxidized conditions throughout the dredged material profile will help minimize leaching, but a high pH or slow development of oxidized conditions could contribute to substantial contamination of subsurface aquifers. Except possibly for certain species especially sensitive to arsenic, long-term plant toxicity will generally not be a problem as arsenic tends to be present in the less toxic arsenate form in oxidized soils and dredged materials and adsorbed to hydrous iron oxides. However, dredged materials highly contaminated with arsenic should not be used for agricultural soil amendment or specifically for habitat development.

### Iron and manganese

166. Iron and manganese are discussed together because of their chemical similarity in sediment-water systems. Both may be toxic under certain conditions. They are essential trace nutrients, and they are important in regulating the release or retention of more toxic materials from soils and sediments. Unlike many of the other trace metals, both iron and manganese are subject to valence state transformations which occur within the range of pH and redox potential commonly

encountered in the environment and especially in dredged sediments. The activity and toxicity of the reduced form of each are accentuated under anaerobic low pH conditions. Under weakly acid to alkaline oxidized conditions, both form very insoluble oxides and hydroxides which can better be described as a mixture of compounds (usually present as clay-sized particulates or coatings on the clay mineral fraction).

167. Although iron accumulation by benthic organisms on contaminated sediments has been noted (Neff et al., 1978), iron is so slightly toxic it is usually not considered a problem to aquatic and benthic fauna. Under strongly anaerobic conditions where little to no sulfide is present, especially under acid conditions, it is more frequently toxic to plants. Even this situation is not a problem for most marsh plants as they have specialized air-transport tissue which tends to immobilize iron as insoluble oxides near root surfaces.

168. Manganese may be more of a problem as it may be toxic to plants and animals. Manganese is believed by many to be potentially the greatest or the most frequent metal toxicity problem anticipated with dredged material disposal. However, Shuba et al. (1978) did not implicate manganese as a toxicity problem to numerous benthic species in laboratory studies of high exposure to contaminated sediment. At most subaqueous disposal sites, dilution and mixing should effectively prevent impairment of surface water quality due to manganese release. Although it may be present because of contamination, natural levels in most soils and sediments may be sufficiently high for considerable manganese release under certain physicochemical conditions in the absence of dilution. There is an important kinetic difference between iron and manganese oxidation rates in sediment-water systems. Soluble ferrous iron will oxidize to ferric forms very quickly when reduced soluble interstitial iron is mixed with an oxygenated surface water. The oxidation of manganese is much slower, which accounts for the observed greater release of soluble manganese at subaqueous disposal sites and in effluents from upland confinement sites, even though transporting waters may be oxygenated.

169. Iron and manganese release from dredged material in laboratory and field studies. A number of laboratory studies and monitoring of subaqueous disposal sites have shown substantial release of manganese (Baumgartner et al., 1978; Brannon et al., 1976; Chen et al., 1976; G. F. Lee et al., 1975, 1977; Brannon et al., 1978), and much of this is in dissolved form. Iron does not usually show comparable short-term release because of its rapid oxidation and precipitation.

170. Long-term release studies show little or no increase in dissolved manganese because of its eventual oxidation and precipitation (Brannon et al., 1978; G. F. Lee et al., 1975). Manganese and iron have been reported to be released in relatively high levels in effluent from upland confined sites (Lu et al., 1978). Although most of this release is in particulate forms, dissolved levels may also be elevated.

171. Though manganese in pipeline discharge or upland effluents is considered a potential short-term water quality problem, many experts believe it will rarely be a problem in practice because of rapid settling of manganese-contaminated particulates, scavenging by hydrous iron oxides, and especially by dilution in receiving waters (Baumgartner et al., 1978; G. F. Lee et al., 1975). Mang et al. (1978) have reported that both iron and manganese are potentially serious problems in leachate from upland confinement sites in the absence of dilution effects. Both iron and manganese levels in leachates were reported to be very high and to exceed existing water quality criteria standards. Though these laboratory leachate columns simulating upland disposal were monitored for several months, well-oxidized conditions may not have been obtained contributing to substantial leaching of reduced iron and manganese forms. However, dredged materials which become moderately to strongly acid upon eventual oxidation would likely also leach excess iron and manganese on a long-term basis.

172. Physicochemical effects. Brannon et al. (1976) and Gambrell et al. (1977a) have used selective chemical extraction procedures to determine the predominant form of these metals in sediment-water

systems. A substantial portion of the total iron and manganese content was found in potentially reactive forms subject to redox transformations. Reduced noncalcareous soils and sediments with appreciable reactive iron (iron in dissolved, exchangeable, and especially reducible forms) may become moderately acid as a result of long-term oxidation under upland conditions. Where high levels of sulfide are present, acidity development due to long-term sulfide oxidation can be much more intense. However, in considering the suitability of a noncalcareous contaminated dredged material for upland disposal, both sulfide and reactive iron levels should be considered as development of acid oxidizing conditions can reduce the scavenging effect of hydrous ferric oxides and may result in release of a number of toxic metals into leachates.

173. The adsorption and coprecipitation of heavy metals with colloidal hydrous oxides of iron and manganese is an important process regulating the availability of trace metals in soils and sediments (Taylor and McKenzie, 1966; Jenne, 1968, G. F. Lee, 1973). Considerable quantities of soluble and easily exchangeable divalent iron and manganese are usually present in reduced sediments. When large quantities of oxygenated surface waters are mixed with interstitial water and reduced sediments containing ferrous iron, as occurs during dredging and dredged material disposal, rapid oxidation of the soluble ferrous iron to the amorphous ferric oxyhydroxide particulate form occurs rapidly. Freshly precipitated colloidal hydrous oxides are thought to be much more effective in adsorbing trace metals than are aged materials (G. F. Lee, 1973; Windom, 1972). This aging effect is likely due to the improved crystallinity and reduced surface area of hydrous oxides that occur with time (MacKenzie and Meldau, 1959; Langmuir and Wittemore, 1971). This process may be especially effective as a trace metal scavenger during dredging and dredged material disposal.

174. Several studies have shown small decreases in the soluble levels of other trace metals in dredged slurries, in surface waters near open-water disposal outfalls, in water from weir outlets draining

diked disposal areas, and in laboratory simulated dredging studies. In these studies, it was suggested that heavy metal scavenging by freshly precipitated ferric oxyhydroxides may be contributing to the observed reduction in soluble metals (Lindberg, Andren, and Harriss, 1973; Windom, 1972, 1973b). Brannon et al. (1976) found that sediments with much iron in interstitial water tended to release less metals and phosphate. Metals coprecipitated with ferric oxyhydroxides are not in equilibrium with the solution phase as long as the pH-redox potential environment favors the stability of the iron and manganese hydrous oxides.

175. Several investigators have reported that cadmium is either not adsorbed or more weakly adsorbed to hydrous oxides than other metals (Brannon et al., 1976; Kinniburgh, Sridhar, and Jackson, 1977; Gambrell et al., 1977a). This may contribute to the substantial increase in cadmium mobility and availability observed under oxidized conditions compared to most of the other metals commonly of interest.

176. The greatest potential acute toxicity problem in anaerobic soil and sediment-water systems is hydrogen sulfide. This highly soluble gaseous material is formed from sulfate reduction under strongly reducing conditions and is extremely toxic to both plants and animals.

177. Because of the usual excess of iron in anaerobic soils and sediments, its reactivity with sulfide, and the extremely low solubility of the resulting ferrous sulfide, hydrogen sulfide is almost never a problem in dredged material even though total sulfide levels are often very high. The only exception to this will be in a few marsh soils where sulfide is especially high and pH is low.

178. Selecting disposal alternatives. Iron is among the least toxic of the trace metals, and acute or chronic toxicity problems associated with dredged material are not expected to occur. One problem area is leaching of high concentrations of soluble iron from upland confinement sites into groundwater at levels which exceed applicable criteria. This potential long-term problem may occur because: (1) many upland applied dredged materials containing high levels of soluble iron may remain reduced for weeks, months, or possibly years releasing iron

to percolating waters; and (2) where upland applied dredged material becomes strongly acid upon eventual oxidation, excess iron may be solubilized because of the pH effect and leach into subsurface aquifers. Where the original soil is fine textured and groundwater aquifers are deep and offer considerable dilution, leaching of iron from upland sites may be of little concern as much of the excess iron may be removed at the dredged material-soil interface. Unless precautions are taken to control long-term leaching, dredged material containing considerable reactive iron should not be placed over shallow aquifers which provide water for domestic purposes.

179. Except for the cases indicated above where acidity development may occur under upland conditions, high levels of reactive iron in dredged material and especially contaminated dredged material should be considered an asset. Excess soluble iron will not persist in non-acid aerobic environments, and the oxidized iron compounds will tend to immobilize most phosphorus and toxic metals at dredged material disposal sites. Excess soluble interstitial iron in contaminated dredged sediments should be especially effective in decreasing short-term soluble levels of more toxic metals at subaqueous disposal sites.

180. Manganese may also be released into leachate water under conditions previously described for iron, possibly creating an intermediate- or long-term problem. Again, this may not be a serious problem unless affected aquifers are important water resources for nearby human consumption.

181. Unlike iron, soluble manganese can be released in potentially toxic levels at subaqueous disposal sites and in initial dewatering effluents from upland confined sites. Practices to minimize suspended solids will be effective in reducing total manganese and iron release.

Subaqueous disposal. Because of its limited toxicity and effective scavenging for more toxic materials under oxidized conditions, iron release will be a desirable process at subaqueous disposal sites. Even in quiescent waters where stable mounding occurs, the formation of a thin oxidized surface horizon on mounds of dredged material

containing appreciable reactive iron will further reduce toxic substances which may diffuse toward the sediment-water interface.

Soluble manganese can potentially be released at toxic levels at subaqueous disposal sites. The potential for acute short-term toxicity problems within a disposal area may be greater for this metal than any other.

i. Short-term considerations. Iron will not be a short-term problem at subaqueous disposal sites. As discussed above, there is the potential for release of excess dissolved manganese which may contribute to short-term adverse effects in the immediate disposal area. Mixing with large volumes of disposal site water should limit toxic manganese levels to the designated disposal site such that adjacent areas will be unaffected and laboratory studies representing worst case conditions (Shuba et al., 1978) suggest there should be no toxicity problem within the disposal site. The use of the elutriate test, mixing zone calculations, and benthic bioassays can identify potential short-term problems associated with a proposed project.

ii. Long-term considerations. No long-term problem from iron or manganese release at subaqueous disposal sites is anticipated.

Intertidal disposal. The potential release modes and problems for iron and manganese at intertidal sites include losses in initial dewatering effluents, leaching, plant uptake and subsequent transport, and possible plant toxicity. Leaching losses into groundwater and adjacent nearshore areas are not expected to be a problem because of the usual small hydraulic gradient, their relatively low toxicity, and the retention of these metals by adsorptive processes and precipitation reactions.

i. Short-term considerations. Implementation of best available technology to reduced suspended solids levels in initial dewatering effluents should reduce most of the iron and much of the manganese in these effluents to meet applicable surface water quality criteria (See Paragraph 240). Soluble manganese levels may sometimes

be present in excess in which case adequate effluent mixing with receiving site waters may be important in reducing manganese to acceptable levels.

ii. Long-term considerations. Because most marsh plants have adapted to high levels of iron and manganese in rooting mediums and because of specialized tissue which maintains an oxidized rooting zone, excessive uptake or toxicity to marsh plants is not expected to cause long-term problems even though levels of available iron and manganese may be high in dredged material placed in intertidal zones.

Upland disposal. Iron and manganese losses in initial dewatering effluents and leaching into groundwater are the greatest potential problems associated with these elements at upland disposal sites. However, under the oxidizing conditions associated with most upland disposal methods, both iron and manganese may play long-term beneficial roles in immobilizing more toxic metals.

i. Short-term considerations. As described for intertidal disposal, potential short-term problems with iron and manganese can be minimized by controlling suspended solids in initial dewatering effluents, though soluble manganese may continue to be a problem if mixing and dilution are limited. Problems, if any, may be more associated with meeting applicable water quality criteria than actual toxicity effects.

ii. Long-term considerations. In noncalcareous dredged materials containing high levels of reactive iron, gradual drainage and subsequent iron oxidation may contribute to development of moderately acid (pH 6.5-pH 5.0) conditions which will enhance the mobility (i.e. leaching) and plant availability of iron and manganese and many other more toxic metals. Where appreciable sulfides are present, acidity formation as a result of sulfide oxidation will tend to mask the effects of iron. In many reduced, upland applied dredged materials which do not become acid upon oxidation, leaching of excess iron and manganese may occur for a few months to a few years before levels decrease because this length of time may be required before drainage and oxidation

of the bulk solids occur. Where strongly acid conditions will not develop upon long-term oxidation, high levels of reactive iron and manganese will effectively contribute to immobilization of potentially toxic metals.

#### Chlorinated hydrocarbons

182. Chlorinated hydrocarbons of interest in dredged sediments include pesticide compounds such as DDT as well as industrial compounds. Polychlorinated biphenyls (PCB's) constitute one class of industrial hydrocarbons often found in sediments which is toxic and very persistent. Manufacture, use, and disposal of many of these compounds have been restricted by Federal action, but contaminated environments may remain contaminated for years (Burks and Engler, 1978). Chlorinated hydrocarbons are widely distributed in inland and coastal sediments and have been found in deep ocean sediments far from shore. PCB's are more frequently detected in sediments than chlorinated pesticides with the possible exception of the DDT group. Other chlorinated hydrocarbon pesticides are often found in sediments subject to dredging, but usually these are the result of localized contamination (Burks and Engler, 1978).

183. Chlorinated hydrocarbons have been found in fin fish tissue, sometimes at concentrations considered a threat should the fish be used for human consumption (Young, Jan, and Heesen, 1977). Some reports have implicated contaminated sediments as the source for observed accumulations by aquatic and benthic organisms (Young et al., 1977, Pavlou et al., 1978; Sameshima, 1977; Hirsch, DiSalvo, and Peddicord, 1978; Belaire and Alexander, 1976). In many of these cases, only small accumulations were noted. Many other studies have emphasized little or no increase in tissue levels of animals exposed to chlorinated hydrocarbons in sediments (Hirsch et al., 1978; G. F. Lee et al., 1977). Shuba et al. (1978) did note some toxicity to benthic organisms exposed in laboratory studies simulating subaqueous disposal, but these studies

represent worst case exposures and the organism response was not always consistent.

184. In a review of the literature, Belaïre and Alexander (1976) reported that even short-term exposure to certain chlorinated hydrocarbons in water has resulted in significant biomagnification in oysters and clams and that water concentrations of certain pesticides and PCB's are apparently high enough at present to cause concentration and bioaccumulation of these materials in organisms of Texas estuaries (Belaïre and Alexander, 1976). Except in highly contaminated sediments, the primary accumulating benthic organisms do not show acute toxicity symptoms and appear to live a normal life cycle. Concern over uptake and accumulation by most of these organisms is directed to unknown chronic effects, bioaccumulation in complex food webs, and particularly chronic effects on human consumers. Many of these compounds have been shown to have deleterious effects at low levels in the environment. PCB's are toxic to freshwater organisms at concentrations below 5 µg/l (USEPA, 1976a). The EPA proposed surface water quality criterion is 0.001 µg/l for PCB's. Because of the documented toxicity of many chlorinated hydrocarbons and the demonstrated potential for their biological accumulation, disposal methods for sediments contaminated with high levels of chlorinated hydrocarbons should be selected for containment to minimize further transport and biological exposure of these materials. Adverse impacts, if any, should then be limited to designated disposal sites.

185. Chlorinated hydrocarbon release from dredged material in laboratory and field studies. Chlorinated hydrocarbons are strongly bound to the solid phase in typical soil and sediment-water systems (Burks and Engler, 1978). Unless a contaminated sediment is coarse textured with low organic matter content, dissolved compounds will exist at extremely low levels such that this form will not be an acute environmental threat. An exception may be where a very high suspended

solids to water ratio exists. In elutriate tests with variable ratios, a 20 percent suspended solids system resulted in release to soluble forms while a 5 percent suspended solids system showed less release or no release (G. F. Lee et al., 1977).

186. The presence of oil and grease in sediments is reported to effectively reduce release of chlorinated hydrocarbons into the water phase (Brannon, 1978; Burks and Engler, 1978) where suspended solids are controlled. Where substantial suspended solids are present, the oil and grease content of the suspended particulates has been found to be much more important in regulating total levels of suspended chlorinated hydrocarbons than actual levels of suspended solids (Burks and Engler, 1978). Some reports have suggested the simultaneous occurrence of both oil and grease and chlorinated hydrocarbons may enhance bio-availability (G. F. Lee et al., 1975).

187. In field studies designed to determine the potential for long-term release at subaqueous disposal sites, no such release has been found (Brannon et al., 1978).

188. Studies of contaminated dredged material disposal have found total chlorinated hydrocarbons in effluents from upland confinement facilities to exceed existing regulatory criteria for surface waters (Lu et al., 1978). Although tightly bound by the suspended particulates, it is believed that this represents a threat as a consequence of transport from the disposal site and possible release after ingestion of contaminated particulates. Disposal methods selected to minimize suspended solids will reduce these risks.

189. In field studies simulating upland dredged material disposal, leaching of chlorinated hydrocarbons has been found to be minimal (Mang et al., 1978). Factors contributing to minimal leaching from upland sites include the following: (a) a fine-textured dredged material underlain by fine-textured soil; (b) high organic matter and possibly hydrous oxide content of both dredged material and disposal site soil; (c) the depth of fine-textured underlying soil between contaminated material and important subsurface aquifers; and (d) water management to reduce leaching potential.

190. Relatively little is known about uptake of toxic synthetic organic compounds by terrestrial vascular plants. A cautious approach in selecting disposal methods would be to minimize opportunity for uptake and subsequent environmental cycling by this route. It has been reported that volatilization of kepone from contaminated dredged materials and subsequent adsorption on aboveground plant tissue may be a more important transport mechanism than uptake and internal plant translocation in some cases (Lunz, 1978). In these studies of contaminant accumulation by marsh plants, Lunz (1978) did not find consistent nor substantial plant accumulation of several chlorinated hydrocarbons to be a major problem.

191. Physicochemical effects. Properties of sediment-water systems affecting flocculation of suspended solids are thought to be important in transport and perhaps bioavailability of chlorinated hydrocarbons. These properties include organic matter content, salinity, iron and manganese content, pH, and oxidation-reduction conditions. Although pH may have an effect on desorption of ionizable synthetic organic molecules, it probably has little effect on neutral compounds (Belaire and Alexander, 1976). Murakami and Takeishi (1977) reported no direct influence of pH and redox potential on the concentration of dissolved PCB's. Oxidation-reduction conditions are known to affect the degradation rate and products of chlorinated hydrocarbons (Gambrell and Patrick, 1978). However, not all compounds are significantly affected by altered physicochemical conditions and there is no information available of physicochemical effects on degradation rates of most chlorinated hydrocarbons.

192. Selecting disposal alternatives. Because of the very strong partitioning of chlorinated hydrocarbon compounds with the solid phase in sediment-water systems, disposal methods for sediments contaminated with these compounds giving long-term confinement of the bulk contaminated solids, and especially control to minimize transport of suspended particulates from the disposal site, will be most effective in reducing the environmental risk associated with disposal of chlorinated hydrocarbon-contaminated sediments.

Subaqueous disposal. Dredged material contaminated with chlorinated hydrocarbons should be isolated from economically and ecologically important biological populations like shellfish beds and key spawning and nursery areas.

Subaqueous disposal sites characterized by low-energy hydraulic regimes (not subject to strong bottom currents due to wind, high discharge flow from rivers, or natural or storm currents) will minimize bulk sediment transport as well as resuspension and transport of contaminated particulates and should result in a very low environmental risk out of the designated disposal area. Covering with clean material in quiescent waters will greatly reduce the possibility of adverse effects even in the disposal area.

i. Short-term considerations. Field studies at the Duwamish disposal site in Washington have shown PCB release to be highly transient and correlated with an increase in suspended solids (Pavlou et al., 1978). Chlorinated pesticides have been shown to be released with levels returning to normal within 30 minutes in San Francisco Bay (Anderlini et al., 1975b). A contaminated, coarse-textured material may result in short-term release of potentially harmful levels of dissolved synthetic organics, but release of harmful concentrations of dissolved forms from typical fine-textured sediments should not be a problem.

ii. Long-term considerations. Because of the long-term stability of many chlorinated hydrocarbons in sediments, their toxicity at very low concentrations, the potential for biological uptake, and their association with the solid phase, confinement of highly contaminated dredged materials should be emphasized to reduce the environmental risk of disposal. Long-term problems with chlorinated hydrocarbon-contaminated sediments, if any, will be associated with gradual release and subsequent accumulation by aquatic and benthic organisms. In quiescent waters, release directly from contaminated sediments to the water column should pose a low environmental risk. Potential long-term problems can be reduced to very low levels by selection of a disposal

site away from economically and ecologically important biological populations, selection of a site giving long-term stable mounding, and covering highly contaminated dredged material with clean or less contaminated dredged material.

Intertidal disposal. Very coarse-textured sediments would not normally accumulate chlorinated hydrocarbons. However, if this were the case because high levels of chemical discharge occurred in a localized area to a sandy sediment, intertidal disposal would present a high risk of mobilization and enhanced biological availability.

Intertidal sites susceptible to gradual erosion and intense biological colonization would present a moderate risk to colonizing organisms and possibly affect quality of nearby surface waters.

i. Short-term considerations. A potential short-term problem with intertidal disposal is transport of chlorinated hydrocarbon-contaminated suspended solids from the disposal area into adjacent near-shore surface waters which tend to be biologically active. As previously discussed, efforts to minimize release of contaminated suspended solids into adjacent surface waters during disposal and dewatering should minimize possible short-term effects on water quality (See Paragraph 240).

ii. Long-term considerations. Until more is known about terrestrial plant uptake and subsequent input into food webs, intertidal disposal of highly contaminated sediments where intensive habitat development will occur should be considered a moderate risk. If the contaminated solids can be physically contained on a long-term basis, a layer of clean material placed over the contaminated sediment should reduce this risk to low levels (See Paragraph 238). The layer of clean material should be sufficiently thick to comprise the rhizosphere of plants which will colonize the sites to minimize plant uptake, ingestion of contaminated particulates by grazing organisms, and surface wind and water erosion of contaminated particulates.

Upland disposal. Highly contaminated materials should probably not comprise a rhizosphere. If the contaminated material is

covered with a layer of clean material and plant populations managed to favor relatively shallow-rooted plants, the risk of chlorinated hydrocarbon accumulation by volatilization or uptake into plants and animals populating the site should be minimal.

Containment in sealed, ponded (no drainage) upland confinement facilities will possibly present the lowest environmental risk of the upland disposal alternatives. However, this rather rigorous alternative should rarely be required to achieve environmentally safe disposal. Also, because of the strong affinity for sediment particulates, non-ponded confinement (managed to enhance dewatering) should present a low environmental risk if effluents are controlled to reduced suspended solid levels.

Use of chlorinated hydrocarbon-contaminated sediments with the specific intention of habitat development, or agricultural soils amendment represents a moderate to high environmental risk.

Unconfined upland disposal not specifically intended for habitat development will generally represent a moderate risk as the site will be subject to biotic colonization with time, and because a larger surface area will be affected than with confined disposal. Covering with a thin layer of clean material for unconfined upland disposal may not be feasible because of the relatively large surface area per unit volume of contaminated material implied with this disposal method.

i. Short-term considerations. Short-term problems, if any, will be associated with impairing the quality of surface waters receiving initial dewatering effluents from contaminated suspended particulates. Practices to minimize suspended particulates from moving into surface waters can be implemented to control short-term release (See Paragraph 243).

ii. Long-term considerations. Leaching and contamination of groundwater will not be a problem unless the contaminated dredged material or disposal site subsurface soil is coarse textured, though a site should not be directly over important subsurface aquifers.

Plant uptake should also present a low risk of cycling chlorinated hydrocarbons in all but highly contaminated sediments. As previously discussed, covering with clean soil or dredged material can reduce this risk.

#### Petroleum hydrocarbons

193. Petroleum hydrocarbons include a wide range of compounds with molecular weights of 16 to well above 20,000. The main structural groups are saturates or straight chains (alkanes or paraffins), branched chains (isoprenoid), naphthenics (cycloparaffins), unsaturates (olefins), and ringed compounds (aromatics).

194. The toxicity of petroleum hydrocarbons generally depends on the content of the aromatic fraction, especially the multiringed aromatics which are likely to persist in sediment for extended periods since they are very resistant to degradation. Alkanes, on the other hand, are the least toxic and also degrade rapidly.

195. Petroleum hydrocarbons from anthropogenic sources are widely distributed in sediments. Some studies have demonstrated potential adverse effects of petroleum hydrocarbons on marine organisms and some accumulation from contaminated sediments and seawater (Pequegnat et al., 1978). Numerous other studies with contaminated sediments have shown that little uptake occurs even under "worst case" conditions and that benthic organisms exposed to badly contaminated sediments do not show significant acute toxicity during exposure periods lasting up to several weeks (Hirsch et al., 1978; DiSalvo et al., 1977). Reported inconsistencies of the adverse biological impact of petroleum hydrocarbons associated with sediments are likely due to differences in species, properties of sediments studied, the chemical nature of the contaminating petroleum hydrocarbons, and other site or study dependent differences and experimental parameters.

196. There are numerous stringent state or Federal water quality criteria establishing maximum acceptable levels for petroleum

hydrocarbons in surface waters. Monitoring of actual disposal operations has shown that total petroleum hydrocarbons in effluents or disposal site water do frequently exceed many of these criteria on a short-term basis. Generally, established criteria are based on organism exposure to dissolved hydrocarbons. Because most of the compounds present in a water column are associated with suspended particulates, the actual impact, if any, may be less than expected based on comparisons of available criteria with total concentrations of petroleum hydrocarbons measured in a water column at the disposal site. Studies of upland confinement facilities have shown that, while total petroleum hydrocarbon levels in effluents often exceed criteria levels, the actual soluble levels are usually well below these criteria.

197. Petroleum hydrocarbons do not pose a long-term threat to surface water quality. This is because of the strong association of petroleum hydrocarbons for solids in sediment-water systems (Van Vleet and Quinn, 1977; DiSalvo et al., 1977) and subsequent settling of suspended solids. Also, volatilization, photomodification, and apparent greater microbial degradation in surface waters than sediments contribute to losses from the water column. The greatest potential adverse impact of petroleum hydrocarbons associated with dredged materials will be long-term concentration by benthic organisms, possible toxicity to these organisms in rare cases, and perhaps slowing of benthic recolonization of new sediments subsequent to dredged material disposal.

198. Oil from major spills is known to disperse rapidly and to have little impact in some areas such as deep ocean waters far from shore, but may persist and remain toxic to organisms for years in protective bays and marshes (Kerr, 1977). Toxicity of oil, where present, may be prolonged by its association with sediment (DiSalvo et al., 1977).

199. Petroleum hydrocarbon release from dredged material in laboratory and field studies. Release of petroleum hydrocarbons into the water column during dredging and dredged material disposal has been shown to be minimal in both laboratory and monitored disposal studies

(G. F. Lee et al., 1977; DiSalvo et al., 1977). Elutriate test results have shown levels in the elutriate were quite low, even with extremely oily sediments (Engineering Science, Inc., 1977). The concentration measured in the dilution water sometimes exceeded levels in the elutriate indicating absorption was occurring even from extremely contaminated sediments. Where release has been found, the material is associated with suspended solids (DiSalvo, 1977; Engineering Science, Inc., 1977).

200. Interest in petroleum hydrocarbon contamination has also been directed to its possible role in mobilizing toxic metals and chlorinated hydrocarbons. Studies have shown that the release of certain chlorinated hydrocarbons into the aqueous phase is less from sediments containing appreciable amounts of petroleum hydrocarbons (Brannon, 1978). However, because of likely greater retention of chlorinated hydrocarbons in oil and grease-contaminated sediments, there is some concern that deposit feeders may accumulate more chlorinated hydrocarbons if sediments contain oil and grease (G. F. Lee et al., 1975). G. F. Lee et al. (1975) also suggested that dredging and perhaps dredged material disposal of oil and grease-contaminated sediments may result in surface slicks enriched in toxic metals as well as toxic cyclic and aromatic hydrocarbons. In one study (Lu et al., 1978), trace metals associated with oil and grease released from an upland containment facility were reported to be negligible. In this particular study, it was also found that the association of chlorinated hydrocarbons with oil and grease was not significant. In another laboratory study of simulated dredged material disposal, there was little conclusive evidence that petroleum hydrocarbons may mobilize trace metals (Blom et al., 1976).

201. Physicochemical effects. Oil and grease have been reported to be more tightly bound to sediments in saline water than fresh water (Engineering Science, Inc., 1977). Oxidation-reduction conditions are reported to have a marked effect on the persistence of petroleum hydrocarbons. Again, there is some conflicting information which is likely

due to differences in the chemical composition of the petroleum hydrocarbons studied and other experimental conditions. Some have reported no differences in degradation rates under aerobic and anaerobic conditions during 30 days (DiSalvo et al., 1977). Others have reported greater loss of volatiles and hexane extractable oil under anaerobic conditions than aerobic conditions (Shelton and Hunter, 1975). It is generally believed that anaerobic conditions favor persistence of petroleum hydrocarbons in sediments relative to aerobic environments (DiSalvo et al., 1977; Walker, Colwell and Petrakis, 1975a, b), possibly as a result of the influence of redox potential on the kinds and activities of microorganisms present.

202. In summary, the literature generally indicates that sediment-bound petroleum hydrocarbons probably have relatively little impact during most dredging and dredged material disposal operations, but represent a potential biological hazard. Thus exposure of organisms from dredging and dredged material disposal should be minimized, though in many cases efforts to confine petroleum hydrocarbons may not need to be as rigorous as for dredged material contaminated with certain other potentially toxic materials.

203. Selecting disposal alternatives. Some petroleum hydrocarbon deposits are more toxic and/or soluble than others due to their chemical composition. Thus, the elutriate test and especially benthic bioassays should be conducted to determine release, benthic availability, and toxicity.

204. An environmental distinction should be made between major petroleum hydrocarbon spills and petroleum hydrocarbon contamination of sediments. Major spills in open ocean waters are apparently dispersed and assimilated into the environment with sometimes surprisingly little measurable impact (Kerr, 1977). The physical and biological effects of major spills are substantial and may be considered no less than disastrous where shorelines, estuaries, and enclosed bays are affected. However, this degree of concern may not be warranted for the environmental threat of petroleum hydrocarbons associated with typically

contaminated sediments. Although potentially harmful to the environment with some documented very localized impact, sediment-bound petroleum hydrocarbons appear to be far less an environmental threat than chlorinated hydrocarbons or some toxic metals at equal levels of contamination. Certainly, disposal of highly contaminated sediments in or near important spawning and nursery areas, especially productive benthic communities, and in areas where production is harvested for human consumption should be avoided.

205. Because the chemical composition and subsequently the toxicity of petroleum hydrocarbon contaminants may vary considerably, results of benthic bioassays and elutriate tests should be considered in addition to total levels of contamination in evaluating the degree of confinement which should be attained with the selected disposal alternatives. As recommended for many other contaminated sediments, disposal alternatives should be selected and managed for more rigorous confinement where the concentration and/or toxicity of the petroleum hydrocarbons is found to be especially high. If the contaminating petroleum hydrocarbons are found to be relatively nontoxic, disposal methods giving a gradual loss of contaminated material from the disposal site may represent a relatively low environmental risk compared to sediments contaminated with many other potentially toxic materials.

Subaqueous disposal. Sediments contaminated with high levels or particularly toxic forms of petroleum hydrocarbons placed into or near economically and ecologically important aquatic and benthic habitats represents a high environmental risk. At sites well away from especially critical habitats, some reworking and resuspension of contaminated dredged material with gradual loss from the disposal site may represent a low risk if bioassays show minimal toxicity (Pequegnat et al., 1978). An example is subaqueous disposal in a moderate- to high-energy water column. A moderate- to high-energy subaqueous disposal site would result in transport of the material into open waters favoring maximum dispersion and dilution. Subaqueous disposal in depressions or low-energy hydraulic regimes where stable mounding will

occur is desirable where the petroleum hydrocarbons are found to be especially toxic. The extra expense in transporting the material to such a site may not be justified for the reduced environmental risk for many petroleum hydrocarbon-contaminated dredged materials. Subaqueous containment will usually result in anaerobic conditions which favor the persistence of petroleum hydrocarbons. Relatively inert, nonsoluble petroleum hydrocarbons in dredged materials which are reworked, resuspended, and gradually dispersed from the disposal site will likely have little short- or long-term adverse environmental impacts (Pequegnat et al., 1978). With typical fine-textured dredged materials, the petroleum hydrocarbons will be tightly bound to the solid phase and essentially unavailable except possibly to deposit and filter feeders. Also, reworking, resuspension, and transport will tend to keep the materials in an aerobic and aquatic environment which may ultimately enhance their degradation. In conclusion, containment of petroleum hydrocarbon-contaminated sediments would be most effective in minimizing environmental impact. However, initial confinement which permits a slow loss of low toxicity material from the disposal site may represent a low environmental risk as the petroleum hydrocarbons will tend to be lost from the sediment-water systems by physical, chemical, and biological processes in oxidized environments associated with gradual dispersion.

i. Short-term considerations. Short-term problems with petroleum hydrocarbon-contaminated sediments may be in conforming to existing surface water quality criteria. The short-term biological effects of subaqueous disposal are expected to be minimal. Very transient increases in petroleum hydrocarbon levels associated with turbidity plumes have been reported at an underwater disposal site in Texas where levels return to predisposal conditions within minutes (G. F. Lee et al., 1977). An exception would be a coarse-textured contaminated dredged material. Although coarse-textured, low organic matter sediments are generally not effective sinks for petroleum

hydrocarbon wastes, localized contamination may occur. Petroleum hydrocarbons associated with such materials may tend to be entrained rather than adsorbed resulting in greater release to a soluble or free form upon disturbing a sediment.

ii. Long-term considerations. Highly toxic petroleum hydrocarbon-contaminated sediments may have a localized adverse effect on benthic organisms within the disposal area. Benthic recolonization of new sediments may be slow relative to clean sediments, but long-term recolonization will not be affected (Burks and Engler, 1978). It is unlikely any adverse impact would occur out of the disposal area if stable mounding (confinement of contaminated solids) were achieved. Out of the designated disposal area, adverse environmental impacts may be minimal even where unconfined disposal (deposition in a high energy regime) is used though caution suggests the site should not be near especially sensitive or productive habitats.

Intertidal disposal. Intertidal disposal will result in predominantly anaerobic conditions for the bulk of the deposited dredged material. This favors the stability of petroleum hydrocarbons. A continuous, thin oxidized layer of variable thickness (depending on tidal duration and frequency) may favor enhanced degradation, volatilization, and photochemical oxidation on the exposed surface. At concentrations found in most contaminated sediments, there will be little adverse effects on plant colonization or growth. Unless the elutriate tests should indicate great release and benthic bioassays indicate substantial toxicity, petroleum-contaminated sediments will offer no environmental threat to vascular plants colonizing an intertidal site and minimal problems to most animal populations, though there could be problems with burrowing animals. However, it is still prudent to avoid intertidal disposal with highly contaminated or very toxic sediments where intense habitat development is expected or planned, especially if adjacent to important nursery and spawning grounds. Intertidal disposal specifically for nonbiological purposes (shoreline stabilization-modification) represents a low environmental risk if the toxicity of the petroleum hydrocarbons is determined to be low.

i. Short-term considerations. Short-term problems focus on meeting applicable surface water quality criteria by effluent from intertidal disposal sites. As discussed elsewhere, excess petroleum hydrocarbon levels in effluents will be associated with suspended particulates, thus management to reduce suspended solids from return flow should reduce this threat to the quality of adjacent surface waters receiving effluents (See Paragraph 240).

ii. Long-term considerations. Intertidal sites should be selected to exclude interaction with especially productive habitats or habitats closely associated with food production for human consumption. Other intertidal disposal methods should offer little long-term adverse environmental impact unless the contaminating hydrocarbons are determined to be especially toxic and soluble.

Upland disposal. Due to strong association with colloidal solids and relatively low solubility in water, dissolved petroleum hydrocarbon losses in surface and subsurface drainage water should not be a problem except possibly if the contaminated dredged materials are very coarse textured. Toxicity and uptake associated with natural colonizing or managed plant populations should not be a problem, although disposal specifically for habitat development or agricultural soil amendment represents a moderate risk and studies should be conducted to examine possible impacts for a particular contaminated sediment under the planned management conditions. Generally, aerobic environments associated with upland disposal will probably result in faster degradation or modification of most petroleum hydrocarbon compounds. Although confinement is desirable, some normal loss of solids by erosion from a well-managed application site should not pose problems.

i. Short-term considerations. As for subaqueous and intertidal disposal methods, the most probable short-term impact will be elevated petroleum hydrocarbon levels from initial dewatering effluents in surface waters adjacent to the disposal site. Because most of the released petroleum hydrocarbons will be associated with

suspended solids, management practices to maximize solids removal from effluents will minimize or eliminate possible short-term impacts (See Paragraph 243).

ii. Long-term considerations. No long-term adverse environmental effects are expected from most upland applications of petroleum hydrocarbon-contaminated sediments. However, as an additional precaution, it is recommended that sites specifically intended for food production and intense habitat development be avoided.

### Nitrogen

206. The DMRP reports and related research have shown that some sediments contain high concentrations of total nitrogen with a significant fraction present as ammonium nitrogen which is potentially available to aquatic organisms (Brannon et al., 1976, 1978; G. F. Lee et al., 1977). The concerns over excessive ammonium and nitrate nitrogen in surface waters are for eutrophication and toxicity effects. The release of high levels of ammonium during dredging and dredged material disposal in nitrogen limiting waters may stimulate biological activity leading to rapid growth of undesirable organisms and eutrophication. Recent studies have shown nitrogen to be the major controlling factor for algal growth in some freshwater lakes and especially coastal waters. In addition to eutrophication, ammonium nitrogen released may be toxic to aquatic organisms. The toxicity of ammonium to aquatic life is dependent on the concentration of un-ionized form of ammonia ( $\text{NH}_3$ ) (USEPA, 1977).

207. Ammonium nitrogen under alkaline conditions may transform to un-ionized molecular form ( $\text{NH}_3$ ) which is highly toxic to aquatic organisms, especially fish. A slight increase in pH may cause a great increase in toxicity as the ammonium ion ( $\text{NH}_4^+$ ) is transformed to ammonia. Factors which may increase ammonia toxicity at a given pH are greater concentration of dissolved oxygen and carbon dioxide elevated

temperatures and bicarbonate alkalinity. Reported levels resulting in acute toxicity range from 0.01 mg/l to 2.0 mg/l of molecular ammonia nitrogen (USEPA, 1977). The fraction of un-ionized ammonia in the aqueous environment can be calculated from the values of ammonium nitrogen, pH, and temperature (Emerson et al., 1975).

208. Nitrogen release from dredged material in laboratory and field studies. Early studies on the release of chemical constituents during dredging operations in Chesapeake Bay (Biggs, 1968) indicated a substantial release of total nitrogen (a 60-fold increase over ambient levels) in the dredging discharge pipe. This includes a high pollution potential due to dredging activities, assuming that a change in the levels of total nitrogen (bulk analysis) during dredging and disposal situations could result in an adverse impact.

209. More recent elutriate tests conducted on dredged sediments collected from active dredging sites in the U.S. also demonstrate substantial release of ammonium nitrogen (G. F. Lee et al., 1977; Baumgartner et al., 1978; Wyeth and Sweeney, 1978; Marine Sciences Res. Center, 1978; Pequegnat et al., 1978). The release of nitrate nitrogen in the elutriate is insignificant. Monitoring of ammonium nitrogen at actual disposal sites indicated that elevated ammonium levels lasted only for a few hours during the passage of the turbidity plume. These studies suggest that the extent of adverse biological effects, if any, should be largely dependent on the rate of dilution and mixing in receiving surface waters. Typical open-water disposal methods should not result in toxic ammonium nitrogen levels except possibly for a small area near the discharge outlet.

210. Disposal of dredged sediments in confined land disposal areas generally results in greater mineralization of organic nitrogen due to longer contact time with the oxidized overlying water, more oxidation of organic material, and a concentration gradient of ammonium nitrogen due to effluent removal (Hoeppel et al., 1978). These altered environmental conditions may result in elevated concentrations of ammonium

nitrogen in the interstitial water and effluents. Some of the released ammonium nitrogen will undergo biological oxidation at higher redox potentials prevailing at the confined disposal site and effluents may contain nitrate nitrogen. The disposal of nitrogen-rich dredged sediments in upland disposal sites under these conditions may have a potential of contaminating receiving waters and groundwaters. However, the occurrence of denitrification and uptake by vegetation may reduce nitrate and ammonium levels to some extent. High nitrogen availability of dredged sediments can be beneficial for many productive use purposes.

211. Lu et al. (1978) investigated the removal efficiency of two confined land disposal areas (Pinto Island, Mobile, Alabama; and Grassy Island disposal site, Detroit, Michigan). The results indicated that total nitrogen in the influent slurries increased from 1 mg/l to 40 mg/l for the Pinto Island disposal site and from 1.0 mg/l to 145 mg/l for Grassy Island samples. The increase in the total nitrogen contributed by ammonium nitrogen and organic nitrogen was 25 percent and 75 percent, respectively, for Pinto Island and 58 percent and 42 percent for Grassy Island. The effluent data show that the removal efficiencies of Grassy Island confined disposal area was 83 percent and 96 percent for ammonium nitrogen and organic nitrogen, respectively. However, high ammonium nitrogen concentrations in the effluents (> 10 mg/l for both sites) exceed EPA water quality standards.

212. In a study of nine dredged material land containment areas located at upland, lowland, and island sites, Hoeppe et al. (1978) concluded that high concentrations of ammonium nitrogen and low removal efficiencies could potentially impact adjacent biological communities. Results of other land disposal study sites indicate significantly high levels of nitrate in addition to high concentrations of ammonium nitrogen in the leachates (Krizek et al., 1976; Mang et al., 1978).

213. Physicochemical effects. In sediment-water systems, several biochemical processes take place resulting in the release of ammonium

nitrogen or in its removal from the overlying water. Ammonium nitrogen, under oxidized (dissolved oxygen present) conditions, may be oxidized to nitrate nitrogen. A pH of 7.0 or higher and warm temperatures substantially accelerate the process of nitrification resulting in reduced levels of ammonium nitrogen. Nitrate nitrogen may be taken up by aquatic organisms including plant and algae and be converted to organic fraction through assimilatory reduction, or be lost to the atmosphere as a gas through a process known as denitrification. Denitrification occurs only in the anaerobic environment as the nitrate diffuses down to the anaerobic zone.

214. Aerobic conditions favor a greater mineralization (transformation of organic nitrogen to inorganic forms) rate than anaerobic or reducing conditions. Thus a change in oxidation conditions of nitrogen-containing water or sediments can result in substantial changes in predominant forms and levels of inorganic nitrogen. The practical significance of this and the greatest potential for transformations giving either beneficial or adverse environmental impacts in terms of dredged material disposal is probably most apparent with intertidal and upland disposal. As previously discussed, upland confined disposal may enhance mineralization and nitrification resulting in dewatering effluents. Also, long-term drainage and subsequent oxidation at upland sites can contribute to substantial mineralization and greatly increase the potential for leaching of excess nitrogen into groundwater. However, the beneficial aspects of plant available nitrogen in dredged sediments for habitat development, land reclamation, and agricultural soils amendments can be substantial.

215. The net effect of an altered physicochemical environment on nitrogen release is often difficult to predict because of the simultaneous occurrence and interactions of different nitrogen transformation processes, often in adjacent compartments in sediment-water systems.

216. Selecting disposal alternatives. Disposal of dredged material in well-mixed water bodies generally poses a very low risk of toxicity at the disposal site and no effects are expected out of the designated disposal area. Dredged sediments containing large quantities of total and inorganic nitrogen may contribute to eutrophication of receiving water where affected surface water bodies are small and dilution and mixing are minimal. The risk of accelerating eutrophication or causing short-term nuisance algae blooms are very low in open-water areas in which a high level of dilution and mixing will occur. Upland disposal may substantially increase long-term nitrogen mineralization and possibly nitrate production in oxidized dredged materials. Under some conditions, this may contribute to nitrate contamination of groundwater. High levels of nitrogen in dredged sediments can also be beneficial in enhancing plant productivity on sites used for habitat development, land reclamation, or agricultural purposes. This section is included to cover possible detrimental effects of nitrogen released from dredged materials. It should be mentioned that nitrogen associated with dredged material has rarely been documented to be a serious environmental problem.

Subaqueous disposal. Continuous discharge of dredged sediments containing appreciable concentration of ammonium nitrogen may affect organisms near the discharge, especially if alkaline conditions exist at the disposal site where ammonium ( $\text{NH}_4^+$ ) nitrogen can be converted to the toxic ammonia ( $\text{NH}_3$ ) form. Generally, disposal of dredged material in well-mixed water poses a very low risk of toxicity at the disposal site and no adverse effects are expected out of the designated disposal area.

i. Short-term considerations. As previously mentioned, short-term toxicity, if present, should only occur during and perhaps shortly after actual subaqueous discharge, and then only in the immediate discharge area. The risk is increased as the size and mixing capacity of the receiving site water is decreased. A temporary increase

in algae productivity from nitrogen release during dredged material disposal should also not be a problem in most waters where substantial dilution and mixing occur. At sites where dilution and mixing may be limiting, scheduling the project for the cool seasons may effectively minimize problems from nitrogen release.

ii. Long-term considerations. Long-term toxicity due to ammonium release from dredged materials at subaqueous disposal sites will not be a problem. Should the disposal site be poorly mixed and shallow and receive dredged sediments containing high nitrogen levels, there is some increased risk of nitrogen release contributing to excess algae production. However, it is doubtful such sites will be considered for reasons other than adverse effects due to nitrogen release.

Intertidal disposal. Toxicity effects, if any, will be associated with elevated levels of ammonium nitrogen in initial dewatering effluents moving into adjacent waters. Where receiving surface water bodies are large and well mixed, no problems are anticipated. At most intertidal sites, the nitrogen in dredged materials will be a valuable resource enhancing plant productivity.

i. Short-term considerations. Short-term problems, should they occur, will result from ammonium release to poorly mixed surface waters receiving initial dewatering effluents and possibly from total nitrogen levels in effluent discharge exceeding applicable water quality criteria. Though considerable levels of soluble ammonium nitrogen can be transported in initial dewatering effluents, total nitrogen levels can be reduced by management practices to reduce suspended solids levels.

ii. Long-term considerations. No long-term toxicity problems are anticipated from nitrogen losses at intertidal sites. Should adjacent water bodies be small and poorly mixed, there is some increased risk of accelerated algae production from nitrogen-enriched surface and subsurface drainage. Nitrogen-enriched dredged sediments should beneficially enhance plant productivity at intertidal sites.

Upland disposal. Comments under intertidal disposal are applicable here as well. In addition, upland disposal where gradual drainage and subsequent oxidation will occur may result in substantial long-term transformation of organic and ammonium nitrogen to nitrate nitrogen. This nitrogen form may leach readily into groundwater and represent a moderate to high health risk should water with elevated levels of nitrate be used for human consumption.

i. Short-term considerations. Potential short-term problems would be associated with elevated levels of soluble ammonium and total nitrogen in dewatering effluents which may impact quality of receiving surface waters in the absence of adequate dilution and mixing. Management practices to reduce suspended particulates will be effective in decreasing this risk. C. R. Lee et al. (1976) discusses managed overland flow through stands of wetland vegetation as an effective method of removing and utilizing nutrients in dewatering effluents from upland dredged material disposal sites.

ii. Long-term considerations. At most upland disposal sites, nitrogen will increase plant growth making high-nitrogen dredged sediments an especially valuable resource for agricultural soils amendment, land reclamation, and habitat development. There is some potential for excess nitrate leaching into groundwater from upland confinement sites, however. Long-term oxidation will enhance nitrogen mineralization (organic to inorganic forms) and oxidation to the nitrate form which is very soluble and moves readily with percolating water. However, development of problem conditions will depend on a number of factors. For example, nitrate may be decreased to low levels by dilution with groundwater. Should anaerobic soil conditions exist in the area of the groundwater, much of the nitrate may be reduced to harmless nitrogen gas by the denitrification process. Also, most of the available nitrogen in thin lifts of dredged material such as may be used for agricultural soils amendment or land reclamation, will be taken up and utilized by plants and unavailable for leaching.

## Phosphorus

217. The concern over phosphorus with respect to dredged material stems from its potential to stimulate nuisance growth of algae and other aquatic plants. Research studies and field surveys conducted in the last decade have provided sufficient evidence to conclude that, for most freshwater bodies, phosphorus is the key limiting nutrient for aquatic plant growth (Gakstatter et al., 1976; G. F. Lee et al., 1978). Marine and coastal waters, on the other hand, usually have sufficient phosphorus for aquatic growth. Phosphorus loading in these areas may have less impact than in fresh waters.

218. Phosphorus release from dredged material in laboratory and field studies. Sediment-adsorbed phosphorus is present in organic and inorganic forms of which the inorganic phosphorus is the nutrient form and is potentially mobile, depending on physical and chemical properties of the sediments. The results of elutriate tests (Brannon et al., 1976; G. F. Lee et al., 1975, 1977) and open-water disposal operations (G. F. Lee et al., 1977; Hoepfel et al., 1978; Holton et al., 1978; Wyeth and Sweeney, 1978; Baumgartner et al., 1978) indicate that orthophosphate did not exhibit consistent release patterns. These results strongly demonstrate that the release of phosphorus is site-specific. The elutriate tests results, however, indicate that dredged materials high in ferrous iron are unlikely to release significant quantities of phosphorus during open-water disposal.

219. Monitoring of confined upland disposal sites showed total and soluble phosphorus removal efficiency to be greater than 95 percent (Hoepfel et al., 1978). No significant leaching of soluble or total phosphorus was observed in controlled studies simulating upland disposal (Mang et al., 1978). These studies found that confined land disposal may be an effective disposal alternative with a minimum impact on surface waters receiving effluents or on groundwater.

220. Physicochemical effects. The important physicochemical parameters that influence the release of sediment-bound phosphorus to the water column during dredging and disposal operations include redox potential, pH, iron chemistry, mixing, and sediment composition. Results of controlled laboratory studies and field experiments (Chen et al., 1976; Brannon et al., 1976; Gambrell et al., 1977a) have shown that highest concentrations of soluble phosphorus occurred in anaerobic sediments. The reduction of ferric compounds to ferrous forms results in the release of phosphorus adsorbed to ferric hydroxides. On the other hand, oxygenation of reduced interstitial waters containing soluble phosphorus and appreciable soluble iron as occurs during subaqueous disposal, would precipitate iron as ferric hydroxide and reduce soluble phosphorus (Burns and Ross, 1971). This iron-phosphorus solubility relationship in sediment-water systems is discussed more fully elsewhere (Syers et al., 1973; Stumm and Morgan, 1970).

221. Selecting disposal alternatives. The potential problem with phosphorus released at dredged material disposal sites will be associated with initiation or acceleration of nuisance growth of algae and possibly vascular aquatic plants. Direct toxicity from excess phosphorus release is not a problem. Phosphorus release may be a problem only where disposal sites impact surface waters where limited mixing and dilution occur. In many cases, water bodies which may be adversely affected already exhibit a tendency for eutrophication. Most subaqueous disposal sites will give adequate mixing with low phosphorus content waters such that an impact from phosphorus release should not be a problem. Some productive uses of dredged materials can utilize high phosphorus levels to enhance plant productivity for soils amendment or habitat development. Disposal of phosphorus-contaminated sediments in freshwater lakes may accelerate biological growth due to the generally phosphorus-limiting nature of the eutrophic lakes in the United States (G. F. Lee et al., 1978; Gakstatter et al., 1976; Peterson, 1977). However, if lake disposal is the only alternative,

phosphorus-contaminated dredged material may be placed in the deeper water and covered with uncontaminated dredged material to minimize release of phosphorus to overlying waters due to mixing, wind currents, and storm action.

Subaqueous disposal. The disposal of phosphorus-rich dredged sediments in open waters that include estuaries, inlet zones, and near-shore areas will have minimal adverse environmental impact where substantial dilution and mixing occurs with typical ocean waters containing low phosphorus levels.

i. Short-term considerations. Except possibly in confined water bodies with limited dilution capacity, phosphorus release should not be a problem. Results of DMRP open-water disposal studies indicate a several-fold increase of soluble phosphate in the disposal area surface waters over predisposal levels may sometimes occur. However, elevated levels last for several minutes to a few hours, then return to near predisposal levels. Should a short-term, temporary impact of phosphorus release be expected, this risk can be reduced by scheduling the project for the cool seasons of the year.

ii. Long-term considerations. Comments given under short-term considerations are applicable here as well. In addition, disposal in quiescent waters where sediment resuspension due to wave and current action is minimized may reduce the long-term risk where some sediment release of phosphorus is thought to present a potential problem. Most coastal marine waters are nitrogen limited and an increase in phosphorus concentrations may not stimulate excessive aquatic growth. In freshwater lakes, however, phosphorus loading due to wave and storm action and physical and chemical destratification may be an important source of internal loading.

Intertidal disposal. Intertidal disposal of phosphorus-rich dredged sediments in marshlands should present a very low environmental risk. Since marine waters are usually not phosphorus limiting, the

addition of phosphorus may not unduly accelerate planktonic or algal growth. Dredged sediments rich in phosphorus may beneficially stimulate plant growth in marsh and habitat development projects.

i. Short-term considerations. If surface waters receiving effluents are phosphorus limiting and subject to minimal mixing with larger water bodies, the release of phosphorus from the disposal sites may enhance nuisance algae blooms resulting in short-term oxygen depletion. This impact can be effectively minimized by discharging effluent in a high-energy environment that would dilute phosphorus concentrations or scheduling the project for the cool season where algae production is limited by temperature until excess phosphorus is removed from poorly mixed waters.

ii. Long-term considerations. Disposal of phosphorus-rich sediments in marsh areas and use for habitat development may be beneficial by increasing plant productivity. Phosphorus is essential for both plants and animals and does not induce toxicity at high levels of accumulation. High phosphate concentrations in the dredged sediments, therefore, may not have any long-term adverse impact upon disposal in selected intertidal areas.

Upland disposal. The use of phosphorus-rich sediments for agricultural soils amendment, land reclamation, and habitat development will effectively utilize the dredged material and its phosphorus content as a resource. As previously noted for subaqueous and intertidal disposal, potential problems will be associated with impairment of poorly mixed surface water quality should dewatering effluents contain excess phosphorus. Slow overland flow of effluents over a vegetated land surface should result in enhanced removal of phosphorus from dewatering effluents (C. R. Lee et al., 1976). Gradual drainage and subsequent oxidation of deposited sediments will enhance adsorption and coprecipitation of phosphorus by ferric hydroxides. The selection of disposal sites with heavy textured soils will increase adsorption of soluble phosphorus. Phosphorus movement in the soil profile is negligible and contamination of groundwater supplies should not be a problem.

i. Short-term considerations. Comments given for short-term intertidal disposal are applicable here.

ii. Long-term considerations. Well-oxidized conditions associated with most upland disposal methods will effectively immobilize phosphorus such that leaching and losses of excess soluble phosphorus in surface runoff will not be a problem if surface runoff of sediment solids is controlled. Dredged materials containing high levels of nitrogen and phosphorus and low levels of potentially toxic materials should be a valuable resource in enhancing plant productivity for agricultural soils amendment or for other land improvement or reclamation projects.

### Sulfur

222. The major forms of sulfur in dredged materials that are likely to be of concern are hydrogen sulfide, pyrite, amorphous metal sulfides, sulfate, and elemental sulfur. Since most dredged material of environmental concern is from maintenance dredging of channels and harbors where the sediments are likely to contain enough organic matter to be reducing, the reduced forms of sulfur (sulfides and pyrite) are most important in determining acceptable disposal methods.

223. Hydrogen sulfide can be a nuisance when anaerobic material is exposed to the atmosphere through dredging and is potentially the most serious short-term problem. Under certain conditions, the concentration can be high enough to discolor surfaces painted with metal-based paints. At very high concentrations, it can be a definite health hazard, especially where a high sulfide-containing material comes into contact with a source of acid that will release combined sulfide as hydrogen sulfide. As pointed out in the section on oxidation-reduction reactions, sediments that contain appreciable iron usually do not release hydrogen sulfide since the sulfide is always precipitated by the excess ferrous iron. Reduced sulfur forms usually remain stable as long as the dredged

material is confined underwater, but, if the material is placed in an upland disposal site where atmospheric oxygen can enter, microbial oxidation processes occur that may change reduced sulfur forms to dilute sulfuric acid and sulfate.

224. There are two major consequences of the oxidation of amorphous metal sulfides and pyrite. If the amount of sulfur involved is large, the amount of sulfuric acid produced can overwhelm the acid-buffering capacity of the sediment, and extremely acid conditions, possibly below pH 3, can result. Acidity this extreme will prevent plants and microbes from growing in the sediment and reduces the use to which the dredged material can be put. Such a condition is especially likely where pyritic material from mining activity has washed into the channel being dredged.

225. The second major consequence of the low pH resulting from upland disposal of sulfide and pyrite containing dredged material is the release of potentially toxic metal ions into the interstitial water and into the drainage water going into the groundwater. Toxic metals that are tightly bound as sulfides can be released into the environment following upland disposal of dredged material. The combined effect of release of the potentially toxic metals by oxidation of the insoluble sulfide and the increased chemical activity and solubility of the released metal ion as a result of a low pH can create severe environmental problems.

226. The environmental significance of the development of strongly acid conditions in upland applied dredged materials has been stressed in this report in association with several contaminants. Although perhaps not a frequent problem, strongly acid conditions are going to occur for some dredged materials subject to upland disposal. For dredged materials which can become strongly acid, selection and management of disposal alternatives should be done accordingly. There is no standardized procedure for testing sediments to determine the potential for acidity development upon long-term oxidation. However, considering the importance of these strongly acid conditions in contaminated dredged materials, some effort in identifying potential problem sediments is warranted.

Though Brannon et al. (1978) were not advocating adoption of their methods as a testing procedure, the simple method they described for measuring material release under long-term agitated conditions should be useful. Three sediment-water mixtures (Oakland Inner Harbor, Oakland Outer Harbor, and Miller Sands) were agitated continuously under aerobic conditions with a motor-driven impeller for 8 months. After 4 months, the pH of the Oakland Inner Harbor material had decreased from 8.0 to 3.7 whereas incubation under quiescent, oxidized water column conditions resulted in little or no change in pH. This transformation to strongly acid conditions was accompanied by a comparatively large net mass release of several metals.

227. Reducing sediments in streams, lake bottoms, and estuaries containing sulfides are a sink for most of the toxic metals that come into contact with the sediment. Metals such as mercury, lead, cadmium, zinc, and copper form extremely insoluble sulfide compounds that were earlier thought to be so inert that they would have no possibility of moving back into the environment unless the sediment became oxidized. In fact, the precipitation of sulfides with metals in anaerobic stream bottoms and estuaries was thought to be a good way to remove these contaminants from industrial effluent and other sources. The presence of unacceptable amounts of mercury in fish from lakes and streams receiving mercury-containing effluent from manufacturing plants led to the discovery that certain specialized bacteria are able to methylate insoluble mercury compounds and turn them into a water-soluble and very bioavailable form of methylmercury. This finding has modified the concept that anaerobic sulfide-containing sediments would serve as an efficient sink for all toxic metals.

228. Except where pyrite is present, most of the sulfide in a sediment is present as amorphous ferrous sulfide which is relatively insoluble. Ferrous iron serves as an efficient remover of sulfides produced microbiologically by breakdown of organic matter or by reduction from the sulfate form. Since ferric iron is easier to reduce to ferrous

iron than sulfate is to reduce to sulfide, there will always be ferrous iron in solution by the time hydrogen sulfide is produced and an immediate precipitate of ferrous sulfide results. Sediments containing appreciable iron oxide, therefore, are very effective in preventing release of hydrogen sulfide.

### Management Practices

229. The purpose of this section is to familiarize project managers with practices applicable to many disposal methods which will complement the disposal alternatives selected in minimizing the mobility and biological availability of potentially toxic substances at the disposal site. Each of these management practices is generally effective for all classes of contaminants found in the dredged material and thus will not be related to specific contaminants. It is not possible in this section to quantitatively predict the degree of benefit expected from these suggested management practices. Many practices may not be suitable for some projects because of the site- and organism-specific interactions influencing mobility and uptake of potentially toxic materials. However, this information should be of value in pointing out management practices which can be applied to certain disposal alternatives to further reduce the environmental risk of disposal of contaminated sediments.

230. The inclusion of this section on management practices is not intended to circumvent the selection of environmentally acceptable disposal alternatives. Management practices may be used to improve a marginally acceptable disposal method, especially where environmentally optimum methods are not feasible for technological or economic reasons. Again, it should be noted that this discussion of supplemental management practices is brief and is only intended to introduce these possibilities. Successful design and implementation of these practices would require site-specific planning.

#### Subaqueous disposal

231. Scheduling to minimize nuisance phytoplankton growth. In surface waters where mixing and dilution are limited, such as shallow lakes or enclosed bays, release of considerable quantities of nutrients by subaqueous dredged material disposal may accentuate phytoplankton

production to nuisance levels. Scheduling the dredging project for the cool season (for example, October-April) may reduce any increase in the severity of the algal blooms related to dredging as cool water temperatures can limit phytoplankton growth even in the presence of excess nutrients. Cool-season dredging allows released nutrients additional time to be assimilated into the sediment-water system in less available forms or to be removed by gradual mixing and dilution.

232. Scheduling to coincide project with least sensitive portions of the life cycles of affected organisms. Disposal sites should be selected to avoid impact on adjacent economically or ecologically important biological populations. Where this is not possible or when a project manager determines extra precautions desirable, some protection may be afforded by timing the project to coincide with the least sensitive portion of the life cycle of the important species threatened (Hirsch et al., 1978). For example, the larva and juvenile forms of many organisms are known to be more sensitive to toxic substances than adult forms. A biological evaluation would be required to determine the populations affected and to evaluate the overall feasibility of this practice for a proposed disposal site.

233. Covering with uncontaminated material. Where available, depositing contaminated dredged material in deep, subaqueous depressions will be an effective method for containing contaminants. The formation of mounds which are stable in deep, quiescent waters will also give good containment of most contaminants. Covering this contaminated dredged material with a layer of clean sediments will essentially seal the buried contaminants from overlying aquatic and benthic organisms. Covering will help in isolating the contaminated material from currents in low- to moderate-energy water columns and may minimize dispersion due to occasional storm currents. Also, the increased diffusion distance coupled with the immobilizing processes within the clean layer will effectively prevent passive transport of trace amounts of contaminants from the depression or mounds by diffusion. Frequently, a large dredging project

will include sediments with a wide range in levels of contamination. Dredging and mounding of the most contaminated material first, followed by covering with cleaner dredged sediments from the same project, may be useful in confining the most contaminated sediments (Rhoads, McCall, and Yinget, 1978).

#### Intertidal disposal

234. Scheduling to minimize nuisance phytoplankton growth. (See Paragraph 231).

235. Scheduling to coincide project with least sensitive portions of the life cycles of affected organisms. (See Paragraph 232).

236. Confinement structures to minimize dispersion and transport by erosion. Some intertidal zones are in low-energy regimes where erosion from wind, wave, and storm currents is not a problem. Many intertidal sites are subject to high-energy hydraulic regimes or storms such that considerable loss of material from an artificial marsh could occur. Contaminated sediments should generally not be used for such sites unless rigorous precautions to physically confine the deposited material are made.

237. Palermo and Zeigler (1976) discussed the engineering feasibility and design of one such containment facility for a marsh expansion project which will prevent excessive erosion and overtopping during all but very severe storms. Once vegetation is established it is doubtful that excessive surface sheet erosion would occur even during severe storms. If the contaminant is subject to leaching or uptake by highly productive plant populations which may colonize the site, physical confinement of contaminated solids alone may not be sufficient to isolate the contaminants at the disposal site (See Paragraphs 245 to 251).

238. Covering with clean material. To minimize uptake and possible concentration of contaminants by benthic fauna and marsh plants, it may be feasible to cover contaminated dredged material with a layer of

uncontaminated soil or clean sediment. Long-term vertical mixing of marsh soils by burrowing benthos and the rooting depth of anticipated plant populations should be considered in determining the depth of clean material to apply.

239. Managing plant populations to minimize uptake. Site management to favor colonization by desirable plant species may be useful in minimizing uptake and environmental cycling of contaminants from marsh creation projects. Contaminated sediments covered with clean material should be colonized by species with shallow rooting depths to effectively isolate toxic substances beneath the rooting zone. Also, selection of species which are known to restrict uptake and translocation of specific toxic substances may be useful in some cases. Plant species and even subspecies differences are often found more important in regulating uptake than the chemical properties of contaminated soils and sediments on which the plants are growing. At this time, there is no comprehensive source of information for selecting suitable marsh plant species for this type of contaminant management practice. Perhaps the best work in this area has been done by C. R. Lee et al. (1976) who has listed a number of species which might be propagated on a disposal area. C. R. Lee et al. (1976) have also discussed detailed plant characteristics (including rooting depth) of a number of species which may be desirable for dewatering dredged material and have given the relative capacity of selected plant species to tolerate or remove various chemical contaminants. This type of information coupled with other site-specific requirements may be helpful in containing contaminants in marginally contaminated dredged materials, especially where marsh creation and habitat development projects are being considered.

240. Reducing contaminant losses associated with suspended solids in dewatering effluents. (See Paragraphs 243 to 244).

241. Reducing leaching losses. Leaching losses may not be significant for most fine-textured intertidally applied dredged material because of low permeability, low hydraulic gradient due to regular

cyclic tidal flooding, and because the bulk volume of these dredged materials will remain strongly reduced, conditions which favor immobilization of most sediment-bound contaminants. However, where leaching is anticipated, certain of the practices mentioned for leaching control from upland confinement sites may be helpful (See Paragraphs 245 to 249).

#### Upland disposal

242. Several practical management procedures are available to complement upland disposal alternatives in minimizing contaminant mobility and availability.

243. Reducing contaminant losses associated with suspended solids in dewatering effluents. Almost all of the contaminants in initial dewatering effluents (with the possible exception of ammonia and manganese) are associated with suspended particulates. In many cases, the levels exceed applicable surface water quality criteria if mixing and dilution with large volumes of receiving water is limited. Maximizing suspended solids removal will be effective in reducing these losses. Design of the confinement facility to increase detention time, settling basin area, and ponded water depth relative to the weir are key parameters in retaining fine-textured contaminated particulates within the disposal facility (Walski and Schroeder, 1978; B. J. Gallagher and Co., 1978).

244. Some laboratory and preliminary field studies have been conducted to enhance flocculation of suspended particulates within the confined disposal site by adding chemical coagulants. Conventional wastewater treatment coagulants may not be practical because of problems with pH and volumes of the material required. However, several synthetic polymers have shown great promise in removing suspended particulates while having little effect on other chemical or physical properties of the settled solids (Wang and Chen, 1977; Jones, Williams, and Moore, 1978).

245. Reducing leaching losses. Disposal sites should not be selected where subsurface drainage could contaminate drinking water

supplies or adjacent surface waters or result in contaminant levels exceeding applicable criteria for these waters. However, management practices to reduce leaching losses may be beneficial in some cases. Some fine-textured dredged material tends to form its own liner as particles settle with percolating drainage water. Coarse-textured materials will tend to drain freely with little impediment with time. Even fine-textured materials will require considerable time for self-sealing to develop. Thus an artificial liner may be useful for some upland sites. Because of the gradual selfsealing nature of many fine-textured dredged materials, temporary (subject to gradual deterioration with time) liners may be adequate in many cases. Mang et al. (1978) present a general discussion of the use of liners to minimize contaminant leaching into groundwater from upland confinement facilities.

246. Mechanical dewatering of confined upland applied dredged material is often done to enhance drying for purposes of reuse or to get more rapid compaction such that additional dredged material can be applied to the same site. One such method involves the use of underground drains (Haliburton, 1978). Because interstitial waters of contaminated materials often contain elevated levels of dissolved toxic substances, the possible adverse impact from discharge of this water should be carefully considered.

247. Another effective dewatering technique is the method of progressive trenching (Haliburton, 1978). Shortly after dredged material deposition and drainage of supernatant water resulting from initial settling, shallow surface channels are constructed to direct surface water (predominately rain water, but some upper pore water drainage) to the effluent weirs. Pore water is removed primarily by evaporation as the channels are progressively deepened. Contaminants present in the interstitial water are thus not removed from the disposal site by this mechanical dewatering procedure.

248. The previously mentioned methods represent mechanical techniques for minimizing leaching losses of contaminants. Chemical methods

may also be effective under some conditions. Many upland applied, non-calcareous dredged materials containing substantial levels of reactive iron and especially sulfide may gradually develop strongly acid conditions as a long-term consequence of oxidation. Strong acid conditions would tend to mobilize a large proportion of the toxic heavy metals associated with the dredged material. Sufficient lime can be applied to prevent the development of acid conditions. In many cases, however, the costs and volumes of lime required to treat all of the dredged material within a confinement facility may make this practice unattractive. Liming is more feasible for pH control to immobilize toxic metals where marginally contaminated, acid-forming dredged material is applied as a thin layer and mixed with a productive soil. Even under these conditions, Gupta et al. (1978) suggests that two or more times the normal lime recommendation for the productive soil may be required to maintain pH at or near neutral conditions to prevent metal mobilization.

249. The Japanese have experience with incapsulation of contaminants by mixing cement with the dredged material (Murakami and Takeishi, 1977). However, when crushed, even this material is known to release mercury, presumably due to the high pH. This technique is costly and requires much additional containment facility capacity, though it might be feasible if the site was planned for industrial development.

250. Minimizing plant uptake. As previously discussed for intertidal disposal, plant populations may be managed to minimize uptake and environmental cycling of metals from contaminated sediments applied upland (See Paragraph 239). Such a technique may be more effective where plant populations are intensively managed as in an agricultural operation since different species and even subspecies differ greatly in their ability to take up and translocate toxic materials. It may be possible to grow crops which are not used for human or animal consumption or to select crops in which metals tend to accumulate in plant tissue which is not harvested. Where contaminated dredged material is used to amend agricultural soil or improve other unproductive soils,

liming can be an economical and effective method of reducing the plant availability of many toxic metals (See Paragraph 248).

251. Considerable information is available in the environmental agricultural literature which is applicable for developing site-specific management practices for contaminated dredged materials under upland disposal conditions.

252. Covering with clean material. Covering contaminated dredged material with clean soil or dredged sediments is a potential management practice that applies to all three of the major disposal alternatives. Where contaminated dredged material is to be used for habitat development, agricultural soils amendment, land reclamation, or as fill for engineering purposes, covering with clean material can be an effective method for isolating contaminants from biological populations growing in or living on the disposal site. The depth of clean material should be sufficient to isolate contaminants from plant roots and burrowing animals. Management for shallow-rooted species may also be beneficial. If long-term leaching is a potentially serious environmental problem, it should be kept in mind that covering contaminated material with a layer of clean soil or sediment will not appreciably affect leaching.

253. The value of covering contaminated materials has recently been documented in Great Britain where livestock have been poisoned from grazing on soils contaminated with metals from mine tailings.\* Plant uptake and subsequent ingestion by the grazing animals were originally thought to be the source of the metals. However, studies showed that metal levels in aboveground plant tissue were not sufficient to account for the poisoning. It was subsequently learned that most of the metals were derived from ingestion of contaminated soil particles present on plant surfaces as a result of rain splashing and various other processes. Up to 10 percent of the total dry weight ingested by some grazing

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animals may be soil particulates. Covering contaminated dredged materials with clean material will reduce the potential for bio-concentration by plants and by more direct associations of animals with contaminated sediments.

## REFERENCES

- Alloway, B. J., and Davies, B. E. "Heavy Metal Contents of Plants Growing on Soils Contaminated by Lead Mining." *J. Agric. Sci.* 76: 321-323 (1971).
- Anderlini, V. A., Chapman, J. W., Girvin, D. C., McCormick, S. J., Newton, A. S., and Risebrough, R. W. "Dredge Disposal Study, San Francisco Bay and Estuary; Appendix H: Pollutant Uptake Study." U.S. Army Engineer District, San Francisco, California (1975a).
- Anderlini, V. A., Chapman, J. W., Newton, A. S., Risebrough, R. W., Cole, B. E., deLappe, B. W., Girvin, B. C., Hodgson, A. T., McCormick, S. J., Nelbach, L., Okazaki, R. K., Panietz, M. H., and Schmidt, T. T. "Dredge Disposal Study, San Francisco Bay and Estuary; Appendix I: Pollutant Availability Study." U.S. Army Engineer District, San Francisco, California (1975b).
- Ayling, G. M. "Uptake of Cadmium, Zinc, Copper, Lead, and Chromium in the Pacific Oysters, *Crassostrea gigas*, Grown in the Tamer River, Tasmania." *Water Resour. Res.* 8: 729-738 (1974).
- B. J. Gallagher and Co. "Investigation of Containment Area Design to Maximize Hydraulic Efficiency." Technical Report D-78-12, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Banus, M. D., Valiela, I., and Teal, J. M. "Lead, Zinc, and Cadmium Budgets in Experimentally Enriched Salt Marsh Ecosystems." *Est. Coastal Mar. Sci.* 3: 421-430 (1975).
- Baumgartner, D. J., Schults, D. W., and Carkin, J. B. "Aquatic Disposal Field Investigations, Duwamish Waterway Disposal Site, Puget Sound, Washington; Appendix D: Chemical and Physical Analyses of Water and Sediment in Relation to Disposal of Dredged Material in Elliot Bay; Volume I: February-June 1978." Technical Report D-77-24, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Belaire, C. E., and Alexander, E. F. "A Study of the Placement of Materials Dredged from Texas Ports and Waterways." Vol. 1, Epscy, Huston, and Assoc., Inc., Austin, Texas. Prepared for General Land Office of Texas, Austin, Texas (1976).
- Biggs, R. B. "Environmental Effects of Overboard Spoil Disposal." *J. Sanit. Engg. Div., Am. Soc. Civil Engrs.* 94: 477-487 (1968).

- Blom, B. E., Jenkins, T. F., Leggett, D. C., and Murrmann, R. P. "Effect of Sediment Organic Matter on Migration of Various Chemical Constituents During Disposal of Dredged Material." Contract Report D-76-7, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1976).
- Brannon, J. M. "Evaluation of Dredged Material Pollution Potential." Technical Report DS-78-6, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Brannon, J. M., Engler, R. M., Rose, J. R., Hunt, P. G., and Smith, Isaac. "Selective Analytical Partitioning of Sediments to Evaluate Potential Mobility of Chemical Constituents During Dredging and Disposal Operations." Technical Report D-76-7, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1976).
- Brannon, J. M., Plumb, R. H., Jr., and Smith, Isaac. "Long-term Release of Contaminants from Dredged Material." Technical Report D-78-49, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Broughton, J. D. "Investigation of Subaqueous Borrow Pits as Potential Sites for Dredged Material Disposal." Technical Report D-77-5, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1977).
- Broyer, T. C., Johnson, C. M., and Paull, R. E. "Some Aspects of Lead in Plant Nutrition." *Plant Soil* 36: 301-313 (1972).
- Burks, S. A., and Engler, R. M. "Water Quality Impacts of Aquatic Dredged Material Disposal (Laboratory Investigations)." Technical Report DS-78-4, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Burns, N. M., and Ross, C. "Nutrient Relationship in a Stratified Eutrophic Lake." *Proc. 14th Conf. Great Lakes Res.*, Toronto, Ontario, Canada 14: 749-760 (1971).
- CAST (Council for Agricultural Science and Technology). "Application of Sewage Sludge to Cropland: Appraisal of Potential Hazards of the Heavy Metals to Plants and Animals." EPA-430/9-76-013, U.S. Environmental Protection Agency, Washington, D. C. (1976).
- Cheam, V., Mudroch, A., Sly, P. G., and Lum-Shue-Cham, K. "Examination of the Elutriate Test, a Screening Procedure for Dredging Regulatory Criteria." *J. Great Lakes Res.* 2: 272-282 (1976).

- Chen, K. Y., Gupta, S. K., Sycip, A. Z., Lu, J. C. S., Knezevic, M., and Choi, Won-Wook. "Research Study on the Effect of Dispersion, Settling, and Resedimentation on Migration of Chemical Constituents During Open-Water Disposal of Dredged Materials." Contract Report D-76-1, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1976).
- Cox, W. J., and Rains, D. W. "Effect of Lime on Lead Uptake by Five Plant Species." *J. Environ. Qual.* 1: 167-169 (1972).
- DeGroot, A. J. "Occurrence and Behavior of Heavy Metals in River Deltas with Special Reference to the Rivers Rhine and Ems." *North Sea Sci.*, M.I.T. Press, Cambridge, Massachusetts, pp. 308-325 (1973).
- DeGroot, A. J., and Allersma, E. "Field Observations on the Transport of Heavy Metals in Sediments." *Prog. Water Technol.* 7: 85-95 (1975).
- DeLaune, R. D., Patrick, W. H., Jr., and Brannon, J. M. "Nutrient Transformations in Louisiana Salt Marsh Soils." Coastal Management Series Publication No. LSU-T-76-009 (Sea Grant), Center for Wetland Resources, Louisiana State University, Baton Rouge, Louisiana (1976).
- DiSalvo, L. H., Guard, H. E., Hirsch, N. D., and Ng, J. "Assessment and Significance of Sediment-Associated Oil and Grease in Aquatic Environment." Technical Report D-77-26, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1977).
- Ellis, B. G., and Knezek, B. D. "Adsorption Reactions of Micronutrients in Soils." *Micronutrients in Agriculture*. R. C. Dinauer, Ed., Soil Sci. Soc. Amer., Inc., Madison, Wisconsin, pp. 59-78 (1972).
- Emerson, K., Russo, R. C., Lund, R. E., and Thurston, R. V. "Aqueous Ammonia Equilibrium Calculations: Effects of pH and Temperature." *J. Fish. Board Can.* 32: 2379-2383 (1975).
- Engineering Science, Inc. "An Evaluation of Oil and Grease Contamination Associated with Dredged Material Containment Areas." Technical Report D-77-25, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1977).
- Environmental Effects Laboratory. "Ecological Evaluation of Proposed Discharge of Dredged or Fill Material into Navigable Waters." Miscellaneous Paper D-76-17, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1976).
- Feick, G., Johanson, E. E., and Yeaple, D. S. "Control of Mercury Contamination in Freshwater Sediments." EPA-R2-72-077, U.S. Environmental Protection Agency, Washington, D. C. (1972).
- Feick, G., Hoyne, R. A., and Yeaple, D. "Release of Mercury from Contaminated Freshwater Sediments by the Runoff of Road De-Icing Salts." *Science* 175: 1142-1143 (1972).

- Folsom, B. L., and Lee, C. R. Unpublished data. U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Fujiki, M., Hirota, R., and Yamaguchi, S. "The Mechanism of Methylmercury Accumulation in Fish." Management of Bottom Sediments Containing Toxic Substances. S. A. Peterson and K. K. Randolph, Eds., EPA-600/3-77-083, Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency, Corvallis, Oregon, pp. 89-95 (1977).
- Gakstatter, J. H., Allum, M. O., and Omernik, J. M. "Lake Eutrophication: Results from the National Eutrophication Survey." Proceedings of EPA-sponsored symposium on Water Quality Criteria Research of the U.S. Environmental Protection Agency, EPA-600/3-76-079, pp. 185-205 (1976).
- Gambrell, R. P., Khalid, R. A., Verloo, M. G., and Patrick, W. H., Jr. "Transformations of Heavy Metals and Plant Nutrients in Dredged Sediments as Affected by Oxidation Reduction Potential and pH; Volume II: Materials and Methods/Results and Discussion." Contract Report D-77-4, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1977a).
- Gambrell, R. P., Collard, V. R., Reddy, C. N., and Patrick, W. H., Jr. "Trace and Toxic Metal Uptake by Marsh Plants as Affected by Eh, pH, and Salinity." Technical Report D-77-40, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1977b).
- Gambrell, R. P., and Patrick, W. H., Jr. "Chemical and Microbiological Properties of Anaerobic Soils and Sediments." Plant Life in Anaerobic Environments. D. D. Hook and R. M. M. Crawford, Eds., Ann Arbor Science Publishers, Inc. Ann Arbor, Michigan, pp. 375-423 (1978).
- Gupta, S. C., Larson, W. E., Gast, R. G., Coombs, S. M., and Dowdy, R. H. "The Agricultural Value of Dredged Material." Technical Report D-78-36, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Haliburton, T. A. "Guidelines for Dewatering/Densifying Confined Dredged Material." Technical Report DS-78-11, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Hirsch, N. D., DiSalvo, L. H., and Peddicord, R. K. "Effects of Dredging and Disposal on Aquatic Organisms." Technical Report DS-78-5, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Hoeppe, R. E., Myers, T. E., and Engler, R. M. "Physical and Chemical Characterization of Dredged Material Influent and Effluent in Confined Land Disposal Areas." Technical Report D-78-24, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).

- Holliday, B. W. "Processes Affecting the Fate of Dredged Material." Technical Report DS-78-2, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Holton, R. L., Cutshall, N. H., Gordon, L. I., and Small, L. F. "Aquatic Disposal Field Investigations, Columbia River Disposal Site, Oregon; Appendix B: Water Column, Primary Productivity, and Sediment Studies." Technical Report D-77-30, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Huggett, R. J., Bender, M. E., and Slone, H. D. "Utilizing Metal Concentration Relationships in the Eastern Oyster (Crassostrea virginica) to Detect Metal Pollution." Water Res. 7: 451-460 (1973).
- Ito, H., and Iimura, K. "Adsorption of Cadmium by Rice Plants in Response to Change of Oxidation-Reduction Conditions of Soils." J. Sci. Soil Manure, Japan 46: 82-88 (1975).
- Jackim, E., Morrison, G., and Steele, R. "Effects of Environmental Factors on Radio-Cadmium Uptake by Four Species of Marine Bivalves." Mar. Biol. 40: 303-308 (1977).
- Jacobs, L. W., Syers, J. K., and Keeney, D. R. "Arsenic Sorption by Soils." Soil Sci. Soc. Amer. Proc. 34: 750-754 (1970).
- Jenne, E. A. "Controls of Mn, Fe, Co, Ni, Cu, and Zn Concentrations in Soils and Water: The Significant Role of Hydrous Mn and Fe Oxides." Trace Inorganics in Water, Advances in Chemistry Series, No. 73. Amer. Chem. Soc., Washington, D. C., pp. 337-387 (1968).
- John, M. K., and VanLaerhoven, C. J. "Lead Uptake by Lettuce and Oats as Affected by Time, Nitrogen, and Sources of Lead." J. Environ. Qual. 1: 169-171 (1972).
- Johnson, L. R., and Hiltbold, A. E. "Arsenic Content of Soil and Crops Following Use of Methanearsonate Herbicides." Soil Sci. Soc. Amer. Proc. 33: 279-282 (1969).
- Johnston, S. W. "The Behavior of Indigenous Arsenic in Flooded Soils and Sediments." M.S. Thesis, Louisiana State University, Baton Rouge, Louisiana (1978).
- Jones, L. H. P., Jarvis, S. C., and Cowling, D. W. "Lead Uptake from Soils by Perennial Ryegrass and its Relation to the Supply of an Essential Element (Sulfur)." Plant Soil 38: 605-619 (1973).
- Jones, R. H., Williams, R. R., and Moore, T. K. "Development and Application of Design and Operation Procedures for Coagulation of Dredged Material Slurry and Containment Area Effluent." Technical Report D-78-54, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).

- Jugsujinda, A., and Patrick, W. H., Jr. "Growth and Nutrient Uptake by Rice in a Flooded Soil Under Controlled Aerobic-Anaerobic and pH Conditions." *Agron. J.* 69: 705-710 (1977).
- Kerr, R. A. "Oil in the Ocean: Circumstances Control its Impact." *Science* 198: 1134-1136 (1977).
- Khalid, R. A., Gambrell, R. P., Verloo, M. G., and Patrick, W. H., Jr. "Transformations of Heavy Metals and Plant Nutrients in Dredged Sediments as Affected by Oxidation Reduction Potential and pH; Volume I: Literature Review." Contract Report D-77-4, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1977).
- Khalid, R. A., Patrick, W. H., Jr., and Gambrell, R. P. "Effect of Dissolved Oxygen on Chemical Transformations of Heavy Metals, Phosphorus and Nitrogen in an Estuarine Sediment." *Est. Coastal Mar. Sci.* 6: 21-35 (1978).
- Kinniburgh, D. G., Sridhar, K., and Jackson, M. L. "Specific Adsorption of Zinc and Cadmium by Iron and Aluminum Hydrous Oxides." Biological Implications of Metals in the Environment. H. Drucker and R. E. Wildung, Chairmen, Proceedings of the 15th Annual Hanford Life Sciences Symposium, Energy Research and Development Administration CONF-750929, pp. 231-239 (1977).
- Krizek, R. J., Gallagher, J., and Karadi, G. M. "Water Quality Effects of a Dredging Disposal Area." *J. Environ. Engg. Div., Proc. Amer. Soc. Civil Engg.* 102: 389-409 (1976).
- Langmuir, D., and Whittemore, D. O. "Variations in the Stability of Precipitated Ferric Oxyhydroxides." Nonequilibrium Systems in Natural Water Chemistry, Advances in Chemistry Series No. 106. Amer. Chem. Soc., Washington, D. C., pp. 209-234 (1971).
- Lee, C. R., Hoeppe, R. E., Hunt, P. G., and Carlson, C. A. "Feasibility of the Functional Use of Vegetation to Filter, Dewater, and Remove Contaminants from Dredged Material." Technical Report D-76-4, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1976).
- Lee, C. R., Smart, R. M., Sturgis, T. C., Gordon, R. N., Sr., and Landin, M. C. "Evaluation of Heavy Metal Uptake by Marsh Plants Based on Chemical Extraction of Heavy Metals from Dredged Material." Technical Report D-78-6, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Lee, G. F. "Role of Hydrous Metal Oxides in the Transport of Heavy Metals in the Environment." Presented at the Symposium on Heavy Metals in the Environment, Vanderbilt University, Nashville, Tennessee, 25 p. (1973).

- Lee, G. F., Piwoni, M. D., Lopez, J. M., Mariani, G. M., Richardson, J. S., Homer, D. H., and Saleh, F. "Research Study for the Development of Dredged Material Disposal Criteria." Contract Report D-75-4, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1975).
- Lee, G. F., and Plumb, R. H. "Literature Review on Research Study for the Development of Dredged Material Disposal Criteria." Contract Report D-74-1, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1974).
- Lee, G. F., Bondyopadhyay, P., Butler, J., Homer, D. H., Jones, R. A., Lopez, J. M., Mariani, G. M., McDonald, C., Nicar, M. J., Piwoni, M. D., and Saleh, F. Y. "Aquatic Disposal Field Investigations, Galveston, Texas Offshore Disposal Site; Appendix B: Investigation of Water-Quality Parameters and Physicochemical Parameters." Technical Report D-77-20, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1977).
- Lee, G. F., Rast, W., and Jones, R. A. "Eutrophication of Water Bodies: Insights for an Age-Old Problem." *Environ. Sci. Technol.* 12: 900-908 (1978).
- Lindberg, S. E., Andren, A. W., and Harriss, R. C. "Geochemistry of Mercury in the Estuarine Environment." Estuarine Research: Recent Advances. Proceedings 2nd International Estuarine Research Conference, Academic Press, New York (1973).
- Lindberg, S. E., and Harriss, R. C. "Mercury-Organic Matter Associations in Estuarine Sediments and Interstitial Water." *Environ. Sci. Technol.* 8: 459-462 (1974).
- Lu, J. C. S., Eichenberger, B., and Chen, K. Y. "Characterization of Confined Disposal Area Influent and Effluent Particulate and Petroleum Fractions." Technical Report D-78-16, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Lunde, G. "Separation and Analysis of Organic-Bound and Inorganic Arsenic in Marine Organisms." *J. Sci. Fd. Agri.* 24: 1021-1027 (1973).
- Lunz, J. D. "Habitat Development Field Investigations, Windmill Point Marsh Development Site, James River, Virginia; Appendix E: Environmental Impacts of Marsh Development with Dredged Material: Metals and Chlorinated Hydrocarbon Compounds in Marsh Soils and Vascular Plant Tissues." Technical Report D-77-23, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- MacKenzie, R. C., and Meldau, R. "The Ageing of Sesquioxide Gels. I. Iron Oxide Gels." *Mineralogical Magazine* 32: 153-165 (1959).

- Mang, J. L., Lu, J. C. S., Lofy, R. J., and Stearns, R. P. "A Study of Leachate from Dredged Material in Upland Areas and/or in Productive Uses." Technical Report D-78-20, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Marine Sciences Research Center. "Aquatic Disposal Field Investigations, Eatons Neck Disposal Site, Long Island Sound; Appendix B: Water-Quality Parameters and Physicochemical Sediment Parameters." Technical Report D-77-6, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Mathis, B. J., and Cummings, T. F. "Distribution of Selected Metals in Bottom Sediments, Water, Clams, Turbificid Annelids, and Fishes of the Middle Illinois River." Research Report 41, Water Resources Research Center, University of Illinois, Urbana, Illinois (1971).
- Murakami, K., and Takeishi, K. "Behavior of Heavy Metals and PCB's in Dredging and Treating of Bottom Deposits." Management of Bottom Sediments Containing Toxic Substances. S. A. Peterson and K. K. Randolph, Eds., EPA-600/3-77-083, Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency, Corvallis, Oregon, pp. 127-143 (1977).
- Neff, J. W., Foster, R. S., and Slowey, J. F. "Availability of Sediment-Adsorbed Heavy Metals to Benthos with Particular Emphasis on Deposit-Feeding Infauna." Technical Report D-78-42, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Page, A. L. "Fate and Effects of Trace Elements in Sewage Sludge when Applied to Agricultural Lands." EPA-670/3-74-005, U.S. Environmental Protection Agency, Cincinnati, Ohio (1974).
- Palermo, M. R., and Zeigler, T. W. "Feasibility Study for Dyke Marsh Demonstration Area, Potomac River, Virginia." Technical Report D-76-6, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1976).
- Pavlou, S. P., Dexter, R. N., Wilson, H. A., Hafferty, A. J., and Kroglund, K. A. "Aquatic Disposal Field Investigations, Duwamish Waterway Disposal Site, Puget Sound, Washington; Appendix E: Release and Distribution of Polychlorinated Biphenyls Induced by Open-Water Dredge Disposal Activities." Technical Report D-77-24, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Pequegnat, W. E., Smith, D. D., Darnell, R. M., Presley, B. J., and Reid, R. O. "An Assessment of the Potential Impact of Dredged Material Disposal in the Open Ocean." Technical Report D-78-2, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).

- Peterson, S. A. "Hydraulic Dredging as a Lake Restoration Technique: Past and Future." Management of Bottom Sediments Containing Toxic Substances. S. A. Peterson and K. K. Randolph, Eds., EPA-600/3-77-083, Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency, Corvallis, Oregon, pp. 202-228 (1977).
- Reddy, C. N., and Patrick, W. H., Jr. "Effect of Redox Potential and pH on the Uptake of Cadmium and Lead by Rice." *J. Environ. Qual.* 6: 259-262 (1976).
- Rhoads, D. C., McCall, P. L., and Yinget, J. Y. "Disturbance and Production on the Estuarine Seafloor." *Amer. Sci.* 66: 577-586 (1978).
- Sameshima, T. "Dredging of Contaminated Bed Sediment in Japan." Management of Bottom Sediments Containing Toxic Substances. S. A. Peterson and K. K. Randolph, Eds., EPA-600/3-77-083, Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency, Corvallis, Oregon, pp. 1-19 (1977).
- Serne, R. J., and Mercer, B. W. "Dredge Disposal Study, San Francisco Bay and Estuary. Appendix F. Crystalline Matrix Study." U.S. Army Engineer District, San Francisco, California (1975).
- Shelton, T. B., and Hunter, J. V. "Anaerobic Decomposition of Oil in Bottom Sediments." *J. Water Poll. Con. Fed.* 47: 2172-2182 (1975).
- Shuba, P. J., Tatem, H. E., and Carroll, J. H. "Biological Assessment Methods to Predict the Impact of Open-Water Disposal of Dredged Material." Technical Report D-78-50, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Stumm, W., and Morgan, J. J. Aquatic Chemistry. Wiley-Interscience, New York, 583 p. (1970).
- Syers, J. K., Harris, R. F., and Armstrong, D. E. "Phosphate Chemistry in Lake Sediments." *J. Environ. Qual.* 2: 1-14 (1973).
- Taylor, R. M., and McKenzie, R. M. "The Association of Trace Elements with Manganese Minerals in Australian Soils." *Australian J. Soil Res.* 4: 29-39 (1966).
- U.S. Army Engineer District, San Francisco. "Dredge Disposal Study, San Francisco Bay and Estuary." Main Report, U.S. Army Engineer District, San Francisco, California (1977).
- U.S. Environmental Protection Agency. "Proposed Criteria for Water Quality." Vols. I and II, U.S. Environmental Protection Agency, Washington, D. C., Vol. I, 425 p., Vol 2., 164 p. (1973).

- U.S. Environmental Protection Agency. "National Conferences on Polychlorinated Biphenyls." (Nov. 19-21, 1975, Chicago, Illinois), March, 1976 Conference Proceedings, EPA-560/6-75-004, U.S. Environmental Protection Agency, Office of Toxic Substances, Washington, D. C. (1976a).
- U.S. Environmental Protection Agency. "PCB's in the United States; Industrial Use and Environmental Distribution." Task I. Final Report, U.S. Environmental Protection Agency, Office of Toxic Substances, Washington, D. C. (1976b).
- U.S. Environmental Protection Agency. "Process Design Planned for Land Treatment of Municipal Wastewater." EPA-625/1-77-008, U.S. Environmental Protection Agency Technology Transfer, Washington, D. C. (1977).
- U.S. Environmental Protection Agency/Corps of Engineers Technical Committee on Criteria for Dredged and Fill Material. "Ecological Evaluation of Proposed Discharge of Dredged Material into Ocean Waters; Implementation Manual for Section 103 of Public Law 92-532 (Marine Protection, Research, and Sanctuaries Act of 1972)." Environmental Effects Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi (1977).
- Van Vleet, E. S., and Quinn, J. G. "Input and Fate of Petroleum Hydrocarbons Entering the Providence River and Upper Narragansett Bay from Wastewater Effluents." Environ. Sci. Technol. 11: 1086-1092 (1977).
- Vincent, M. K. "Habitat Development Field Investigations, Rennie Island Marsh Development Site, Grays Harbor, Washington; Summary Report." Technical Report D-78-11, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Wakeman, T. H. "Mobilization of Heavy Metals from Resuspended Sediments." Paper presented at 168th American Chemical Society National Meeting, Atlantic City, New Jersey (1974).
- Walker, J. D., Colwell, R. R., and Petrakis, L. "Evaluation of Petroleum-Degrading Potential of Bacteria from Water and Sediment." Appli. Microbiol. 30: 1036-1039 (1975a).
- Walker, J. D., Colwell, R. R., and Petrakis, L. "Bacterial Degradation of Motor Oil." J. Water Poll. Con. Fed. 47: 2058-2066 (1975b).
- Walski, T. M., and Schroeder, P. R. "Weir Design to Maintain Effluent Quality from Dredged Material Containment Areas." Technical Report D-78-18, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).

- Wang, Chun-Ching, and Chen, K. Y. "Laboratory Study of Chemical Coagulation as a Means of Treatment for Dredged Material." Technical Report D-77-39, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1977).
- Wier, C. F., and Walter, W. M. "Toxicity of Cadmium in the Freshwater Snail, Physa gyrina Say." J. Environ. Qual. 5: 359-362 (1976).
- Windom, H. L. "Environmental Aspects of Dredging in Estuaries." J. Waterways, Harbors, and Coastal Engr. Div., Proc. Amer. Soc. Civil. Eng. 98: 475-487 (1972).
- Windom, H. L. "Mercury Distribution in Estuarine-Nearshore Environments." J. Waterways, Harbors, and Coastal Eng. Div., Proc. Amer. Soc. Civil Eng. 99: 257-264 (1973a).
- Windom, H. L. "Investigations of Changes in Heavy Metals Concentrations Resulting from Maintenance Dredging of Mobile Bay Ship Channel, Mobile Bay, Alabama." Contract Report DACW01-73-C-0136, Submitted to Mobile District, U.S. Army Corps of Engineers, 46 p. (1973b).
- Wollast, R., Billen, G., and Mackenzie, F. T. "Behavior of Mercury in Natural Systems and its Global Cycle." Ecological Toxicology Research. A. D. McIntyre and C. F. Mills, Eds., Plenum Publishing Corp., New York, pp. 145-167 (1975).
- Woolson, E. A. "Bioaccumulation of Arsenicals." Arsenical Pesticides. E. A. Woolson, Ed., ACS Symposium Series 7, Amer. Chem. Soc., pp. 97-107 (1975).
- Wyeth, R. K., and Sweeney, R. A. "Aquatic Disposal Field Investigations, Ashtabula River Disposal Site, Ohio; Appendix C: Investigation of Water-Quality and Sediment Parameters." Technical Report D-77-42, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi (1978).
- Yoshida, T., and Ikegaki, Y. "A Study on the Behavior of Mercury-Contaminated Sediments in Minamata Bay." Management of Bottom Sediments Containing Toxic Substances. S. A. Peterson and K. K. Randolph, Eds., EPA-600/3-77-083, Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency, Corvallis, Oregon (1977).
- Young, D. R., Jan, Tsu-Kai, and Heesen, T. C. "Waste Cycling in the Southern California Bight." Presented at the 4th Biennial International Estuarine Research Conference, Mt. Pocono, Pennsylvania (1977).

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