OCS Report
MMS 95-0003

Marine Mining Technologies and Mitigation Techniques

A detailed analysis with respect to the mining of specific offshore mineral commodities

July 1996

Contract No. 14-35-0001-30723

MMS U.S. Department of the Interior
Minerals Management Service

Office of International Activities and Marine Minerals (INTERMAR)

The Department of the Interior Mission

As the nations Principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places;and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the nation's Outer Continental Shelf (OCS), collect revenue from federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the Offshore Minerals Management Program administrators the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS Royalty Management Program meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfil its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.

DISCLAIMER

Proposed Marine Mining Technologies and Mitigation Techniques: A detailed analysis with respect to the mining of specific offshore mineral commodities

Contract Report

Prepared for

U.S. Dept. of the Interior, Minerals Management Service

Prepared by

C-CORE

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C-CORE

Centre for Cold Ocean Resources Engineering
Memorial University of Newfoundland
St. John's, NF, A1B 3X5, Canada
Tel. (709) 737-8354 Fax. 709-737-4706

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1.0 Introduction

This report was commissioned by the Minerals Management Service (MMS), U.S. Department of Interior (DOI). The MMS is responsible for the regulation of mineral exploration and development on submerged Federal Lands of the U.S. Outer Continental Shelf (OCS). Environmental protection is an integral part of the mandate of the MMS, and regulatory requirements exist for the enactment of mitigation measures during the conduct of all offshore mineral exploration and development activities. In keeping with the requirements of the National Environmental Policy Act (NEPA) and Council of Environmental Quality (CEQ) regulations, the MMS performs environmental analysis and assessment of proposed offshore mineral developments on a case-by-case basis. This document provides the MMS with practical guidance in prescribing mitigation measures for future marine mining developments on the U.S. OCS.

1.1 Purpose and Objectives

The purpose of this study is to undertake a detailed analysis of available and proposed marine mining technologies and mitigation techniques with respect to the mining of specific mineral commodities on the U.S. Outer Continental Shelf.

The objectives of the study are:

(1) to develop realistic scenarios for marine mining activities that are likely to occur on the U.S. OCS within a ten-year time span

(2) to make predictions of the environmental impacts associated with the marine mining scenarios

(3) to establish guidelines for mitigation of the anticipated environmental impacts

(4) to perform cost-benefit analyses of available and proposed techniques for mitigation of the environmental impacts of marine mining

(5) to formulate recommendations as to the most appropriate mitigation techniques for the scenarios and similar marine mining developments.

1.2 Project Team

To meet the above stated objectives, a unique multi-disciplinary team was formed consisting of environmental scientists and marine mining and dredging specialists. The Project Team consisted of four principal groups, or nodes, which included a Management node, a Mining Engineering node, a Physical Environmental Effects node and a Biological/Chemical Environmental Effects node.

The Management node was based at the Centre for Cold Ocean Resources Engineering, Memorial University of Newfoundland, Canada. The Mining Engineering and Mitigation node was led by Richard Garnett, Ph.D., C.Eng., an international mining consultant and President of Valrik Enterprises of Ontario, Canada. The Physical Environmental Effects node was headed by Laurie Davidson, physical oceanographer and President of Seaborne Information Technologies Ltd., located in St. John's, Newfoundland, Canada. The Biological/Chemical Effects node was directed by Derek Ellis, Ph.D., R.P.Bio., professor of biology at the University of Victoria, Canada, and Principal of Derek V. Ellis Ltd., marine environmental consultants.

This report was authored primarily by the node leaders. Supporting contributions were made by Tom Pederson, Ph.D. (environmental chemist; University of British Columbia), Jack Littlepage, Ph.D. (pelagic biologist; University of Victoria), Robert Jantzen (dredging engineer; Jantzen Engineering Co., Inc.), Donald Hodgins, Ph.D. (physical oceanographer; Seaconsult Ltd.), and Laurence Davis, M.Sc. (project manager and marine geoscientist; C-CORE).

1.3 Approach and Methodology

1.3.1 Marine Mining Scenarios

A variety of mineral commodities exists on the U.S. OCS and are potential targets for future exploitation. These include sand resources suitable for beach nourishment, marine aggregates, heavy minerals, precious metals, phosphorites, and others. Their exploitation will inevitably result in environmental impacts that will vary in degree depending on factors such as the scale of operation, the extraction technology used, and the nature of the geological and environmental setting.

This study deals with two fundamental questions. What are the likely environmental impacts associated with mining of specific mineral commodities on the U.S. OCS? How might those impacts be mitigated in a cost-effective manner? These questions are addressed through analysis of a number of marine mining scenarios. They describe the scale of operation, extraction technology, and environmental setting of marine mining operations that target a range of mineral commodities.

The mining scenarios were developed in close consultation with the MMS, and their selection was based on the following criteria:

(1) Potential for near-term development:

Only mineral commodities likely to be exploited within a ten-year time span were considered. Other mineral commodities were excluded on the basis of market and technological constraints.

(2) Commodity resource information:

Much of the available information pertaining to the distribution of mineral commodities on the U.S. OCS is regional and lacks sufficient resolution to derive reserve or even resource estimates.

However, there is sufficient detail at least to target general areas of interest (scale of kilometres) and sometimes more specific areas.

(3) Proximity to markets and market demand:

The proximity to the commodity market, and the market demand, are important considerations for all potential marine mining developments. The MMS provided valuable advice with respect to market requirements, which helped considerably in determining the most appropriate site-selections for the mining scenarios.

(4) Availability of environmental data:

A final but secondary consideration in selecting the marine mining scenarios was the availability of local environmental data. Where environmental data were sparse or lacking, it was possible to make appropriate generalizations about distributions of biological assemblages and about likely ecological responses based on regional information and knowledge of the habitat.

A total of five marine mining scenarios were selected and developed in detail. These include:

(1) Precious metal mining, Alaska - bucket ladder dredge

(2) Precious metal mining, Alaska - underwater miner

(3) Marine aggregate mining, Massachusetts Bay

(4) Heavy mineral mining, offshore Virginia

(5) Beach nourishment, Ocean City, Maryland.

The first scenario is a case history of a large-scale placer gold mining operation offshore Nome, Alaska, carried out by Western Gold Exploration and Mining Company (WestGold) Limited Partnership during the late 1980's. While the scale of operation and use of a bucket ladder dredge are not likely to be repeated in any future offshore mining activities in the region, the scenario is highly instructive in that it documents real experience with the practice of marine mining environmental impact mitigation. It is also the only large-scale marine mining development to occur in U.S. waters to date.

The second scenario, which involves precious metals mining using an underwater mining vehicle, is based on actual non-production trials carried out towards the end of the WestGold project life. The two mining methods are at opposite ends of the spectrum in terms of scale of operation and precision of extraction. They provide a useful comparison of the effects of using different extraction techniques to mine the same mineral commodity.

Offshore aggregate mining, the subject of the third scenario, is thought to be a likely prospect in the near-term. The first markets to be served by such an industry will probably be the greater-metropolitan areas of Boston and New York. Recognizing that marine aggregate resources in the region are potentially widespread, the choice of a location in Massachusetts Bay for a hypothetical aggregate mining operation was based mainly on the availability of environmental information. A comprehensive baseline environmental study was carried out in the early 1970's in preparation for an experimental offshore aggregate mining project. The experiment did not proceed, but the baseline environmental information gathered serves as a useful resource for this study.

Although the baseline study also provides what is still perhaps the most complete site-specific assessment of aggregate resources in the region, it reveals that the geology of the site under consideration is not particularly conducive to economic dredging operation. The sediments are poorly sorted and contain, on average, higher proportions of silt and clay than are normally desirable for an aggregate target. Therefore, the hypothetical marine aggregate mining operation presented in this report represents a worst case scenario both environmentally and economically. As a marginal operation the aggregate mining scenario is a sensitive monitor of the economic costs of mitigation.

The fourth scenario, again hypothetical, involves dredging of heavy mineral sands in Federal waters off Virginia Beach, Virginia. The site selection for this scenario is based mainly on commodity resource information. Concentrations of industrial heavy minerals are known to exist offshore Virginia as well-sorted placer deposits. The geology and environmental setting are thought to be representative of most areas on the U.S. OCS where heavy minerals could be targeted. Any proposal for offshore mining development in the area will have to address potential conflicts with other uses, including commercial fishing, ocean dumping, and military practice.

The fifth scenario considers the use of sand resources in Federal waters (three nautical miles seaward of the coastline) for beach nourishment. The site selected for the scenario, Ocean City, Maryland, has undergone repeated coastal restoration projects, the most recent was in the fall of 1994. Borrow sites have moved progressively offshore and the need for sand resources from Federal waters appears imminent.

1.3.2 Mitigation Analysis

As stated in Section 1.1 above, the ultimate objective of this study is to develop recommendations as to the most appropriate techniques for mitigation of the environmental impacts associated with mining of specific mineral commodities on the U.S. OCS. The recommendations are derived from analyses of a broad range of available and proposed mitigation measures with consideration given to their relative cost and effectiveness. The selection of mitigation techniques for analysis was based upon the environmental impacts and mitigation objectives identified for each of the mining scenarios.

1.4 Structure of the Report

Section 2, Environmental Issues, provides a detailed overview of the environmental impacts of marine mining with special emphasis on key issues relevant to the marine mining scenarios.

Issues relating to modelling, and to environmental monitoring and quality assurance/quality control (QA/QC) protocols, are also introduced and discussed in the context of environmental impact mitigation.

The marine mining scenarios are presented in Section 3. Details are provided of their environmental settings, the commodity resource characteristics, and the extraction and processing methods. Predictions of the potential environmental impacts of each extraction technology are provided along with guidelines for mitigation of those impacts.

In Section 4, techniques for mitigation of the environmental impacts of marine mining are reviewed and in Section 5 these are applied in detail to the marine mining scenarios. Recommendations are made as to the most appropriate selection of mitigation measures for each mining scenario. Conclusions and final recommendations are presented in Section 6.

2.0 Environmental Issues

This section provides an overview of the environmental issues associated with marine mining. Physical, chemical and biological issues are addressed, with particular emphasis placed on the ultimate biological impacts of marine mining and how they can be recognized and monitored. The Mining Scenarios (Section 3) provide examples of the application of the issues to specific sites.

The final section (2.7) is a summary of the environmental information presented in the context of mitigation. Section 2.7 presents a framework for application of the issues to the mining scenarios. The framework consists of:

(1) predicting environmental impact

(2) setting mitigation objectives

(3) providing criteria for monitoring achievement of the mitigation objectives.

2.1 Physical Environmental Issues

There are two key physical environmental issues: (1) defining the processes and factors that are relevant to marine mining methods, potential impacts, and mitigative technologies, and (2) understanding how these physical processes and factors are connected to potential negative environmental impacts from mining operations, and how these impacts might be mitigated.

Solutions to these issues are best achieved by (1) establishing a working definition of the term "physical environment", in contrast with associated terms which at least include "geochemical environment", "biological environment", and "mining operation"; (2) identifying the two distinct ways in which physical marine processes affect an offshore mining operation, and (3) considering the knowledge of the physical environment which may be required to successfully mitigate the potential environmental impacts of marine mining operations. The following text individually addresses these three matters.

2.1.1 Physical Environment Definition

For the purposes of this discussion, physical environmental processes are deemed to be those processes that determine the characteristics and motion of the oceanic water column, and affect its interaction with its top and bottom boundaries (the atmosphere and the seabed respectively). Included in this definition are all issues associated with the interaction of the atmosphere and the ocean, most particularly heat input, precipitation, and energy input from the wind. Floating ice is considered to be a component of the water column, and hence is incorporated in the spectrum of physical environmental issues. In addition to spatial and temporal distributions of temperature, salinity and density, other true water column phenomena of interest include currents (at all length and time scales), surface waves, internal waves, and changes in water level elevation due to tide, surge, etc. Particularly important is the fact that the turbidity of the water column is considered to be an aspect of physical environmental considerations.

Excluded from this definition of physical environmental processes and factors are all aspects of the seabed, including the physical characteristics and particle properties of the mobile sediment layer (considered as geological issues), all living organisms in the water column or on the seabed (considered as biological issues), and all issues associated with the man-induced introduction of materials into the water column from mining activities (considered as mining operation issues).

2.1.2 Physical Environmental Effects on Marine Mining Operations

The physical environmental processes and factors, discussed above, affect marine mining operations in two ways. Firstly, these processes and factors constrain or control the actual conduct of the mining operation, and thus are significant in determining the potential environmental impacts of the operation. Secondly, physical processes govern water column movements which redistribute particulates returned to the sea by the mining operation, thus also influencing potential impacts.

The first issue is the direct effect of the physical environment on the mining activity. Those principal factors exercising control over mining operations may vary in importance with the mode of mining, but in most instances include wind, waves, currents and ice. Temperature, precipitation and water level considerations are usually of secondary interest, except possibly in locations where unusually high tides or tidal ranges might impose operating constraints. Seasonal as well as short time scale changes in these conditions combine to determine both the annual operating season for a mining activity, and dictate the viability of particular operations or activities on a particular day.

It is generally true that as these physical factors increase in severity (higher winds, higher waves, stronger currents, more and thicker ice, lower temperatures, etc.), the viability of mining operations decreases. As with most other industrial activities at sea, there are normally well-defined thresholds for wind, wave, current, and ice beyond which certain mining activities are required to be suspended. With respect to the extraction, transport and processing aspects of the mining operation, these may be considered to represent a self-protecting or self-mitigating situation: as the environmental factors intensify and increase the risk of disruption to the mining operation, the operation is forced to respond by reducing its scale or level of activity.

A directly opposite circumstance generally pertains to any physical activities employed at the mine site to mitigate the zone of impact of particulates transported through the water column. In this instance, it is generally true that as the severity of the environmental factors increases, the difficulty in maintaining the mitigative measures also increases. For example, one potential mitigative technique might be to release slurry from a dredge via pipes extending down into the water column to introduce the effluent nearer the seabed than would be achieved from a surface release. The intent of such a technique would be to limit the horizontal zone of influence of particulates by minimizing the time during descent that the particulates are subjected to the advective effects of horizontal currents. The structural integrity of such an effluent disposal system would be increasingly threatened with increasing severity of environmental conditions. Hence, maintaining the effectiveness of the mitigative technique would similarly be threatened.

The principal sources of potential environmental impact from mining operations are physical disruption of the seabed, the deposition of disturbed and/or mined materials over undisturbed portions of the seabed, and the dispersion of particulate material through the water column. Another issue is the role of physical processes in determining the distribution and motion of this particulate load through the water column, the timing and location of the deposition of this load, and the possible resuspension and redeposition of unconsolidated materials after initial deposition on the sea floor. Horizontal currents in the water column are the critical factors in sediment redistribution. The magnitude and variability of horizontal currents, and the grain size distribution of particulates (and particulate cohesive properties), determine both the residence time in the water column, and the range of horizontal transport of the particles.

Secondary physical issues are stratification (as defined by temperature, salinity, and hence density distributions) and waves. Strong stratification can inhibit the vertical motion of settling particulates, and hence can result in such matter being transported greater distances from source than would be the case in the absence of stratification. This effect is more likely to be important in deep than in shallow water. Surface waves can be the source of turbulence which increases the dispersion of suspended sediments. As well, waves interacting with the seabed can cause resuspension of deposited sediments, and transport them away from their source. Unlike the first issue described above (impact of the physical environment on the mining operation), it is not possible to generalize about the positive or negative consequences of increased horizontal dispersion of sediments. Increased dispersion to minimize the concentration of deposited sediment at any one location may be most desirable in some scenarios, depending on such factors as chemical, sedimentary and biological regimes. In other cases, minimizing the zone of influence may be the priority. In yet others, broad dispersion in some directions may be desirable, if the key issue is the protection of sensitive resources located in other directions from the sediment source. Clearly, an understanding of the physical transport mechanisms is not sufficient to determine the nature or severity of environmental impacts. The key point is that physical processes do not dictate impact. Rather, physical processes are transport mechanisms. The consequences of the transport of suspended material determine environmental impacts. Hence, understanding physical processes is only one of a necessary series of steps required to quantify the environmental impact of mining operations.

2.1.3 Required Physical Environmental Knowledge

The task of predicting environmental impacts from marine mining operations requires knowledge of physical environmental processes and factors. The specific parameters, time and length scales of variability of prime interest are dictated by the specific details of that circumstance. Such specific details are almost always associated with biological, chemical, and/or mining operations issues. Direct measurements and numerical modelling are the two available methods of acquiring the requisite physical environmental knowledge.

2.2 Geochemistry

2.2.1 Diagenetic Zonation and Production of Hydrogen Sulphide

Marine organic matter in seabed deposits fuels a suite of bacterially-mediated post-depositional (diagenetic) reactions in which the organic material is progressively degraded as oxidants are consumed (Shimmield and Pedersen, 1990; Perry, 1995). The reactions yield a number of products which may have direct or indirect environmental implications, and these are briefly reviewed in this section.

Organic matter represents a highly reduced form of carbon which is rich in electrons and is therefore a primary energy source. Over most of the seabed, marine organic materials are degraded by aerobic bacteria, wherein oxygen is the terminal electron acceptor in the reaction $CH_2O + O_2 = CO_2 + H_2O$. Where oxygen is absent, the bacterial community takes advantage of other electron acceptors, which (in thermodynamic order) include nitrate, manganese and iron oxides and sulphate. Thus, aerobes are succeeded by nitrate-reducing bacteria, and later by sulphate-reducing bacteria as long as degradable organic matter remains. This suite of reactions leads to a biogeochemical zonation in sediments, as shown in Figure 2.1 (modified from Pedersen and Pelletier, 1989, and Poling, 1995).

Anoxia results where oxygen supply via advection or diffusion is exceeded by demand of aerobes and by inorganic consumption of oxygen by a reaction with reduced species such as Fe^{2+}. Anoxic conditions at relatively shallow depths (a few centimetres or less) are typical in most coastal and inner continental shelf sediments. The depth to the oxic-anoxic boundary is highly variable. It depends on:

(1) The rate of sedimentation, which physically influences the diffusive influx of oxygen into the deposits

(2) the marine organic matter accumulation rate (i.e. the rate of accumulation of "oxidant demand")

(3) the extent of bioturbation, which can physically introduce oxygen to the deposits by mixing in oxygenated seawater

(4) the bottom water oxygen content, which can vary between near saturation and zero, depending on the residence time of the water at a given site and the length of time since the water was exposed to the atmosphere.

Of the many products that the oxidation reactions yield, the most important from an environmental perspective is hydrogen sulphide, which is produced during sulphate reduction. The depth at which sulphate reduction is first encountered in marine sediments ranges from as much as 2 to 3 m in some continental shelf deposits to as little as a few millimetres in many nearshore organic-rich sediments.

A review of mine tailings production and their subsequent chemical stability in the marine environment is given by Poling (1995). Anoxia stabilizes most heavy metal compounds; hence, the depth at which pore waters become anoxic is an important environmental parameter at proposed dredging sites.

2.2.2 Potential Consequences of H_2S Generation

Two effects of H_2S production warrant mention. First, hydrogen sulphide is highly toxic. In nearshore settings where the rate of deposition of organic matter is high as a result of high primary productivity or anthropogenic nutrient or organic inputs (e.g. sewage or pulp mill effluent, nutrient-rich runoff from agricultural sources), several millimoles per litre of dissolved H_2S species can be present in the interstitial waters within the upper metre. The hydrogen sulphide will quickly de-gas to the atmosphere if such organic-rich sediments are brought to the surface during dredging operations, and this could pose a significant safety hazard to humans.

Organic matter has a low density, and organic particles tend to behave hydraulically as if they were fine-grained. Invariably, relatively coarse-grained dredging targets such as sands and gravels are impoverished in organic materials and are associated with a low oxidant demand. Sulphate reduction would not be profound in such settings; hazardous concentrations of H_2S would therefore not be expected.

The second consideration is that dissolved H_2S species react readily with a number of metals, producing sulphide phases which are relatively insoluble as long as the deposits remain anoxic. For example, the dissolved iron produced in the iron oxide reduction zone (see Fig. 2.1) reacts with upward-diffusing HS^- to produce FeS and/or FeS_2 (pyrite). Similarly, molybdenum reacts to produce MoS_2 (molybdenite), arsenic to produce $FeAsS_2$ (arsenopyrite), copper to produce CuS (covellite), and so on. In extreme cases where sulphate reduction occurs very near the sediment-water interface, metals such as molybdenum, which is relatively common in seawater, can diffuse into the bottom to be fixed as the metal sulphide. This can lead to a natural enrichment of molybdenum and other metals which behave in a geochemically analogous way.

Anoxic sediments are naturally enriched in metal sulphides. If these sediments are exposed to oxygenated water or the atmosphere, the potential exists for at least partial oxidation of the sulphides and consequent release to solution of the formerly-reduced bound metals. Molybdenum is known to be released under such circumstances (Shaw *et al.* 1990), as are uranium (which is frequently enriched in sediments as UO_2 [uraninite]) and arsenic (Shaw *et al.* 1990 and 1994). However, oxidation of the reduced species is not instantaneous, and the concentrations in the solid phase are usually low (up to several parts per million for uranium, and up to several tens of ppm for molybdenum and arsenic in extreme cases). The result is that the quantum of metals released to solution during oxidation is small. Deleterious environmental impacts would not usually be expected under such circumstances. In addition, both molybdenum and uranium occur at relatively high concentrations naturally in seawater as the refractory species MoO_4^{2} and $[UO_2(CO_3)_3]^{4}$ respectively; coastal waters are therefore not environmentally sensitive to this pair of metals.

The discussion above applies only marginally to coarse marine sediments because these are rarely anoxic to the extent that metals have become naturally enriched. Hence, the potential to produce negative chemical impacts as a result of dredging aggregate or placer deposits is low to very low. This conclusion is borne out by evaluation of monitoring data accumulated during the WestGold placer gold mining operation near Nome, Alaska, (summarized in Section 3.2.3). Nevertheless it is appropriate to consider the potential for these effects site-specifically by appropriate measures, and the relevance of applicable sediment quality guidelines (Section 2.6).

2.3 Seabed Biodiversity

Benthic (seabed) organisms are the base feedstock for fishery and wildlife resources such as seabed feeding fish, diving waterfowl and marine mammals, and also contribute to the larval biodiversity of the water column. Their populations allow calculations of biodiversity, and biodiversity can be used as a yardstick for gauging environmental impact.

Biodiversity is measured by: (1) how many different kinds of organisms are present, and (2) the relative numbers of each (i.e. which are common, which are rare). These are *Species diversity* and *Numerical diversity* respectively.

Organisms should be identified to *species* where possible, because species as biological units are the base measure for biodiversity calculations. At most sites there is some uncertainty about the species identity of many forms present, but separation to species can still be achieved by identifying to a higher order taxonomic level, say to genus or family. Thus, although the biodiversity unit is not precisely named, it is measured as one unit for biodiversity calculations.

Detailed lists of species present at any one time are summarised where relevant because, according to Thorson's (1957) theory of *Parallel Level-Bottom Communities*, such lists have some predictive value. It should be possible to predict the kinds of organisms which will recur on similar deposits. It is very noticeable that identical genera tend to occur on similar habitats, whereas the actual species within the genus differs from site to site.

At present there is no numerical model which does more than predict biodiversity in a generalised way. Poiner & Kennedy (1984) show, and develop a model for, increases in total biomass (weights of organisms) in the far field of a dredging plume. Biomass is related to numerical abundance in a general way, but not in detail, because the large individuals of a species tend to be more rare than the small younger individuals.

The benthos of coarse-grained marine placer and aggregate deposits is not well known because conventional grab samplers (Holme and McIntyre, 1984), used on softer mud and fine sand to sample the burrowing infauna, do not penetrate well in gravel, or even in coarse sand. Dredges and trawls sampling the mobile epifauna hang up on rocks, bounce on the surface if towed too fast, and frighten away the fastest moving fish and shellfish. Such dredges may sample the attached epifauna, providing they can dislodge the attached organisms, or pick up whole rocks and cobbles large enough to support growth.

There is little information about the biology of gravel and coarse sand deposits; therefore, there are no up-to-date reviews on which to base a generalised state-of-the-ecosystem statement. There are, however, some common biological features of marine deposits that apply regardless of grade (see Section 2.3.4). There are also some recent surveys that demonstrate the biodiversity of these deposits in a mining context (see Section 2.3.3). A selection of articles is reviewed. These sections lead to the issue of monitoring sampling design and analysis to document benthic biodiversity (Section 2.3.6).

Regardless of the grade of deposit extracted, there are two sets of risks arising from dredging operations: (1) extraction risks (i.e. removal of habitat material with some surrounding disturbance), and (2) discharge risks (i.e. deposition of discharged tailings). These are introduced in Sections 2.3.1 and 2.3.2 respectively. This review does not consider impacts derived from dredging for removal of contaminated deposits, nor impacts from the mining of metalliferous muds.

2.3.1 Extraction Risks

2.3.1.1 Resource Losses

Extraction removes sediment habitat and the organisms living within the sediment (infauna), or on it (epifauna). The burrowing forms are relatively immobile and cannot swim away from the cutting face of the mining excavation. These benthic organisms include fish and prawn resource species that maintain burrows, and many species of smaller creatures which can function as feedstock for resource species.

Epifauna come in two forms. The mobile epifauna generally live on the surface of the deposits. They may be able to remove themselves from the immediate dredge area. Examples include flatfish, crabs, sea cucumbers and sea urchins (almost immobile), scallops, and other resource species. The other epifaunal form is sessile, and is attached to the large cobbles, boulders, or any rock outcrops. They are generally attached so firmly that they are only removed if their host substrate is removed. In general, seabed mining will have an impact on resource species, their feedstock and habitat.

2.3.1.2 Anoxic Sediments

The sediment habitat characteristically is aerated close to the surface. Most organisms live within the surface aerated layer. However, oxygen reduces with sediment depth depending on porosity and permeability. Coarse, well-sorted sands and gravels have the thickest well oxygenated layer, and silts and clays the thinnest. The consequence to bio-diversity of reducing oxygen within the sediment is that most organisms are competing for space within a shallow aerated zone. Some, usually the larger forms, can live in deeper protective burrows within the reduced-oxygen (even anoxic) zone provided they maintain contact with an oxygen and food supply. In general, minerals dredging is not targeted at low oxygen, fine-grained sediments. However, patches of fine silts and clays may occur in a dredging area. If they are detectable they should be avoided for both economic and environmental reasons (such as the release of anoxic or toxic pore water).

2.3.1.3 Organism Depth Within Deposits

In minerals dredging, coarse sediments are to be expected, hence there is likely to be a deep aerated layer of probably 1 m or more. Constraints on depth to which organisms can live within these deposits are related to their abilities to burrow and maintain contact with the surface. Hence larger organisms tend to live at deeper levels than small organisms. The larger forms tend to be resource species that may live at depths of 1 to 2 m within the sediment. Conventionally, infaunal biologists accept 10 cm of seabed penetration as an effective sampling depth, with little documentation as to whether retrieval to this depth collects all specimens or not. Large deep-living forms present a further concern in that they may be long-living, slow-growing forms whose biomass may have taken 100 or more years to form. Once these forms, such as horse clams and geoducks, are lost it may take decades to reestablish a potentially sustainable fishery. The loss may even be permanent.

2.3.1.4 Sediment Suspension and Settlement

Extraction involves physical disturbance of the seabed at the dredgehead due to cutting, and/or suction, and removal. This inevitably involves suspension of sediments, causing raised turbidity over the seabed with a plume drifting with tidal currents. The resuspended sediments resettle nearby or at some distance depending on current velocities and particle size. Resettlement can be in areas of similar or dissimilar deposits (see Section 2.3.2 Discharge Risks, for further concerns arising from deposition).

2.3.1.5 Benthic Primary Biological Production

In very shallow water, for example 5 to 10 m depth, dredging-induced turbidity may reduce primary biological production of plant growth downcurrent of the dredged area

2.3.1.6 Organism Exposure

The cutting action of seabed mining will expose immobile organisms to predators, and exposed injured or dead organisms attract scavengers and predators. A disturbed area can become temporarily more active biologically, and more attractive for fishing but at unsustainable levels.

2.3.2 Discharge Risks

A discharged tailings slurry falls through the water column, with some dispersion of fines (also see Section 2.4 Biological Oceanography), and eventually reaches the seabed as a density current. After initial impact, the tailings spread in some pattern as a seabed dispersal field, deposition occurring with coarser particles settling first.

2.3.2.1 Smothering

Large amounts of tailings may smother and kill organisms over a broad area. Deposition of the tailings may occur more rapidly than the inhabiting organisms can avoid, or too fast for the inhabitants to maintain contact with life-giving aerated water, or their feedstock, above or around them. Smothering kills benthic organisms by preventing them from breathing or feeding. In general the ability of benthos to avoid smothering, or to burrow up faster than smothering deposits can settle, is not known. At Island Copper Mine shallow water fiord benthos on silts and clays can tolerate an accumulation rate of tailings of about 1 cm a year (Ellis and Hoover, 1990). The data do not indicate the highest deposition rate that can be tolerated (but see Section 2.3.5.2). During tailings discharge there is an area within the seabed depositional field where benthos cannot tolerate rapid deposition, and are smothered, or their survival is affected in some other way. This area represents only a part of the region where deposited tailings can be identified.

2.3.2.2 Crustacean Stocks

Crabs, lobsters and other epifaunal omnivorous forms may be able to maintain themselves during the tailings discharge phase. Although the reasons for this are not well established, it may be that damaged feed organisms are available for scavenging. There can be no guarantee that the maintenance of crab fisheries, as at Island Copper Mine and the WestGold marine placer operation, will occur at other dredging locations.

2.3.3 Benthos of Gravel and Sand Deposits

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Table 2.1 provides summary ecosystem data from four selected investigations of gravel and sand deposits. These deposits are where dredging operations have been conducted or were planned. The parameters shown have been selected to indicate important components of the habitat but do not include other relevant and normally recorded oceanographic parameters such as water temperature, salinity and dissolved oxygen.

2.3.3.1 Formatting Benthic Data

The form of the Summary Table 2.2 needs some explanation. Survey reports are listed by author (Column 1), and a location descriptor is given in Column 2. The environmental data in Columns 3 to 5 provide descriptor terms and the objective substrate characteristics documented, such as particle size data and relevant geochemical parameters.

The generalised terms "gravel" and "sand" (Column 3) are useful indicators of deposit grade, but there is considerable variation in their use. Particle size data (Column 4) are more explicit. For particle size it helps to follow convention by including an average statistic such as the median, and also a sorting coefficient. The latter shows whether the deposit is well- or poorly-sorted (see above). Poorly-sorted deposits with a geochemically active mud fraction are very different ecologically from well-sorted deposits with high porosity and good aeration. In addition, if there are cobbles and boulders present, there will be more attached sessile organisms. These tend to be slower recolonizers than mobile forms (see Section 2.3.5).

The most important biological data consist of species identifications, counts of organisms, and calculations of diversity and biomass (Columns 6, 8 and 9). Species identifications are the fundamental biological unit on which statistics are based. On occasions, identifications may be undertaken only to Higher Order Taxa (HOT's - Column 7) such as to Genera, Families, Classes, Orders or even Phyla. This may be appropriate site-specifically (and for comparisons).

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2.3.3.2 Scope of Reports Reviewed

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An exhaustive compilation of data for the areas involved in the mining scenarios has not been attempted for the reasons above. Two current, relevant projects, plus a recent review of the impact of beach nourishment dredging, will influence assessment procedures in the future. These projects are:

(1) The MMS-funded study entitled "Impacts and Direct Effects of Marine Mining Activities on Benthic Organisms" by the University of South Florida, St. Petersburg. When complete, this will update and substantially extend prior investigations of dredging impact for beach nourishment (e.g. Salomon *et al.* 1982)

(2) The NOAA/NMFS computerised benthic database for the east coast extending from Nova Scotia to Florida. This database is now being prepared for access by CD-ROM, diskette, etc. (Theroux, 1994). It will allow electronic access to nearly 200,000 records from over 11,700 sampling sites extending over all types of deposits. The database will allow retrieval of site- and time-specific benthos surveys in the future, but species lists taken from it will have little quantitative predictive power for what will be present at any one time. A selection of information about this database is provided in Appendix 1. The distribution of deposit types for the United States eastern seaboard is mapped, as is the distribution of recorded benthic samples. The distribution and abundance of major taxonomic groups is also mapped and tabulated. Historical fisheries information is included.

(3) A comprehensive review article by Hurme and Pullen (1988) of dredging impact surveys by the U.S. Army Corps of Engineers, including references to relevant European literature. Selected pages of this report are provided in Appendix 2. One of the survey reports is summarised below; for the reason that the investigators (Salomon *et al.* 1982) provide documentation from post-dredging surveys that were started within 2 days of closure, earlier than any other known surveys.

Details supporting the comments and issues raised by each of the following reports are provided in Appendix 1 to 6 by Tables and Figures from these reports, and by summary tables in which original data have been put into a more consistent format. Taxonomic lists are given where relevant, as certain types of organisms tend to recur. These lists indicate the levels of identification that are needed for biodiversity assessment at dredging sites.

2.3.3.3 *Kenny and Rees (1994; 1993)* - Appendix 3

These two articles report on pre- and post-dredging surveys at Test and Reference sites on an aggregate source in the North Sea, U.K. After dredging, the median particle size rose from 0.355 to 2 mm due to exposure of underlying gravel. Biological samples were obtained with a 0.2 m^2 Hamon grab, supplemented by observations from underwater still and video cameras. There was substantial change in the benthos with loss of species abundances, diversity, biomass and species mean biomass. Unfortunately, the actual numbers differ between the two articles, although the trends are identical. The polychaete worms particularly showed massive reductions in numbers and species. However there was some, although incomplete, recovery within 7 months in this high energy, open coastal setting. This was clearly illustrated by an ordination procedure (Appendix 3, Figure 6).

Two dominant gravel epifaunal species, a barnacle *Balanus crenatus* and a tunicate *Dendrodoa grossularia*, recovered to pre-dredging numbers, but at the same time Reference site levels had increased from 3- to 7-fold during the interval (the spawning season), but with smaller-sized organisms.

It was concluded from underwater photography that post-dredging deposition of superficial sand reduced the area of hard surface available for recruitment of the sessile epifauna, and that loss of adult stock reduced potential for juvenile recruitment. Natural differences between the Test and Reference sites (1.6 km apart) were considered possible but unlikely. There was marked similarity between the fauna of Test and Reference sites, and at the Reference site before and after dredging. This is presumably a function of the close proximity of the sites, and the short (9-month) period between the initial and final surveys.

In view of the known seasonality of larval recruitment, natural annual fluctuations in biodiversity and biomass (Thorson, 1957), and the substantial recovery shown within 7 months at the Test site, it appears that pre- and post-dredging surveys should be implemented within a time period over which there is little natural change in the populations, for example about 3 to 6 months apart.

2.3.3.4 *Salomon et al. (1982)* - Appendix 4

These investigations are unique in the close timing of their shallow-water (6 - 9 m) surveys. One set of three pre-dredging surveys was timed for April, June and July 1976. Post-dredging surveys were started on August 10, just 2 days after dredging ceased, and continued weekly for a month, twice the next month, and then monthly until November 1976. Divers took replicated cores each sampling 0.0156 m^2 surface area.

Sediments uncovered by dredging were of similar grain size to the former seabed, so the original habitat was maintained. In this high energy, wave-exposed dredging area the excavated pits were filled and smoothed out with sands of similar grain size after a few weeks. Initially, divers recorded soft silts but these were covered over the next month. After one year, the Station 1 borrow pit, initially 3 to 5 m deep, had filled to within 1 m of the surrounding seabed.

Two days after dredging there was a reduced fauna at the Station 1 borrow pit (81 organisms in the samples, representing 21 species). At 16 replicates of 0.0156 m^2, this provides an estimate of 324 organisms per m^2. The biodiversity rapidly increased over the next two weeks to 534 organisms and 60 species, within the range of values collected over the next year. Dominant species tended to be polychaetes, but bivalve mollusc and amphipod species also became abundant. There were dominance changes with time. Similarity analysis showed no distinction between dredge and control samples one year after dredging.

The authors conclude that the loss of biodiversity by removal of organisms was recovered within 1 year, although biodiversity differences remained between the borrow pits and seabed outside the pits. Their data show substantial recovery within 3 weeks. They ascribe recovery to the high energy wave-exposed habitat moving local sand into the pits, and covering the silt-clay deposits which initially accumulated there. The sand presumably carried many of the local organisms with it, and was supplemented by regional spawning.

2.3.3.5 *Padan (1977)* - Appendix 5

This is a baseline report completed in 1973 prior to a planned experimental aggregate mining project. Several types of habitat were described but only four stations characterized by cobbles are reviewed here. These stations had from 1640 to 7535 organisms per m^2, with number of species ranging from averages of 31 to 113 depending on whether they were classified as "invertebrates" or "motile". The deposits were generally quite poorly sorted.

Most dominant organisms on cobble were polychaete worms or amphipods, but occasionally there were sea urchins or molluscs. Many of the cobble substrate species and dominants were also found on hard substrate (i.e. were sessile epifaunal forms).

The significance of this report when considered with the recent reports of Kenny and Rees (1994; 1993) above, is the predominating biodiversity of epifauna attached to the cobbles. For assessing and mitigating dredging impact on aggregates, it will be necessary to consider the cobble fraction and its sessile epifauna. The Padan (1977) report is considered in more detail in the Massachusetts Bay aggregate mining scenario (Section 3.4).

2.3.3.6 *ENSR (1991)* - Appendix 6

This extensive report is a compilation of environmental data from the WestGold offshore dredging site at Nome, Alaska, between 1986 and 1990. It reveals the logistical problem, inherent in placer mining, of determining the pre-dredging monitoring sites. The intended dredging sites may change with new ore delineation information. As a result no true Before & After assessment was achieved by WestGold. There was one hindsight monitoring station (R6) initiated in 1988 two years after dredging. One other station (R7), initiated during a year of dredging nearby (1987), was maintained in 1988 (not 1989) and 1990 with more dredging nearby. Several control stations with similar cobble or sand were maintained so that a Test & Reference sampling paradigm was achieved.

The 1986 dredge footprint was substantially smoothed by 1990. The 1987 data for the sandy areas showed biodiversity being substantially lower than for the control station, but by 1990 values were much higher, and were approaching those of the controls. The Cobble test site between dredging courses of 1987 to 1990 showed lower values in 1987, with values dropping through 1988 and 1990 as dredging continued. However, the cobble site dredged in 1986 showed higher values of all biological parameters in 1988 and 1990, but still generally less than control stations S3 and C3. It appears that biodiversity was increasing but was by no means back to normal four years after dredging.

Lists of dominant species show a variety of forms spread over many groups, but there was no distinction made between sessile epifauna attached to cobbles, and infauna burrowing into the deposits. Survey results support the above-described scenarios, showing that sand deposits can recover their biodiversity more quickly than gravels. The Nome deposit is less well-sorted than deposits used for aggregate and beach nourishment, with a correspondingly slow biodiversity recovery. The reasons for slow recovery cannot be established from the data reviewed here, but may relate to temperature, as well as to deposit geochemistry and the discharge of tailings. The survey results are considered in more detail in Section 3.2.

2.3.3.7 Seabed Biodiversity Patterns

In general terms benthic biodiversity can be expected to be sufficiently high on both gravel and sand beds to allow measurement of the environmental impact. Example counts for burrowing organisms (the infauna) separated from their deposits by a 0.1 mm^2 mesh, would be 50 to 100 different species in and on 1 m^2 of seabed, and 1,000 to 10,000 individuals of those species.

Both gravel and sand beds support species ranging over a diverse array of Higher Order Taxa. There are abundant polychaete worms (both particle feeders and predators), small and large crustacea (which tend to be omnivores), molluscs (both bivalves [particle feeders] and gastropods [predators]) and many other types. The major distinction between gravel and sand beds is the presence of sessile species attached to the surface of cobbles and boulders. These include such forms as barnacles and tunicates.

The infauna of poorly sorted gravel and sand beds tend to be similar, with species reflecting the particle size and degree of sorting. For example, there are species that characterize poorly-sorted silty sands regardless of whether there are cobbles and boulders present. These species include many of the delicate polychaete worms, that are not able to tolerate high-energy environments with mobile coarse-grained beds. Small crustacea swim over the still surface, and brittle stars browse on the organic load. In contrast, there are species that occur abundantly or almost entirely on relatively well-sorted sands (such as cockles and the small clams of genus *Tellina*). Well-sorted sands thus have species associations clearly different from those on gravel and poorly sorted sands.

Superimposed on this biodiversity pattern related to substrate, is a pattern related to water depth. Although the effect of increasing depth on the fauna is in part driven by reducing wave energy, and hence particle size, other factors such as surface primary production and distance from land (and river input of nutrients) are also involved. In principle, with increasing depth across a deposit, changes in biodiversity are to be expected. Relatively slight changes within the surface euphotic zone (say 0 to 50 m water depth) are most likely to be changes in the actual species present, rather than changes in species and numerical diversity. In summary, with changing depth the array of species may change.

2.3.4 Biology of Marine Deposits Relevant to Dredging

Natural annual fluctuations in biodiversity (both number of species, and number of organisms) are enormous. The classic work of Boysen Jensen (1920) documented the abundance changes for dominant species from year to year. That study showed the available plaice food was much larger in 1914 than in 1911 but less than in 1912, with a different array of most abundant species. Such year to year changes are typical.

A recent data set (Table 2.2) from Test and Reference stations for monitoring STD (Submarine Tailings Disposal) shows changes in numbers of different species over a 20 year period. There are no obvious differences in the great range of number of species between sampling stations from little or no tailings. There are obviously major reductions in number of species under thick tailings, but even these areas show considerable variability from year to year, often reaching the lower end of the natural range of the unaffected areas.

Such natural fluctuations cause great difficulty in describing ambient faunas and environmental impact on benthos. This shortcoming applies to measuring biodiversity before dredging operations start, assessing changes derived from the dredging operations, and assessing the progress of recolonisation after dredging.

Spatial differences in biodiversity on uniform deposits means that the fauna of Dredging (Test) and nearby Reference sites will inevitably differ to some extent from natural causes, and from year to year. These spatial differences are due to the biology of the species present. Many benthic species live in clusters (McIntyre *et al.* 1984). It is quite possible to have a localized herd of sea urchins crawling on a sand bed over a dense patch of newly burrowed-in clam larvae. These two species will then dominate the numerical biodiversity at that point. Patchiness of this type seriously impedes faunal comparisons, because counts of organisms present in samples are not normally distributed (in a statistical sense). There may be no cost-effective way to obtain accurate and precise biodiversity estimates of benthos with different and varying patchiness. Crude quantitative estimates may have to be accepted.

The discussion above applies only marginally to coarse marine sediments because these are rarely anoxic to the extent that metals have become naturally enriched. Hence, the potential to produce negative chemical impacts as a result of dredging aggregate or placer deposits is low to very low. This conclusion is borne out by evaluation of monitoring data accumulated during the WestGold placer gold mining operation near Nome, Alaska, (summarized in Section 3.2.3). Nevertheless it is appropriate to consider the potential for these effects site-specifically by appropriate measures, and the relevance of applicable sediment quality guidelines (Section 2.6).

2.3 Seabed Biodiversity

Benthic (seabed) organisms are the base feedstock for fishery and wildlife resources such as seabed feeding fish, diving waterfowl and marine mammals, and also contribute to the larval biodiversity of the water column. Their populations allow calculations of biodiversity, and biodiversity can be used as a yardstick for gauging environmental impact.

Biodiversity is measured by: (1) how many different kinds of organisms are present, and (2) the relative numbers of each (i.e. which are common, which are rare). These are *Species diversity* and *Numerical diversity* respectively.

Organisms should be identified to *species* where possible, because species as biological units are the base measure for biodiversity calculations. At most sites there is some uncertainty about the species identity of many forms present, but separation to species can still be achieved by identifying to a higher order taxonomic level, say to genus or family. Thus, although the biodiversity unit is not precisely named, it is measured as one unit for biodiversity calculations.

Detailed lists of species present at any one time are summarised where relevant because, according to Thorson's (1957) theory of *Parallel Level-Bottom Communities*, such lists have some predictive value. It should be possible to predict the kinds of organisms which will recur on similar deposits. It is very noticeable that identical genera tend to occur on similar habitats, whereas the actual species within the genus differs from site to site.

At present there is no numerical model which does more than predict biodiversity in a generalised way. Poiner & Kennedy (1984) show, and develop a model for, increases in total biomass (weights of organisms) in the far field of a dredging plume. Biomass is related to numerical abundance in a general way, but not in detail, because the large individuals of a species tend to be more rare than the small younger individuals.

The benthos of coarse-grained marine placer and aggregate deposits is not well known because conventional grab samplers (Holme and McIntyre, 1984), used on softer mud and fine sand to sample the burrowing infauna, do not penetrate well in gravel, or even in coarse sand. Dredges and trawls sampling the mobile epifauna hang up on rocks, bounce on the surface if towed too fast, and frighten away the fastest moving fish and shellfish. Such dredges may sample the attached epifauna, providing they can dislodge the attached organisms, or pick up whole rocks and cobbles large enough to support growth.

There is little information about the biology of gravel and coarse sand deposits; therefore, there are no up-to-date reviews on which to base a generalised state-of-the-ecosystem statement. There are, however, some common biological features of marine deposits that apply regardless of grade (see Section 2.3.4). There are also some recent surveys that demonstrate the biodiversity of these deposits in a mining context (see Section 2.3.3). A selection of articles is reviewed. These sections lead to the issue of monitoring sampling design and analysis to document benthic biodiversity (Section 2.3.6).

Regardless of the grade of deposit extracted, there are two sets of risks arising from dredging operations: (1) extraction risks (i.e. removal of habitat material with some surrounding disturbance), and (2) discharge risks (i.e. deposition of discharged tailings). These are introduced in Sections 2.3.1 and 2.3.2 respectively. This review does not consider impacts derived from dredging for removal of contaminated deposits, nor impacts from the mining of metalliferous muds.

2.3.1 Extraction Risks

2.3.1.1 Resource Losses

Extraction removes sediment habitat and the organisms living within the sediment (infauna), or on it (epifauna). The burrowing forms are relatively immobile and cannot swim away from the cutting face of the mining excavation. These benthic organisms include fish and prawn resource species that maintain burrows, and many species of smaller creatures which can function as feedstock for resource species.

Epifauna come in two forms. The mobile epifauna generally live on the surface of the deposits. They may be able to remove themselves from the immediate dredge area. Examples include flatfish, crabs, sea cucumbers and sea urchins (almost immobile), scallops, and other resource species. The other epifaunal form is sessile, and is attached to the large cobbles, boulders, or any rock outcrops. They are generally attached so firmly that they are only removed if their host substrate is removed. In general, seabed mining will have an impact on resource species, their feedstock and habitat.

2.3.1.2 Anoxic Sediments

The sediment habitat characteristically is aerated close to the surface. Most organisms live within the surface aerated layer. However, oxygen reduces with sediment depth depending on porosity and permeability. Coarse, well-sorted sands and gravels have the thickest well oxygenated layer, and silts and clays the thinnest. The consequence to bio-diversity of reducing oxygen within the sediment is that most organisms are competing for space within a shallow aerated zone. Some, usually the larger forms, can live in deeper protective burrows within the reduced-oxygen (even anoxic) zone provided they maintain contact with an oxygen and food supply. In general, minerals dredging is not targeted at low oxygen, fine-grained sediments. However, patches of fine silts and clays may occur in a dredging area. If they are detectable they should be avoided for both economic and environmental reasons (such as the release of anoxic or toxic pore water).

2.3.1.3 Organism Depth Within Deposits

In minerals dredging, coarse sediments are to be expected, hence there is likely to be a deep aerated layer of probably 1 m or more. Constraints on depth to which organisms can live within these deposits are related to their abilities to burrow and maintain contact with the surface. Hence larger organisms tend to live at deeper levels than small organisms. The larger forms tend to be resource species that may live at depths of 1 to 2 m within the sediment. Conventionally, infaunal biologists accept 10 cm of seabed penetration as an effective sampling depth, with little documentation as to whether retrieval to this depth collects all specimens or not. Large deep-living forms present a further concern in that they may be long-living, slow-growing forms whose biomass may have taken 100 or more years to form. Once these forms, such as horse clams and geoducks, are lost it may take decades to reestablish a potentially sustainable fishery. The loss may even be permanent.

2.3.1.4 Sediment Suspension and Settlement

Extraction involves physical disturbance of the seabed at the dredgehead due to cutting, and/or suction, and removal. This inevitably involves suspension of sediments, causing raised turbidity over the seabed with a plume drifting with tidal currents. The resuspended sediments resettle nearby or at some distance depending on current velocities and particle size. Resettlement can be in areas of similar or dissimilar deposits (see Section 2.3.2 Discharge Risks, for further concerns arising from deposition).

2.3.1.5 Benthic Primary Biological Production

In very shallow water, for example 5 to 10 m depth, dredging-induced turbidity may reduce primary biological production of plant growth downcurrent of the dredged area

2.3.1.6 Organism Exposure

The cutting action of seabed mining will expose immobile organisms to predators, and exposed injured or dead organisms attract scavengers and predators. A disturbed area can become temporarily more active biologically, and more attractive for fishing but at unsustainable levels.

2.3.2 Discharge Risks

A discharged tailings slurry falls through the water column, with some dispersion of fines (also see Section 2.4 Biological Oceanography), and eventually reaches the seabed as a density current. After initial impact, the tailings spread in some pattern as a seabed dispersal field, deposition occurring with coarser particles settling first.

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Large amounts of tailings may smother and kill organisms over a broad area. Deposition of the tailings may occur more rapidly than the inhabiting organisms can avoid, or too fast for the inhabitants to maintain contact with life-giving aerated water, or their feedstock, above or around them. Smothering kills benthic organisms by preventing them from breathing or feeding. In general the ability of benthos to avoid smothering, or to burrow up faster than smothering deposits can settle, is not known. At Island Copper Mine shallow water fiord benthos on silts and clays can tolerate an accumulation rate of tailings of about 1 cm a year (Ellis and Hoover, 1990). The data do not indicate the highest deposition rate that can be tolerated (but see Section 2.3.5.2). During tailings discharge there is an area within the seabed depositional field where benthos cannot tolerate rapid deposition, and are smothered, or their survival is affected in some other way. This area represents only a part of the region where deposited tailings can be identified.

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Table 2.1 is not intended to be an exhaustive compilation of the relevant literature but shows the typical types of data collected and methods of analysis for gravel and sand beds, and the format of data presentation for ease of understanding the biological impacts of dredging. It is apparent how little reporting uniformity there is in presenting biological statistics. It is difficult to compare the results of different surveys without some data on benthic and fisheries biodiversity and productivity and without reformatting the data presentation in a consistent manner.

An exhaustive compilation of data for the areas involved in the mining scenarios has not been attempted for the reasons above. Two current, relevant projects, plus a recent review of the impact of beach nourishment dredging, will influence assessment procedures in the future. These projects are:

(1) The MMS-funded study entitled "Impacts and Direct Effects of Marine Mining Activities on Benthic Organisms" by the University of South Florida, St. Petersburg. When complete, this will update and substantially extend prior investigations of dredging impact for beach nourishment (e.g. Salomon *et al.* 1982)

(2) The NOAA/NMFS computerised benthic database for the east coast extending from Nova Scotia to Florida. This database is now being prepared for access by CD-ROM, diskette, etc. (Theroux, 1994). It will allow electronic access to nearly 200,000 records from over 11,700 sampling sites extending over all types of deposits. The database will allow retrieval of site- and time-specific benthos surveys in the future, but species lists taken from it will have little quantitative predictive power for what will be present at any one time. A selection of information about this database is provided in Appendix 1. The distribution of deposit types for the United States eastern seaboard is mapped, as is the distribution of recorded benthic samples. The distribution and abundance of major taxonomic groups is also mapped and tabulated. Historical fisheries information is included.

(3) A comprehensive review article by Hurme and Pullen (1988) of dredging impact surveys by the U.S. Army Corps of Engineers, including references to relevant European literature. Selected pages of this report are provided in Appendix 2. One of the survey reports is summarised below; for the reason that the investigators (Salomon *et al.* 1982) provide documentation from post-dredging surveys that were started within 2 days of closure, earlier than any other known surveys.

Details supporting the comments and issues raised by each of the following reports are provided in Appendix 1 to 6 by Tables and Figures from these reports, and by summary tables in which original data have been put into a more consistent format. Taxonomic lists are given where relevant, as certain types of organisms tend to recur. These lists indicate the levels of identification that are needed for biodiversity assessment at dredging sites.

2.3.3.3 *Kenny and Rees (1994; 1993)* - Appendix 3

These two articles report on pre- and post-dredging surveys at Test and Reference sites on an aggregate source in the North Sea, U.K. After dredging, the median particle size rose from 0.355 to 2 mm due to exposure of underlying gravel. Biological samples were obtained with a 0.2 m^2 Hamon grab, supplemented by observations from underwater still and video cameras. There was substantial change in the benthos with loss of species abundances, diversity, biomass and species mean biomass. Unfortunately, the actual numbers differ between the two articles, although the trends are identical. The polychaete worms particularly showed massive reductions in numbers and species. However there was some, although incomplete, recovery within 7 months in this high energy, open coastal setting. This was clearly illustrated by an ordination procedure (Appendix 3, Figure 6).

Two dominant gravel epifaunal species, a barnacle *Balanus crenatus* and a tunicate *Dendrodoa grossularia*, recovered to pre-dredging numbers, but at the same time Reference site levels had increased from 3- to 7-fold during the interval (the spawning season), but with smaller-sized organisms.

It was concluded from underwater photography that post-dredging deposition of superficial sand reduced the area of hard surface available for recruitment of the sessile epifauna, and that loss of adult stock reduced potential for juvenile recruitment. Natural differences between the Test and Reference sites (1.6 km apart) were considered possible but unlikely. There was marked similarity between the fauna of Test and Reference sites, and at the Reference site before and after dredging. This is presumably a function of the close proximity of the sites, and the short (9-month) period between the initial and final surveys.

In view of the known seasonality of larval recruitment, natural annual fluctuations in biodiversity and biomass (Thorson, 1957), and the substantial recovery shown within 7 months at the Test site, it appears that pre- and post-dredging surveys should be implemented within a time period over which there is little natural change in the populations, for example about 3 to 6 months apart.

2.3.3.4 *Salomon et al. (1982)* - Appendix 4

These investigations are unique in the close timing of their shallow-water (6 - 9 m) surveys. One set of three pre-dredging surveys was timed for April, June and July 1976. Post-dredging surveys were started on August 10, just 2 days after dredging ceased, and continued weekly for a month, twice the next month, and then monthly until November 1976. Divers took replicated cores each sampling 0.0156 m^2 surface area.

Sediments uncovered by dredging were of similar grain size to the former seabed, so the original habitat was maintained. In this high energy, wave-exposed dredging area the excavated pits were filled and smoothed out with sands of similar grain size after a few weeks. Initially, divers recorded soft silts but these were covered over the next month. After one year, the Station 1 borrow pit, initially 3 to 5 m deep, had filled to within 1 m of the surrounding seabed.

Two days after dredging there was a reduced fauna at the Station 1 borrow pit (81 organisms in the samples, representing 21 species). At 16 replicates of 0.0156 m^2, this provides an estimate of 324 organisms per m^2. The biodiversity rapidly increased over the next two weeks to 534 organisms and 60 species, within the range of values collected over the next year. Dominant species tended to be polychaetes, but bivalve mollusc and amphipod species also became abundant. There were dominance changes with time. Similarity analysis showed no distinction between dredge and control samples one year after dredging.

The authors conclude that the loss of biodiversity by removal of organisms was recovered within 1 year, although biodiversity differences remained between the borrow pits and seabed outside the pits. Their data show substantial recovery within 3 weeks. They ascribe recovery to the high energy wave-exposed habitat moving local sand into the pits, and covering the silt-clay deposits which initially accumulated there. The sand presumably carried many of the local organisms with it, and was supplemented by regional spawning.

2.3.3.5 *Padan (1977)* - Appendix 5

This is a baseline report completed in 1973 prior to a planned experimental aggregate mining project. Several types of habitat were described but only four stations characterized by cobbles are reviewed here. These stations had from 1640 to 7535 organisms per m^2, with number of species ranging from averages of 31 to 113 depending on whether they were classified as "invertebrates" or "motile". The deposits were generally quite poorly sorted.

Most dominant organisms on cobble were polychaete worms or amphipods, but occasionally there were sea urchins or molluscs. Many of the cobble substrate species and dominants were also found on hard substrate (i.e. were sessile epifaunal forms).

The significance of this report when considered with the recent reports of Kenny and Rees (1994; 1993) above, is the predominating biodiversity of epifauna attached to the cobbles. For assessing and mitigating dredging impact on aggregates, it will be necessary to consider the cobble fraction and its sessile epifauna. The Padan (1977) report is considered in more detail in the Massachusetts Bay aggregate mining scenario (Section 3.4).

2.3.3.6 *ENSR (1991)* - Appendix 6

This extensive report is a compilation of environmental data from the WestGold offshore dredging site at Nome, Alaska, between 1986 and 1990. It reveals the logistical problem, inherent in placer mining, of determining the pre-dredging monitoring sites. The intended dredging sites may change with new ore delineation information. As a result no true Before & After assessment was achieved by WestGold. There was one hindsight monitoring station (R6) initiated in 1988 two years after dredging. One other station (R7), initiated during a year of dredging nearby (1987), was maintained in 1988 (not 1989) and 1990 with more dredging nearby. Several control stations with similar cobble or sand were maintained so that a Test & Reference sampling paradigm was achieved.

The 1986 dredge footprint was substantially smoothed by 1990. The 1987 data for the sandy areas showed biodiversity being substantially lower than for the control station, but by 1990 values were much higher, and were approaching those of the controls. The Cobble test site between dredging courses of 1987 to 1990 showed lower values in 1987, with values dropping through 1988 and 1990 as dredging continued. However, the cobble site dredged in 1986 showed higher values of all biological parameters in 1988 and 1990, but still generally less than control stations S3 and C3. It appears that biodiversity was increasing but was by no means back to normal four years after dredging.

Lists of dominant species show a variety of forms spread over many groups, but there was no distinction made between sessile epifauna attached to cobbles, and infauna burrowing into the deposits. Survey results support the above-described scenarios, showing that sand deposits can recover their biodiversity more quickly than gravels. The Nome deposit is less well-sorted than deposits used for aggregate and beach nourishment, with a correspondingly slow biodiversity recovery. The reasons for slow recovery cannot be established from the data reviewed here, but may relate to temperature, as well as to deposit geochemistry and the discharge of tailings. The survey results are considered in more detail in Section 3.2.

2.3.3.7 Seabed Biodiversity Patterns

In general terms benthic biodiversity can be expected to be sufficiently high on both gravel and sand beds to allow measurement of the environmental impact. Example counts for burrowing organisms (the infauna) separated from their deposits by a 0.1 mm^2 mesh, would be 50 to 100 different species in and on 1 m^2 of seabed, and 1,000 to 10,000 individuals of those species.

Both gravel and sand beds support species ranging over a diverse array of Higher Order Taxa. There are abundant polychaete worms (both particle feeders and predators), small and large crustacea (which tend to be omnivores), molluscs (both bivalves [particle feeders] and gastropods [predators]) and many other types. The major distinction between gravel and sand beds is the presence of sessile species attached to the surface of cobbles and boulders. These include such forms as barnacles and tunicates.

The infauna of poorly sorted gravel and sand beds tend to be similar, with species reflecting the particle size and degree of sorting. For example, there are species that characterize poorly-sorted silty sands regardless of whether there are cobbles and boulders present. These species include many of the delicate polychaete worms, that are not able to tolerate high-energy environments with mobile coarse-grained beds. Small crustacea swim over the still surface, and brittle stars browse on the organic load. In contrast, there are species that occur abundantly or almost entirely on relatively well-sorted sands (such as cockles and the small clams of genus *Tellina*). Well-sorted sands thus have species associations clearly different from those on gravel and poorly sorted sands.

Superimposed on this biodiversity pattern related to substrate, is a pattern related to water depth. Although the effect of increasing depth on the fauna is in part driven by reducing wave energy, and hence particle size, other factors such as surface primary production and distance from land (and river input of nutrients) are also involved. In principle, with increasing depth across a deposit, changes in biodiversity are to be expected. Relatively slight changes within the surface euphotic zone (say 0 to 50 m water depth) are most likely to be changes in the actual species present, rather than changes in species and numerical diversity. In summary, with changing depth the array of species may change.

2.3.4 Biology of Marine Deposits Relevant to Dredging

Natural annual fluctuations in biodiversity (both number of species, and number of organisms) are enormous. The classic work of Boysen Jensen (1920) documented the abundance changes for dominant species from year to year. That study showed the available plaice food was much larger in 1914 than in 1911 but less than in 1912, with a different array of most abundant species. Such year to year changes are typical.

A recent data set (Table 2.2) from Test and Reference stations for monitoring STD (Submarine Tailings Disposal) shows changes in numbers of different species over a 20 year period. There are no obvious differences in the great range of number of species between sampling stations from little or no tailings. There are obviously major reductions in number of species under thick tailings, but even these areas show considerable variability from year to year, often reaching the lower end of the natural range of the unaffected areas.

Such natural fluctuations cause great difficulty in describing ambient faunas and environmental impact on benthos. This shortcoming applies to measuring biodiversity before dredging operations start, assessing changes derived from the dredging operations, and assessing the progress of recolonisation after dredging.

Spatial differences in biodiversity on uniform deposits means that the fauna of Dredging (Test) and nearby Reference sites will inevitably differ to some extent from natural causes, and from year to year. These spatial differences are due to the biology of the species present. Many benthic species live in clusters (McIntyre *et al.* 1984). It is quite possible to have a localized herd of sea urchins crawling on a sand bed over a dense patch of newly burrowed-in clam larvae. These two species will then dominate the numerical biodiversity at that point. Patchiness of this type seriously impedes faunal comparisons, because counts of organisms present in samples are not normally distributed (in a statistical sense). There may be no cost-effective way to obtain accurate and precise biodiversity estimates of benthos with different and varying patchiness. Crude quantitative estimates may have to be accepted.

Apart from sampling variability derived from the biology of the organisms, a further level of variability arises from the sampling process such as: different sampler types (e.g. Van Veen and Peterson grabs), different sizes of the same sampler (e.g. 0.1 m^2 and 0.2 m^2 Van Veen grabs), different sampler penetration depths on soft and hard sediments (muds vs. sands), and different sieve meshes to retain organisms when being extracted (generally 0.5 or 1 mm). The level of taxonomic identification also affects measures of biodiversity (Wu, 1982; Ellis, 1985).

Various numerical techniques are used to measure similarity between Test and Reference sites, and between Before and After sampling (Burd *et al.* 1990). Currently, they tend to be measures of similarity based on number of species and their abundances, with or without ordination related to environmental parameters (Burd *et al.* 1990). Various Diversity Indices may be used (Washington, 1984), or simple comparisons may be given of basic summary statistics about the total fauna and the most abundant (dominant) species present. Examples from the mining industry are by ENSR (1991) and Ellis and Hoover (1990). There are arguments as to whether counts are sufficient measures, or whether weights should be included (Burd *et al.* 1990). Weights (biomass) present further difficulties for obtaining accurate measures (Ellis, 1987).

In contrast to the burrowing infauna, benthic-feeding fishery species (groundfish, cod, crabs, lobsters, etc) occur in consistent locations designated as "fishing grounds". Therefore the local patchiness and annual fluctuations of their benthic feedstock within those grounds can be taken as inconsequential to their continuing presence. Such species are feeding opportunists, capable of optimizing their foraging strategies and picking the richest food for the least effort. The important benthic parameter in this context is benthic productivity (biomass produced per time interval), rather than the biodiversity present at any one time. Measuring this adds a further level of complexity and inaccuracy in benthic biodiversity assessment.

For measuring dredging impact on the benthos this means:

(1) only gross changes or gross differences in simple measures of biodiversity can be taken to reflect real population changes or differences.

(2) these measures must be made by site-specific surveys designed for the purpose and cannot be assembled from old data-bases.

(3) minor changes and differences in biodiversity probably have no significance in monitoring population changes or differences.

(4) the simplest measures of number of species, and the relative numbers of each, will be the most cost-effective for monitoring benthic biodiversity.

2.3.5 Benthic Recovery After Impact

2.3.5.1 Recolonization

Ninety-five percent of benthos breed by producing pelagic larvae in the tropics, and 95% by non-pelagic larvae (swim/crawl-in forms) in polar regions and the deep sea (Thorson, 1950; 1957). The proportion changes by latitude, but mid-latitude proportional figures have not been located. However, Rosenburg (1976) shows how unoccupied seabed recovering from pollution in a Swedish fjord is colonised first by species with pelagic larvae.

Larvae live for an average of 3 weeks (Thorson, 1950) and larvae of shelf species even longer (Scheltema, 1986). At a current speed of 1 knot (1.85 km/h), a 3 week lifetime allows larvae to drift about 900 km before they die off. Whatever the details, we know from the high latitude site of WestGold's operation in Alaska (ENSR, 1991, and Section 3.2.4) that there were benthos present within 1 year following termination of dredging, and greatly extended a year later. At lower latitude sand extraction sites, settlement is within weeks (Salomon *et al.* 1982, Appendix 4) as has been found with *in vivo* experimental boxes in the Baltic Sea (Arntz and Rumohr, 1982). At Island Copper Mine the number of juveniles is known to be higher in recolonizing tailings than on unaffected substrates (Burd and Ellis, 1995).

In this context, mitigation procedures facilitating recolonization by pelagic larvae drifting in from sources up to several hundred kilometres distant, are desirable. Any immigration by crawl/swim-in forms is a bonus, and does not need to be engineered.

Times to recovery of a reasonable biodiversity for three different deposit grain sizes are given in Table 2.3. Fine-grained tailings may need only 1 year before achieving a recovery level biodiversity, medium-grained deposits 1 to 3 years, and coarse-grained deposits 5 or more years. Recovery is defined as attaining a successional community of opportunistic species providing evidence of progression towards a community equivalent to that previously present, or at non-impacted reference sites.

Equivalency in the above definition can be measured in terms of standing crop, biomass, number of species and numbers of most abundant species, etc. These criteria must be defined during preparation of an Environmental Impact Statement (or equivalent document) for any site. The definition depends on the best available monitoring techniques suitable for biodiversity assessment at that site. In general terms the recovery data from Island Copper Mine (Table 2.2) show that 1 to 2 years after a defaunation event (that may persist for several years) numbers of species return to 10 to 15/0.15 m^2. Burd and Ellis (1995) show that numbers of organisms return to 5,000 to 10,000/m^2.

2.3.5.2 Tailings Deposition

Tailings have been deposited offshore from Island Copper Mine over 23 years in beds 40 to 50 m thick (Ellis *et al.* 1995). There is substantial defaunation under such rates of accumulation (approximately 2 m/yr.). Sampling stations receiving tailings accumulations of less than about 20 cm over 23 years (about 1 cm/yr.) have a biodiversity indistinguishable from sampling stations without tailings.

There is some indication in the biodiversity data from Island Copper Mine (Table 223) that an accumulation rate of fine-grained tailings higher than 1 cm/yr. can be tolerated. Stations 5 and 6 do not show defaunation events. Station 5 received approximately 40 cm of tailings over 20 years, and Station 6 received 32 cm of tailings over 10 years. Station 19, which shows lesser biodiversity, received 60 cm of tailings over 15 years. Thus 1 cm/yr. is a safe estimate of tolerated accumulation rate for fine tailings. Two cm/yr. might be tolerable, but 4 cm/yr. appears to affect the biodiversity. At these slow deposition rates the deposits probably settle in pulses (e.g. 1 cm may accumulate in a matter of 2 to 3 days but only once a year). This comment applies to silt-sized tailings. There is no available information relating to sand- and gravel-sized tailings.

2.3.5.3 Benthic Sensitivity to Substrate Change

Benthos are sensitive to substrate change in that predominant species show measurable variation. Fishery species with dependent, specialist feeding and habitat requirements also change. In contrast, crabs and some polychaete worms can be very tolerant of such changes. There are no quantitative models relating benthic species response to altered deposits. Without site- and time-specific Environmental Impact Assessments (EIA's), as at WestGold's Nome dredge site (Section 3.2), collating species lists spanning many years and different sampling instruments, even if they provide some population numbers, have little predictive value for recolonising species at any site.

For dredging impact assessment two options concerning habitat change should be considered for any Scenario:

(1) Habitat change not tolerable (for site-specific reasons such as herring spawning ground) - seabed may be dredged and tailings replaced only in ways which leave similar habitat (leave a layer of the substrate as with sand or aggregate extraction, and/or replace substrate with similar grade, e.g. as with placer mining).

(2) Habitat change tolerable (usual scenario), although possibly with specific constraints (such as no return of large boulders to trawling grounds) - in this case it has to be recognised that there will be unpredictable differences in the species array between the recolonised area and elsewhere. Application of appropriate biodiversity criteria can set a required number of species and organisms to be present, even if they are different from what was there before, or from the species that have appeared at undredged reference sites nearby.

In summary, in any one year there may be several hundred benthic species present, of which only 10 or so will be abundant. The 10 abundant species plus all the others can change from year to year naturally and unpredictably. Fishery species are less variable if the habitat, as opposed to benthos, remains stable. Bottom fish tend to be opportunistic feeders and take anything that they see, smell or hear moving.

For dredging mitigation, the criteria are either to leave deposits as similar as possible to what was there before, or if a substrate change is accepted to set biodiversity recolonization objectives. These objectives have to be based on a site-specific pre-permitting EIA.

2.3.6 Design and Analysis of Monitoring Programs

The variability in benthic faunas from place to place, and with time, presents problems in designing a monitoring program. The need is to demonstrate that biological impacts, and recovery from dredging, are as predicted. The problem is that Reference site biodiversity is changing naturally, while the Test sites are changing from impact (but would also have changed naturally). In spite of this natural variability, multivariate statistical analyses can distinguish between the biodiversity of grossly impacted Test and Reference stations. For example, the routine similarity analyses undertaken at Island Copper Mine, Canada, on the type of data shown in Table 2.3, were used to produce maps of impacted areas as shown in Figure 2.2. These have been derived from an intermediate step measuring similarities between stations (Figure 2.3) or ordinating similarities in some way (Kenny and Rees, 1994, Appendix 3). To achieve this kind of biodiversity impact documentation, the following generalised Before and After, Test and Reference sampling design and analyses are suggested:

(1) At least 1 year in advance of mining, sample an appropriate grid of stations (single samples) within and surrounding the proposed mining area (the Before samples).

(2) Undertake an appropriate multivariate statistical analysis to demonstrate clusters of sampling stations with similar faunas.

(3) Designate 2 sampling sites per cluster of similar sites as "Initially Conserved Areas (ICA's)" for subsequent annual monitoring thus documenting Reference conditions each year. The location and area of each ICA must be sufficient to avoid impact from the nearest dredging operations.

(4) Starting prior to mining, monitor the ICA's annually (same season each year) with at least 3 replicate samples per ICA. Designate sampler(s) and sieving mesh (to separate the organisms), and use them consistently through the entire life of the mining operation. Follow required sample processing protocols (Before and After sampling).

(5) Allocate the remainder of mining area for dredging in a pattern to be determined site-specifically, and adjust according to updated ore delineation information.

(6) As soon as a dredging course with distinctive deposit and fauna is completed (i.e. within 1 month), sample from the course to establish baseline for documentation of recovery at Dredging Test Areas (DTA's). If timing is off the annual ICA routine monitoring, undertake additional routine sampling at the appropriate matching ICA's.

(7) Add each DTA to the annual monitoring program.

(8) ICA's may be mined after two similar DTA's have achieved recovery as shown by the adopted multivariate statistical technique.

2.4 Biological Oceanography

The water column is a highly dynamic environment where changes occur minute by minute as a result of sea, meteorological, tidal and biological alterations. A consequence of these alterations is that environmental change which may take months or years to occur in benthic environments will take place in minutes or hours in the water column. Conversely, these changes may just as rapidly disappear by the action of dilution or advection. Mining impact assessment and mining mitigation procedures directed towards the pelagic environment must take these rapid changes into account. Most assessment and monitoring programs operate on a time and spatial scale designed to detect long term environmental changes inappropriate to water column monitoring. However many of these long term changes are brought about via the water column. Deposition of sediments, sediment metal accumulation, bio-accumulation of metals, biota alterations, and disruption of migration patterns are just a few of the long term environmental changes that may be driven by ephemeral alterations of the water column. Principal water column risk factors associated with marine mining may be grouped into three general categories:

(1) Production of a suspended sediment turbidity plume resulting from; a) disturbance of the bottom sediments; b) loss of dredged material during transport to the surface and c) return of unwanted sediments and process water to the ocean either as initial reject overburden or as tailings (see Section 3.2.4, and Garnett and Ellis, 1995)

(2) Release of low oxygen pore water or toxic materials (metals, H_2S, etc.) either from the dredged material or from newly exposed mined seabed sediments either directly into the water column (dissolved) or attached to fine particles (particulate). (see Section 2.2)

(3) A hidden risk factor in all assessment is that the environmental sampling may be faulty and fail to describe the situation adequately. This is especially true for water column monitoring for the reasons stated above. An inadequate monitoring program increases the likelihood that changes will go unnoticed until significant environmental impact occurs.

Water column impact assessment must consider all three of these potential risks: suspended sediments/turbidity; toxic materials and monitoring/analytical procedures.

2.4.1 Suspended Sediments/Turbidity

Suspended sediments within the water column can be divided into two distinct classes: large particles in the process of settling and deposition, and fine particles that may remain suspended in the water column for long periods of time and which may be transported great distances.

Particles greater than a few micrometers in diameter rapidly settle out of the water column and form density currents extending from point sources. Well documented examples occur at Island

Copper Mine (Ellis *et al.* 1995) and Kitsault Molybdenum Mine (Pedersen *et al.* 1995). The extent and direction of these density currents and the subsequent bottom migration of these sediments may be influenced by water column dynamics such as currents and wave action (see Section 2.1).

Fine particles may remain suspended for long periods of time because of high surface-to-volume ratios. This is especially true of particles suspended in fresh water where surface charges tend to keep particles from coalescing. In the electrolytic marine environment particles are more likely to aggregate and settle out. Nevertheless, large turbidity plumes of allochthonous fine suspended sediments do form both naturally as a result of river input and from industrial discharges to the sea surface (Pedersen *et al.* 1995). Plumes of autochthonous fine sediment may occur as a result of turbidity currents, tidal scouring and other subsurface events. Such turbidity plumes may persist for long periods of time in sea water. The total amount of suspended material, by weight, is generally extremely small when compared to deposited sediments but they may reduce light penetration in the ocean (Island Copper, 1994) and may contain high levels of heavy metals, both of which may cause adverse biological effects. Allochthonous turbidity plumes resulting from industrial activities may also contain process water, dissolved heavy metals, process chemicals and other wastes.

Anderson and Mackas (1986) reported that Kitsault mine tailings (by bioassay) reduced survival time for zooplankton at 560 mg/l, and respiration rates at 100 mg/l. Tailings concentrations at low levels (e.g. 40 mg/l) were associated with enhanced survival times and respiration rates. At the mine site, tailings were less than 15 mg/l 0.5 km from the outfall, and it was concluded that there was no effect on zooplankton from this and from the field studies (Mackas and Anderson, 1986).

Island Copper Mine (1994) reported that tailings consistently doubled the original ambient seawater turbidity in Rupert Inlet to approximately 1.00 NTU (Nephelometric Turbidity Unit) (Figure 2.4). Chlorophyll *a* and zooplankton levels in Rupert Inlet do not show consistent differences from elsewhere (Figure 2.5 and Figure 2.6, also Chapter 6 in Ellis, 1989).

Parsons *et al.* (1986), from experiments in a very large mesocosm (CEPEX), concluded that Kitsault mine tailings at both 30 and 300 ppm molybdenum caused: (1) a delay in primary productivity and chlorophyll a maxima; (2) a shift in the balance of phytoplankton species, and (3) an increased production of zooplankton. In this context, the information supports discharging tailings below the euphotic zone if the water is deep enough, with the outfall engineered to minimize dispersion in the water column. However, some dispersion at low concentrations is acceptable.

Other more complex problems that may be associated with turbidity plumes include food web alterations, such as changes to the microbial loop, and decrease in primary productivity due to light reduction. Secondary alterations to the zooplankton population might occur also but available data indicate little or no effect of moderate turbidity plumes on zooplankton. Studies have shown no reduction in feeding activities. In fact zooplankton may be instrumental in increasing the fall-out rate of particles by incorporation of fine particles into large, rapidly settling fecal pellets (Anderson and Mackas, 1986). This activity removes not only suspended sediments from the water column but also associated bound metals, transferring the problems, if any, to the benthos.

In some environments, such as glacially fed high runoff inlets, seasonal turbidity plumes covering hundreds of square kilometres are the norm. Such inlets may have reduced primary production but otherwise appear to have normal planktonic food webs and often support apparently normal populations of migrating adult and juvenile salmonids.

2.4.2 Release of Toxic Plumes

Effects of newly exposed sediments on the water column depend on the mining method and the energetics of the water column at that site. Shallow water excavations are likely to be in a highly energetic environment. Oxygen-rich water would rapidly oxidize exposed sediments without any noticeable chemical oxygen demand loading of the water. Exposed soluble metals would be rapidly diluted below detection limits (see Section 2.2). In contrast, deep water dredging may be in a low energy environment where currents and other advective forces are minimal. Here, deep narrow cuts could leave relatively stagnant pits. Extraction of sediment salts or advection of seasonally high salinity water could result in increased water density and lead to stable water masses within the dredge pits. Long term exposure of this water to reducing sediments could create considerable chemical oxygen demand and under extreme conditions result in anoxia, and death of organisms. Occasional (seasonal?) flushing of these "dredge pits" might occur releasing pulses of dense, low-oxygen water. Fortunately such a scenario is very unlikely and could be detected easily by simple conductivity/temperature/depth (CTD) monitoring.

Although it is unlikely that toxic materials will be released at offshore dredging sites (see Section 2.2), the potential at any site for a toxic plume to be released to the water column needs assessment. Both excavational and tailings discharge should be assessed in this context. Prior anthropogenic disturbance by addition of mercury at WestGold's Nome dredge site (see Section 3.2.3), and the unusual tailings geochemistry at Black Angel Lead-Zinc Mine, Greenland (Poling and Ellis, 1995), illustrate the nature and consequences of these concerns. At Nome, mercury did not become a problem. At Black Angel mine there was serious contamination of a fjord by cadmium, lead, and zinc.

2.4.3 Monitoring

In comparison with benthic monitoring, water column monitoring is of short duration and high intensity, and is directed at determining whether water quality guidelines, as set by the appropriate regulatory agency, are being met. Water column turbidity measurements are conventionally made with a nephelometer. The Environmental Protection Agency (1986) states a requirement of "no more than 10% reduction of depth for photosynthesis", which means in this context that tailings should be discharged below the compensation point (which must be measured for each site). California (1990) gives some numbers for acceptable settleable solids levels in effluents (e.g. max 3.0 ml/l) and turbidity (e.g. max 225 NTU). A recent example is provided by a beach nourishment project off Jacksonville Florida, for which the MMS required daily nephelometer readings at the water surface, at the bottom, and at mid-depth. Turbidity was not to exceed 29 NTU's at any time or dredging operations were to cease.

2.4.5 Fishery and Wildlife Resources

In the context of this study, wildlife resources comprise marine mammals, birds and possibly some reptiles (such as sea turtles). Fishery resources include those of the water column (pelagic resources) such as tuna, marlin and sardines, and resources of the seabed (shellfish or groundfish) such as lobsters, crabs, sole, flounder and cod.

There are two sets of risk factors for wildlife and fish: dredge-derived and biologically-derived. When they occur together, the resource involved may be impacted in a manner which is difficult to document. A coincidence of biologically-derived risks can be easily underestimated due to the difficulty of appraising the biological factors (such as documenting that many million fish may follow a precisely determined route underwater, or that a few hundred individuals of an endangered marine mammal species may be dependent on well-separated staging habitats). Where wildlife or fishery resources are present considerable care should be given to assessing the biological risk factors.

2.5 Dredge-derived Risk Factors

2.5.1 Turbidity

Turbidity can be very high at a dredge site and tailings discharge point. Submersible observations of tailings at Island Copper Mine have shown such high turbidity that visibility is effectively nil (Ellis & Heim, 1985). Although some wildlife and fish can live in highly turbid conditions they rely on sonic or hydraulic sensory systems for information about their environment.

2.5.2 Noise

Noise levels will be high from dredge and mill operations. Marine mammals, particularly whales and dolphins, use sonar as the main sensory system for feeding and travel. Just as excessive noise distracts humans, it is likely that high noise levels from dredge operations are a risk to marine mammals affecting their ability to feed, protect themselves and breed. The topic is little investigated and needs consideration at any site where marine mammals are a resource.

2.6 Biologically-derived Risk Factors for Wildlife

2.6.1 Territoriality and Homing

Mammals and birds characteristically set up a home site at some stage in their lives. This may be permanent or temporary. A home site greatly facilitates wildlife survival as the individuals quickly learn how best to use their home in providing food and protection. Where colonies of a species become resident in an area, then dislodgement by human action affects many individuals simultaneously. Although it is unlikely that an offshore dredge site will be functioning as a colony site for marine birds and mammals, the risk may be significant for groundfish, such as halibut, sole and herring (Oulasvirta & Lehtonen, 1988) that may have aggregated on particularly favourable gravel beds for feeding or breeding.

Some marine mammals may settle at home sites permanently or temporarily, and then be resistant to leaving. If they are forced away from home sites, their survival can be reduced due to other suitable home sites being already occupied.

2.6.2 Mass Migrations

Many marine birds and mammals make long-distance migrations along set routes, such as the flyways of waterfowl. These routes may cross extensive shallow water marine areas, and the birds may set down for prolonged periods to feed. Marine mammals appear to have set routes and seasons for migration in clan aggregates or family pods, keeping in contact with each other and direction finding by sonar. Marine turtles also migrate along set routes and at set seasons. The same applies to fish and some crustacea. Where such set routes and seasonal mass movements coincide with a dredge site, then a large number, possibly the whole stock of a species, will be exposed to dredge-derived risk factors. Commonly, such mass migrations are not readily visible when occurring, as the animals concerned pass by a moving boat-based observer in separated groups, communicating sonically if underwater, or by flock movements if flying.

2.6.3 Noise

The increase in noise by dredging or other industrial operations over the ambient noise level may be significant. Marine mammals nearshore generally occupy a noisy environment due to waves and sediment transport, so may be less environmentally sensitive to noise pollution than offshore species. Coastal waters generally have higher levels of noise when compared to the deep oceans or high seas. The levels of ambient noise can vary widely and environmental factors such as rain and wind can greatly increase ambient noise levels. In areas of high ship traffic like the North American Atlantic coast it is possible that marine mammals have already changed their habits to avoid loud sources or have become habituated to them. Even remote areas such as WestGold's site at Nome, Alaska, may have a moderate degree of ship noise due to vessel traffic in and out of the nearby harbour. Although the issue of vessel-derived noise impacting wildlife has been investigated for pure research purposes, and for oil drilling and production purposes, there is limited information available.

The frequency of sound in a particular band range (in Hz to MHz) appears to be important when examining animal reactions to sound. Studying the types and frequencies of sounds made by different marine mammals should give insight into what they can hear (Turl, 1982).

In general, mysticete (baleen) whales have good low frequency hearing for communication, odontocetes (toothed whales) use high frequency sounds (1 to 100 kHz) to echo-locate and communicate and pinnipeds use mid-range levels with a maximum sensitivity between 10 to 50 kHz. The high frequency sounds made by the toothed whales tend to be directional and better capable of discriminating against unwanted background noise (Gales, 1982). This capability to discriminate by directional quality in making noise is referred to as the directivity index (DI) in decibels (Gales, 1982). Numerous auditory sensitivity curves have been created for smaller odontocete whales and pinnipeds (Cosens and Dueck, 1993). Measurements of the hearing capability of the large mysticete whales are not available, although there are numerous recordings of mysticete whale vocalizations (e.g. Thompson *et al.* 1992).

One study showed beluga whales (*Delphinapterus leucas*) and narwhals (*Monodon monoceros*) changing their behaviour 40 km or more from ships (Finley *et al.* 1990). Another study calculated a detection distance of 30 km for belugas and narwhals for a particular ship and the high frequency noise component (5,010 Hz) it generates (Cosens and Dueck, 1993). This study, and others, in the Eastern Canadian Arctic, may be dealing with very naive populations that react to any unusual sound because of the quiet nature of their environment. Populations of the same species in the Beaufort Sea (which has much higher levels of ship noise) may react less to unnatural noises (Cosens and Dueck, 1993). The models of Gales (1982) have shown that marine mammals may be able to hear the sounds of offshore oil and gas exploration as far as 190 km away and even farther under favourable conditions.

The use of underwater acoustical harassment devices (AHD's) in attempts to scare off harbour seals (*Phoca vitulina*) from poaching at fish farms on the central British Columbia coast may have resulted in eliciting avoidance responses in minke whales (*Balaenoptera acutorostrata*), humpback whales (*Mageptera novaeangliae*) and harbour porpoise (*Phocoena phocoena*) in areas where they were previously seen (Morton, 1994). Observations of the playback of drillship noise and airgun (acoustic geophysical device) concussion sounds to gray whales near St. Lawrence Island in the Bering Sea was published by Malme *et al.* (1986). They found that drillship noise of 110 dB was the lowest level that may cause a disturbance of whale feeding activity. At 120 dB, greater than 50% of the local population will avoid a feeding area. 163 dB was considered a level at which feeding disturbance was possible for an airgun firing. It was found that 173 dB was the level at which 50% of the local whale population would avoid a feeding area (Malme *et al.* 1986). Similarly bowhead whales (*Balaena mysticetus*) reacted adversely to playback of 122 dB dredging noises (see Morton, 1994). Observations taken by crew members on oil drilling platforms in Cook Inlet in Alaska noted that beluga whales came very close to the platform when it was in operation but reacted to noise such as machinery being turned on, and helicopters and boats (Gales, 1982).

Baleen whales may be of greatest concern to marine mining because of their low frequency communication and endangered status. However, it is difficult to perform controlled studies of them. Broad band low frequency sounds produced by offshore operations (e.g. dredging, oil platforms) might be audible to baleen whales over very long distances assuming optimal conditions. Means of dampening the sounds of machinery may be needed. The human pain threshold is 120 dB in air, and these levels may also apply to aquatic systems for marine mammals (Turl, 1982 and Morton, 1994).

In principle it is appropriate to design dredges to be as quiet as possible. Experienced dredge operators have anecdotal stores of knowledge about the reactions of marine mammals and other wildlife to their vessels, and means should be found to record and make use of this information.

3.2 Scenario 1: Precious Metal Mining, Alaska - Bucket Ladder Dredge

3.2.1 Mining Scenario

Within the U.S. OCS, the precious metals gold and platinum are known to occur predominantly around the Alaska coast. Potential areas for exploration and eventual marine mining are indicated by the existence of onshore placers and by glaciation which has carried sediments offshore. Dredging for gold has been attempted several times this century but only WestGold achieved a significant production using a bucket ladder dredge from 1986 through 1990. The exploration efforts and the environmental research of WestGold are fairly well documented in various publications. Much of the experimental work on reducing the environmental effects of the WestGold dredging is applicable to other forms of dredging. Therefore the Nome bucket ladder dredging project constitutes a very useful scenario for study, even though, given the present gold price, future marine mining efforts are more likely to be directed towards the recovery of aggregates and heavy minerals by other dredging systems of excavation.

3.2.1.2 Location

In order of priority, the main areas of interest are as follows:

(1) Various sites around the Seward peninsula, especially opposite the City of Nome;

(2) Offshore from Goodnews Bay (platinum) in the Southern Kuskokwim Bay;

(3) The northern part of the Gulf of Alaska, especially between Cordova and Lituya Bay (gold) and around Kodiak Island.

All of the above areas are in State waters and some, including that of Nome, extend into Federal waters beyond the 3 mile limit.

3.2.1.3 Marine Conditions

Each Alaskan area is exposed to the variable climatic conditions characteristic of the Bering Sea. The harshest climate is that prevailing around the coast of the Seward peninsula, including Nome. Other potential mining areas may experience less harsh winter climates but are more exposed or offer less infrastructure. The differences all impact on the economics of potential offshore mineral deposits which is the final arbiter. Nome illustrates all the features of importance and the figures quoted are actual ones.

Weather in the Nome area is dominated by the circulation of winds about the relatively stationary low pressure cell that lies over the Gulf of Alaska and the high pressure cell over the Arctic Ocean. Circulation around the low in the winter brings winds from the east or northeast most of the time. Expansion of the Arctic high southward in the summer brings winds from the west during most of the summer season. The wind blows predominantly from the SW to NW in June.

It gradually veers south, but exhibits a full range in August. Swinging to the east it blows predominantly from the east and north by November. The average wind speed gradually increases from 16 to 18 km/h in June/July until it reaches 19 to 26 km/h in November. The maximum 3-hour wind speed of 56 km/h is attainable at any time from June through November. By September the wind may be blowing and gusting at more than 48 km/h for nearly one fifth of the time. A persistent wind constantly exceeding 32 km/h may blow in June/July for nearly 20 hours duration, a figure which increases to over 50 hours in October.

Air temperatures range from a maximum of 30° C observed in July to a minimum of -41° C in February. Average temperatures are more moderate, being in the range 15 to 24° C in summer and, except for cold spells, in the -12 to -7° C range in winter. Precipitation is light, averaging about 40 cm/yr., about half as snowfall and the rest as light rains and drizzle.

Water temperatures decrease from around 12° C in early August to -3° C which is attained in the last week of October or first week of November. By then the average daily air temperature has declined to between -12 to -7° C. Usually by the second week of November the sea has frozen over.

Ice develops along the shore of the open sea in early November, but generally is not shore-fast until mid to late January. Ice cover reaches a maximum thickness of about 1.2 m in March over 80 to 90% of the sea surface. Wind shifting causes rafting and pressure ridging which result in much greater ice thickness locally. Break-up in the spring can be at any time from early May to early June.

Sea salinity ranges from about 20‰ in summer to about 34‰ in winter. The summer decrease is caused by river input and mixing. The low salinities and temperatures in summer retard corrosion of immersed metals to a rate significantly less than that experienced further south along the west coast of the U.S.A. The sea water is clearest in late winter. By mid-July the suspended sediment load increases from around 2 to 7 mg/l offshore to around 15 mg/l closer inshore (Hood *et al.* 1974). Thereafter it increases steadily with the inflow from local rivers. The natural load increases with depth. It rises to 100 mg/l or more later in the summer, especially with the incidence of summer storms.

The Nome coastline is subjected to a significant deep water swell from the southwest with a wave period which averages between 6 and 8 seconds. One third of the swells exceed a period of 8 seconds. The swells exceed 1.8 m in height in September, October and November when they may reach 3.6 m in height. They are exaggerated in inshore water depths of less than 18 m. The average wind-generated sea wave height superimposed on the swells steadily increases from about 0.6 m in June to 1.2 m in October. A storm is officially defined as the maintenance of 56 km/h (or greater) winds for 6 hours or longer. On this basis, an average of three storms occur each year from May through November; one third in each of October and early November, and the remainder throughout May to September, inclusive. During the worst of these storms the waves regularly exceed 4.6 m, with sustained wind speeds of at least 74 km/h (Oceanographic Services, Inc. 1974; 1975). The wave height is sustained for a day or more. The worst storms, usually in October, combine sustained wind speeds of around 93 km/h with gusts exceeding 185 km/h. Wave heights of 6.1 m may be maintained for up to 12 hours.

3.2.1.4 Geological Background

Kaufman and Hopkins (1988) attributed the spacial distribution of particulate gold in the sediments covering the coastal plain at Nome, including the offshore, to "a complex late Cenozoic geologic history. The diverse glacial, marine, fluvial, and deformational processes that shaped the sedimentary sequence on the emergent coastal plain have operated on the submerged continental shelf south of the Seward Peninsula." Kaufman and Hopkins (1988) believed that "the upper 20 m of the offshore deposits have been pervasively reworked. Below 20 m, sediments accumulated more continuously in marine conditions and contain minor amounts of particulate gold. The greatest (gold) concentrations are found within 4 m of the sea floor; lag gravel deposits formed on till of the present sea floor are especially enriched." An understanding of the gold distribution "must take into account the possibility that glaciers advanced on to the coastal plain" including what is now the offshore "during a period of low relative sea level."

Geological interpretations and all further references to lithologies and grades are derived from seabed samples, aided by the interpretation of seismic and side-scan sonar records. The seabed samples were obtained either by drilling with a Becker 180 hammer drill (over 7500 completed) over a fixed grid, by bulk sampling with a back-hoe in shallow water through the winter ice, or by sampling the loaded dredge buckets during dredging operations.

Dredged Material

Various writers have attempted to classify the offshore gold-bearing sediments in terms of either their origin or their constituents. The glaciers extending into the present day ocean eroded not only bedrock but earlier gold placers of marine and alluvial origin. The transported load was dumped as glacial moraine and outwash deposits which were subsequently modified by marine agents to create beaches and lag gravels. All the offshore sediments may be described in generic terms (till, lag gravels, outwash, beach, etc.), as quantified admixtures of silt/clay, sand, pebble and cobbles, or in terms of their complete particle size distributions. The deep seated till and all the other glacial and marine products may be described in these terms. The different sediments have been redistributed to varying degrees by faulting and over- thrusting with the result that they now exist as an intermingled, partly stratified accumulation of mud, clay, sand, gravel and till. Changes tend to occur over 10's or 100's of metres laterally and over less than 1 m vertically. Whatever the sequence at a particular location it is usually overlain at the seabed by a lag gravel with discontinuous thin rippled sand. In places, remnants of beaches and drowned sand spits are discernible. Some drowned fluvial sediments, deposited in erosional channels that cut into the till, exist offshore. The sediments in the upper 3 m are usually till (often referred to as diamict or clay-rich diamict), together with overlying and inter-bedded sand, gravel, sandy mud and mud. The sequence, topped with a lag gravel, may be repeated at depth. The *in situ* sediment density varies from about 2.0 to 2.35 g/cc for till, and is around 2.35 g/cc for silty sand. The water content immediately below the seabed averages 10 to 15 %.

Size Variations in Dredged Material

The percentage representation of each grain-size classification, if containing gold whatsoever, is illustrated in Table 3.3. During some drilling programs, and in dredging operations, the qualitative classification of a sample is based on a visual examination rather than on a rigorous, quantitative, size analysis. In reality, however, each descriptive classification is a mixture of defined particle sizes. Thus, sand contains some silt and gravel, gravel contains some sand, and till contains between 50 to 75% silt and sand.

The particle size distribution at any given dredging site depends on the extent to which each lithology is represented in the dredged ground at the site and on the very localized size characteristics of the lithology. For dredging production purposes there are three main constituents of importance: (a) silt, because it causes turbidity in the water; (b) clay, because it may cause losses of clay in the treatment plant, as well as generating more silt when it is successfully treated to liberate the contained gold, and (c) cobbles and boulders which reduce the throughput rate. Bulk sampling through the winter ice provides the best samples for measurement purposes. Otherwise drill samples, if properly collected, may be used to estimate the silt and clay content of ground to be dredged.

During production the monitoring of trommel oversize generates the cobble/boulder content. Seabed sampling by divers or the sampling of dredge buckets can give biased results. Depending on the exact location and the depth of the dredging (below the seabed), the combined silt and clay content may vary between 10 to 40%. The silt content of the dredged ground increases seawards, as indicated by drilling in 1 m vertical sections is given in Table 3.4. In general, around 2% of the dredged ground down to 3 m below the seabed exceeds a particle size of 30.5 cm and this fraction is sub-angular to rounded and often slab-shaped. Locally, higher concentrations of boulder occur. Rounded, erratic granite boulders up to 1 m in diameter occur in places.

Distribution of Gold

Gold exists throughout all the ground types to varying degrees. A part of the Nome offshore area is represented by typical figures in Table 3.5. On average, the gold exists in a very widespread sense at a low grade, but reserves must be delineated with a proven grade several times that widespread figure. The highest gold grades generally occur in the uppermost 2 m of the sediments, and especially in the top 0.5 m where the gold is concentrated in a lag gravel. Such a sequence may be repeated at a depth of a few metres in localized areas. In places the highest grades tend to occur where the measured sand content is 50 to 70%; this may take the form of a sandy gravel in which the silt content may average nearly 10%, or of a washed till with a silt content of around 15%. The total gold resource is oriented parallel to the coast. It has a length of about 24.8 km and extends from the foreshore to, in places, beyond the 3 mile limit into Federal waters. The offshore extent reflects the boundaries of the footprint of glacial deposition. It also mirrors the local intensity and distribution of placer mining activities onshore.

Isolated occurrences of gold, not yet investigated by drilling, have been worked on the foreshore for several miles to both the east and west. Scout drilling is at a spacing of about 300 m or more. Possible reserves are delineated by 100 x 100 m or 200 x 200 m drilling. A drillhole spacing of 50 m, or in places much less, is required to establish proven reserves. The grade, as measured by drilling, varies very significantly over distances of a few metres. Water depths increase seaward from the low water mark to about 17 to 20 m at the 3 mile limit. Thereafter the depth increases gradually offshore to a limit of about 27.4 m. Subtle variations in seabed elevation reflect the outline of the glacial debris and of possible, more recent beaches and still-stands. No beach is as well defined as the present one. The evidence is supported by side-scan survey data.

Geotechnical Data

Blowcount observations throughout the resource, coupled with standard penetration tests, indicate a relative density for the sediments varying from medium dense to very dense (R.& M. Consultants, 1988). The relative density generally increases with depth and most areas mined are classified as "dense" within 3 to 5 m below the seabed. Drilling is normally terminated at 10 m or less if penetration is refused at around 300 to 400 blows per metre. From triaxial tests the surficial silt is defined as "soft" but as the sand and fine gravel content and depth below seabed increase the material quickly becomes "stiff", "firm", and eventually "very firm". The sediments show consistent signs of over-consolidation. A mixture of clay, silt, sand, gravel and till exhibits a swell of 10 to 15% with some daily figures as high as 20%. Although permafrost has not been identified offshore it exists over large areas immediately above the high water mark. Its possible presence at depth offshore below the resource and, thus, its influence on the characteristics of the sediments, determining the ease with which they may be excavated, cannot be discounted.

3.2.2 Dredging System

The dredge typically used for such hard digging conditions as occur offshore Nome is a bucket ladder dredge. Onshore, Alaska Gold has, until recently, continued to employ two 255 litre bucket ladder dredges to work ground geologically similar to that existing offshore. The dredges are capable of achieving their theoretical throughput, however, only if the ground is thoroughly thawed in preparation. One dredge, No. 6, has been working immediately onshore from the high water mark.

Dredging offshore was conducted by WestGold using the world's largest ocean-going bucket ladder dredge, the BIMA, with 850 litre bucket capacity (Garnett, 1996a) (Figures 3.8 and 3.9). Detailed descriptions and specifications of the BIMA are given in sections 3.2.2.2 to 3.2.2.5. The dredge is manoeuvred on 4 anchored side lines and an anchored headline. During storms a stern line is also deployed. The ground dug by the buckets is delivered to two revolving trommels fitted with 9.52 mm and 25.4 mm screens. The undersize is delivered to a treatment plant comprising multi-stage jigging and final clean-up on shaking tables. Some screen oversize passes through a clay treatment plant before being returned to the main circuit. The dredge is fitted with a diesel-driven power plant of more than 5220 kW, generating 440 volts AC. Some components are DC motor-driven through thyristors from the main power system. The vessel meets with Bureau Veritas approval and complies with all the rules and regulations of the U.S. Government and the U.S. Coast Guard.

The dredge maintains a forward pressure by means of an 800 m headline anchor, about which it swings on an approximately 150 m face. Its lateral motion is achieved through 4 sidelines: 2 forward each of 250 m length, and 2 aft each of 300 m length (Figure 3.10). Except during the very early part of the dredging season, the dredge ladder is maintained in a position facing the incoming swells. The dredge effluents, principally the trommel oversize and the combined jig tailings, are therefore normally discharged on the shoreward side of the dredge.

Where the dredge cut is several metres deep so as to excavate more than one higher grade horizon, the dredge advances between 3.0 m and 3.5 m at a time with a drop of 0.5 m. The other extreme is where a single, shallow cut is required to remove the single, surficial lag horizon, in which case the advance is about 6 m. After a total advance of around 100 m the angles formed by the side lines relative to the line of advance of the dredge require that all the anchors be moved ahead accordingly by the same distance. A complete forward move of the anchor sets can be achieved well within the 12 hour day shift in good wind/wave conditions. Under less than good conditions it either takes longer or becomes impossible. The face width may be as great as 200 m, depending on a number of features such as the drill spacing and the need for selective extraction occasioned by the distribution of the reserves and the geology.

The rate of throughput is dictated by the speed of the buckets (buckets/minute), and the bucket fill factor which, if the correct bucket shape/size is used and the swing speed, bucket speed, and ladder angle, etc. are optimum, is governed by the characteristics of the ground being dredged, expressed as its resistance to digging. The performance is also sensitive to the wind/wave conditions. In very good digging conditions the dredge should operate at 28 buckets/minute with a maintained bucket fill factor of 70 to 75%.

Typical operating conditions at the Nome site are given in Table 3.6. The dredge operating season extends from approximately the first week of June to the second week of November, both limits being determined by the presence of sea ice. During winter the dredge is anchored at the docking facility, protected from moving ice fronts by an all-surrounding snow berm. On average the total possible number of operating days is between 155 and160.

The gold values do not extend down to bedrock. Enrichment, if any, occurs on a "false bedrock" clay, which often represents the interface between the base of a lag gravel and the underlying till. All material dredged is fully treated. Offshore Nome the bucket speed varies between 14 and 28 buckets per minute, with an average of around 20 buckets per minute. The maximum dredging depth is rarely as much as 20 m of water and ground combined and the depth of cut below the seabed does not exceed 10 m. Very frequently it is only 3 m and a minimum cut of 2 m has been achieved in places. The fill factor varies between 10 to 60% in shallower water of less than 10 m, with an average of about 40%. In deeper water of more than 10 m the fill factor varies from 30 to 80% with an average of about 60%. The eventual throughput rate, on a daily basis, varies between a range of 200 to 600 m^3/hour in shallow water of less than 10 m with a cut depth of 2 to 9 m, and a range of 500 to 800 m^3/hour in deeper water of more than 10 m with a cut depth of 2 to 4 m.

3.2.2.1 Design Criteria

The BIMA was designed for dredging to a maximum depth of 45 m below sea level at a ladder angle of 55° below the horizontal. The minimum water depth for dredging is 10 m, and an ideal digging face slope is 1:2. Maximum output of the bucket line is 2,043 m^3/hr. Under ideal conditions the maximum capacity of the treatment plant is almost 3,000 dry metric tons/operating hour. A speed-controlled 1,343 kW drive gives 30 to 36 buckets/minute at maximum horse power or 0 to 30 buckets/minute at maximum torque. Dredging in waves is possible if the maximum movement of the bottom tumbler does not exceed 2 m vertically and longitudinally, or 0.4 m laterally. The dimensions and specifications of the BIMA are given in Table 3.7.

3.2.2.2 Treatment Plant and Products

Two revolving circular screens, each with a perforated length of 17.2 m and a diameter of 3.4 m, with sparge and monitor water, receive dredged ground from the bucket line via the drop chute. Undersize at 25.4 mm passes to the primary jigs which aim to recover all the contained gold. Oversize from the screens is discharged into the sea down the screen oversize chute. Ideally, all materials are slurried so as to liberate fully the gold. The concentrate from the primary jigs is passed to the secondary jigs which serve to concentrate the gold and thence pass it to the gold room. Tailings from both the primary and secondary jigs are combined and discharged into the sea down the twin tailings launders which extend aft of the dredge. The small tailings discharge from the gold room enters the sea over the side of the pontoon. Barren or unpayable ground may by-pass the treatment section altogether and be discharged aft via the single overburden stripping chute. No chemicals, reagents or substances of any kind are added to the dredged material for the purpose of gold recovery.

3.2.2.3 Support Facilities

The operation is supported by offshore and onshore facilities as shown in Table 3.8

3.2.2.4 Dredge Products and Effluents

The main dredge effluents are the screen oversize and the tailings from the primary and secondary jigs and from the gold plant. The product is the gold-bearing concentrate which is transported ashore by helicopter for final clean-up. Both the gold concentrate product and the discharged effluents can be quantified by observation and deduction. Suspended material from the excavation process is introduced into the water column underwater at the bottom tumbler and from off the loaded, rising buckets. Spillage also re-enters the water via the ladder well if it is not collected by the save-all (Figure 3.11). It is possible to make a guess at the volume of solids entering the water column in these ways, but there is no practical way to quantify them. Under ideal conditions treating, for example, 900 m^3 of ground per hour the distribution of solids and water is as shown in Table 3.9. All the water intake is discharged with the primary and secondary jig tailings which are combined in the two tailings launders. At Nome, some of the varying conditions are indicated by the reconstructed annual average figures for the more important performance parameters (Table 3.10). The numbers in this table are based on both direct measurements and professional deduction. The annual variations in performance reflect not only the gradual improvement in screening efficiency over the years but also the variability of the ground. For example, a typical monthly average feed (from 1987) as recorded on the dredge might be comprised of an observed combination of silt, clay, sand, gravel and till. But taking into account the integral composition of each of the above field classifications the silt content becomes emphasized (Table 3.11). There is, in fact, twice the amount of silt and 50% more sand than the dredge observation indicates. Both the material dredged and the throughput rate vary considerably not only from one day to the next but also throughout a single day. The ease of excavation, the existence of clay, and the presence of boulders all serve to influence the throughput rate. In shallower water of less than 10 m very rarely do 3 consecutive days show less than a 20% variation in throughput rate: it is more usually 20 - 50% on consecutive days. In deeper water the variation is usually 10-30% from one day to the next.

The relative content of silt, sand, and gravel being discharged from the dredge, together with the rate of discharge, often therefore bear little relationship to the monthly and annual averages. They may change from one hour to the next, according to the nature of the ground being dredged, regardless of the efforts of the dredge management to maintain uniformity of feed and rate. The throughput rate changes accordingly and is affected by the prevailing wind/wave conditions. The metallurgical efficiency of the treatment plant shows an inverse relationship to the throughput rate within some ranges. However, the most important attainments in order to maximize the daily gold production are maximum operating hours per day and maximum throughput rate.

3.2.3 Geochemistry

Environmental information on the WestGold operation is extensive, but much of the discussion on chemical effects associated with dredging by the BIMA is equivocal. This stems from a number of common problems in sampling methodologies (collection and handling), chemical analysis, and reporting. There is also no information on the *in situ* geochemical character of the deposits that were dredged, other than the bulk chemical analysis of grab samples. In particular, no data are presented on the presence or absence of dissolved H_2S, arsenic, iron or manganese in the sediment pore waters. It is now known that such data are needed if a reasonably rigorous assessment of post-dredging chemical behaviour is to be made (see Section 2.2). Nevertheless, if data are carefully selected from the databank (e.g. dissolved and total metals measurements from splits of the same bulk sample) it is apparent that the occasionally high metals levels reported stem from particulate loads only and not from metals in solution. There is no evidence for systematic addition of dissolved metals to the waters in the vicinity of the dredge. Similarly, there are no unequivocal data that indicate uptake of metals by organisms in the area.

There are indications that red king crab may accumulate arsenic and nickel, and also that the crabs might be able to purge themselves of nickel and chromium when moulting their shells. Some of the crab feed-stock species show erratic elevations of trace metals at the test sites, and in some cases reductions. These variations illustrate the technical difficulty of reaching clear conclusions with the known variability of trace metal tissue levels. The variability is derived both from analytical procedures and the biology of the species being tested. Specifically, there is no evidence for contamination effects particularly from mercury. It is reasonable to conclude that the WestGold dredging operation did not produce significant deleterious chemical impacts on the local marine environment. This conclusion is consistent with the principles described earlier in Section 2.2.

Caution is needed when using the WestGold information for determining impacts and mitigation procedures. Providing that potential sites have the same sedimentological and oceanographic characteristics as those for offshore Nome, the conclusion in the above paragraph may be extrapolated to such locations. From the broader perspective, only limited generalizations can be made from the WestGold operation's geochemical information.

Although chemical impacts can be expected realistically to be minor or negligible in the dredging of coarse sedimentary substrates, different sediment textures, organic contents, and types of organic material can establish geochemical contrasts from site to site. The adoption of a precautionary approach requires that these characteristics be taken into account on a site-specific basis in future projections of environmental impact.

3.2.4 Seabed Biodiversity and Resources

3.2.4.1 Locality and Dredging Characteristics Affecting Benthos

The WestGold site is a shallow area with depths sloping gently to approximately 30 m (Figure 3.12). Dredging was confined to a range of 7 to 20 m (Fig. 3.13). This depth range is sufficient that the benthos show depth-related changes. As a high-energy coastline the substrate is characteristically poorly sorted with a high gravel content (Appendix 6), and clay contents ranging up to 24% at some localities and up to 97% at the deepest sites (20 m). Environmentally significant operating parameters for the bucket ladder dredge, BIMA, are shown in Table 3.12.

The distribution of substrate types in 1990 following dredging and sampling include "fine sand/mud", "gravel/sand", "sand waves", and "cobble". From Section 3.2.3 it is reasonable to conclude that the redox boundary was probably 0.1 to 0.5 m below the seabed. This is sufficiently deep for ample small burrowing benthos requiring aerated conditions.

Sampling stations providing the most relevant data are stations C2 and C3 (Controls) ; S2 and S3 (Subsistence) and R6 and R7 (Dredged) (Figure 3.13 and Appendix 6). Subsistence stations were in areas used for subsistence fishing by the local community. All sampling stations were characterized by cobble and sand areas. Station R6 was dredged in 1986. Station R7 was dredged in 1988, but was impacted by nearby dredging in 1987, 1989 and 1990. Following changes in the original mining pattern, sampling at Stations R6 and R7 was initiated after or during dredging, hence no before and after comparisons are possible. However the two dredged stations (R6 and R7, both areas of cobble and sand) can be compared with equivalent areas at both Control and Subsistence stations. Effectively there were two sets of Control stations for all Dredged stations. Reviews are provided by ENSR (1991) and Garnett and Ellis (1995).

3.2.4.2 Benthos Pre-dredging

ENSR (1991) provides details of biodiversity from 1985 to 1990 (Appendix 6). The number of taxa (species biodiversity) before dredging at the various stations ranged upward from about 30, with numerical diversity ranging upward from about 500/m^2. These fall within global ranges for seabeds. On sand deposits the most abundant forms present in 1985 before dredging included several hundred specimens/m^2 of two species of known sand-bed genera of bivalve molluscs, *Tellina lutea* and *Macoma lama*. The remaining dominant species were polychaete worms, with the exception of the sand dollar *Echinarachnius parma*, also a sand-bed genus. In both Reference stations the five dominant forms alone totalled no more than 1,000 organisms/m^2.

On cobble substrate the pre-dredging benthos in 1986 were less abundant with total numbers ranging up from about 500/m^2. The dominant species were also different from those on sand pre-dredging a year earlier with no species overlap. Polychaete worms remained abundant but with different species. The mollusc present in largest numbers was the cockle *Clinocardium californiense*. The echinoderm fauna was represented most abundantly by both sea urchins *Strongylocentrotus droebachiensis* and brittle stars *Diamphiodia craterodmeta.*

3.2.4.3 Benthos Post-dredging

On sand beds, species and numerical diversity were low at the R6 and R7 sampling stations in 1987 and 1988 one year after dredging. Numbers were lower than were maintained before and after the dredging years at the various Reference Stations. These reductions also show in the dominant species list (Appendix 6). In 1987 at R6, four species of small crustacea, one of which was new, were most abundant. By 1988, Station R6 was recovering with more usual species, and this trend continued to 1990. At Station R7 there was a similar pattern of reduced species but recovery was progressing more slowly. However, there were molluscs present in 1988 and 1989, which may be slower to recolonise than polychaete worms and crustacea.

On cobble beds there was a similar pattern of reduced biodiversity in the year of, and following, dredging in 1987, with little indication of recovery by 1990. Lists of dominant species also show reduced numbers. Species present are generally the same as in the Reference stations, although there are a few novel species in the recovering areas.

In general terms the sand bed biodiversity started to recover within 1 year of dredging. A few new species entered the fauna and later disappeared, but there is no clear successional pattern. By 1990, four years after dredging at Station R6, the biodiversity was clearly back into the range of the four Reference stations.

Cobble bed biodiversity appears to have recovered more slowly. The number of species remained as high as the Reference Stations, or almost so, even 1 year after dredging. However, the number of organisms showed a reduction barely reaching the lower end of the year to year range at the Reference Stations. By 1990, R6 had done better than R7, dredged a year later. The corresponding physical changes for the 1986 dredged area (containing Station R6) are shown in Figure 3.15.

The ENSR (1991) report in summary states:

(1) "The extreme physical disturbance of dredging causes significant alteration of benthic invertebrate communities."

(2) "Recolonization of these disturbed communities appears to begin immediately after dredging stops."

(3) "Recovery of these communities to their original structure may not occur; instead a somewhat different assemblage of the original species may result."

(4) "Recolonization of the dredged areas with comparable density, biomass and number of taxa to control sites may require 3 to 4 years for sand substrate and 5 or more years for cobble substrate."

(5) "Recolonized dredged areas may have altered community structure but functionally are similar to the original communities."

3.2.5 Fisheries and Wildlife Resources

The one fishery species monitored in detail was the red king crab (*Paralithodes camtschatica*). It was found that crabs move locally over distances which allowed them to transfer between dredged and undredged areas. Their movements prior to dredging were apparently random, although crabs often have seasonal shifts with depth. Crabs were fished from both dredged and undredged areas, with more competition by boats for fishing sites in the dredged than the undredged areas after mining started. Feeding habits of the crabs at dredged and undredged sites appeared not to differ. Crabs are opportunistic feeders and take almost whatever is available. Crab monitoring was scheduled to be discontinued in 1991 due to satisfaction that the feeding studies were adequate, but also due to the technical impossibility of obtaining clearer results on crab movements relative to dredged and undredged sites (Garnett & Ellis, 1995). A list of resource species in the area is provided in Table 3.13. No impact was demonstrated on these species that, in general, are opportunists not selecting localized areas in conflict with dredging operations.

3.2.6 Biological Oceanography

A bucket ladder operation may produce several distinct types of water column effects because of the large volume of materials dredged from and returned to the sea floor (500 to 1000 m^3/hr). Particles larger than silt (> 0.06 mm) fall rapidly to the bottom creating a turbidity plume a few metres in diameter extending from the surface discharge point to bottom impact. Due to the density of this plume, anything not able to avoid it will be destroyed. From the inevitable noise level of the operation it is doubtful that many large fish, birds and mammals would remain in the immediate area during dredging operations and therefore there would be little direct impact on this population. However fish are known to aggregate around tailings plumes (e.g. the Marcopper Mine in the Philippines) and to support local subsistence fisheries (Ellis *et al.* 1995). Planktonic organisms such as algae, copepods, jellyfish etc. are unable to avoid the tailings discharge plume and some will be entrained and destroyed. Given the low density of biomass within the water column (mg/m^3) and the restricted area of impact (150 to 300 m^2/hr) direct biomass destruction can be predicted to be only a few grams wet weight per operating hour.

Fines (clay and silt < 0.06 mm) enter into the water column through the dredging process, dredge bucket spillage, and surface discharge of tailings slurry. The amount of fines in the tailings slurry depends to a large extent on the clays and silts in the feed composition. At WestGold's Nome site this reached as much as 25% of the total dredge throughput (125 to 250 m^3/hr). Such fine material settles very slowly and can be expected to remain suspended in the water column for considerable periods of time and over extended distances.

Sediment turbidity plumes generated by WestGold's Nome operation were modelled by the DIFCD (Disposal from a Continuous Discharge) numerical model (ENSR, 1991). Model results indicated that the extent and concentrations of the turbidity plumes were sensitive to operating conditions (throughput and depth) but depended primarily on the composition of the dredged materials (i.e. the percentage of silt) and the physical oceanography at the site. Under the most stringent conditions of high clays and rapid currents, turbidity plumes >25 NTU over background were predicted at all depths up to 4 km from the source. At WestGold's Nome site turbidity plumes were easily recognized visually at a distance of 1 km or more from the dredge. Further details concerning plume modelling at WestGold's dredge site are provided in Section 5.1.5.3.

In Alice Arm, B.C., tailings from the Kitsault Mine (approx. 270 m^3 solids/hr) that were discharged continuously at a depth of 100 m remained in suspension as a near-bottom turbidity plume at an average distance of 5 km from the source (Pedersen *et al.* 1995). Natural glacial runoff turbidity in Alice Arm extended for an average of 8 km down-inlet in surface waters. Therefore the predicted distance of 4 km for a dredge's tailings plume is not unreasonable. There was no evidence that the plume arising from WestGold operations was environmentally damaging. In Alice Arm an intensive short duration program to determine the effects of tailings discharge on the inlet was not able to determine any adverse effects of this turbidity on water column biota (Rambold and Stucchi, 1983).

Bucket ladder dredging did not introduce unusually high trace metal levels to the water column (ENSR, 1991). Mussels suspended within the turbidity plume for a 1 year period did not show any bioaccumulation of metals that could be linked to the turbidity plume. Apart from visual discoloration and minor losses in primary production due to light scatter, there was little direct effect of turbidity on the biota.

3.2.7 Summary of Environmental Impacts, Mitigation Objectives and Assessment Criteria for Scenario 1

3.2.7.1 Environmental Impacts

Water column impact was limited to a turbidity plume extending from the dredge discharge points. Seabed disturbance was caused by the dredge cuts and deposition of tailings. Dredge footprints were substantially smoothed by wave and current action within 3 to5 years, even on the coarsest gravel/cobble habitat. A level of biodiversity encompassing several tens of species and several hundred organisms/m^2 had recolonized the impacted areas within 3 to 5 years, with recovery slower on coarser fraction gravel and cobble habitat.

There was no deleterious impact on the local fishery for red king crab, neither in terms of stock or contamination (from bioactivation of prior mercury settling). There was competition for fishing sites close to the dredged areas.

3.2.7.2 Mitigation Objectives

Specific mitigation objectives included minimization of turbidity, minimization of release of toxic materials and bioaccumulation of mercury (residue from prior beach mining). There was also to be minimal effect on the local red king crab fishery. Benthic disturbance was not constrained, but a sampling program was required to monitor impact and recovery on both sand and gravel substrates. Responses included a sub-surface outfall discharge, constraints by the regulatory agency on discharges and receiving area conditions, and a substantial monitoring program to assess whether the constraining criteria were met.

Examples of effluent and receiving area constraints set by the regulatory agencies are provided in Tables 7 and 8, Appendix 6. The major receiving area constraint was a requirement for <25 NTU (turbidity) units above background at a 500 m radius from the point of discharge at the dredge's stern. Maximum trace metal levels were also specified for a 100 m radius mixing-zone boundary. Sensitive species and habitat were not an issue at this site.

3.2.7.3 Mitigation Achievement Criteria

Turbidity reduction at surface was appraised by appropriate monitoring with the sampling plan shown in Figure 3.16. Achievement of the permit constraints were appraised by monitoring effluent and receiving area as frequently as 3 times daily (see Tables 7 and 8, Appendix 6). The red king crab fishery was considered to be unaffected based on 5 years of monitoring by test fishing. Test for the release and bioaccumulation of mercury presented considerable analytical problems initially, but once resolved provided no evidence of impact.

3.3 Scenario 2: Precious Metal Mining, Alaska - Underwater Miner

Precious metals are known to exist offshore as surficial concentrations in lag gravels or with industrial heavy minerals in the upper surface of sand bars, banks and spits. They are also concentrated in outwash channels on gold-bearing glacial moraines that have since been inundated by the sea. Examples of such deposits exist around the Alaskan coastline. A Surficial concentration, especially if no more than 0.25 to 0.5 m in thickness, constitutes a target deposit for excavation by an underwater miner if:

(1) the deposit is beyond the reach of conventional offshore dredging equipment such as a trailing suction hopper dredge

(2) the deposit is too close inshore for other equipment to be deployed safely

(3) the deposit is too small to justify the mobilization of larger equipment

(4) the sea conditions prevent the deployment of a suitably small alternative dredging unit

(5) very selective extraction is required, or

(6) the grade is high enough.

An underwater miner (UWM) constitutes the opposite extreme of a large bucket ladder dredge: it has a comparatively very low throughput, is limited in terms of the depth to which it can dig below the seabed, and has the ability to be very selective in its extraction, both laterally and vertically. Dilution is minimal but unit volume costs are high. A bucket ladder dredge, by contrast, relies for its economic success on its digging power and its high throughput, resulting in a low unit volume cost. It is very non-selective, laterally and vertically, and a surficial deposit worked by it is heavily diluted in grade.

WestGold deployed a UWM in the Nome area of Alaska in the summer of 1989 (Garnett, 1991). This was the first recorded occasion when such equipment had been used for an offshore mineral recovery program other than remotely operated collectors in the earlier deep ocean manganese nodule projects. The UWM used was the "Tramrod", model 250, developed and manufactured by Alluvial Mining of the United Kingdom.

Another UWM, the original version of which was designed and built in France, has been employed since 1990 in the 120 to 140 m-deep west coast waters of Namibia in Southern Africa (Garnett, 1995). It is used for the excavation of diamondiferous gravels approximately 20 km offshore. The deployment of additional units, both marine and shoreline versions, is presently being investigated. The equipment also may be used for small-scale beach renourishment projects, excavating small, localized pockets of potential beach sand.

3.3.1 Mining Scenario

3.3.1.1 Location

Examples of the deposits amenable to exploitation by means of a UWM exist around the Alaskan coastline, including the Alaskan panhandle. All of the areas are in State waters and some, including that at Nome, Alaska, extend into Federal waters beyond the 3 mile limit.

3.3.1.2 Marine Conditions

Most areas along the Alaskan coast are exposed, to varying degrees, to the climatic conditions characteristic of the Bering Sea or Gulf of Alaska. More extreme conditions exist on the north coast of the Seward peninsula. However, offshore Nome, with its winter freezing of the sea and variation from calm seas to major storm conditions during the summer, exhibits all the surface features likely to be encountered to different degrees at all the potential locations.

A full description of the Nome marine conditions is given in Section 3.2.1.3 (Mining scenario 1). In some other areas the winter conditions are more harsh and the summer is of a shorter duration. In places, no sea ice may form and the winter months are an extension of the least favourable Nome conditions experienced in October and November. Local variations occur in terms of wind speed and direction, wave heights and swell, precipitation, water temperatures, and salinity.

3.3.1.3 Geological Background

Gold and platinum occur on large areas of the seabed in Alaska as lag gravel concentrations in the uppermost metre of the sediments (Nelson & Hopkins, 1972). In places the veneer of lag gravel is thin, around 0.25 m. Both the thickness of the lag gravels and the degree of concentration of the precious metals are dependent in part on the past and present water depth. The seabed is, or has been, within the range of storm effects that serve to winnow out the finer particles. Mineralized lag gravels may be developed over a range of gold-bearing sediments but are especially prevalent over glacial till and diamicton. Gold and platinum also are locally concentrated offshore in three distinct modes of occurrence:

(1) dendritic patterns of narrow and shallow filled channels formed, in now inundated glacial outwash and related sediments, by former surface-flowing streams

(2) beaches and still-stand areas characterized by well sorted sand and gravel, and

(3) sand spits and sand banks that have been supplied with transported metal particles from elsewhere.

3.3.1.4 Mined Ground

The UWM selectively strips off the surficial deposit from underlying lower grade material. The vertical cut-off horizon may be dictated either by declining grade or by increasing resistance offered to excavation, or both. The lag gravel sequence usually comprises an upper surface armoured with pebbles and cobbles from which all small, lighter particles have been winnowed. In places the cobbles may attain boulder size. Beneath the stone armouring is sand which possesses an increasing silt content with greater depth. The loose silt/sand, with some gravel, usually rests on a clay horizon that may contain cobbles and gravel. The clay is often the upper, slightly softened, surface of an underlying glacial diamict, but may also represent other lithological components of glacial moraine and surrounding host sediments. The whole vertical section may be enclosed within a 1 m interval.

Within a few hundred metres of the shoreline the basal diamict may be loosened to a deeper extent than further offshore by the mechanical action of sea ice gouging. It may be buried beneath a few metres of silt, sand, gravel and cobbles. The overall particle size distribution may be similar to the underlying basal unit - the only difference is the looser structure near surface.

3.3.1.5 Size Variations in Excavated Material

The composition of lag gravels from two different areas representing different parts and styles of glacial moraine are given in Table 3.14. Seabed channels filled with outwash gravel contain less silt and sand and in places reveal fairly well-sorted gravel. A typical example contains 40% exceeding 19.05 mm particle size and none exceeding about 0.15 m. Approximately 10% comprises silt. Beach sand and sand spit deposits consist of 90% extremely well sorted sand with about 65% of the sediment being -65 + 100 mesh (- 0.212 + 0.106 mm). About 10 to 15% comprises silt. Some beaches may be characterized by larger cobbles and boulders if they have developed on the flank of a terminal or lateral moraine. For excavation purposes there are five main constituents and ground types of importance:

(1) silt, because it is easily excavated but causes turbidity in the water

(2) clay, because it may cause losses of gold in the treatment plant, as well as generate more silt when it is successfully treated to liberate the contained gold

(3) clay/gravel mixtures which can be excavated only at a lower rate

(4) larger cobbles and boulders which cannot be excavated and pumped, eventually bringing production to a halt, and

(5) till and diamict which contain too little gold and which can be excavated at a low rate only with difficulty.

In places silt or mud with a high gold content may attain a thickness of about 1 m or more, but the lateral extent of a very thick and high grade sequence is usually no more than a few metres. Such an occurrence is insufficient in volume to constitute a discrete mine planning unit.

3.3.1.6 Distribution of Gold

The lag gravels with contained gold are widespread. Their gold content decreases logarithmically with depth in an undisturbed lag sequence, and is very variable laterally. The exact location of higher concentrations in the beach and channel deposits depends entirely on local conditions. For reserve definition purposes a sample spacing of as little as 10 m is necessary.

3.3.2 Mining System

The UWM is normally deployed offshore from an ocean-going barge or self-propelled vessel which carries a full mineral treatment plant and the UWM's support facilities.

3.3.2.1 Underwater Miner

The "Tramrod" model 250 UWM is a remotely operated, track-mounted machine which is entirely within the control of an operator at the surface. The machine has undergone several modifications and design changes since 1985 when it was first deployed in the North Sea. These changes include general strengthening and the addition of optional cutting devices as shown in Figure 3.17. The machine consists of a tracked undercarriage on which is mounted an hydraulically controlled dredging arm. Excavating power is achieved by means of a powerful jet pump assembly capable of pumping solids of up to 250 mm diameter. High pressure water is supplied to the jet pump by a 1,035 kPa, surface-mounted pump via two 152 mm diameter hoses. The jet pump system can be replaced by a centrifugal pump attached to the dredging arm, that increases both the density of material dredged and the throughput rate. When cutting of the sediments is necessary an optional cutting wheel, designed to cut clays up to 500 kPa shear strength, may be added to the dredging arm. This addition improves the throughput where otherwise the suction device alone is ineffective against resistant soils.

The "Tramrod" UWM is connected to surface by an umbilical cable which carries all control and other signals as well as electrical power for hydraulic drives. The standard items of equipment installed on the UWM for operations are given in Table 3.15.

3.3.2.2 Deployment

The UWM usually operates at distances of more than 100 to 200 m from the shore, depending on the prevailing water depth and other local conditions. The only limitation to its distance offshore is the water depth which is not exceeded by most of the localities of interest. The machine is deployed from a 76 m long by 23 m wide and 4.9 m deep ocean-going barge (Figures 3.18 & 3.19). With a draught of only 1.5 m the barge can enter any harbour. The barge is secured and manoeuvred by means of a 5-point anchoring system powered by D.C. electric motors. Each anchor winch is equipped with 610 m of steel cable.

The UWM is placed on, and recovered from, the seabed by a truck-mounted 210 tonne-capacity crane. Mined sediments, to a maximum of 0.25 m in particle size, are suctioned through a 25 cm-diameter intake and pumped to surface through a 0.305 m internal diameter floating pipeline. A 0.38 m intake can be fitted, together with an appropriately sized pipeline. Boosted by a 0.305 x 0.356 m, 11.36 m^3/min. pump on deck, the slurried material is delivered to the treatment plant on the barge.

3.3.2.3 Treatment Plant

The conventional recovery circuit has a nameplate capacity of 250 m^3/hour. It commences with a 22.3 m^2 area grizzley with 0.20 m bar spacing. The washed oversize at +0.20 m is discharged directly into the sea and this size fraction generally represents about 10% of the feed. The grizzley undersize at -0.20 m is fed, by a vibrating rock chute, to a 20.7 m rotating trommel of 1.83 m diameter. The trommel receives approximately 200,000 l/hour of sparge water and delivers 3 products:

(1) -12.7 mm which is delivered as a slurry to the jig circuit

(2) -38.1 mm and +12.7 mm which is discharged, via a nugget trap, into the sea, and

(3) +38.1 mm which is discharged directly into the sea.

Products (2) and (3) combined, being +12.7 mm, generally represent about 20 to 30% of the feed. Product (3), comprising about 60 to 70% of the feed on average, passes to a de-watering cyclone ahead of the jig plant. The cyclone over-flow is discharged directly to the sea, while the under-flow passes through a 2-stage jig plant. The combined primary and secondary jig tailings are discharged as a slurry (5 to 10% solids) to the sea and the gold concentrate is up-graded on a shaking table.

3.3.2.4 Support Facilities

The support vessel requirements are shown in Table 3.16.

3.3.3 Operations

The barge is deployed on its 5-point anchor spread (one bow and 4 side-lines), bow into the incoming swells. The UWM is lowered to the seabed from the stern, oriented so that its forward movement takes it directly away from the barge and on the extension of the barge's centre line. The machine is connected by its umbilical cord, the twin water hoses and the floating pipeline. In addition, the crane hook is kept attached to the UWM lifting strip to ensure a quick machine recovery from the seabed if necessary.

Mining is effected by the UWM advancing along a pre-determined corridor, excavating a fairly uniform cut after an initial downward access ramp. The cut is about 1 m deep, but may be significantly more or less. The depth of the cut is governed by economic considerations such as grade and geotechnical characteristics, and defines the horizon on which the UWM traverses. The initial corridor resembles a wide, shallow trench in which the UWM moves forward on the trench floor, progressively extending the trench. If possible, the forward movement is continuous, but in places the machine must halt, or reverse, so as to ensure that the base of the cut is being cleaned up sufficiently.

The barge follows the UWM stern first at the rear of the machine on a discontinuous basis. When the pipelines, cord and securing line from the barge to the UWM are judged to possess too little slack for the conditions, the barge is moved on its spread by an appropriate distance to bring its stern to a point immediately behind the rear of the UWM. The limit of the UWM's advance is either the boundary of the pre-determined mining unit or the anchor spread limit of movement of the barge. Where the limit is reached the machine may be hoisted on deck, or may be reversed down its excavated corridor as the barge returns almost to its original starting position. The barge and UWM then manoeuvre so as to commence the excavation of a second corridor parallel, and adjacent, to the first. All effluents are discharged on either port or starboard side of the barge so as to not dilute virgin ground. The operating capabilities of the UWM are shown in Table 3.17. The daily throughput rates vary according to the accuracy of digging required and the extent to which cobbles and boulders may be present. The main objective of future developments of the UWM for precious metal mining is an increase in the throughput rate. The next plateau to be reached, and which already has been considered in the design stage, is an average throughput rate of 300 m^3/operating hour. This will involve:

(1) increasing the excavating capability by means of fitting a greater width of cutting wheel (bucket wheel) and drawing on the experience gained in the use of continuous-wheel miners in the open-pit mining industry

(2) screening out the larger (e.g. +0.30 m) cobbles and boulders at seabed level on a grizzley integrated into the UWM

(3) increasing the power supply at the highest possible voltage, and

(4) installing a slurry pump on the UWM, assuming that a pump capacity would be required of 300 m^3/hour at 20% solids.

The corridor width depends on whether or not a cutter or other special feature is added. Without a cutter (suction only) the maximum width is 12.3 m; with a cutter the maximum width is 8.7 m, and with special features (at a rate of 300 m^3 solids/hour) a width of 15 to 20 m.

3.3.3.1 Mining Products and Effluents

The main effluents from the UWM operation are the grizzley oversize, the trommel mid-size and oversize, the de-watering hydro-cyclone overflow, and the combined primary and jig tailings (Table 3.18).

3.3.4 Geochemistry

See Section 3.2.3.

3.3.5 Seabed Biodiversity and Resources

3.3.5.1 Locality and Mining Characteristics Affecting Benthos

Variable types of deposits are expected shoreward of the 3 to 20 m depths monitored for Scenario 1. Mining is a relatively high precision operation, removing sediments to a depth of about 1 m or less. The UWM can be manipulated to a precision of about 0.2 m vertically. Hence mining is selective, normally to extract the highest grade deposits. The deposits are localized in lenses, shaped by wave action, or in strings following irregularly-shaped submerged relic stream courses. Thus there is extensive, almost identical, benthic habitat left alongside and between dredge courses. The non-dredged areas may be affected by tailings deposition, thus care is needed in selecting sampling stations for monitoring purposes. Environmentally significant operating and mining parameters for the "Tramrod" UWM are shown in Tables 3.19 and 3.20 respectively.

3.3.5.2 Benthos Pre-mining

Beds of marine grasses and algae may be present between 3 to 20 m, and the associated benthos are expected to be as abundant and productive as in the deeper water dredged during 1986 to 1990 (ENSR, 1991), with a probable exception at low tide level. In the intertidal zone the benthos are subjected to an extremely high energy environment, characterized by continuous wave-induced substrate movement, ice scouring in winter, and melt-water runoff in summer. Considerable turbidity is expected from continuous wave action on this exposed coast (Figure 3.12), and intensified during storms in summer. The organisms present are thus exposed to natural conditions similar to those that are generated temporarily in an extreme form by dredging operations.

3.3.5.3 Benthos Post-mining

Given the natural conditions of periodic wave and turbidity exposure, the small-scale of operations and known impact from the larger-scale bucket ladder dredge operations offshore, this form of mining should create only localized effects immediately around the UWM and zone of tailings discharge. The two main risks are: (1) losses from physical extraction, and (2) smothering from rapid tailings deposition. The impacts in part overlap depending on discharge location, and hence probably cannot be distinguished by monitoring. Further from the UWM, raised water column turbidity from dredging and tailings discharge and settling are not seen as risks to the benthos.

Marine grass beds, and to a lesser extent algal beds (if they occur), are at risk. If high grade gold deposits occur in such beds it is desirable to use the first extractions as an experiment to determine the extent of loss and the recovery rates relative to the same features for other local beds. The environmental significance of future extractions can then be appraised.

3.3.5.4 Fisheries and Wildlife Resources

A stock of king crabs supports subsistence and artisanal fisheries (see Scenario 1). Other resource stocks are present, including marine mammals and birds which support subsistence use. The more intensive and extensive dredging offshore had no detectable impact on these resources. The UWM, similarly, has little impact.

3.3.6 Biological Oceanography

Although the operating principles of the UWM are quite different from those of the bucket ladder dredge, water column effects are similar, differing only in degree. Oversized material is either avoided on the seabed or is pumped to a surface grizzley and trommel from where it is returned to the sea. Turbidity plumes are produced at the dredge cutter-head of the UWM and at the surface discharge point. In shallow water the effects are similar to, but less than, those caused by a bucket ladder dredge (Scenario 1). There is almost no environmental risk associated with sub-surface discharge of tailings materials and almost none with deep discharge.

3.3.7 Summary of Predicted Environmental Impacts, Resulting Mitigation Objectives, and Achievement Criteria for Scenario 2

3.3.7.1 Predicted Environmental Impacts

The precision mining technique of the UWM has low impact producing little cutting face turbidity and benthic impacts are slight from the precision cutting.

3.3.7.2 Mitigation Objectives

Mitigation objectives should include: (1) minimizing turbidity at the cutting face, and (2) prevention of elevated of surface turbidity, as described in the generalised turbidity objectives (Section 2.7)

3.3.7.3 Achievement Criteria

Achievement criteria should include:

(1) turbidity from cutting face activity must not rise to surface

(2) surface turbidities should be as stated in the generalised criteria (Table 2.8)

(3) dissolved oxygen levels should be as stated in the generalised criteria (Table 2.8).

3.4 Scenario 3: Marine Aggregate Mining, Massachusetts Bay

3.4.1 Mining Scenario

This scenario describes a hypothetical marine aggregate mining operation in Massachusetts Bay, serving the Boston area market. Geological and environmental information relevant to this scenario are derived from the NOMES (New England Offshore Mining Environmental Study) report (Padan, 1977), which details the results of a baseline environmental study carried out in preparation for a proposed marine aggregate dredging experiment.

3.4.1.1 Marine Conditions

The NOMES study was initiated in 1972 by the Commonwealth of Massachusetts and the U.S. National Oceanic and Atmospheric Administration (NOAA), with the intention of resolving marine environmental impact uncertainties associated with nearshore marine mining. Multi-disciplinary studies were centred at location 40° 21' 41" N by 70° 47' 10" W in Massachusetts Bay, about 16 km offshore of Boston Harbour in 20 m water depth (Figure 3.20). The project was terminated in July 1973 as a result of the failure of the Commonwealth to arrange for a suitable site for the disposal of the three-quarters of a million cubic metres of sand and gravel that was to have been dredged during a planned spring 1974 test. Although much of the survey work in progress was interrupted by premature termination of the project, funds were allocated for publication of such work as had been accomplished. The comprehensive report on the NOMES project (Padan, 1977) includes a chapter on physical oceanographic processes that summarizes the oceanographic setting in Massachusetts Bay. The following information is derived from Padan (1977).

Massachusetts Bay lies on the west side of the Gulf of Maine. It is bounded on the north by Cape Ann, on the west by the Massachusetts coastline centred at Boston, and on the south by Cape Cod Bay and Cape Cod. Seventy-five percent of Massachusetts Bay and Cape Cod Bay is surrounded by land. Oceanographic conditions near the eastern mouth of the Bay are influenced by Stellwagen Bank, a submarine ridge that rises to within 20 m of the surface, and which opens at either end in channels of about 60 m water depth. The location of the dredging described in this scenario is inshore of Stellwagen Bank, in 20 m of water.

Historical data were assembled and analyzed to describe the seasonal cycle of temperature and salinity variation in Massachusetts Bay. The annual temperature cycle in the Bay includes the development and decay of stratification, but this is felt mostly in waters deeper than at the hypothetical mine site. Winter temperature and density conditions are vertically mixed with no stratification. The isothermal temperature minimum occurs in February at 0 to 3° C. The vertical gradient anywhere in the Bay in February is normally less than 1°C. Warming through April gradually raises the gradient to about 2° C, at which time the gradient is still diffuse and restricted to the upper 30 m. In June surface temperatures rise to 13 to 17° C, and peak in August at more than 20° C. Gradients increase to maximum strength during this interval; however, vertical mixing in the surface layer extends to at least 15 m depth, suggesting that it is only the very bottom waters at the site of interest which may feel the stratification effects.

Salinity at the surface ranges between 30‰ and 33‰, with the minimum occurring in May and the maximum in March. The mean bottom salinity ranges from 31.6 to 32.5‰. During vertical mixing in winter the average difference between surface and bottom salinity is 0.2‰ or less.

Currents in coastal waters are characterized by their time scales as mean currents, tidal currents, and higher frequency currents associated with turbulence and waves. The most obvious features are tidal currents that are frequently modified by the wind. The semi-diurnal tidal oscillation in Massachusetts Bay results in a mean tidal range of about 3 m. The flood tide sets westward into Massachusetts Bay, and the corresponding ebb is oriented northeastward to eastward. Tidal currents have been measured 1 m above the bottom in various parts of the Bay. Maximum tidal current speeds occurring in the deep basin west of Stellwagen Bank, east of the mine site, were 26 to 29 cm/s, and were weaker than those over the Bank (32 to 47 cm/s).

The surface drift west of Stellwagen Bank is cyclonic, tending to follow the coastline southward south of Cape Ann into Massachusetts Bay, southward past the mouth of Boston Harbour, and then around Cape Cod and northward past the northern tip of Cape Cod. Bottom residual drifts are an order of magnitude slower than the surface drifts. In general these bottom drifts are oriented southward to southwestward over the inner part of the Bay.

As part of the activity within NOMES a survey of current directions, velocities and dispersion rates was undertaken over two days in late July 1972. Rhodamine dye was introduced and tracked by vessels and aircraft. Surface and subsurface drifters were also deployed. In total, 18 drogues were tracked. The currents in the area of the proposed mining site possessed a southerly component of velocity during the early stages of both flood and ebb. Average velocities were 27 cm/s (shallow drogue at 1.5 m below surface) and 11 cm/s (deep drogue at 9.0 m below surface).

Experiments were conducted at the NOMES site (Hess and Nelson, 1975; Nelson *et al.* 1977; Mayer, 1975) to predict the fate of a discharge plume from the proposed mining site. These investigations were reviewed by Padan (1977). To simulate the dispersing plume 2700 kg of fine particles (0.5 to 50 μm diameter) were released to the water surface in the form of a slurry simulating the overflow of a hopper dredge. The movement of the resultant plume was traced by drogues for ten days, and the plume was sampled for temporal and spatial distributions of particles.

During the month of the particle dispersion experiment, a strong north-south current shear zone was observed. The mean motions within 10 km of shore were predominantly northward, beyond that, the motions were exactly southward. The investigators concluded that in this experiment east-west tidal motion transported the tracers through the sharp current shear zone, into the southerly flow. They note that it is quite conceivable that the whole experiment could have evolved differently if the tracers had been deployed at different times, and on different phases of the tide. Conclusions are that very site-specific, local conditions, with short time and length scales, had significant effects on the large-scale results of the experiment. Basic conclusions of the work were that dispersion of the particle plume was contingent on (1) the tidal phase at the time of introduction; (2) the seasonal stratification of the water column; and (3) transient storm effects. The NOMES dispersion experiment was a unique attempt to deal empirically with marine mining dispersion issues, and offers important guidance for any such similar investigations that might be undertaken at other sites in the future.

3.4.1.2 Market-based Determination of Annual Output

Sand and gravel production is a market-driven industry. The production scale is determined by the total market size and the expected market share. Product quality is all important. Given that:

(1) the population of greater Boston is about 2.0 million

(2) the U.S. national average aggregate consumption is about 3.2 metric tons per person per year

(3) the per capita aggregate consumption in a U.S. urban concentration is probably twice that overall nationwide, and

(4) the management of a new operation would probably seek to achieve a 25% market share

therefore the possible annual production from Massachusetts Bay is 3.2 (2.0 x 3.2 x 2 x 0.25) million tonnes per year of aggregate (mixed sand and gravel). Assuming a factor of 0.75 m^3 of aggregate to 1.36 metric tons, the annual production is (3.2/1.36) x 0.75, equivalent to approximately 1.8 million m^3/year.

3.4.1.3 Deposit Details

Details of the dredging area are provided on pages 55 to 62, and 64 to 65 [Table 22], inclusive, of Padan (1977) (see Appendix 5). The location within the 3 mile limit offshore from Boston is shown in Figure 3.20.

The deposit is part of a complex mixture of glacial products very similar to that offshore Nome, Alaska. It is described on page 60 of Padan (1977). Bedrock is overlain by ".... glacial till, a heterogeneous mixture of boulders, gravel, sand, silt, and clay ranging in thickness from a thin veneer to nearly 30 m. Two marine clays, separated by an erosional unconformity, overlie the glacial till" and "the NOMES deposit appears to be a gradational feature resting on, and yet geologically part of, the upper marine clay. " The surficial veneer of "sand and gravel" has been investigated by vibrocore at 32 sites. The lithology changes rapidly over short horizontal distances and with each vertical metre below the seabed, as shown by the 3 figures on page 59 of Padan (1977) (Appendix 5).

The dimensions of the square area illustrated on page 59 of Padan (1977) are 4.25 x 4.24 km. A mixture of "gravelly sand", "sand", "mud", and "muddy sand" underlies the 1.5 m-thick main body of surficial "sandy gravel" (surface dimensions approximately 3.5 x 1.0 km). The volume of sandy gravel is therefore 5.25 million m^3 (3,500 x 1,000 x 1.5). Similarly, Padan (1977) states on page 58 that there are probably "...over 5 million m^3 of sand and gravel..."

It may be assumed that in reality the variation and distribution of the different lithologies is more complicated than is shown on page 59 of Padan (1977). The complexity is a function of the sampling density (approx. 0.10 km^2 per vibrocore sample) and the line spacing of the side-scan sonar survey (approx. 185 m). Some of the complexity visible on a 3 x 3 km scale may become visible during production on a 0.5 x 0.5 km scale. All the lithologies listed in Table 21 on page 57 of Padan (1977) will be dredged because the dredging operation cannot be too selective if costs are to be contained.

It should be noted that the proportions of "sandy gravel", "gravelly sand", "muddy sand" "sand" and "mud" that will be dredged during production can only be grossly estimated at this stage. Whatever the blend of "soils" brought on board the dredge there will be a mud content of 0 to 33.5%. This statement remains true even if selective dredging is 100% successful and only "sandy gravel" and "gravelly sand" are excavated. No precise definitions are given for the different lithologies but presumably they conform to standard definitions. The area will require more exploration before it could may a production site.

3.4.1.4 Daily Production Rate

Assuming 7 months of operation per year (because of the frequency of adverse sea conditions in the winter), and 25 days of operation per month (i.e. no Sunday working) then the daily production rate is 10,286 m^3/day [$1.8 \times 10^6/(7 \times 25)$], equivalent to 18,000 tonnes/day.

3.4.1.5 Project Life

The potential dredge area reportedly comprises about 5.25 million m^3 of sand and gravel in water depths of less than 18 m. Assuming that 100% extraction is achieved, then the productive life of the deposit is 2.9 years. The minimum required project life is 10 years, and preferably 20 years or more. Therefore, in practice, additional or (more likely) alternative dredging sites will have to be found before the project is started.

3.4.1.6 Dredging and Production Methods

The type of dredge to be used will be an ocean-going trailing suction hopper dredge (Figure 3.21). The methods of excavation, shipboard treatment, and onshore processing of the sands/gravels are described on pages 112 to 116 of Padan (1977). The dredging method adopted will be the pre-determined movement of the dredge along prescribed lines, backwards and forwards across the area designated. The dredged furrow remains as a shallow trench, the dimensions of which depend on the size and specifications of the single or twin drag-head. An area may be dredged several times creating overlapping, adjacent, and/or coincident furrows.

The dredge product is optimized according to market requirements by selective dredging, if possible, on-board sorting of the dredged sediment and onshore processing of the landed sand/gravel. Selective dredging may take the form of either returning all the dredged material intermittently to the seabed if it is unsuitable, or attempting to define sufficiently large areas of consistent sediment.

On-board sorting takes the form of allowing the fines (disintegrated, dredged "mud") to overflow the dredge hopper into the sea as dredge effluent. Alternatively, if there is too much fine sand (determined by marketing requirements), screening the dredged sediment will immediately return both fine sands and fines to the sea (Figure 3.22). Onshore processing usually comprises washing to remove salt and any remnant fines, and screening for products of different size characteristics.

Another approach might be to use, instead of a self-propelled hopper dredge, a barge propelled by a tug in the notch. The "Long Island" (formerly the "Ezra Sensibar") is an example of such a design and is shown in Figure 4 of Padan (1977) (Appendix 5). It is possible to use one 3,000 h.p. (2,237 kW) tug and two barges. The tug may be leased because it is not required during the winter.

3.4.2 Dredging System

The basic system will be a self-digging barge (integrated digging and transport) similar in capacity and dimensions to a Great Lakes Dredge and Dock Co. barge. It will be an ocean-going, trailing suction hopper dredge. Features of the dredge are given in Table 3.21.

3.4.2.1 Dredge Pumping System

A range of performance is possible with different sediments as shown in Table 3.22.

3.4.2.2 Effluent

As determined above, the rate of effluent discharge is 170,300 l/min. when dredging fine gravel and sand, and 257,400 l/min. when dredging coarse gravel. Generally, one would expect the discharge to vary within these limits. The fines effluent contains solid particles which are -200 mesh (-80 microns) in size. Normally, less than 10% (3.8 to 6.2%) of the soils dredged and delivered to surface are discharged at sea as effluent overflow. For the purposes of this scenario it is assumed that no screening is undertaken at sea. However, the high reported mud content of the NOMES deposit may result in a range between 0 to 33.5% of the solids being in the reject category.

3.4.3 Dredging Cycle Times

3.4.3.1 Loading

For each 1 m of dredge advance the drag-heads each excavate a furrow 2.7 m wide and 60 cm deep, i.e. 1.6 m^3 in volume. Two such drag-heads excavate a total of 3.2 m^3 per 1 m of dredge advance. With a dredging speed of 6.5 km/h the hourly advance is 6,500 m, resulting in excavation rate of 20,800 m^3/hour (6500 x 3.2). Therefore, the time required to load 5,100 m^3 (trip capacity) is 15 minutes (5,100/20,800 hours). If the cut depth is reduced from 155 to 77.5 cm then the loading time is increased from 15 minutes to 30 minutes. Allowance for other factors and activities increases the loading time to approximately 75 minutes.

3.4.3.2 Unloading

Assuming that discharge is effected with an 11.4 m^3 capacity clamshell with a cycle time of 1 minute then the number of cycles needed to unload the vessel per trip is 447 loads (trip capacity of 5,100/11.4). The unloading time is 7 hours and 27 minutes.

3.4.3.3 Travelling Time

Assuming that the travelling speed from the digging area to the discharge point is 11 km/h and the distance from the digging area to the discharge point is 28 km then the travel time in each direction is 2.5 hours (28/11) each way.

3.4.3.4 Total Time

The total cycle time, estimated from the above assumptions, is 13 hours 42 minutes. This time could be reduced to 8 hours 54 minutes by increasing the travelling speed and reducing the unloading time by using a larger, 20 m^3, clamshell for unloading (Table 3.23).

3.4.4 Number of Dredging Units Required

Using the figures given in Table 3.23 the number of dredging units required is 1 unit (with a night shift worked) or 2 units (with no night shift worked).

3.4.5 Costs

The landed sales price of washed and screened aggregate in Boston is reported to be $5.50 per tonne (equal to $9.87/$m^3$) and from two other independent sources that the price is $9.21 and $ 10.52/m^3. Assuming a capital cost of $25 million, a project life of 10 years, and a production rate of 1.8 million m^3 per year, equating to a cost of $1.41/$m^3$, then a required profit of $1.97/$m^3$ leaves $6.49 per m^3 [$9.87 - (1.41 + 1.97)] for cash working costs, including overheads and fixed costs.

3.4.6 Possible Problems

Possible problems include:

(1) the selected dredging site is inside the 3 mile limit

(2) the ground is of glacial sands/gravels with a high mud content

(3) the deposit has a limited productive life

(4) no obvious aggregate storage area exists if the product has to be stored during the winter.

3.4.7 Seabed Biodiversity and Resources

3.4.7.1 Locality and dredging characteristics affecting benthos

The Massachusetts Bay scenario is an extensive and low selectivity dredging operation, therefore all the very different lithologies present from mud to gravel (see Appendix 5, Fig. 5, Tables 3 and 4) are liable to be dredged. Trailer dredging creates paired, 3 m-wide furrows of at least 1,000 to 2,000 m length, with the pairs of furrows 8 m apart. Multiple series of these lines are produced, some of which overlap. Environmentally significant operating and mining parameters for the dredge operation are given in Tables 3.24 and 3.25.

According to Padan (1977), "for each cubic metre of sand and gravel extracted, approximately 10 m^3 of bottom also would have been withdrawn during the planned operation. During each of the planned 2-hour mining cycles, approximately 370 m^3 of fine material would have been discharged from the dredge......Roughly 250 km^2 of the sea floor was expected to be covered by fine sediment to a depth greater than 0.01 m." The proposed mining scenario will last longer, and spread impacts over a greater area.

3.4.7.2 Benthos Pre-dredging

The fauna of the Massachusetts Bay area were documented by Padan (1977) during the summer of 1973 (see Appendix 5, Tables 5 to 7, and 13). The biodiversity was rich and variable with differences between epifauna on hard rock (including on exposed cobble surfaces) and the burrowing infauna. Padan (1977) described habitats of hard, cobble, sand and mud substrates. Over 650 species were sampled. The number of species per station ranged dramatically, from 31 to 146 per station, as did the number of organisms/m^2, from 305 to over 11,000. Sedentary polychaete worms (filter feeders) dominated on most substrate types, but rankings for specific stations showed errant polychaete worms (carnivores) and amphipod crustacea (omnivores) dominating at some sites. Ranking by feeding guilds showed some dominance of harder substrates by suspension feeders and of softer substrates by deposit feeders.

The species complexes found at different substrate types differed but statistical correlation with deposit type was not possible. The temporal variation was enormous from month to month, making the use of dominant species only possible at specific site locations that cannot be generalised to a substrate level. Padan (1977) recommended that if further pre-mining sampling is carried out then fewer, less frequently sampled stations are needed, but that more replicates per station should be taken to better understand the patchy distribution of the benthos. It also noted that the different benthic communities might be better described if both numbers of organisms and biomasses were recorded. Another possibility is to characterize differences by monitoring feeding guilds as in Table 8, Appendix 5.

3.4.7.3 Benthos Post-dredging

Benthic communities directly in the path of the dredge are destroyed. The benthos in undredged areas between the furrow lines (8 m apart) are affected by the increased turbidity and sedimentation. The impacts depend on the depth of sediment that accumulates and depth of the furrows. Some benthic communities can survive tailings sedimentation rates of at least 1 cm per year (Island Copper Mine, 1994 and see Section 2.3).

Unlike those scenarios in which most of the extracted sediments are returned to the seabed, during the dredging of aggregates a substantial percentage is removed. This changes the particle size characteristics of the remaining deposits. Larvae that recolonize the altered environment reflect these changes. It is probable that the silt/clay fractions will increase in the dredged area because the coarser sediments are retained by the dredging process.

Soft-bottom communities should recover faster than communities found on coarse sediments, or than the epifauna on cobbles and boulders. Expected times to recovery can be based on data in Kenny and Rees (1993; 1994), and ENSR (1991) with summary data in Appendices 3 and 6 respectively. These data suggest times to recovery of 1+ years on deposits with least cobbles, with slower recovery where substantial cobbles are removed. The observed recovery time of 4 to 5 years at the Nome, Alaska site may be indicative of recovery of the coarsest areas and their associated epifauna. It is to be expected that infaunal benthos reproducing by pelagic larvae will start to recolonise during the next larval settlement stage after closure, and that there will be substantial recovery of some of these forms within a year. However, based on experience gained in the U.K. aggregate dredging industry in the North Sea (Kenny and Rees, 1993; 1994), it is to be expected that the epifauna of hard rock and cobble will recolonise more slowly than the infauna of soft deposits. This appears to be a function of reduced surface area for attachment of hard rock epifauna attachment related to the depletion of cobbles and boulders. However, such "hard rock organisms" generally are less available to feeding fish and shellfish, due to their ability to protect themselves by secreting cemented-down and non-removable shells.

The pattern of dredging is partially dictated by the pattern of recovery in the benthic community. The area between dredged furrows, not heavily impacted by the tailings disposal or affected by unstable sediment, may allow some degree of localized recolonisation of species that do not have a planktonic stage.

There may be a release of nutrients and/or toxins from the disturbed deposits. The toxins may be derived from sulphur-reducing deposit conditions (see Section 2.2), or directly from human waste disposal systems close to the area. In view of the proximity of the Boston urbanised area the latter is quite likely. The potential for toxin release needs to be determined by appropriate geochemical risk assessment in advance of mining.

3.4.8 Biological Oceanography

During aggregate extraction the sand and gravel fraction is retained but silts and clays are returned as tailings to the sea. Discharges include overflow washing from the dredge hopper, and also unsuitable sediments (high in fines) may be discharged to the sea. These may contribute to substantial surface and water column turbidity downcurrent from the dredge.

Turbidity at the seabed produced by the trailing drag-head suction dredge is expected to be low, and will not significantly affect the water column. The narrow dredge furrow area and shallow highly oxygenated waters make water column changes unlikely as a result of oxidation of exposed sediments.

Losses in primary production due to light scatter (see Section 2.4) are a possible result of increased surface turbidity. However there is little likelihood of impact on planktonic organisms because of ephemeral exposure to a dispersing turbidity plume (Section 2.4). In some cases plankton may actually benefit from increased feeding because of organic materials bound to the particles. Species shifts have been correlated with high turbidity levels (Section 2.4), although it is not clear that this would be deleterious.

3.4.9 Fisheries and Wildlife Resources

The NOMES report mentions only briefly the resource species of the area. In a proposed mining scenario the pre-mining stock and life cycles of resource species of commercial and recreational importance must be investigated. The resource species are obviously diverse and support substantial local commercial and recreational fishing.

Experience elsewhere suggests that on a regional scale, overall fish stocks are not likely to be significantly altered. However site specific stocks of gravel-spawning fish like herring could be affected over the long term (Drinnan and Bliss, 1986; Oulasvirta and Lehtonen, 1988). During dredging operations commercial fishing presumably is not able to proceed in these areas. Some species may be attracted to the dredging sites and, during temporary (seasonal?) dredging-related closure, commercial fishing may restart. The seasonal nature of some local fishing and eco-tourism (marine mammal/bird watching and sports fishing) industries may conflict directly with dredging, effectively eliminating them around the site.

Rock scallops, like the blue mussel, may be sensitive to elevated levels of siltation. The eastern lobster (*Homarus americanus*) seems capable of tolerating a fair degree of siltation. But in laboratory experiments their larval stages have been shown to be sensitive to unnaturally high levels of kaolin clay and finely ground quartz in the water column and may not survive in their presence (Cobb, 1972). This may also be true for other commercial groundfish. Some of the commercially important groundfish like cod and winter flounder are known to be attracted to sediment plumes caused by mechanical clam digging, possibly attracted by the large numbers of benthic organisms stirred up into the water column (Padan, 1977).

A lack of resource information for both the aggregate dredging and fishing industries can limit the planning process (Drinnan and Bliss, 1986). It is important to map the breeding grounds and migratory routes of all potentially commercial resource species before extraction takes place (Oulasvirta and Lehtonen, 1988).

3.4.10 Prediction of Environmental Impacts, Setting of Mitigation Objectives and Achievement Criteria for Scenario 3

3.4.10.1 Prediction of Environmental Impacts

Apart from the expected impacts (described in Section 2.7) there is the site-specific consideration that the surficial geology is variable. Thus a main impact will be from surface turbidity plumes from the dredge due to the separation of fines from the aggregate, from hopper overflow and from discharge of unwanted sediment. Dredging will destroy benthos on the seabed, and the overflow discharge of silt and clay particles may alter the habitat. Consequently a different benthos can be expected to recolonise than was previously present, and the substrate change may affect the variety of fin-fish and shellfish species present. An Environmental Impact Statement will be needed.

3.4.10.2 Mitigation Objectives

Mitigation objectives should include:

(1) reduction of dredge-derived turbidity through improved outfall design and vessel operations

(2) development of alternative enhancement uses for under-sized and over-sized fractions

(3) return of fines to the dredge footprint.

3.4.10.3 Achievement Criteria

The following criteria should be satisfied during dredging:

(1) EPA turbidity criteria for minimizing impact on primary biological production, as described in Section 2.7

(2) development of benthos recovery in the dredge footprint, as described in Section 2.7.

3.5 Scenario 4: Heavy Mineral Sands, Virginia

3.5.1 Mining Scenario

This scenario describes a hypothetical heavy mineral dredging operation in Federal waters offshore of Virginia Beach, Virginia. The complex subjects of market share and of product suitability and pricing to determine the scale of an operation are not considered in this scenario.

3.5.1.1 Marine Conditions

Quantitative measures of surface and subsurface currents offshore from Virginia Beach, just south of Cape Henry, are contained in a report by Boicourt (1981). The two studies in this report are instructive in assessing the potential for transport of sediment produced from marine mining activity in this location. In defining circulation in the Chesapeake Bay entrance region Boicourt (1981) analyzed the results of eleven vertical arrays of current meters and temperature/salinity recorders deployed in the Bay entrance and on the adjacent inner shelf during the early months of 1979. These measurements were later supplemented with data from an additional twenty moorings deployed in summer 1980. Of relevance to the mining site is Boicourt's winter 1979 site, MF6 (36° 52' N by 75° 57' W), in about 10 m water depth, about 3 km directly off the northern end of the city of Virginia Beach. Key findings of earlier work were that (1) as the Chesapeake Bay low salinity outflow rounds Cape Henry, it turns to the south and flows as a quasi-geostrophic jet along the Virginia and North Carolina coasts (Boicourt, 1973), and (2) the inner shelf of the Middle Atlantic Bight, away from the mouths of estuaries, is dominated by wind forcing (Boicourt and Hacker, 1976). The 1979 and 1980 measurements corroborate this earlier directional evidence, and provide representative speed values. Specifically at mooring MF6, the mean velocity for a 240 hour interval in February 1979, at 5.8 m depth, was 10 cm/s oriented exactly parallel to the coast, and flowing consistently southward under the influence of both the outflow coastal jet and of the winter winds. Boicourt provides no detail as to extreme near-bottom current speeds.

In the summer 1980 measurement program, the nearest relevant mooring (MF7) was located further offshore at the same latitude as the winter mooring (MF6). Located 9 km offshore (at 36° 52' N by 75° 53' W) in 16 m water depth, mooring MF7 had current meters at 3.7 m and 13.1 m depth. Over a 38-day interval beginning in late June 1980, the near surface mean flow was parallel to the coast, flowing southward at 6 cm/s. The deeper, near bottom mean flow at 13.1 m was of slightly greater magnitude (8 cm/s), but was oriented towards the north northwest, flowing into Chesapeake Bay. These flow velocities suggest that there is insignificant energy in the nearshore, near bottom currents, and such currents would probably restrict the horizontal advection of particulates entering the water column as a result of marine mining activity. However, the directional consistency of the nearshore winter mooring (MF6) suggests that any sediment plume evolving from mining activity off Virginia Beach might be expected to be asymmetrically elongated in the downstream (southerly) direction.

Current measurements analyzed and reported by Ludwick (1978) provide more of a quantitative understanding of flow conditions on the nearshore shelf directly offshore from the city of Virginia Beach. Data were collected between July and October 1973 along a band paralleling Virginia Beach 3.5 km offshore, just seaward of the littoral zone. The original purpose of the measurements was to support environmental studies for a proposed ocean outfall at Sandbridge, Virginia. The analysis described by Ludwick (1978) makes use of these early data to consider sediment transport potential in the circulation off Virginia Beach. Locations of the six measurement sites are displayed in Figure 3.23. Descriptions of water depth, distance offshore, and vertical depth for each instrument are presented in Table 3.26. Key results of the analysis, including both vector mean and measured maximum current values for each instrument record, are given in Table 3.27.

Figure 3.23 shows that Site 1, at the mouth of Chesapeake Bay northeast of Cape Henry, is possibly situated in a different flow regime from the remaining five sites. Statistics of most interest are those from Sites 2 through 6. At all but one of these sites the surface maximum values exceed 51 cm/s, ranging from 52.1 cm/s at Site 5 in October to 79.6 cm/s at Site 6 in October. The only maximum value less than 51 cm/s is 42.3 cm/s at Site 4 in July/August. Near bottom, the measured current maxima generally fall between 25 to 51 cm/s. Extreme values reach 66.8 cm/s at Site 6 in October. The directions associated with most maximum speeds are oriented towards the southeast or south. There is greater directional variability in the occurrence of extreme flows near bottom than near surface. Vector mean current speeds are as much as an order of magnitude less than the extreme speeds and are evidence of the rotary nature of tidal currents in this shelf region. Ludwick (1978) noted that "... tidal currents are rotary, with long ellipse axes approximately parallel to the shoreline ... Maximum tidal current speed decreases with distance to the south away from the entrance to Chesapeake Bay".

Applying temporal filtering techniques to the very thorough set of current measurements described by Tables 3.26 and 3.27, Ludwick (1978) assessed the implications for sediment transport. He concluded that "... north-directed sediment transport in the littoral zone off Virginia Beach exists along with a south-directed intermittent sand stream on the sea floor farther offshore in a zone approximately 5 km in width extending from, say, 8 - 15 m depths". The implications of these measurements and analyses are significant to the present work. It is clear that any mining operation in 10 to 20 m water depth off Virginia Beach will be subject to considerable longshore sediment transport due the strength and orientation of local tidal currents.

Dredge planning must take into account both the possibility of sediment transport due to coastal currents and the local wave climate. Regional data from Meserve (1974) (Figure 3.3) provide estimates of the frequency of occurrence of waves above certain height thresholds, applicable to the entire shelf region offshore Virginia and Maryland. These statistics are expected to over-estimate the severity of the nearshore wave climate. Data presented by Maa (1993) describe wave conditions at Site CHLV2, located on a shoal (approximately 36° 55' N by 75° 43' W), some 20 km directly offshore Virginia Beach, in 12 m water depth. Surrounding water depths are typically 20 m. Figure 3.24 displays the wave height exceedance curve for this location over the interval February 1985 to December 1992. The curve was developed from a joint distribution of significant wave height versus peak wave energy period. The log-normal plot allows easy interpretation of the probability of occurrence of extreme wave heights. Exceedance values for lesser wave heights, scaled from a linear version of this plot (not displayed) are given in Table 3.28. These values, derived from almost eight years of wave measurements provide an excellent representation of the severity of the wave climate on the nearshore shelf. It is immediately clear that the statistics quoted from Meserve (1974) are significant over-estimates of the wave climate severity very near to the coast.

3.5.1.2 Deposit Details

Details of the deposit are taken from Berquist and Hobbs (1988). Grab sample data only are available for the area immediately offshore Virginia Beach, but the results of 60 vibrocore holes (25 by the Minerals Management Service and 35 by the U.S. Geological Survey) are available from the general offshore vicinity.

3.5.1.3 Deposit Thickness

Thickness of the deposit is defined from core data reported by Berquist and Hobbs (1988) (Table 3.29).

3.5.1.4 Grade

Berquist and Hobbs (1988) stated that "The total heavy mineral concentration for all samples averaged 3.5% and the highest value was 14%. Offshore sediments....... average about 30 feet [9 m] in thickness" and ".....economic mineral occurrences exist on the inner continental shelf" (page iv, abstract). However, the data presented in the report do not appear to support the above statements without major qualifications. The area immediately offshore Virginia Beach has been subject to grab sampling only, a technique which does not indicate the grade over any significant depth. The above-mentioned vibrocoring results provide the best basis for measuring the realistic deposit parameters. Weighted for core length, vibracore results reveal an average total heavy mineral (THM) content of 2.91%. However, an incremental analysis (1 m vertical intervals) reveals that the THM content is 3.65% in the uppermost metre. The THM content decreases steadily with increasing depth below the seabed, and the incremental THM content, on average, falls to slightly less than 3% (the grade most probably required in such an offshore operation) at a depth of 4 m.

3.5.1.5 Grain-Size Distribution

Characteristics of the uppermost 4 m of sediments are given in Table 3.30. There is no calcification of the sands, compared with cemented layers often encountered during on-land dredging for heavy minerals (personal communication, Carl Hobbs, Virginia Institute of Marine Sciences). On-land dredging of cemented sand layers ("hard-pan") results in a swell factor of 20%. Two different drilling contractors were used, each achieving the same results; the clay recovered in the cores occurs in thin beds about 2 cm thick and is very sticky and sometimes very stiff.

3.5.2 Dredging and Production Methods

There are 3 components to the excavation and treatment of the heavy mineral bearing sands:

(1) the excavation of the sands and their delivery to surface

(2) the first treatment, at sea (completed in the "wet mill"), whereby oversize is screened off and a heavy mineral concentrate is separated from the undersize

(3) the final treatment ashore, in the "dry mill", to produce the saleable products, determined by mineral constituent and grade.

3.5.2.1 Dredge

The dredge is a 68.6 to 76.2 cm-diameter cutter suction type, with a throughput of 115,000 to 150,000 l of slurry per minute (Figure 3.25). Two possibilities exist for mounting the cutter in the prevailing water depths of 12 to 15 m, beyond the 3-mile limit: (1) a floating pontoon with a cutter suction arm in which the dredge is secured by a 5-anchor spread, with the headline providing forward pull and the sidelines dictating the arc through which the cutter moves, or (2) a jack-up platform, capable of remaining on-site through all storms, and from which the cutter arm is deployed. The choice is open to discussion, but is decided by the comparative availabilities achieved by each system, depending on the relative performance under inclement weather conditions and the relative time lost in moving forward.

The minimum practical cut that may be taken by the specified cutter suction dredge is 3 m. For this scenario the average cut is assumed to be 4 m, with isolated areas extending to 5 - 6 m. Any ground with a payable total heavy mineral content extending for less than 3 m below the seabed could be unpayable.

3.5.2.2 Wet Mill

The wet mill is installed on a separate pontoon about 300 m astern of the dredge (or the jack-up platform). The wet mill pontoon is approximately 10 times the size of the dredge pontoon. The flowsheet commences with screening, with closed circuit crushing if any cemented sands exist. Screen undersize of < 6 mm is fed to rougher spirals. The resulting concentrate is passed over cleaner and finisher spirals, the rejects from which are re-cycled. The rejects from the rougher spirals are rejected.

The wet mill has a feed capacity of 2,032 tonnes per hour of THM-bearing sands, being all the cutter suction product conveyed by pipe line, and yields three "products":

(1) a heavy mineral concentrate (~75% THM) from the finisher spirals, amounting to 4 to 5% of the feed, which is transported ashore for processing in the dry mill

(2) a trommel oversize, usually > 1.25 cm (and amounting to about 5% of the feed if a cemented sand "hard-pan" exists), discharged into the sea

(3) the balance of the feed as an effluent, being all sediments < 0.6 cm and amounting to about 90 - 91% of the total solids feed (95 - 96% if there is no trommel oversize), discharged into the sea.

It should be noted that excess water, perhaps half the wet mill feed, possibly requires removal from the flowsheet by means of cycloning ahead of the rougher spirals. Most of the -200-mesh particles accompany the excess water. The heavy mineral concentrate is transported ashore at regular intervals by a separate vessel which is also used for crew changes.

3.5.2.3 Dry Mill

The heavy mineral concentrate is treated ashore in two stages: (1) scrubbing with NaOH in scrub tanks to remove surficial mineral coatings, and (2) dry magnetic separation to yield separate products of ilmenite, leucoxene/rutile, staurolite and zircon.

3.5.2.4 Tailings Disposal

Tailings could be disposed of as follows: (1) from the wet mill at sea, tailings could be pumped ashore for beach rejuvenation, provided that the material is within the required size and quality specifications; (2) from the dry mill on land, tailings could be trucked to the beach for rejuvenation purposes.

3.5.3 Seabed Biodiversity and Resources

3.5.3.1 Locality and Dredging Characteristics Affecting Benthos

The proposed dredging is a fairly large scale operation, with a high throughput of well-sorted sands (2,000 tonnes/operating hour). Only 4 to 5% of the sediment dredged is kept as concentrate, with the balance returned to the seabed as tailings. Most of the excavated sediments could be replaced at or near the site of dredging. Environmentally significant operating and mining parameters for the dredge operation are given in Tables 3.31 and 3.32.

3.5.3.2 Benthos Pre-dredging

It is expected that these sands will have a high biodiversity, as is usual at this latitude and water depth. In the old terminology of Thorson (1957) the area would be expected to have a sand-bottom *Venus* community. At this site prior human disturbance has probably erratically introduced contaminants or otherwise rendered the ground unsuitable or even dangerous for dredging. There are dump-sites and areas of other uses indicated on hydrographic charts (Figure 3.26), and the benthos will probably show localized impact from these uses. These effects must be determined by site-specific baseline surveys.

On this exposed coast the benthos may have been subject to frequent natural as well as anthropogenic disturbance. The area is close to a Navy firing range and a dump site for dredged material is located nearby. A disturbed area such as this may show even more than normal variation between sites. Extensive pre-dredging sampling is needed to show if there are areas of recent disturbance with little benthos, stable areas with a normal variability of the fauna, and areas in which elevated levels of benthos may occur due to enhancement effects of the nearby disturbance (Poiner and Kennedy, 1984). The site's close proximity to the City of Virginia Beach may pose further stresses to the environment from sewage, storm drain and industrial runoff. Existing status of fishery and fish-nursery must be documented by an appropriate literature search.

3.5.3.3 Benthos Post-dredging

Impact will come from a combination of the removal of substrate and then smothering from the large amounts of tailings. Impacts will be extensive, as experienced at the WestGold bucket ladder dredge operation (Section 3.2.4.3.), with time to recovery determined by the nature of the deposit and energy level of the site. In general terms recovery on sand beds can be expected within 3 to 5 years.

Benthos directly in the path of the dredges will be destroyed, and surrounding benthos will be affected by sedimentation and turbidity. Trenches will develop as will elevated areas but these should be smoothed from wave action and storms. Recolonisation should begin immediately. As studies in Alaska have shown, sandy bottom communities should recover in 3 to 5 years but the exact composition of the fauna will vary from place to place, and may not resemble the original fauna, or whatever is then present at the reference monitoring sites. Monitoring the nature of the recovery due to mining may be difficult because the area already may be affected by other anthropogenic influences, and these may continue to affect the site.

3.5.4 Fisheries and Wildlife Resources

Loggerhead turtles breed on beaches as far north as Virginia and breeding records should be obtained in case they are near the proposed dredge site. Groundfish should be able to move out of the way of the dredging operation. Fish may be attracted to the sediment plume to some degree. Fish which lay eggs in the sediment could have spawning grounds destroyed if they are present during the mining and those nearby may show a reduction in productivity. Invertebrate resource species such as crustacea and bivalve molluscs may show an initial drop in numbers locally, but should not be affected in the long term, with recruitment from surrounding areas.

3.5.5 Biological Oceanography

This project is very similar in concept and scale to the WestGold operation in Alaska (Scenario 1). As such the comments in Section 3.2.6 apply here. However, the shallow water (~ 15 m), action of longshore currents and the presence of humans in coastal communities complicate the issue. The visual effect of the mining operation will be obvious to residents, fishers and tourists. Over 95% of the dredged materials will be returned to the sea after treatment. If discharged to the sea surface this will result in an extensive surface turbidity plume which may extend down-current along the coastline for several kilometres.

3.5.6 Prediction of Environmental Impacts, Mitigation Objectives and Achievement Criteria

3.5.6.1 Prediction of Environmental Impacts

There will be a substantial turbidity plume produced by discharge of tailings (95% of extracted materials). This may have only slight effects on primary productivity (see Section 2.4), but will be highly visible if at surface. The return of large amounts of tailings to the seabed will smother benthos within and beyond the dredge footprint. Recolonization within a dredge course should have progressed to a biodiverse successional community within 3 to 4 years after final tailings deposition from adjacent dredge courses.

3.5.6.2 Mitigation Objectives

Objectives should include:

(1) minimization of surface turbidity (see Table 2.8)

(2) reduction of benthic impact by constraining tailings discharge to the dredge footprint and nearby

(3) development of an alternative enhancement project to remove previously-dumped material may be possible.

3.5.6.3 Achievement Criteria

Achievement can be measured by applying the water column, seabed and fisheries and wildlife criteria as given in Table 2.8.

3.6 Scenario 5: Beach Nourishment, Maryland

3.6.1 Mining Scenario

Ocean City's beach is eroded at a rate of about 1 m per year and requires replenishment, by agreement with the authorities, every 2 to 3 years. The program, one of flood protection, is funded 30% by the State, 65% Federally, and 5% by Ocean City. The length of beach subject to renourishment is from the Ocean City harbour northwards to the Maryland/Delaware line, a distance of about 9.7 km. The process consists of three stages:

(1) excavation of sand from an offshore site

(2) transport of sand to the beach which requires renourishment

(3) disposal of sand on the beach in an approved manner.

Ocean City has a harbour (Figure 3.27) with a very difficult entrance, even in good sea conditions, and water depths against the jetty are approximately 3 m. Weather is critical to the mining operation. Storms develop from the southeast but the waves approach the beach from the northeast.

3.6.1.1 Marine Conditions

As one component of a major 1989 hurricane protection project for the coast of Maryland (U.S. Army Corps of Engineers, 1989), nearshore wave conditions and natural sediment transport volumes for Ocean City were analyzed. This study provided the best available site specific information for characterising marine environmental conditions in this vicinity. Attention is focused on the nature of storms which generate maximum wave and surge, thereby affecting beach erosion. Sediment transport volumes are estimated, but no quantitative detail regarding the vertical distribution of currents is provided. Relevant observations from this work are summarized in the following paragraphs.

The Maryland coastline is subject to two distinct types of severe storms, hurricanes and "Northeasters" which cause high waves and which raise coastal water levels due to storm surge. The term hurricane refers to a tropical cyclone in which the winds spiral inwards toward a low pressure "eye", and in which maximum surface winds exceed 130 km/h. Hurricanes originate principally during the months of August through October. In most instances hurricane intensity has diminished considerably by the time such a storm reaches as far north as Maryland. The most severe storm type affecting the Maryland coastline is locally known as a "Northeaster". These storms occur frequently during the interval of September through March, and are characterized by strong onshore winds, predominantly from the northeast. Storms of this nature can stall in the region, or move slowly eastward, resulting in long persistence intervals for onshore winds, and consequently for severe waves. Storm population analyses undertaken as part of the 1989 work confirmed that due to the mid-latitude location of the Maryland coast, and to the particular orientation and offshore bathymetry

The choice of dewatering system depends on the characteristics of the material being handled, the volume to be treated, and the practicality of incorporation of the system on board the dredge with its inherent spacial and layout limitations.

No system provides a perfect separation between solids and water. In each case solid particles of less than a certain size will separate with the water. Hydro-cycloning generally extracts particles coarser than about 75 microns; finer particles remain with the waste water effluent. This is a significant limitation where the waste solids are predominantly clay-size. Hydro-cyclones have been used for dewatering on land-based dredges for thirty years but their employment has been directed towards the improvement of treatment plant efficiency. They have, however, proved to be useful in de-watering the tailings effluent from bucket ladder dredges.

Where sediments are predominantly silts the potential benefits to be gained from dewatering are minimal. Another problem is that the finer sediment becomes bulked in the process of separation resulting in some loss of the efficiency gained by use of the hydrocyclone (Maintenance Dredging, 1987). Solids collection sumps, like hydro-cyclones, benefit from their simplicity of design and have an application in some forms of dredging, such as the treatment of overflow water from trailer suction hopper dredges (Figure 4.5).

Having separated the solids from the water, various options remain for the dredge operator, for example:

(1) to discharge the solids and waste water simultaneously but independently from each other

(2) retain the solids for disposal or alternate use elsewhere

(3) attempt to recirculate either the water or the solids, depending on the volumes involved and the consequent, perhaps prohibitive, build-up in the system.

4.4.3.2 Optimization of Effluent Discharge System

A single dredge effluent may consist of a wide range of particle sizes from silt to small boulders, or the reject from the dredge may have been sized before discharge. The settlement of coarse material through the water column is dictated primarily by gravity. The movement of finer material is more complex. To design appropriate engineering responses with the objective of minimizing the effect of significant dredge effluent discharge, it is first necessary to understand the physical processes that dictate the fate of effluents discharged into the sea.

These processes are summarized here. Two basically independent processes dictate the fate of discharged particulates from an effluent stream: (1) sedimentation of the effluent from the discharge point to the seabed, and the three-dimensional dispersion of this material through the water column, and (2) the susceptibility of the deposited materials to be transported along or near the sea bottom in response to wave and current forces.

Effective mitigation of effluent dispersal is best achieved if prior knowledge is obtainable concerning the probable behaviour of the effluent stream in a mining operation prior to the design and implementation of mitigative techniques. Such knowledge is most readily gained through the application of numerical models. Hence the modelling of sedimentation and of potential sediment transport constitutes a practical first step in the mitigation process. Variables that affect sedimentation and sediment transport are given in Table 4.1.

Discharge Design

Significant decrease of the initial velocity of effluent discharge and associated turbulence can be achieved through design modification of the effluent conduit. Success, however, requires an interactive process of full-scale experimentation at sea, monitoring, and model calibration for a particular site. One of the most important variables to be considered in the design of the discharge is its position relative to sea level.

Sub-surface Discharge

In any marine mining operation the most convenient and economical practice is to discharge effluents directly at the sea surface. However, this practice leads typically to high elevations of surface water turbidity and to broad dispersion of suspended particulates. Reduction of sea water turbidity and of the areal extent of solids deposition can be achieved by discharging effluents below the sea surface.

The depth of discharge below surface is critical. There are two basic design considerations: (1) sea state and the related potential for shearing of the effluent conduit, and (2) proximity to the seabed: where discharged effluents have a high initial velocity, sediment scouring and reflection of the effluent stream can occur if energy is imparted to the seabed, thereby generating excessive turbidity.

Discharge of dredge effluent below the water surface may be achieved in association with extraction technology, and yields significant environmental benefit when properly implemented.

Discharge Location

In some marine mining operations the on-board treatment process requires early segregation of the excavated sediments into different grain sizes, usually as a result of screening. The separated waste products are discharged as effluents into the sea at different locations depending on their point of generation in the treatment flowsheet.

If a large dredge is being used the discharge points may be separated by tens of metres. In shallow water the redeposition of the falling sediments on the seabed may reflect that separation. The forward and sideways movement of the dredge during its continuous operation therefore results in sediments, deposited by the most rear-mounted discharge, covering and obscuring the sediments discharged from more forward locations.

Thus, a seabed with an original lithology characterized by a mixture of fine and very coarse sediments may be converted by dredging into one of sand if the fine tailings are discharged at the stern. Cobbles and boulders may become completely obscured by sand tailings. Conversely, reversing the discharge locations may result in a modified seabed of cobbles and boulders.

The effectiveness of this technique is dependent on the grain-size distribution of the different effluents. Where there is a particularly high proportion of silt and clay any attempt at an ordered discharge is rendered ineffective. The residence time of fines suspended in the water column will far exceed the practical retention time of tailings in the processing stream, with the result that the entire seabed may finally consist of a thin cover of sand and silt.

4.4.3.3 Control of Discharged Effluent

Polymers

The residence time of solids suspended in the water column is mainly dependent upon particle size. Silt- and clay-size particles can remain suspended for time scales ranging from hours to days, and therefore have potentially wide-reaching effects. The settling time of fine-grained particulates can be accelerated through the use of organic polymers which come in two forms: organic flocculants and various coagulants.

Both organic and inorganic flocculants and coagulants work on the principle that charged ions attract and cause flocculation of particles with the opposite charge (Littler, 1990). Their addition improves the settling velocities of finer particles (Spargo, 1986). Groups of loosely-bonded particles, or flocs, behave in a manner equivalent to larger particles. Flocs thus have greater mass and faster settling rates. Colloidal matter smaller than 1 micron in diameter never settles but can be flocculated out of suspension (Littler, 1990).

Organic flocculants are relatively long chain molecules that have either positive or negative charge sites (Personal Communication, Mr. C. Pfleegor, Nalco Chemical Co.). They may be categorized into three groups: cationic (positively charged), anionic (negatively charged) and non-ionic (zero net charge). The charge sites attract the opposite charge sites on the suspended particles, pulling them together to form large flocs.

Flocculants are oil-based and are not ready for use in their delivered form: they must be activated by rapid mixing with clean water prior to use. A small amount of fast mixing of the polymer solution and the water is required to force the solid particles and the polymer together. Excessive mixing of the water and polymer solution can cause the floc to break up, resulting in less than optimum settling.

Coagulants are chemicals which, when properly used, make cloudy water look crystal clear. These chemicals are used by municipal water plants to clarify drinking water. Coagulants are water-based and are supplied "ready to use". Coagulants can be entirely organic, blends of organic and inorganic, or inorganic (e.g. aluminum sulphate, ferric chloride, and hydrated ferrous sulphate). The inorganic coagulants typically are acid-based and the contained, treated water usually requires a second chemical to raise the pH after the chemicals are applied (Littler, 1990).

The addition of coagulants causes destabilization of the electrical charges that generally allow particles to repel one another to form a stable system. Following destabilization, further mixing with flocculants is frequently necessary in order to encourage aggregation into larger particles (Spargo, 1986).

Flocculants cause suspended solids to settle faster than when conditioned with a coagulant. But, unlike coagulants, flocculants do not clarify the water. They are an important means for managing the silt- and clay-size fraction of dredge effluents, with the potential to reduce both the degree of turbidity and the size of the mixing zone in the sea.

Flocculating agents are currently used in some civil dredging applications and in certain forms of industrial waste-water treatment. Organic polymers have been employed for many years to accelerate the settling of silts dredged from the bottoms of lakes. They have also been used to clarify the slimes that collect in the ponds of land-based dredges. Although their application has been questioned on environmental grounds they are biodegradable and a number of flocculants have been approved for potable use. However, despite their use on land, it is likely that further research concerning the environmental implications of flocculants and their practical and effective use at sea will be needed before they are accepted as a viable mitigation option.

Silt Curtains

The use of silt curtains, vertically-suspended, weighted material used to contain fine-grained suspended sediments within a prescribed area, is a mitigation technique that has received wide use in connection with small-scale dredging and construction projects in inland waterways. The turbidity mixing zone created by a dredging operation can be reduced by using silt curtains to contain the plume within a specified area. However, the limitations and disadvantages of this system are considerable (Continental Shelf Associates, Inc. 1993):

(1) it cannot be used where the currents are more than 2 km/h

(2) noticeable waves and swell render it inoperative so that it can be used in only the most calm and sheltered sea conditions such as harbours and estuaries

(3) it is applicable only for small-scale, anchored operations

(4) it limits the maneuverability of the dredge

(5) being susceptible to rapid destruction in the open sea it constitutes not only a hazard to the seaworthiness of the dredge but also a potential danger to other shipping in the area.

Though it is frequently proposed as a mitigation technique for offshore marine mining, its potential application is extremely limited. With the exception of a modified form for Scenario 2, the use of a silt curtain is not considered as a mitigation option for any of the mining scenarios.

4.5 Remediation

4.5.1 Re-Dredging

Of the various effects of marine dredging only the remediation of changed seabed profile and seabed lithology are technically feasible. At the extreme a dredged area could be re-dredged to remove erratic topography caused by the previous excavation. Such an attempt probably would require the application of a different type of dredge from that used in the original mining and could never return the seabed profile and lithology to exactly the same original state. This method would be prohibitively expensive, raising the costs by about 100%. However, according to location, views differ considerably regarding the need to rehabilitate the seabed profile. For example, in Japan, where coastal trawling is not a popular fishing technique an irregular, undulating, seabed is not considered to be a problem. Marine aggregate miners are therefore not required to reclaim the sea bottom (Narumi, 1989).

4.5.2 Bed Leveller

Bed-levellers are seafloor-smoothing devices towed over the seabed by tugs or other smaller craft following the passage of a dredge which has either been working fine-grained sediments or has left behind a seafloor covered with mud and/or sand. Tolerances in the region of 10 to 20 cm are claimed in some situations but the operator may not always consider it economical to attempt such accuracy (Maintenance Dredging, 1987). Bed-levellers may have a wider application. For example, it has been reported that the system has been used successfully in the United Kingdom to flatten isolated outcrops of boulder clay by as much as 2.5 m (Van de Graaf, 1987). Another example was reported when a contractor successfully used a bed-leveller permanently fitted to a trailer dredge without experiencing any problems with propeller damage. Provided that a bed-leveller can be towed behind a dredge and operated simultaneously with the excavation process it could probably be applied usefully, perhaps mechanically combined with each individual drag shoe on a trailing suction hopper dredge.

4.6 Compensation: Alternative Enhancement

An advantage of the offshore mining industry is that dredges can be made available, when not otherwise occupied on mining projects, to undertake one-off projects such as reclamation, beach nourishment and coastal or offshore substrate stabilisation. In the United Kingdom such projects play an important role in establishing the present day economic viability of aggregate dredging operations (Nunny and Chillingworth, 1986).

A dredge engaged in recovering heavy minerals from an offshore sand produces huge quantities of fine and coarse sand as a by-product - the very same products which may be in short supply on an eroded beach nearby. Such a by-product thus may become a resource either for beach renourishment, removing the necessity for dedicated beach renourishment dredging or for use in the construction aggregate industry (Industrial Minerals, 1990).

Some examples of such imaginative applications which could benefit both the marine mining industry and address major environmental concerns already exist. One U.S. local authority is already pursuing a program to maximize the beneficial use of dredged material by creating a 9 hectare wetland habitat in West Galveston Bay. The scheduled dredging, through the Aransas National Wildlife Refuge, will also include the beneficial use of the dredged material to create and protect vital habitat of the endangered whooping crane (U.S. Army Corps of Engineers, 1992). There is, therefore, potential under certain circumstances for alternative enhancement projects which could be incorporated into a marine mining operation to compensate for environmental impacts associated with such an operation. Examples of such projects include:

(1) use of tailings for beach nourishment or the creation, restoration or protection and maintenance of coastal wetlands

(2) deployment of artificial reef materials and seabed landscaping for habitat enhancement

(3) remedial dredging of contaminated sediments.

(4) use of dredged-out pits for burial and capping of contaminated wastes or dredge spoils.

Ideally the by-product sediments, usually tailings, should be capable of simultaneous transport by barge or pipeline to the enhancement site. Flexibility in terms of ship maneuverability and discharge capabilities are obviously a distinct advantage (Nunny and Chillingworth, 1986). However, the dredging operation and requirement for reclamation material are not necessarily coincident in time, even if the relative locations are ideal. There may be a need to stockpile perhaps hundreds of thousands of tonnes of material produced by dredging until it is required for the alternative enhancement project. For stockpiling to be economic the temporary storage site usually must be in shallow accessible water where later recovery is facilitated and no irreversible environmental impact is envisaged (Maintenance Dredging, 1987).

4.7 Regulatory Mechanisms

Although the procedure for licensing of offshore mining is a subject in itself and beyond the scope of this report, the subject is of considerable importance when considering mitigation. The licence should stipulate what equipment may be used, how it may be used, and what measures must be applied in order to mitigate against the consequent environmental effects. Regulatory mechanisms constitute a form of mitigative measure by not allowing mining to start if such operations are capable of inflicting environmental damage.

The United Kingdom and Japan together account for about 85 % of the world's output of marine aggregates by offshore dredging. In the United Kingdom the production in 1990 amounted to nearly 25 million tonnes annually, equivalent to 16 to 17% of the country's total from all sources. In Japan, the leading producer, the equivalent figure is almost 40 million tonnes (Benbow, 1990).

4.7.1 International Examples

4.7.1.1 United Kingdom

In the United Kingdom the marine dredging activity is almost entirely for sand and gravel aggregates (> 5 mm in size). The industry is dominated by half a dozen major producers operating a total of about 50 dredges. Almost all of the dredges are of the trailing suction hopper design and the most modern additions to the fleets represent the state of the art in western European dredge design and construction.

Two types of licences are required: a prospecting licence, valid for 2 or 4 years, and a production licence. There is also a provision for the collection of a 1,000 tonne bulk sample (Webb, 1988). For a new licence to be granted the following factors must be taken into account (Fox, 1989):

(1) the likelihood, nature, and extent of conflicts with other users of the seabed (fishing, defence, and navigation interests)

(2) whether the residual seabed after exploitation will retain a suitable surface compatible with the original configuration

(3) the possible effects on the coastline and coastline stability

(4) the existence of an acceptable resource management scheme ensuring optimum use of the available materials.

The lead agency in the United Kingdom, the Crown Estate Commissioners, consults five government ministries plus about five agencies. Local authorities are also involved. There is a special procedure for minimizing the effect on ocean fisheries set out in the ministry's "Code of Practice for the Extraction of Marine Aggregates" (Nunny and Chillingworth, 1986) which requires the dredge operator to:

(1) maintain close communication between the dredge and the local fishermen

(2) restrict dredge operations to specific areas on a short term basis, thus allowing unhindered fishing over the majority of the licensed area (called the "strip grazing" principle)

(3) dredge the ground in such a way that, on cessation of dredging, previous fishing areas recover ecologically and become available again to the local fleet.

4.7.1.2 Japan

In contrast to that of the United Kingdom, the Japanese marine aggregates industry is highly fragmented, with, in 1988, about 250 companies operating approximately 450 dredges. Dredging is by clamshell, suction pump and booster pump with all the product being sand (Industrial Minerals, 1990; Narumi, 1989).

Registered Japanese companies may apply for either a provincial or a federal extraction licence: in both cases for one year and renewable. The provincial licence, however, covers only 1 km^2 in area and is non-exclusive. The federal licence requires the submission of a dredging plan and the completion of an environmental impact study.

Approval for the issue of a licence must also be given by relevant Japanese fisher's cooperatives, and an agreement is generally reached between each fishing organization and the mining company. Under such an agreement, which is not standardized, the cooperative receives a negotiated financial compensation for the dredging activities based on a charge per m^3 of sand extracted. The fishery organization then applies some of this compensation money to the modernization of the fishery (Narumi, 1989).

Of the several problems that need to be resolved in the Japanese marine aggregate mining business, the most important is the regulatory mechanisms. In particular, the required standards for application and approval have not been consistently established throughout the country. This deficiency, especially with regard to the various arrangements to be made with the fishing cooperatives, has destabilized the Japanese marine aggregate business and needs to be resolved (Narumi, 1989).

4.7.2 Requirements

4.7.2.1 Clear Jurisdiction

Some important guidelines, critical to the start-up and success of an offshore mining industry emerge from the experience of existing and previous marine operators in the United Kingdom, Japan and North America. The same guidelines, if followed, are more likely to ensure that the optimum mitigation techniques are researched and applied by the mining company. Their application is, in effect, one of the most important mitigation methods available (Table 4.2).

The U.S. Bureau of Mines' post-mortem on the WestGold marine gold placer project in Alaska constitutes an invaluable record of the agency-company relationship from both viewpoints (Gardner, 1992).

Permits issued to an operating company will impose monitoring and mitigation requirements. Ideally these should not involve, nor be perceived to involve, the application of double standards, especially in the forms and extent of mitigation required. One apparent standard for existing marine industries and another that is considerably more harsh in its standards for a contemplated or developing marine mining industry, would do little to encourage the further development of marine mining. Any suspicion that such a situation exists will discourage and deter potential founders of, or entrants into, the marine mining industry.

4.7.2.2 Data Availability

Application Review

The lead regulatory agency in reality has a double role: to determine the ability of the dredging company to develop appropriate operational plans, and to ensure that the company adheres to its plans, especially those for mitigation.

The forms of offshore mining described in this report are examples of marine placer mining. Experience of on-land placer mining has demonstrated repeatedly that the technical/financial risk lies in two areas: the reliable estimation of the ore reserves, and the correct selection of the most appropriate mining equipment (Garnett, 1996b).

Offshore exploration is more expensive and is more susceptible to error and misjudgment than on land, thus an exploration program designed to estimate the reserves in support of any application is vital (Fox, 1989). An inexperienced mining company, as a result of lack of appropriate experience, may tend not to award the necessary importance and funds to the exploration phase. As a part of the exploration program it is necessary to accumulate geotechnical information to assist in dredge selection.

The final result may be reduced operational profitability and a consequent lack of enthusiasm or inability to undertake the mitigative measures necessary, especially if the operating company is a small one. The extreme case is premature termination of the project, leaving some of the environmental mitigation programs incomplete. Such a scenario is particularly important when considering precious metal mining ventures offshore. Smaller organisations cannot easily compete in the marketing-dominated heavy minerals and aggregate industries, but face no such impediment in considering a small offshore gold mining venture. The role of the appropriately experienced consultant in the review of applications cannot be over-emphasized.

Data Collection

In the United Kingdom production licences are usually granted within 2 years of the application date. Denial or delay of a licence is often attributable to the inadequacy of the data supplied in connection with fishery and coastal protection issues rather than because of any official conviction that harmful effects will occur (Nunny and Chillingworth, 1986).

During the exploration and planning stage the baseline environmental data should be collected in support of a permit application. This stage is an ideal opportunity in which to gather data that may be directly relevant to both reserve management and eventual protection of the environment. Data collected for one is invariably of importance for the other: a further example of good mitigation techniques being synonymous with good engineering practice. For example, underwater photography should not only provide the necessary data concerning biota but may unexpectedly reveal the presence of problematic cobbles and boulders to be considered during equipment selection and design (Nunny and Chillingworth, 1986).

Information regarding ocean current direction and speed may allow the dredge course to be designed so as to minimize over-sanding (that is, the disposal of tailings on virgin ground). However, this is not an opportunity to impose unrealistic data gathering demands on the aspiring company. In the United Kingdom, for example, it is recognized that "With environmental data collection, the scale of any program needs to be closely tied to the expected level of return from the project " (Nunny and Chillingworth, 1986).

At all stages from permit application to post-mining, data measurement and its ensured reliability constitutes a weak link in the whole process of dredging (Maintenance Dredging, 1987). The deficiency manifests itself in three important and inter-connected subjects, for each of which a solution to the problem is necessary for the eventual successful application of mitigative techniques:

(1) baseline studies during the exploration phase

(2) environmental monitoring around the dredge operations

(3) dredge operation management.

A technical advance in measurement techniques applicable to one of the above is immediately and directly of benefit to the others. In recent years enormous improvements have become possible through the use of sophisticated instrumentation and electronics, and the ability of dredgers to monitor their production operations has been greatly improved. For example, continuous-reading in-pipe flow and density meters are now available (Bide, 1989). Several systems are now available which can give an accurate particle size distribution, within minutes, of both intake and effluent (Ports and Dredging, 1993a). For example, the visual size identification (VSI) system was developed to meet the frequent demand for a means of measuring oversize in a slurry flow. It does not provide definitive statements of oversize or product size distribution, but "produces regular feedback of trends as each sample is analyzed" (Quarry Management, 1990). Ultrasonic techniques are now available to measure water flow rates, and radioactive probes can determine concentrations of solids. The product of the two parameters yields the mass flow rate (Maintenance Dredging, 1987). Another major improvement of recent years is in navigational equipment. For the dredging industry continuous positioning is now possible through the Global Positioning System (GPS) (Ports and Dredging, 1992) the accuracy of which is at times remarkable but which varies from place to place.

Accelerating advances in computer technology have been accepted rather slowly by the generally conservative dredging industry. Computers allow more advanced data collection and monitoring (Taggart, 1992; Ports and Dredging, 1990c; 1989). A high degree of automation is now possible (Maintenance Dredging, 1987; Ports and Dredging, 1991a).

There are obvious advantages in the improved monitoring of slurry characteristics and aggregate quality in conjunction with knowledge of a dredge's accurate position whilst dredging (Bide, 1989). A continuous record of the quantity and nature of dredged material with the exact location from which it was dredged would be an essential management tool on board any dredge. It would provide invaluable information on the resource being excavated as well as providing data to compare with any simultaneous environmental measurements (Parrish, F.G. 1989). There is a danger, however, that such improved monitoring could be regarded by the dredge operator as policing of the dredging operations (McDonnell, T.M. and R.K. Tillman. 1992). Nevertheless, the on-board provision of such instrumentation and "black boxes for dredges" will become an essential part of the successful application of mitigation techniques.

However, "... sophistication of instrumentation does not necessarily mean greater accuracy of measurement" (Maintenance Dredging, 1987). The reliability of the data is as important as the quantity. A voluminous amount of dubious data is of no advantage to either the operator or the regulator. But the extent to which snap-shot measurements and analyses are representative must also be questioned. For example, the large variability in measured turbidity may be greatly reduced and be better understood by analyzing continuously recorded data. Such data may be averaged over chosen periods to give a more realistic picture of the water quality, and short term averaging of continuously recorded data should be the adopted procedure.

4.8 Economics

4.8.1 Marine Mining Costs

Dredging costs are divisible into capital costs (i.e. dredge and auxiliary equipment) and operating costs (i.e. salaries, fuel, maintenance, and insurance). The fixed cost element of operating costs can be surprisingly high for precious metal dredging operations in inhospitable marine environments. While revenue is not being earned during downtime most costs continue to be incurred. Some of the variable costs, such as fuel, may be saved.

It is generally not recognized that marine mining is considerably more expensive, on a $\$/m^3$ basis, in terms of capital investment and operating costs, than its onshore equivalent. The difference, of course, is attributable to the generally greater downtime experienced, the larger and more sophisticated equipment, and the greater back-up facilities required. In the United Kingdom the cost of producing seabed aggregates is higher than from equivalent land-based deposits (Fox, 1989). As a result the sales price (ex-wharf) of marine material is generally higher than land-won aggregates of the same quality (Nunny and Chillingworth, 1986). An example from Alaska is a direct comparison between two bucket ladder dredges. Both produced gold from almost identical glacial sediments. One, WestGold's "Bima", was working 1.5 km offshore and the other, Alaska Gold's "D6", immediately onshore. WestGold's costs were approximately three times that of Alaska Gold per m^3. Similar evidence from offshore tin dredging in South East Asia and the marine mining of diamonds on the western coast of southern Africa (Garnett, 1995) confirms that the unit cost of marine production can be between two and five times higher than that of equivalent on-land production.

Dredge capital and operating costs are summarized for each of the mining scenarios in proportional terms. Actual dollar values are not presented for reasons of confidentiality and because proportional values are more meaningful in the long-term as costs increase due to inflation.

Methods of capital financing may be different for any new offshore mine development: leasing, public flotation, retained equity, etc. For uniformity, the capital cost of a dredge with auxiliary equipment is in each case based on a "tax shelter" lease arrangement with the following terms: a ten-year lease with a ten-year internal revenue life for depreciation; a mid-year start date for depreciation; a 30% salvage value after ten years; and payments based on the seven-year treasury note interest rate at the start of the operation. A minimum ten-year project life would be expected for most marine mining developments. In the case of a projected twenty-year life, the lease could be renegotiated after ten years such that payments are then less than half the original rate.

The question of profit is not dealt with in detail but warrants mention as profit expectation is the determining factor in proceeding with any marine mining development and operation. Simply stated, profit is the remaining balance of commodity sales revenue once all operating and capital-derived (depreciation, etc.) expenses are paid. Profit requirements vary from company to company and commodity values can fluctuate considerably over time, so it is neither appropriate nor meaningful to include quantified profit in economic considerations of the hypothetical mining scenarios.

Profit objectives can only be met if the expected excess of commodity sales revenue over operating costs is realized at the conclusion of each operating season. The balance can be seriously altered by unscheduled downtime associated with extreme storm events, emergency maintenance and certain forms of mitigative action that previously were not stipulated. Unscheduled downtime translates into a loss of commodity sales while fixed and some variable operational costs are still incurred, with a corresponding loss of profit.

4.8.2 Investment

The use of the correct equipment is of major importance in marine mining not only in terms of type but also the scale or capacity (Garnett, 1996a,b,c). With some important exceptions where selectivity of extraction is more important than throughput, the larger dredges will operate at lower cash costs. In Japan productivity is low from the regional, small-scale, operations (Narumi, 1989).

The necessary capital investment, however, is greater for higher capacity dredging systems, a situation which requires more careful assessment of the risk involved. If a company considers that offshore dredging licences will not be granted it will postpone investment in the appropriate new vessels. Conversely, without suitable vessels the company is unable to apply for a licence when the opportunity arises. For example, it is generally recognized in the United Kingdom that "... the uncertainties brought about by the lack of new licences has generally delayed further investment by many of the companies involved" (Nunny and Chillingworth, 1986).

In a marine aggregate industry the onshore processing plant, with its attendant capital investment, must match the offshore capacity. The absence of certain onshore facilities such as drag scrapers and belt-conveyor systems prevents the Japanese industry from using larger-sized ships (Narumi,1989).

The cost of exploration, with no guarantee of success, represents a considerable investment for most companies, and one which is lost if a production licence is refused. In the United Kingdom this burden has been recognized and it has been suggested that the lead agency, the CEC, "... might encourage more detailed prospecting by offering partial recompense of prospecting costs for failed licence applications" (Nunny and Chillingworth, 1986).

4.8.3 Mitigation Costs

Aside from their success or otherwise in minimizing or preventing environmental impact, all mitigation techniques must be judged not only in terms of their practicality of use at sea but also in terms of their effect on costs. The cost of implementing various mitigation techniques can be similarly categorized into capital and operating (fixed and variable). If the techniques are substantially operational in approach they may lead to increased operating expenses. If technology-based they will involve capital outlay with some negative effect on the operating costs such as fuel and labour.

An additional economic cost may be involved in the implementation of mitigation techniques: an opportunity cost which represents the loss of revenue, and thus of potential profit. It may be incurred by either the curtailment of productive capacity or downtime caused by the installation and maintenance of special mitigative equipment. Some suggested forms of mitigation, while possessing technical merit, are capable of erasing profits by overwhelming erosion of revenue through lost operating time.

The above considers the cost of application of mitigation methods from the viewpoint only of the operating company. The whole cost of marine mining, including the mitigation, should be examined in the context of the benefits to the host country of an on-going marine mining industry. The benefits of the mining activities must be viewed in the light of the losses that might occur as a result of a decrease in the size or total catch of an existing fishing industry which may be disrupted by the mining activities.

To undertake such a cost-benefit analysis requires a quantification of the relative value of inshore fishing compared with the mining. In the United Kingdom it has been suggested that this major study be undertaken in order to assist the government in developing its view on dredging licence applications (Bide, 1989).

5.0 Application of Mitigation Techniques

The mitigation objectives and techniques outlined above do not apply equally, if at all, to each of the five selected scenarios. Rather than using a repetitive, approach the following scenarios are used to illustrate a particular technique in detail. Descriptions are given of the most appropriate choices of mitigation techniques for the scenarios and similar marine mining developments. Invariably the choice is dictated by practicality. Mitigation techniques which clearly should not be taken under consideration are also identified.

5.1 Scenario 1: Precious Metal Mining, Alaska - Bucket Ladder Dredge

5.1.1 Background

The placer gold mining operation carried out by Western Gold Exploration and Mining Company (WestGold) Limited Partnership from 1986 to 1990, inclusive, in state waters off Nome, Alaska, was the subject of comprehensive permitting and an intensive environmental monitoring program overseen by both state and federal regulators. The permits awarded by the state and federal authorities determined the extent and nature of various programs designed to monitor the following:

(1) dredge effluents

(2) water turbidity and trace metal content

(3) impact on, and biological recovery of, sand and gravel substrates.

Constraints were applied by the permitting agencies involved and the monitoring programs were designed to:

(1) assess whether the constraining criteria were being met

(2) aid in the design of mitigation techniques intended to: a) meet the criteria on a continuous basis, and b) reduce the effects of the dredging even further.

Sample collection was undertaken in such a manner that the same procedures and samples could be used for a variety of purposes. Specific mitigation objectives were neither set nor itemized at the start-up of the operation but in principle included minimization of water turbidity and minimization of release of toxic materials. The objectives were quantified once dredging was underway.

5.1.2 Regulatory Authorities for the Permitting Processes

As related by Gardner (1992) "the project activities under regulatory scrutiny included the dredging of gold-bearing sediments, the discharge of process water, and the discharge of dredged material back on to the seabed, approximately along the dredged path and to the rear of the advancing dredge."

Several features resulted from the unique nature of the project and from the offshore location within Alaskan state waters and the federally-mandated coastal zone. The project did not conform to the existing regulatory mould and numerous agencies were involved, issuing permits at federal, state and local levels (Table 5.1).

The Alaska project consistency review commences with the identification by the Alaskan Division of Governmental Coordination (ADGC) of the requirements in the form of information and permits required by the following three state resource agencies in accordance with Alaska Statutes and Alaska Administrative Code:

(1) Alaska Department of Natural Resources (ADNR)

(2) Alaska Department of Environmental Conservation (ADEC)

(3) Alaska Department of Fish and Game (ADF&G).

In addition, the USEPA must determine whether unreasonable degradation of the ocean will result from the discharge of any or all of the effluents from the dredge, based on a consideration of the following:

(1) quantities, composition, and potential for bio-accumulation or persistence of the pollutants discharged

(2) potential transport of such pollutants

(3) the composition and vulnerability of biological communities exposed to such pollutants

(4) the importance of receiving water area to the surrounding biological community

(5) the existence of special aquatic sites

(6) potential impacts on human health and on recreational and commercial fishing

(7) the applicable requirements of approved Coastal Zone Management Plans, and marine water quality criteria developed pursuant to the Clean Water Act.

The various reviews, by both the public and the agencies involved, are subject to 60-day and 180-day time lines which are frequently exceeded.

5.1.3 Regulatory Authorities for Environmental Monitoring

Both the state and federal permitting processes require environmental monitoring programs. The Environmental Protection Agency, in compliance with the Clean Water Act, requires the dredge operator to undertake a monitoring program in order to determine whether the effluents comply with the limitations imposed by the permits and to assist in the development of effluent limitations. The Alaska Department of Governmental Coordination requires that environmental monitoring requirements are met in order that the dredging operation is consistent with the Alaska Coastal Management Program.

5.1.4 Regulatory Authorities for Post-Mining Requirements

Alaska may stipulate any post-mining requirements, such as continued monitoring or rehabilitation, through the Alaska Coastal Management Program, in an Approved Plan of Operations and the various permits. Federally, the Environmental Protection Agency may also dictate post-mining requirements through the NPDES permit.

5.1.5 Water Quality

5.1.5.1 Tailings Plume

The NPDES permit No. AK-004319-2 originally issued to WestGold required the company, as operator, to comply with both federal and state water quality criteria at the edge of the mixing zone at a 500 m radius from the point of discharge of the dredge effluent. State water quality criteria required that turbidity levels should not exceed 25 NTU's above background. There were three main sources of turbidity within the mixing zone, each creating a distinct plume visible at surface, in the following order of decreasing importance:

(1) the jig tailings carried along two stern launders and discharged into the sea

(2) the excavating action of the dredge stirring up fines into the water column through turbulence around the bottom tumbler and from being washed off the rising, loaded dredge buckets

(3) the trommel oversize discharged immediately astern of the vessel.

The behaviour of tailings effluent disposed of as a single stream into open water may be described as comprising three phases (Figure 5.1):

(1) Convective Descent

The material behaves as a jet descending towards the sea floor. Jet movement is governed by its initial momentum as it leaves the disposal pipe, by gravity forces due to the density difference between the jet (consisting of a water/sediment mixture) and the ambient receiving water and by viscous shear at the jet's periphery. Viscous shear action causes turbidity in the water column as the jet mixes with the ambient water. Sediment particles in the mixing zone begin to act independently, rather than as a part of the jet.

(2) Dynamic Collapse

When the jet impacts on the seabed it collapses. It becomes a major source of turbidity as it scours and re-suspends material, including re-deposited tailings, from the seabed. The momentum of the jet may be partially conserved and be re-directed both upward and laterally, suspending material in the water column. In shallow water a "boiling" effect is created.

(3) Long-term Diffusion

Once the momentum of the jet is dissipated during dynamic collapse, material that has been suspended in the water column is convected by ambient currents and diffused by turbulence. Individual sediment particles fall through the water column and are deposited on the seabed.

For trace metal concentrations, federal marine water quality criteria led to the establishment of a 100 m-radius mixing zone from the point of effluent discharge with the requirement that trace metal levels for 8 elements should not be exceeded at its periphery for 4-day averages and 1-hour maxima.

5.1.5.2 Monitoring

Monitoring involved the collection of samples of the following intake and effluents, it being impossible to sample the trommel oversize or the excavation discharges:

(1) tailings launder effluent

(2) gold room effluent

(3) sea water both up-current and down-current of the dredge.

Turbidity and water quality monitoring stations, with some changes from year to year, were sited at the following distances from the dredge (Figure 3.16) and at different water depths:

(1) Up-current: 0, 500 and 2,000 m

(2) Down-current from the tailings discharge: 0, 50, 100, 480, 500, 520, 800 and 1,000 m

(3) Down-current from the bottom tumbler: 50, 100 and 500 m

5.1.5.3 Plume Modelling

Software

WestGold and its consultants employed the DIFCD (Disposal from a Continuous Discharge) 3-dimensional water quality and sediment plume computer model developed by the U.S. Army Corps of Engineers Waterways Experiment Station. It was used in conjunction with a Wave Current Sediment Resuspension Prediction (WCSRP) model. The DIFCD and WCSRP computer programs proved to be invaluable in predicting the plume creation behaviour of the tailings discharge.

The DIFCD model "simulates the movement of disposed material as it falls through the water column, is transported and diffused as suspended sediment by the ambient current, and is deposited on the bottom. It computes the movement of disposed material in a continuous fashion at a constant discharge rate. It takes into account the ambient environment at the disposal site, the characteristics of the material, the disposal system, and the general physics involved" (R.& M. Consultants, 1988).

To overcome a major limitation of the DIFCD model, namely, the basic assumption that once solid particles are deposited on the bottom they remain there, the model was used in conjunction with the WCSRP model. "The underlying assumption of the WCSRP model is that naturally occurring sediment resuspension in the near-bottom waters is controlled by the intensity of the bottom boundary shear stress associated with wave oscillatory flow and tidal currents, storm surges, or currents associated with other mechanisms. In general, there exists a threshold boundary shear stress below which no apparent resuspension could occur. Once bottom boundary shear stress exceeds the threshold value, sediment resuspension occurs and will increase or decrease according to the magnitude of the boundary shear stress. The model uses the flow conditions and bottom sediment grain size as input for computing the bottom boundary shear stress" (R.& M. Consultants, 1988).

The DIFCD model was calibrated and used, with the WCSRP model, to:

(1) predict (for each set of operating conditions, such as water depth) tailings effluent discharge depth and discharge rate and the distance from the dredge where water quality standards would be met

(2) predict the tailings effluent discharge pipe configuration, and pipe depth below the water surface, resulting in the lowest turbidity and metal concentrations at the edge of the mixing zone

(3) simulate the range of conditions, including dredge operating water depths, expected to be encountered during the life of the offshore dredging project, using both an average range of conditions and a worst case scenario.

Predictive Capacity

Actual conditions observed through the monitoring program were used to determine the predictive accuracy of the computer models. The process was interactive, allowing a gradual upgrading of the mitigating techniques, and resulting in a reduction in turbidity and an improvement in the validity of the model. The monitoring was conducted in conjunction with bathymetric and side-scan sonar surveys of the seabed both before and after dredging.

The predictive precision of the models was good. At 500 m downstream, on the edge of the mixing zone where the permit called for no more than 25 NTU above background, the precision was +/- 7.3 NTU with a standard deviation of 9.9 NTU. At other distal locations a similar precision was achieved, but it decreased at proximal, near-dredge, locations. The WCSRP model predicted reasonably well the background turbidity during storms when, with dredging halted, the turbidity would rise to between 40 and 60 NTU.

Contributing Factors

The results indicated, as expected, that at a given distance (such as the edge of the mixing zone) turbidity increased as silt content of the discharge increased and as the rate of discharge increased. Turbidity increased from a minimum at the water surface to a maximum at the sea floor, most probably due to settling of the turbid discharge. Turbidity decreased logarithmically with increasing distance from the dredge. As expected the plume became diluted during movement away from the point of discharge. However, the discharge plume was not homogeneous in character and clouds or eddies of turbid water persisted amid the surrounding, much clearer water which consisted of either unaffected seawater or rapidly diluted portions of the plume.

The most significant increase in turbidity was associated with the change from average to maximum silt content of the dredged material and by the effect of increasing ambient currents from average to maximum values. The turbidity was least sensitive to changes in the dredge throughput rate and thus to the rate of discharge of the jig tailings. Within the normal range of dredge production rates the effects of changes in the production rate on turbidity were small when compared with the impact of changing environmental conditions.

Contrary to first expectations, the water turbidity increased with the dredge operating depth, despite the greater column of water available for dispersion. The phenomenon was apparently a result of the increasing silt content of the ground dredged in deeper waters. The trebling of the percentage silt content between 7 m to 20 m water depth was detectable only from the drill logs and not from any other seabed sampling techniques. The turbidity also increased in very shallow water, although the ground contained less silt, because of the smaller water column available for dispersion.

5.1.6 Water Quality Mitigation

5.1.6.1 Discharge Control of the Jig Tailings Effluent

A large variety of mitigation techniques were considered and many were tried over the 1986 to 1990 operation period of the BIMA dredge. The most important was the control of the tailings effluent discharge so as to minimize the degree and extent of sea water turbidity. The relative contribution of each of the two processes of convective descent and dynamic collapse as a source of sea water turbidity is important in determining which is the preferable discharge alternative. The long-term diffusion phase is not a source of turbidity but a continuing result of the previous two phases. In practice, if the major contributor to turbidity is mixing at the tailings jet periphery during convective descent, then turbidity is reduced by minimizing the opportunity for mixing. Alternatively, if the major contributor to turbidity is dynamic collapse, then turbidity is reduced by minimizing tailings jet velocity at the seabed.

Experimentation on the optimum jig tailings discharge configuration continued from 1986 to 1990 (Rusanowski, 1990). Several designs were tested (Table 5.2) in varying depths of water from about 5 to 21 m for each of the two identical tailings launders (Figures 5.2 to 5.6). The various discharge systems that were tried suffered from several disadvantages (Rusanowski, 1990). The sea state required that their construction be rugged and rigid to prevent immediate damage or destruction. Their repair or replacement at sea, even in relatively calm seas, was not only very difficult and dangerous but also involved the cessation of dredging, usually when the potential for a high rate of production was at its greatest.

Direct surface discharge produced the largest turbidity plume visible at surface. Flexible pipes, especially the initial panels, were severely loosened, damaged, or destroyed by both the abrasive action of the tailings slurry and the waves in the first of the frequent summer storms. Their life span was sometimes no more than a few days. The large surface area of vertical flexible pipe exposed to horizontal currents also tended to result in the pipe becoming seriously bent.

Larger diameter pipe caused the tailings effluent to form a large vortex within the pipe entrance. Air became trapped in the tailings slurry and was carried down the pipe into the sea where it caused a portion of the plume to rise causing, at the water surface, a massive "boiling" action and a consequent increase in the extent of the turbidity (Figure 5.7). Flexible pipe also tended to float due to buoyancy of the entrained air.

These problems were overcome by using a smaller (0.50 m-diameter) rigid steel pipe, the constriction of which inhibited the formation of a vortex. The deflector plate (Figure 5.3) proved to be a slight advantage, causing diversion of the slurry jet, but abrasion by the fast-moving slurry resulted in its destruction before the end of the summer season (Rusanowski, 1990).

Experience over a number of years showed that the different systems each possessed advantages in particular conditions of water depth and current speed. However, none was the optimum design under all conditions to be expected during a single dredging season. But once the dredging season was started the system installed prior to start-up could not be changed. Emphasis, therefore, was directed towards the installation of a discharge system that would survive the marine state, did not require maintenance, and provided some reasonable mitigation under all the operating conditions expected and planned for the dredging season. Ease and rapidity of repair were the decisive factors in the adopted design.

The optimal design developed from four years of dredge-operating experience comprised fitting the existing 1.8 m-diameter header pipes with cones that terminated in a flanged collar of 0.50 m diameter. A straight circular steel pipe was attached to the flange and extended vertically down to within about 0.5 m of the water surface. A flexible hose of the same diameter was affixed to the steel pipe and extended 2.7 m below the water surface (Rusanowski, 1990; Ellis and Garnett, 1996).

Several other configurations were considered but were not employed. They were discarded in the design stage after operating experience quickly demonstrated their impracticality under the prevailing marine and dredging conditions. They included multiport systems (Figures 5.8 and 5.9), a form of controlled surface discharge (Figure 5.10) and flexible stinger pipe designed to lie on the seabed.

The multiport system, a cluster of small pipes, proved to be no different from a single pipe. To be effective, its construction necessitated such large spacing between the individual smaller pipes that the tailings were dispersed over too wide an area. A flexible stinger pipe could have interfered with the operations and safety of the dredge. The controlled surface discharge was considered to possess a too short potential operating life in the face of the obvious engineering difficulties in the local marine conditions.

Exhaustive experimentation and the use of the two computer models allowed a series of nomograms to be produced (Figure 5.11). The nomograms indicate, for future planned operations, whether or not the permit stipulations regarding turbidity at the edge of the mixing zone will be complied with under different conditions of silt content, ambient current and the dredge operating depth and production (discharge) rate.

5.1.6.2 Operational Procedures

A feature of the Nome offshore deposit was the occurrence of glacial kettle holes and paleo-lagoons behind the storm water marks of previous beaches. Both features are characterized by concentrations of mud and clay which in places border or cover payable gold-bearing ground. Such areas, easily identified by prior seismic surveys, were avoided and excluded from the dredge course plans so as to avoid undue generation of fines and excessive water turbidity.

5.1.7. Seabed Profile and Mitigation

At the outset of WestGold's operation there was an important agency stipulation regarding dredging in Alaskan state waters. The stipulation was that tailings from the dredge of any form should not cause change in seabed topography such that the water depth after dredging should be less than 1.8 m deep, and thus tailings should not approach to within less than 1.8 m of the sea surface. In deeper water, adherence to this regulation was not difficult but in shallow water problems arose due to the swell factor of discharged tailings and the method of dredge operation.

5.1.7.1 Discharge Control of the Trommel Oversize

The Nome precious metal deposit was created by a high energy environment, resulting in an average gravel content of 20 to 50%. The treatment plant of the BIMA therefore produced a trommel oversize effluent that represented a high proportion of the excavated sediments. The fine sediment matrix of the gravel was discharged separately as the jig tailings. After return to the seabed the gravel and fines were not recombined and consolidated. As a result an original 1 m^3 volume of *in situ* sediment occupied a greater volume after excavation and treatment. The new volume of 1.1 to 1.3 m^3 was expressed as a swell factor of 10 to 30%.

The trommel oversize discharge rate varied between 88 and 236 m^3/hour (Table 3.10). The lower effluent rate was the result of efficient disaggregation of clay in the trommel so that the discharged effluent consisted of gravel only, with cobbles and boulders up to 1 m in diameter. At higher discharge rates the gravels were mixed with large lumps of clay in which case a swell factor was always evident.

Discharged trommel oversize was not easily redistributed by normal wave action. Isolated mounds of oversize, therefore, remained on the seabed that were covered by a blanket of jig tailings as the dredge passed. Major storms or ice gouging were the agents that smoothed this artificially-created topography. In practice a partial solution to this swell factor problem may be achieved by mechanically recombining, where feasible, the fine and coarse effluents during discharge. By siting the discharge points as close together as possible maximum re-mixing may be achieved with a subsequent reduction in swell factor (though never to 0%).

5.1.7.2 Operational Procedures

Figure 4.4 illustrates how the effluents from a bucket ladder dredge are deposited on the seabed relative to the excavation. At the start of the dredge course the jig tailings and trommel oversize are discharged more than 100 m to the rear of the dredge. The exact distance behind the start-up face is given by the horizontal separation between the bottom tumbler and the various discharge points. After the dredge has advanced from the start-up face by a distance greater than the defined separation the effluents are discharged into the excavation.

A problem may be created when the dredging conditions involve a combination of shallow water and deep digging (Figure 4.4a). The solution is to gain digging depth slowly, but this may be achieved at an economic cost. Either unpayable ground must be dug ahead of the deposit block, or some of the deeper reserves must be sacrificed by remaining undug and then covered by tailings.

The operational difficulties can be decreased in shallow water by selecting an appropriate face width (Figure 3.10). The problems described above can be minimized by starting with a small face width which is gradually increased as digging depth is gained. However, a narrow face width may create another problem. With the bow away from the centre line an experienced dredge operator will angle the dredge into the two corners of the face to achieve complete excavation at the base of the cut. This practice results in the trommel oversize being discharged only in the centre of the dredge course, accentuating the swell effect and causing the tailings to reduce water depth.

5.1.8 Costs of Mitigation

The total operating costs during a representative 24 month period between 1987 and 1990 are given in Table 5.3. Environmental monitoring alone added exactly \$ 0.50 per m^3 of sediment excavated to the dredge's operating costs. Other expenditures involved in the construction of effluent discharge devices, etc., were absorbed in the dredge maintenance costs and probably added another \$ 0.50 per m^3, approximately, of dredged sediment.

5.2 Scenario 2: Precious Metals Mining, Alaska - Underwater Miner

5.2.1 Background

In the summer of 1989 Western Gold Exploration and Mining Company (WestGold) Limited Partnership conducted the trial operation of an underwater miner (UWM) for a period of four months off Nome, Alaska. Like the operation of the BIMA, the test project was the subject of comprehensive permitting and an intensive environmental monitoring program overseen by both state and federal regulators.

With respect to mitigation, trials with the UWM "Tramrod", focused on controlling the discharge of effluents to the sea with the aim of minimizing surface water turbidity and the extent of sedimentation.

5.2.2 Impact Avoidance

A number of location-related restrictions applied to the operation that were designed mainly to protect migrating salmon. Dredging could not take place:

(1) within 30 m of the low water mark

(2) within 1.6 km of the mouth of a river used by migrating salmon

(3) in water depths of less than 5 m.

The Environmental Protection Agency concluded that the primary determinants of the turbid plume were sea current velocity and the percentage of fines contained in the dredge effluent. The Agency found that discharges of solids from dredging operations at depths of 5 m or greater should comply with the Alaska state water quality standards under the various expected conditions of currents and silt content, except for high current velocity and high silt content. In addition, solids discharge in water depths of 7 m or greater should comply with state standards under all conditions of current velocity and silt content. The operating constraints therefore prohibited dredging in water depths of less than 5 m and required judgement and mitigation procedures, such as decrease of the throughput rate, to be applied between 5 and 7 m.

5.2.3 Appropriate Technology

As noted previously, the highest grades of gold are concentrated within the uppermost 1 m of seabed, and frequently within 0.30 m of the seabed. To avoid dilution in both the vertical and horizontal sense an excavating unit is required which is capable of digging to an accuracy of about 0.10 m vertically and to within about 3 m horizontally. No floating system of excavation in the open sea offshore Alaska allows such accuracy because of continuous ocean swell. The secret to economic success is the almost surgical extraction of ground versus the bulk mining approach of a dredge which seriously dilutes the grade by its lack of selectivity.

The use, on such a resource, of any marine mining system other than an UWM during the summer, ice-free months, results in excessive ground being excavated from the seabed. There is a consequent, and unnecessarily greater, environmental impact because of the larger volumes of tailings being generated per ounce of gold recovered. The use of a selective, small scale, operation allows greater flexibility in mitigating the deleterious effects of the effluent discharges.

The use of an UWM also serves to mitigate the important impact of changing seabed profile caused by dredging. A frequent feature of mining by bucket ladder dredge is the subsequently elevated seabed profile which can be caused by the swelling of sediments during processing and disposal of tailings. The effluent discharge arrangement may be designed in such a way that the trommel oversize and the undersized jig tailings may be discharged close together because the mining operation is smaller. By this means the coarse and fine material may be allowed to remix naturally on the seabed, thereby preventing both the development of a high swell factor and reduction of the water depth.

The flowsheet arrangement on the barge deck is a modular one and it can be changed without any significant structural modifications to the barge assembly. The physical arrangement of the flowsheet and the points of discharge of the effluents therefore may be modified so as to optimize discharge mixing. The lengthy downtime, requiring significant dock facilities, needed by a conventional dredge is thusavoided, with considerable economic benefit.

5.2.4 Water Quality Mitigation

Several approaches may be taken to mitigating theeffluent discharges. The incentive for minimizing the mixing zone is also economic. Unless the tailings are discharged down-current from the excavation there is the possibility of over-sanding (the disposal of tailings on virgin ground). The most simple disposal arrangement is a single discharge pipe extending to approximately 1.5 m below the water surface, equal to the draft of the barge.

5.2.4.1 Discharge Preparation by Cycloning

Just as the jig feed is de-watered by means of a hydro-cyclone, there are advantages in similarly de-watering the jig tailings before discharge into the sea. The two cyclone products, the sand underflow andthe water/fines overflow may then be discharged separately. The sands may be discharged from a single outfall where they may enter the water and settle under the force of gravity. The overflow waste water and fines may be discharged separately. The intent of this method is to minimize the kinetic energy (and thus turbulence) of the sands at the point of discharge, thereby reducing particle dispersion. Cycloning does not concentrate solids finer than 75 microns, so all clays remain with the waste waters. The advantageof this grain-size sorting is that the sand sinks quickly without being caught up in the higher volume and more turbulent slurry containing the fines. The sand is therefore distributed over a smaller area, lessening the chance of over-sanding and increasing the extent to which it naturally re-mixes with the trommel oversize.

5.2.4.2 Curtain Containment

A technique which justifies further evaluation is the deployment of a small diameter, circularcurtain containment structure surrounding the fines slurry discharge pipe, the curtain effectively containing the mixing zone. Such a system may be either floating and tethered to the barge or may be suspended from an outrigger and cable system. However it is deployed it should be on the lee side of the vessel if possible and should be capable of being recovered fairly quickly in the event of a storm.

The curtain may provide a pool of about 5 m maximum diameter within which the most severe turbulence may be contained. It may have a full depth of at least 3 m below the sea surface which in the shallowest water will place it within 2 m of the seabed. It is a device which is applicable only to asmall scale operation such as the one described here for an UWM. Any mining system with a greater throughput and effluent discharge requires a larger silt curtain to be deployed. The size quickly becomes unmanageable and the financial investment increase in equipment which will be destroyed and lost altogether in the first rough seas.

5.2.4.3 Diffusion Launder

Another novel outfall design, consisting of two large troughs fixed along both sides of the treatment plant barge, was used by WestGold to collect and discharge the jig tailings effluent. The trough was perforated along its base to provide discharge ports so that the slurry was released as a series of small point discharges. The slurry may be discharged in the sea either from above or may be fed down a series of flexible hoses, with quick-coupling disconnect fittings, capable of discharging at various depths above the seabed. Diffusion of the effluent around the barge perimeter, coupled with the low gradient of the flexible subsea hoses, minimized the turbulent kinetic energy of the discharge. This approach was made especially practical by the comparatively low throughput rate of the UWM.

Constructed of steel and approximately 30 m long, each trough was 0.3 m wide and 0.4 - 0.6 m deep and was affixed to the port and starboard sides of the barge. The two were inclined at an appropriate angle to ensure free and easy flow of the slurry away from the point of entry into the trough. A total of 10 to 15 discharge ports were located along each trough. Depending on required length and location, each port was between 7.6 and 15.0 cm in diameter and was originally designed to be controlled by a manually-operated on/off valve.

5.3. Scenario 3: Marine Aggregate Mining, Massachusetts Bay

5.3.1 Background

Dredging of marine aggregates by means of trailing suction hopper dredges is a well established industry in the North Sea of western Europe. The experience gained there has led to a good understanding of the optimum method of dredge operation and of the effects of their use.

In terms of the development of hull design and sea-handling characteristics, a trailing suction hopper dredge designed for aggregate recovery at sea is generally indistinguishable from any mercantile fleet vessel (Nunny and Chillingworth, 1986). Most modern European hopper dredges have one or two drag-arms. If there are two drag-arms then one is mounted on each side of the dredge. Each drag-arm is fitted with an in-pipe suction pump which gives the dredge a depth pumping capability of 45 to 50 m (Nunny and Chillingworth, 1986). During trailing-dredging the ship lowers the drag-head(s) to the seabed. The ship then steams in a straight line, raising and lowering the drag-head as appropriate with reference to an echo-sounder plot on the bridge. When fully lowered, the drag-head is pulled across the seabed by the drag-arm. Steaming is usually either with, or directly against, the run of the tide (Littler, 1990).

The seabed sediments are hydraulically lifted by the drag-head which may be custom designed for the area. Sediments are transported up the drag-arm and, after screening out of the undesired oversize fractions, are stored in hopper bins in the dredge's hull. Low density turbid water at the surface of the filled hoppers contains silt and fine sand which reduces the value of the cargo.

The average aggregate storage capacity of dredges employed in western Europe has increased to around 4,000 to 4,500 tonnes (approaching 10,000 m^3). Each vessel is purpose-built and incorporates all the latest navigational and dredging technology (Webb, 1988). Each is around 100 m in length with a draft, when loaded, of 6 to 6.5 m, with service speeds of 12.5 to 13.0 knots. The vessels meet all the current regulations of the marine classification societies for construction and safety at sea. A cargo of about 4,500tonnes of sand and gravel can be dredged in approximately 2 hours (Littler, 1990).

A typical smaller dredge vessel has an overall length of 65 to 70 m, a breadth 13.0 m, a loaded draft of 4.0 m. With a cargo capacity 1,300 tonnes (approximately 750 m^3) and a speed of about 10 knots it can operate at distances of more than 25 km from the coast. Typically, the operations are automated with the engine room unmanned in the open sea. Such vessels are classified by Bureau Veritas as "Dredger Coastal Waters".

During the filling operation turbid water carrying fines continually overflows. The higher density gravel and coarser sand remain in the hopper and constitute the desired product. The water containing silt and fine sand is usually discharged through ports located on both sides of the dredge. Each dredge master is concerned with maximizing the load of marketable product per trip. Therefore, pumping of the seabed sediments and the discharge of the dredged material as a slurry into the hoppers is often continued after the hoppers have been filled.

During the dredging operation re-suspension of fine-grained sediments is caused in four ways:

(1) the drag-heads stir up clouds of fine material as they are pulled through the sediment

courses are controlled by hydrographic constraints rather than by the geology of a deposit (Nunny and Chillingworth, 1986). Any effects such as significant changes to the seabed lithology and profile are therefore accelerated. Dredging carried out in stages in different areas avoids concentrating undue amounts of change to the seabed within the total region to be dredged. An "unacceptable degree of adverse effect on fishing interests" is also avoided (Webb, 1988).

5.3.3.1 Seabed Lithology and Mitigation

Repeated excavation of aggregates within a dredge course eventually may reveal different lithologies. As the workable deposit thins through repeated removal of sediments, high-spots in the underlying sequences are eventually exposed. These may be hard bedrock or glacial clay. To the dredge operator such exposure raises the possibility of unwanted cargo contamination. When this contamination exceeds a certain critical level dictated by the marketing restraints the aggregate reserves within the dredge course are considered to be worked out and a new dredge course or dredging location is sought (Nunny and Chillingworth, 1986).

Over-dredging has other effects. Local fishing may be affected if boulders become exposed since the potential for damaging trawling gear is increased (Continental Shelf Associates, Inc. 1993). A layer of the original substrate should be left on the seabed to increase the ability of the original benthic communities to recolonize (Nunny and Chillingworth, *op. cit.*). The problem of over-dredging to too great a depth, thereby revealing a different lithology, is especially common when dredging glacial till and other sediment similar to that proposed as the aggregate source in Massachusetts Bay. The content ofsuch glacial sediment concentrations is unpredictable in terms of their three dimensional distribution if sufficient exploration has not been carried out.

The mitigative solution is two-fold. Either avoid such concentrations of glacial sediments, or apply restrictions to the extent that aggregate may be removed only from the top of the vertical sediment sequence. Alternatively, the dredging company could be required to undertake side-scan sonar surveys at intervals before and during dredging to reveal the extent, if any, to which the seabed lithology is changing as a result of mining activity.

A significant change in the characteristics of the seabed sediments also may result from the preferential non-removal of oversize material which is too large to pass through the drag-head trash bars. After dredging is complete the oversize is left *in situ* as a residual deposit on the seabed. This effect is particularly common when a deposit is dredged, especially a glacial one, that contains substantial quantities of cobbles and boulders (Nunny and Chillingworth, 1986). The only mitigative process available may be a decision not to licence such areas for aggregate dredging.

In western Europe it is now common practice to screen the pumped aggregate at sea before it is discharged into the dredge hopper. A percentage of the sand content of the pumped aggregate is removed so as to provide a saleable cargo with the optimum ratio of sand to gravel. The screened out sand is immediately returned to the sea within the dredging licence area. The long term effect is a gradual increase in the percentage of sand within the upper sediment layers of the sea floor (Nunny and Chillingworth, 1986). To the disadvantage of the operator, reserves of gravel may become lost to dredging beneath a cap of sand that has been reworked many times. As discussed in a subsequent section, one recourse is to prohibit on-board screening of aggregate at sea.

On average, depending on its particle size, sand settles at rates of between 3 and 20 mm/second. Assuming an average rate of 5 mm/second, then in 25 m of water the sand is transported 40 m from the dredge for each relative 1.75 km/h of tide (Nunny and Chillingworth, 1986). To some extent this drifting effect of the sand can reduce over-sanding. To harness this effect different areas can be dredged on the ebb and flood tides, working inwards from the parallel boundaries of the deposit, and steaming at a slight angle to the tide. The rejected sand is carried to one side of the vessel and back-fills the dredged area. If the tide is strong enough to disperse rejected sand on the seabed then it may be necessary to dredge from only one side of the vessel during only half of the tide.

5.3.3.2 Seabed Profile and Mitigation

Ideally, the drag-head furrows left by a trailing suction hopper dredger in a single pass are only 20 to 30 cm deep, so there should be minimal danger of creating significant change to the seabed profile. However, there is always the temptation for the dredge master to excavate repeatedlyin a favourite location. The intensive working of such a dredge course can produce a large scale shallow trench in the seabed (Nunny and Chillingworth, 1986).

Even if some care is taken by the avoidance of an excessively repetitive dredge course and direction, trailer suction hopper dredging does not always yield a sufficiently flat seabed profile. After final excavation the seabed surface frequently contains too many peaks and valleys because the drag-heads have a tendency to track the previous excavation. Contrary to theory, the dredging results in several deep tracks separated by unworked seabed representing remnant reserves of aggregate (Maintenance Dredging, 1987). Such dredge furrows may persist for years (Nunny and Chillingworth, 1986). The objective of dredging should be to plane, rather than to trench, the seabed. Operators should attempt to dredge courses adapted to the seabed geology, even if the courses are oriented across tidal flow. Ideally, the courses should be adapted to the contours of equal sediment thickness (isopachytes) (Nunny and Chillingworth, 1986). Courses intersecting at shallow angles can be superimposed over a period of time, while still being generally aligned to the direction of strongest tidal flow (Nunny and Chillingworth, *op. cit.*). The use of GPS (Global Positioning System) navigation removes any possible excuse that such necessary precision is unobtainable

Another pre-requisite is accurate data from initial prospecting of the deposit. Both the operator and the environment benefit from the advantages of achieving such accuracy. For the operator there is less chance that areas of unworked aggregate reserves are left on the seabed, and the possibility of contamination by other lithologies is also reduced. Environmentally, a relatively smoother sea floor of uniform substrate type remains.

To counter the formation of trenches, pits, mounds and the exposure of boulders on the seabed, "the French have experimented with abutting dredging tracks to obtain an unobstructed seabed. In other cases, rejected oversize materials can be guided back into the collector tracks immediately behind the mining device" (Continental Shelf Associates, Inc. 1993).

5.3.4 Water Quality Mitigation

5.3.4.1 On-board Processing

The on-board screening of slurry and the rejection of unwanted particle sizes results in an effluent which is discharged continuously and usually from above the water surface. On-board processing presents considerable practical problems. The cost and operational difficulties experienced have caused the European marine aggregates industry to limit its processing equipment at sea to single deck screens (Nunny and Chillingworth, 1986).

Efforts continue to be made by the industry to improve the operational performance of on-board screens. The objective is to clean up hopper feed so as to achieve particle size characteristics that approximate the market-dictated requirements (Nunny and Chillingworth, 1986). Someoperators claim that there are no major advantages offered by processing at sea and that screening and sorting is best undertaken in a shore-based plant that has improved quality control. Although on-board screening continues, the extent of turbid water created by effluent discharge can be minimized by the design and installation of appropriate discharge arrangements as described in connection with Scenario 1.

5.3.4.2 Hopper Overflow Operation

A major cost in aggregate dredging is that of transport at sea between the dredging zone and the unloading area. To offset these costs by enhancing productivity the maximum loading of marketable solids must be attained in the hopper (Ports and Dredging, 1991b; 1991c). Ideally, the vessel must return to its shore-based unloading station with a hold full of saleable product. For coarse sand and gravel deposits with high settling velocities a maximum load can be obtained by overflowing relatively clear water from the hopper. If the sediments being dredged comprise clean sand the overflow contains a low percentage of solids. Economic loading is generally achieved by pumping slurry into the hold until all the feed is overflowing (Raymond, 1984).

The rate at which the level of slurry rises in the hopper during loading ranges from about 5 mm to well over 10 mm/second (Scott, 1992). This method of operation ensures that where dirtier sediments are being dredged most of the suspended clay and silt pumped into the vessel's hold returns to the sea with the overflowing hold water. The silt (<75 microns) content in the hopper is thereby maintained at the low level required for concreting aggregates (Littler, 1990). Once the hopper loading exceeds a certain percentage the overflow increases dramatically, together with the loss of marketable coarse sand. At 65% of capacity the loss of coarse sand as overflow exceeds 10%. When the loading reaches 80% of capacity, the loss of coarse sand reaches 40%. If fine sand is being dredged the hopper cannot be filled completely because the overflow losses become 100% when the hopper loading reaches about 85% (see graph on p. 256 of Herbich, 1975). The optimization of loading can be assisted by instrumentation which is now available (Ports and Dredging, 1991b; 1991c). The turbidity caused by overflowing high concentrations of suspended fine sediments is the most important cause of the turbidity plume associated with trailing suction hopper dredges (Scott, 1992).

5.3.4.3 Overflow Mitigation: Operational Technique

A practical mitigative technique is to delay the commencementof hopper overflow. This is achieved by emptying all water out of the hopper before starting to pump any sediments on board. Water is discharged directly overboard as the dredge pump is primed. A switching mechanism is then used to direct the slurry to the hopper once sediments are entrained in the pumping system. As a result overflow does notoccur until the hopper is filled to within 60 to 70% of its dredged material capacity. The time during which sediment-laden waters are released to the sea is thereby substantially reduced.

Aggregate quality can be judged visually. However, the installation of a drag-head sensor automatically coupled to a voiding valve immediately down-flow from the pump would result in major advantages (Nunny and Chillingworth, 1986). Poor quality dredge feed could be recognized and diverted more rapidly. Both contamination of the loaded aggregate and high silt overflowwould thereby be reduced. An additional benefit would be that a continuous record of pumped aggregate quality and impurity concentration would be provided. In conjunction with position fixing and data logging systems the information would substantially supplement the prospecting data.

5.3.4.4 Overflow Mitigation: Re-cycling

The drag-heads of some trailing suction hopper dredges are equipped with water jets that are designed to assist in the liberation of compacted sediments when dredging hardground. A small percentage of the hopper overflow water can be pumped to the drag-head jets instead of using clean seawater, reducing slightly the total volume of sediment-laden overflow (Shepsis and Hartman, 1992).

In Japan a system has been developed whereby all the turbid overflow water from the hopper is re-cycled to the drag-head intakes. This system is said to improve efficiency by increasing the density of the sand slurry (Ofuji and Ishimatsu, 1976). The concentration of suspended particles is reduced and the transparency of hopper overflow water is increased after the installation of such an anti-turbiditysystem. The results have reportedly been reviewed favourably by the local fishing industry representatives (Nunny and Chillingworth, 1986). An inherent problem with this technique is that the overflow water continually recirculates in a closed loop. The slurry becomes increasingly laden with silts and clays until it attainsa density beyond the capabilities of the dredge pump. The benefits are therefore short-term since the only solution is to purge the system at intervals. Short duration discharges of high density effluent are produced, as opposed to a more continuous dilute overflow, with a minimal overall net benefit.

5.3.4.5 Overflow Mitigation: Hopper Design

The level of the aggregate surface in a loaded hopper always must be above the load line in order to prevent surplus water from being transported to shore in addition to the solids. This can be achieved by modifying the shape of the hopper to keep much of the contents above the load line. Alternatively, special compartments may be employed on either side of the hopper (Figure 4.5) (Maintenance Dredging, 1987).

Recent developments include deeploading and semi-deeploading systems (Maintenance Dredging, 1987). The purpose of these systems is to reduce the amount of energy required to load the hopper and to limit the volume of air in the supernatant water passing to the overflow. A reduction in the turbidity of the overflow water, and thus that surrounding the vessel, also can be achieved by means of an anti-turbidity valve which can be installed in the IHC telescopic, cylindrical overflow weir (Figure 5.12) (Maintenance Dredging, 1987).

Several methods for increasing solids concentration in the hopper are in the experimental stage and represent examples of how environmental mitigation simultaneously improves the economics of the dredging operation (Scott, 1992). They include the use of:

(1) slurry feed diffusers to reduce turbulence in the hopper and to enhance the settling of suspended sediments

(2) centrifugal separation to de-water the solids

(3) inclined plates in the hopper to increase the settling rate of the slurry suspension.

5.3.4.6 Overflow Mitigation: Overflow Collection

An anti-turbidity measure proposed for hopper dredging is to install compartments on both sides of the dredge (Figure 4.5). These are designed to intercept and temporarily retain the overflow, allowing partial settling of suspended silts within them. However, the following disadvantages of this approach are all potentially serious, practical, limitations:

(1) the retention time needed for substantial settling to occur

(2) the need, at intervals, to dispose of the accumulated silts

(3) the significantly reduced hopper capacity caused from the loss of vessel space by incorporating settling compartments.

5.3.4.7 Overflow Mitigation: Effluent Discharge

A relatively simple technique for handling hopper overflow, called an anti-turbidity overflow system (ATOS), has been developed in Japan (Nunny and Chillingworth, 1986) (Figure 5.12). The overflow collection system is streamlined to minimize the entrapment of air bubbles in the overflow water. Removal of the air bubbles, which otherwise make the particles buoyant and prolongs settling, allows thefines to settle at a faster rate. This system has been successfully applied to trailing suction hopper dredges off the coast of Japan (Ofuji and Ishimatsu, 1976). In addition, the overflow discharge ports are moved from the sides of the vessel to the bottom of the dredge's hull (Raymond, 1984) (Figure 5.13). Discharged particles descend rapidly in the water column with a minimum amount of dispersion. The improvement has been incorporated in existing dredges through modifications of their overflow systems. Japanese dredges with hopper capacities of between 2,000 and 4,000 m^3 have been converted with the result that the turbidity in the uppermost 1 m of the surface waters has been reduced from around 110 to 120 g/l to 6-9 g/l at 30 m aft of a dredge. The system does not, however, reduce overall resuspension, only surface turbidity (Raymond *op. cit.*).

5.3.5 Onshore Processing

Discharge at a shore plant can be by crane, self-discharge by scraper and conveyor, or self-discharge by pumping. The sediments are washed to remove salt, the content of which may exceed construction standards, and screened into marketable product(s). During this process waste wash water containing salt is produced. The silt can be settled out (Quarry Management, 1986). Occasionally, flocculant is added to the slurry stream in order to settle the solids quickly and more evenly (Littler, 1990). The rate of settling generally increases with the amount of flocculant used, but only up to a certain dosage (Quarry Management, 1986).

Onshore desalting is popular with operators but difficulties often arise in the supply and the environmentally acceptable disposal of the flushing water. Re-circulation is only a partial answer. Sometimes the problem may be overcome by blending the salt-contaminated marine aggregate with a salt-free one from a land source to obtain a product that conforms to the required quality standard. Alternatively, an on-board desalting process can be used while the vessel is still at sea, with a beneficial impact on the economics. Vessels may be fitted with an appropriate freshwater tank and the contaminated wash water is discharged at sea (Narumi, 1989).

5.3.6 Economics

5.3.6.1 Operating Costs

The operating costs of a trailing suction hopper dredge include royalties, fuel, wages, maintenance, port dues, pilotage, unloading and insurance (Nunny and Chillingworth, 1986). Fuel is the most important item contributing to costs. Fuel consumption, and therefore cost, increases with the distance to the dredging area and thus with the steaming time. Crew costs are next in order of importance. The ratio of cargo capacity to number of crew is related to the vessel size which may vary within the limitations imposed by features such as harbour entrance dimensions (Nunny and Chillingworth, *op. cit.*) Maintenance costs are affected by the type of aggregate being dredged. Sand and gravel is more costly to produce than is sand because of the higher abrasive effect of the contained gravel (Nunny and Chillingworth, *op. cit.*).

Dredging costs are heavily dependent on the cycle time from loading, steaming to port, unloading, and steaming back to the loading site. The extent to which the cycle time meshes with the tides on which a vessel can land its cargo affects the overall economics (Littler, 1990). The most efficient operations are those for which the cycle time equates to one tidal cycle. Larger vessels dredging more distant grounds operate on a 2-tide cycle, and 3-tide cycle dredging is not unknown in Europe (Nunny and Chillingworth, *op. cit.*).

In western Europe the target for most dredges is to be fully operational for 24 hours/day for about 350 days/year. However, downtime averages about 20% due to annual refits, operational delays, breakdowns and poor weather. Weather conditions rarely prevent steaming but may seriously reduce the rate at which loading is accomplished. It may also affect the ability of a dredge to enter its harbour for unloading (Nunny and Chillingworth, *op. cit.*).

5.3.6.2 Capital Costs

In western Europe a modern trailing suction hopper dredge capable of supplying 1.0 to 1.25 million tonnes of aggregates annually cost around U.S. $12-15 million in the late 1980's and has since increased. That capital cost is inflated by an additional 50% for the provision of a system capable of handling material being discharged directly from the vessel at a rate of about 2,000 tonnes/hr, including receiving, washing, grading and stocking facilities (Webb, 1988). A few years later a new 5,000 tonne-capacity vessel cost about U.S. $16 million (Hollinsworth, 1994).

Although the capital cost of a new dredge is normally amortised over 15 to 20 years, its productive life is usually a minimum of 20 years. If a major refurbishment is implemented after 20 years its active use can be extended for a further 10 years (Nunny and Chillingworth, *op. cit.*). The best return on the capital investment is achieved by maximizing the life and the availability of the vessel (Nunny and Chillingworth, *op. cit.*).

A major decision facing a company producing marine aggregates is when to invest in a new vessel. Most operators understandably are not prepared to commit to the investment unless they have possession of delineated reserves fully licenced for immediate mining (Nunny and Chillingworth, *op. cit.*). An existing, or reasonably anticipated, market share for the planned production is also essential. The delivered price of the marine aggregate is the major factor influencing the extent to which the product can penetrate a local market. Onshore haulage cost and user prejudice are both of critical importance (Nunny and Chillingworth, *op. cit.*).

The after tax rate of return for a marine operation is considerably less than that normally available from a conventional onshore operation of the same scale of output because of higher capital costs (Industrial Minerals, 1990). Onshore aggregate operations normally involve less onerous capital investment in machinery for the extraction and transport of sand and gravel material to a processing plant (Nunny and Chillingworth, *op. cit.*).

5.3.6.3 Mitigation Costs

The most visible effect of trailer suction hopper dredging, and consequently of public environmental concern, is the turbidity caused by on-board screening and by hopper overflow. Complete disallowance of overflow clearly limits the efficiency of the dredging operation. An alternative is to classify the sediments and allow the overflow of none or only some of the classifications (Maintenance Dredging, 1987). Ideally, the overflow and screening restrictions should be clearly stated and imposed at the outset. Such a procedure allows potential operators to consider the cost of converting any existing vessels or to allow for overflow mitigation methods in the design of new vessels. Restrictions should not be imposed after the commencement of operations when a more relaxed initial approach may be considered to have been inappropriate.

If imposed without any forewarning, the prohibition of overflow as an operating technique significantly raises the cost of production of marine aggregates. Trailer suction hopper dredges are designed with a certain hopper capacity intended to hold sand and gravel with a density of 1.8 to 2.0 tonnes/m^3. If the operator cannot discharge at sea any contained silt, which has a density of 1.1 to 1.2 tonnes/m^3, then the load capacity of the vessel cannot be fully utilized. It therefore operates uneconomically (Maintenance Dredging, 1987). Excessive enforcement of mitigation measures can prevent an infant industry from securing and maintaining its market share. The cost to the operator may be an operating loss for a period, followed by closure.

The environmental arguments in favour of marine mining of aggregates have been well stated in the informed media. "Adverse environmental effects (of onshore aggregate mining) are visited upon the surrounding community by conventional sand and gravel open pit operations." They include "... the diseconomics of noise, fugitive dust and added traffic burden associated with extraction, processing and distribution" (Industrial Minerals, 1990). Offshore aggregate mining "... does not involve valuable land which is more cost effective for urban development than for the mining of construction aggregate. In addition, people do not want (onshore) mining activity, with its attendant dust, noise, traffic and environmental concerns, in their neighbourhoods" and "... increasingly tough zoning, environmental and reclamation laws (are) restricting the industry's expansion by dry land methods" (Industrial Minerals, 1990).

There are four specific advantages of marine aggregate mining: "First, marine transportation costs of this low value, high bulk commodity are much lower than onshore transportation, so that sand and gravel can be mined farther from the market area. Second, marine aggregate can be delivered directly to urban water fronts close to the centre of demand... Third, marine dredging, when properly conducted, does not result in the environmental problem commonly associated with on-land operations Finally, marine deposits are very large, so depletion of the source is unlikely" (Industrial Minerals, *op. cit.*).

5.4 Scenario 4: Heavy Mineral Sands, Virginia

5.4.1 Background

The dredging of heavy mineral sands for their titanium content is an established onshore industry in the south-eastern U.S.A. In other countries the onshore reserves have been mined out and the on-going dredging activity has moved to the coastline (e.g. Australia, New Zealand and South Africa). Environmental conflicts have developed as a result of proposed and operational mining of coastal, mineral-bearing dunes, beaches, and offshore sand bars. Several regulatory authorities have enforced location-based and time-based constraints on the dredging operations. Concerns over environmental effects during permitted dredging have taken several forms related to the creation of water turbidity and to changes in the seabed lithology and profile.

5.4.2 Impact Avoidance

Mitigation through voluntary downtime can take two forms; one being anticipated downtime during an environmentally sensitive period, such as an annual or seasonal spawning event, and the other involving unscheduled downtime in the event that members of a particular protected species are detected in the vicinity of the mining operation, as with walruses off Nome, Alaska (Scenario 1).

5.4.3 Water Quality Mitigation: Cutter-Generated Turbidity

During the operation of a cutter suction dredge seabed sediments become suspended in the water close to the cutter-head as the dredge swings back and forth across the dredge face. A properly designed cutter-head excavates the sediments and guides them efficiently towards the hydraulic suction intake. However, the cutting action and the water turbulence created by the rotation of the cutter cause some of the sediments to be become suspended. The degree of suspension is directly related to the type and quantity of sediments disturbed by the cutter-head but which remain on the seafloor. The suction's inability to gather up and entrain these loosened sediments determines the quantity that remains on the seabed or that is lifted into suspension in the surrounding water (Raymond, 1984).

The amount of sediments suspended by the suction dredge's cutter-head is reported to increase exponentially (Barnard, 1978) as the following increase :

(1) thickness of cut

(2) rate of cutter swing (usually about 0.1 m/second)

(3) rate of cutter rotation

(4) rate of production.

Within about 3 m of the cutter-head the concentrations of suspended solids vary considerably, but may be as high as a 1,000 mg/l. Immediately above the seabed concentrations may remain elevated at a few hundred milligrams per litre for distances of up to 300 m from the cutter-head. Above the cutter-head concentrations decrease exponentially with decreasing water depth. The amount of sediment lifted into suspension increases with increased current speeds (Raymond, 1984).

5.4.3.1 Operational Mitigation

Several operational controls are recommended for the reduction of sediment resuspension (Raymond, *op. cit.*). Most involve the manner of excavation. Very thick single-pass cuts should be avoided, because the cutter-head tends to become buried. As a result more sediment is excavated and dislodged than the suction can successfully entrain, leading to high levels of suspension. A thick deposit is best excavated by means of several horizontal slices, each layer of excavation being a single thin cut depth. Excessive layer cutting, however, also may be responsible for unacceptable levels of turbidity. Loose sediments remaining on the newly exposed seabed after each cut are easily resuspended by the returning cutter-head.

In other places, depending on the depth below the seabed to which payable grades of heavy minerals extend, it may be more economical to excavate and remove most of the sediments very roughly in a single cut. Final clean-up to the base of the pay zone may be delayed until the final stage. However, the loosened sediments, while awaiting clean-up, may be at risk of suspension in a variety of ways.

Where the mining plan involves dredging to a few metres below the seabed within a defined block the operation should proceed without excavating vertical walls in each cut. The sides should be inclined sufficiently so as to inhibit the slumping of loose sediments into the cut. The final walls of a cut should be terraced by reducing the area of cut with each successively deeper slice. On a smaller scale the formation of distinct cuts should be minimized. The dredge should be swung and advanced so as to cover equally all the seabed within the block. The cutter-head should be advanced by increments that are sufficiently small to ensure that very close concentric arcs are described on the seafloor with each swing of the cutter-head.

5.4.3.2 Design Mitigation

The cutter-head's suction should be sufficiently powerful to collect all the sediments it disturbs. To enhance the pick-up capability and to decrease the amount of suspended solids several features should be incorporated in the dredge design. These include water jet booster systems or ladder-mounted submerged pumps. Another factor that may influence the amount of suspended sediment is the shape of the cutter-head (Raymond, 1984). The cutter-head may be designed in such a way that the suction is brought closer to the sediments (see Figure 8 of Raymond, *op. cit.*), thereby improving the chances of entrainment. Differences in shape are particularly important if the cutter-head is not completely buried in the sediments.

The acute angle between the base of the cutter tooth and the upper surface of the sediments is referred to as the rake angle (Figure 5.14). Proper design of the cutter-head with an appropriate rake angle is an important mitigation factor. If the rake angle is too large, a gouging action throws soft, fine-grained sediments outward. If the rake angle is too small, however, resuspension occurs through impact.

5.4.4 Water Quality Mitigation: Plant Effluent

The most obvious water turbidity is created by the surface discharge of slurry effluents as tailings from the treatment plant. Approximately 95% of the sediments dredged are returned to the sea as tailings. Of this amount more than 85%, on average, is sand. Mitigation may be attempted by:

(1) minimizing the possibilities of re-digging of the settled tailings through operational procedures

(2) improving the nature of the effluent by de-sliming, dewatering or degassing

(3) optimizing the manner in which effluent is discharged by employing sub-surface discharge and/or discharge diffusion

(4) modifying effluent behaviour in the sea by the use of flocculants.

5.4.4.1 Operational Mitigation

An important stage in the production of marine heavy minerals is the estimation of reserves and the delineation of an approved dredge course. Not only must the planned dredging program allow for optimum mineral recovery but it must also take into account the environmental effects of possible re-dredging of previous tailings (Garnett, 1996c).

Re-dredging of previously excavated areas, even on their boundaries, may result in two negative effects. Previously deposited tailings may be more easily suspended than undisturbed sediments. Secondly, previously dredged areas, at some stage of recovery from the previous incursion of the dredge, will be disturbed a second time due to overflow, or over-sanding, by tailings returned by the dredge and plant.

The mine plan should be designed so as to avoid, if possible, significant encroachment of the dredge on the boundaries of a mining block which previously has been dredged and the surface of which is now covered with tailings. The deliberate exclusion of areas of low-grade ground from a first dredge course, on the assumption that they may be dredged as part of a subsequent program, should be avoided (Ellis and Garnett, 1996). Mining in an area should be continued until it is unlikely that operations will return close to, and disturb, a recovered site.

5.4.4.2 De-Sliming and Dewatering

Separation of the effluent flow into its component parts of solids and water allows the materials to be discharged into the sea with less impact. The solids are not held suspended in the water by the boiling action which otherwise is evident. The water, although containing some fines, is more rapidly diluted by the surrounding sea water. The objective in de-sliming and dewatering is the same: to separate the water and slimes from the coarser solids.

De-sliming and dewatering can be achieved in a number of ways with different equipment. Various proven systems are in standard use onshore in a variety of industries, including those involved in the production of aggregates and heavy minerals. Such systems include hydrocyclones, hindered settling classifiers, bucket-wheels, and screws and dewatering screens (Littler, 1990).

The hydrocyclone is the most commonly used tool for classification of coarse sand and silt slurries. It is an extremely simple mechanical device with no moving parts. Cylindro-conical in shape, the cyclone is mounted with the long axis aligned vertically, and may be up to nearly 1 m in width for the treatment of the largest particle sizes. Slurry is fed continuously by either a centrifugal pump or a gravity feed system. The feed head is converted to both angular and linear acceleration, creating a cyclone effect whereby the particles in the slurry are separated by size and/or specific gravity (Schilt *et al.* 1992). An acceleration by about 50 times the natural free-settling process is achieved.

Dewatering by cycloning is conventionally employed at the beginning of an on-board flowsheet for the recovery of heavy minerals. The cyclone removes excess water from the undersize feed, after separation of the oversize, before the sands are fed to the spirals. A dewatering cyclone should also be incorporated at the end of the process stream to remove excess water from the sand constituent of the tailings. The solids comprise about 20% by volume of the total effluent, and if discharged separately they are not subjected to a turbulent dispersion in the sea. The water, generally containing particles finer than 200 microns, is discharged separately.

The cyclone is the most suitable dewatering system for installation on board a dredge or wet mill pontoon because it does not require deck space and is easy to install. It has been used in the onshore mineral dredging industry for over 30 years, especially for dewatering jig tailings before their discharge astern of a bucket ladder dredge. Other variations of the same cyclone principle exist, such as the Linatex Separator (Figure 5.15) and the Linafuge (Littler, 1990).

5.4.4.3 Degassing

It is not known whether methane or hydrogen sulphide are present in seabed sediments offshore Virginia in the vicinity of the mining site, though it appears that the geology and benthic environment may not be conducive to natural gas generation. If either of these gases does occur degassing equipment should be employed downstream of the dredge pump to prevent de-priming. Both the pump and degasser must be installed underwater because the water depth is greater than 10 m. To limit water column turbulence associated with released gases the installation of a conduit from the degasser to the surface is necessary to allow gases to be vented to the atmosphere.

5.4.4.4 Effluent Discharge Design

Surface water turbidity and the deposition of tailings on the seabed around the wet mill pontoon can be controlled to a significant extent by using a sub-surface discharge. Such an arrangement consists of a reinforced rubber pipe, probably with a nominal inside diameter of approximately 1 m, attached to the pontoon by a beam and/or steel cables. There may be many variations in the configuration of the discharge pipe. It may be deployed in any attitude ranging from vertical to near horizontal. A near vertical orientation may be preferable but it may also be desirable to redirect the outlet so that the effluent stream can be released at depth with minimal direct impact of the bottom. The optimal configuration and depth below surface of the discharge will have to be determined for each mine site through a combination of numerical modelling and field experimentation. It is likely that all effluents could be discharged through dedicated, single, sub-surface pipes. A reduced effluent discharge velocity could also be achieved, within practical limits, by fitting the end of a discharge pipe with a flared opening. This modification may require some experimentation to achieve the optimum arrangement.

5.4.4.5 Flocculants

It is possible to inject a continuous, metered dosage of chemical flocculants into the effluent stream prior to its discharge from the wet mill and introduction to the sea. The use of flocculants comprises the only means available of speeding the settlement of entrained silts. They have been widely used for many years to great effect in the onshore mineral dredging industry. However, there is little experience of their use in the open sea. Their effectiveness depends on many factors and site specific experimentation will be necessary before flocculants may be used with confidence.

Flocculants have two effects. Firstly, because they are flocculated, the fine sand and silt are deposited together, thus preventing the natural separation of fine sand and silt that occurs during settling with increasing distance from the effluent discharge pipe. Secondly, the deposited silt is increased in volume by the entrapment of water. However, volumetric increase should be minimal if the correct amount of flocculant is used (Littler, 1990).

A flocculant is usually purchased in powder form and is diluted to a 0.1% solution before introduction into the effluent. Dosage rates are between 0.5 to 5 ppm. The lowest dosage typically creates flocs of around 1 mm in diameter which possess an increased settling rate to 10 to 15 cm/min. At higher dosage rates larger flocs up to 3 to 4 mm across settle out rapidly at approximately 560 cm/min (Littler, 1990).

The feed equipment is typically a 500 gallon tank with a propeller mixer to invert or mix the polymers with clean water for a period of 20 to 30 minutes. The resulting solution can be injected as a continuous, metered dosage of chemical flocculants to the effluent stream prior to its introduction to the sea. Under some circumstances undiluted polymer and effluent can be mixed rapidly but with less quality control. For short-term operations a flocculant in soluble brick form can be suspended in wire baskets within the effluent flow (Littler, 1990).

5.4.5 Seabed Profile and Mitigation

During the marine mining of precious metals and heavy minerals, almost all of the excavated sediments are returned to the sea after dredging. Contrary to a simplified view of the digging process, the screen oversize is not returned as tailings to exactly their point of origin on the seabed. They are discharged astern and fall quickly to the seabed at a distance equal to that of the discharge point in plan from the excavation head.

The cutter suction unit employed for heavy mineral dredging rotates about the long headline. Because of the deployment of sidelines the dredge describes an arc (in plan view) whereby the travel distance of the cutter-head is greater than that of the vessel's stern and of the wet mill pontoon astern. Material that is excavated, treated, and then discarded during the digging process is therefore deposited, as the dredge moves forward, over a smaller area than that from which it was dug. If the ground contains significant amounts of screen oversize and coarse sand these accumulate on the seabed as a ridge that forms along the track of the dredge.

The accumulation of tailings on the seafloor astern is exaggerated when the dredge commences its cut in a mining block. At the start of the dredge course excavated sediments are dumped on to the original seabed instead of into a cavity created immediately beforehand by passage of the dredge. The seabed elevation may be raised as a result by an amount at least equal to the depth of cut.

Where gravels and very coarse sand occurs the volume of the deposited sediments may be increased over the *in situ* volume by an amount indicated by the swell factor. A high swell factor is created when the discharged fines are not re-mixed with the coarse screen oversize on the seabed. The pore spaces between the larger particles remain unfilled by fines, unlike those in undisturbed sediments.

5.4.5.1 Operational Procedures

The creation of elevated ridges of tailings on the seabed along the dredge course, especially at its start, may be minimized during operations in several ways:

(1) a sufficiently wide cut face must be dredged

(2) the dredge must not be restrained by sidelines which are so short as to cause it to angle excessively

(3) the dredge must not be angled deliberately and unnecessarily into the corners of the cut face

(4) the gaining of depth at the start of a deep cut must be undertaken at a slow rate.

5.4.5.2 Discharge Control of the Trommel Oversize

Every effort should be made at sea to re-mix the oversize and the undersize. This involves discharging the screen oversize as closely as possible to the solids produced as the cyclone product, without causing unnecessary turbulence.

5.4.6 Alternative Enhancement

Considerable potential exists for alternative enhancement initiatives when dredging for heavy minerals. In particular, the undersize tailings can be pumped ashore, if needed, for beach renourishment, the remediation of contaminated areas, and the creation of wetlands.

5.4.7 Economics

The annual costs of the heavy mineral mining scenario offshore Virginia is summarized in Table 5.4. With the exception of voluntary downtime and the use of flocculants as an ongoing operational mitigation measure, all of the techniques given in Table 5.4 are technology-based. They therefore entail an initial capital outlay in the first year of the project. Subsequent costs would only be for maintenance and supplies unless replacements or upgrades are required.

Maximum excavation efficiency and throughput rates are attained by digging deeper, rather than shallower: cuts such as a 45° ladder depression versus a 20° ladder depression for the same depth. Any restrictions in the operational procedures on the incremental depth of cut and the rate at which the full depth of cut is attained at start-up seriously impact the efficiency and economics of the operation.

The cost of unscheduled downtime is very high. An annual operating window is seasonally defined and must be achieved in order to meet production objectives. The resulting loss of commodity sales and, consequently, of profits as a result of unplanned shutdowns of long duration could render an operation uneconomic.

5.5 Scenario 5: Beach Nourishment, Maryland

5.5.1 Background

Of prime concern in all marine mining, even if conducted well out to sea, is the possibility of coastal erosion. This scenario offers an opportunity to explore the mitigation techniques which are available.

Seabed excavation, for whatever reason, invariably produces some changes in bathymetry. Extreme examples are provided by the dredging of aggregates and the removal of sand for beach renourishment, both of which involve the removal of almost all of the excavated sediments. The criteria for judgement of likely coastal impact are several (Brampton, 1985). Critical questions include whether or not:

(1) the dredging area is within the zone of seasonal beach sediment change

(2) the sediments at the dredge site are mobile

(3) the dredging area includes sand banks that, if removed, would increase wave activity at the shoreline

(4) the area is sufficiently distant from the coastline.

All such dredging that results in bathymetric changes may cause a change in the local wave climate. Erosion, especially of beaches, may occur with the sediments being transported and accumulated in another locality. The original formation of a beach is primarily attributable to the action of waves against a shoreline. The minimum grain-size of the beach particles is approximately 180 microns. Below this figure normal wave action effectively winnows out the finer particles and transports them out to sea (Nunny and Chillingworth, 1986). The irony of this situation is that if sufficient technical research is not undertaken beforehand then the very act of removal of sand from offshore banks to re-nourish nearby beaches may lead eventually to erosion of the same beaches.

5.5.2 Prevention of Coastal Erosion

Coastal erosion may result if the wave- and sediment movement patterns are sufficiently modified in the nearshore by an offshore excavation. To avoid the possibility of erosion both the local hydrodynamic conditions and the sediment characteristics of the deposit being dredged must be considered. Wave refraction analyses and wave transformation modelling are a necessary input to a study (Byrnes *et al.* 1991). Prevention of erosion may be achieved by adopting a correct licensing procedure and by restricting the operation of a dredge to specified water depths and/or areas.

5.5.2.1 Licensing Procedures

In western Europe the role of marine dredging in previous cases of coastal erosion around the North Sea has been closely studied. In Britain, for example, experienced scientific advice is available to the licensing authorities. The national Hydraulics Research Station provides a reasoned view as to whether or not an individual application for a dredging licence is likely, if granted, to place the nearest coastline at risk (Spreull and Uren, 1986). Each licence application is judged on its merits, and the authorities take into account details of the proposed dredging site (Table 5.5). A licence is issued only if all the criteria are met. However, even if the Hydraulics Research Station approves an application other involved authorities may object, possibly delaying an application for several years (Spreull and Uren, 1986).

5.5.2.2 Operating Restrictions

The regulatory authorities may specify a minimum working distance from the coastline or a minimum water depth based on the local wave climate. For example, in Holland, dredging for sand and gravel is not permitted within 20 km of the coast. In Britain the minimum permitted distance from the coast is 5 km (Cronan, 1986). Regarding acceptable water depths, an interim guide to safe practice is obtainable from British experience. In coastal waters of the North Sea dredging for aggregates "... reportedly causes no problems in water depths greater than half the normal wave length or more than one fifth the length of extreme waves" (Drinnan and Bliss, 1986; Continental Shelf Associates, Inc. 1993).

European authorities have attempted to translate the technical advice into quantified water depths. As a general guideline the British Crown Estates Commission, the regulatory authority, has adopted a water depth of 18 m as the minimum for offshore dredging (Nunny and Chillingworth, 1986). The actual depth limit identified for potential damage was 13 m but an additional 5 m was added as a precautionary measure" (Continental Shelf Associates, Inc. 1993). In practice, dredging in waters deeper than 20 m is usually approved by the authorities. A licence application for dredging in 10 to 20 m of water receives a more detailed review and requires specific information regarding the site. A proposal to dredge in waters shallower than 10 m requires substantial study (Drinnan and Bliss, 1986; Continental Shelf Associates, Inc. 1993).

Unlimited dredging of offshore deposits of sand can be detrimental by altering the wave climate in relatively shallow waters. Restrictions are therefore placed on the permitted extent of removal. On the coast of New Jersey, for example, where a dredge operator planned to excavate sand from an offshore sand bar, the authorities insisted that part of the bar be left undredged. The remnant bar served as an additional protective barrier between the borrow area and the sand beach (World Dredging, Mining and Construction, 1992a) Under such circumstances a dustpan dredge has some advantage because it can be operated in such a manner that thin, precise, layers of sand can be skimmed from the seabed (World Dredging, Mining and Construction, 1993). Fine silt is an unwanted size fraction for beach renourishment so the operator of a trailing suction hopper dredge will allow the unwanted fines to flow overboard during hopper loading at sea. A generally coarser and more stable material is placed on the beach (World Dredging Mining and Construction, 1992b).

6.0 Summary and Recommendations

As outlined in Section 1, the purpose of this study is to undertake a detailed analysis of available and proposed marine mining technologies and mitigation techniques with respect to the mining of specific mineral commodities on the U.S. OCS.

The approach has been to develop a number of marine mining scenarios that target mineral commodities which have the potential for exploitation within a ten-year time span. The scenarios are presented in Section 3, and provide details of the geological and environmental settings, the extraction and processing methods, the scales of operation and the observed or anticipated environmental impacts.

An overview of the environmental issues related to marine mining is presented in Section 2. It provides a framework for the discussion of environmental impacts associated with each mining scenario. A general discussion of marine mining mitigation techniques is presented in Section 4, and the application of mitigation techniques to each of the scenarios is discussed in Section 5.

Sections 6.1.1 to 6.1.5 below provide brief summaries of the mining scenarios with particular emphasis on the predicted environmental impacts and relevant mitigation techniques. The most appropriate mitigation techniques for the scenarios and for similar marine mining operations, based on relative cost, effectiveness and practicality are rcommended. A summary of the conclusions of this study is provided in Section 6.2.

6.1 Summary of Marine Mining Scenarios

6.1.1 Precious Metal Mining, Alaska - Bucket Ladder Dredge

Scenario 1 documents a bucket ladder dredging operation carried out by WestGold offshore of Nome, Alaska. The scenario provides a comprehensive case history of the only large-scale marine mining operation that has been conducted to date in U.S. waters. This scenario provides practical experience with marine mining mitigation.

The mined ground comprised mainly gold-bearing glacigenic sediments that were inundated and reworked by the transgressing sea. Gold concentrations were greatest in lag gravels forming the uppermost 0.5 m of seabed. Mining was by means of a large ocean-going bucket ladder dredge (the BIMA) with an 850 litre bucket capacity and an onboard treatment plant. The choice of a large bucket ladder dredge was influenced by the difficult ground conditions which characterized the deposit. The depth of cut was generally 3 m or more which led to some dilution of gold grades. During mining, the dredge was secured by 5 winch-controlled anchor lines (one head line) which moved the dredge up to 200 m laterally while slowly advancing along its course. The average rate of throughput was 300 to 600 m^3 per hour with more than 95% of mined material returned to the sea as effluents.

Environmental monitoring and mitigation were directed mainly at the observation and control of tailings discharges to the sea, with the objective of minimizing water column turbidity and the areal extent of re-sedimentation. Of particular interest was the response of the king crab population, which supported a local fishery, to the effects of seabed disturbance and tailings deposition.

This scenario is particularly valuable in terms of the practical experience gained in tailings management and disposal. A successful, iterative approach to the design of a sub-surface tailings discharge system was adopted that coupled numerical plume modelling with water column monitoring and successive discharge design modifications. A similar approach is advocated for future marine mining operations that involve the disposal of the majority of mined materials at sea as waste product. The incorporation of a sub-surface tailings discharge designed for the local operating conditions represents a small portion of the capital cost of a dredge, and yields significant environmental benefits by reducing far-field turbidity and the areal extent of sedimentation.

Seabed gold concentrations offshore Nome are localized and variable, and required intensive sampling to obtain reserve estimates and to direct the dredging program. Location-based constraints were imposed on the WestGold project from the outset. Such constraints would likely be imposed on the mining of any precious metal or heavy mineral deposit, and highlights the need to identify potential restricted areas (e.g. sensitive habitats) well in advance of project initiation. This enables the economics of the mining operation to be realistically assessed.

A time-based constraint placed on the WestGold operation involved the interruption of mining whenever one or more sea mammals came in sight of the dredge. Unpredictable constraints of this nature can have significant economic implications, particularly when mining in a harsh environment with a limited operating season. From an economic perspective, similar constraints on future mining operations are not generally advisable and should be considered cautiously.

Another mitigation method proposed for the WestGold operation was the reduction of throughput rate when anomalously fine-grained sediments were encountered. This technique is not particularly effective because it serves to prolong the period when finer-grained sediments are discharged, and does not substantially affect the ultimate disposition of fines on the seabed. It also has very significant negative economic implications because the profitability of an operation is based on the maximum possible rate of throughput.

6.1.2 Precious Metal Mining, Alaska - Underwater Miner

Scenario 2 documents production trials carried out by WestGold using the underwater mining vehicle "TRAMROD". The UWM experience provides a useful comparison with the BIMA operation, because a more precise, selective and smaller-scale extraction technique was applied to the same mineral deposit. The UWM is a track-mounted vehicle that supports a hydraulically controlled dredging arm. The vehicle was deployed by crane from a barge and was remotely-controlled from the surface. The barge also contained the treatment plant. The solids discharge rate averaged 150 m^3 per hour. As discussed in Section 5.2, the low throughput rate associated with the underwater miner also facilitated the development and use of relatively simple but effective systems for dewatering, diffusing and controlling tailings. The depth of cut was as little as 10 cm, so that the UWM selectively extracted higher grade, surficial lag deposits. The environmental impacts of such an operation are of lesser magnitude than those associated with a bucket ladder operation by virtue of the low throughput rate and high degree of selectivity of mined seabed.

An UWM can only be used to mine high value commodities such as placer gold or diamonds, because the low throughput rate will not support economic production of lower value ones, such as heavy minerals. When the combined deposit characteristics and economic considerations indicate a viable operation based on an UWM then the use of such a system constitutes a mitigative measure.

6.1.3 Marine Aggregate Mining, Massachusetts Bay

Scenario 3 describes a hypothetical aggregate mining operation in Massachusetts bay serving the Boston area market. The site selection and details of the environmental and geological settings were based on studies conducted in the 1970's (project NOMES) in preparation for an experimental aggregate mining operation that was designed to assess potential environmental effects of marine mining. The experimental mining project did not proceed, but the baseline study results have provided a useful foundation for the development of this scenario.

The aggregate resource was investigated by coring, sidescan sonar and other methods and was found to be of glacial origin and, in general, more poorly sorted than is desirable for an aggregate target. Extraction would be by means of a large ocean-going trailing suction hopper dredge. The operation would produce about 18,000 metric tonnes of aggregate daily for 25 days each month, and would run for approximately 7 months of the year (winter sea conditions prevent year-round operation). Cycle times would be in the range of 8 to 13 hours depending on vessel speed and the capabilities of the offloading facilities.

During dredging, muds are discharged to the sea with the hopper overflow. While excavating, the twin trailing drag-heads create parallel furrows in the seabed each about 2.7 m wide and 0.5 m deep. Potential environmental impacts include the destruction of benthic fauna entrained by the dredge, changes in substrate grain size through exposure of different lithologies or settlement of fine sediments (possibly leading to recolonization by a different benthos), habitat alteration through modification of the seabed topography, and transient water column effects on primary production related to elevated turbidity levels.

A number of practical and cost-effective mitigation techniques can be implemented to reduce the extent of deposition of fines and water column turbidity (see Section 5.3). An example of such a technique is hopper overflow that may delayed by emptying the hopper of all water before pumping sediments on-board. Overflow does not occur until the hopper achieves 60% to 70% of fill capacity, thereby significantly reducing the total time of overflow discharge.

For drag-heads equipped with water jets to dislodge compacted sediments, it is possible to recycle a portion of the hopper waste water to the jets to reduce the total surface discharge. Preventing overflow by recirculating all process water to the drag-heads is not of particular benefit because the slurry quickly reaches a density beyond the pump capabilities, so that the system needs to be purged at intervals. The adoption of sub-surface discharge systems, such as the IHC and Japanese anti-turbidity overflow systems, may reduce significantly surface water turbidity and sediment dispersion and should be considered as a mitigation option.

Changes to seabed lithology and topography can be minimized through careful planning of dredge course locations and frequencies. The depth of seabed dredged can be limited to avoid revealing different underlying lithologies, as guided by detailed geological survey data and on-board feed monitoring systems. Dredge courses should be planned to avoid overdredging (overdeepening) and oversanding, to limit repeated disturbance of areas of seabed undergoing benthic recolonization, and to take into account as much as possible the areal and sub-surface distribution of the aggregate resource, within the constraints of dominant current directions.

6.1.4 Heavy Mineral Sands, Virginia

Scenario 4 describes a hypothetical heavy mineral mining operation offshore Virginia Beach, Virginia. The resource is comprised of well-sorted sands with heavy mineral concentrations averaging about 3 to 4% by weight, occurring mainly in the uppermost 3.5 m of seabed. Potential mining is by cutter suction dredging from a floating or jack-up platform. The dredge advances with the aid of winch-controlled anchor lines and the cutter-head arm moves through a broad arc with an average cut depth of 4 m. The feed is screened and heavy minerals are concentrated in the onboard wet mill. Approximately 95% of the sediments dredged are returned to the sea as tailings.

The primary potential environmental impacts of such an operation include the destruction of biota entrained by the dredge, modification of benthic habitat through changes in bottom topography, smothering of benthos by deposited tailings, and transient effects on primary productivity due to elevated water column turbidity.

As discussed in Section 5.4.4.4, the site specific design and implementation of a (subsurface) tailings discharge system is a cost-effective and recommended mitigation technique. Other cost-effective approaches to limiting the turbulent dispersion of sediments introduced to the sea include the use of de-gassing and de-sliming equipment, and end-of-stream cycloning to dewater as much as possible the solids effluent.

The use of chemical flocculants to enhance settling of discharged fines holds some potential but requires further investigation of its practical application at sea and of potential environmental implications. Flocculants are costly and would be expected to increase annual mining costs by more than 10%. For these reasons, the use of chemical flocculants is not unconditionally recommended.

Turbidity generated at the cut-face can be reduced practically by appropriate cutter-head design and by the dredging technique (i.e. controlled depth of cut, sloped vs. vertical cut face, etc.). Dredging technique can also affect the degree of seabed modification (e.g. extent of lateral cut face vs. dredge advance) and can be modified as appropriate within reasonable economic bounds.

As in the case of Scenario 1, the heterogenous nature of heavy mineral deposits means that location-based constraints placed on the mining operation can significantly affect its economic viability. Such constraints should be prescribed prior to commencement of the project.

6.1.5 Beach Nourishment, Maryland

Scenario 5 details a beach nourishment project at Ocean City, Maryland, utilizing a sand resource (borrow site) located in Federal waters seaward of the State boundary. The dredge is expected to be either a cutter suction dredge with transport of sand to shore by pipeline, or a trailing suction hopper dredge that delivers sand to a shore-connected pumping station. In each case there is virtually no solids effluent discharged at sea, and resuspended materials are localized to the vicinity of the excavation tool.

Potential environmental impacts include (but are not necessarily limited to) the destruction of benthos, transient water column effects related to increased turbidity, and alteration of bottom topography leading to either the development of anoxic dredge pits or the risk of shoreline erosion. The potential risk of inducing shoreline erosion warrants consideration with any beach nourishment project and can be minimized through numerical modelling and informed, appropriate selection of borrow sites.

6.2 General Recommendations

General recommendations derived from the analysis presented in this report include:

(1) The use of Best Available Technology should be practiced with any marine mining operation. The use of Best Available Technology is not only beneficial environmentally but in most cases improves operational efficiency and is therefore of value to the operator

(2) Numerical modelling is a useful and cost-effective tool in the development of effluent discharge systems, the design of environmental monitoring programs, and the assessment of the potential risk of coastal erosion. Modelling should be implemented as part of any mining project that involves substantial discharge of effluents at sea, or of projects that may potentially affect coastal stability

(3) Well-designed environmental monitoring programs with appropriate QA/QC are a necessary component of any marine mining project. Monitoring ensures that regulatory constraints are observed, and also provides the operator with ongoing guidance as to the level of effort needed to meet those constraints

(4) Operational constraints of location, time and scale need to be determined before the initiation of any mining project, so that the economic viability of the project can be realistically assessed. From an operational and economic perspective, constraints on operations that are based on random occurrences such as sightings of particular species in the mining area are

detrimental and potentially very costly. The possible implications of such constraints should be carefully considered

(5) In some cases mitigation can be achieved cost-effectively through changes in operational procedures, such as the planned order and distribution of dredge courses or the depth and width of cut. The planning of any new marine mining venture should take into consideration the range of operational mitigation techniques presented in this report

(6) Many technology-based mitigation techniques, such as sub-surface tailings discharge systems, dewatering and degassing systems, and onboard feed monitoring systems, measurably reduce the impacts associated with a mining operation and can be implemented at reasonable cost. The implementation of these techniques should be considered for any future offshore mining development

(7) The potential for Alternative Enhancement projects should be explored during the planning stages of future marine mining developments. For example, consideration should be given to the possibility of using tailings produced by a heavy mineral mining operation for beneficial purposes, such as beach nourishment or the creation or restoration of coastal wetlands.

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Table 2.1 Summary of the scope of environmental and biological data from selected surveys of gravel and sand deposits

Environmental Data					Biological Data					Other Data				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Reference	Location	Gravel or Sand	Particle Size	Sediment & Water Chemistry	Species (sp) Counts	HOTS[1] Counts	Diversity Indices[2]	Biomass	Noted Taxa	Dredging Impact	Smothering Impacts	Sampling Paradigm[3]	No. of Cruises (& sites/ cruises)	No. of Stations/ site (reps/ station)
Kenny & Rees, 1994 and	North Sea	Gravel	Particle size	-	√(no raw data)	-	# of sp.	√	sp.	√	?	B/A T/R	4(2)	2(2-5)
Kenny & Rees, 1993	North Sea	Gravel	Particle size	-	√(no raw data)	√	# of sp.	√	sp. + HOTs	√	?	B/A T/R	4(2)	2(2-5)
Saloman *et al* 1982	Gulf Coast of Florida	Sand	Grain size, Phi, %	Temp, Salinity, Carbon	√	-	√, # of sp.	-	sp. + HOTs	√	-	B/A T/R	4 + 3	2(4) + 1(32,35,36) +6(90)
Padan, 1977	Atlantic Ocean (Massachu setts Bay)	Cobble, gravel + sand	None	Water Chemistry	√	√	√	-	√, feeding guilds	-	-	B T/R	8	8 (varies) mud stations excluded
ENSR, 1991	Bering Sea	Sand + Gravel	Grain size, %	Water Chemistry	√	√	√	√	√	√	√	T/R		7(8-6)

[1] Higher Order Taxa
[2] One or more calculated Diversity Indices
[3] B/A = Before and After Impact, T/R = Test and Reference, B = Baseline
√ = present

Table 2.2 Example of variation in number of taxa from year to year

	No visible tailings						Tailings 1-20 cms									Tailings > 20 cms									
Survey	24	1	8	11	21	25[1]	2	3	4	7	10	12	20	22	23		5	6	9	13	14	15	16	17	19
1970 Jan		16					8	9	10	15	20	10	17	23			5	7		16	15		7	10	21
1971 Jun		60	34	25	28		7	14	11	29	29	31	26	42	42		18	23	42	4	28	26	13	29	18
1971 Dec[2]		41					15		20								18	35	24		52	25	13	63	26
1972 Jun		24	41	31	26		11	10	10	20	32	31	30	39	17		11	15	13	10	34	1	nd[3]	10	15
1972 Dec		34	23	43	28		8	10	16	29	32	34	26	40	49		18	21	19	4	14	3	nd	10	13
1977 Sep[4]	20	24	36	28	20		18	15	17	23	29	18	18	25	43	13	19	17	12	14	16	4	4	4	17
1978	20	30	28	22	25		13	16	13	26	19	23	21	31	27	20	17	24	12	7	16	5	0	1	13
1979	19	31	31	26	27	29	13	15	19	29	27	25	23	41	46	17	23	15	13	8	23	4	3	9	10
1980	18	31	38	40	31	15	21	17	15	33	35	32	27	40	38	18	17	18	22	1	28	9	8	13	13
1981	36	22	37	42	60	57	17	9	12	40	25	35	29	44	74	nd	24	23	10	9	17	1	3	16	13
1982	30	21	45	46	52	57	25	16	19	42	38	33	32	63	47	11	23	25	5	4	19	0	5	11	20
1983	45	41	43	54	50	54	27	10	23	55	37	32	37	64	83	12	24	23	13	4	30	2	2	6	15
1984	40	43	37	54	61	52	28	29	31	54	61	41	35	69	84	11	37	34	29	14	40	2	4	4	19
1985	43	41	54	40	49	49	24	23	28	41	46	39	28	55	70	10	25	27	12	8	27	11	4	6	11
1986	40	76	63	92	102	63	19	26	25	71	52	45	31	93	111	20	39	37	32	22	43	8	2	4	14
1987	48	78	77	84	103	59	25	31	28	88	99	66	50	83	121	8	42	20	22	11	49	3	9	13	25
1988	64	85	75	78	83	77	28	34	25	89	76	48	54	120	142	13	32	18	26	18	49	6	10	15	30
1989	53	89	52	93	87	72	26	19	25	61	48	39	52	116	139	15	23	27	18	5	35	7	10	15	19
1990	58	124	73	77	101	100	34	24	32	85	70	64	49	120	154	27	28	28	32	14	35	5	8	15	15
1991	54	88	73	95	77	126	27	31	28	69	64	59	68	100	132	8	39	27	8	8	32	3	15	14	22
1992	55	79	59	78	76	121	31	42	30	81	71	71	46	107	123	10	26	25	20	10	37	8	10	9	6
1993	54	81	57	76	67	115	32	24	31	62	55	51	42	118	123	nd	30	22	16	14	36	4	8	9	6

[1] 3 cm mixed tailing in 1993
[2] Tailing discharge started October 1971
[3] nd = no data
[4] Samples taken during September from 1977 onwards. Diversity values not obtained 1973-1976

Data taken from $3x0.05m^2$ sampler at each of a set of Test and Reference sampling stations around a tailings outfall. (Data courtesy of Island Copper Mine, Canada).

Table 2.3 Time periods to recovery for benthic biodiversity

(1) Fine-grained deposits[1] muds/silts/clays can contain some rocks and boulders	1 year
(2) Medium-grained deposits[2] sands can contain some silts/clays and gravel	1-3 years
(3) Coarse-grained deposits[3]	
gravels can contain some finer fraction and some rocks and boulders	5 years
gravels with many rocks and boulders	5+ years

Recovery times are based on no further impact from dredging at adjacent sites (e.g. no settling of a drifting tailings plume).

Recovery is defined as attaining a successional community of opportunistic species providing evidence of progression towards a community equivalent to that previously present, or at non-impacted reference sites.

Equivalency can be measured in terms of standing crop, biomass, number of species and numbers of most abundant species, etc. These criteria will need definition during preparation of an Environmental Impact Statement (or equivalent document) at any site. The definition will depend on the Best Available Monitoring techniques suitable for biodiversity assessment at that site.

[1] See Ellis *et al.* 1995 (Island Copper Mine tailings disposal)

[2] Sands - See 3.2 Scenario 1: Precious Metal Mining, Alaska - bucket ladder dredge and Appendix 4, Salomon *et al.* 1982. See also Garnett and Ellis (1995)

[3] Gravels - See 3.2 Scenario 1: Precious Metal Mining, Alaska - bucket ladder dredge and Appendix 3, Kenny and Rees 1993;1994. See also Garnett and Ellis (1995)

Table 2.4 **The Quality Assurance/Quality Control CODIS system (Continental and Oceanographic Data Information System) of Blyth *et al.* (1993)**

0 =	Data are found to be wrong. The data source contains obvious errors.
1 =	Data are suspect because of suspected internal inconsistencies; patterns or trends within the data are probably not real.
2 =	Insufficient information is provided to assess the quality of the dataset; trends in the data may, or may not, be real.
3 =	Data are internally consistent; patterns of trends within the data are probably real; comparisons with other datasets may be difficult or impossible.
4 =	Data are internally consistent and are sufficiently standardized to permit comparison with other datasets of this quality rating.
9 =	Data not yet rated.

Table 2.5 Environmental screening information needed for development of mitigation procedures at offshore dredging sites

(1) Fisheries

Stocks present, and current use
Includes both bottom and open water stocks
Includes fin-fish and shell-fish
Feeding habits, and level of habitat dependency

(2) Sensitive Species and Habitats

Wildlife (mammals), waterfowl (birds) and others such as reptiles
Stocks present, numbers, timing and patterns of seasonal changes

Spawning grounds (fish), migration routes and migration stopover sites (mammals and birds), and timing of their use. Importance of the site to the species, i.e. is the site unique or one of how many others?

(3) Benthic Habitat and Biodiversity

Particle size analysis and geochemistry of deposit
Number of species and their numbers per unit area
Identifications of most abundant (characterising) species

(4) Physical/Chemical Oceanography

Wind and Seastate records
Current records - patterns of velocity and direction
Water clarity, and turbidity plume dispersion modelling
Basic seawater characteristics - temperature, salinity, dissolved oxygen, etc, and seasonal variations

(5) Biological Oceanography

Characteristic levels of primary production
Characteristic phytoplankton, zooplankton and nekton

(6) Geochemistry

Natural variables determining benthic biodiversity - depth within deposit of reduced oxygen layer and associated geochemistries

Anthropogenic variables - presence of site-specific toxins determined from prior site use, or proximity to anthropogenic input, i.e. cities, major shipping routes, dump-sites, etc.

Screening information is to be assembled during preparation of a preliminary Environmental Impact Statement (EIS). Some field surveys may be needed to update or extend archived information.

Table 2.6 Likely availability of environmental screening information prior to implementation of an environmental impact statement (based on data searches, 1994-5)

(1)	Fisheries - probably non-technical fishing maps Much archived information in Federal files
(2)	Sensitive species/habitats Much archived information in Federal files Non-technical documents may be readily available
(3)	Benthic biodiversity Much archived species information in government and university records, but probably old, non-quantitative and not site-specific
(4)	Physical/Chemical Oceanography Much archived information in government and university records. Probably accessible electronically.
(5)	Biological Oceanography Much archived information in government and university records, but probably old, may be quantitative, but not site-specific
(6)	Geochemistry Probably some archived information, but may not be site specific. If there are prior pollution studies, there may be a recent compilation.

Table 2.7 Toxin concentration guidelines for sediment, U.S.A. and Canada (Table Cont'd)

Chemical	Low Values		High Values		EP Values
	U.S.A. Effects Range Low[1]	Canada Threshold Effects Levels[2]	U.S.A. Effects Range Median[3]	Canada Probable Effects Levels[4]	1% Carbon Sediment
METALS (ppm):					
Antimony	2	-	25	-	-
Arsenic	33(8.2)	7.24	85(70)	41.6	8.2
Cadmium	5(1.2)	0.676	9.0(9.6)	4.21	7.7
Chromium	80(81)	52.3	145(370)	160	
Copper	70(34)	18.7	390(270)	108	34
Lead	35(46.7)	30.2	110(218)	112	33
Mercury	0.15	0.13	1.3(0.71)	0.70	0.008
Nickel	30(20.9)	15.9	50(51.6)	42.8	-
Silver	1	0.73	2.2(3.7)	1.77	-
Tin	-	-	-	-	-
Zinc	120(150)	124	270(410)	271	190
POLYCYCLIC AROMATIC HYDROCARBONS (ppb):					
Acenaphthene	150(16)	6.71	650(500)	88.9	-
Acenaphthylene	(44)	5.87	(640)	128	-
Anthracene	85(85.3)	46.9	960(1100)	245	-
Fluorene	35(19)	21.2	640(540)	144	-
2-methylnaphthalene	65(70)	20.2	670	201	-
Naphthalene	340(160)	34.6	2100	391	-
Phenanthrene	225(240)	86.7	1380(1500)	543.5	-
Benz(a)anthracene	(261)	74.8	(1600)	693	-
Benzo(a)anthracene	230	-	1600	-	-
Benzo(a)pyrene	400(430)	88.8	2500(1600)	763	-
Benzo(e)pyrene	-	-	-	-	-
Biphenyl	-	-	-	-	-
Chrysene	400(384)	107.8	2800	846.0	-
Dibenzo(a,h)anthracene	(63.4)	6.22	(260)	135	-
Dibenz(a,h)anthracene	60	-	260	-	-
2,6-dimethylnaphthylene	-	-	-	-	-
Fluoranthene	600	113	3600(5100)	1494	3600
1-methylnaphthalene	-	-	-	-	-
1-methylphenanthrene	-	-	-	-	-
Perylene	-	-	-	-	-
Pyrene	350(665)	153	2200(2600)	1398	-
2,3,5-trimethylnaphthalene	-	-	-	-	-
	-	-	-	-	-
Total Polycyclic Aromatic Hydrocarbons	4000(4022)	-	35000(44792)	-	-
	-	-	-	-	-
Low molecular weight PAH	(552)	-	(3160)	-	-
High molecular weight PAH	(1700)	-	(9600)	-	-

Table 2.7 Toxin concentration guidelines for sediment, U.S.A. and Canada (Cont'd)

Chemical	Low Values		High Values		EP Values
	U.S.A. Effects Range Low[1]	Canada Threshold Effects Levels[2]	U.S.A. Effects Range Median[3]	Canada Probable Effects Levels[4]	1% Carbon Sediment
PESTICIDES (ppb):					
Lindane	-	-	-	-	-
Chlordane	0.5	2.26	6	4.79	-
Heptachlor	-	-	-	-	-
p'p'-DDD	2	1.22	20	7.81	3240
p'p'-DDE	2(2.2)	2.07	15(27)	374	6930
p'p'-DDT	1	1.19	7	4.77	1.6
DDT, total	3(1.58)	3.89	350(46.1)	51.7	-
Aldrin	-	-	-	-	-
Dieldrin	0.02	0.715	8	4.3	-
Endrin	0.02	-	45	-	-
Lindane	-	0.32	-	0.99	-
Mirex	-	-	-	-	-
MISCELLANEOUS ORGANICS (ppb):					
PCBs, total	50(22.7)	21.5	400(180)	189	29
Bis(2ethylexyl)phthalate	-	182	-	2647	-

1 "concentrations above which adverse effects may begin" (Long and Morgan, (1991)
2 "concentrations below which effects rarely occurred" (Anon, 1994)
3 "concentrations above which effects were frequently or always observed" (Long and Morgan, 1991)
4 "concentrations above which effects frequently occurred" (Anon. 1994)

Numbers in brackets are from Long *et al.* (1995)

Table 2.8 Example of environmental impacts, mitigation objectives and achievement criteria for proposed mine sites

1. Water column Impacts (turbidity)

Impact (Primary):
- reduced primary biological production and changed species

Impact (Secondary-derived):
- modified secondary production of zooplankton, hence possibly fish.

Objective:
- minimize elevations of surface water turbidity

Criteria:
- surface turbidity does not reduce the compensation depth by more than 10%. Increase of surface turbidity is less than a site-specific preset value (a dilution zone may be set within which these objectives need not be reached)

2. Seabed Impacts

Impact (Primary):
- benthic kills, toxin releases, and altered substrate (habitat)

Impact (Secondary):
- changed benthic biodiversity, fisheries changes (losses or enhancement both possible)

Objectives:
- minimize dredge course overlaps and gaps
- minimize return of tailings outside dredge footprint
- leave surface at same grade
- no release of contaminants
- no anoxic dredge furrows
- recovery to a successional community within time scale of: silts - 2 years, sands - 3 years, gravels - 5 years
- avoid sensitive areas - endangered species, isolated breeding grounds, etc.

Criteria:
- to be set on basis of dredging plan, and site-specific EIA
- dissolved oxygen level >3 mg/l
- apply EPA or NOAA guidelines for specific contaminants
- set recovery criteria site-specifically in terms of biodiversity (number of species, number of organisms and, possibly, selected species)

3. Impacts on Fisheries and Wildlife Resources

Impacts:
- little impact expected usually, as wildlife and fish are able to avoid vessels
- fisheries may be impacted by presence of mining vessels
- seabed spawning grounds may be seriously impacted
- local reactions by wildlife are known to occur at noisy oil rigs, generalised avoidance may occur

Objectives:
- avoid sensitive habitats, such as finfish and shellfish spawning grounds, and wildlife migration staging grounds or intense migration routes
- design quiet vessels to Best Practical Technology

Criteria:
- changes in migration, spawning and other behaviour of wildlife as set site-specifically
- noise measures to be set site-specifically if needed to protect sensitive species
- dredge plan implementation monitored

Table 2.9a Weather statistics for the U.S. east coast offshore (from Meserve, 1974) Site 20: represents offshore Massachusetts

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
WIND												
Scalar mean wind speed [kts]	18.9	19.6	18.5	15.7	12.9	11.2	10.5	10.8	12.7	15.2	17.5	18.7
Wind directions with >20% frequency [from]	NW W	W NW	W NW	W	NONE	SW	SW	SW W	NONE	NONE	NW W	NW W
Vector mean wind speed [kts]	8.4	9.0	7.5	4.9	2.7	3.5	4.4	3.1	2.4	4.3	6.0	8.4
Vector mean wind direction [from]	NW	NW	NW	NW	W	SW	SW	SW	NW	NW	NW	NW
Percent frequency winds > 28 kts [%]	19	22	18	11	4	2	1	3	4	10	16	18
Percent frequency winds > 34 kts [%]	9	11	8	4	1	<1	<1	1	1	4	8	9
AIR TEMPERATURE												
90% upper limit air temp [deg. C]	13	12	12	15	19	22	25	25	24	21	18	14
Mean air temperature [deg. C]	6	4	6	8	13	17	21	21	19	16	11	8
10% lower limit air temp [deg. C]	0	-1	1	4	7	12	16	17	15	11	6	2
SEA SURFACE TEMPERATURE												
90% upper limit sea surface temp [deg. C]	16	16	16	17	20	23	25	25	25	23	20	17
Mean sea surface temperature [deg. C]	9	9	8	10	13	17	21	22	21	18	14	12
10% lower limit sea surface temp [deg. C]	4	3	3	4	6	10	14	17	16	13	10	7
PRECIPITATION AND VISIBILITY												
Percent frequency precipitation [1%]	23	24	18	11	9	7	8	7	8	10	15	21
Percent freq. restricted visibility < 2 n mi [%]	5	6	5	6	11	14	12	9	4	4	3	3
SIGNIFICANT WAVE HEIGHT												
Percent frequency wave height > 3 m [%]	28	29	22	16	9	3	3	3	7	15	23	27
Percent frequency wave height > 4 m [%]	13	15	9	6	4	1	1	1	2	5	10	14
Percent frequency wave height > 6 m [%]	3	5	3	2	1		<1	<1	<1	1	2	4
Percent frequency wave height > 8 m [%]	1	<1	1	1						<1	<1	2

Table 2.9b Weather statistics for the U.S. east coast offshore (from Meserve, 1974) Site H: Represents Offshore Virginia/Maryland

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
WIND												
Scalar mean wind speed [kts]	20.3	21.9	20.9	18.9	16.0	12.9	12.4	13.2	13.8	15.2	17.9	20.5
Wind directions with >20% frequency [from]	NWSW	NW W	NW	SW S	SW	SW	SW	SW	NONE	NE	NW	NW W
Vector mean wind speed [kts]	9.1	9.9	8.5	7.1	6.0	4.4	8.1	4.4	0.9	2.9	4.9	9.3
Vector mean wind direction [from]	W	W	W	SW	SW	SW	SW	SW	E	NE	W	W
Percent frequency winds > 28 kts [%]	24	30	25	18	8	3	2	3	5	7	19	25
Percent frequency winds > 34 kts [%]	12	16	13	8	2	<1	<1	1	1	2	8	12
AIR TEMPERATURE												
90% upper limit air temp [deg. C]	19	18	18	21	23	26	27	27	27	25	22	20
Mean air temperature [deg. C]	15	13	13	19	21	23	26	26	25	22	18	15
10% lower limit air temp [deg. C]	8	6	6	13	18	21	24	24	22	18	11	8
SEA SURFACE TEMPERATURE												
90% upper limit sea surface temp [deg. C]	22	22	21	21	24	26	27	27	28	26	24	22
Mean sea surface temperature [deg. C]	19	19	19	19	22	24	26	26	27	24	22	20
10% lower limit sea surface temp [deg. C]	13	13	12	18	21	22	25	25	25	21	17	15
PRECIPITATION AND VISIBILITY												
Percent frequency precipitation [1%]	21	20	18	13	11	9	10	8	8	11	15	18
Percent freq. restricted visibility < 2 n mi [%]	4	4	1	<1	<1	<1	<1	<1	<1	<1	<1	2
SIGNIFICANT WAVE HEIGHT												
Percent frequency wave height > 3 m [%]	36	40	35	27	11	6	6	7	10	14	28	33
Percent frequency wave height > 4 m [%]	17	21	17	10	2	2	1	2	2	6	12	15
Percent frequency wave height > 6 m [%]	5	5	4	2		<1		<1	<1	1	2	4
Percent frequency wave height > 8 m [%]	2	<1	1							<1	<1	1

Table 3.1 Typical seasonal ocean current velocities expected for the Virginia Beach and Ocean City sites (based on data from U.S. Department of the Interior, Minerals Management Service, 1985)

	Nearshore Virginia	Nearshore Maryland
Spring	<40 cm/s to SE	<40 cm/s to SW
Summer	<40 cm/s to SE	<10 cm/s to SW
Fall	<40 cm/s to S	<10 cm/s to SSE
Winter	<40 cm/s to SE	<40 cm/s to SW

Table 3.2 Summary of ocean current flow for the Virginia Beach and Ocean City sites

	Nearshore Virginia	Nearshore Maryland
Average surface current speed	10 cm/s toward south	10 cm/s toward southwest
Typical bidirectional tidal surface current speed, oriented along the coastline	20 - 30 cm/s	20 - 30 cm/s
Extreme bidirectional tidal surface current speed, oriented along the coastline	50 cm/s	50 cm/s
Extreme magnitude of transient flow (variable directions)	50 cm/s	50 cm/s
Average bottom current speed (variable directions)	2 cm/s	2 cm/s

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Table 2.1 Summary of the scope of environmental and biological data from selected surveys of gravel and sand deposits

	Environmental Data				Biological Data					Other Data				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Reference	Location	Gravel or Sand	Particle Size	Sediment & Water Chemistry	Species (sp) Counts	HOTS[1] Counts	Diversity Indices[2]	Biomass	Noted Taxa	Dredging Impact	Smothering Impacts	Sampling Paradigm[3]	No. of Cruises (& sites/ cruises)	No. of Stations/ site (reps/ station)
Kenny & Rees, 1994 and	North Sea	Gravel	Particle size	-	√(no raw data)	-	# of sp.	√	sp.	√	?	B/A T/R	4(2)	2(2-5)
Kenny & Rees, 1993	North Sea	Gravel	Particle size	-	√(no raw data)	√	# of sp.	√	sp. + HOTs	√	?	B/A T/R	4(2)	2(2-5)
Saloman *et al* 1982	Gulf Coast of Florida	Sand	Grain size, Phi, %	Temp, Salinity, Carbon	√	-	√, # of sp.	-	sp. + HOTs	√	-	B/A T/R	4 + 3	2(4) + 1(32,35,36) +6(90)
Padan, 1977	Atlantic Ocean (Massachusetts Bay)	Cobble, gravel + sand	None	Water Chemistry	√	√	√	-	√, feeding guilds	-	-	B T/R	8	8 (varies) mud stations excluded
ENSR, 1991	Bering Sea	Sand + Gravel	Grain size, %	Water Chemistry	√	√	√	√	√	√	√	T/R		7(8-6)

[1] Higher Order Taxa
[2] One or more calculated Diversity Indices
[3] B/A = Before and After Impact, T/R = Test and Reference, B = Baseline
√ = present

Table 2.2 Example of variation in number of taxa from year to year

	No visible tailings						Tailings 1-20 cms									Tailings > 20 cms									
Survey	24	1	8	11	21	25[1]	2	3	4	7	10	12	20	22	23		5	6	9	13	14	15	16	17	19
1970 Jan		16					8	9	10	15	20	10	17	23			5	7		16	15		7	10	21
1971 Jun		60	34	25	28		7	14	11	29	29	31	26	42	42		18	23	42	4	28	26	13	29	18
1971 Dec[2]		41					15		20								18	35	24		52	25	13	63	26
1972 Jun		24	41	31	26		11	10	10	20	32	31	30	39	17		11	15	13	10	34	1	nd[3]	10	15
1972 Dec		34	23	43	28		8	10	16	29	32	34	26	40	49		18	21	19	4	14	3	nd	10	13
1977 Sep[4]	20	24	36	28	20		18	15	17	23	29	18	18	25	43	13	19	17	12	14	16	4	4	4	17
1978	20	30	28	22	25		13	16	13	26	19	23	21	31	27	20	17	24	12	7	16	5	0	1	13
1979	19	31	31	26	27	29	13	15	19	29	27	25	23	41	46	17	23	15	13	8	23	4	3	9	10
1980	18	31	38	40	31	15	21	17	15	33	35	32	27	40	38	18	17	18	22	1	28	9	8	13	13
1981	36	22	37	42	60	57	17	9	12	40	25	35	29	44	74	nd	24	23	10	9	17	1	3	16	13
1982	30	21	45	46	52	57	25	16	19	42	38	33	32	63	47	11	23	25	5	4	19	0	5	11	20
1983	45	41	43	54	50	54	27	10	23	55	37	32	37	64	83	12	24	23	13	4	30	2	2	6	15
1984	40	43	37	54	61	52	28	29	31	54	61	41	35	69	84	11	37	34	29	14	40	2	4	4	19
1985	43	41	54	40	49	49	24	23	28	41	46	39	28	55	70	10	25	27	12	8	27	11	4	6	11
1986	40	76	63	92	102	63	19	26	25	71	52	45	31	93	111	20	39	37	32	22	43	8	2	4	14
1987	48	78	77	84	103	59	25	31	28	88	99	66	50	83	121	8	42	20	22	11	49	3	9	13	25
1988	64	85	75	78	83	77	28	34	25	89	76	48	54	120	142	13	32	18	26	18	49	6	10	15	30
1989	53	89	52	93	87	72	26	19	25	61	48	39	52	116	139	15	23	27	18	5	35	7	10	15	19
1990	58	124	73	77	101	100	34	24	32	85	70	64	49	120	154	27	28	28	32	14	35	5	8	15	15
1991	54	88	73	95	77	126	27	31	28	69	64	59	68	100	132	8	39	27	8	8	32	3	15	14	22
1992	55	79	59	78	76	121	31	42	30	81	71	71	46	107	123	10	26	25	20	10	37	8	10	9	6
1993	54	81	57	76	67	115	32	24	31	62	55	51	42	118	123	nd	30	22	16	14	36	4	8	9	6

[1] 3 cm mixed tailing in 1993
[2] Tailing discharge started October 1971
[3] nd = no data
[4] Samples taken during September from 1977 onwards. Diversity values not obtained 1973-1976

Data taken from $3x0.05m^2$ sampler at each of a set of Test and Reference sampling stations around a tailings outfall. (Data courtesy of Island Copper Mine, Canada).

Table 2.3 Time periods to recovery for benthic biodiversity

(1) Fine-grained deposits[1] muds/silts/clays can contain some rocks and boulders	1 year
(2) Medium-grained deposits[2] sands can contain some silts/clays and gravel	1-3 years
(3) Coarse-grained deposits[3]	
gravels can contain some finer fraction and some rocks and boulders	5 years
gravels with many rocks and boulders	5+ years

Recovery times are based on no further impact from dredging at adjacent sites (e.g. no settling of a drifting tailings plume).

Recovery is defined as attaining a successional community of opportunistic species providing evidence of progression towards a community equivalent to that previously present, or at non-impacted reference sites.

Equivalency can be measured in terms of standing crop, biomass, number of species and numbers of most abundant species, etc. These criteria will need definition during preparation of an Environmental Impact Statement (or equivalent document) at any site. The definition will depend on the Best Available Monitoring techniques suitable for biodiversity assessment at that site.

[1] See Ellis *et al.* 1995 (Island Copper Mine tailings disposal)

[2] Sands - See 3.2 Scenario 1: Precious Metal Mining, Alaska - bucket ladder dredge and Appendix 4, Salomon *et al.* 1982. See also Garnett and Ellis (1995)

[3] Gravels - See 3.2 Scenario 1: Precious Metal Mining, Alaska - bucket ladder dredge and Appendix 3, Kenny and Rees 1993;1994. See also Garnett and Ellis (1995)

Table 3.3 **Grain sizes from drillhole program, offshore Nome (American Smelting and Refining Company, 1974)**

Number of Drillholes	568	500
	Grain Size %	Grain Size %
Clay (<0.0039 mm):	20	24
Silt (and mud) (0.0039 - 0.0625 mm):	4	1
Sand (0.0625 - 2.0 mm):	5	24
Gravels (2.0 - 64 mm):	35	37
Till:	28	0
Other (including rock):	9	15

Table 3.4 **Silt content of dredged ground showing increase with increasing water depth, offshore Nome (ENSR Consulting & Engineering, 1991)**

Water Depth (m)	Average Silt Content %	Maximum Silt Content %
7	2.3	26
10	6.5	22
15	6.5	33
20	7.5	97

Table 3.5 Typical figures of gold grade after application of a suitable cut-off grade, offshore Nome

Ground Type	Total Ground (%)	Average Gold Grade (average =100)	Total Contained Gold (%)
Clay	5	144	1
Silt	8	166	13
Sand	28	56	17
Gravel	52	117	65
Till	5	55	3
Broken rock	2	47	1

Table 3.6 Typical operating conditions at the Nome site mined by WestGold

Expected throughput rates when dredging loose mud, sand and gravel to about 15 m below seabed in about 10 m of water:

- stripping: 1,200 m^3 per operating hour
- treating: 800 - 900 m^3 per operating hour, and
- average: 1,000 - 1,100 m^3 per operating hour.

Average downtime:

- Mechanical:	12%
- Electrical:	3%
- Weather:	8%
- Operational:	7%
- Total	30%

Average dredge performance from 1987 through 1990:

Operating time per year:	2,700 hours
Throughput rate:	457 m^3 per operating hour
Average area dredged:	37.2 ha/year
Average depth of cut:	3.2 m
Average grade recovered:	775 mg gold/m^3

Table 3.7 Dimensions and specifications of the bucket-ladder dredge BIMA

Length of pontoon: 110 m Breadth of pontoon: 30 m Depth of pontoon (at side): 6.5 m Length of ladder: 88 m
Average draft when working with 100% dead weight of 1,800 tonnes: 3.73 m. Maximum displacement: ± 12,000 m^3 Bucket capacity: 850 litres at a dredging depth of 26 m Number of buckets installed: 137
Total installed diesel power: 5,667 kW Total output of bucket bank drive motors: 1,342 kW 3 fuel-oil storage tanks, each with a 318 m^3 capacity Total lubricating and sludge oil tanks capacity: 22 m^3
Outreach of overburden stripping chute: 42 m @ 1:6.6 slope. Outreach of twin tailing launders: 22.7 m @ 1:18 slope Outreach of screen oversize chute: 11 m @ 1:4 slope Discharge height of overburden chute above sea level: 6.5 m Discharge height of tailings launders above sea level: 4.0 m

Table 3.8 Support facilities for the WestGold mining operation, Nome

Offshore: - ocean-going tug for anchor moves and dredge towing - supplies transport vessel - personnel carrying helicopter - part-time drilling vessel - part-time geophysical survey vessel
Onshore: - workshop - office, laboratory and warehouse - docking facility - camp accommodation
Personnel levels, including both supervisory and hourly paid, total about 70 during the dredging season, falling to 30 - 50 during the winter months.

Table 3.9 The distribution of solids and water under ideal conditions, WestGold mining operation, offshore Nome

Feed:	900 m^3 per operating hour
Water intake:	6.15 m^3/m^3 of feed
Total water requirements:	5535 m^3 per operating hour
Screen oversize:	90 m^3 per operating hour (10%)
Primary and secondary tailings:	808 m^3 per operating hour contained in 5,535 m^3 of water

Table 3.10 Dredge products and effluents, WestGold mining operation, offshore Nome

	1987	1988	1989	1990
Operating hours per day	15.8	18.2	17.0	16.1
Feed throughput rate (m^3/hour)	423	590	353	429
Water intake rate (m^3/m^3 feed)	11.3	--	--	--
Total water intake (m^3/hour)	4780	4780	4780	--
Trommel oversize (m^3/hour)	105-210 [25-50%]	236 [40%]	88 [25%]	86-107 [20-25%]
Primary jig tailings (m^3/hour)	85-155	295	220	--
Secondary jig tailings (m^3/hour)	58-233	58	45	--
Total Jig tailings (m^3/hour)	213-318	353	265	322-343

Table 3.11 Dredge feed composition, WestGold mining operation, offshore Nome

	Observed composition of the dredge feed (%)	Deduced composition of the dredge feed (%)
Silt	--	30
Silt and clay	14	--
Sand	31	45
Gravel	18	--
Till	37	--
Gravel and Cobbles	--	25

Table 3.12 Environmentally significant operating parameters for the bucket ladder dredge, BIMA, at the WestGold mining operation, offshore Nome (Cont'd next page)

Annual Period of Operations: Average 155-160 days per year, during summer
Specifications of the bucket ladder dredge BIMA: Length (pontoon): 110 m Width (pontoon): 30 m Height: 22.7m above main deck to top tumbler Draft (average): 3.7 m Cutting system: buckets (850l capacity) Delivery system: buckets, line-mounted on ladder
Scale of Operations: Throughput: approx. 500 - 800 m^3/hr in water > 10 m depth approx. < 600 m^2/hr. in water < 10m depth approx. average 457 m^3/hr Maximum: approx. 1000 m^3/hr
Dredge Course Parameters: Face width: 100 - 150 m Cut thickness (average): 3.2 m Maximum depth: 9.0 m in practice, but designed to be capable of approx. 35 m Course continuation (length, area, timing) ie. amount of advance before moving dredge: approx. 100 m Average area dredged/year: 37.2 ha Course length: 100's of metres
Area: average 37.2 ha/yr
Water feed: 4,780 m^3 per operating hour (average)
Tailings discharge rate (= total onboard feed, throughput and water): average 457 m^3/operating hour 11.3m^3 + water/ m^3 feed/operating hour 5,964 m^3 water/operating hour
Selectivity: vertically: ± 0.50 m horizontally: minimum face width of approx. 150 m with positioning of ± 2 - 3 m
Dredging Conditions:
Water Depths: 7 - 20 m
Size Fractions: silt/clay: 28% sand: 1% gravel: 28% cobbles: 43%
Total Area of of WestGold's Nome lease: 8,802 ha

Table 3.12 Environmentally significant operating parameters for the bucket ladder dredge, BIMA, at the WestGold mining operation, offshore Nome (Cont'd)

Effluents:

Type 1: Screen Oversize:

Discharge rate: 86 - 236 m^3/hr
Particle size: 0.953 mm - 1.0 m
Position of discharge point on vessel: 11 m beyond the stern

Type 2: Jig Tailings:

Discharge rate: 213 - 343 m^3/hr
Particle size: < 9.53 mm
Position of discharge point on vessel: 22.7 m beyond the stern

Table 3.13 Wildlife species in the Nome area and their feeding habits (Cont'd next page)

SEABIRDS -

	Feeding Guild	Habitat/Status
Family Alcidae		
Least Auklets Crested Auklets	Planktivore	Critical Breeding Habitat
Common Murres Thick Billed Murres	Piscivore	Breeding Habitat
Family Laridae(?)		
Black Legged Kittiwake	Piscivore	Breeding Habitat

Numerous other Seabirds breed here including the rare Aleutian Tern.

WATERFOWL AND SHOREBIRDS -

Large nesting concentrations of waterfowl and shorebirds:	Yukon River Delta
Other important areas:	South shore of the Seward Peninsula St. Lawrence Island, Golovin Lagoon Moses Point lagoon and delta
Species comprising majority of Alaskan and/or North American population:	Emperor goose, Cackling Canada goose, Black Brant, Spectacled Eider, Steller's
Eider	American Golden Plover, Whimbrel,
Red Knot,	Black Turnstone, Western Sandpiper,
Rock Sandpiper,	Dunlin and Bristle-thighed Curlew
Endangered Bird Species:	Peregrine Falcon - Feeds and lives near seabird colonies.

SEABED-FEEDING MAMMALS -

Ringed Seal (*Phoca hispida*):

primarily a seabed feeder: cod, sculpin, shrimp, mysids and amphipods
- most common and abundant. 1-1.5 million
- breeds in Norton Sound during winter on land-fast ice?

Bearded Seal (*Erignathus barbatus*):

a bottom feeder: crabs, clams, shrimp and some fish (cod and sculpins)
-commonly found throughout Norton Sound
- live on moving ice overlying shallow water.

Pacific Walrus (*Odobenus rosmarus*):

a bottom feeder: primarily clams, specifically the Greenland cockle (*Serripes groenlandicus*)
- less common but populations on increase
- calving in deltas in summer, reported in Norton Sound.

Other seabed-feeding mammals reported in Norton Sound:
Gray Whales, Steller's Sea Lion and Sea Otter.

Table 3.13 Wildlife species in the Nome area and their feeding habits (Cont'd)

MARINE MAMMALS (not feeding from seabed)

Spotted Seal (*Phoca vitulina largha*):

- primarily feed on pelagic fish
- common throughout Norton Sound in summer to fall
- breeding?

Beluga Whales (*Delphinapterus leucas*):

- feeds on pelagic and benthic organisms particularly Herring in early summer
- common throughout Norton Sound in summer
- calving reported in Norton Sound, estuarine deltas preferred.

Polar Bear (*Ursus maritimus*):

- feeds on seal and walrus
- enters Norton Sound in fall with the advancing ice following seals
- breeding?

Other marine mammals found in Norton Sound:

Ribbon Seal, Killer Whale, Minke Whale, Bowhead Whale and other large whales.

Table 3.14 Composition of lag gravel from two different types of glacial moraine, offshore Nome

	Area 1 %	Area 2 %
Silt (and clay)	6-20	8-46
Sand	38-74	30-47
Gravel	20-30	8-24
Cobbles and Boulders	0-7	0-30

Table 3.15 Specifications of the Underwater Miner, "Tramrod", used at WestGold's dredge site, offshore Nome

Equipment installed on "Tramrod"

- Submersible hydraulic power pack: 37 - 56 kW
- Reverse flush valve
- Hydraulic control valves in one atmosphere chamber
- Hydraulic compensators for pressure and volumetric displacement
- Marinized hydraulic rams
- Optional centrifugal slurry pump
- Sealed and lubricated track chains
- S.I.T. video cameras
- Scanning sonar
- Directional gyroscope
- Bathymetric suites

Dimensions of "Tramrod"

Ground length of tracks:	4.0 m
Overall length of tracked undercarriage:	5.8 m
Overall width of tracks:	4.2 m
Diameter of cutting wheel (if attached):	1.25 m
Maximum possible reach of ladder assembly:	9.7 m
Slewing angles from centre-line of machine:	50°
Deepest digging depth below seabed level:	2.0 m
Greatest digging height above seabed level:	2.8 m
Operating depth (maximum to date):	310 m
Design depth:	800 m
Minimum depth to date:	3 m

Dimensions of "Tramrod" with associated equipment

Item	**Quantity**	**Dimensions (m)**	**Weight (metric tons)**
Tramrod without cutter:	1	12.65 x 4.2 x 4.0	38.2
Tramrod with cutter:	1	10.5 x 4.2 x 4.0	42.5
Control cabin:	1	6.0 x 2.3 x 2.5	4.0
Water pump (+ 1 spare):	2	4.0 x 1.6 x 2.0	4.5
Umbilical spooler:	1	3.0 x 2.5 x 2.0	4.0
Workshop:	1	6.0 x 2.4 x 2.5	4.0
Spares container:	1	6.0 x 2.4 x 1.0	4.0
Motive hose spooler:	1	3.0 x 2.5 x 2.0	4.5

Table 3.16 Support facilities for WestGold's "Tramrod" mining operation, offshore Nome

The support vessel requirements:	
- Power supply without cutter	150 kVA 440v 60 Hz 3 phase;
- Power supply with cutter	250 kVA 440v 60 Hz 3 phase;
- High pressure water supply to suction intake	9093 l/minute @ 1034 kPa;
- Compressed air supply:	724 kPa @ 2.83 m^3/minute (minimum requirement);
- Crane capacity:	SWL 50 tonnes @ 6 m/minute from vessel's side with single fall preferred;
- Deck space:	250 - 300 m^2
- Deck loading:	6-7 tonnes/m^2
Offshore support facilities:	
- ocean-going tug for anchor moves and barge towing	
- vessel for transporting supplies and personnel	
- part-time geophysical and sampling vessel(s)	
Onshore support facilities:	
- workshop, office, laboratory, and warehouse	
- availability of docking or harbour facilities	

Table 3.17 Operating Capabilities of the "Tramrod" Underwater Miner

Maximum, non-digging, traverse speed on level ground:	400 m/hour
Maximum gradient negotiable:	45°
Maximum width of digging corridor:	
- without cutter:	12.3 m
- with cutter:	8.7 m
Attainable dredging accuracy:	0.10 m
Selective extraction capability:	
- variable thickness mud layers:	0.20 m
- thickness of dense fine sand:	0.15 m
Maximum solids content of dredged soil:	60%

Maintained throughput rate capabilities of the Underwater Miner:

Material being Dug	**Without Cutter (m^3/hr)**	**With Cutter (m^3/hr)**	**With Special Features (m^3/hr)**
Silt (only) depending on thickness:	-	-	100-500 [1]
Soft mud:	80	100	~150 [2]
Sand and gravel:	80	-	~150 [2]
Small gravels:	80	-	~150 [2]
Coarse gravels:	25-50	-	~150 [2]
Clay (150 kPa shear strength):	-	50	
Soft rock (e.g. chalk):	-	50	

[1] - Design stage completed and partly tested.
[2] - Design stage completed, with a target throughput of 300 m^3/operating hour.

Table 3.18 The main effluents from WestGold's "Tramrod" mining operation, offshore Nome

	Size Range	Rate of Solids Discharge (m^3/hr)	Solids (%)	Rate of Water Discharge (1/hr)
Grizzley oversize:	+0.20 m	15	100,000	-
Trommel oversize:	-0.20 m +38.1 mm	~ 34	*	Very low
Trommel mid-size:	-38.1 mm +12.7 mm	~ 3	*	Very low
Hydro-cyclone overflow:	-	-	**	Very variable
Primary & secondary jig tailings	-12.7 mm	98	~ 10	1,000 very variable
Total solids discharged per hour = 150 m^3				

* - accompanied by a little water
** - water only

The above conditions are true for a solids feed rate of 150 m^3/operating hour; an accompanying water feed rate of approximately 700,300 l/hour, or 11,700 l/minute; for the jigging circuit and other purposes an extra water feed rate of approximately 341,000 l/hour or 5,700 l/minute

Table 3.19 Environmentally significant operating parameters for the "Tramrod" Underwater Miner operation, offshore Nome

Annual Period of Operations:	Early June to early November (summer operations); possibly January - March (winter operations under ice)	
Scale of Operations:		
Throughput:	approx. 100-300 m^3/operating hour; average 150 m^3/operating hour	
Cut thickness:	$\leq$ 1.0 m	
Face width:	8.7 - 15.0 m	
Course length:	100 to several 100 m	
Area:	average 150 - 300 m^2/operating hour in total summer: 400,000 - 800,000 m^2 (40-80 ha.)	
Water feed:	for average throughput: 700 m^3 + 340 m^3 = 1040 m^3/operating hour	
Tailings discharge rate (= total onboard feed, throughput and water): average 150 m^3/operating hour + 1040 m^3 water/operating hour		
Selectivity:	vertically (approx. 0.20 m) horizontally - minimum face width approx. 5.0 m	
Mining Conditions:		
Water depths: 3 - 20 m (but "Tramrod" technically capable of working in considerably deeper water)		
Size fractions:	silt/clay:	6-46%
	sand:	30-74%
	gravel:	8-30%
	cobbles:	0-30%

Table 3.20 Mining parameters for the "Tramrod" Underwater Miner operation, offshore Nome

"Tramrod" characteristics:	
Cutting system:	bucket wheel
Delivery system:	hydraulic
Vessel type:	barge
Timing (refit needs, weather):	160-170 days per year during summer
Vessel (barge) Specifications:	
Length:	76 m
Width:	23 m
Draft:	1.5 m
Mining Course Parameters:	
Cut thickness (usual depth):	$\leq$ 1.0 m
Usual range:	0.20 - 1.00 m
Maximum depth:	2 - 3 m
Course continuation (length, area, timing) i.e. amount of advance before moving barge: approx. 30 - 50 m	
Effluents (averages):	
<u>Type 1 - Grizzley Oversize</u>:	
Discharge rate:	15 m^3 solids/operating hour
Particle size:	> 0.20 m
Position of discharge point on vessel:	rear starboard
<u>Type 2 - Trommel Oversize</u>:	
Discharge rate:	approx. 37 m^3 solids/operating hour
Particle size:	>12.7 mm < 0.20 m
Position of discharge point on vessel:	rear starboard
<u>Type 3</u>:	
Discharge rate:	approx. 98 m^3 of solids/operating hour
Particle size:	< 12.7mm
Position of discharge point on vessel:	starboard

Table 3.21 Features of a typical ocean-going, trailing suction hopper dredge for the Massachusetts Bay site

- trip capacity (i.e. hopper capacity) of 5,100 m^3
- digging depth capability of ~21 m
- twin trailing drag-heads
- cut depth of 40 - 60 cm below the seabed
- furrow width of 2.7 m (i.e. a 2.4 m drag-head width)
- drag-head separation of 25 m between the centre lines
- minimum furrow length of 300 - 600 m
- dredging speed of 6.5 km/h
- travelling time of 11 km/h

Table 3.22 Range of dredge pumping system performance for a trailing suction hopper dredge

	Fine gravel and sand	Coarse gravel	With mud
Number of pumps	2	2	--
Size of pumps (cm)	76.2	81.3	--
Throughput of slurry pumped (l/min/pump)	113,562	151,416	--
Total throughput of slurry (l/min)	227,124	302,832	--
Volume of solids in the slurry (%)	25 - 26	15 - 16	--
Volume of solids retained (%)	25	15	--
Volume of solids discarded (%)	1	1	--
Sediments dredged (%)	3.8	6.2	0 - 33.5
Rate of effluent discharge (l/min)	227,124 x 0.75= 170,343	302,832 x 0.85= 257,407	--

Table 3.23 Estimated and possible minimum total cycle time for travel, dredging and unloading by a suction hopper dredge, Massachusetts Bay dredge site

Operation	Estimated	Possible Minimum
Travel to dredging site	2 hr 30 min	1 hr 42 min [1]
Dredging (loading)	1 hr 15 min	1 hr 15 min
Travel to unloading site	2 hr 30 min	1 hr 42 min [1]
Unloading	7 hr 27 min	4 hr 15 min [2]
Total	13 hr 42 min	8 hr 54 min

[1] Assuming a travelling speed of 16.5 km/h (optimistic)
[2] Unloading time if using a 20 m^3 clamshell

Table 3.24 Environmentally significant operating parameters for marine aggregate mining, Massachusetts Bay

Annual Period of Operations:	7 months/year (25 days/month, 24 hour/day)
Scale of operations:	
Throughput:	approx. 1.8 million m^3/year produced
Cut thickness:	0.4 - 0.6 m
Face width:	2.75 m
Course length:	minimum of 300 - 600 m
Area:	approx. 360 ha excavated (minimum)
Water feed:	approx. 225-300 m^3/operating minute
Tailing discharge rate (= total onboard feed, throughput and water):	170 m^3/operating minute @ 3.8% solids to 257 m^3/operating minute @ 6.2% solids
Selectivity:	only by dredge location
Dredging Conditions:	
Water depths:	30 - 40 m
Size fractionsof surficial units (from Appendix 5 [Padan, 1977]):	sand units: 0 - 25% gravel: 75 - 100 % sand: 0 - 25% mud sandy gravel units: 33.5 - 75% gravel: 12.5 - 50% sand: 0 - 33.5% mud gravelly sand units: 12.5 - 50% gravel: 33.5 - 75% sand: 0 - 33.5% mud
Total Area of Prospect:	18 km^2

Table 3.25 Dredge and dredging parameters for marine aggregate mining, Massachusetts Bay

Trailing Suction Hopper Dredge Characteristics:	
Length:	106 m
Width:	21 m
Height:	9 m
Draft:	8 m
Volume:	4,600 m^3
Cutting system:	drag heads (twin)
Cut width:	2.75 m
Delivery system:	hydraulic
Timing (refit needs, weather):	7 months/year (24 hr./day, 25 days/month)
Dredge Course Parameters:	
Face width:	24.4 m between centre lines of drag heads
Cut thickness (usual depth):	0.4 - 0.6 m
Mminimum length of furrow:	300 - 600 m
Effluents:	
Type 1- Overflows:	
Discharge rate:	170 - 257 m^3/minute
Particle size:	silt and fine sand (3.8 - 6.2 ?% solids)
Position of discharge point on vessel:	port and starboard
Type 2 - Jig Tailings:	N/A

Table 3.26 Virginia Beach current measurement sites for 1973 (reported by Ludwick, 1978)

Site	Latitude/ Longitude	Distance offshore (km)	Water depth (m)	Position of current meter above bottom (m)	Start date	Record length (days)
1	36° 58' N 75° 59' W	4.1	23.8	14.9 upper 1.8 lower	Jul 22	27 upper 29 lower
2	36° 53' N 75° 57' W	3.5	8.2	3.7 upper 1.8 lower	Jul 22	27 upper 5 lower
3	36° 50' N 75° 56' W	3.6	9.1	4.9 upper 1.8 lower	Jul 21	29 upper 29 lower
4	36° 47' N 75° 55' W	3.6	9.8	5.5 upper 1.8 lower	Jul 21	34 upper 34 lower
5	36° 47' N 75° 53' W	7.1	15.2	11.0 upper 1.8 lower	Jul 21	29 upper 29 upper
6	36° 44' N 75° 54' W	3.9	12.5	8.2 upper 1.8 lower	Jul 21	29 upper 10 lower
4	36° 47' N 75° 55' W	3.6	9.8	5.5 upper 1.8 lower	Sep 02	28 upper 28 lower
1	36° 58' N 75° 59' W	4.1	23.8	16.1 upper	Sep 30	5 upper 31 lower
3	36° 50' N 75° 56' W	3.6	9.1	4.3 upper 1.2 lower	Sep 30	30 upper 30 lower
4	36° 47' N 75° 55' W	3.6	9.8	5.2 upper 1.2 lower	Sep 30	30 upper 30 lower
5	36° 47' N 75° 53' W	7.1	15.2	10.4 upper 1.2 lower	Sep 30	30 upper 30 lower
6	36° 47' N 75° 53' W	3.9	12.8	7.6 upper 1.2 lower	Sep 30	30 upper 30 lower

Table 3.27 **Maximum and mean current vectors, Virginia Beach current measurement sites for 1973 (reported by Ludwick, 1978)**

Site	Month	Position of current meter above bottom (m)	Maximum current speed (cm/s)	Current direction at maximum speed (toward °T)	Vector mean current speed (cm/s)	Vector mean current direction (toward °T)
		Near Bottom				
1	Jul/Aug		52.5	282°	8.8	296°
2	Jul/Aug	1.8	37.9	004°	2.1	156°
3	Jul/Aug	1.8	32.1	164°	0.4	344°
4	Jul/Aug	1.8	30.4	158°	0.7	128°
5	Jul/Aug	1.8	28.4	012°	1.8	272°
6	Jul/Aug	1.8	21.9	340°	1.1	000°
		1.8				
4	Sep		42.4	167°	0.5	143°
		1.8				
3	Oct		50.6	169°	0.6	144°
4	Oct	1.2	46.2	172°	2.6	192°
5	Oct	1.2	31.2	107°	1.0	328°
6	Oct	1.2	66.8	165°	0.8	335°
		1.2				
		Near Surface				
1	Jul/Aug		86.5	301°	7.2	270°
2	Jul/Aug	14.9	72.1	330°	2.8	214°
3	Jul/Aug	3.7	58.4	166°	7.9	217°
4	Jul/Aug	4.9	42.3	170°	5.6	184°
5	Jul/Aug	5.5	60.7	155°	9.1	171°
6	Jul/Aug	11.0	66.2	159°	10.6	178°
		8.2				
4	Sep		66.0	172°	5.0	185°
		5.5				
1	Oct		75.5	097°	12.2	080°
3	Oct	16.1	64.2	165°	3.4	197°
4	Oct	4.3	61.1	170°	4.3	152°
5	Oct	5.2	52.1	183°	5.6	163°
6	Oct	10.4	79.6	175°	6.5	158°
		7.6				

Table 3.28 Wave height exceedence probability offshore Virginia Beach between 1985-1992

Exceedance Probability (%)	Wave Height (m)
50%	2.00 m
75%	1.63 m
90%	1.18 m
95%	0.84 m

Table 3.29 Deposit thickness, offshore Virginia Beach (from core data reported by Berquist and Hobbs, 1988)

	Minimum core length (m)	Maximum core length (m)	Average core length (m)
Minerals Management Service cores	1.30	6.40	3.45
U.S. Geological Survey cores	1.45	8.20	3.50

Table 3.30 Grain size distribution of the uppermost 4 m of sediments, offshore Virginia Beach

- average sand content (>0.063 mm and <2 mm) of 86.56%
- average mud content (<0.063 mm) of 11.95%
- average gravel (>2 mm) content of 1.46%

Grain size distributions of samples from one typical drill hole

Granules (>2 mm)	3.9%
Very coarse sand (1 - 2 mm)	6.6%
Coarse sand (0.5 - 1 mm)	20.6%
Medium sand (0.25 - 0.5 mm)	57.8%
Fine sand (0.125 - 0.25 mm)	6.5%
Very fine sand (0.063 - 0.125 mm)	0.7%
TOTAL	96.1%

Ranges in grain size recoverable during drilling over short time periods (several minutes) and long periods (several days)

	Short Periods (%)	Long Periods (%)
Mud	0 - 41%	8.0 - 12.5%
Sand	54 - 98%	85.5 - 86.0%
Gravel	0 - 19%	0.7 - 2.5%6

Table 3.31 Environmentally significant operating parameters for dredging heavy mineral sands, Virginia

Scale of Operations:	
Throughput:	approx. 6,900 - 9,000 m^3/operating hour
Cut thickness:	average 4 m
Face width:	120 m
Course length:	60 m
Dredging Conditions:	
Water depth:	12 - 15 m
Size fractions:	
silt/clay:	11.95%
sand:	86.56%
gravel:	1.46%

Table 3.32 Parameters for a cutter suction dredge, heavy mineral sands, Virginia

Cutter Suction Dredge Characteristics:			
Cutting system:	cutter		
Delivery system:	hydraulic (69 - 76 cm diameter)		
sel type:	cutter suction dredge with separate floating wet mill		
Dredge Parameters:		**Wet Mill Parameters:**	
Specifications:			
Hull length:	180 m, hinged	Hull length:	180 m
Hull width:	24 m	Hull width:	120 m
Hull depth:	6 m	Hull depth:	9 m
Draft:	3 m	Draft:	6 m
Parameters of Cutting/Delivery System:			
Operating water depth:	12 - 15 m		
Cut width:	120 m		
Dredge Course Parameters:			
Face width:	120m		
Cut thickness:			
Usual depth:	1.3 - 6.4 m (average 4 m)		
Maximum depth:	55 m		
Course continuation (length, area, timing) i.e. amount of advance before moving dredge:	600 m		
Effluents:			
Type 1 - Trommel oversize:			
Discharge rate:	100 tonnes/operating hour (about 5% of feed)		
Particle size:	> 12.7mm		
Position of discharge point on wet mill:	port or starboard		
Type 2 - Spirals tailings:			
Discharge rate:	1800 tonnes/operating hour (about 90% of feed): Note, some may be discharged separately by cycloning		

Table 3.33 Extreme storm surge and wave height estimates for Ocean City

Return period	Storm surge height (m)	Extreme wave height (m)
5 years	1.31	4.33
10 years	1.43	4.79
20 years	1.59	5.37
50 years	1.71	5.73
100 years	1.83	6.19
250 years	1.98	n/a

Table 3.34 **Average particle size for each vertical 30 cm section interval below the seabed between drill holes, offshore Virginia Beach (drill log data from U.S. Army Corps of Engineers, 1994)**

Vertical Interval	Grain Size
0 - 0.3 m	0.32 - 0.7 mm
0.3 - 0.6 m	0.35 - 0.7 mm
0.6 - 0.9 m	0.35 - 0.74 mm
0.9 - 1.2 m	0.35 - 0.78 mm

Table 3.35 Typical cycle time expected for a suction hopper dredge operating offshore Ocean City

	hours/day
Loading	1.00
Turning and docking	0.75
Discharging	2.50
Weather	0.50 - 0.75
Total cycle time (excluding repairs)	4.75 - 5.00

These figures assume a working distance of 4.2 km from the discharge station and the dredge operating 24 hours/day.

Table 3.36 Dredge and dredging parameters for beach nourishment, Maryland

Suction Cutter Dredge General Characteristics:		**Trailing Suction Hopper Dredge General Characteristics:**
Water depth:	> 15 m	> 15 m
Cutting system:	Cutter	Drag heads
Delivery system:	Pipeline to shore & hydraulic	Hydraulic
Length:	90 m	100 m
Width:	15 m	20 m
Height:	5 m	9 m
Draft:	3 m	8 m
Parameters of Cutting/ Delivery System:		
Operating depth:	15 m	15 m
Cut width:	90 m	24 m
Dredge Course Parameters:		
Average cut thickness:	1.22 m	
Maximum cut thickness:	1.52 m	
Course length:	600 m	600 m
Throughput:		
Average:	1,500m^3/hr	2,000 m^3/hr
Total area of source sand:	2.5 million m^2	

Table 4.1 Variables that affect sedimentation and sediment transport

(1) Factors outside the operator's control: naturally varying oceanographic parameters such as:

- water depth
- ambient horizontal current velocity
- water column stratification
- wave- or current-generated water column turbulence.

(2) Factors partly within the operator's control:

- rate and velocity of effluent discharge
- particle size distribution of solids in the effluent.

(3) Factors wholly within the operator's control:

- design, orientation and depth/height, relative to sea level, of the effluent discharge.

Note:

Several of the above are only partly independent. With the exception of oceanographic features, they can be influenced to some degree by the selection and design of the dredge and related on-board technologies in use.

Table 4.2 Jurisdictional guidelines for optimizing mitigation

(1)	The minimum possible number of agencies should be involved and the jurisdictional responsibilities of each should be clearly defined
(2)	One lead agency clearly appointed and through which communication with the mining company is maintained
(3)	Recognize that all forms of placer mining, but especially marine systems, are extremely cost-sensitive. Such operations cannot withstand imposed expenditures on generic environmental research programs geographically well outside the zone of influence of the dredging operation
(4)	If individuals with the necessary industrial experience to interface with the mining companies are not available within the agencies then appropriate industry consultants should be retained as is the case in the United Kingdom (E.G. Hydraulics Research Ltd.)

Table 5.1 Legislation and agencies that had jurisdiction over WestGold's mining operation, offshore Nome

(1) National Environmental Policy Act (NEPA) of 1969 which required the production of an Environmental Assessment (EA) and an Environmental Impact Statement (EIS)

(2) Rivers and Harbors Act of 3 March 1899: A U.S. Corps of Engineers (USCOE) Department of the Army Permit required pursuant to Section 10

(3) Clean Water Act of 1977:

- A U.S. Corps of Engineers Department of the Army authorization to discharge material into the water required pursuant to Section 404
- A National Pollutant Discharge Elimination System (NPDES) permit required to be issued by the U.S. Environmental Protection Agency (USEPA) for ocean discharges in compliance with the Ocean Discharge Criteria pursuant to Section 403

(4) State of Alaska Water Quality Standards: A Certificate of Reasonable Assurance, issued by the Alaska Department of Environmental Conservation (ADEC), together with a Water Quality Certification, required under the Clean Water Act and in compliance with the requirements of (5) immediately below

(5) Standards of the Alaska Coastal Management Act of 1977 through the Federal Coastal Zone Management Act of 1972: a state project consistency review and approval required through the Alaska Coastal Management Program

Table 5.2 Jig tailings discharge designs tested from the BIMA between 1986 and 1990 in water depths of 5 to 21 m, offshore Nome

(1)	Direct surface discharge from the launder 6 m above the water surface (Figure 5.2)
(2)	Steel square-section, pipe, 0.60 x 0.60 m, extending 1.0 m below the water surface
(3)	1.8 m-diameter steel pipe, 2.5 m below the water surface, around the circumference of which were attached six, overlapping, 6 m-long, flexible, heavy rubber panels held together at the bottom by a weighted ring collar (Figure 5.4)
(4)	1.8 m-diameter steel pipe, 2.5 m below the water surface, to the end of which was attached a flexible, weighted, rubber pipe of the same diameter extending approximately to 3.5 m below the water surface (Figure 5.5)
(5)	1.8 m-diameter steel pipe, beneath and over which was suspended a 2.1 m telescopic sleeve, made of rubber or a lightweight membrane, with its base at a variable depth below the water surface (Figure 5.5)
(6)	Flexible pipe of 0.60 m diameter either held at the surface or 0.50 m below the water surface
(7)	Steel pipe, reducing from 1.8 m to 0.50 m in diameter, either held at 1.5 m or 4.5 m below the water surface (Figure 5.6)
(8)	Steel pipe, reducing from 1.8 m to 0.50 m in diameter, fitted with a steel deflector plate (to break the jet action), either held at 1.5 m or 7.0 m below the water surface (Figure 5.3)

Table 5.3 **Total operating costs (in percent) during a representative 24 month period between 1987 and 1990 for the WestGold dredging operation, offshore Nome**

Dredge Maintenance	26	
Dredge Operations	19	
Admininstration & Overheads	13	
Support Vessels	4	
Winter Berthing of Dredge	4	
Environmental Monitoring	4	
	sub-total	70
Depreciation,Depletion & Amortization	13	
	sub-total	13
Drilling	11	
Other	1	
Sales Deductions	5	
	sub-total	17
	TOTAL	**100**

Table 5.4 Estimated annual costs of the heavy mineral mining scenario, offshore Virginia Beach

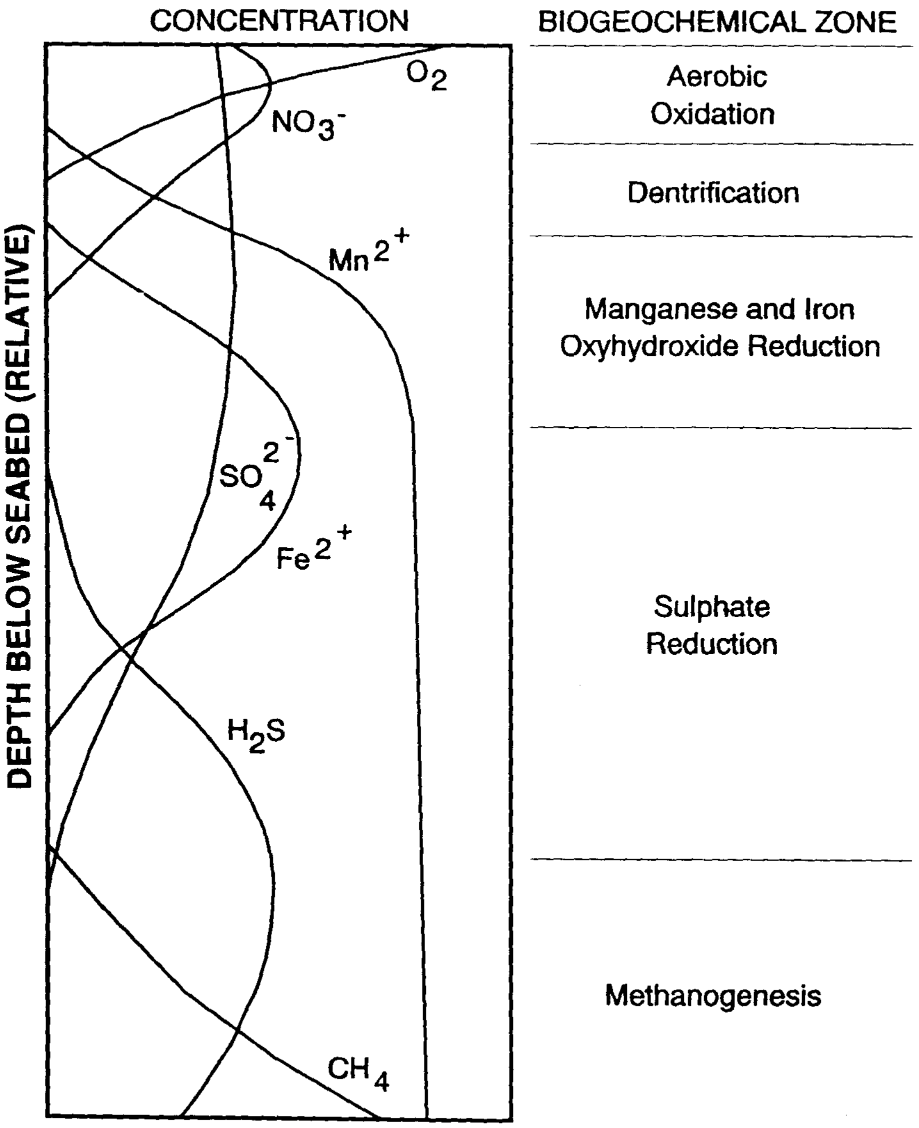
	%
Capital lease	61
Personnel	26
Fuel	5
Insurance	4
Maintenance	4
TOTAL	100

Estimated additional costs of implementing mitigation techniques.

	Additional Costs %
Use of flocculants	10.5
Scheduled downtime (per 10 days)	3.3
Desliming/Dewatering	0.4
Sub-surface discharge pipe (including modifications)	0.2
Degassing equipment	0.2

Table 5.5 Typical details of a proposed dredging site taken into account by licensing authorities

(1)	Depth of water and distance offshore
(2)	Existing bathymetric variations and the arrangement of any sediment banks
(3)	Degree of exposure, and the direction of prevailing winds
(4)	Direction and velocity of tides
(5)	Frequency, direction and severity of storms
(6)	Reflection and refraction of waves
(7)	Characteristics and degree of mobility of the seabed sediments



Schematic distribution of biogeochemically important molecules and ions in interstitial waters in sediments showing the zonation typically observed in marine and lacustrine sediments. This distribution will stretch or compress in response to changing physical, chemical and biological conditions.

Figure 2.1 **Schematic of geochemical zonation in sediments (after Pederson and Pelletier, 1989)**

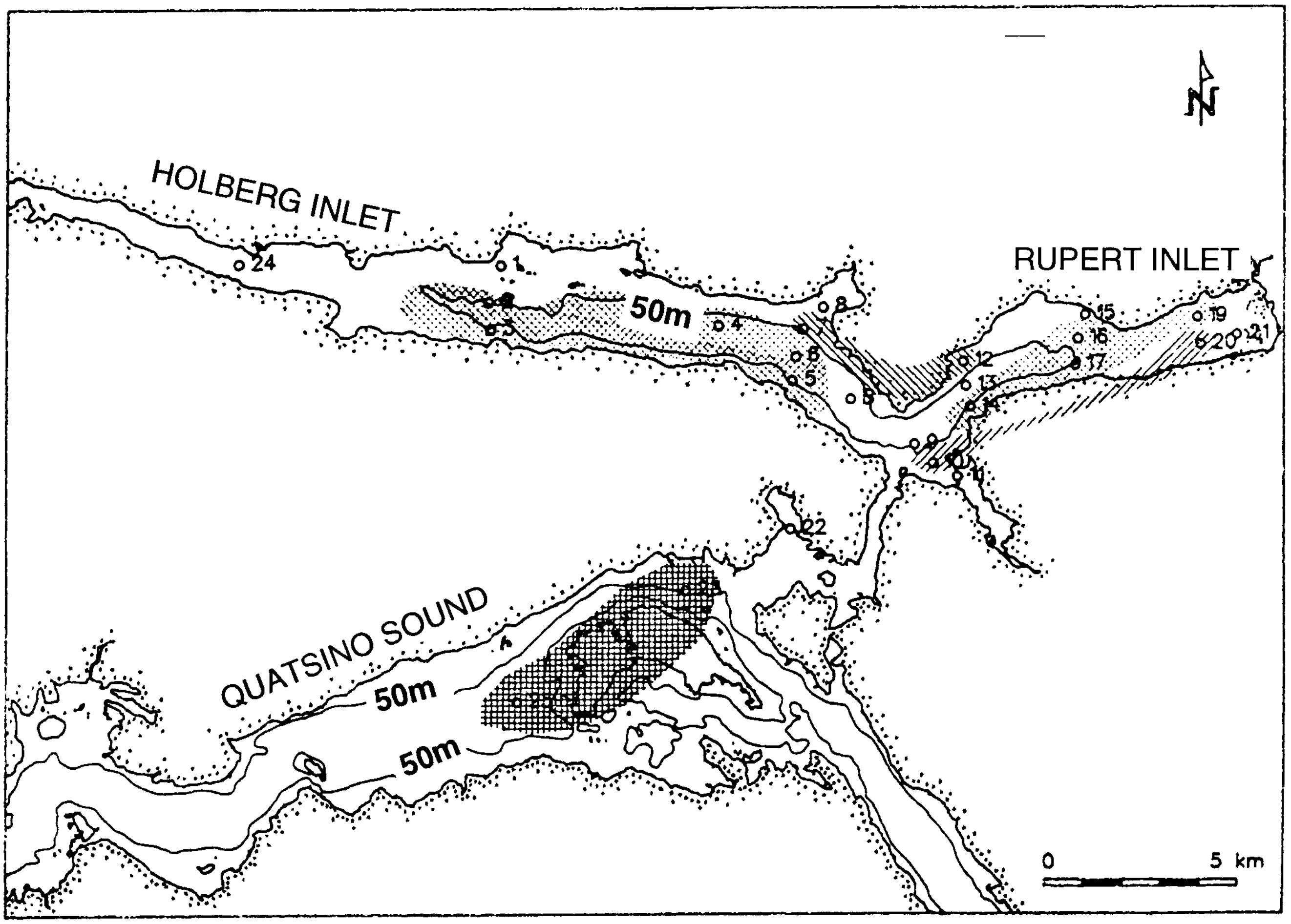
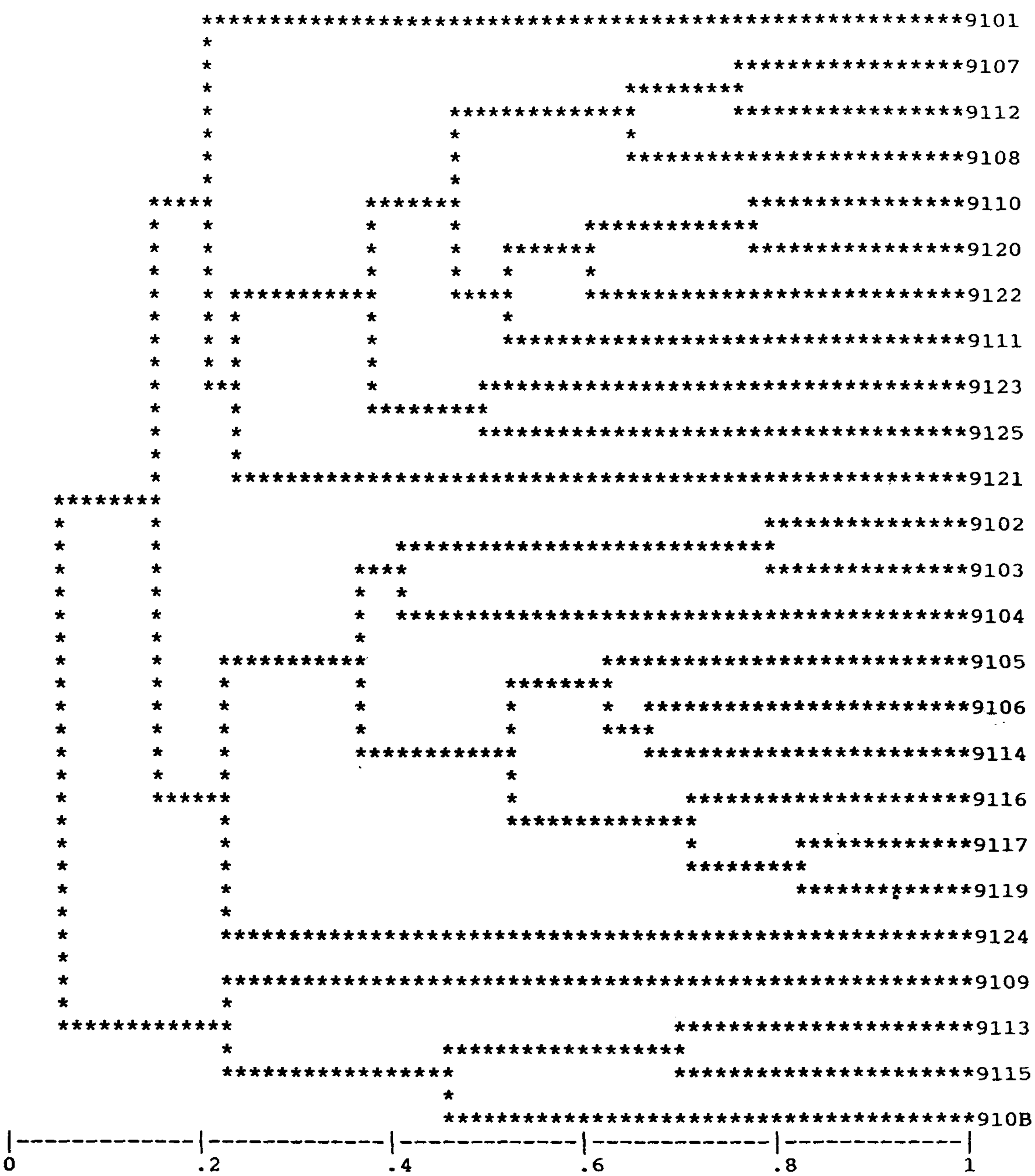


Figure 2.2 Significant cluster groups of benthos in 1991, Island Copper Mine, Canada (after Burd and Ellis, 1995). Similar groups can be identified for an area using statistical techniques (Figure 2.3) and mapped. Similar deep and shallow benthic faunas are shown here by similarly shaded areas. Submarine tailings are discharged into deep water from the mine in Rupert Inlet (Figures 2.4 to 2.6)

Cluster dendrogram and significances for linkages: 1991



SIMILARITY Scale Factor = 0.1E+01

Figure 2.3 Cluster diagram for 1991 data showing similarity for stations shown in Figure 2.2. Stations B, 9, 13 and 15 represent a group of similar benthos and are not shown in Figure 2.2

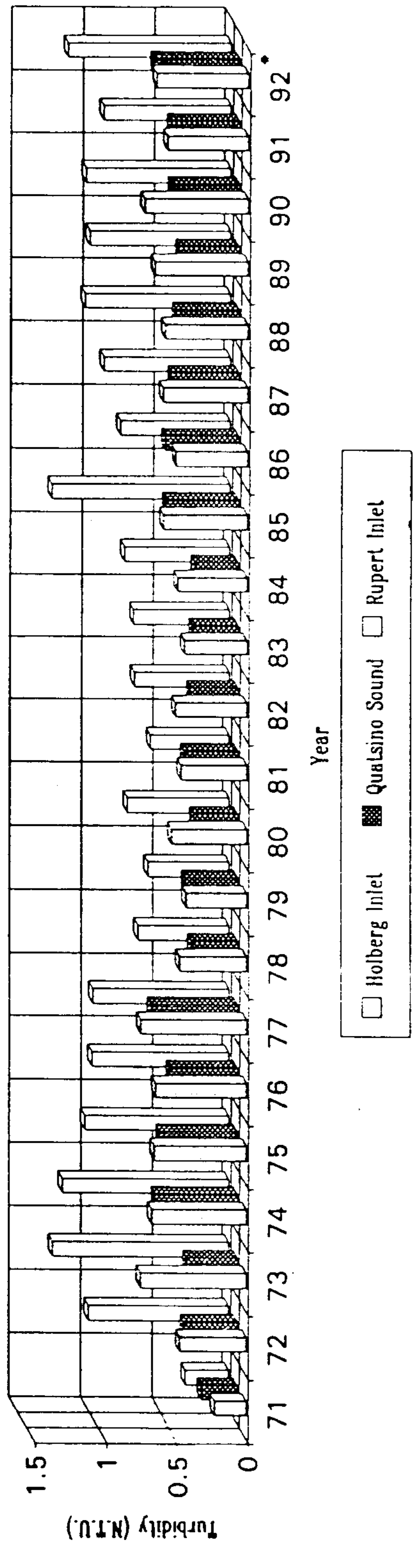


Figure 2.4 Comparative mean annual water column turbidity (at 30 m water depth) near Island Copper Mine, 1971 to 1992. The mine discharges tailings into Rupert Inlet where turbidity increased to approximately 1 NTU (Nephelometric Turbidity Unit) from pre-discharge levels of 0.5 NTU in 1971 (after Island Copper Mine, 1994). Note that sampling stations differ for turbidity, chlorophyll (Figure 2.5), zooplankton (Figure 2.6) and benthos (Figures 2.2 and 2.3)

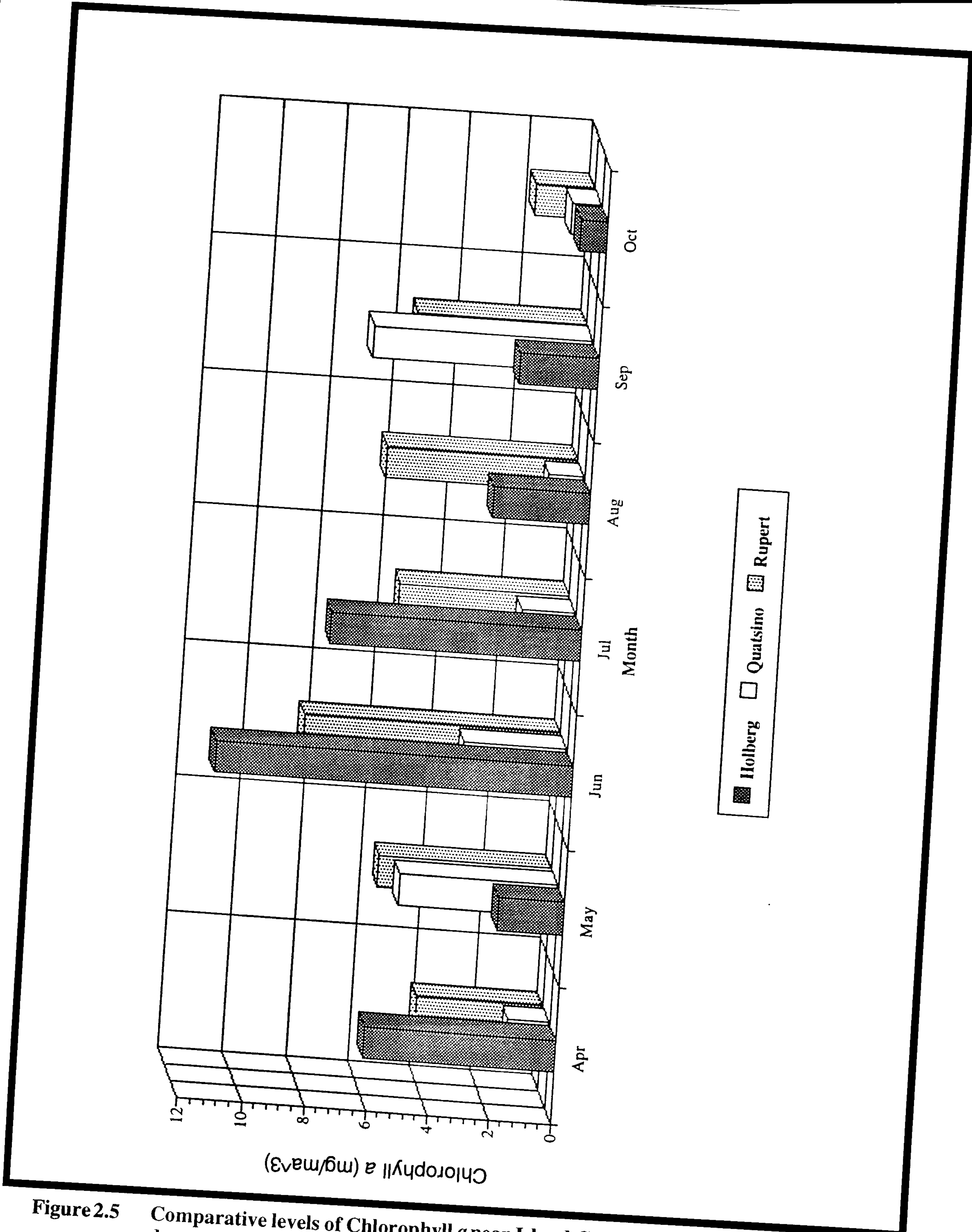


Figure 2.5 **Comparative levels of Chlorophyll *a* near Island Copper Mine in 1992. The levels do not show tailings-related differences, unlike turbidity (Figure 2.4) (after Island Copper Mine, 1994)**

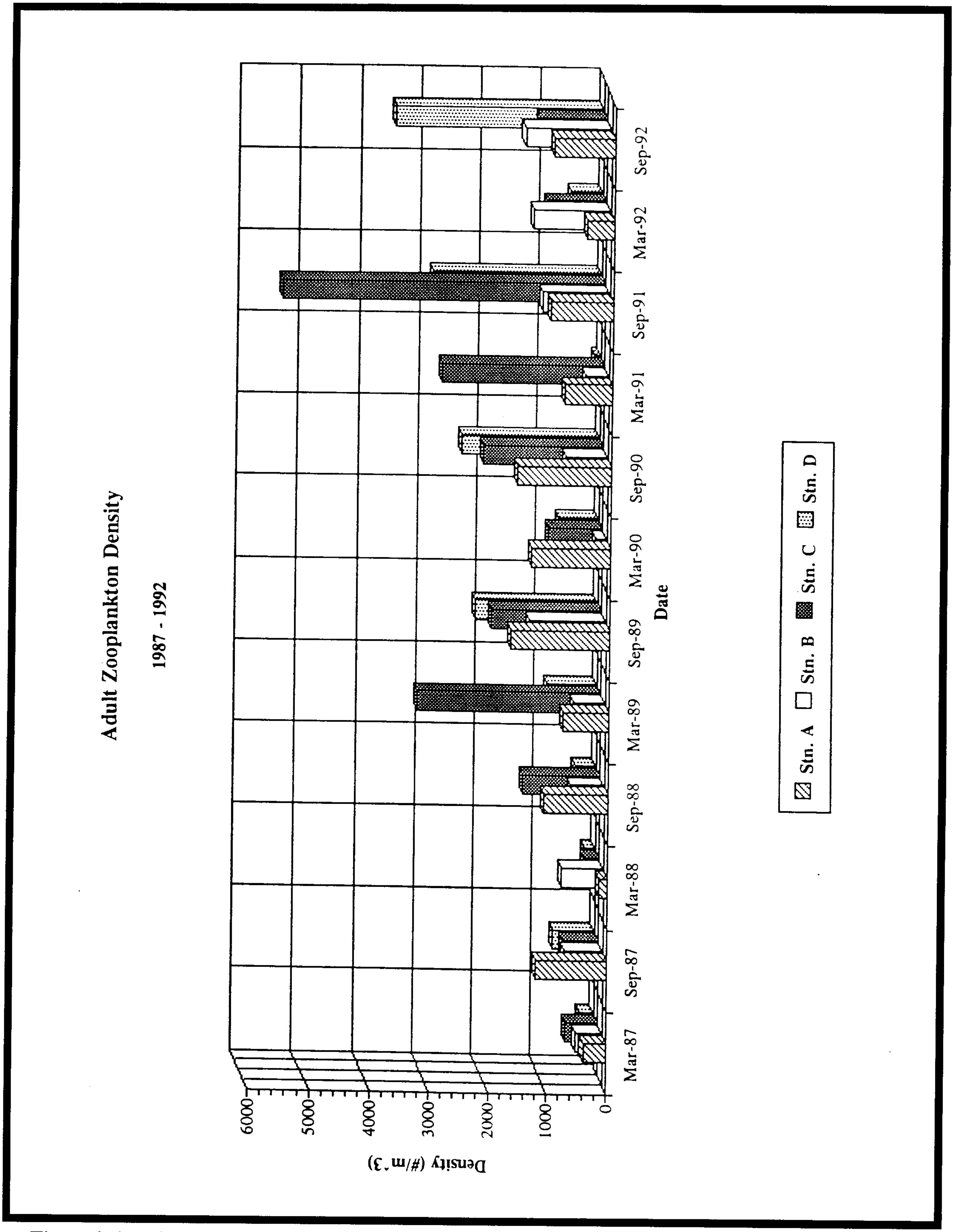
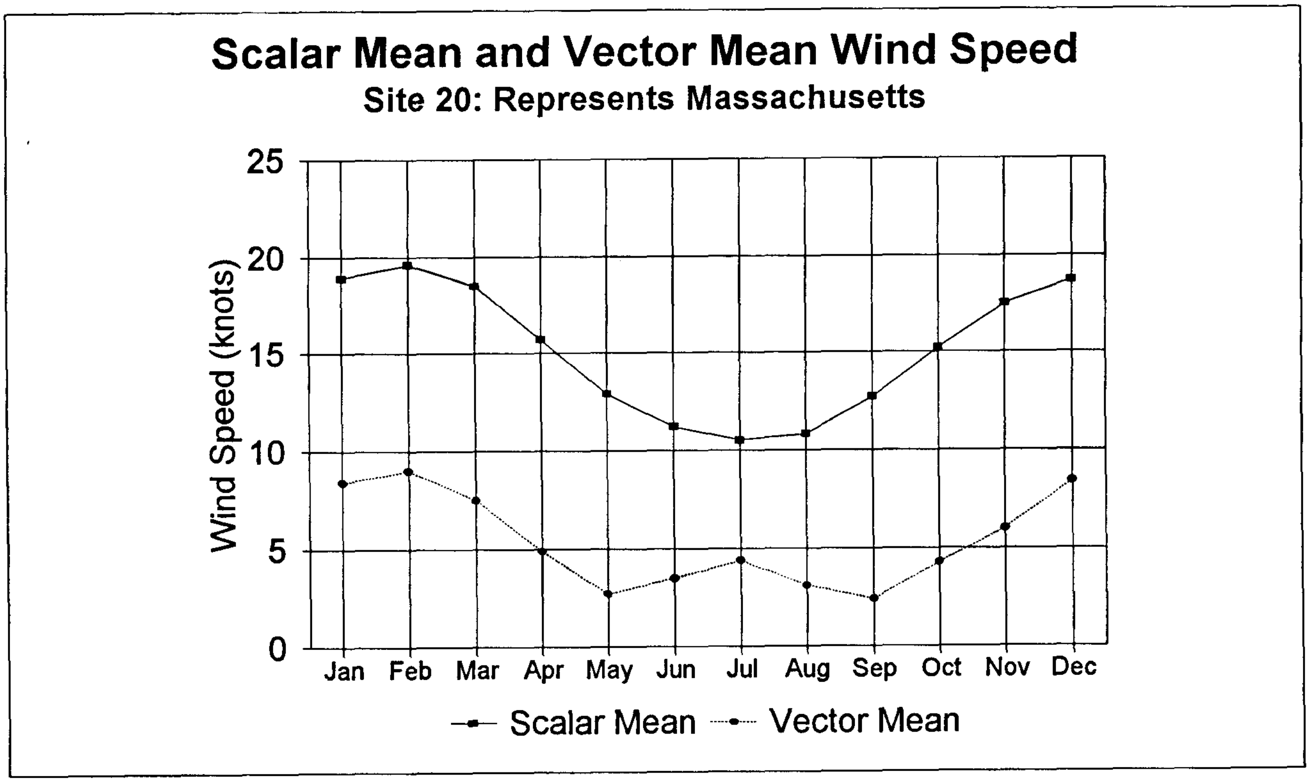


Figure 2.6 **Comparative density of adult zooplankton near Island Copper Mine, 1987 to 1992. The densities show no consistent differences between the fiords. Station A is closest to the mine in Rupert Inlet**



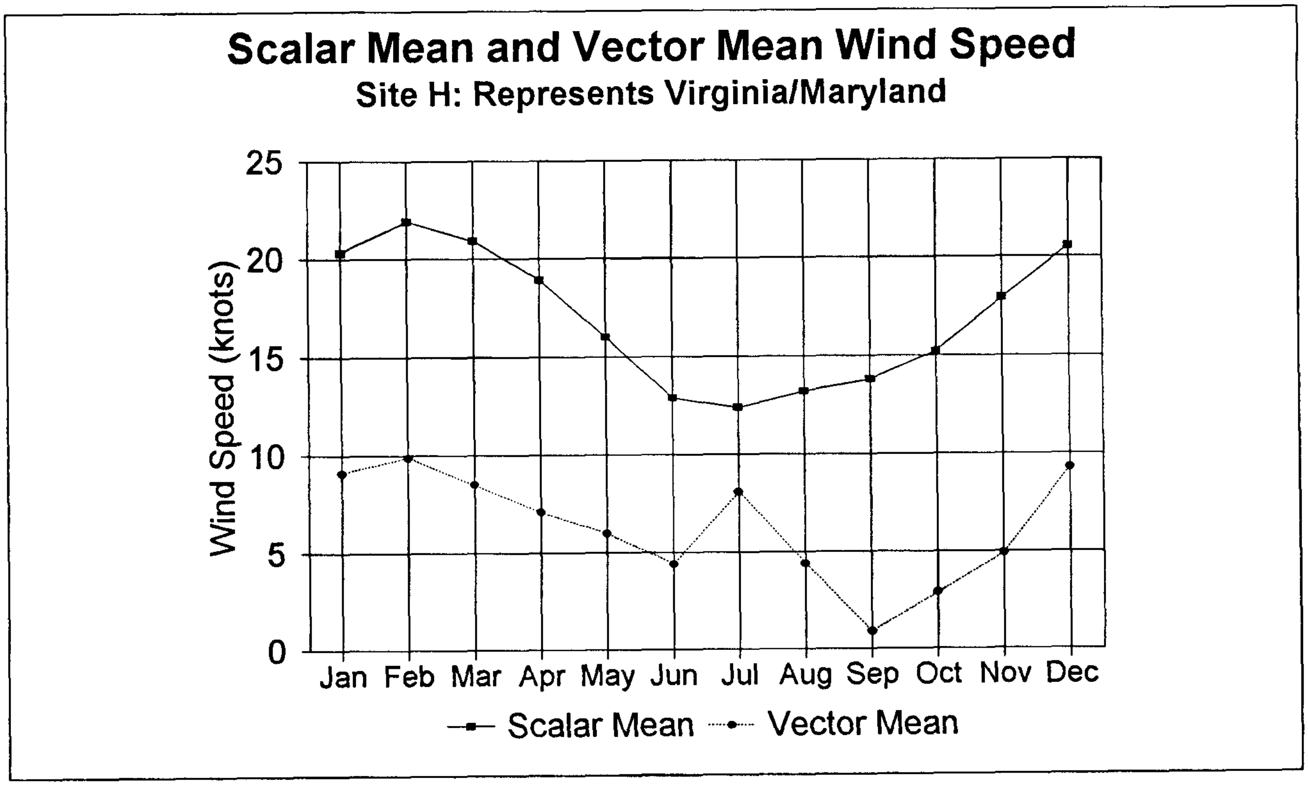
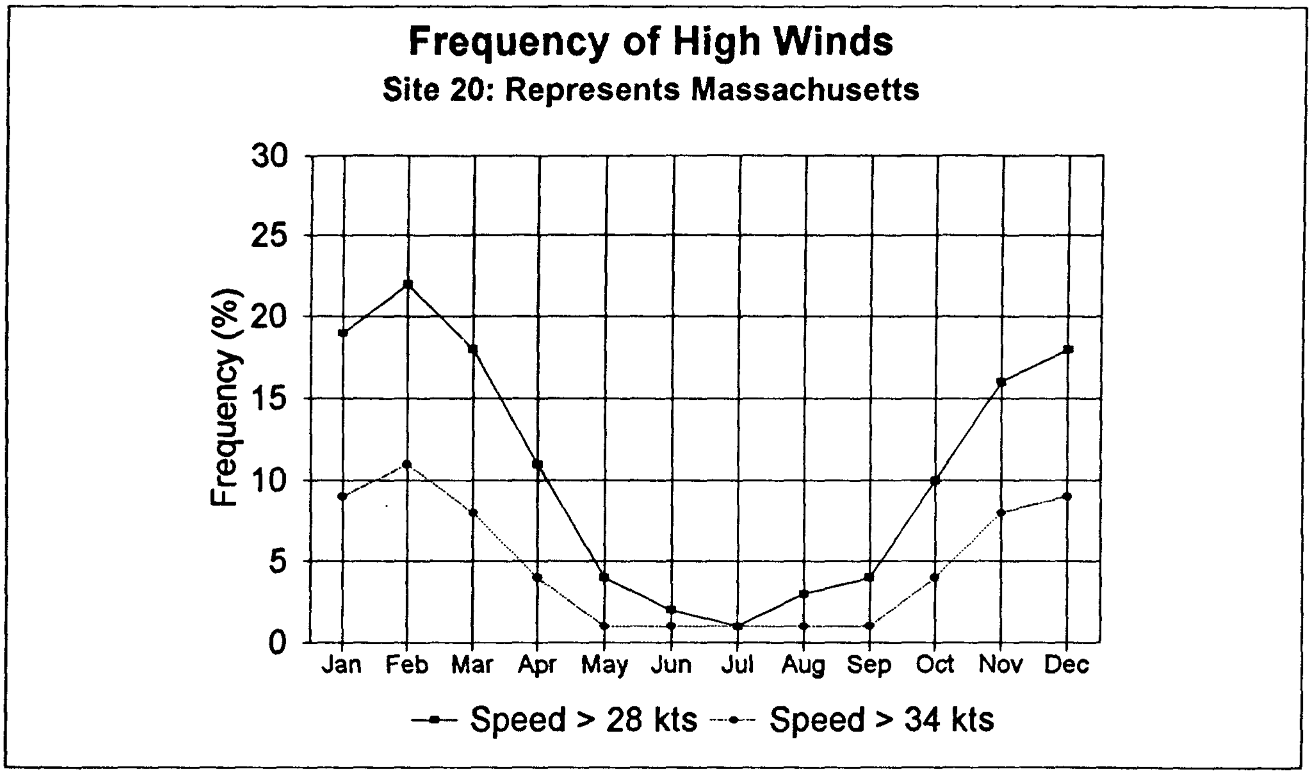


Figure 3.1 (a) and (b) Scalar mean and vector mean wind speed



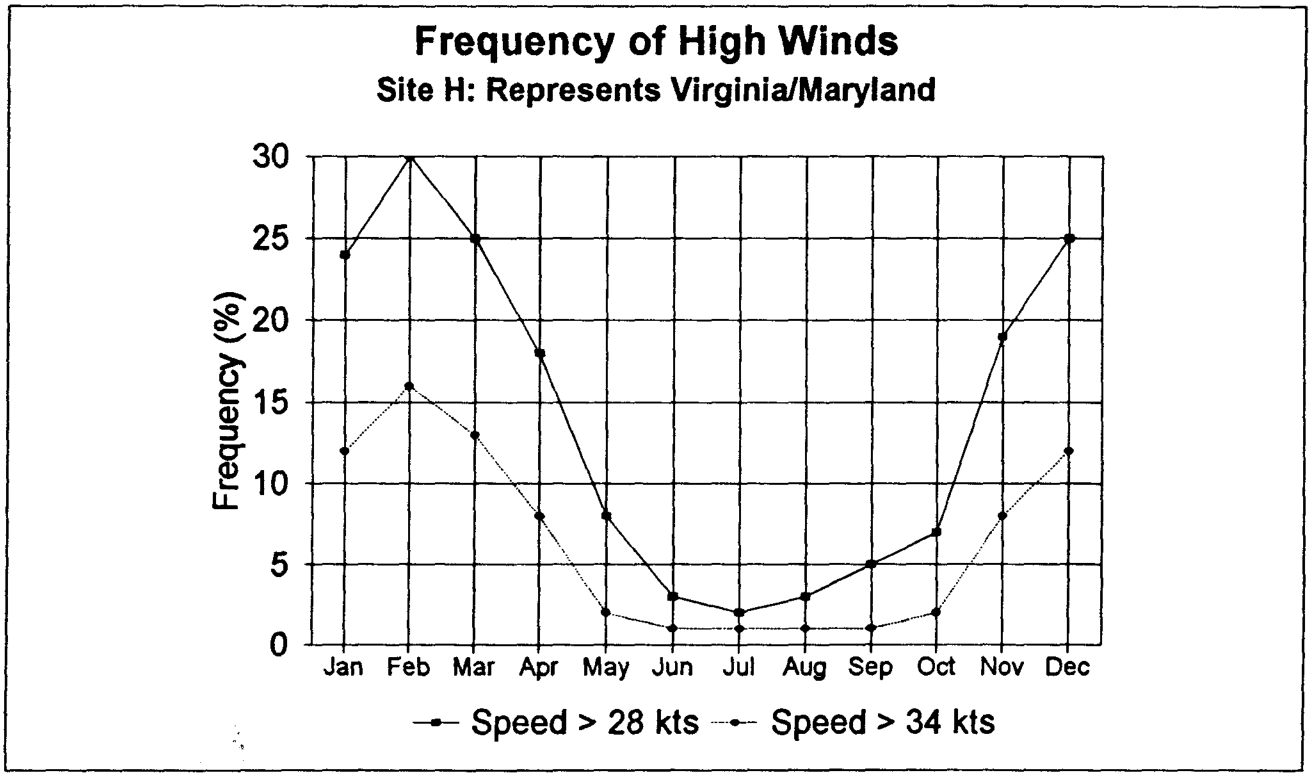
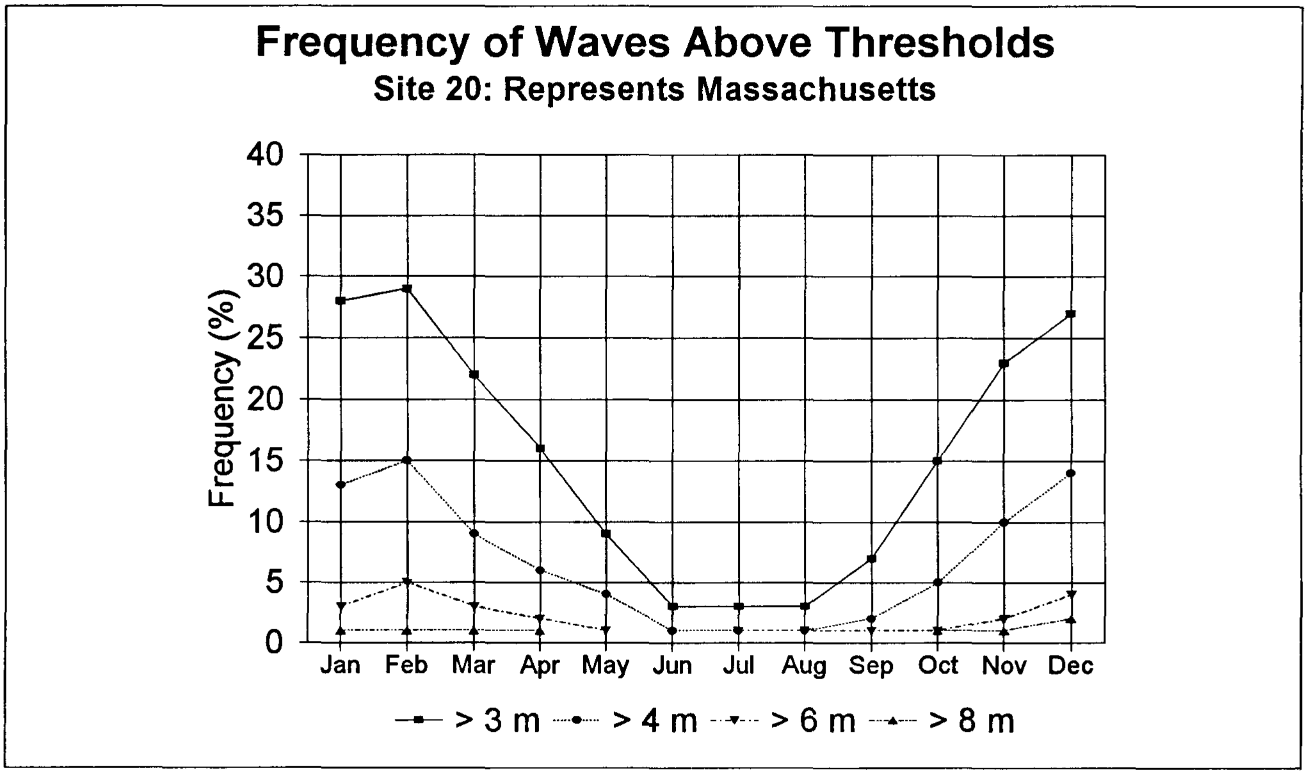


Figure 3.2 (a) and (b) Frequency of high winds (> 28 knots [52 km/h]: > 34 knots [64 km/h])



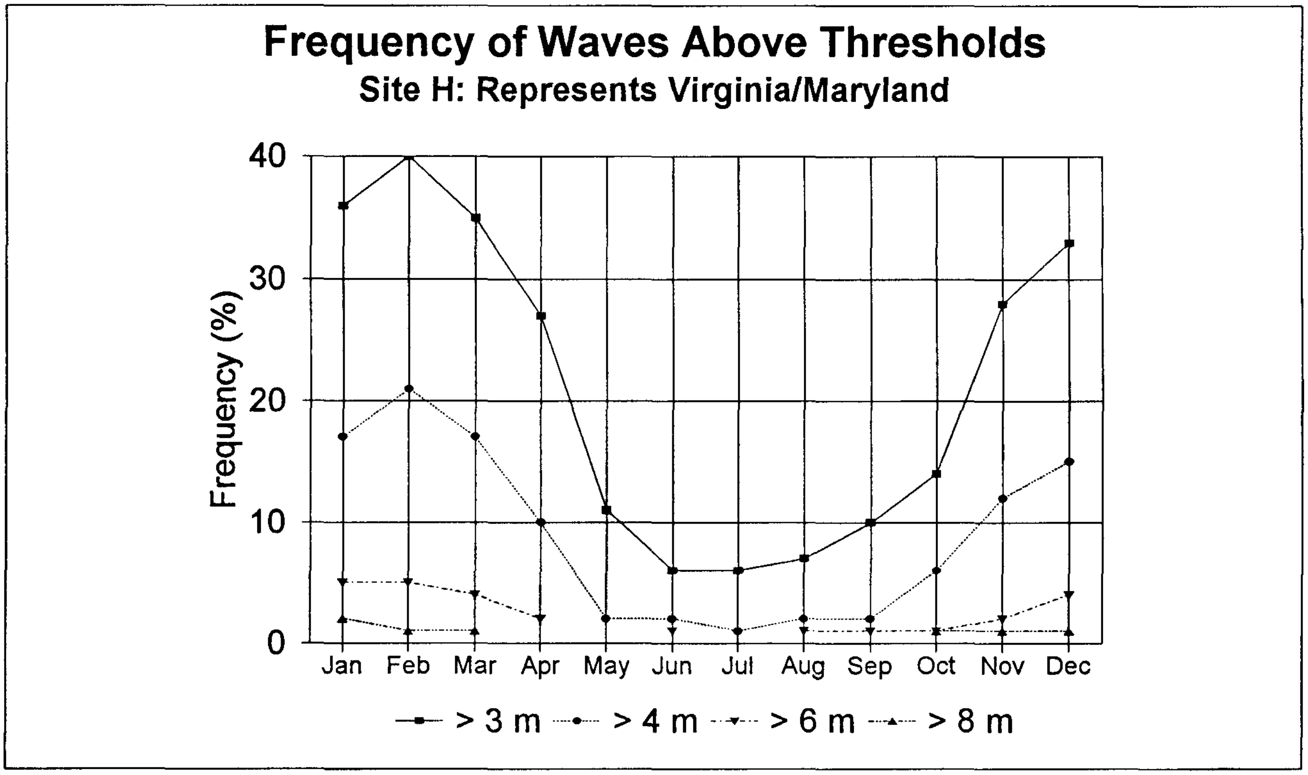


Figure 3.3 (a) and (b) Frequency of waves above thresholds

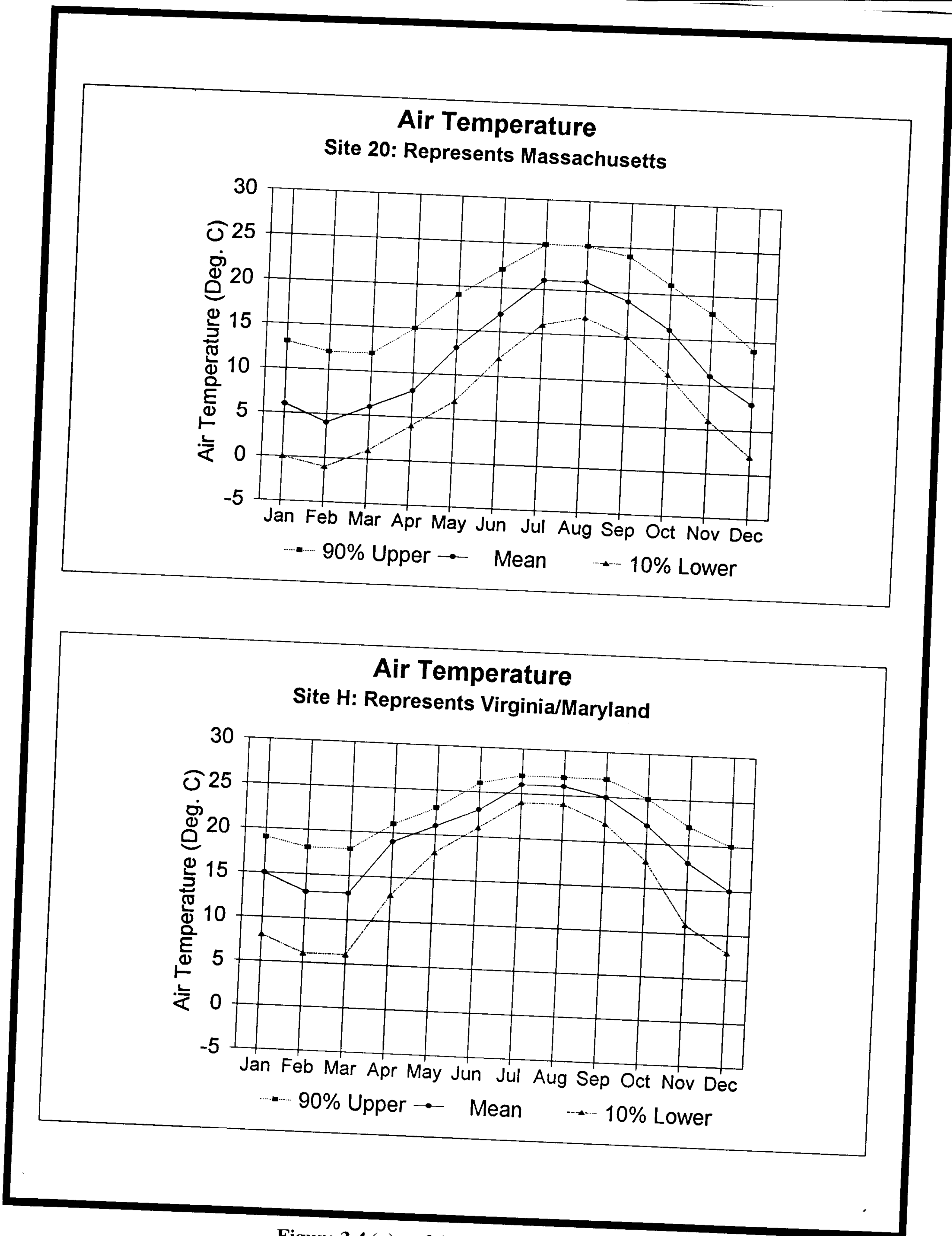
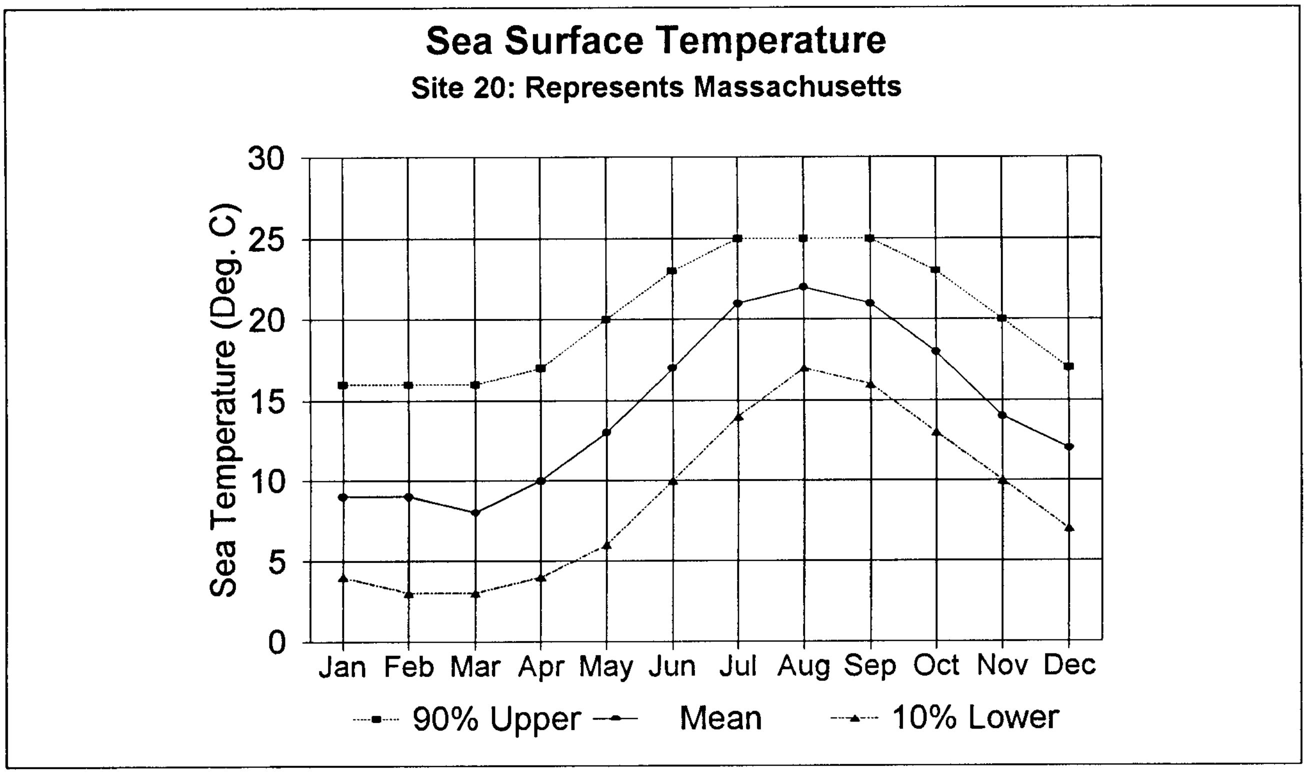


Figure 3.4 (a) and (b) Air temperature



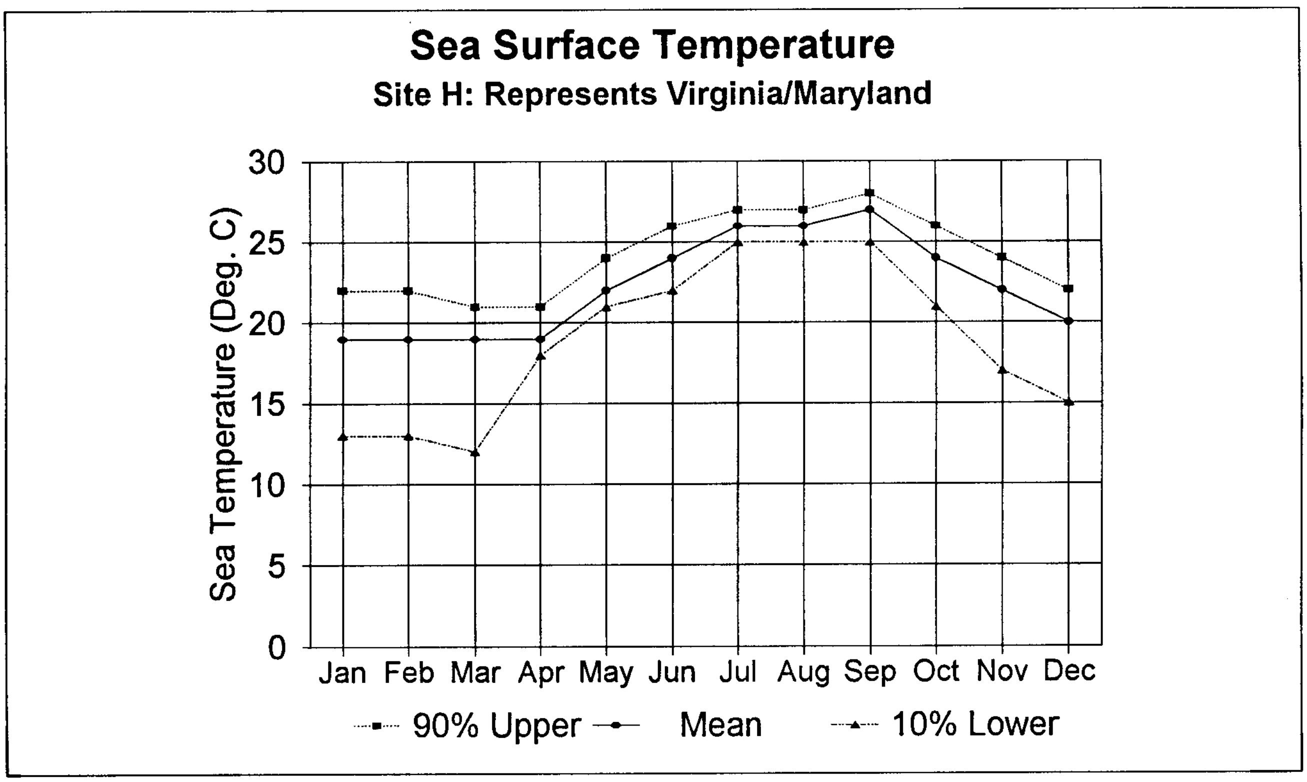
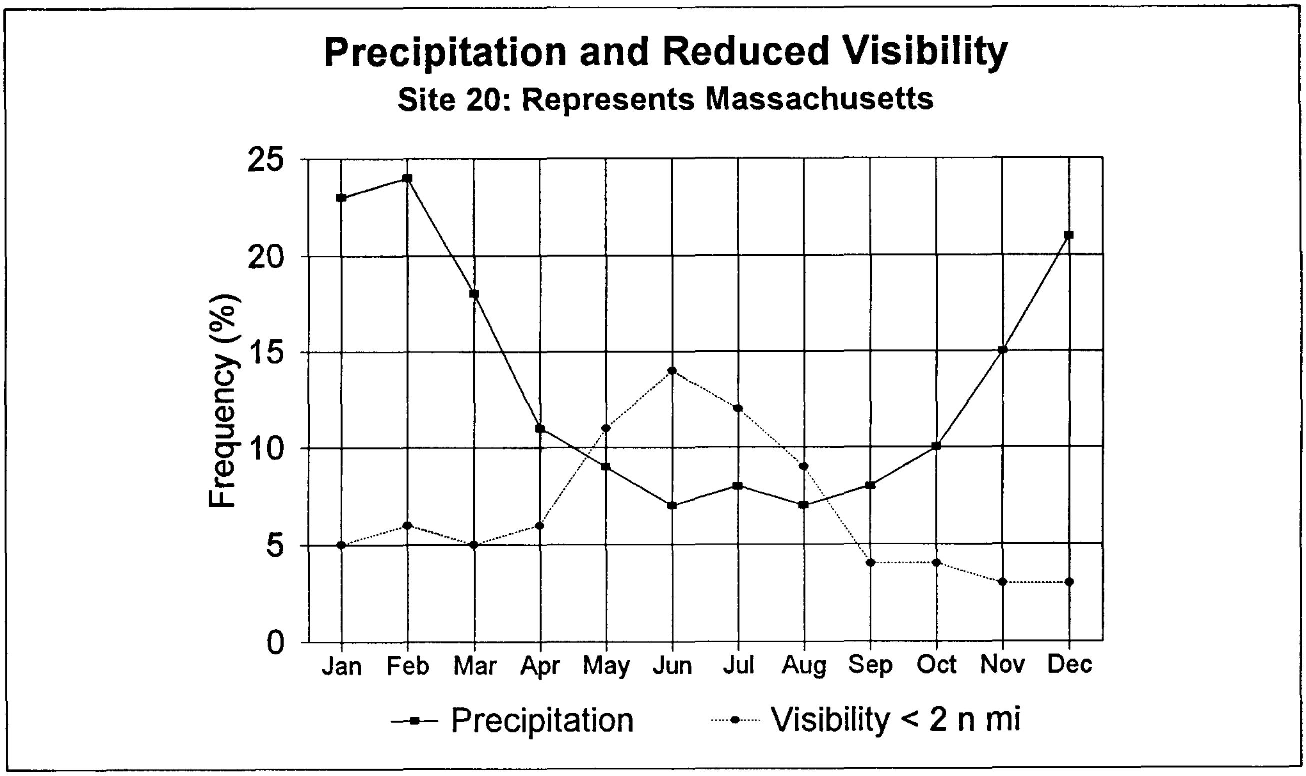


Figure 3.5 (a) and (b) Sea surface temperature



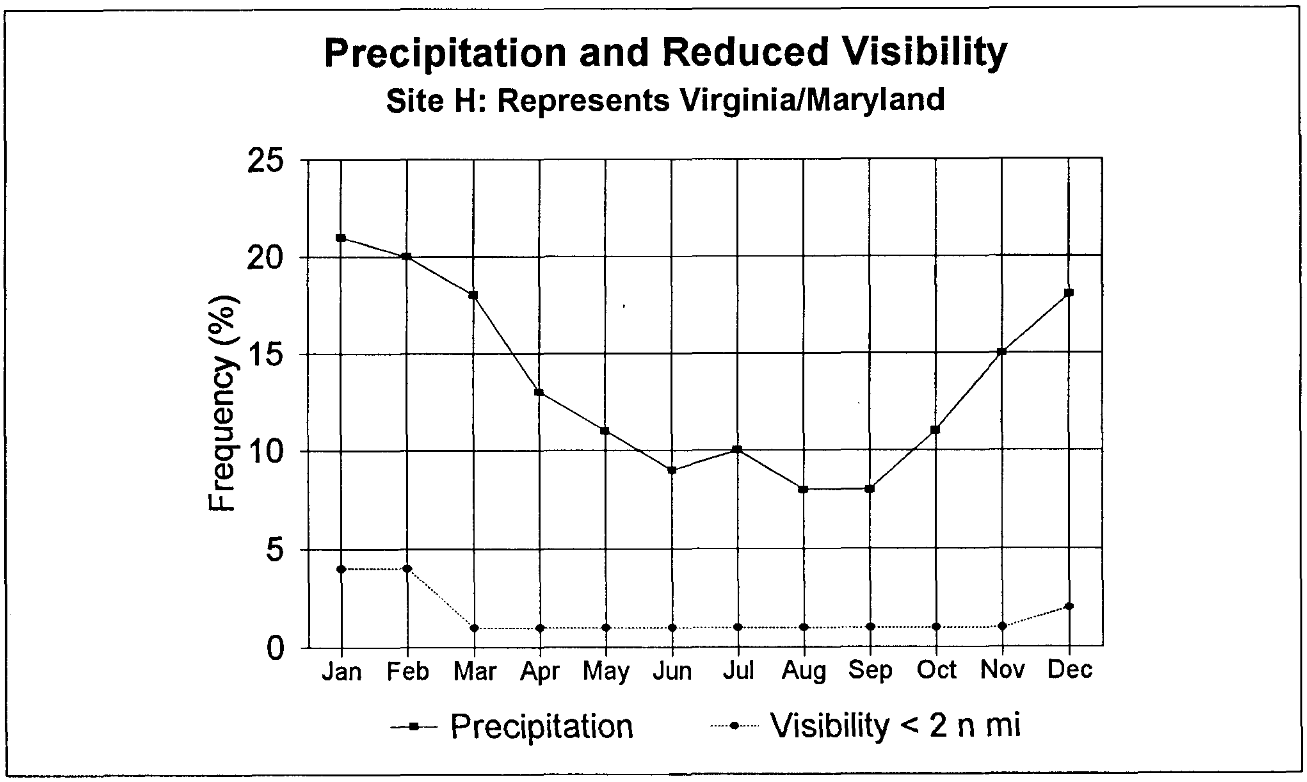


Figure 3.6 (a) and (b) Frequency of precipitation and visibility < 2 nautical miles (3.7 km)

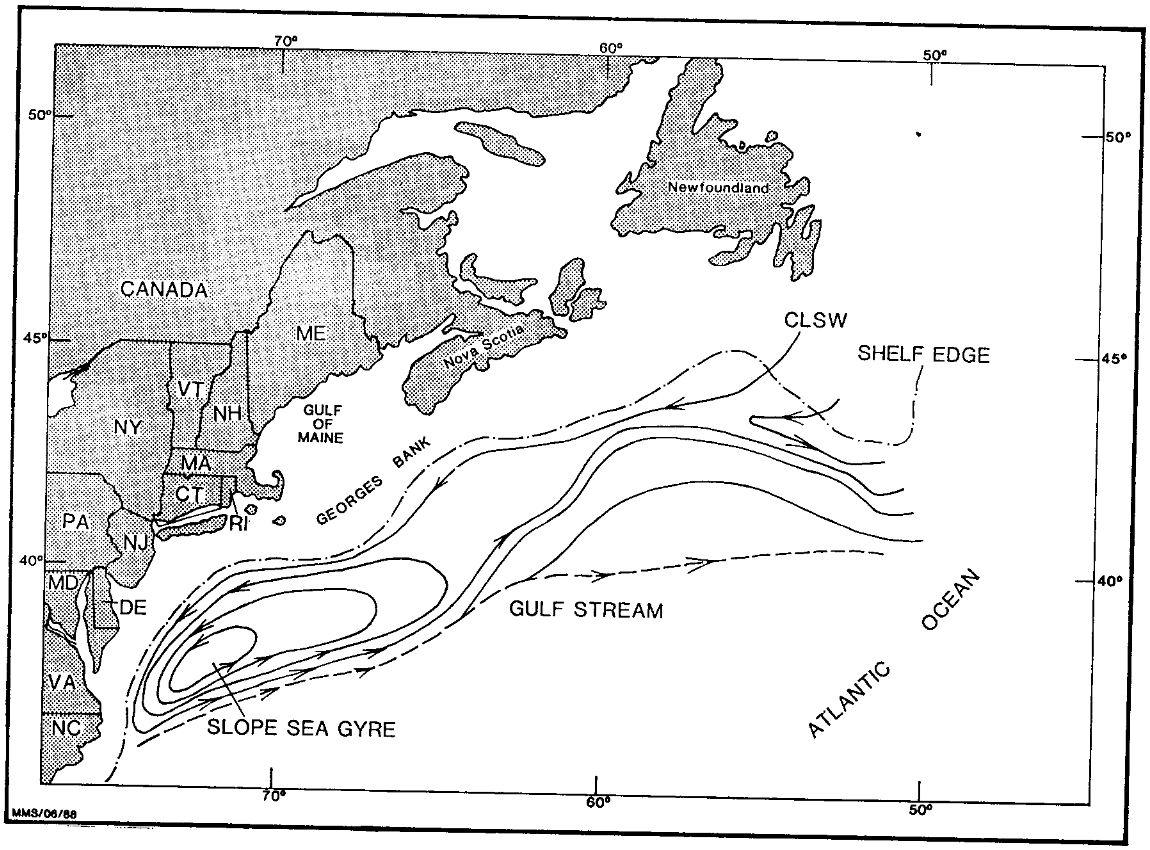


Figure 3.7 Slopewater circulation of the U.S. east coast (from SAIC, 1987)

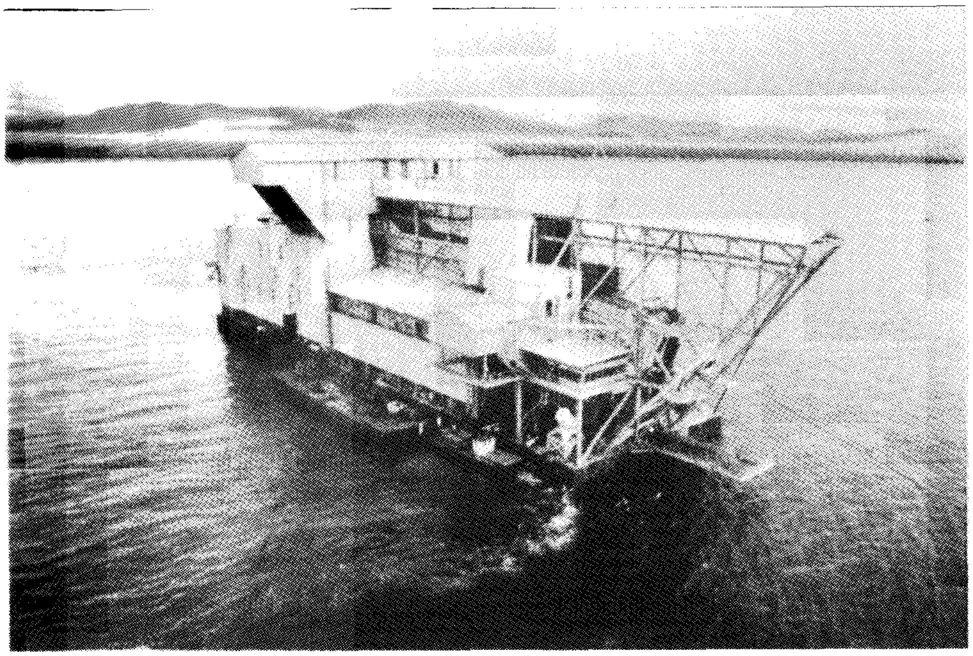


Figure 3.8 The BIMA bucket ladder dredge offshore Nome, Alaska (photograph courtesy of WestGold staff)

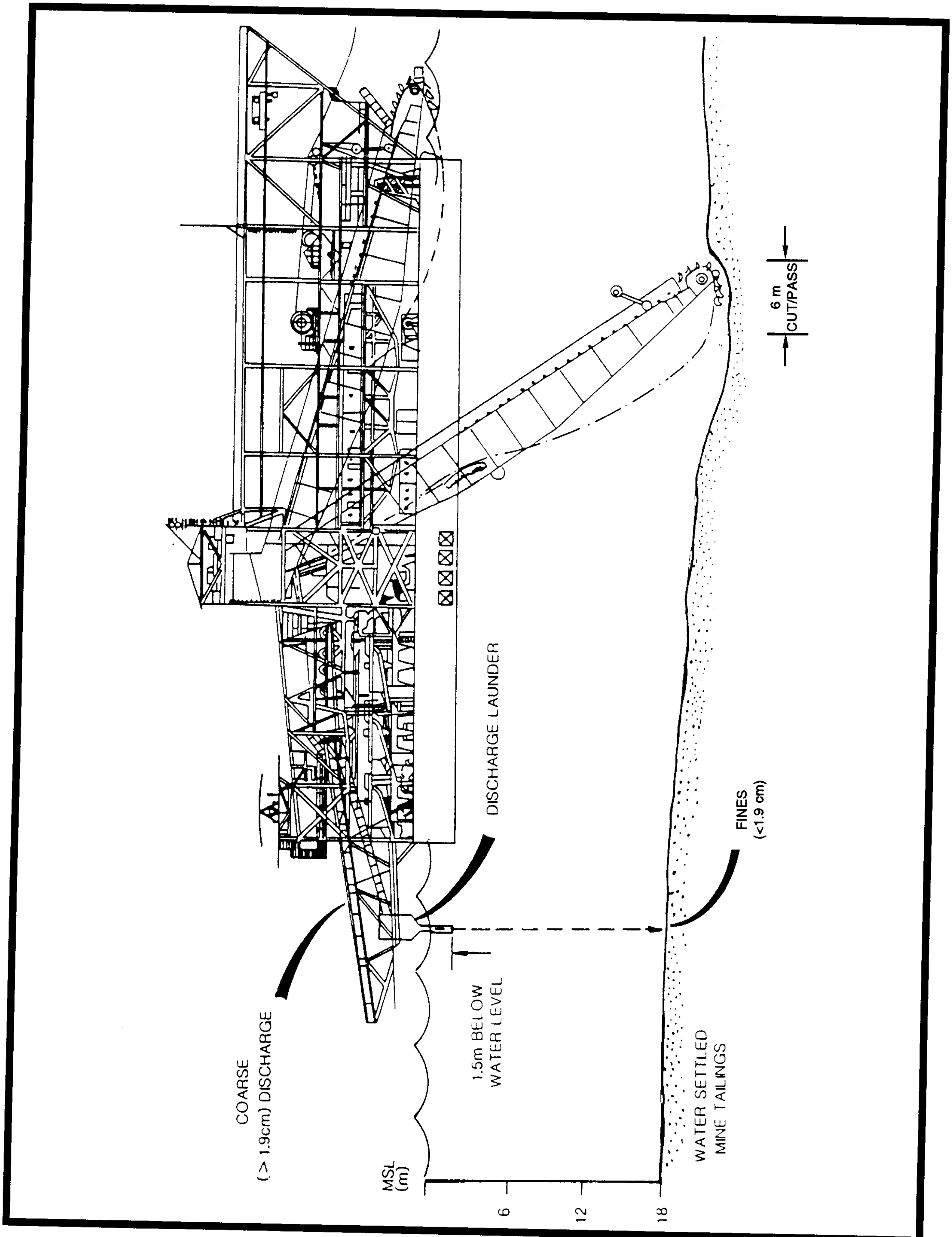


Figure 3.9 Schematic of the bucket ladder dredge BIMA (after Jewett *et al.* 1991)

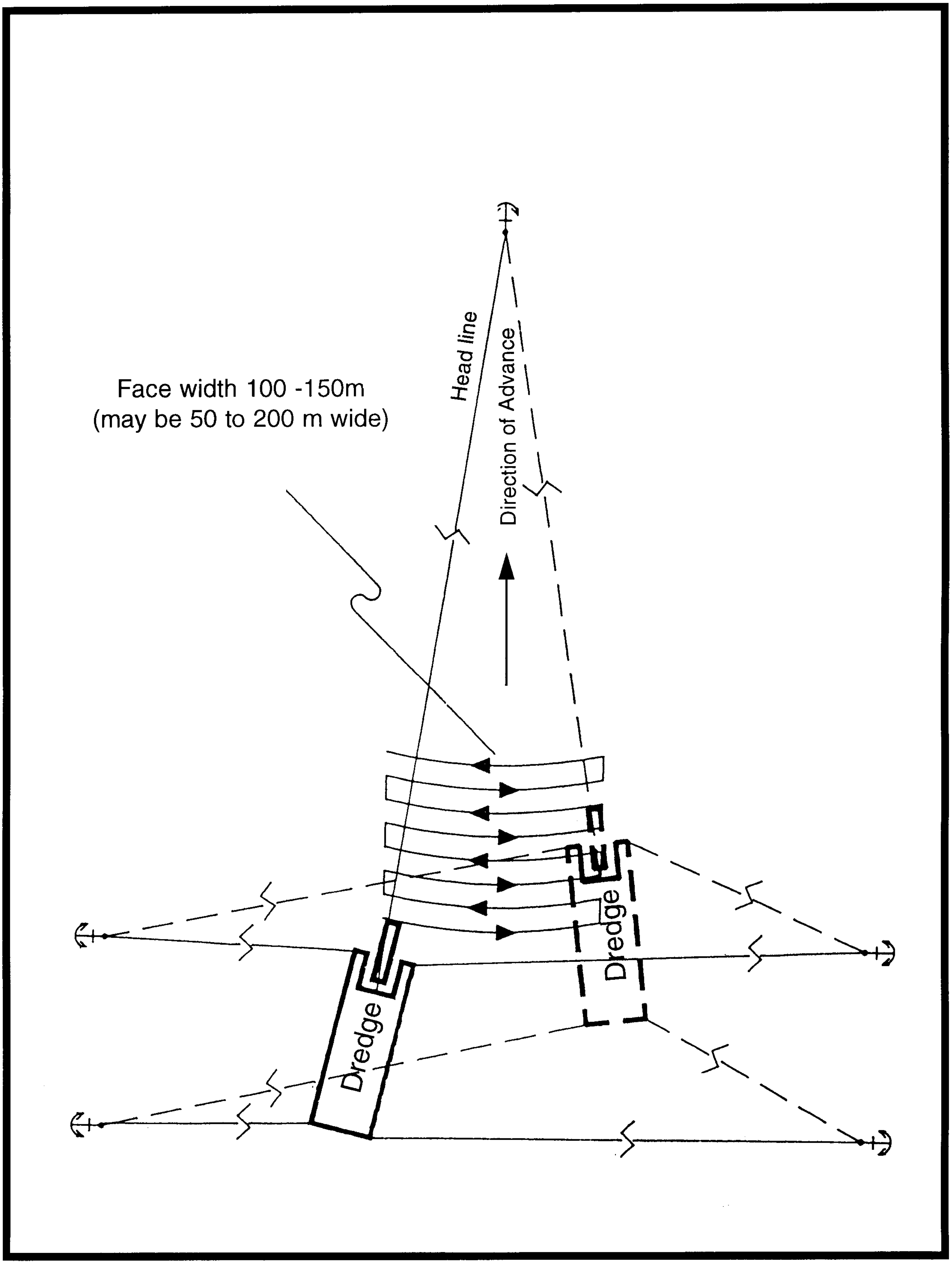


Figure 3.10 Plan view of dredging procedure for a bucket ladder dredge (after Bray, 1979).

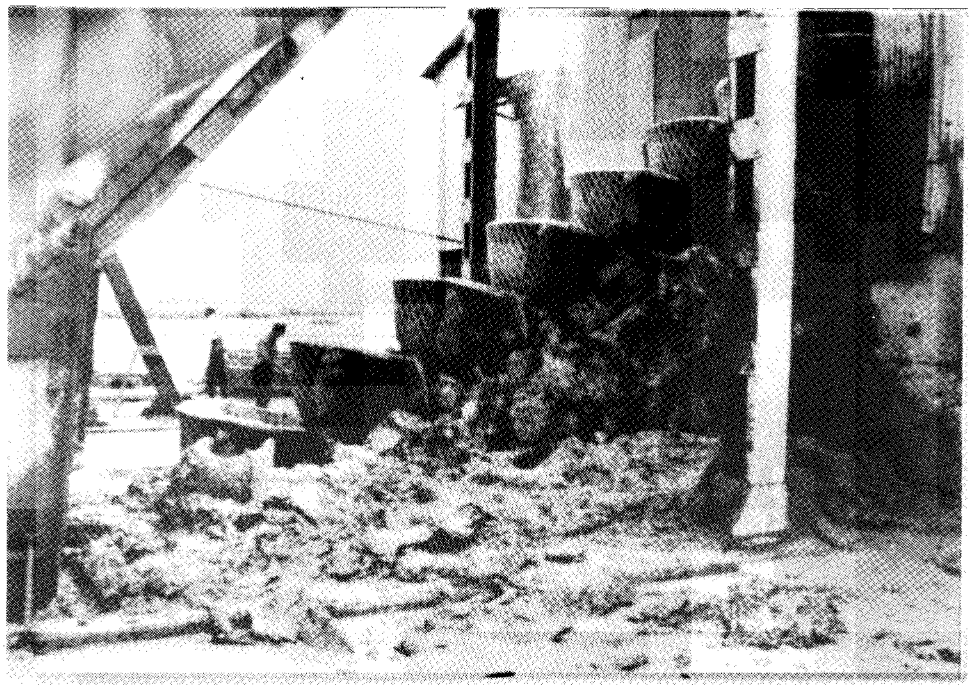


Figure 3.11 Extreme bucket spillage conditions onboard the BIMA (photograph courtesy of R. Garnett)

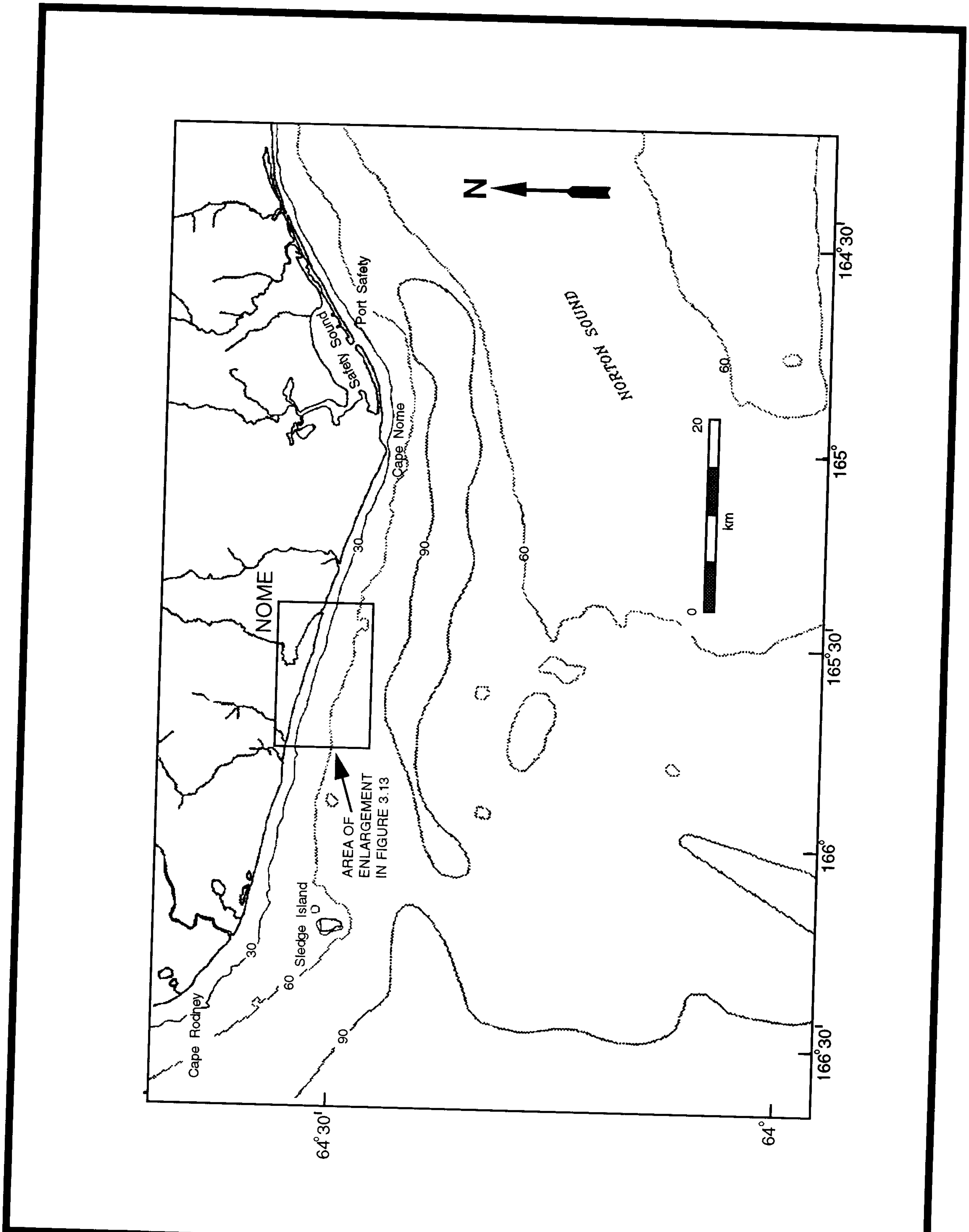


Figure 3.12 **Offshore bathymetry (in feet) near Nome, Alaska (adapted from a WestGold original chart)**

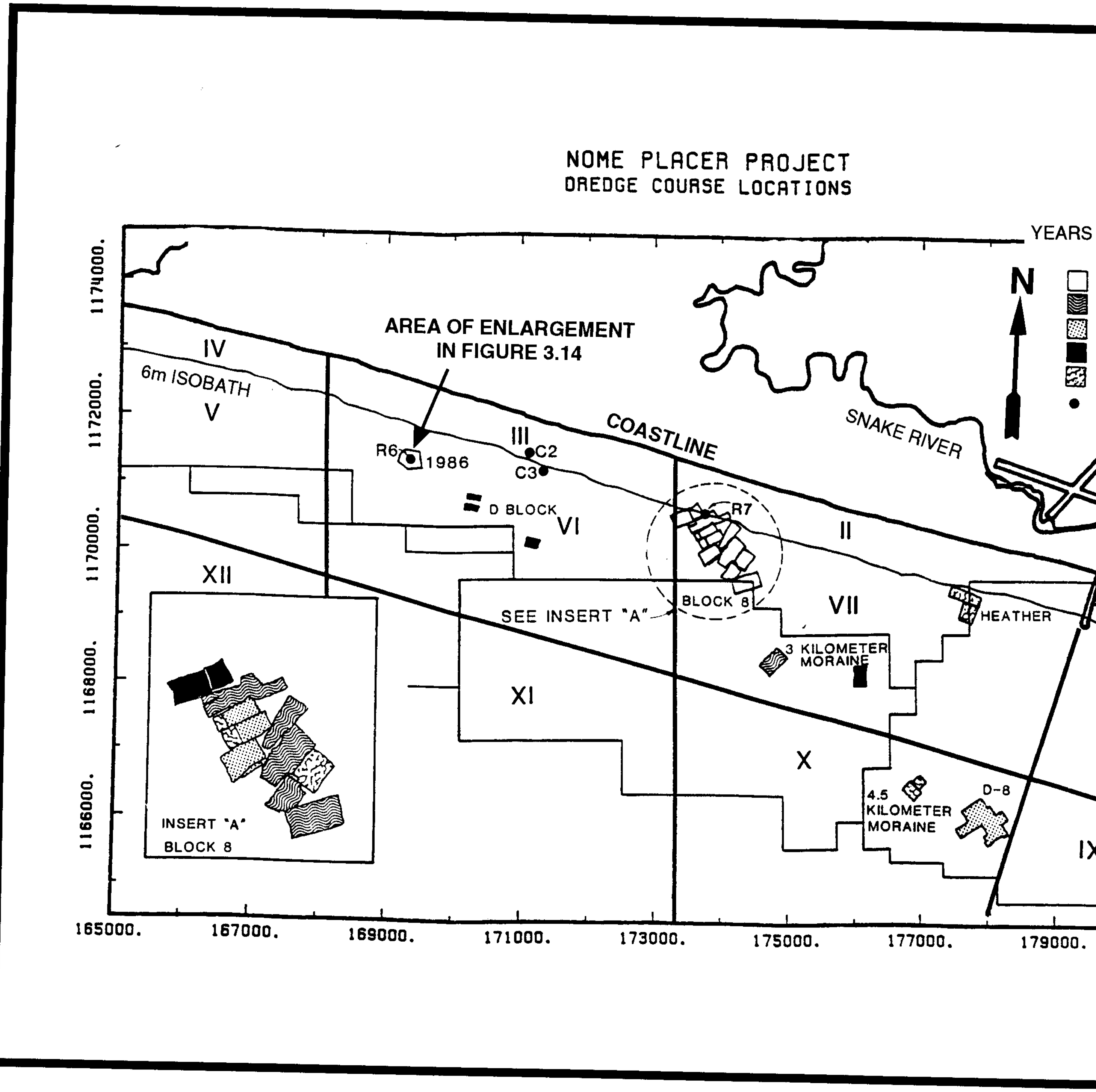


Figure 3.13 Dredge course locations for the WestGold operation, offshore Nome, Alaska (after Jewett *et al.* 1991)

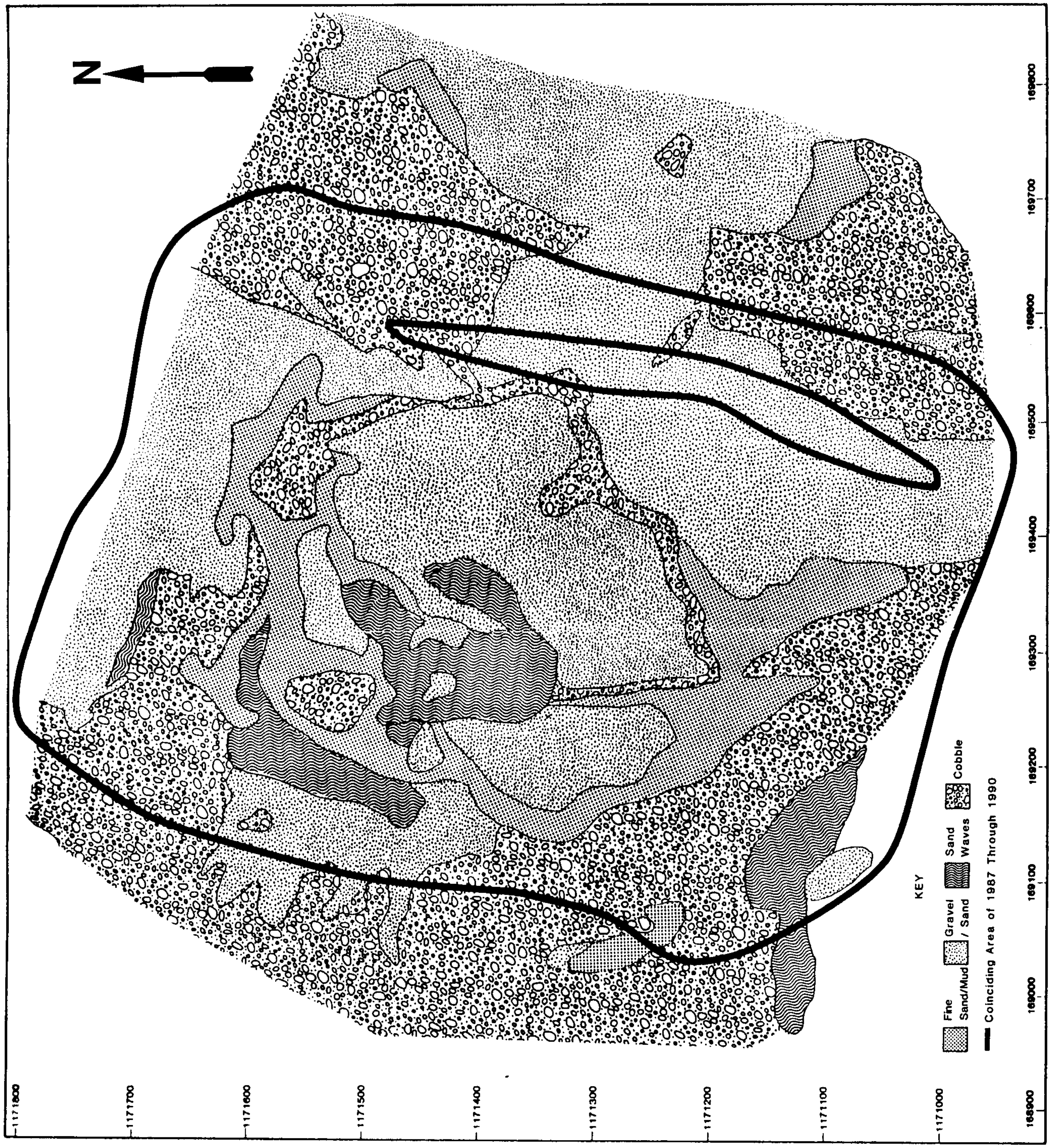


Figure 3.14 Seafloor substrate types at WestGold's 1986 dredge site, offshore Nome, Alaska (after Jewett *et al.* 1991)

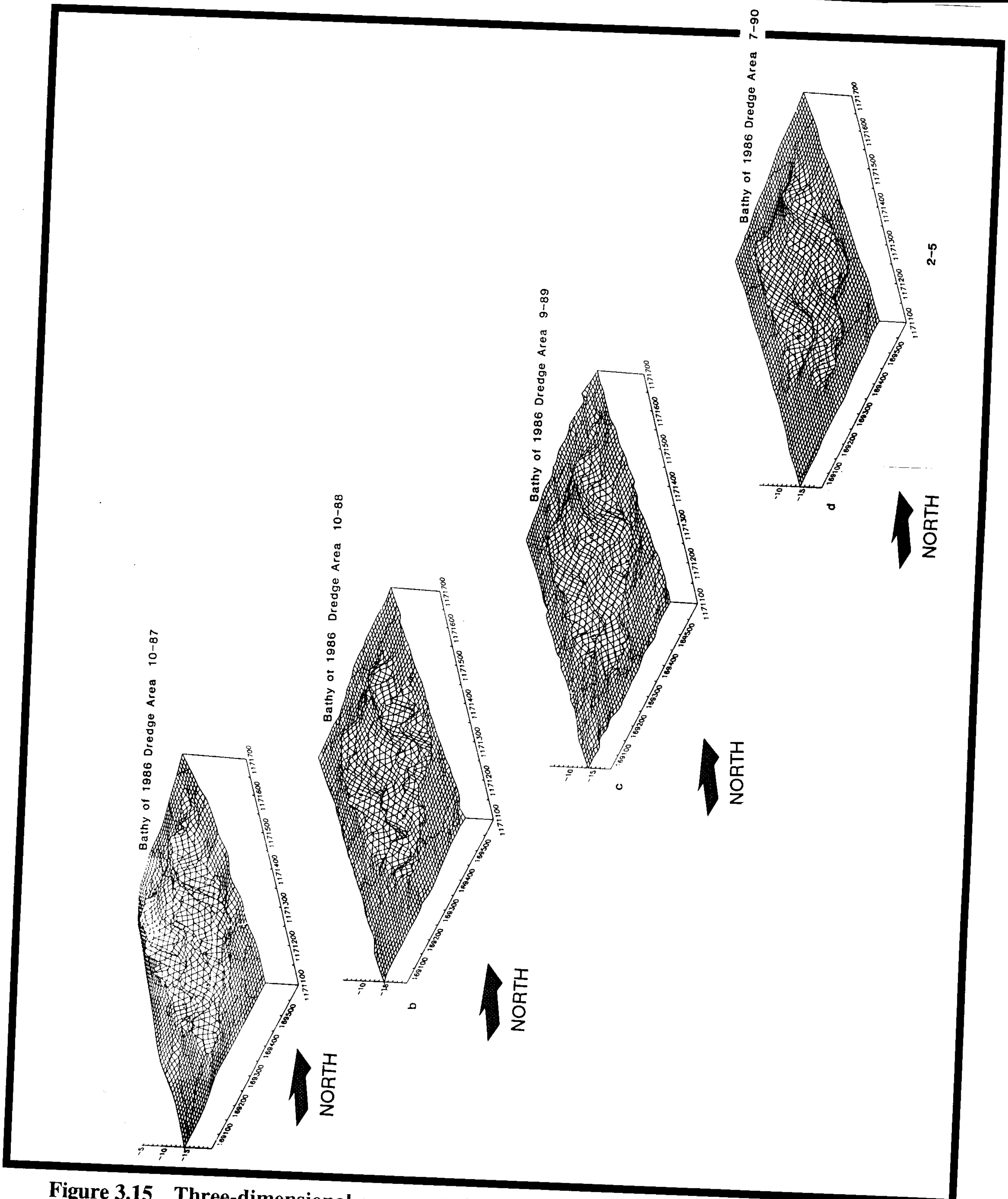
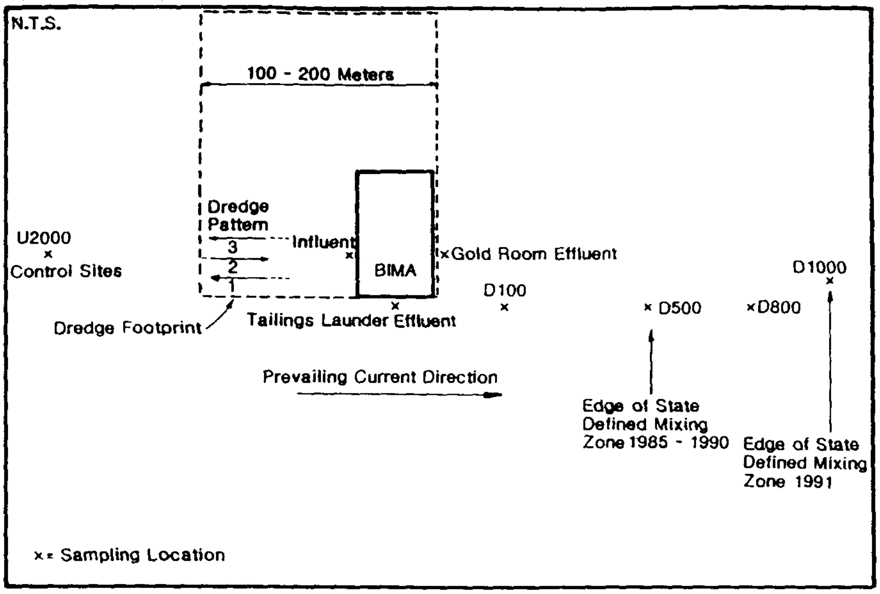
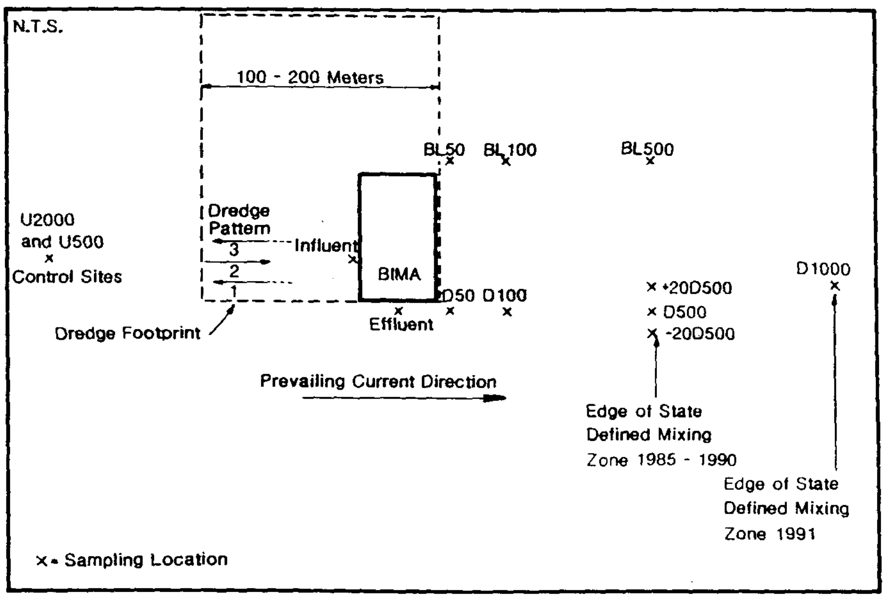


Figure 3.15 Three-dimensional representation of bathymetry of the area dredged in 1986 showing condition in (a) October 1987; (b) October 1987; (c) September 1989; (d) July 1990. The vertical axis scale (in metres) is 10 times the horizontal to exaggerate relief. The two horizontal axes (in metres) correspond to the coordinates and axes in Figure 3.4. (after Jewett *et al.*1991)



General sampling pattern for 1990 NPDES water quality monitoring program in relation to the BIMA mining vessel dredging pattern.



General sampling pattern for NPDES water quality monitoring program in relation to the BIMA mining vessel dredging pattern. Turbidity plume will disperse in direction of prevailing current. U2000 and D1000 were added in 1989; BL50, 100, and 500 and U500 were sampled in 1988.

Figure 3.16 Turbidity monitoring sampling pattern at WestGold's dredge area, offshore Nome, Alaska (after Jewett *et al.* 1991)

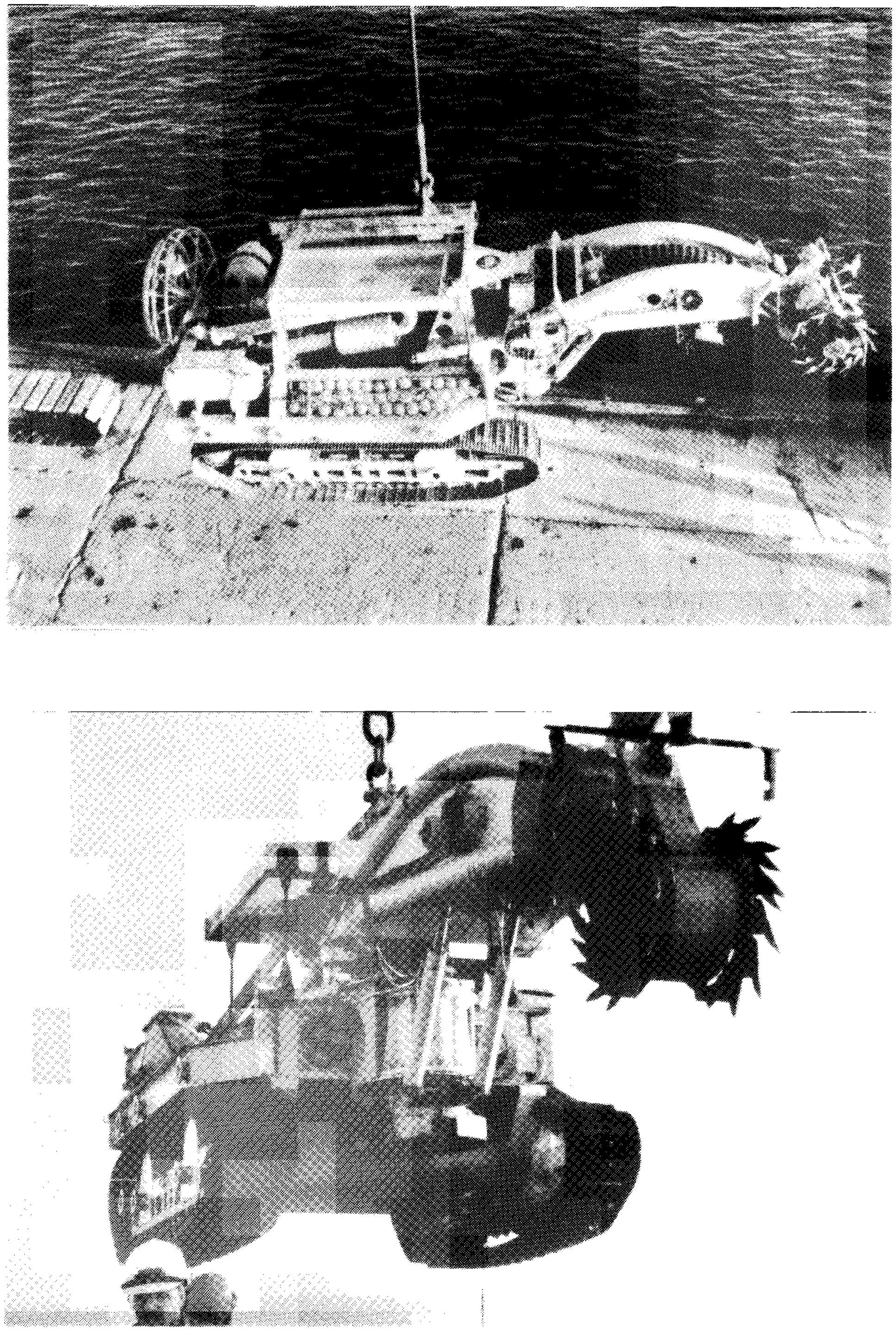


Figure 3.17 (a) and (b) Side view of the underwater mining vehicle "Tramrod" (photographs courtesy of Alluvial Mining, U.K.)

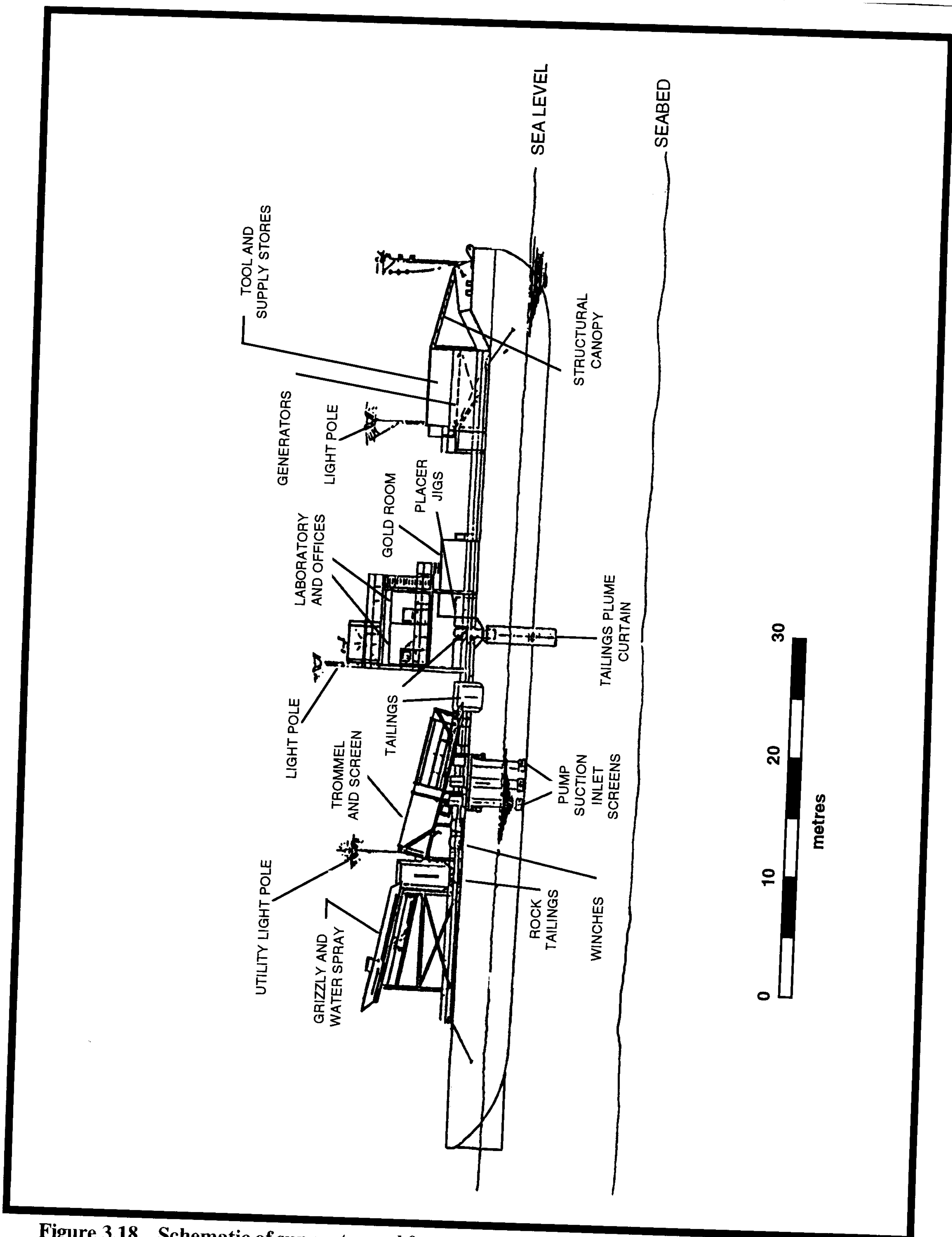


Figure 3.18 Schematic of support vessel for the underwater mining vehicle "Tramrod" with onboard treatment plant (adapted from a WestGold original schematic)

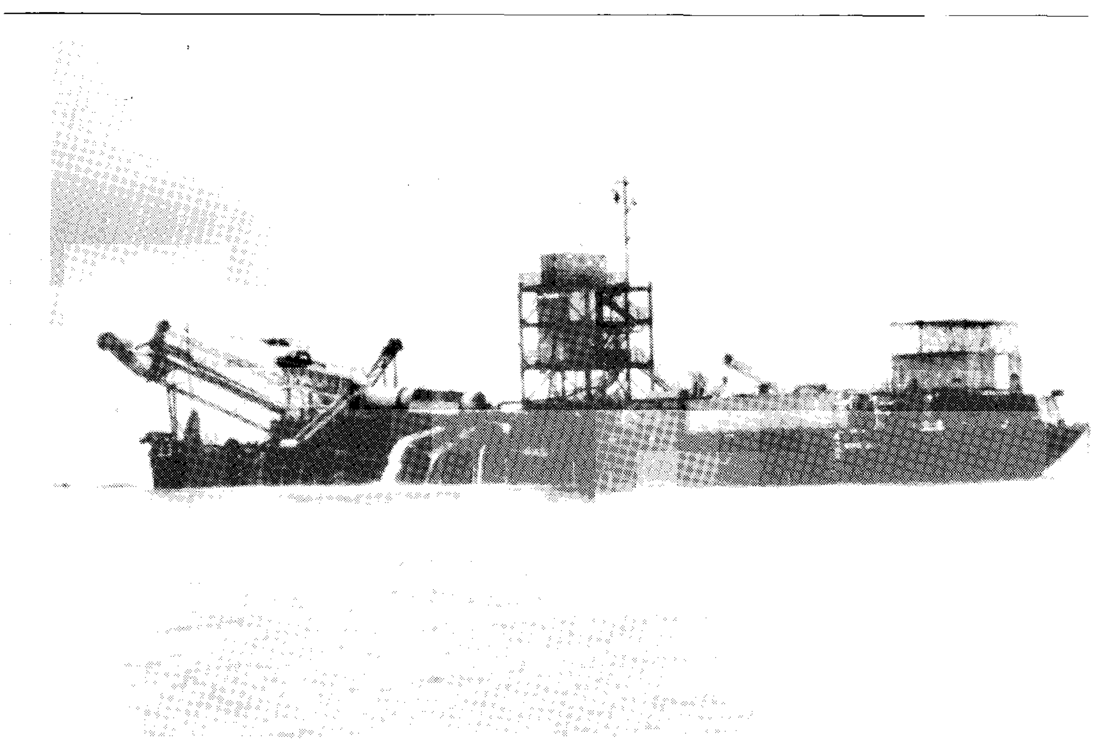


Figure 3.19 Support vessel for the underwater mining vehicle "Tramrod", offshore Nome, Alaska (photograph courtesy of R. Garnett)

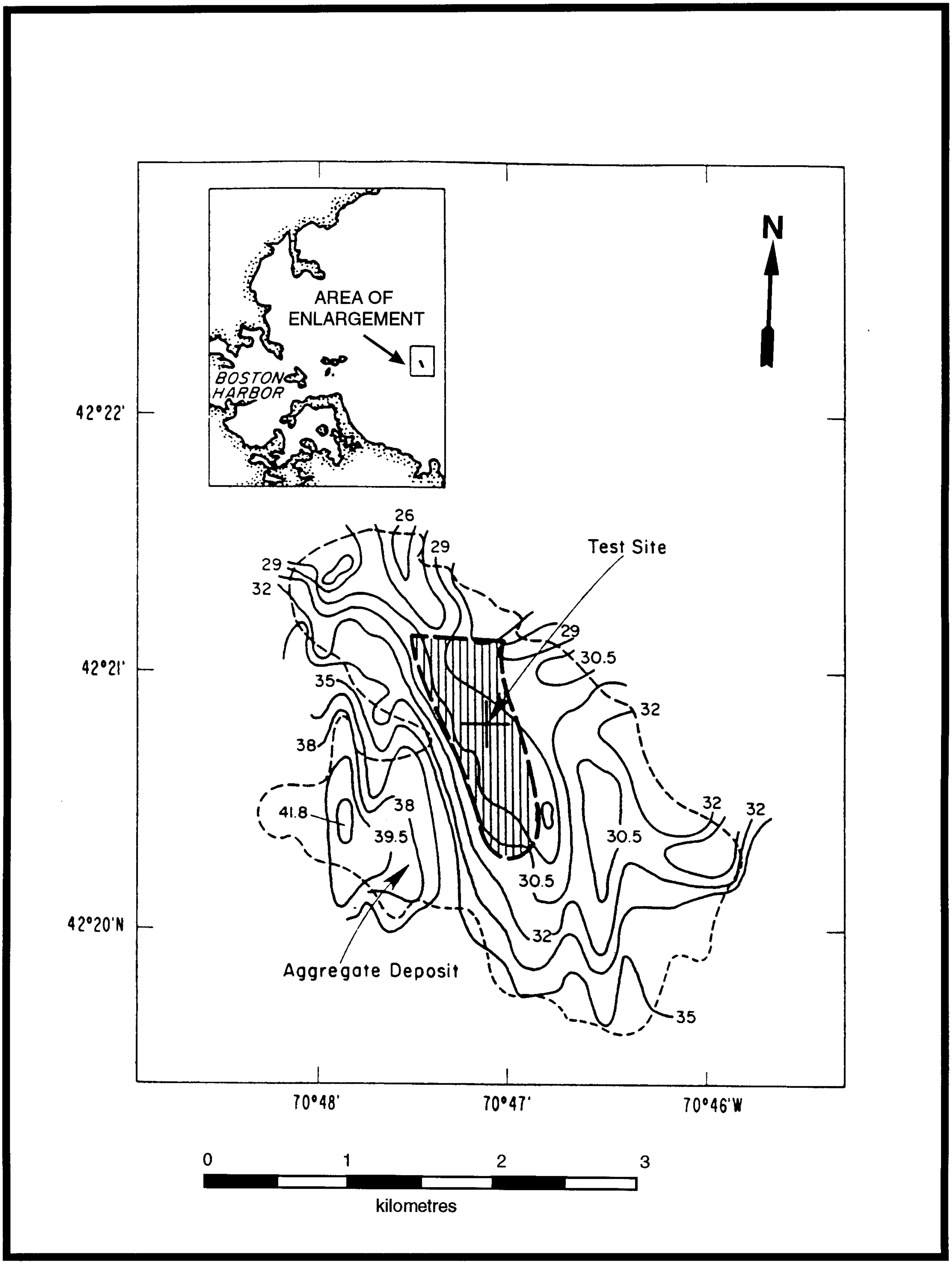


Figure 3.20 Location of the study area and proposed NOMES test mine site (shaded) offshore Boston Harbour. Isobaths in metres (from Padan, 1977)

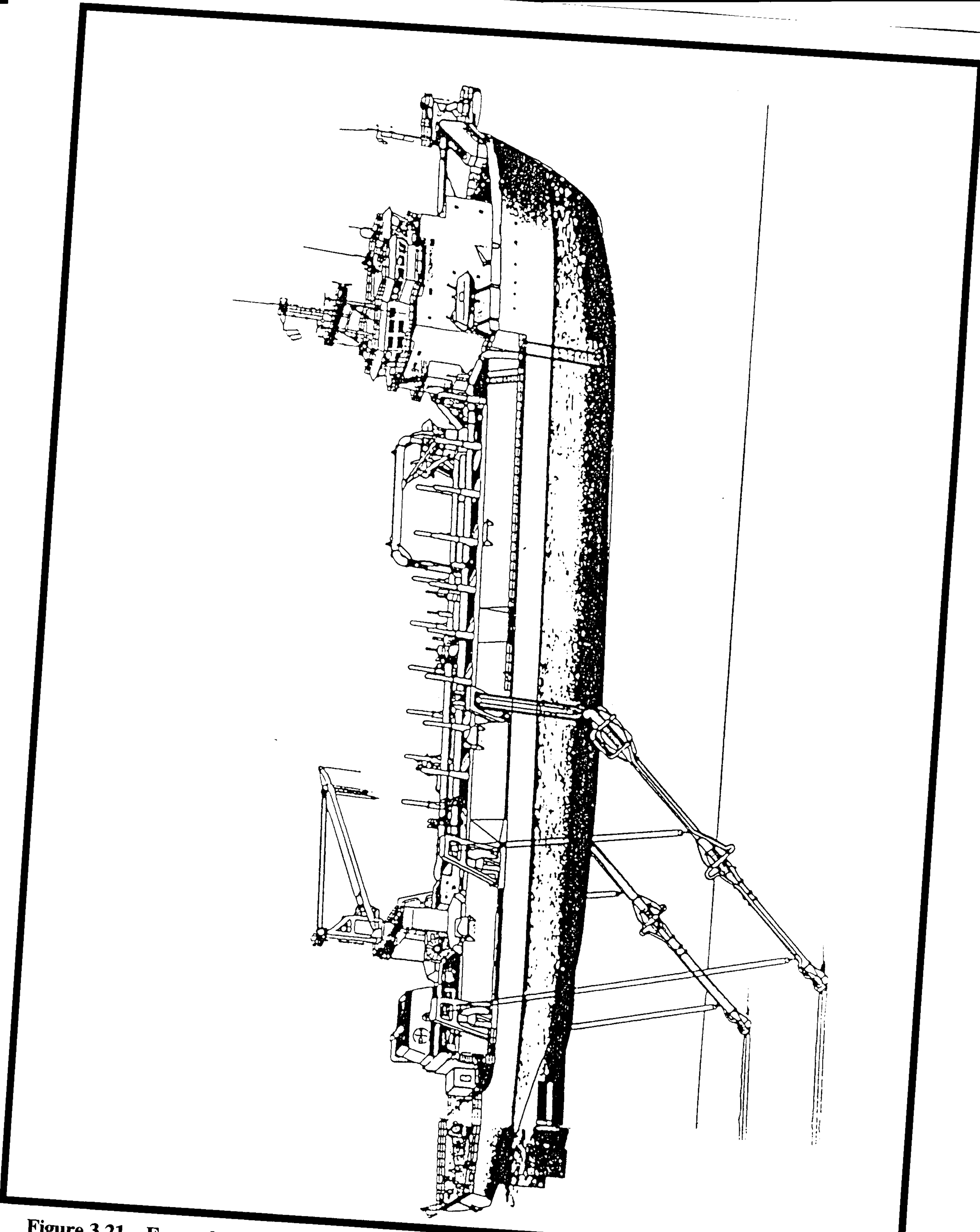


Figure 3.21 Example of a typical trailing suction hopper dredge (provided by Jan de Nul n.v., Holland)

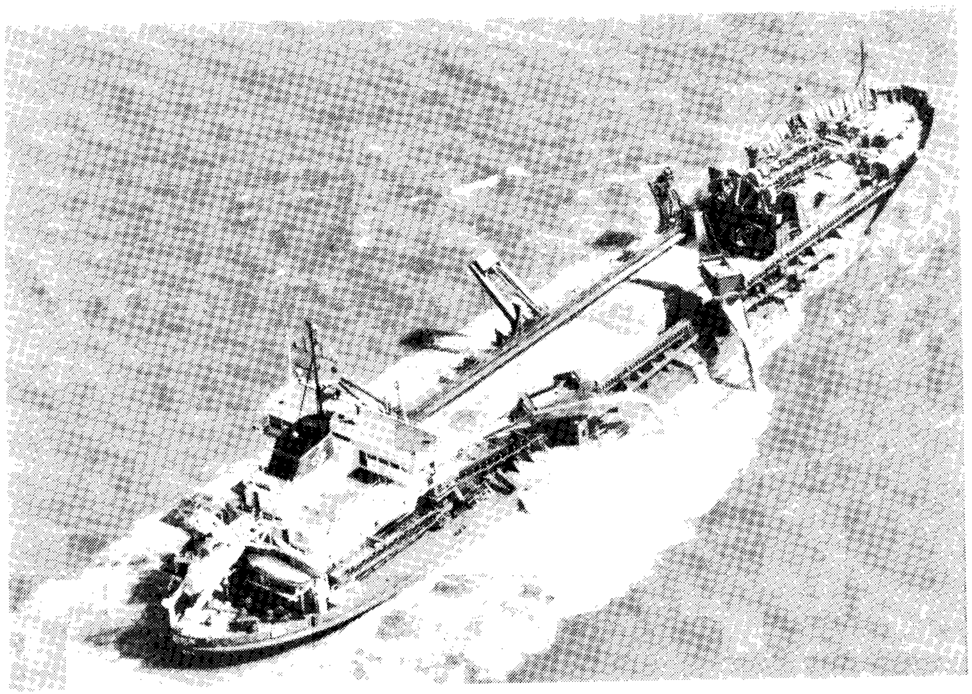


Figure 3.22 Trailing suction hopper dredge discharging fines (photograph from Ports and Dredging magazine)

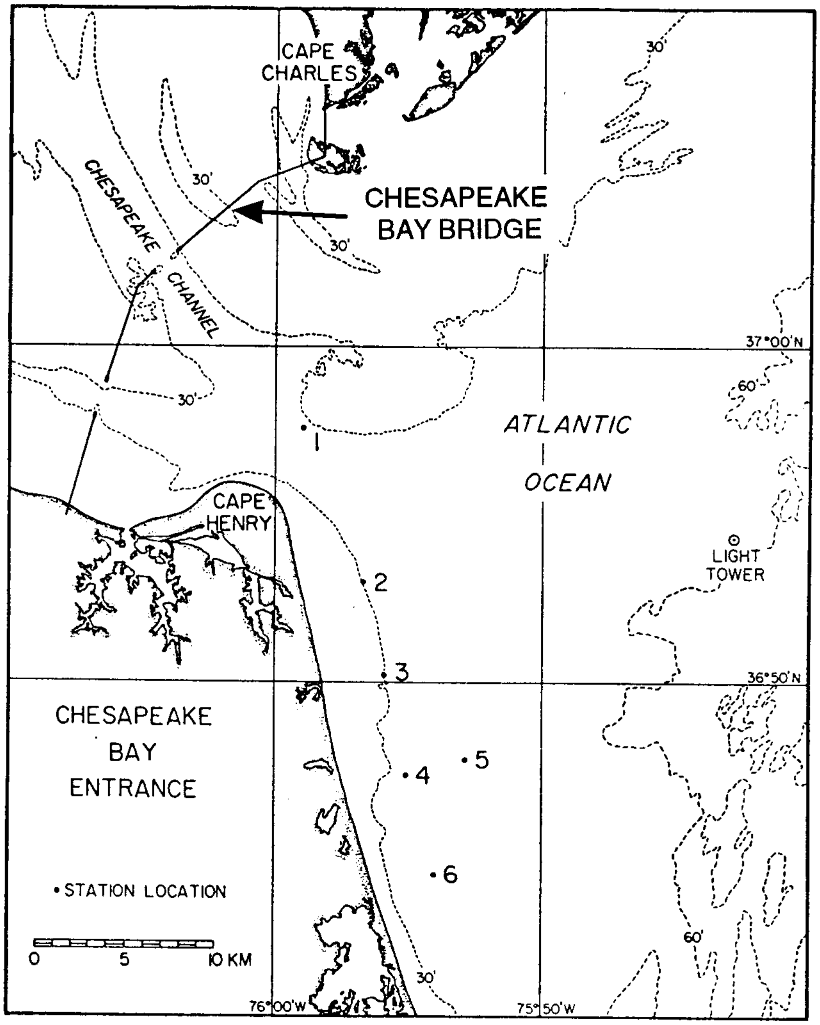


Figure 3.23 Location of current measurement sites, offshore Virginia Beach (1973) used by Ludwick (1978)

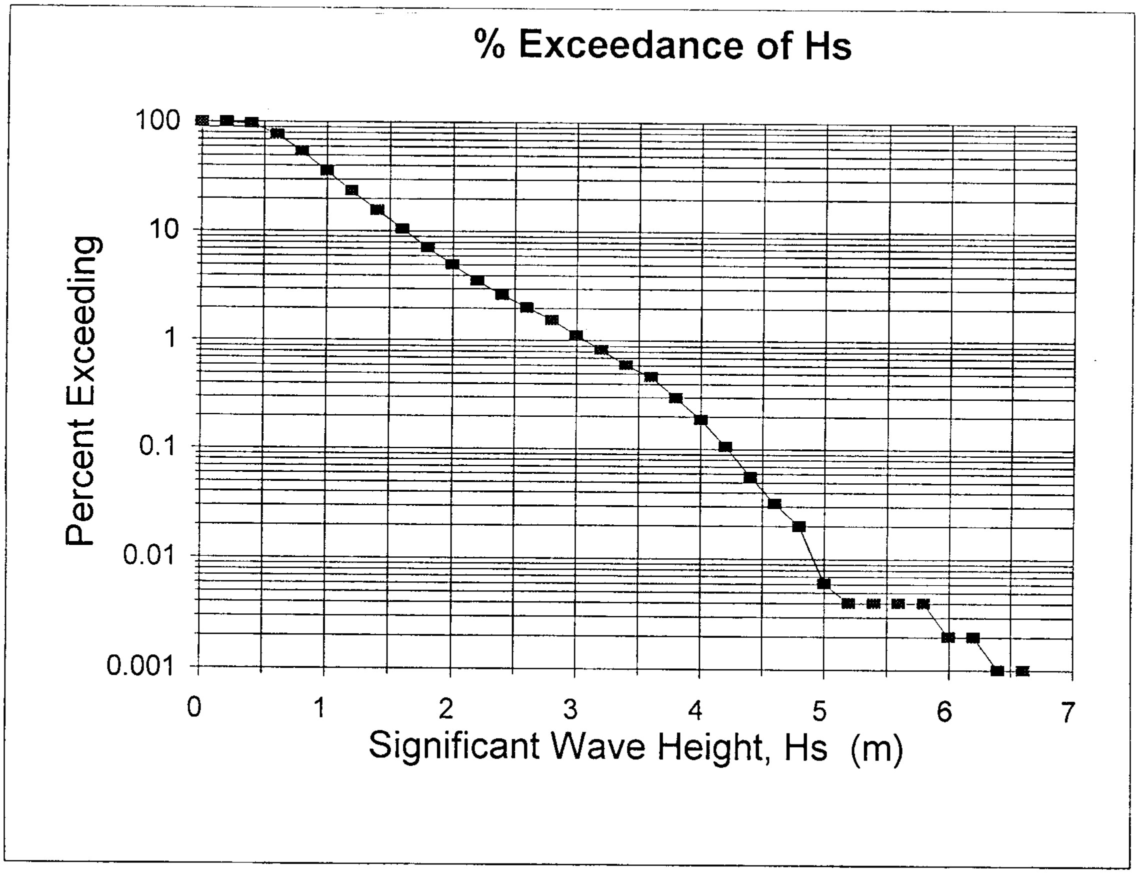


Figure 3.24 Exceedence of significant wave height immediately offshore Virginia Beach

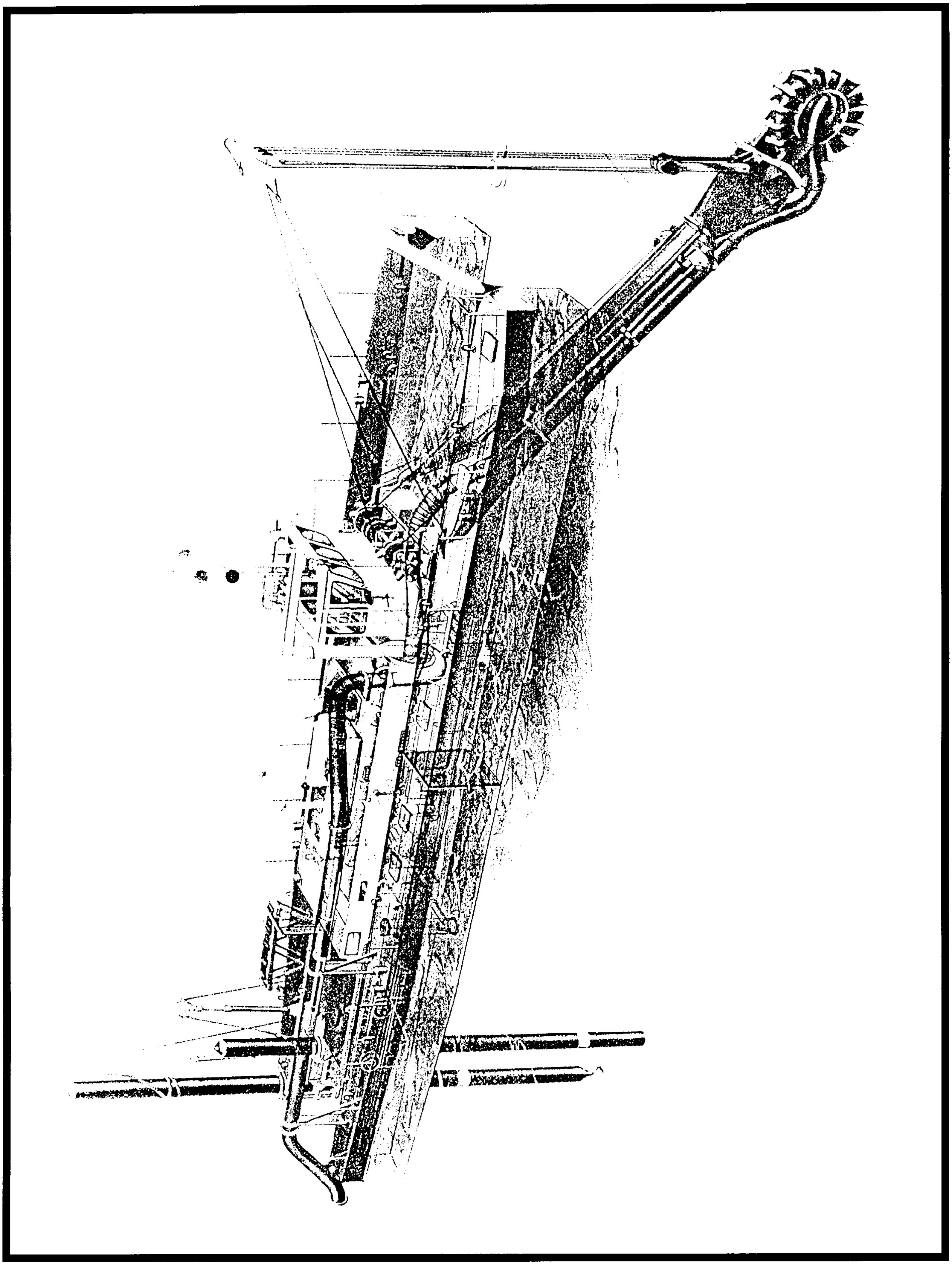


Figure 3.25 Example of a typical spud-powered cutter suction dredge

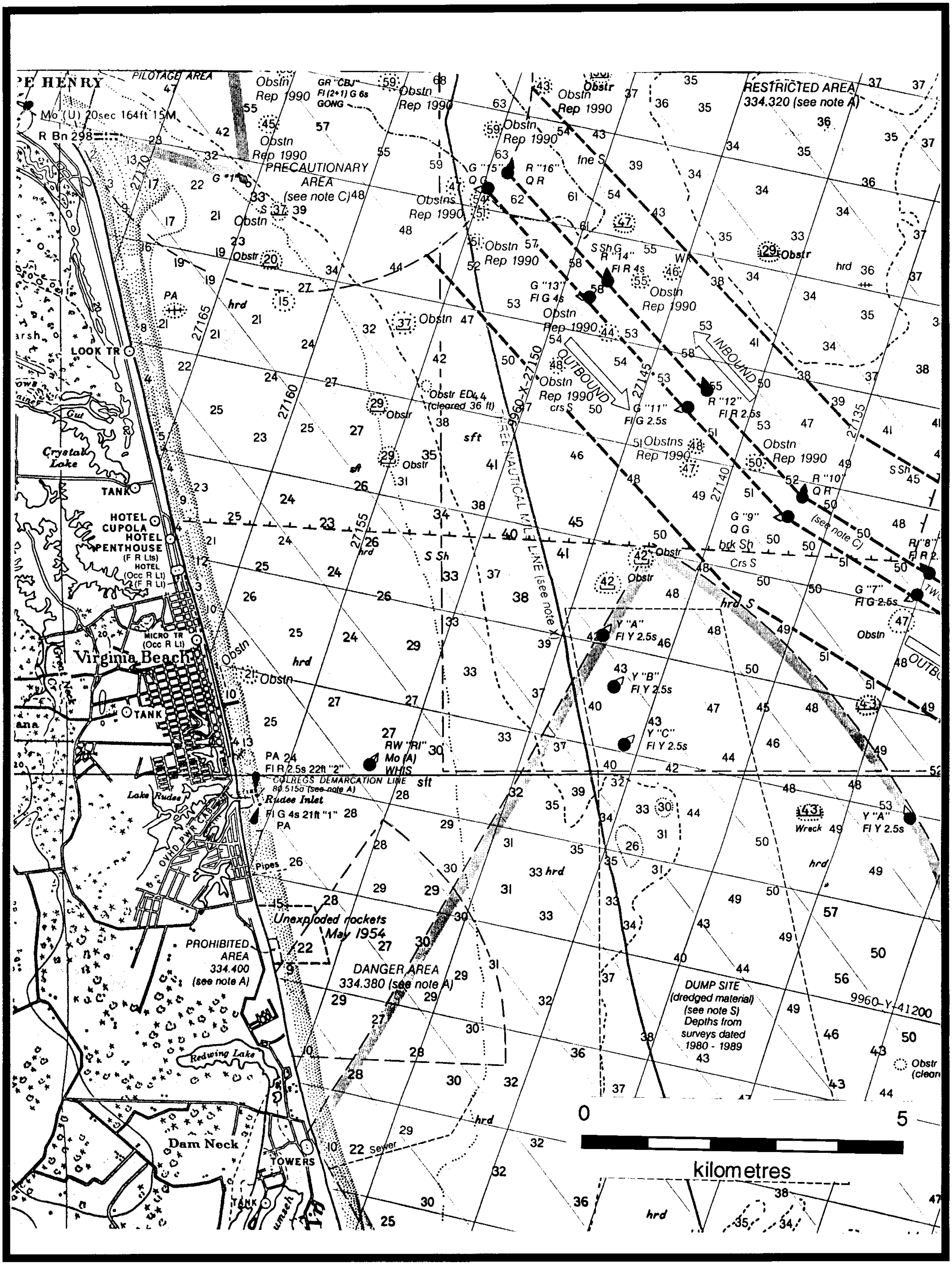


Figure 3.26 Bathymetry off Virginia Beach (depths in feet)

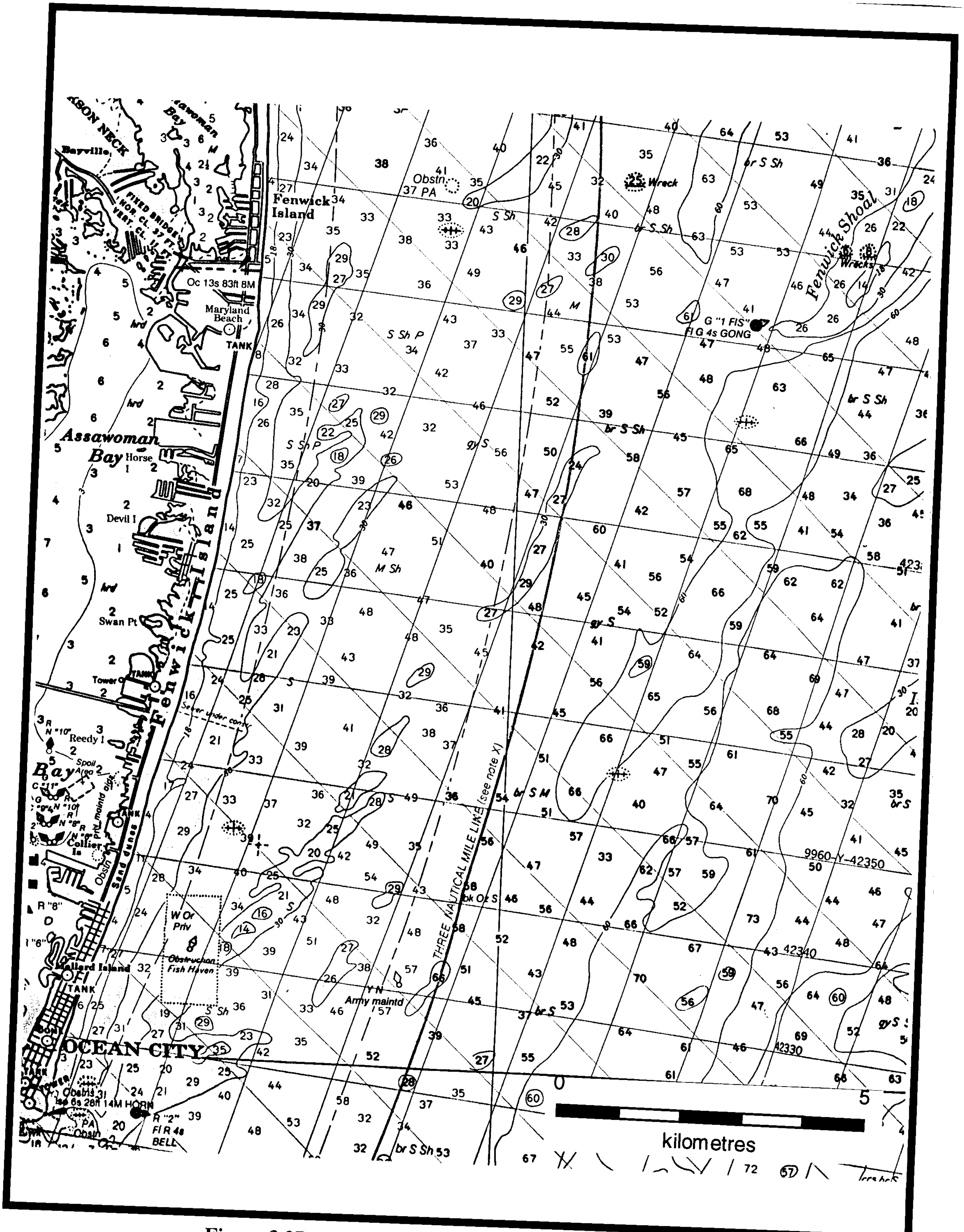


Figure 3.27 Bathymetry off Ocean City (depths in feet)

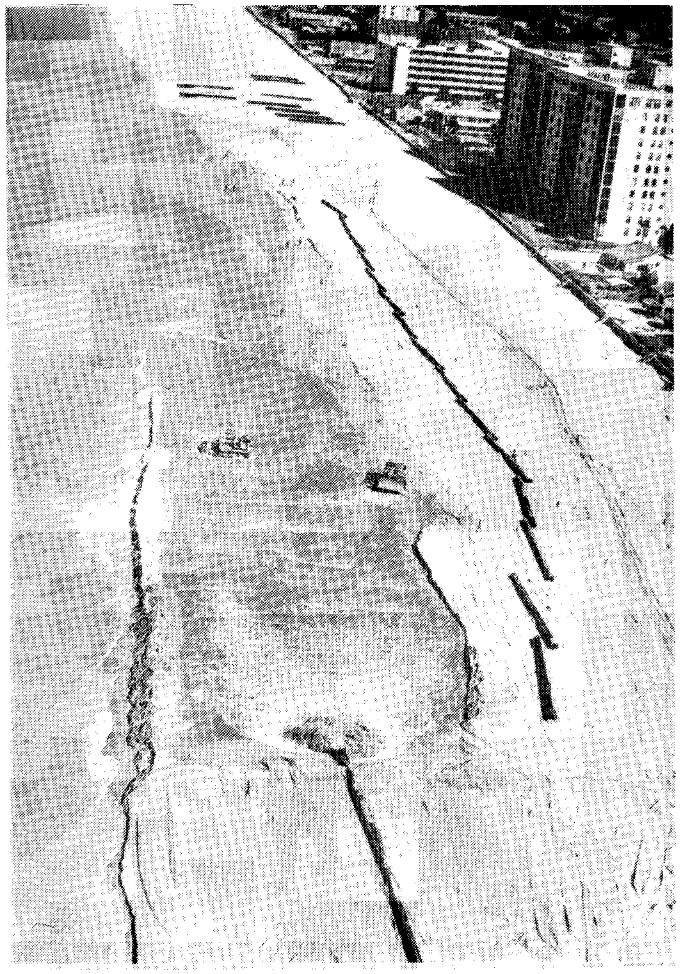


Figure 3.28 Beach nourishment project in progress; note the toe dyke to the left (photograph taken from World Dredging, Mining and Construction magazine, April, 1992)

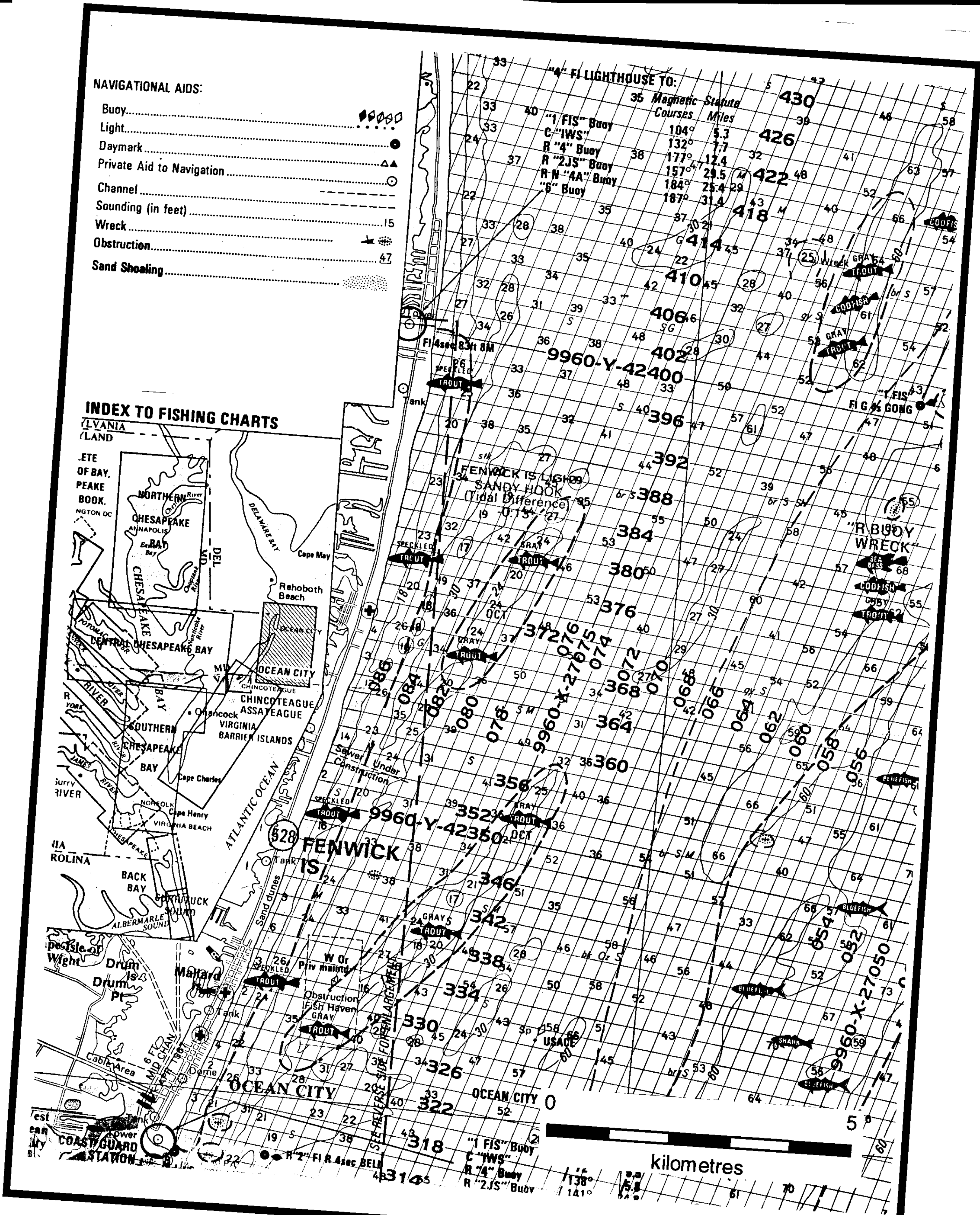


Figure 3.29 Fishing chart for offshore Ocean City (depths in feet)

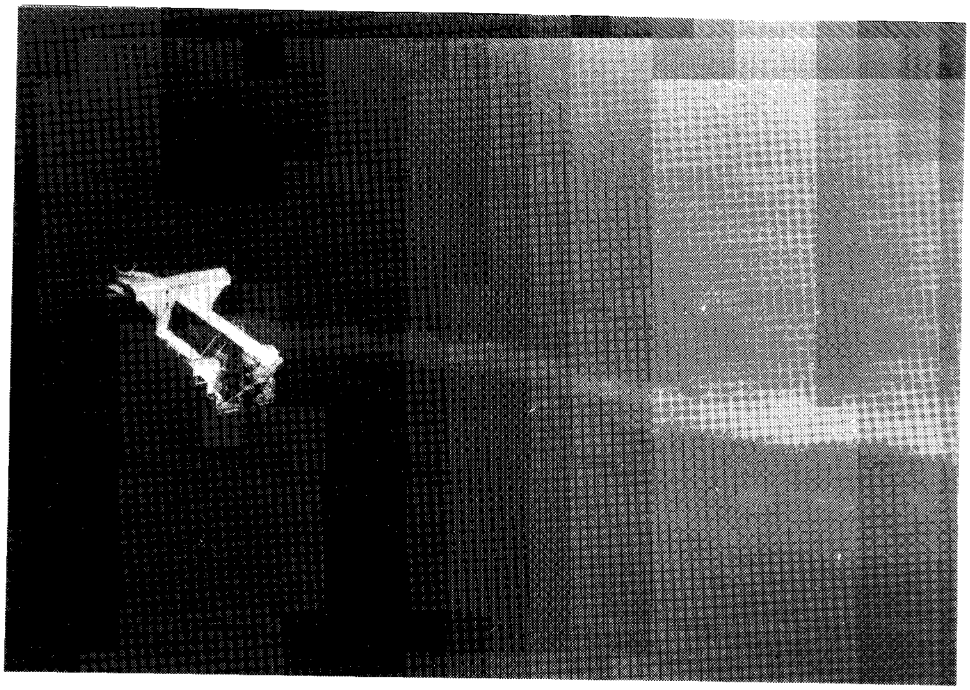


Figure 3.30 Aerial view of the BIMA working offshore Nome, Alaska. Note the two turbidity plumes (photograph courtesy of R. Garnett)

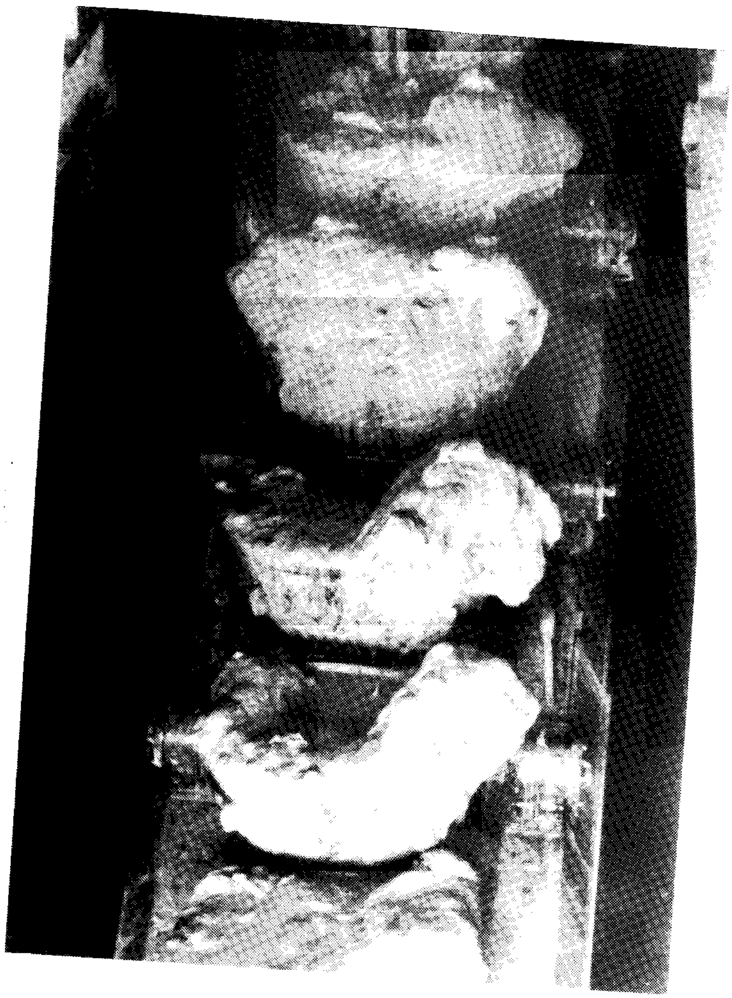


Figure 4.1 Buckets on the BIMA's bucket ladder overflowing with fine sediment (photograph courtesy of R. Garnett)

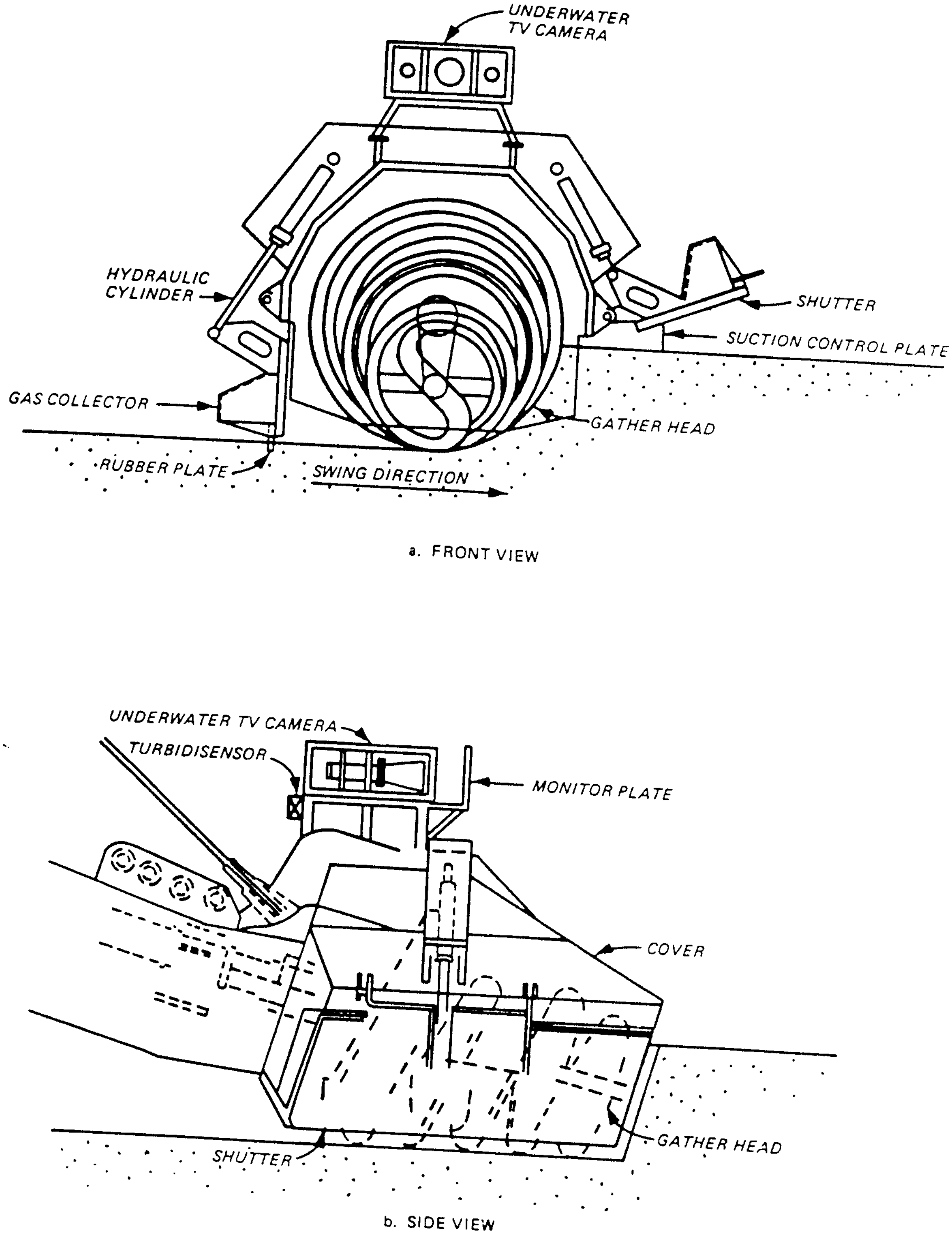


Figure 4.2 **Front and side view schematic of the Japanese "refresher" dredge system (after Raymond, 1984)**

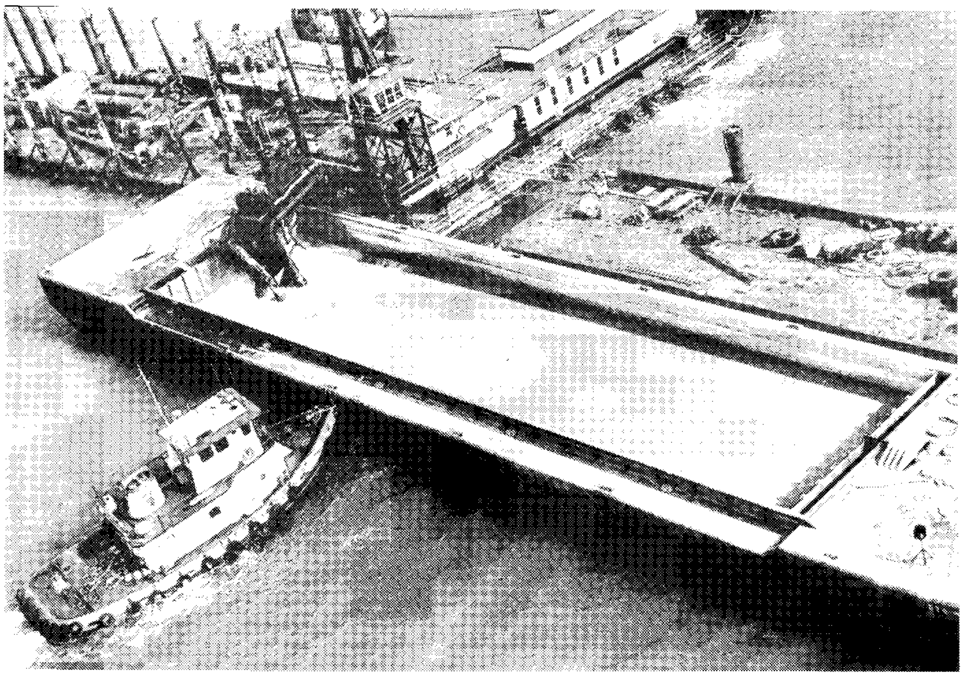


Figure 4.3 Marine aggregate unloading facility (photograph taken from World Dredging, Mining and Construction magazine, April, 1992)

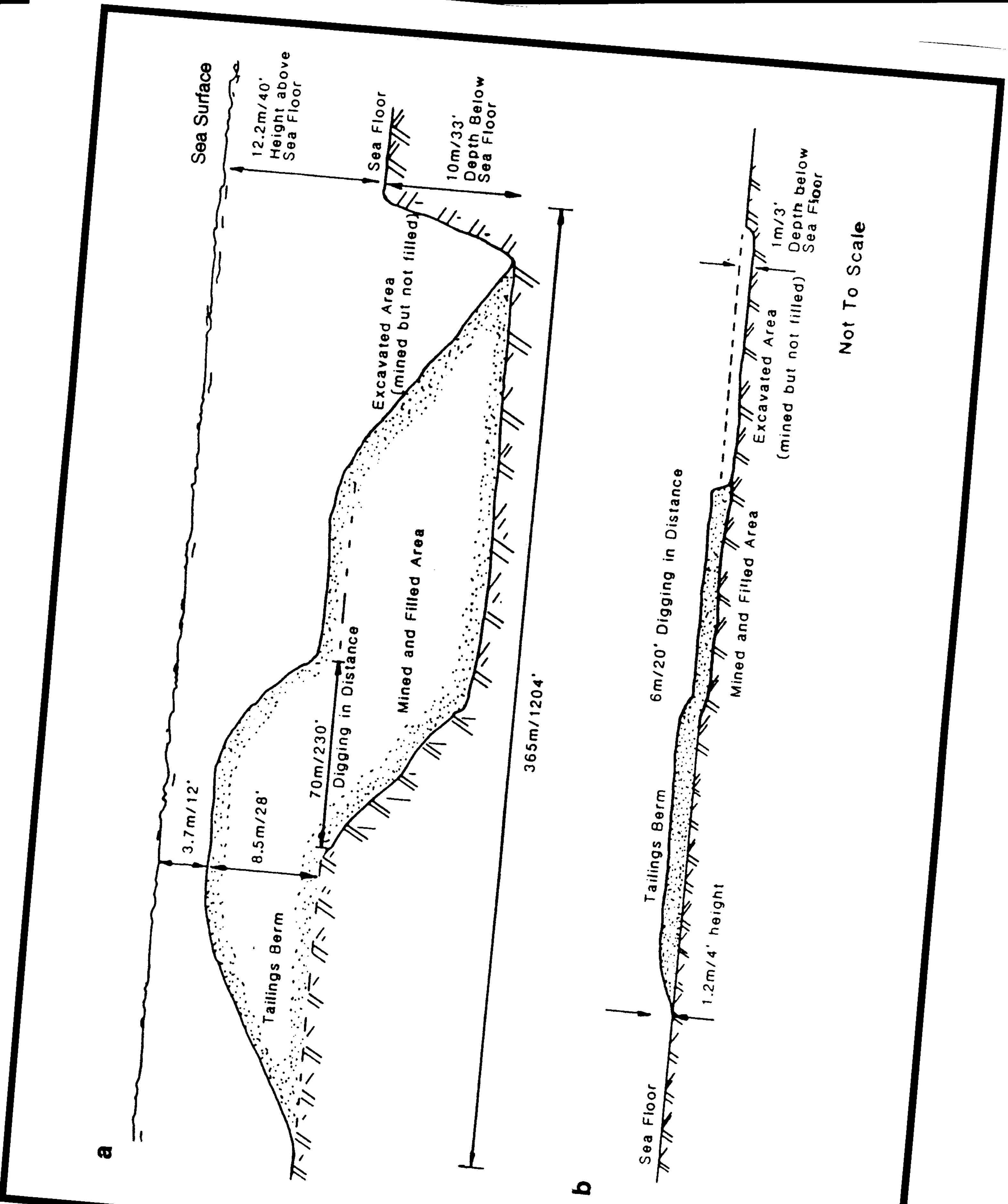


Figure 4.4 **Diagram to illustrate tailings distribution over a dredge course: (a) cross-section of digging depth of 10 m; (b) cross-section of a digging depth of 1 m (after Jewett *et al.* 1991)**

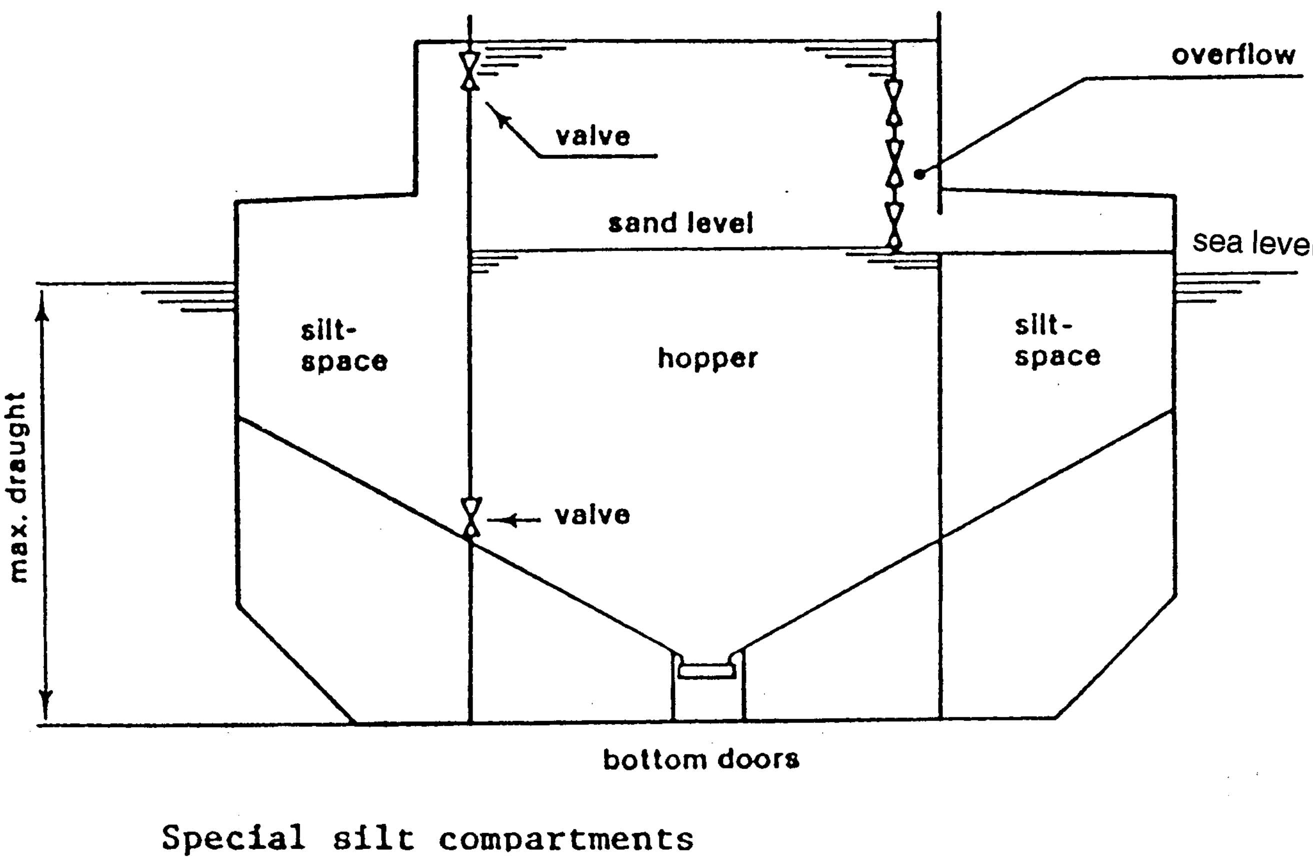


Figure 4.5 Transverse section through a trailing suction hopper dredge showing conceptual system for waste solids retention (after Van Drimmelen and Van Zutphen, 1987)

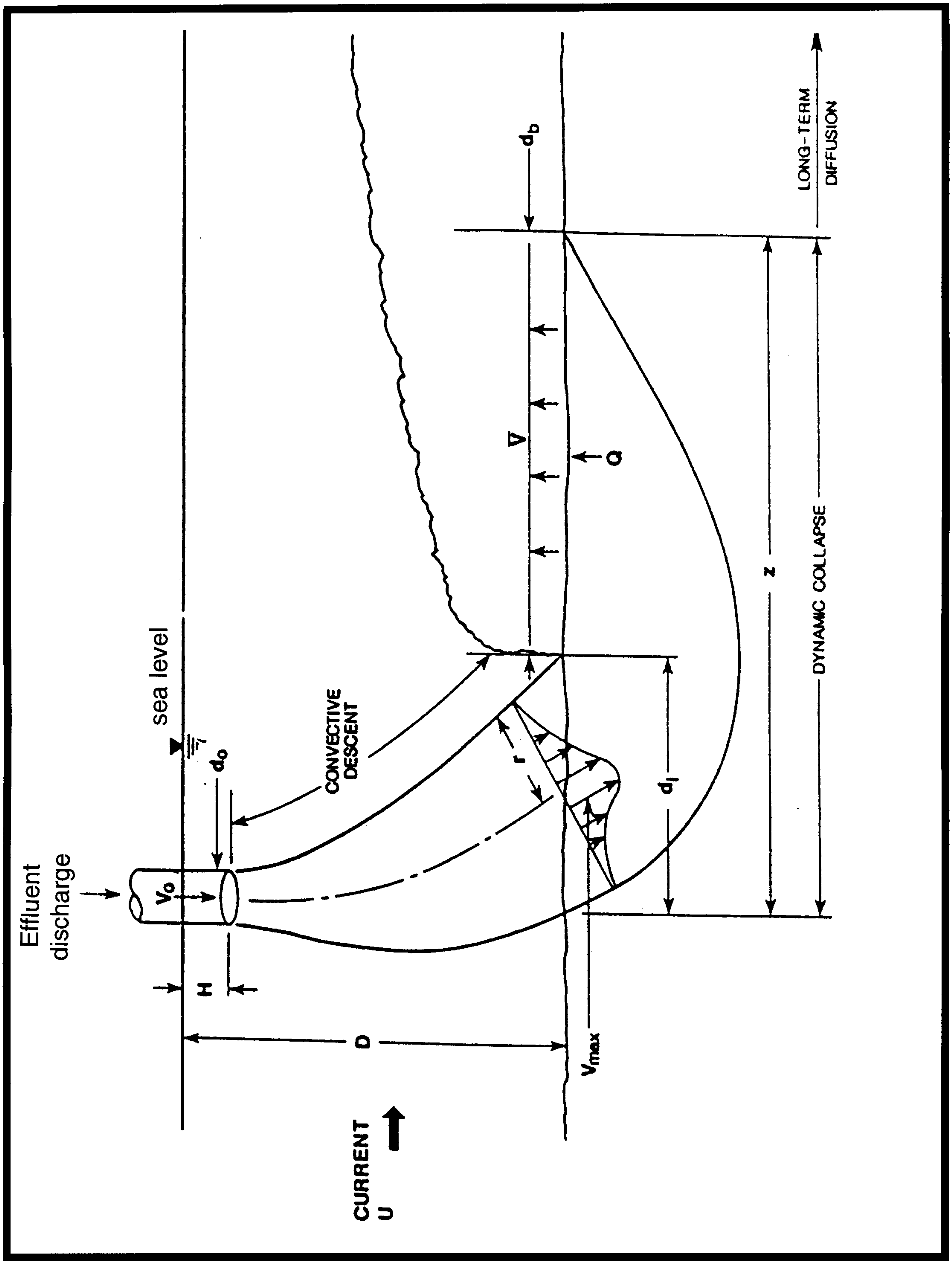


Figure 5.1 Diagram to illustrate the physics of the tailings plume formation process (after Jewett *et al.* 1991)

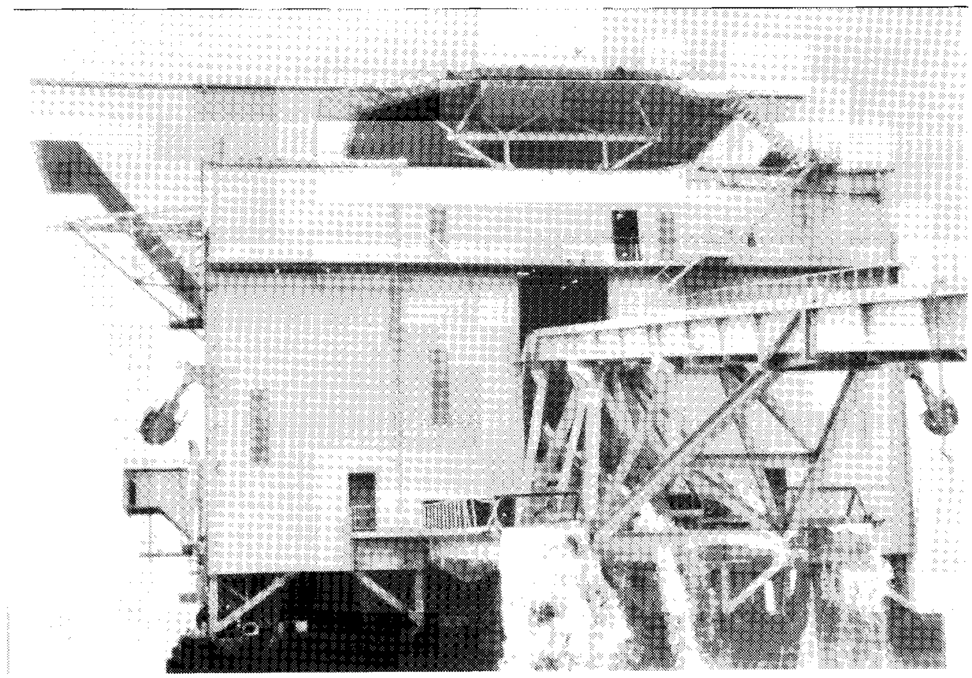


Figure 5.2 Above-surface discharge of tailings from the BIMA, offshore Nome, Alaska (photograph courtesy of R. Garnett)

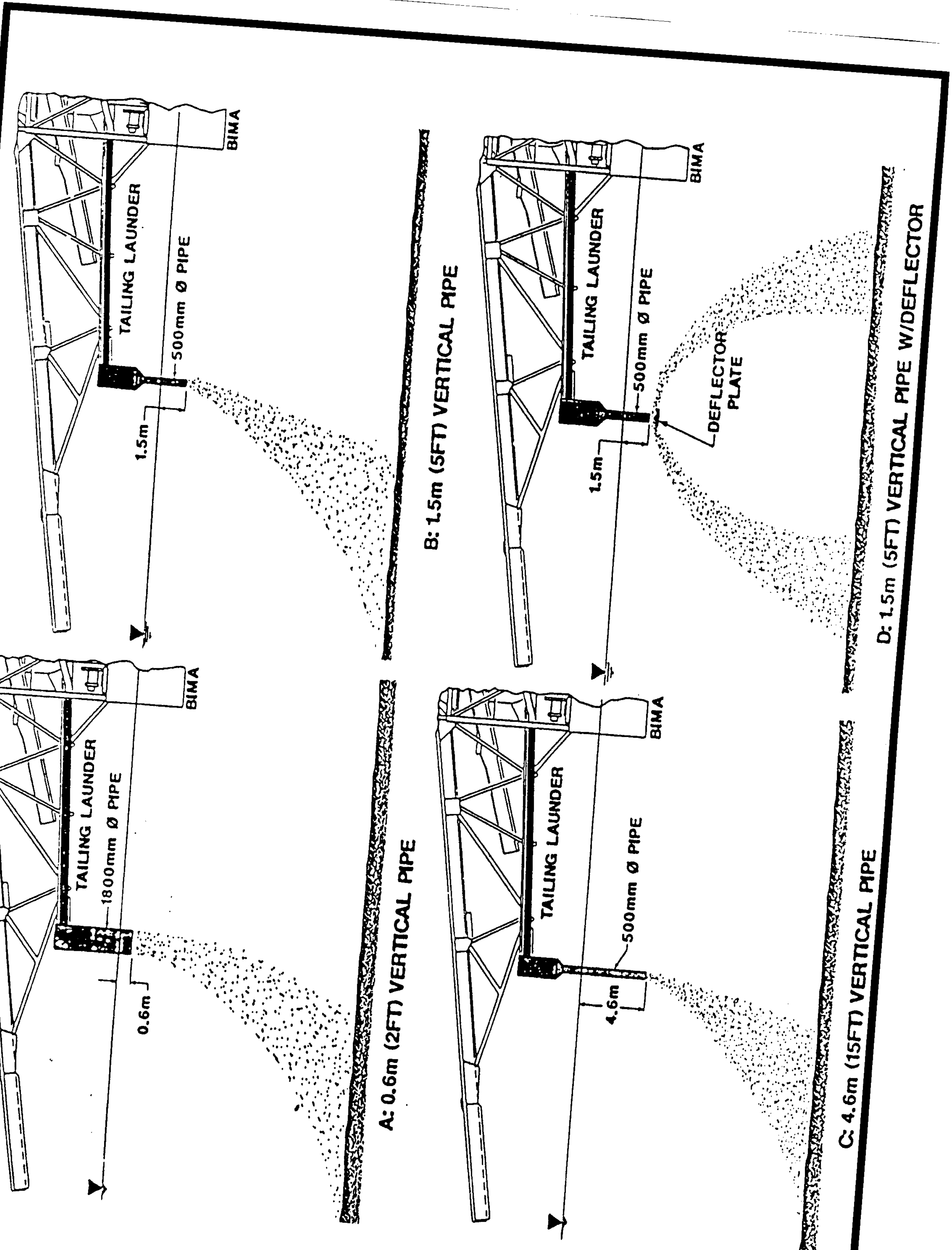


Figure 5.3 Tailings discharge configurations used on the BIMA (after Jewett *et al.* 1991)

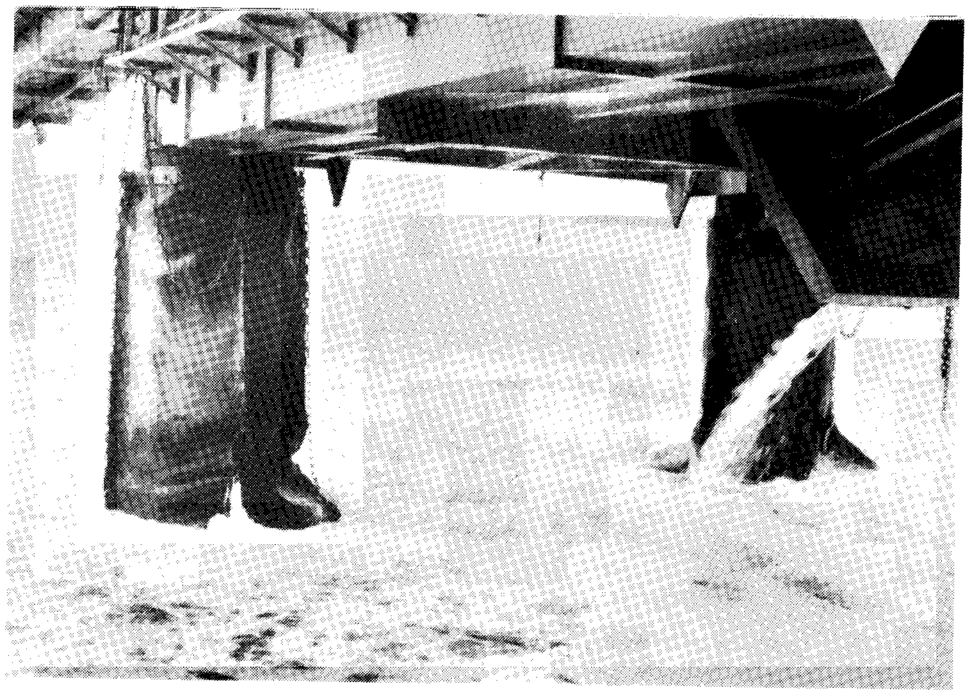


Figure 5.4 Twin tailings launders of the BIMA with surrounding rubber panels (photograph courtesy of R. Garnett)

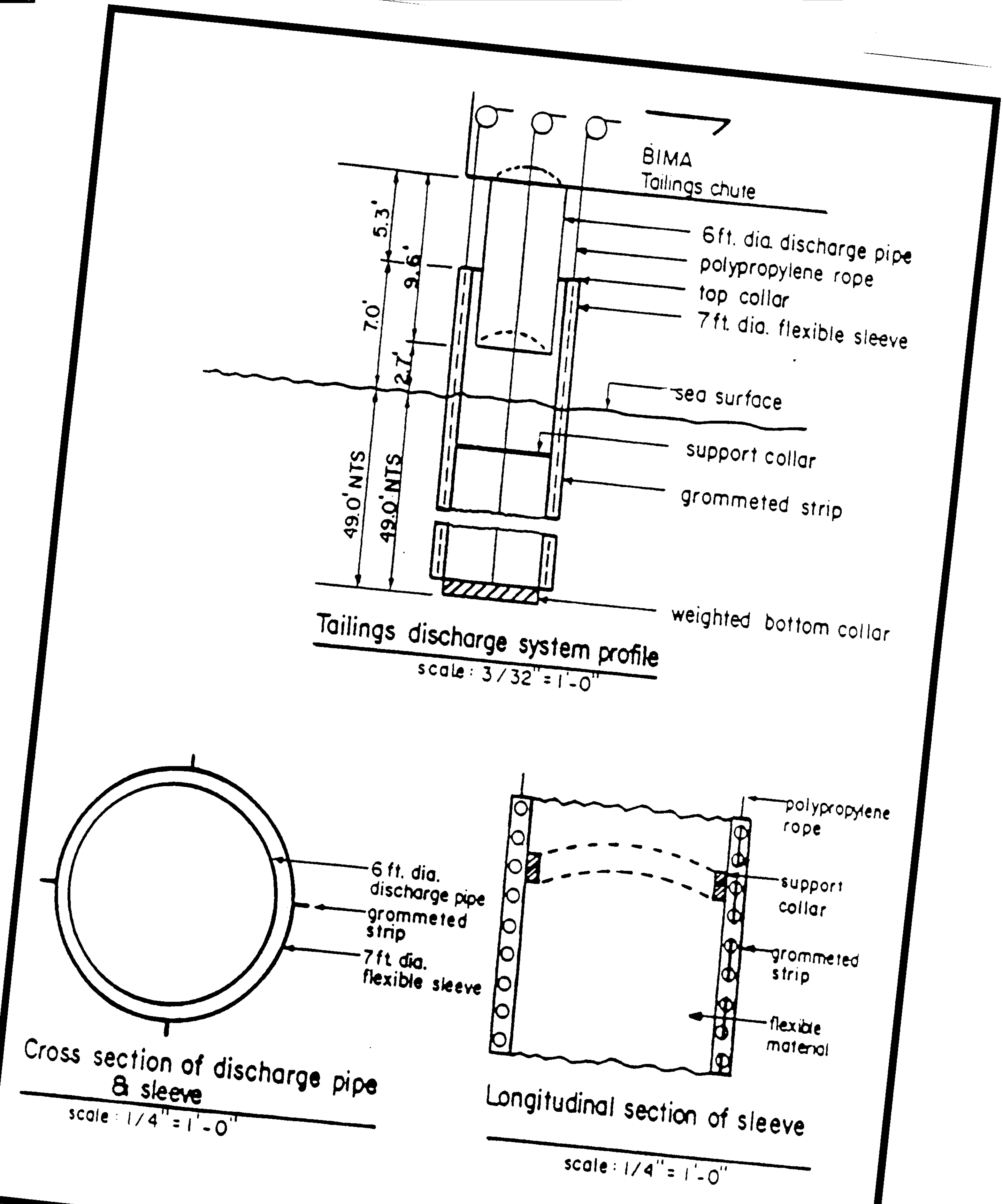


Figure 5.5 Details of 1998 tailings discharge configuration for the BIMA

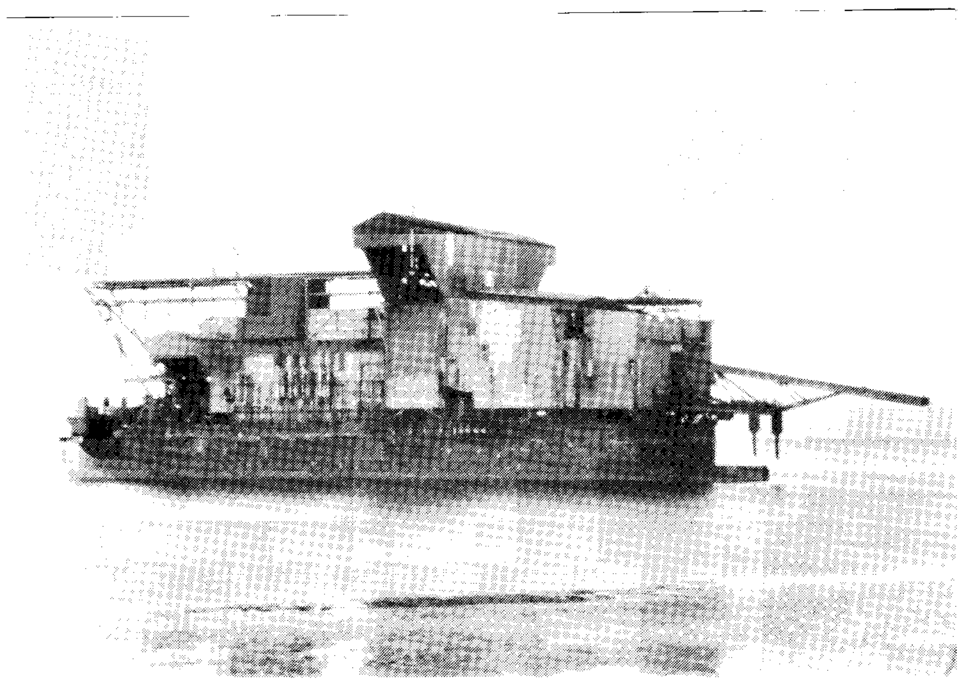


Figure 5.6 The BIMA, with tailings discharge system (twin, reduced steel pipes hanging vertically on right), raised from the water by dry-tow barge (photograph courtesy of R. Garnett)

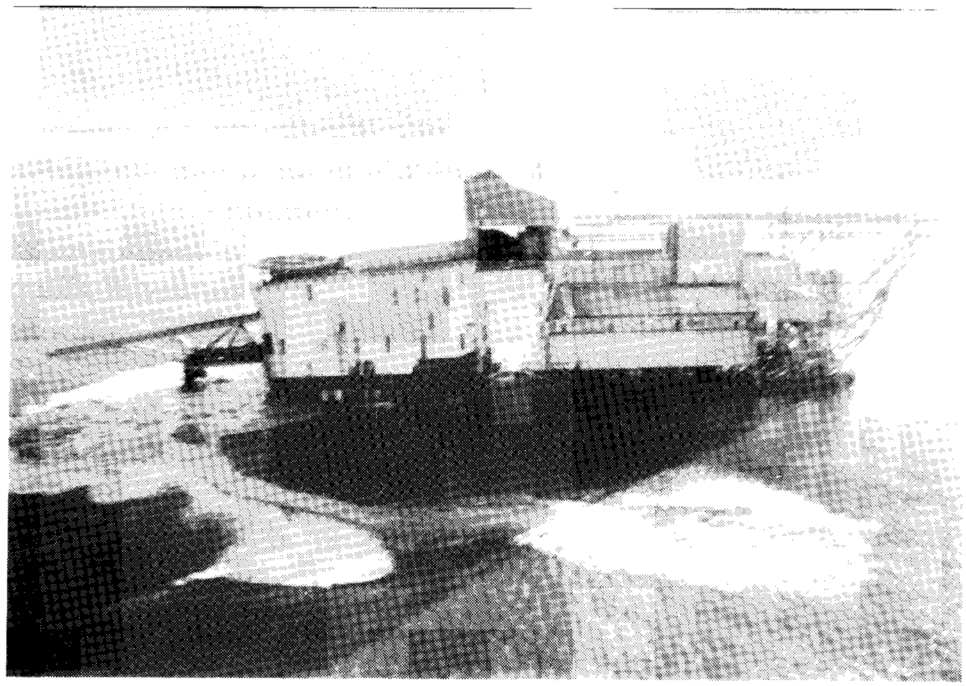


Figure 5.7 Aerial view of the BIMA showing turbulent upwelling experienced with the larger diameter tailings discharge pipes (photograph courtesy of R. Garnett)

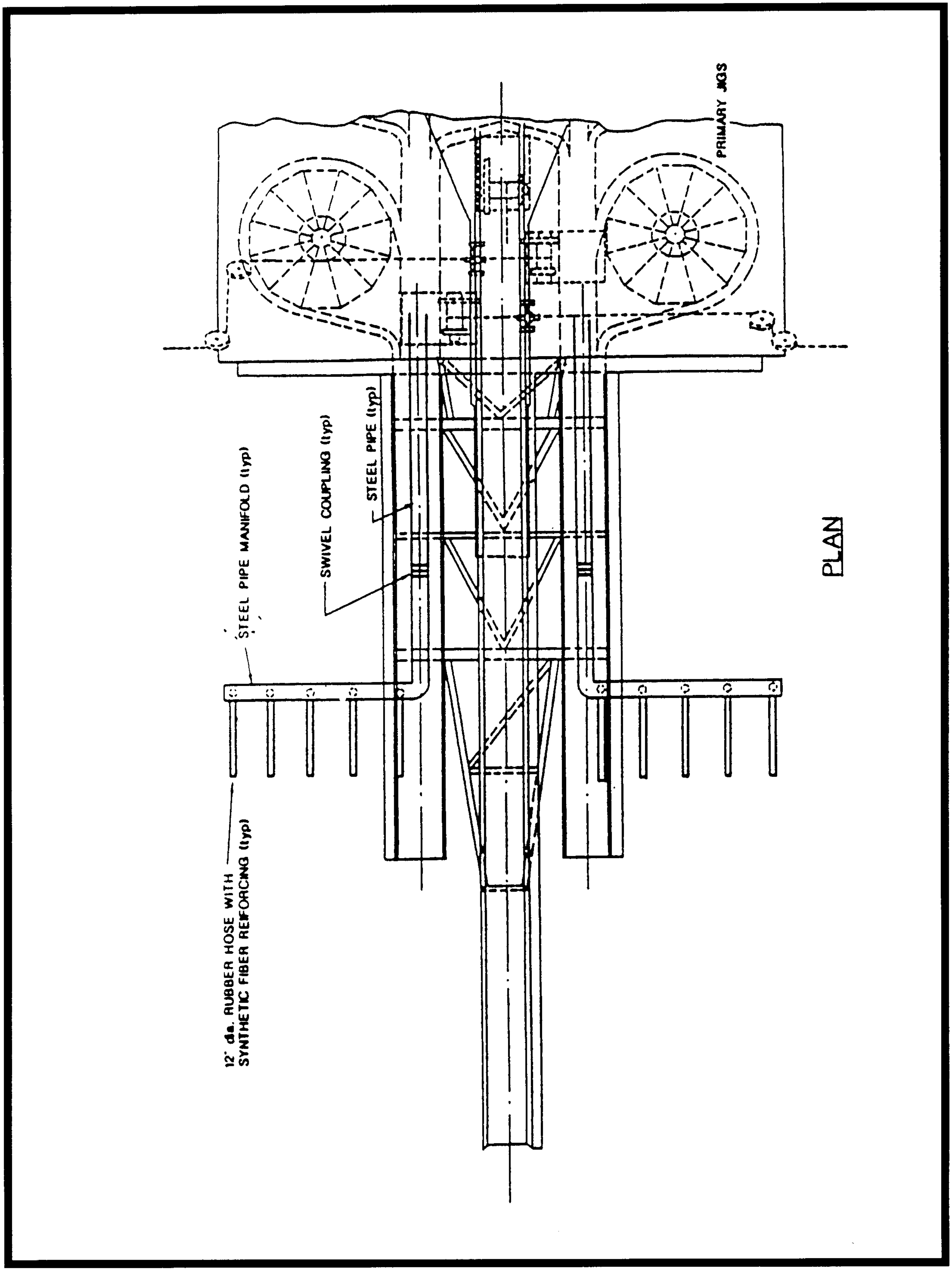


Figure 5.8 Potential multiport discharge system configuration considered for the BIMA (after Jewett *et al.* 1991)

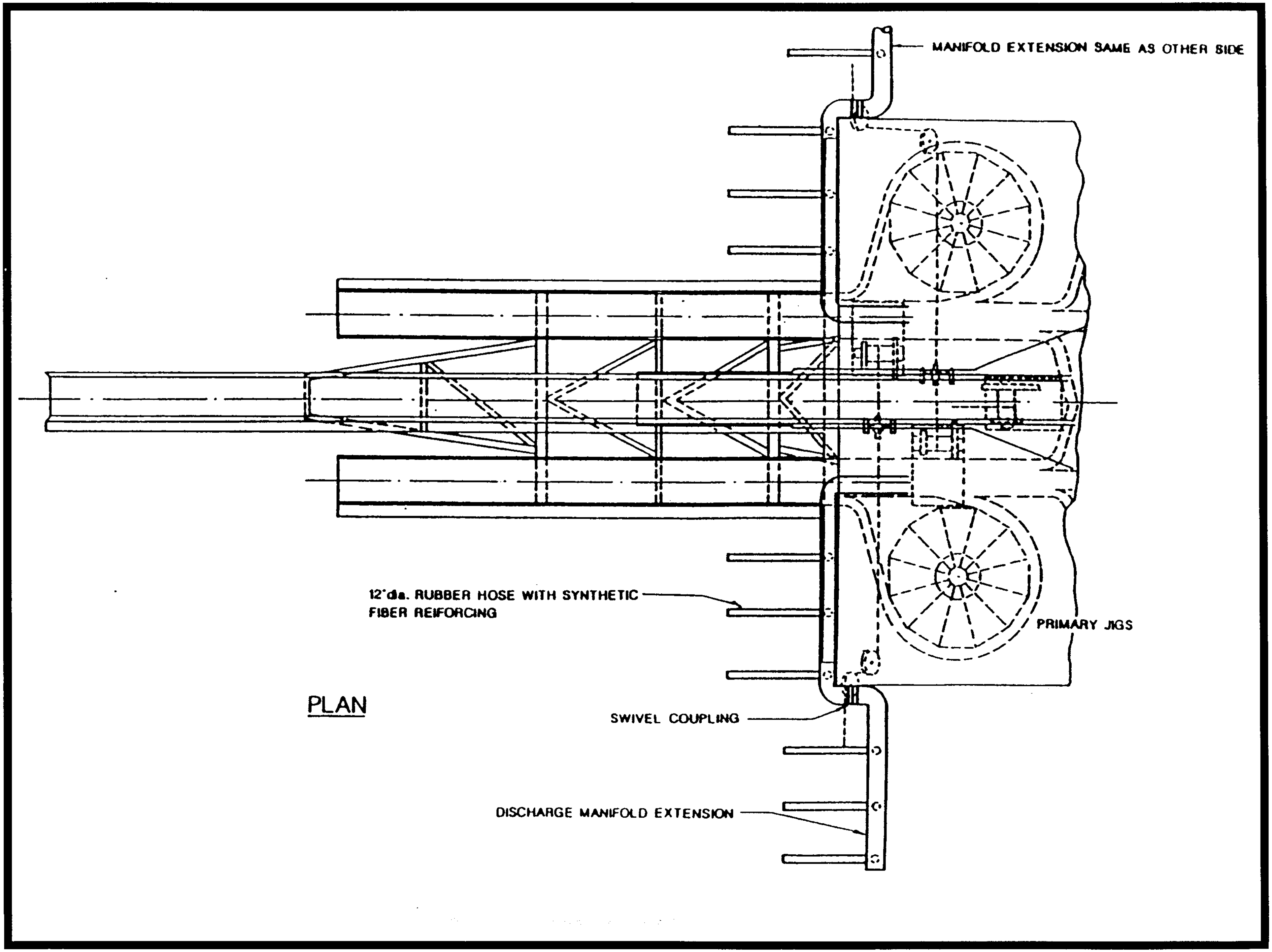


Figure 5.9 Alternative multiport discharge system configuration considered for the BIMA (after Jewett *et al.* 1991)

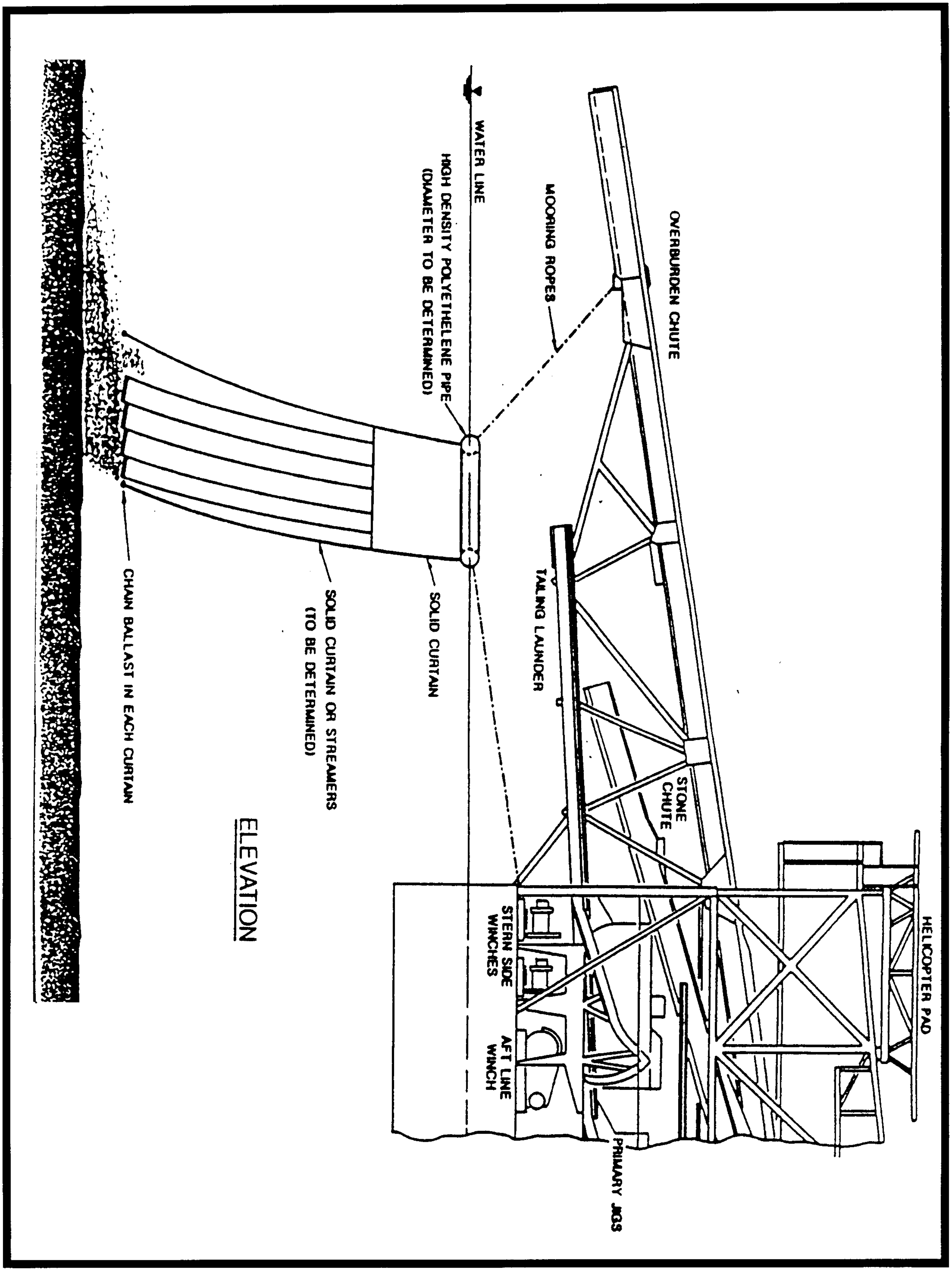


Figure 5.10 Controlled surface discharge configuration considered for the BIMA (after Jewett *et al.* 1991)

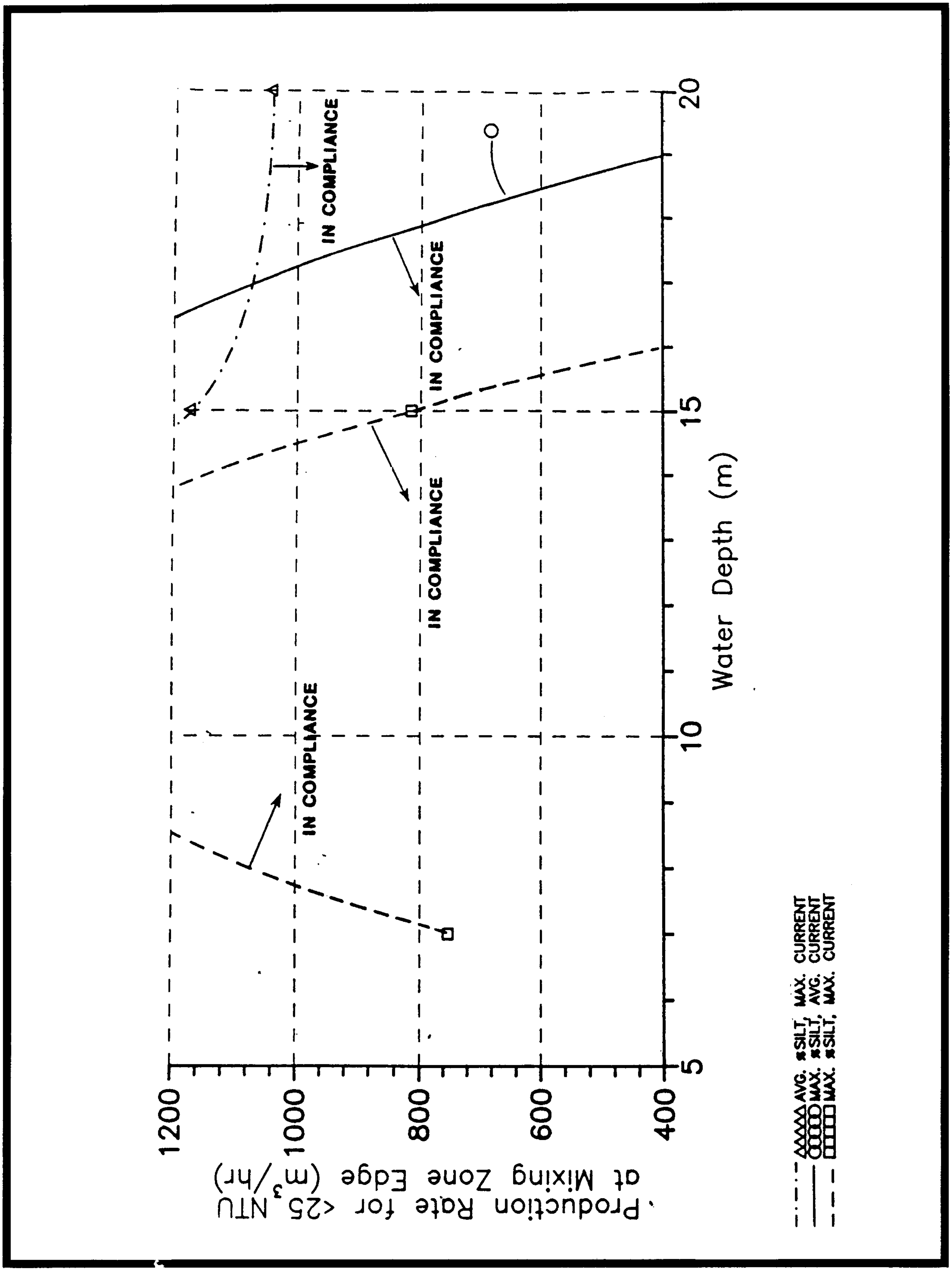


Figure 5.11 **Example of a nomogram for predicting allowable production rates under different operating conditions (after Jewett *et al.* 1991)**

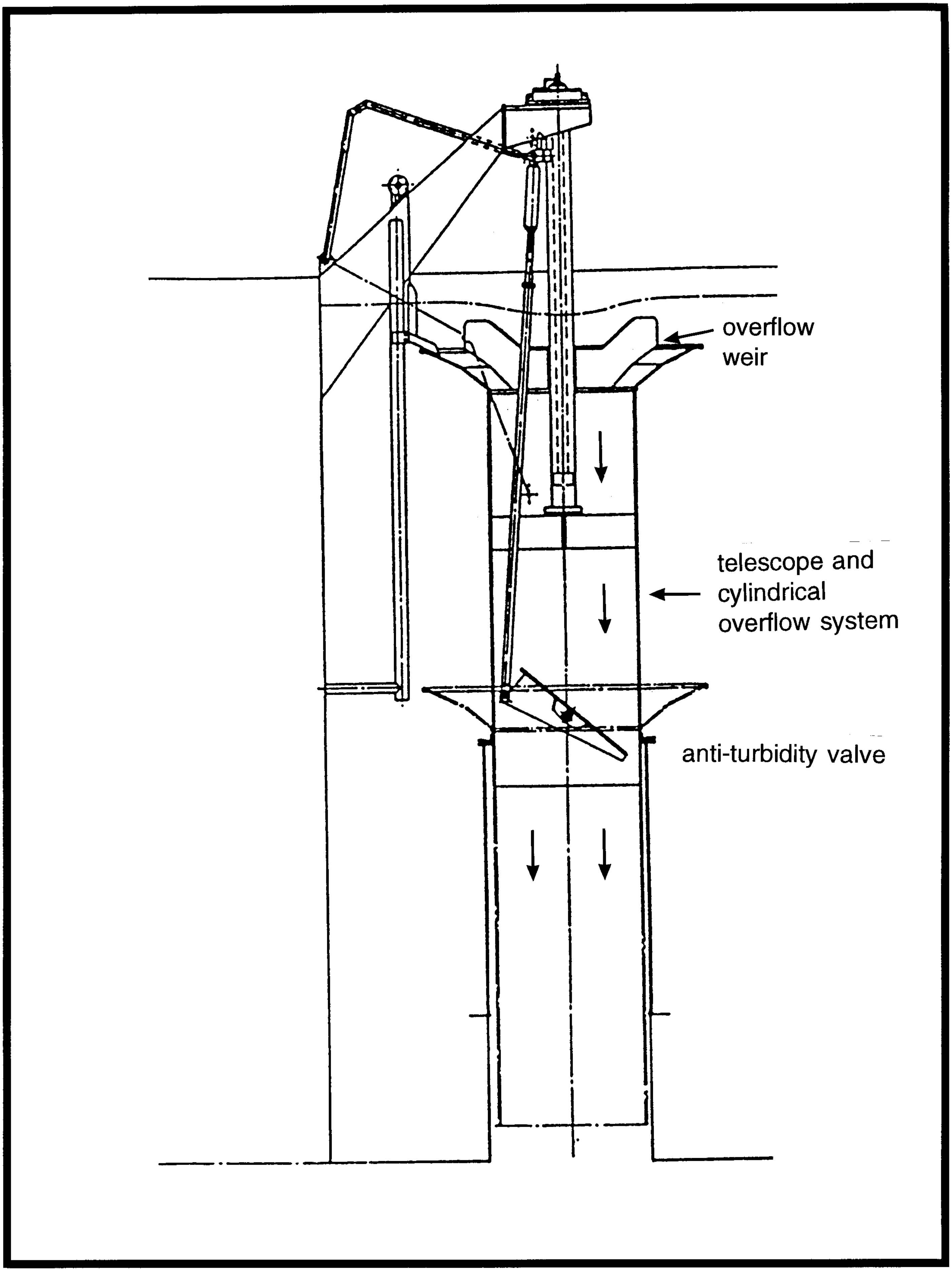


Figure 5.12 Schematic diagram of the IHC anti-turbidity overflow system (after Van Drimmelen and Van Zutphen, 1987)

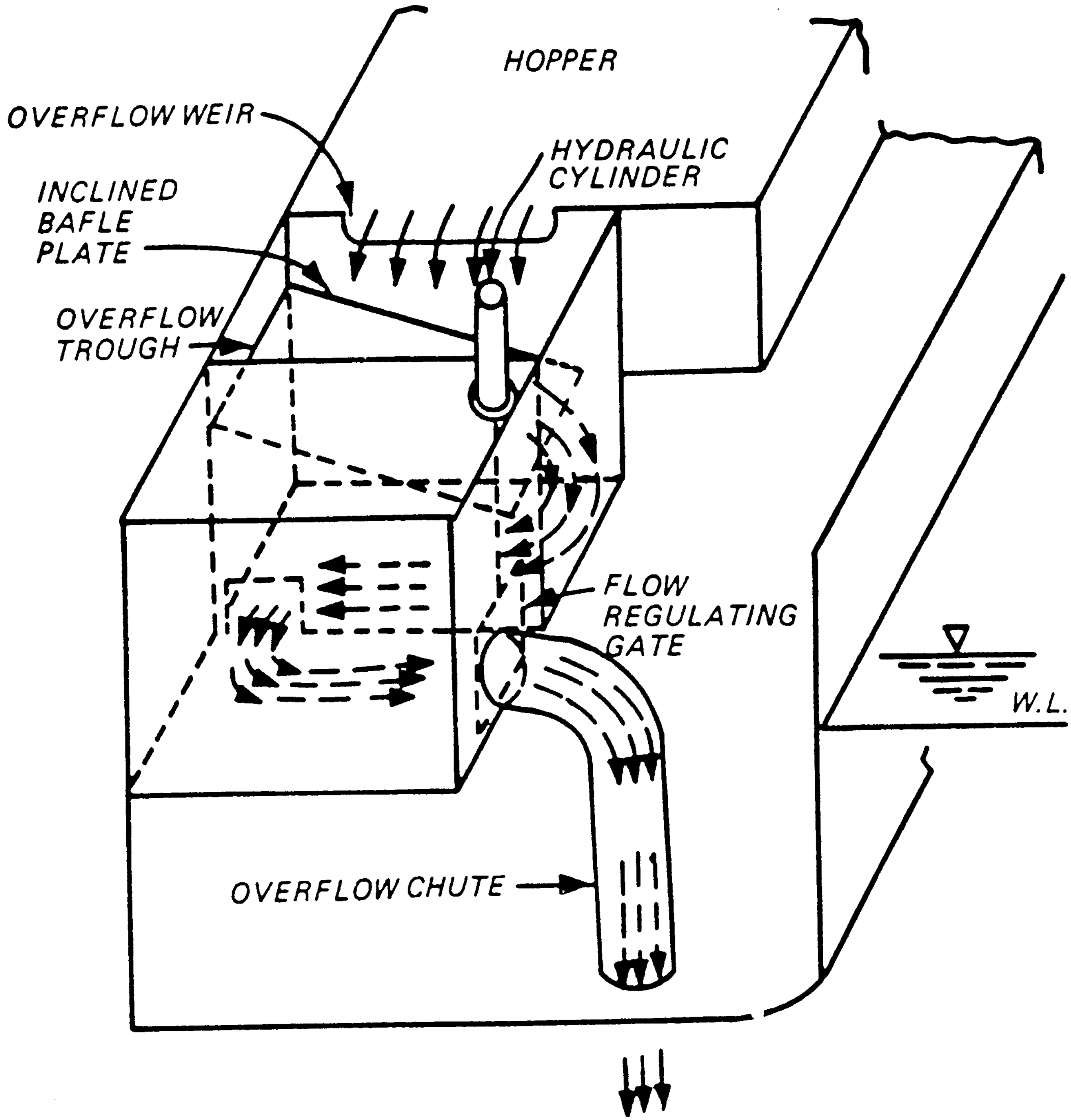


Figure 5.13 Schematic diagram of a hopper dredge bin equipped with the Japanese-designed Anti-Turbidity Overflow System (ATOS) (after Raymond, 1984)

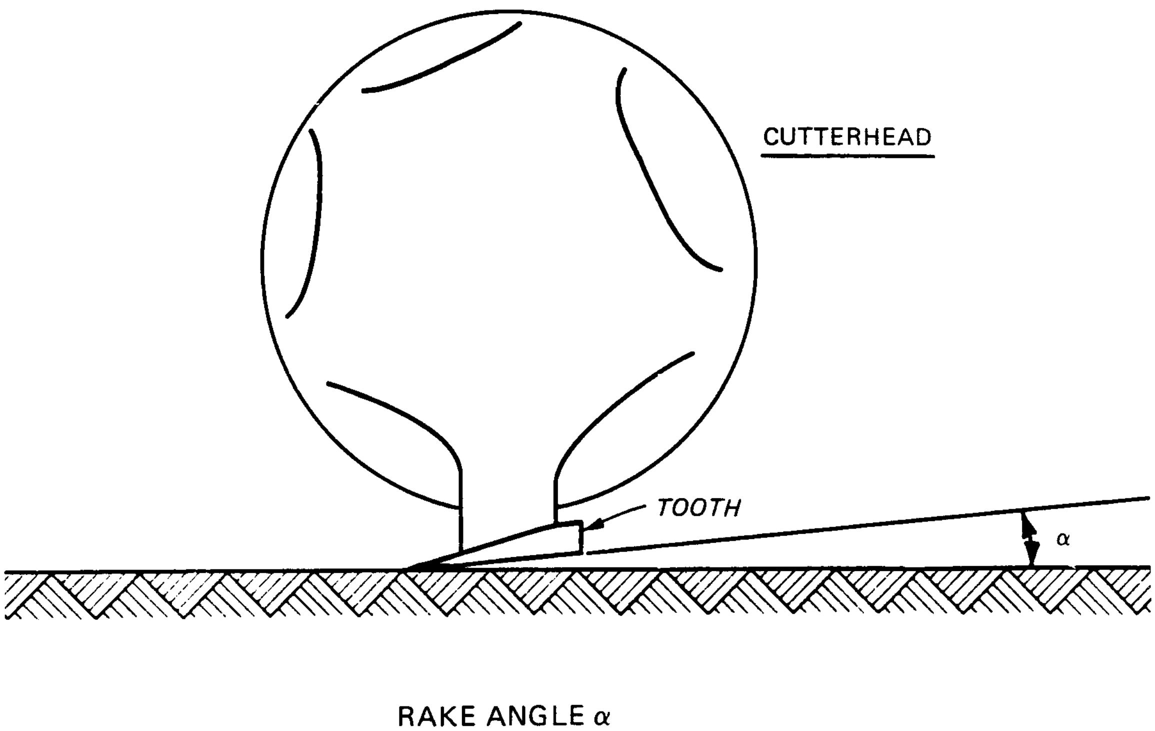


Figure 5.14 Schematic diagram showing front view of a cutter-head showing the cutter tooth rake angle (after Raymond, 1984)

Appendix 1

*Excerpts from: A*rticles on the NOAA/NMFS Benthic Database.

Gulf of Maine NEWS

Regional Association for Research on the Gulf of Maine Winter 1994

Vol. 2, No. 1

Benthic Data Base Update Available in 1994

Roger B. Theroux, Northeast Fisheries Science Center

The Woods Hole Laboratory of the NOAA/NMFS Northeast Fisheries Science Center has, through the years, accumulated an extensive data base of qualitative and quantitative (wet weight and number per square meter) data on the composition, distribution and abundance (including a variety of environmental measurements) of the macrobenthic invertebrate fauna of the U.S. east coast continental shelf, slope and upper rise ranging from the mouth of the Bay of Fundy to Key West, Florida.

This data base is currently being updated with results of numerous taxonomic studies, and assembled into a form which is expected to be made available to the scientific community within a year. At this time the intent is to make the data available on a variety of media (e.g. networks, CD-ROM, diskette, etc.) and to reside in a variety of localities (i.e. NEFSC master database, NOAA database, NODC, USGS, USNM/SI, etc.).

The data base consists of nearly 200,000 individual records from somewhat over 11,700 sampling sites. The samples were obtained by a wide variety of means including hand collecting in the intertidal zone to the use of research vessels (17 different ones) on 208 separate cruises using 49 different types of sampling gear (ranging from dipnets to trawls, dredges, grab type devices etc.) at sea out to 4,000 meters depth. The split between qualitative and quantitative samples is 9,580 vs. 2,210. Slightly over 8,000 benthic sampling stations are represented from the Gulf of Maine region alone, including the Bay of Fundy, Georges Bank and as far west and south as Nantucket Shoals; more than 3,000 of these samples are from the principal basins of the GOM. The time frame involved extends from 1881 to 1975; however, the majority of records are from 1953 to 1975. Supporting data for each sampling site or station include date, location, depth, sediment type, gear type, vessel, bottom temperature, taxonomic code and name, weight, number, etc.

The vast majority of the quantitative grab samples in this biological data base have an exact match (on a station basis) with a detailed geological data base (including physical and chemical characteristics) maintained by the U.S. Geological Survey which was generated by the U.S. Continental Margin Program during the 1960's and early 1970's. Information relating to this and other databases maintained by USGS may be obtained from Marilyn ten Brink at the USGS in Woods Hole.

The entire data base is backed up with a comprehensive Specimen Reference Collection which, since June of 1993, is housed at the U.S. National Museum of Natural History at the Smithsonian Institution in Washington, DC. The phylogenetic representation in this collection (and in the data base) ranges from Protozoa (Foraminifera) to Choradata (Urochordata); including some lesser protosomes: (Pogonophora, Sipunculida, Echiurida, Priapulida); and Chaetognatha. Also included are collections of animal and plant remains and a variety of marine fossil materials, chiefly mollusk shells. Systematic diversity includes over 11,000 taxonomic names maintained in a data base taxonomic code file associated with the master data base and the Specimen Reference Collection. Information relating to accessibility and use of the Specimen Reference Collection at the Smithsonian may be obtained from the Invertebrate Collection Manager Dr. Michael Sweeney at USNM.

Interest in and studies relating to the benthic invertebrate fauna of the marine environment off the coasts of the United States formally began in a systematically organized manner with the establishment, by Spencer F. Baird, of the U.S. Fish Commission in 1871. Woods Hole, Massachusetts was chosen as the site of the first permanent laboratory in the U.S. solely devoted to the scientific study of all aspects of the marine environment. Collections and data gathered on the benthic fauna from those early days, for the most part, were distributed to many other institutions and museums through the intervening years. However, some material (specimens and data) were preserved at the Woods Hole Laboratory and have been incorporated into the data base and Specimen Reference Collection under discussion herein. The vast majority of the data and specimens, however, are the result of activities conducted at the Woods Hole Laboratory, beginning in the mid 1950's, as part of studies relating to the feeding habits of commercially important demersal fishes. The perceived lack of ecologically oriented data on the composition, distribution, abundance, and ecological and environmental relationships of the benthic fauna making up the diet of these fishes led to the establishment of studies designed to provide the necessary information on those topics. When the USGS Continental Margin Program was initiated in the early 1960's in cooperation with the Woods Hole Oceanographic Institution, the Woods Hole Fisheries Lab's Benthic Dynamics Investigation, then conducting similar studies, was invited to join the effort to provide biological expertise. The data bases created as a result of these joint efforts remain to this day without peer in the scientific world.

The benthic data base and the invertebrate collection continue to be used by ecologists, systematists, and taxonomists, to great advantage in preparing environmental impact statements, characterizing the benthic fauna of selected sites for a host of specific purposes (e.g. mining, dumping, drilling, marine sanctuaries, etc.). Through the years many (well over 40 at last count) specialists in a variety of disciplines have made use of these data and specimens for a multitude of purposes. In addition to numerous unpublished reports in the gray literature, these holdings have resulted, to date, in more than 100 formal, peer reviewed, scientific papers and reports on a variety of subjects, as well as yielding eleven new species to science.

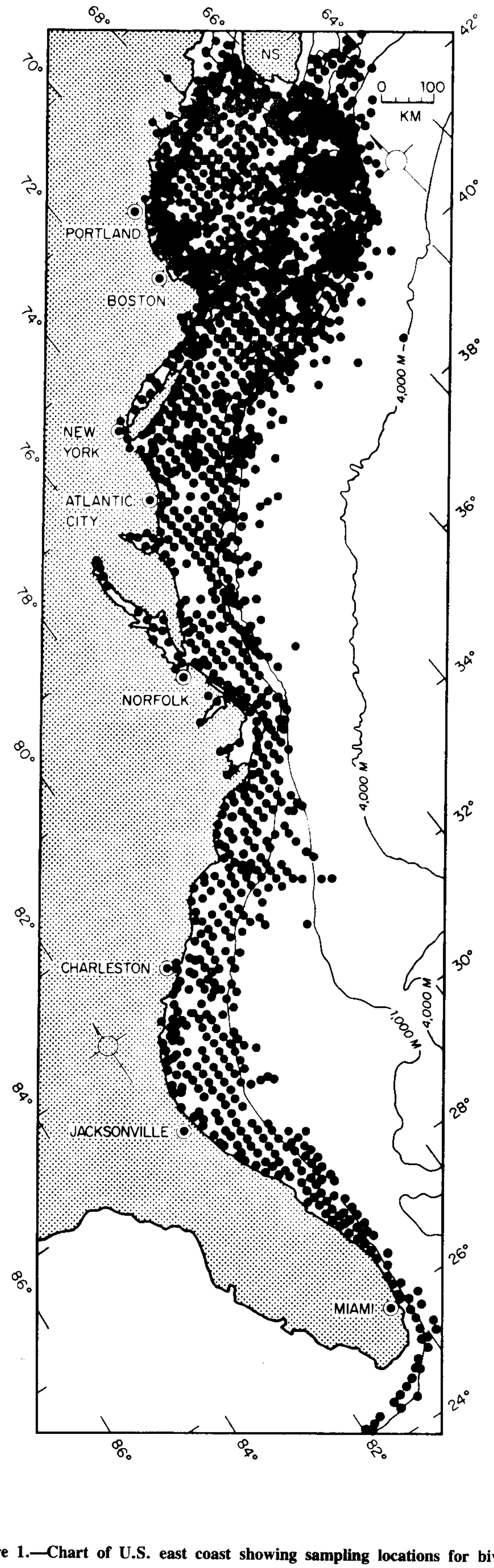


Figure 1.—Chart of U.S. east coast showing sampling locations for bivalve collection.

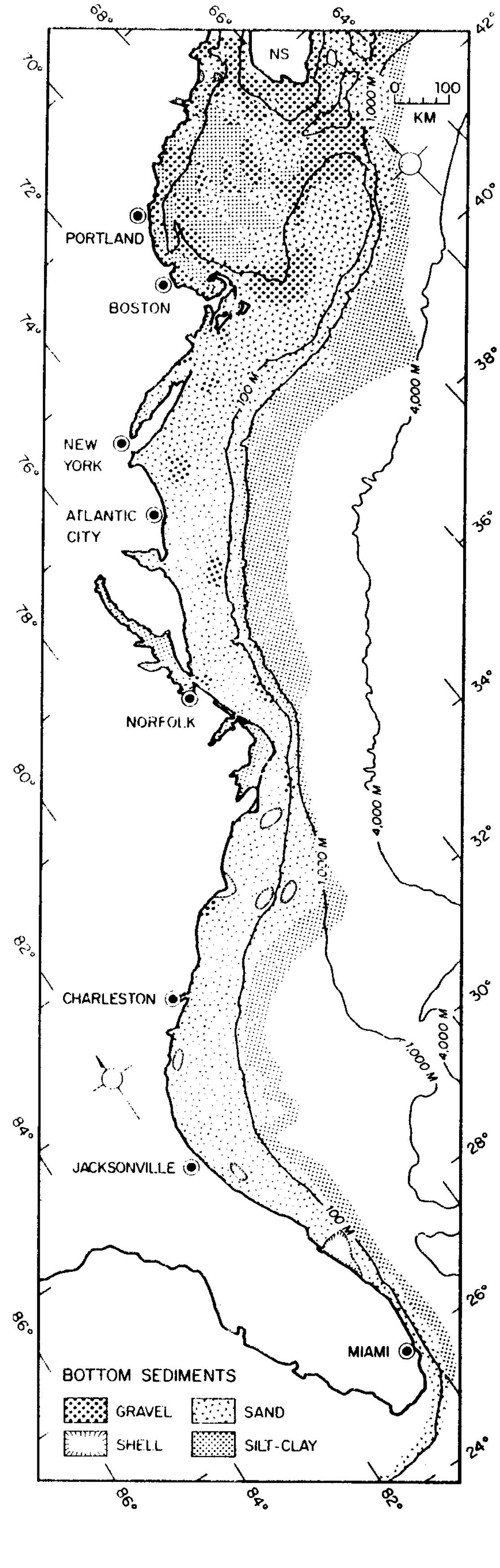


Figure 2.—Distribution of predominant bottom sediments.

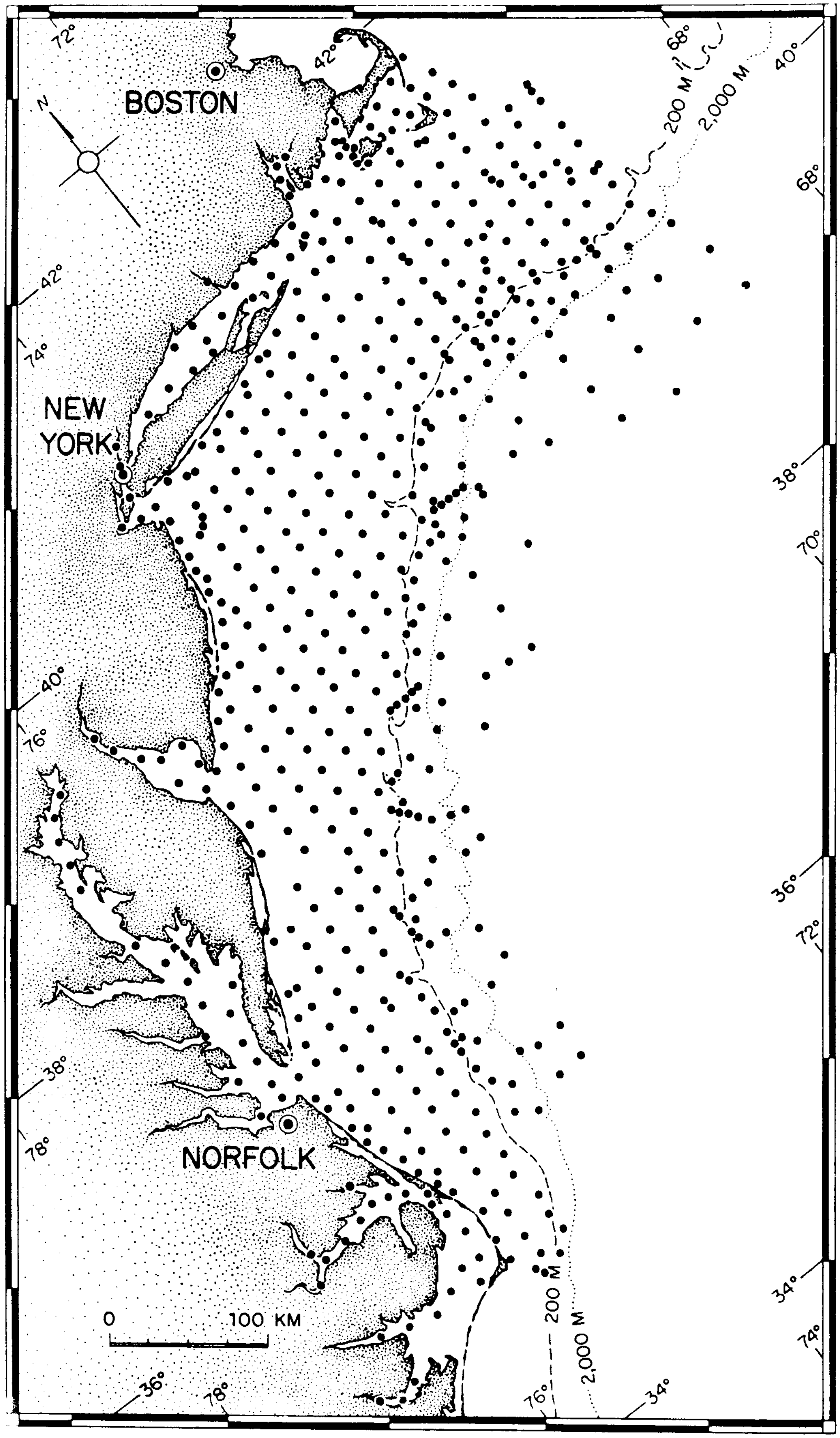


Figure 1.—Station location in the Middle Atlantic Bight where quantitative grab samples were collected. (After Wigley and Theroux 1979.)

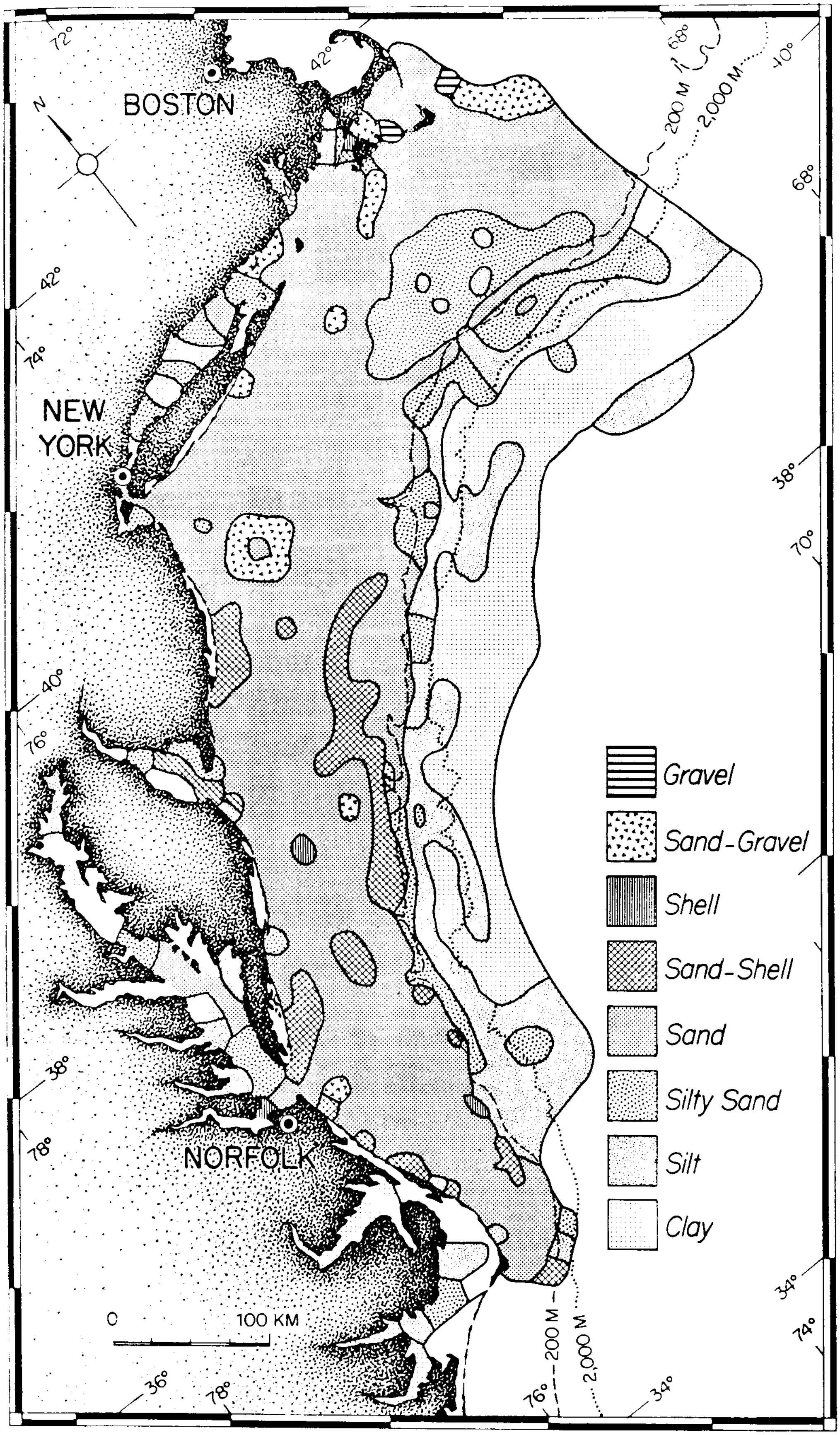


Figure 3.—Geographic distribution of bottom sediment types in the Middle Atlantic Bight. (After Wigley and Theroux 1979.)

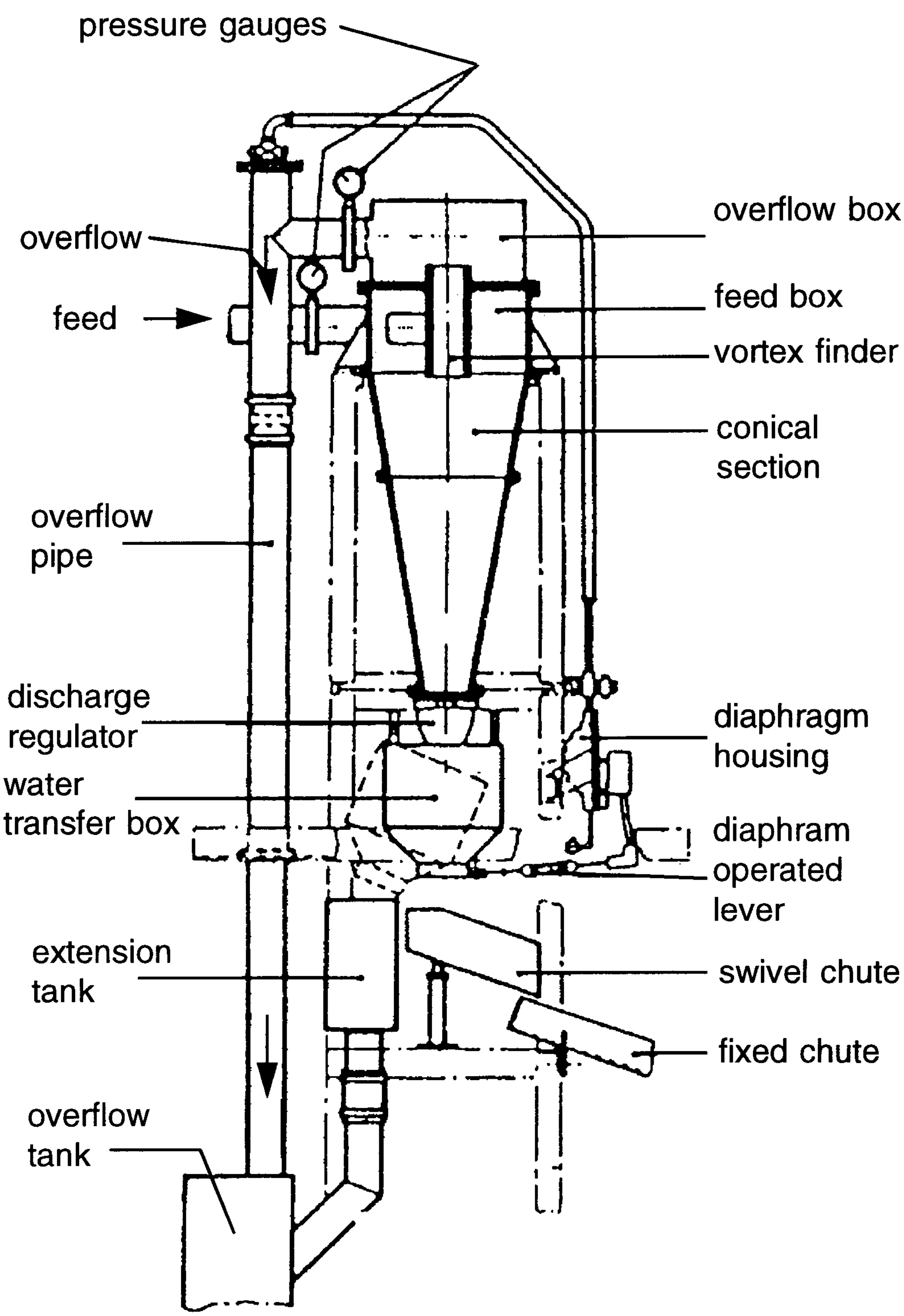


Figure 5.15 Schematic diagram of the Linatex separator (after Littler, 1990)

Appendix 2

Excerpts from: Hurme, A.K. and E.J. Pullen . 1988. Biological effects of sand mining and fill placement for beach replenishment: Lessons for other uses. *Marine Mining* 7: 123-136.

Biological Effects of Offshore Borrowing

Offshore borrowing for beach replenishment is an attractive alternative when suitable material from channel dredging is unavailable. Borrowing from nearshore bays and estuaries is often unacceptable because valuable bottom habitat may be destroyed or altered, and sediments are usually unsuitable from a coastal engineering perspective (U.S. Army Corps of Engineers 1981). Upland sources of sand are becoming scarce as demand for onshore construction sites, trucking costs, and hauling distances increase. Numerous offshore sites have been identified in many regions as containing suitable replenishment materials (Duane and Stubblefield 1986; Williams 1986).

The literature on the effects of offshore borrowing is sparse; study techniques and findings vary widely. A literature review by Thompson (1973) found few studies addressing directly the potential impact of offshore mining. Extrapolating from estuarine research, a more thoroughly studied coastal ecosystem, Thompson predicted that the effect of offshore dredging depended on the magnitude of the disturbance created and the site selected. Shifting sands, rather than stable beds, would provide the ecological advantages of sparse, transitory plant and animal communities of lesser commercial value. As a practical matter, shifting beds provide a source of course, pure sand without mixtures of mud, silt, or detritus.

Borrow sites in active areas would be quickly refilled, erasing the physical effects of dredging. He concluded that even extensive dredging operations on shifting beds would have little long-term environmental effect in contrast to dredging of more productive stable bottoms. Shallow dredging over an extensive area rather than deep pit dredging, he predicted, would also cause less environmental effect. He encouraged further studies on fill-in rates and biota repopulation under a wide range of conditions and bottom types.

The New England Offshore Mining Environmental Study (NOMES) (Padan 1977) was designed to address the impact of commercial-scale mining. Baseline conditions for benthos and phytoplankton were measured for a full year in Massachusetts Bay. High biological variability in the natural environment confirmed the difficulty in adequately sampling this environment. Unfortunately, the study was terminated prior to the actual test mining. However, the NOMES Final Report provides a good projection of the potential direct and indirect environmental effects of sand and gravel mining.

The NOMES study identified a number of potential consequences of offshore hydraulic mining of sand and gravel. For example, the excavation process, while broadening the market base and lessening the impacts associated with onshore mining, might have negative impacts by causing stagnant water to form in the pits, causing beach slump or coastal erosion if located too close to the shore, or impacting the water table if the freshwater aquifer were penetrated. Further, the fishery could be either harmed or improved depending on the nature of the bottom after mining.

The potential impacts from the discharge plume and the resultant blanket of fines were generally felt to be deleterious unless needed nutrients and/or new substratum for colonization by desirable species resulted. Potential negative impacts include the introduction of pollutants and unwanted nutrients; the interference with filtering, feeding and respiratory mechanisms in ocean species; the smothering of benthic species and attendant loss of food or habitat; reduced photosynthesis and oxygen levels; or an unpleasant appearance to the water. Also changes in bathymetry and bottom type could alter populations, migration patterns or result in unwanted deposition of materials in navigation channels or in coastal areas in general.

Padan (1977) discusses each of these concerns more fully and specifically applies them to the NOMES case when possible. However, the actual likelihood of the effects occurring at all, or in sufficient magnitude to be of concern, is not addressed because of insufficient information caused by the termination of the study.

Brinkhuis (1980) assesses the potential biological effects of sand and gravel mining in the Lower Bay of New York Harbor, based on the literature. He concludes, "The probable effects of sand mining operations on biota *per se* appear to be minimal." However, he notes that, although there is little quantitative data on the seasonal abundance and distribution of species, much of the Lower Bay may be characterized as impoverished and perturbated by pollution; therefore, impacts attributed to marine mining might be difficult to detect.

De Groot (1986) presents an overview of the information published by the International Council for the Exploration of the Sea (ICES) and other work, by country, in the North Atlantic, North Sea, and Baltic Sea. Most marine mining activity for sand and gravel production occurs in the southern part of the North

Sea. He concludes that where ". . . the nature and structure of the substrate do not differ substantially before and after dredging, the bottom communities will recover from the effects." However, where conditions and bottom substrate are changed, the potential negative effects on fisheries, although never clearly, demonstrated, might occur. He discusses the proposed ICES (1975) code of practice for marine aggregate dredging as protecting fisheries interests. The code addresses the physical and geological aspects of regulation rather than the biological considerations themselves. It was proposed by the Netherlands and has been adopted in part by France and the United Kingdom. Canada is currently considering adopting portions of the code as well to regulate marine mining. De Groot (1981) updated a bibliography of pertinent literature, including many European publications not commonly identified in the United States.

Studies of nearshore borrow areas in the United States show that the persistence of the borrow area as an identifiable bathymetric feature may vary greatly. Repopulation of the borrow area's benthic community varies depending on the size and configuration of the borrow area, its exposure to waves and currents, the similarity of the sediments surrounding the area, the new sediment-water interface, and possible changes in water quality. Given the wide range of possible biological responses to offshore borrowing, the selection and benthic survey of the borrow sites may be more important than the survey of the beach to be replenished. Although the physical environment was altered and benthic communities destroyed, recovery was almost immediate for some motile species, and almost complete within one year for dominant groups including annelids, mollusks, and crustaceans (Saloman et al. 1982). However, recovery of coral in Hawaii was long-term (5 years or more) or did not occur in the length of the study (Maragos 1974; 1979). Increased suspended sediments, changed bathymetry, and destruction of the benthic population were most evident during and immediately following dredging. Increases in suspended sediments were usually localized and of short duration and are in direct relationship to the grain size of the material dredged (Courtenay et al. 1974; Maragos et al. 1977).

Inshore borrow pits in areas of low wave energy isolated from currents and located in sheltered bays and estuaries have created problems in the past. If in an area of fine bottom sediments with high levels of organic materials, the pits are apt to fill slowly and develop anaerobic conditions (Saloman 1974).

Fortunately, many of the borrow pits studied in conjunction with beach nourishment were in the nearshore zone, exposed to wave action and nearshore currents, and surrounded by similar sediments. Benthic recolonization is fairly rapid under such circumstances (Applied Biology, Inc. 1979; Saloman et al. 1982; Culter and Mahadevan 1982), even if the pits do not refill rapidly (Turbeville and Marsh 1982). Fish and other motile animals are able to avoid unfavorable conditions and usually return after dredging ceases.

Sand and gravel have been mined in the Lower Bay of New York Harbor since the early 1950s, in addition to regular channel maintenance dredging. However, no controlled before and after studies have been conducted. The pits are relatively deep, some more than 15 meters below adjacent bottom, and generally in areas with restricted circulation and low wave energy. They have accumulated fine organic sediments from adjacent areas. Studies by Cerrato and Scheier (1984) showed differences in the number of species, species composition, species diversity and abundance between the pits and the surrounding bottom.

Current Concerns About Impacts of Offshore Sand and Gravel Mining on Marine Benthos

The National Oceanic and Atmospheric Administration (NOAA) prepares a "Federal Plan for Ocean Pollution Research, Development and Monitoring" every three years. The most recent plan for fiscal years 1985–1989 concludes, "The effects of sand, gravel, and shell mining in coastal areas (excluding Alaska) are largely known from previous studies conducted or supported by the U.S. Army Corps of Engineers and others. . . . There are currently no environmental studies being supported by the Federal Government which are directly related to the effects of marine sand, gravel, and shell mining." (U.S. Department of Commerce 1985).

Although no active research programs addressing marine sand and gravel mining activities are presently being conducted in the United States, analysis of the 15 years of research on beach replenishment by the U.S. Army Corps of Engineers and other studies permit the projection of certain key elements for forecasting the biological effects of marine sand and gravel mining. Several statements can be made which should lessen concerns of the potential impact on the marine environment. First, the technology for marine mining of sand and gravel is not new, and will likely be similar to that of marine mining for beach nourishment. Excavation of clean, offshore deposits will not release toxic pollutants through resuspension of the sediments (Cruickshank and Hess 1975). Second, the preferred mining sites will have surficial deposits where the amount of fine material is small, and the removal of large amounts of overburden will not be required. Duane and Stubblefield (1986) note that, with certain exceptions, surficial sand and gravel deposits on the U.S. Atlantic continental shelf will contain less than five percent clay and silt. Third, appropriate navigation and positioning systems will assist in avoiding known valuable biological resources. Fourth, appropriate marine mining equipment will assure that the desired final bathymetric form of the borrow area will be created and that large areas of dissimilar surface sediments will not be exposed unless considered desirable. Fifth, mining will occur in areas where surficial sediments are being reworked by waves and currents. And finally, the [governmental] permit process for leasing of offshore mining sites may provide some degree of review and monitoring of impacts.

The value of shoals and undersea ridges as desirable habitat for many fish species is well known. Although much work has been done on the effects of building artificial reefs to create new fish habitat, little is known about the potential effects of modifying the general offshore bathymetry on fisheries. Since offshore mining could be conducted to either eliminate or modify ridges, or it could create ridges and troughs, the final effect could vary. Therefore, any mining which would substantially change the form of the existing bathymetry should be undertaken with caution.

Guidelines for Planning Ecologically Sound Offshore Mining Projects

Applying the knowledge learned from beach nourishment and replenishment studies as they relate to nearshore borrowing, a number of guidelines can be proposed to assure ecologically sound offshore mining of sand and gravel (Naqvi & Pullen 1982). These suggestions are: 1. Conduct a pre-project baseline survey in the source areas to avoid important benthic resources such as clam beds or active spawning areas, and to determine the need for further sampling. 2. Time the borrowing period to avoid the peak spawning seasons of marine species using the site. 3. Leave a sufficient layer of sediments that match as closely as possible the original surface layer to avoid exposing a dissimilar sediment unless exposing a new substratum is desired. 4. Use equipment and techniques which will minimize high suspended solids and siltation when sensitive species such as hard corals are nearby. Dredge only when currents do not carry suspended sediments to nearby sensitive resources. 5. Take borrow materials from broad, shallow pits in deeper waters with an actively shifting bottom.

Conclusion

The U.S. Army Corps of Engineers and others have monitored and evaluated the disruption and recovery of the physical and biological environment during beach replenishment operations. While primary focus has been on beach areas where the material is deposited, borrow areas from which the material has been taken have also been examined. Currently, replenishment material is obtained from new channel construction, dredging operations, nearshore and inshore borrowing.

Based on what is known about the biological impacts of beach nourishment and nearshore borrow areas, nearshore and offshore mining operations should not create long-term adverse impacts on organisms and physical characteristics in the area if appropriate site selection, timing, techniques, and monitoring are carefully performed. Operations should be planned to avoid important bethnic resources and peak spawning seasons. Material should be taken from broad, shallow pits in areas with an actively shifting bottom, leaving a sufficient surficial layer of similar sediments for recolonization by benthic species. State-of-the-art technology and equipment for navigation and dredging can reduce the risk of indiscriminate impacts on marine resources. Monitoring may be required as part of the (governmental) permit process to assure wise use of valuable marine resources.

Acknowledgments

Permission from the Corps of Engineers to publish this paper is appreciated. However, the views and conclusions are the responsibility of the authors and do not represent official Corps position unless accompanied by other authorizing documents.

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Appendix 3

(A) *Excerpts from*: Kenny, A.J. and H.L. Rees. 1994. The effects of marine gravel extraction on the macrobenthos: early post-dredging recolonization. *Marine Pollution Bulletin*, 28 (7): 442-447.

and

(B) Kenny, A.J. and H.L. Rees. 1993. Preliminary results on the effects of marine gravel extraction on benthos: post-dredging recolonization. *ICES Report,* Annex VIII.

Summary of: Kenny, A.J. and H.L. Rees. 1994. The effects of marine gravel extraction on the macrobenthos: early post-dredging recolonization. *Marine Pollution Bulletin* 28 (7): 442-447. (See also Kenny & Rees, 1993).

Location: North Sea. English East Coast (see Figure 1).

Equipment: 0.2 m^2 Hamon grab, plus underwater still and television cameras.
Sieve: 5 + 1 mm. Sediment volume 10-20 litres.
Biomass: Wet and dry calculation (Elefthuriou and Basford, 1989 accuracy ±0.0001.
Collection Dates: Before dredging March 1992; After dredging May, December 1992
Deposit description: Gravel

General Site Characteristics and Changes:

	Deposit Median (mm)	No. of organisms/ m^2	No. of species	Biomass Dry Wt/m^2
Before	0.355	5,000-10,000	30-40	20-50 g
After	2.0	100-5,000	13-26	2-7 g
	Fig. 3	Figs 4 and 5.		

Biological Characteristics:

Taxa noted:

Balanus crenatus (CB)[1]	- epifauna	44% total organisms
Dendrodoa grossularia (Tu)	- epifauna	45% total organisms
Flustra foliacea (Br)	- epifauna	
Modiolus modiolus (MB)	- epifauna	heaviest.
Polychaete worms	- epi or infauna	
Sabellaria spinulosa (PS)	- epifauna	
Amphipods	- epi or infauna	

Quantitative details - Table 1.

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[1]CB = Crustacea, Barnacle
Tu = Tunicate
Br = Bryozoa
MB = Mollusc, Bivalve
PS = Polychaete, Sedentary

	MIB (Mean Individual Biomass) in gm = No. organisms/biomass	
	B. crenatus	*D. grossularia*
Before	4.1-5.6	0.7-1.7
After	1.4	0.1

Statistical analyses -see Figure 6.

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The Effects of Marine Gravel Extraction on the Macrobenthos: Early Post-dredging Recolonization

A. J. KENNY and H. L. REES
MAFF Directorate of Fisheries Research, Fisheries Laboratory, Burnham-on-Crouch, Essex CM0 8HA, UK

A small area of sea bed off the English east coast was experimentally dredged by a commercial suction-trailer dredger. Some 50 000 t of mixed aggregate were removed, representing about 70% of the sea bed area down to an average depth of 0.3 m. Results from benthic surveys undertaken at the experimental site and at a nearby reference site, indicate that significant reductions had occurred in the variety, abundance and biomass of benthic organisms as a consequence of dredging. Subsequent recolonization of dunuded substrates by the dominant taxa proceeded relatively rapidly, although the dredged site had clearly not fully recovered some 7 months later. Differences in the recruitment success of the dominant taxa, notably *Dendrodoa grossularia* and *Balanus crenatus*, between the reference and treatment sites pre- and post-dredging were observed. Possible explanations for these differences in relation to the observed physical alterations to the sea bed are discussed.

During the 1980s the demand for aggregates in the United Kingdom (from both land-based and marine deposits) steadily increased. The presence of large quantities of 'high quality' aggregates in coastal areas adjacent to the major markets in the south and east of England provided an opportunity to meet the increased demand by increasing the production of sand and gravel from marine resources. Consequently the dredging industry invested in new ships which allowed existing licensed deposits to be exploited more efficiently and new deeper water resources to be dredged.

Accompanying these developments has been growing concern over the effects of marine aggregate extraction on the marine environment, in particular, the damage caused to benthic communities and their dependent commercial fisheries. This concern was recognized by the International Council for the Exploration of the Sea (ICES) which, in 1975, established a scientific working group on the 'Effects on Fisheries of Marine Sand and Gravel Extraction'. This provided a forum for member states, including the UK, to present their research findings and to recommend appropriate management actions (ICES, 1975, 1992).

In the United Kingdom, during the 1970s, research into the environmental effects of aggregate dredging was undertaken by the Ministry of Agriculture, Fisheries and Food (MAFF). For example, Shelton & Rolfe (1972) and Dickson & Lee (1972) examined the impacts of suction-anchor dredging on a shingle bank in the English Channel, while Millner & Dickson (1977) examined the impacts of suction-trailer dredging off Southwold in the southern North Sea. More recently, Lees *et al.* (1990) studied the impacts of suction-trailer dredging at a licensed extraction area off the Isle of Wight in the English Channel. However, due to difficulties of sampling coarse sediment, the above studies were not able to accurately quantify the impacts on the benthos or describe the processes of recolonization on cessation of dredging.

This paper presents some of the results from a continuing study jointly sponsored by MAFF and the Crown Estate Commissioners (CEC). The research aims to combine an assessment of the initial impacts of marine aggregate extraction on the benthic macrofauna and the subsequent processes of recolonization following dredging.

Methods

Selection of an offshore experimental site

A wide-scale survey of gravel communities off the English east and south coasts (Kenny *et al.*, 1991) indicated potential sites for an offshore field experiment. The chosen location was off North Norfolk, England (Fig. 1a), where the gravel deposits were of commercial quality and which supported a relatively 'rich' and stable epifauna. Among the most common species present, were the barnacle *Balanus crenatus*, the sea-squirt *Dendrodoa grosularia*, the 'horn wrack' *Flustra foliacea* and the 'horse mussel' *Modiolus modiolus*. A 'reference' site (about 1 mile distant) was also sampled to provide information on the natural physical and biological changes during the 'recovery' of the experimental 'treatment' site (Fig. 1b).

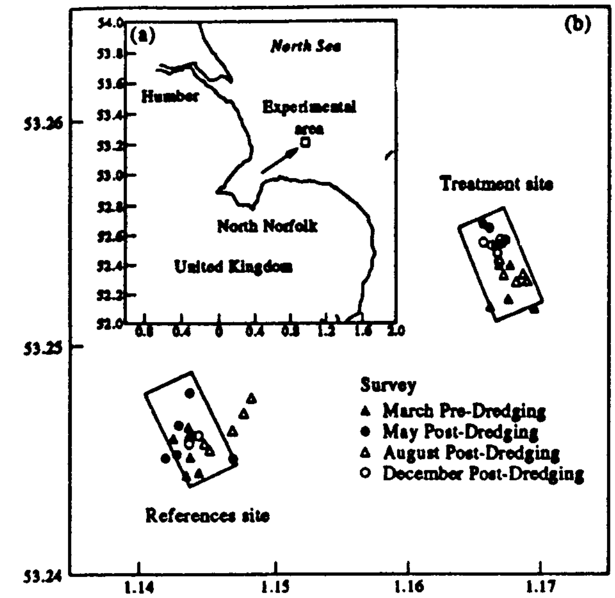

Fig. 1 (a) Location of the experimental area off North Norfolk. (b) Location of the experimental 'treatment' and 'reference' sites showing the sample positions for each survey.

Experimental dredging

During 5 days in April 1992, the MV *Sand Harrier*, a modern commercial suction-trailer dredger, extracted a total of 52 000 t of mixed aggregate from an area measuring 500×270 m. In order to ensure that an impact could subsequently be detected using conventional remote sampling techniques, it was necessary to systematically dredge the entire site. The dredging operation was closely monitored using a Sercel 'NR53' differential Global Positioning System (GPS) which was previously calibrated against a 'range–range' system which showed that the GPS was accurate to ±10 m.

Field sampling procedures

Ship-board sampling of the benthos was achieved using a Hamon grab (see Holme & McIntyre, 1984) which proved to be effective in the quantitative sampling of coarse sediments. The Hamon grab operates by taking a scoop out of the sea bed with a relatively constant surface area of 0.2 m^2. Pictures of the sea bed post-dredging were obtained using an underwater camera sledge fitted with a single-lens reflex camera and an underwater television camera which provided images covering an area of about 0.75 m^2.

Grab stations were located at random within the 'treatment' and 'reference' sites (Fig. 1b). On retrieval, an estimate of the sample volume was made, which typically ranged between 10 and 20 l. Following the removal of a 1 l sub-sample for particle size analysis, the samples were washed with seawater over 5 mm and 1 mm square mesh sieves to remove the excess sediment. The retained macrofauna were fixed in 4–6% formaldehyde solution (diluted with seawater) for laboratory identification and enumeration.

Laboratory procedures

Samples were first washed with freshwater over a 1 mm square mesh sieve in a fume cupboard to remove the excess formaldehyde solution. Samples were then sorted and the specimens placed in jars or petri-dishes containing a preservative mixture of 70% methanol, 10% glycerol and 20% tap-water. Specimens were identified to species level, as far as possible, using the standard taxonomic keys. For each positive identification a representative specimen was retained in order to establish a reference collection.

Partial wet weights for each species were determined by placing specimens on blotting paper for ~12 h before measuring their weights to an accuracy of ±0.0001 g. Biomass estimates in g ash free dry wt m^{-2} were then calculated from partial wet weights using conversion factors given in Eleftheriou & Basford (1989).

Sediment sub-samples were analysed for their particle size distributions according to the Udden–Wentworth Phi classification, where $\text{Phi} = -\log_2 d$ and d is the particle diameter in millimetres. Each sample was first wet sieved on a 63 μm mesh sieve to provide an estimate of the fine fraction (<63 μm). The remaining sample was then oven-dried for approximately 12 h at 100°C, and allowed to cool to room temperature before being sieved through a stack of geological test-sieves ranging from −6 Phi (64 mm) to +4 Phi (64 μm). A weight for each size fraction was measured using a top-pan balance to an accuracy of ±0.01 g.

Non-metric Multi-dimensional Scaling ordination (MDS; Kruskal & Wish, 1978) was performed on a (dis)similarity matrix derived from $\log(x+1)$ transformed species abundance data using the Bray–Curtis dissimilarity index $[B=(\Sigma|X_{ij}-X_{ik}|)(\Sigma(X_{ij}+X_{ik}))]^{-1}$ (Bray & Curtis, 1957). The MDS plot provides a two-dimensional summary of inter-sample affinities, i.e. the distance measured between any two samples, or sample groups, provides a measure of biological (dis)similarity.

Results

Physical observations

On examination of the sea bed using side-scan sonar and underwater cameras it was apparent that the drag-head had created well-defined furrows measuring 1–2 m wide and 0.3–0.5 m deep. It was estimated that the sea bed had been lowered by nearly 2 m in areas where the dredge tracks had crossed each other several times. The dredge tracks invariably had a layer of sand ripples along their base which, upon inspection by SCUBA divers, was found to be 1–2 cm thick (Fig. 2a,b). Despite these superficial accumulations of sand, particle size analysis of samples taken at the treatment site (Fig. 3a) indicated that the gravel content of the sediment (>2 mm; <−1 Phi) had actually increased from 30% in March (pre-dredging) to 50% in May (post-dredging), although this had fallen slightly to 43% in August (post-dredging). By contrast, the proportion of gravel (>2 mm) at the reference site remained relatively constant at 36% (Fig. 3b). A possible explanation for these differences is given below.

Biological observations

The average number of species recorded from five

Fig. 2a Photograph of the sea bed taken at the 'reference' site during the post-dredging survey in May.

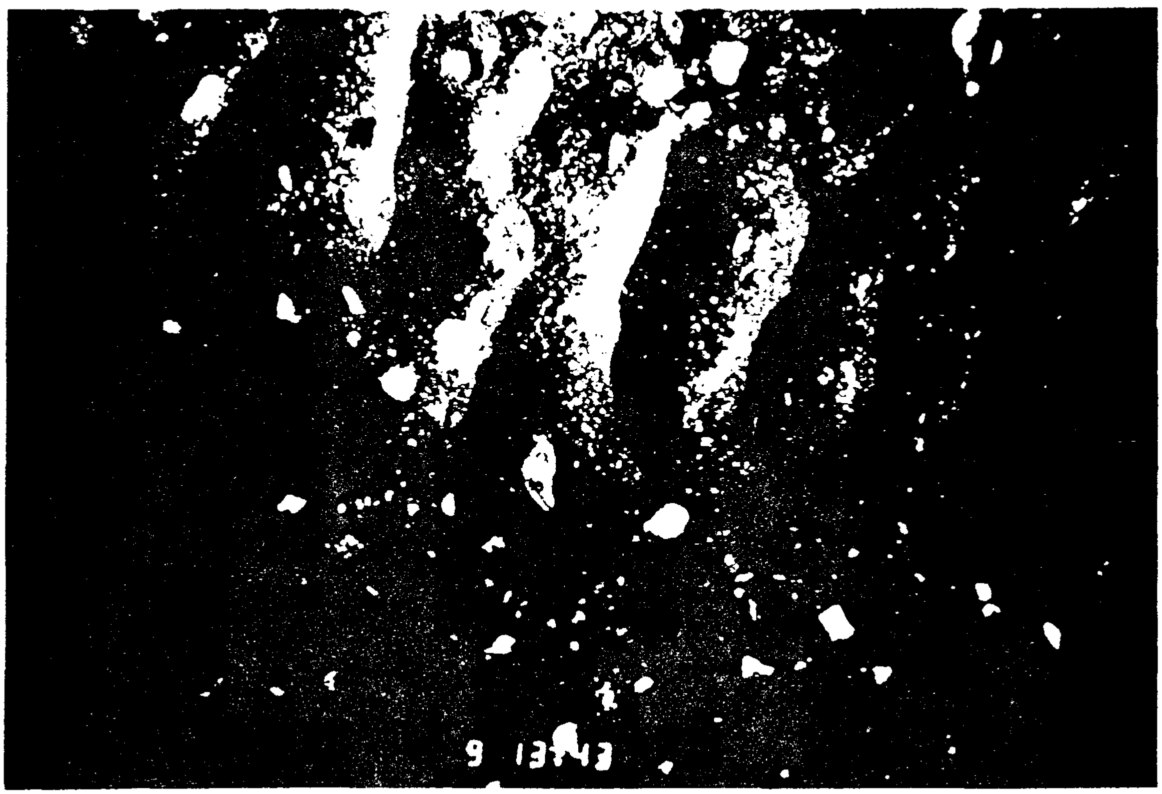

Fig. 2b Photograph of the sea bed taken at the 'treatment' site during the same survey showing the sand ripples associated with a dredge track.

Hamon grab samples taken at the treatment and reference sites pre- and post-dredging is shown in Fig. 4. The number of species remained almost constant at the reference site (about 35) during the 8-month sampling period, whereas at the treatment site the numbers fell from 38 to 13 immediately following dredging. A limited increase in the number of species during the 7-month post-dredging period from 13 to 26 species suggests that some recolonization had occurred.

The most abundant animals, both before and after dredging, were *Balanus crenatus* and *Dendrodoa grossularia*; these accounted for, respectively, 44 and

45% of the total number of individuals found during the sampling period. There was a marked reduction in the abundance of *D. grossularia* and *B. crenatus* immediately post-dredging, but substantial recolonization was evident in later samples (Table 1B). This was also the case for amphipod crustaceans and the 'Ross' worm *Sabellaria spinulosa*. However, it can be seen that the 'starting' densities of these two taxa were relatively low (Table 1). Densities of all taxa at the treatment and reference sites are shown in Fig. 5a. An average of 2769

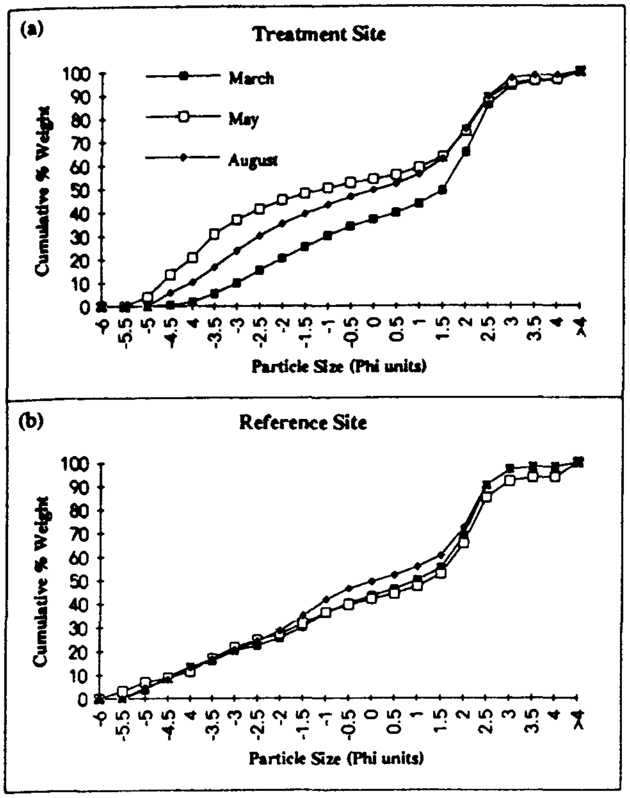

Fig. 3 (a) Cumulative curves of particle sizes at the 'treatment' site pre- and post-dredging. (b) Cumulative curves of particle sizes at the 'reference' site pre- and post-dredging. Each curve represents the average of five samples.

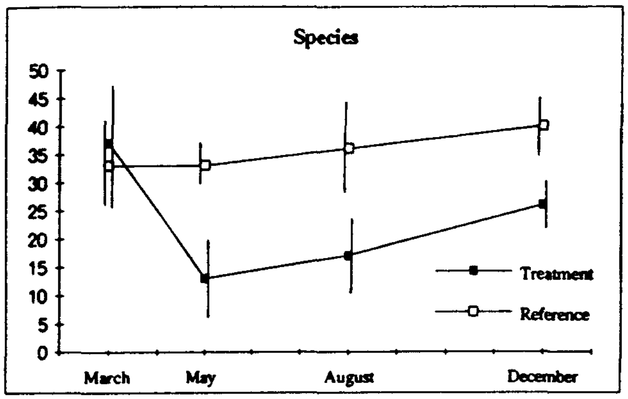

Fig. 4 Average number of species from five Hamon grab samples taken at the 'treatment' and 'reference' sites pre- and post-dredging with 95% confidence limits.

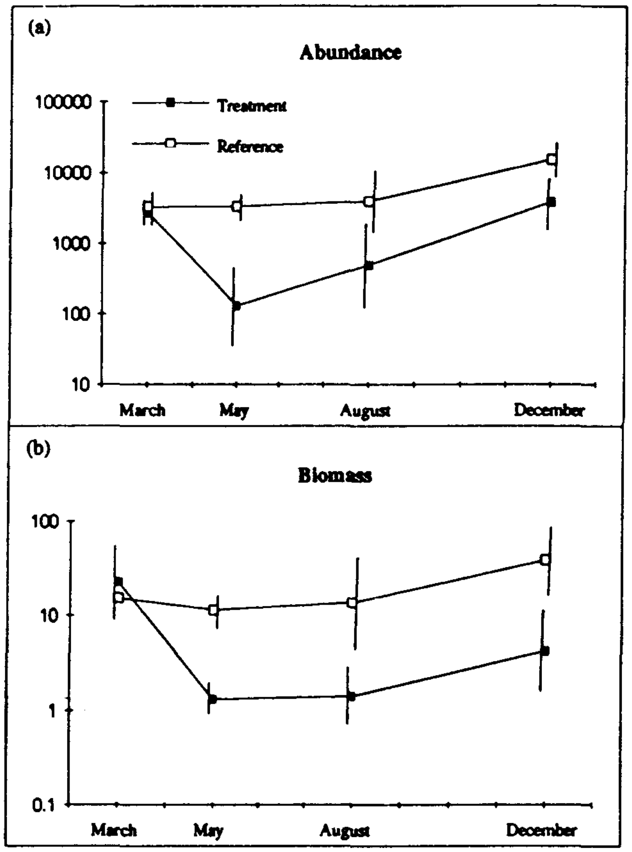

Fig. 5 (a) Derived mean 'treatment' and 'reference' site abundances m^{-2} from five Hamon grab samples pre- and post-dredging with 95% confidence limits. (b) Derived mean 'treatment' and 'reference' site biomass in g ash free dry wt m^{-2} from five Hamon grab samples pre- and post-dredging with 95% confidence limits.

TABLE 1

Average 'reference' (A) and 'treatment' (B) site abundance and biomass values (g ash free dry wt) for *D. grossularia*, *B. crenatus*, amphipods and *S. spinulosa* from five Hamon grab samples (0.2 m^2 per sample) taken pre- and post-dredging with 95% confidence limits (CL).

	D. grossularia				*B. crenatus*				Amphipods				*S. spinulosa*			
	Abun.	CL	Bio.	CL	Abun.	CL	Bio.	CL	Abun.	CL	Bio.	CL	Abun.	CL	Bio.	CL
(A) Reference site																
March	1010	493	0.7	0.4	1743	549	7.2	2.8	114	55	<0.1	<0.1	32	16	<0.1	<0.1
May	1096	245	0.8	0.2	1683	690	7.3	2.3	170	43	<0.1	<0.1	57	32	0.1	<0.1
August	1703	1180	0.3	0.2	2468	1518	11.1	9.2	245	165	<0.1	<0.1	14	10	0.1	0.1
December	7740	2401	2.3	0.8	7020	2591	33.2	15.9	333	126	<0.1	<0.1	104	54	0.2	0.1
(B) Treatment site																
March	757	337	1.3	0.5	1508	631	8.5	3.6	134	60	<0.1	<0.1	45	26	<0.1	<0.1
May	48	46	<0.1	<0.1	41	59	0.1	0.2	24	8	<0.1	<0.1	2	2	<0.1	<0.1
August	304	100	<0.1	<0.1	122	120	0.2	0.3	458	482	<0.1	<0.1	3	5	<0.1	<0.1
December	3065	1648	0.3	0.4	1067	1759	1.5	2.6	151	131	0.1	0.1	123	80	<0.1	<0.1

individuals m^{-2} were present at the treatment site in March, whereas in May (post-dredging) this had fallen to 129 individuals m^{-2}. At the reference site the mean densities in March and May remained similar at 3299 and 3347 individuals m^{-2}, respectively.

Biomass data for each site pre- and post-dredging support the abundance data (Fig. 5b). The presence of *Modiolus modiolus* in two of the samples taken in March (pre-dredging) from the treatment site accounted for the high mean biomass at this time. However, immediately post-dredging the biomass was reduced from 23 to 1 g (ash free dry wt) m^{-2}, whereas at the reference site the biomass remained relatively constant at 13 g (ash free dry wt) m^{-2}. The difference between the two sites pre- and post-dredging is again highlighted by comparing the biomass data for the numerically dominant *B. crenatus* and *D. grossularia* in Table 1.

It is apparent from the output of non-metric MDS ordination (Fig. 6) that the reference site samples have been grouped with the treatment site samples taken in March (pre-dredging), indicating that both sites were biologically similar before dredging. In addition, there was very little variation between the samples at the reference site throughout the 8-month sampling period. However, at the treatment site, the samples taken immediately after dredging were clearly separated to the left of the main cluster and an increase in the derived variance (S^2) of the data between sampling times was apparent, especially for May and August. This would support the contention of Warwick & Clarke (1993) that increased variance may be interpreted as a symptom of 'stress'. Figure 6 also indicates that there is a shift in the fauna with time towards the pre-dredging state, that is towards 'recovery', although this is clearly not yet complete.

Discussion

The apparent increase in the proportion of gravel (> 2 mm) in the sediment at the treatment site following dredging was unexpected. However, examination of a vibrocore sample taken at the treatment site before dredging indicated that a greater proportion of gravel was present in a layer between 0.05 and 0.7 m deep. The action of suction-trailer dredging would therefore have resulted in exposure of this layer. Nevertheless, a proportion of fine sediment would have been re-distributed on the sea bed by tidal currents and wave action following disturbance by the drag-head and an amount of sediment would also have returned to sea via the spillways on the dredger itself. These two sources of suspended sediment may account for the presence of the thin superficial layer of sand within dredge tracks which was observed by SCUBA divers and underwater cameras.

Samples taken at the treatment site in March (pre-dredging) had large numbers of species which were generally abundant, whereas in May (post-dredging) the

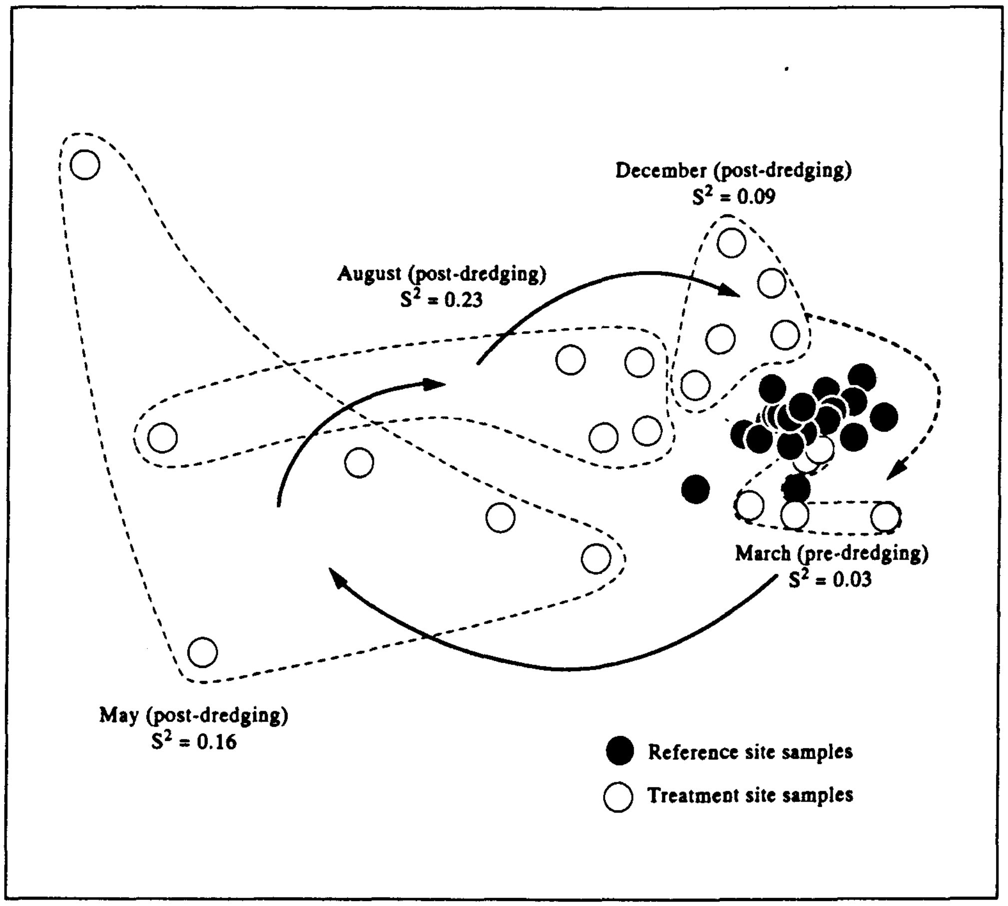

Fig. 6 MDS ordination on $\log(x+1)$ transformed species abundance data from both 'treatment' and 'reference' site samples pre- and post-dredging. Estimates of the variation of log-transformed counts between sampling times are super-imposed.

number of species was greatly reduced as were their counts. However, comparing May samples with those taken in December, it was apparent that certain taxa present immediately post-dredging had increased in abundance. Notable among these were *B. crenatus*, *D. grossularia*, amphipod crustaceans and *S. spinulosa* (Table 1). It is known that *S. spinulosa* may be predated upon by the pink shrimp *Pandalus* (Warren, 1973), although the densities of this worm observed in the present study were too low to provide a significant food source.

A comparison of the ratios of abundance and biomass (i.e. mean weights per individual; see Pearson & Rosenberg, 1978) for the dominant taxa provides a useful insight into the early processes of recolonization. The Mean Individual Biomass (MIB) of *B. crenatus* at the reference site in March and December was 4.1 and 4.7 (g ash free dry wt × 1000), respectively. However, at the treatment site the MIB of *B. crenatus* had fallen from 5.6 in March to 1.4 (g ash free dry wt × 1000) in December. This indicates that a high proportion of the individuals present at the treatment site, 7 months after dredging, were new recruits. For *D. grossularia* the MIB at the reference site was 0.7 in March and 0.3 (g ash free dry wt × 1000) in December, whereas at the treatment site it was 1.7 in March and 0.1 (g ash free dry wt × 1000) in December. The reduction in the MIB for *D. grossularia* at both sites, between March and December, indicates that the reference site, like the treatment site, had a high proportion of juveniles. This is perhaps not surprising since *D. grossularia* is known to live for 1 or 2 years only (Svane & Young, 1989).

Between March and December, populations of the 'opportunists' *D. grossularia* and *B. crenatus* at the reference site showed an eight-fold and four-fold increase in abundance, respectively (Table 1). However, during the same period at the treatment site (Table 1), *D. grossularia* showed a four-fold increase while the density of *B. crenatus* remained about the same.

The above differences in the mean individual weights and densities of *B. crenatus* and *D. grossularia* between the treatment and reference sites may be explained by a combination of the following:

1. At the treatment site, deposits of superficial sand present within the dredge tracks reduced the area available for recruitment, since these taxa require stable coarse substrates on which to settle.

2. There may be natural variability in the densities of larvae available for recruitment between locations. However, this is considered very unlikely given the close proximity of the sites.

3. The loss of adult sessile populations at the treatment site may have reduced the potential for juvenile recruitment. For example, *B. crenatus* may require the presence of adult populations in order to stimulate settlement, as has been observed for *B. balanoides* (see Rodriguez *et al.*, 1993). In the case of *D. grossularia*, larvae are not transported in the plankton but settle within a few metres of their parents, often on the tunics of other ascidians (Svane & Young, 1989). Consequently, since many adults were removed by dredging, the source of juveniles which recruit locally (within 100 m) was likely to have been significantly reduced.

To date, sampling has covered the immediate post-dredging period and, while it is evident that substantial recolonization has taken place, the community structure at the dredged area has not yet returned to its pre-dredging state. Surveys at these sites are continuing, and the results will be reported at a later date.

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Summary of: Kenny, A.J. and H.L. Rees. 1993. Preliminary results on the effects of marine gravel extraction on benthos: post-dredging recolonisation. ICES Report, Annex VIII. *This report is expanded in Kenny and Rees (1994). Both reports use the same field data.*

Site characteristics and Changes (note differences from Kenny & Rees, 1994):

	Abundance/0.2 m^2 Fig. 6		No. of species Fig 5.		Biomass (g/m^2) Fig. 7.	
	Treatment	Reference	Treatment	Reference	Treatment	Reference
Before (March)	~230	~230	70	62	182	~80
After (May)	30	209	30	64	.4	80
December			53	68		

Featured Taxa:

Polychaete worms showed greatest diversity originally and greatest reduction in species (Fig. 5) then recovery.
Balanus crenatus (CB)[2] and *Dendrodoa grossularia* (Tu) two most abundant species showed marked reduction, then recovery (See Figs 5-7).
Modiolus modiolus (MB) heaviest mollusc marked reduction, little recovery.

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[2]CB = Crustacea, Barnacle
Tu = Tunicate
MB = Mollusc, Bivalve

APRIL 1993

PRELIMINARY RESULTS ON THE EFFECTS OF MARINE GRAVEL EXTRACTION ON BENTHOS: POST-DREDGING RECOLONISATION

A J Kenny and H L Rees

MAFF Directorate of Fisheries Research
Fisheries Laboratory
Burnham-on-Crouch
Essex
CM0 8HA

INTRODUCTION

Background

During the 1980's the demand for aggregates in the UK steadily increased, primarily as a result of the boom in the construction industries which required the basic raw materials for "ballast" and concrete. In addition, there was a need for high quality aggregates which could be supplied from the marine environment. The recent advances in marine mining technologies, the short supply of land-based sources and favourable market economics have paved the way for increased production of aggregates from marine resources. However, during the 1970's, concern was growing over the environmental impact of marine aggregate extraction, and in particular the potential threat to benthic communities and their dependent fisheries (Lart, 1991). Initial research was undertaken by the Ministry of Agriculture, Fisheries and Food (MAFF) but the impacts on the benthos and the rates of recolonisation were not fully quantified. Accordingly, in October 1990 a three-year research programme was initiated by the Crown Estate Commission (CEC) and MAFF to determine: i. the initial impacts of dredging on the benthos and sediments; ii. the processes of recolonisation post dredging; iii. the natural faunistic differences between gravels on a wide-scale; and iv. coarse sediment quantitative sampling methods.

Previous Studies

There are few original scientific investigations which describe the effects of marine aggregate extraction on benthos. Some of the early observations in the UK were made during the 1970's by Shelton and Rolfe (1972) and Dickson and Lee (1973) who examined the impacts of suction-anchor dredging on a shingle bank in the English Channel. Millner and Dickson (1977) examined the impacts of suction-trailer dredging off Southwold in the Southern North Sea. More recently, investigations have been undertaken off the Isle of Wight (Lees *et al,* 1990) and off Dieppe (Desprez *et al,* 1992) in the English Channel. In addition, a comprehensive study of the effects of suction-trailer dredging on the benthic communities and seabed topography has been made at an experimental site on the Klaverbank in the Dutch sector of the central Southern North Sea (Sips and Waardenburg, 989; Von Moorsel and Waardenburg, 1990, 1991).

METHODS

Selection of an Experimental Dredging Site

A wide-scale survey of gravel communities off the English Eastern and Southern coasts (Kenny *et al*, 1991) indicated potential sites for an offshore field experiment. These were located off North Norfolk, England (Figure 1). The gravel deposits off North Norfolk were found to support a relatively rich and stable epifaunal community, with the presence of long-lived sessile organisms such as the bryozoan *Flustra foliacea* ('horn wrack') and the hydroid *Nemertesia antennina*. This site was therefore considered to be well suited for experimental dredging. However, in order to determine the exact location of the 'treatment' and 'reference' sites, further sampling using a 3m vibrocore was undertaken to assess the thickness of the gravel deposits and to ensure that dredging would not expose an underlying stratum which was different in nature from the superficial substrate. The treatment site for the offshore dredging experiment was finally selected 17 miles North of Cromer, North Norfolk in September 1991 (Figure 1).

Experimental Dredging

During 5 days in April 1992, the MV "Sand Harrier", an "H" class commercial suction-trailer dredger, removed a total of 52,000 tonnes of mixed aggregate representing 11 hopper loads from an area measuring 500 by 270 metres.

The position and speed of the "Sand Harrier" was monitored using a Sea Information Systems "Microplot v3.1" installed on Compaq PC linked to a "RoxAnn" seabed sediment discriminator. Together they displayed a constant real-time image of the dredging operations. High navigational accuracy was achieved using a Sercel "NR53" differential Global Positioning System (GPS) which had been previously calibrated against a "range-range" differential GPS operated by BritSurvey. This gave an almost constant accuracy of $\pm$10m. Figure 2 shows the track output generated by "Microplot" for the entire operation, which represents a total of 200 tracks covering approximately 70% of the experimental area.

Pre- and Post- Dredging Surveys

An array of benthic sampling equipment was used to survey the treatment and reference sites pre- and post-dredging. Remote sampling of benthos was achieved using a Hamon grab (Figure 3). The Hamon grab was found to be ideally suited for quantitative sampling of coarse (or compacted) sediments. It operates by taking a scoop out of the sediment, and the sample bucket is then forced against a metal plate which prevents the sample from being washed away during retrieval.

In order to obtain an instant view of the seabed and provide detailed information on the occurrence, distribution and behaviour of benthic organisms, an underwater camera sledge was used. The sledge was towed for ~1 hour along a transect through the treatment and reference sites. In addition, an acoustic map of the dredged site was generated using a EG+G dual frequency (100kHz, 500kHz) side-scan sonar.

Field Procedures

Hamon grab stations were randomly located within the defined boundaries of the treatment and reference sites. Samples were washed over 5mm and 1mm square mesh sieves so as to remove excess sediment and obtain all the colonial and solitary benthos. The benthos was fixed in a 4-6% buffered formaldehyde solution (diluted with sea water) with "Rose Bengal" (a vital stain) and stored for laboratory identification and enumeration. In addition a 1 litre sub-sample was taken for particle size analysis.

The underwater camera sledge was fitted with a television camera linked via an umbilical to a TV monitor and U-matic video recorder present on the RV. A single lens Reflex (SLR) camera loaded with a 200 exposure colour 35mm film pre-set to take one exposure every 20 seconds was also attached.

Laboratory Procedures

Hamon grab samples were first washed with fresh water over a 1mm mesh sieve in a fume cupboard to remove excess formaldehyde solution. Samples were then sorted on plastic trays and specimens were placed into jars or petri dishes containing a preservative mixture of 70% methanol (GPR) , 10% glycerol and 20% tap-water. For each species a representative specimen was recorded, preserved and stored separately in a glass vial to establish a reference collection and provide a means for the verification of species identifications. Whenever possible specimens were identified to species level using the standard taxonomic keys.

Partial wet-weights for each species were determined by placing specimens on a plastic tray covered with white blotting paper for 12 hours before measuring their weights on a Sartorius 2004 MP five figure balance. Biomass estimates were then calculated from partial-wet weights using conversion factors given in Eleftheriou and Basford (1989).

Sediment sub-samples were analysed for their particle size distributions according to the Udden-Wentworth Phi Classification where $Phi(0) = -\log_2 d$ and d is the particle diameter in millimetres. Each sample was first wet sieved on a 63 micron mesh sieve to provide an estimate of the fines fraction (<63 microns). The remaining sample was then oven dried for approximately 12 hours at 100^{o} C and allowed to cool to room temperature before being sieved through a stack of geological test-sieves ranging from -6 phi (64mm) to +4 phi (0.0063mm). A weight for each size fraction was measured using a Sartorius top-pan balance to an accuracy of $\pm$0.01g.

RESULTS

Physical Observations

Particle size data for 6 samples taken from the treatment site (Cruise COR 4/92) in March 1992, 4 weeks before dredging, were compared to 6 samples taken 2 weeks after dredging (Cruise COR 6/92) in May 1992. Results showed that the gravel content (>2mm) of the sediment increased from 36% to 56% (Figure 4).

Upon examination of the seabed using side-scan sonar and UW TV it was apparent that the dredge tracks have become infilled with sand, suggesting a redistribution of sediment has occurred. The action of the draghead on the seabed has agitated and vibrated the sediment to such an extent that gravel (>2mm) has consolidated to form ridges between furrows of sand. Inspection, by SCUBA divers, of the sand accumulations within the tracks showed that the deposits are superficial sand-ripple features, 1-2cm deep. In addition, the apparent increase in the gravel content at the treatment site may be caused by the preferential removal of sand by the suction action of the draghead.

Biological Observations

The total number of species recorded from 5 Hamon grab samples taken at the treatment and reference sites pre- and post-dredging are shown by major phyla in Figure 5. The total numbers of species 4 weeks before dredging (Cruise COR 4/92) at the treatment and reference sites were broadly similar at 70 and 62 species, respectively. However, 2 weeks after dredging (Cruise COR 6/92) the number of species at the treatment site had fallen to 30 (the polychaetes showed the most noticeable reduction from 35 to 16 species). At the reference site, the number of species has remained generally constant, having only increased slightly from May (64 species) to December (68 species). However, at the treatment site the number of species has increased from May (30 species) to December (53 species), which suggests that some readjustment or recolonisation has occurred.

The impact of dredging is more apparent when the abundance data are compared from each site, pre- and post-dredging. (Figure 6). The total abundance of animals recorded at the treatment and reference sites 4 weeks before dredging (Cruise COR 4/92) are broadly similar at $230/0.2m^2$. However, a dramatic reduction in the abundance has occurred at the treatment site post-dredging ($30/0.2m^2$), compared to the reference site ($209/0.2m^2$). The crustaceans and "others" phyla were numerically dominated by the barnacle *Balanus crenatus* and the sea-squirt *Dendrodoa grossularia.* Both showed an increase in abundance from May to December as a result of Summer recruitment. However, the increase at the reference site was greater than that at the treatment site (possible explanations are given below).

Biomass data for each site pre- and post-dredging (Figure 7) support the observations made on the abundance data (Figure 6). A large reduction in the biomass has occurred at the treatment site post-dredging: from $182g(AFDW)/m^2$ in March (Cruise COR 4/92) to $0.4g(AFDW)/m^2$ in May (Cruise COR 6/92). However, at the reference site the biomass figures remain high at

80g(AFDW)/m^{2}. At the treatment site in December, *B. crenatus* and *D. grossularia* contribute very little to the biomass, although they are present in relatively large numbers (Figure 6), suggesting they are new recruits. However, at the reference site the biomass figures for December are relatively large, reflecting the mixed populations of adults and juveniles of *B. crenatus* and *D. grossularia* present.

DISCUSSION

Dredging at the experimental site in April 1992 preceded the natural Summer recruitment of benthos. The 'opportunists' *D. grossularia* and *B. crenatus*, which were numerically dominant before dredging, showed the greatest increase in abundance post-dredging. However, the increase was greatest at the reference site. This may be explained by a combination of the following: i. The treatment site is physically stressed compared to the reference site, due to deposits of mobile sand being present within the dredge tracks, thereby reducing the recruitment success of sessile epibenthos such as *Sabellaria spinulosa*, *D. grossularia* and *B. crenatus*; ii. there may be spatial differences in recruitment success between the reference and treatment sites such that a larger settlement has occurred at the reference site; iii. the loss of adult sessile epibenthic populations at the treatment site has reduced the recruitment potential of juveniles, since the "cues" to settle are no longer present. For example, *B. crenatus* may require the presence of adult populations in order to stimulate settlement, as has been observed for *B. balanoides* (Stubbings, 1975). In addition, as many adults have been removed by dredging the source of juveniles which recruit locally (within 100m) is reduced; for example, *D. grossularia* larvae are not transported in the plankton but settle within a few metres of their parents (Svane and Young, 1989).

The effects of seasonality should be borne in mind. The data cover a period of seven months post-dredging and mortalities will have occurred during the winter of 1992, thereby reducing the observed gains in abundance at the treatment site.

It remains to be seen whether the populations at the treatment site adjust to the newly-created physical regime by shifting from a relatively stable community to one characteristic of a more mobile sediment.

The results from future surveys, planned for 1993 and 1994, will help to further clarify the processes of recolonisation, and the resultant community structure, post-dredging.

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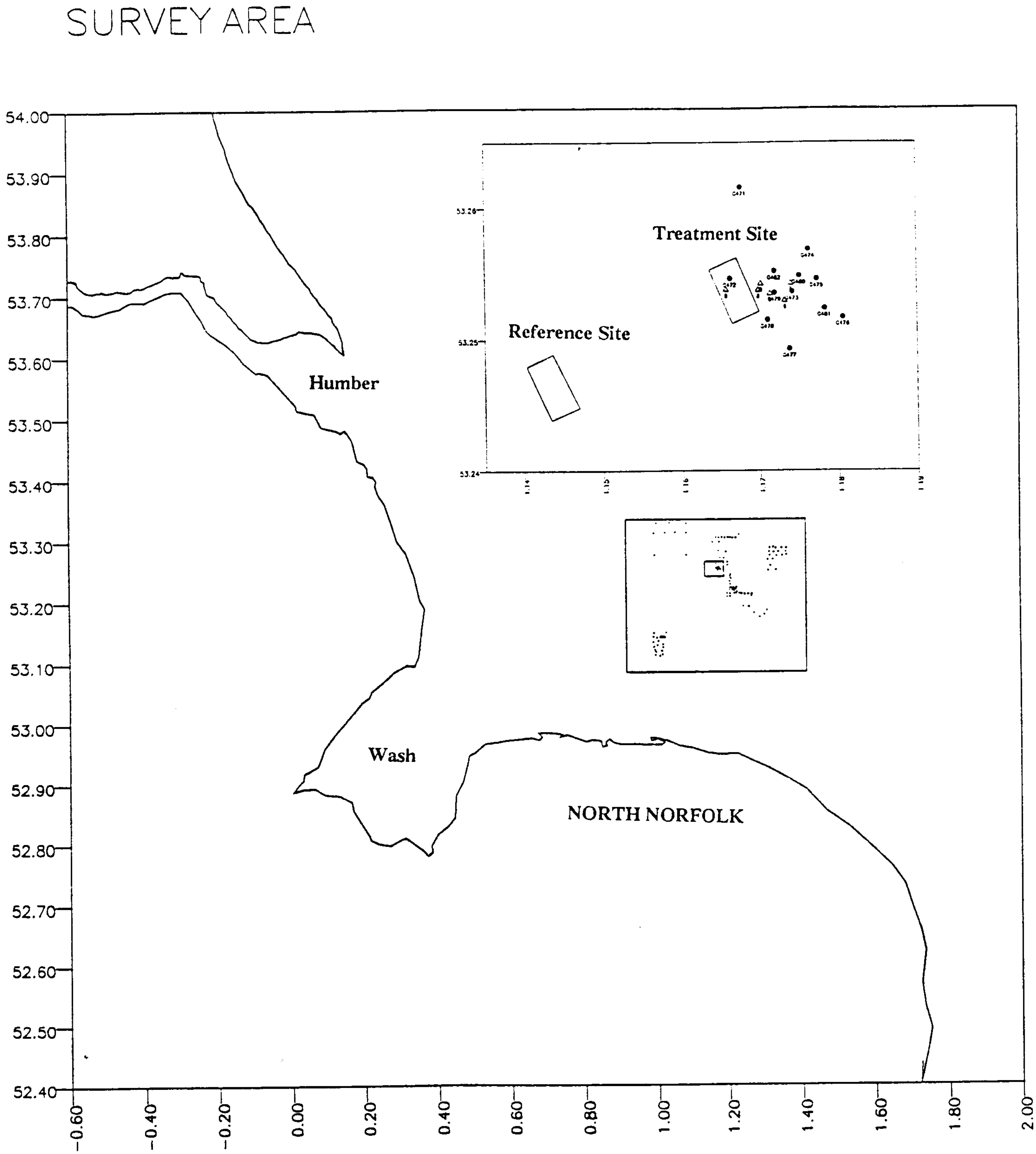


Figure 1: Benthic survey off North Norfolk (small box) in order to locate the experimental dredging and reference sites (large box).

Figure 2: Tracks generated by the suction trailer dredger MV "Sand Harrier" at the experimental dredging site showing ~70% of the seabed area has been dredged.

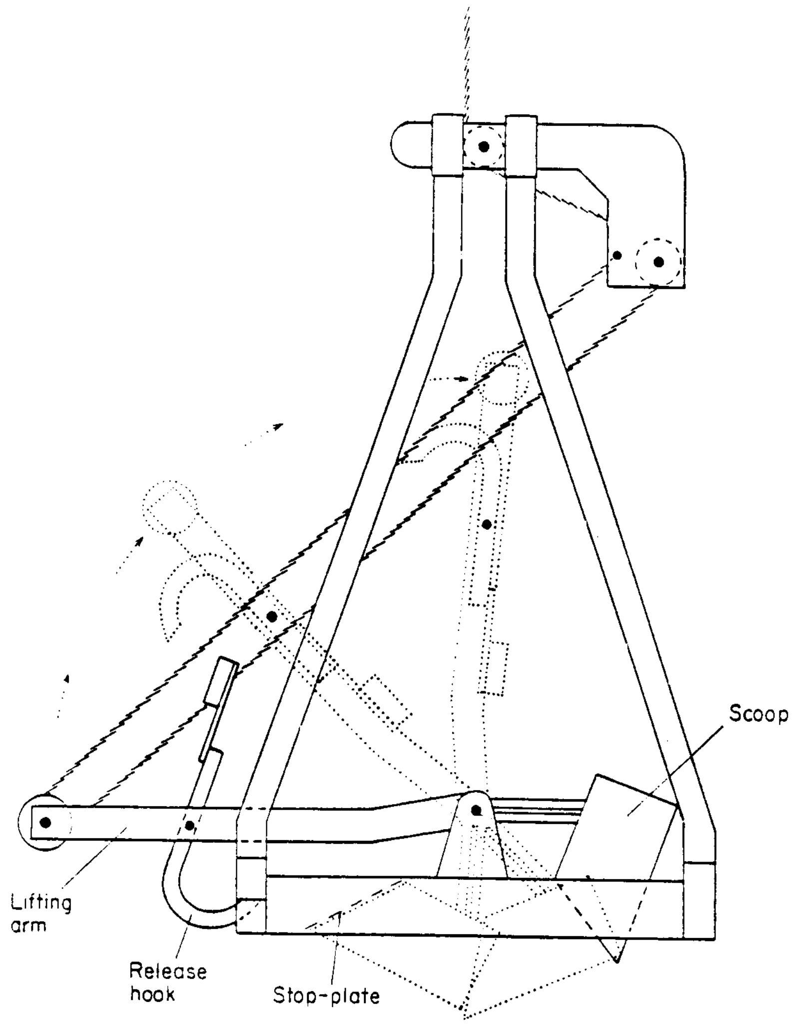


Figure 3: Schematic diagram of the Hamon grab (taken from Holme and McIntyre, 1984, after Oele, 1978).

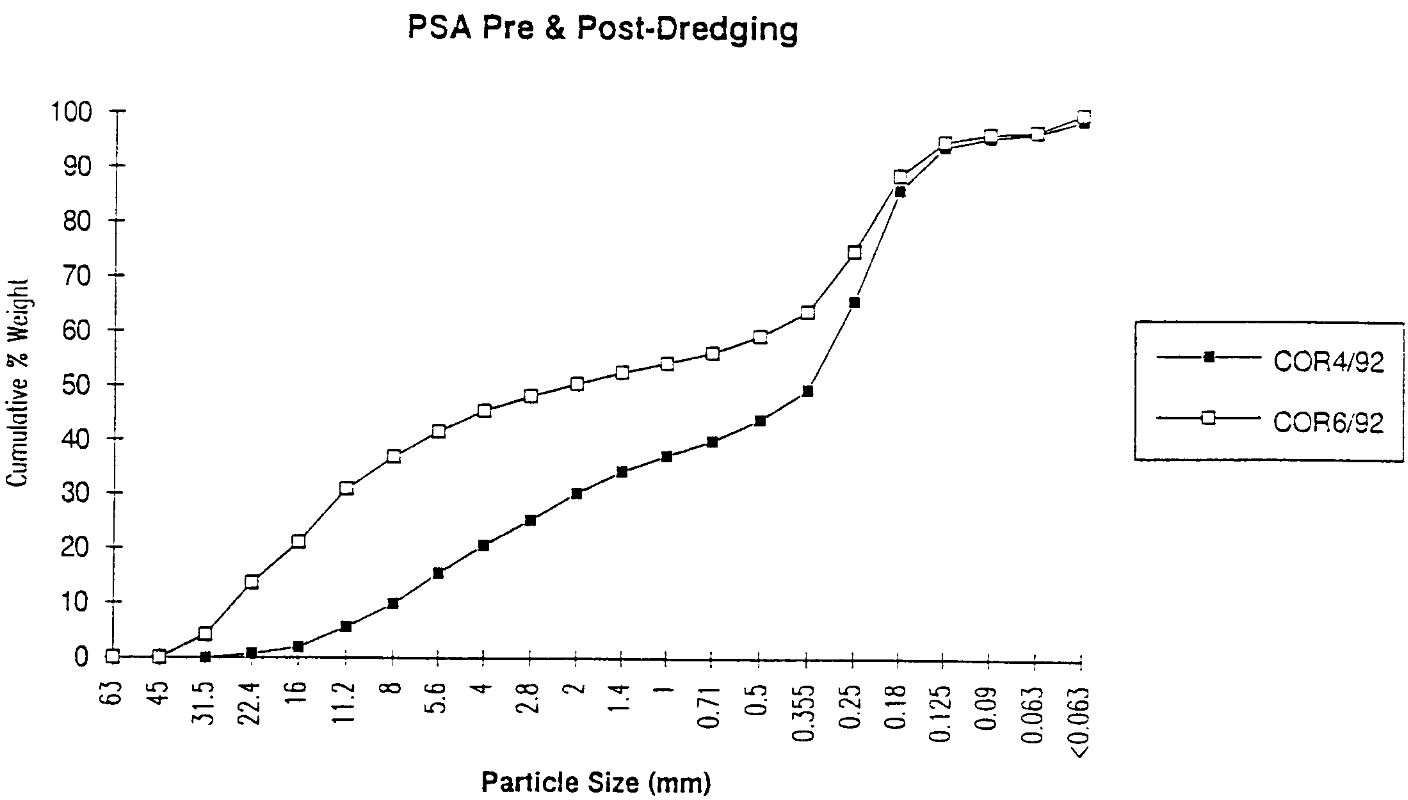
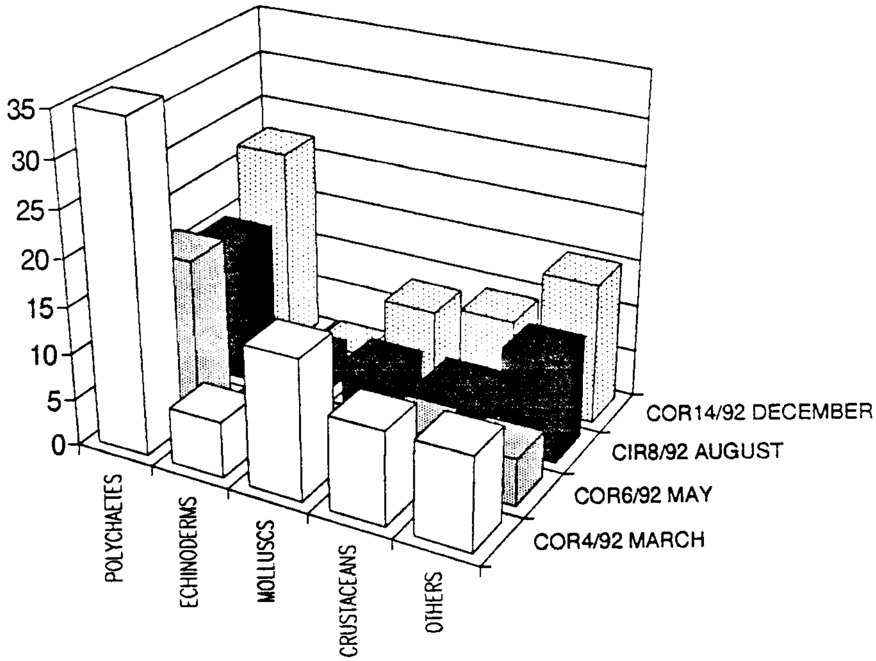


Figure 4: Average cumulative particle size distribution curves for samples taken before dredging (Cruise COR 4/92) and post-dredging (Cruise COR 6/92).

TREATMENT SITE SPECIES NUMBERS/1.05m



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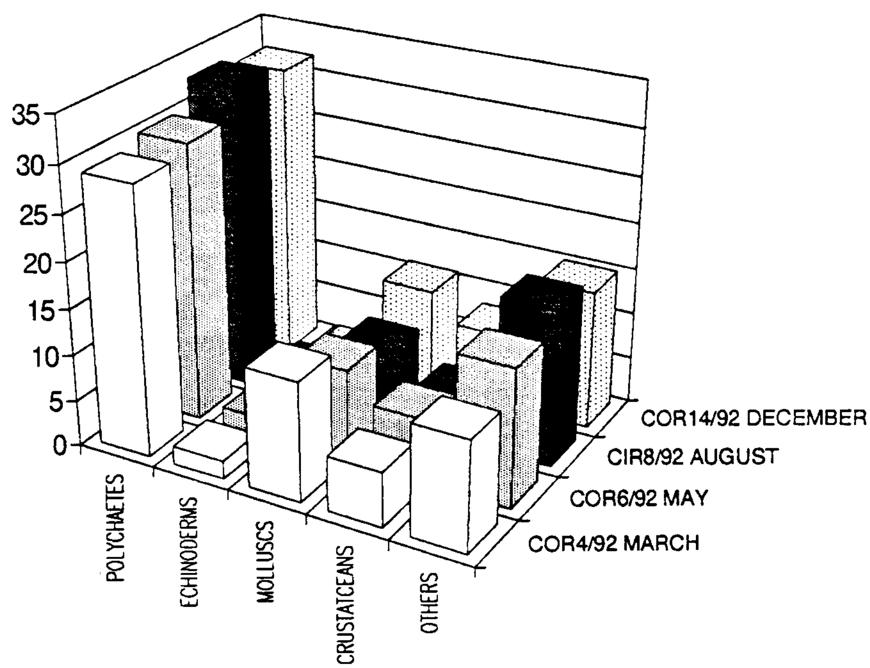
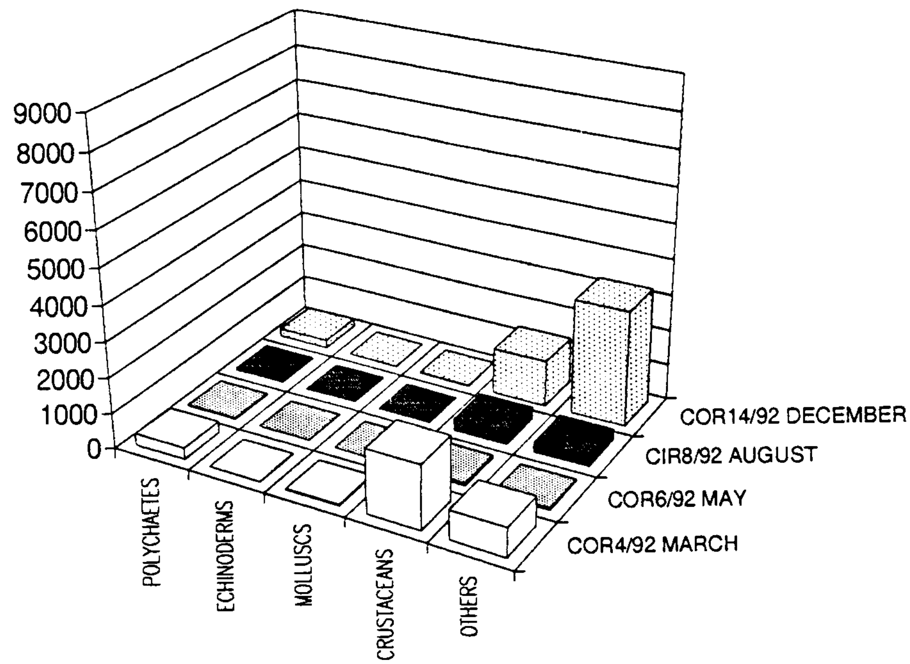


Figure 5: Number of species by major phyla for samples taken before dredging (Cruise COR 4/92) and post-dredging (Cruises COR 6/92, CIR 8/92 and COR 14/92) from the treatment and reference sites.

TREATMENT SITE ABUNDANCE 1.05/m



REFERENCE SITE ABUNDANCE/1.05m

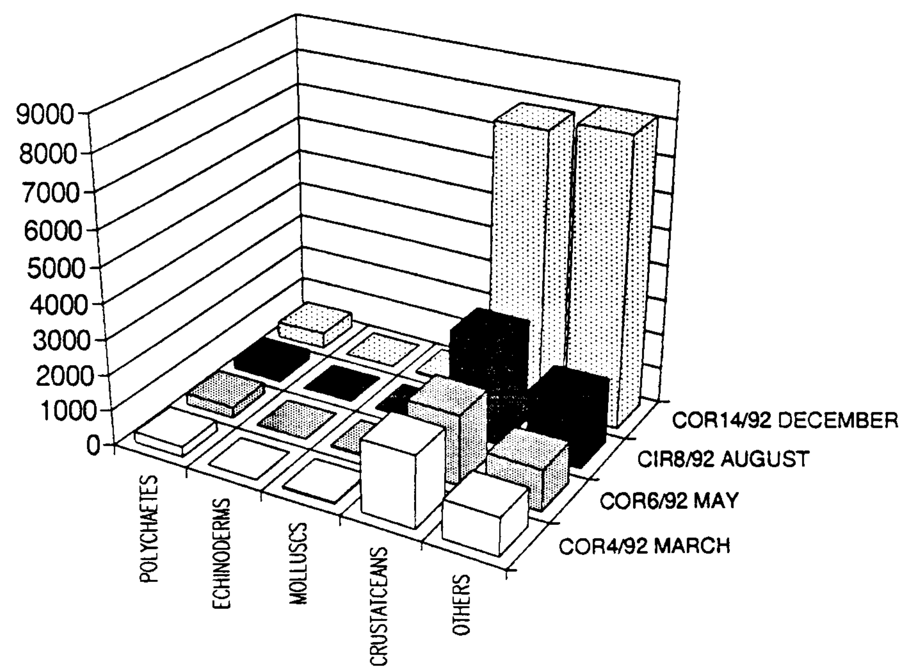
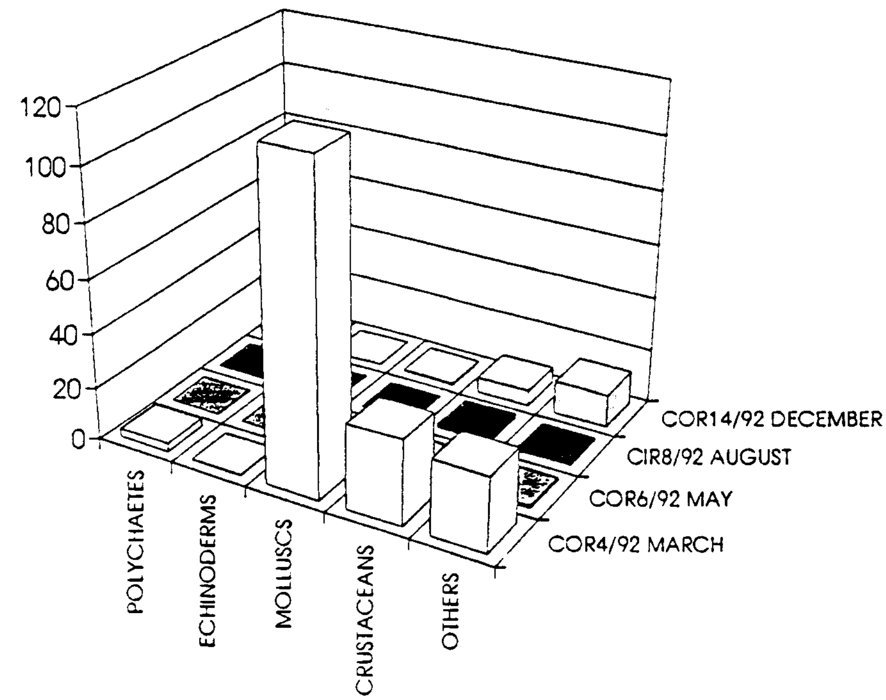


Figure 6: Abundance by major phyla for samples taken before dredging (Cruise COR 4/92) and post-dredging (Cruises COR 6/92, CIR 8/92 and COR 14/92) from the treatment and reference sites.

TREATMENT SITE BIOMASS g(AFDW)/m



REFERENCE SITE BIOMASS g(AFDW)/m

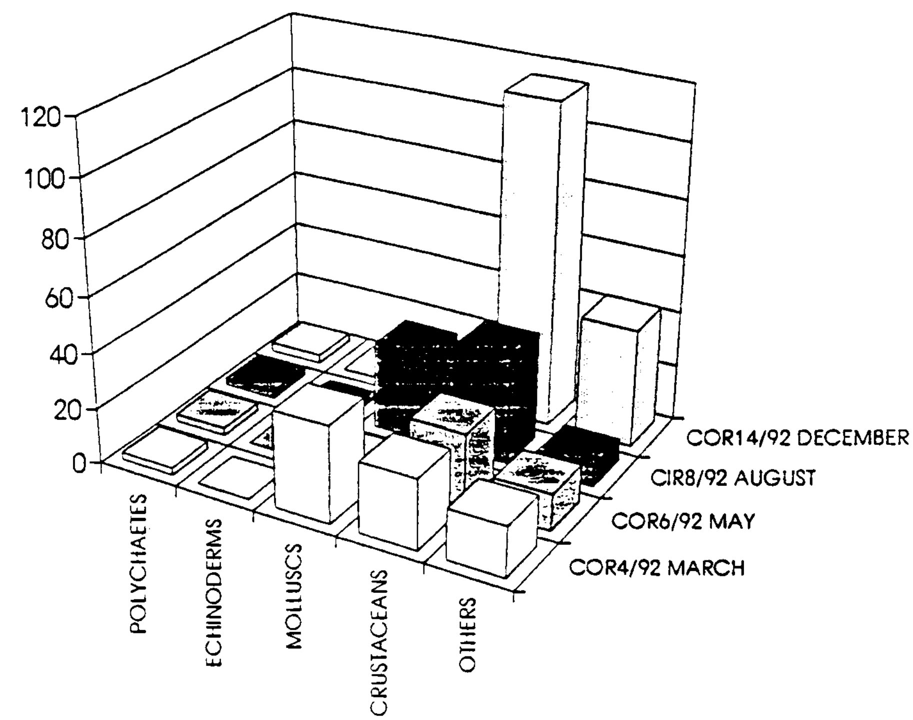


Figure 7: Biomass by major phyla for samples taken before dredging (Cruise COR 4/92) and post-dredging (Cruises COR 6/92, CIR 8/92 and COR 14/92) from the treatment and reference sites.

Appendix 4

Excerpts from: Saloman, C.H., S.P. Naughton and J.L. Taylor, 1982. Benthic Community response to dredging borrow pits. Panama City Beach, Florida. M.R. 82-3. U.S. Army Corps of Coastal Engineering Research Center, Fort Belvoir, Va.: 139 p.

Summary of:

Saloman, C.H., S.P. Naughton and J.L. Taylor. 1982. Benthic community response to dredging borrow pits, Panama City Beach, Florida. M.R. 82-3. U.S. Army Corps of Coastal Engineering Research Center. Fort Belvoir, Va. 138 p.

Location : Gulf Coast of Florida.

Equipment: Diver-operated 0.0156 m-2 core.
Penetration 23 cm
Sieve 0.7 mm

Borrow Pit Depth:	3-5 m?
Collection Date:	1974-1977
Collection Period	Varied
Deposit Description	Sand

General Site Characteristics and Changes:

	Deposit Mean (mm)	Organisms/ m^2	No. of Species	Biomass
Before	~0.17-0.2	1506-7178	15-120	None
After	~0.177-0.3	324-4037	20-114	None
Controls (After)		1408-5576	53-112	None

Biological Characteristics:

Total # of Species = 362

Phyla	#
Annelids	152 (42%)
Arthropods	108 (30%)
Mollusks	69 (19%)

Remaining 33 species (9%) divided among 11 groups

Total # individuals = 58,068

Phyla	%
Annelids	55%
Mollusks	19%
Arthropods	18%
Cnidaria	2%
Cephalochordata	2%
Nematoda	1%
Echinodermata	1%

Remaining 7 phyla comprised 2%

See Table 3 for numerically dominant species.

20 species (first collection after dredging).
114 species (1 year after dredging).

Number of species collected over 3 weeks after dredging (3 weekly samplings):

Total #:	81
Annelids	35 (43%)
Arthropods	24 (30%)
Mollusks	9 (11%)
Echinoderms	3 (4%)
9 other phyla	10 (13%)

Dominant species after dredging:

1 week after (total abundance 81)		2 weeks after (total abundance 279)		3 weeks after (total abundance 534)	
Lumbrineris cruzensis PE[1]	38 (47%)	*Lumbrineris cruzensis* PE	113 (40%)	*Lumbrineris cruzensis* PE	170 (32%)
Tellina versicolor MB	12 (15%)	*Prionospio cristata* PS	43 (15%)	*Prionospio cristata* PS	114 (21%)
Scoloplos armiger PS	5 (6%)	*Branchiostoma floridae* CC	32 (11%)	*Pseudoplatyischnopus sp.* CA	31 (6%)
Onuphis nebulosa PE	4 (5%)	*Tellina versicolor* MB	18 (6%)	*Ampelisca verrilli* CA	27 (5%)
Protohaustorius sp. CA	4 (5%)	*Scoloplos armiger* PS	7 (3%)	*Tellina versicolor* MB	23 (4%)

PE = Polychaete, Errant.
MB = Mollusc, Bivalve
PS = Polychaete, Sedentary
CA = Crustacea, Amphipod
C = Cephalochordata

Number of Species:

1 week	2 weeks	3 weeks
Annelids 10(48%)	Annelids 18(44%)	Annelids 27(45%)
Arthropods 4(19%)	Arthropods 14(34%)	Arthropods 17(28%)
Molluscs 2(9.5%)	Molluscs 3 (75)	Molluscs 7(12%)
5 phyla 5(24%)	6 phyla 6(15%)	8 phyla 9(15%)
Totals: 21	41	60

Total Abundance.

1 week	2 weeks	3 weeks
Annelids 54(67%)	Annelids 185(66%)	Annelids 390 (73%)
Molluscs 13(16%)	Cephalocordata 32(12%)	Arthropods 76(14%)
Arthropods 7(9%)	Arthropods 29(10%)	Molluscs 40(8%)
5 other phyla have 1or 2 inds.	Molluscs 23(8%)	
Totals: 81	279	534

ABSTRACT *(re-typed from original manuscript of Saloman et al. 1982)*

This report gives biological and physical oceanographic data from baseline work, and studies of dredged and undredged sediments before and after dredging (9-meter contour) for beach nourishment at Panama City Beach, Florida. These studies were designed to show major short-term environmental effects of offshore dredging and included analyses of hydrology, sediments and benthos.

Hydrological measurements were limited to water temperature and salinity. Analysis of surface sediments included particle-size distribution, carbon chemistry, and statistical properties of mean grain size, sorting, skewness, and kurtosis. Average and extreme periods of water temperature and salinity were recorded. Regional nearshore sediments proved to be fine sand, containing less than 1 percent silt-clay, that was moderately well to well sorted, symmetrical to coarsely skewed, and leptokurtic. Total carbon content averaged less than 0.30 percent, and most of that occurred in the form of carbonate deposits. Over a postdredging study period of 1 year, sediment samples from borrow pits showed little variation from these general features.

In studies of the benthos, 362 species and 58,068 individuals were recorded among 14 invertebrate phyla and bony fishes. Dominant groups by species and abundance included annelida, mollusca, and arthropoda (crustacea). Faunal comparisons between dredged and undredged areas were made on the basis of species richness and abundance, the Shannon-Weaver index of diversity (H'), Pielou's index of equitability (J'), Morisita's index of faunal similarity (together with matrices and classification diagrams derived from that index), and two statistical derivations, based on diversity and abundance data, that were designed to show sample-to-sample faunal variations and the time period required for faunal recovery in borrow pits. Information obtained from these procedures showed that recovery began soon after dredging was complete, or nearly so, within 1 year.

These results were similar in most respects to those from study of offshore dredging elsewhere in comparable geographic settings. Even so, the need for close association between ecological research and coastal engineering programs is emphasized.

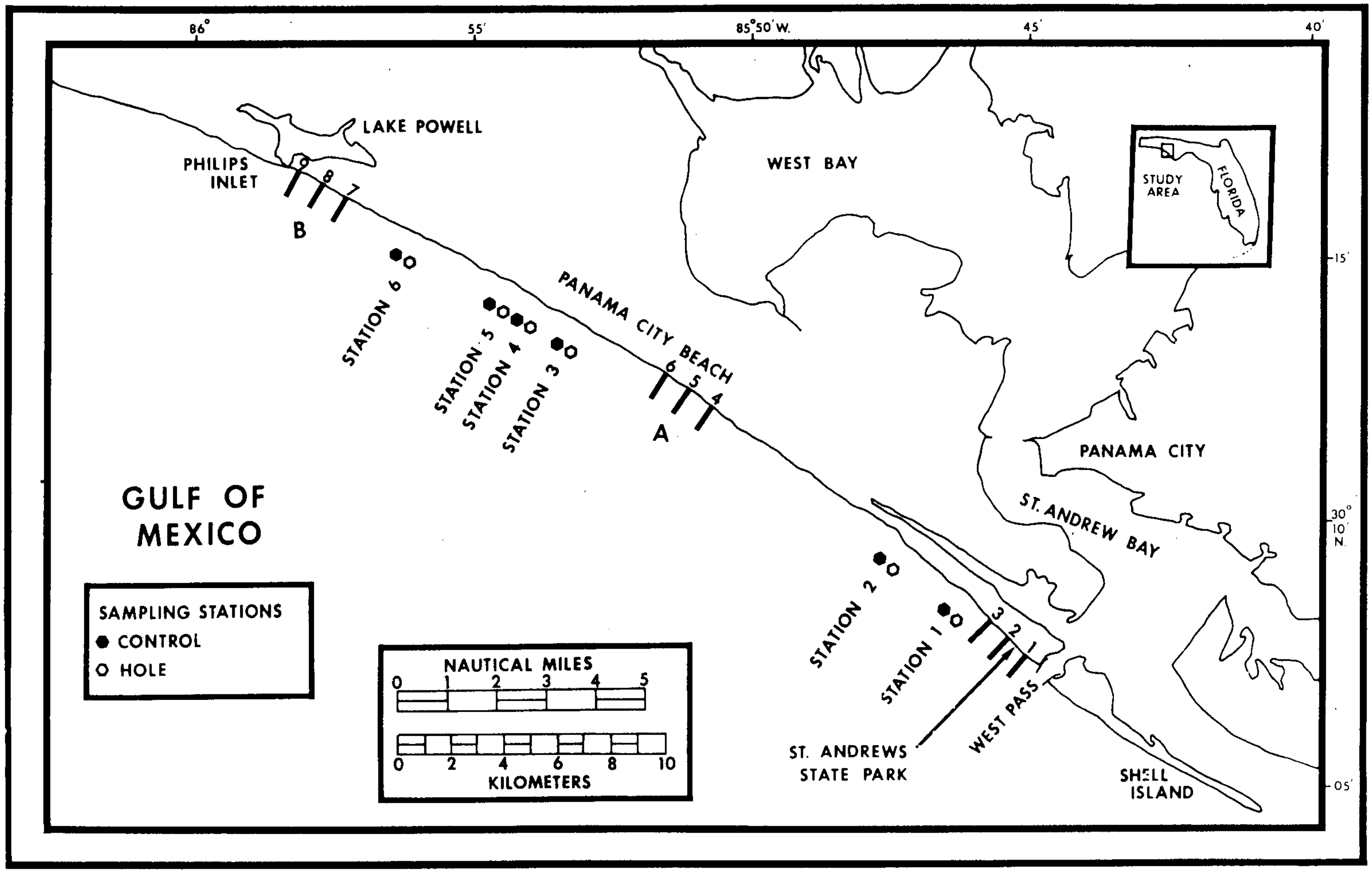


Figure 1. Study area at Panama City Beach, Florida, showing stations 1 to 6, July 1977.

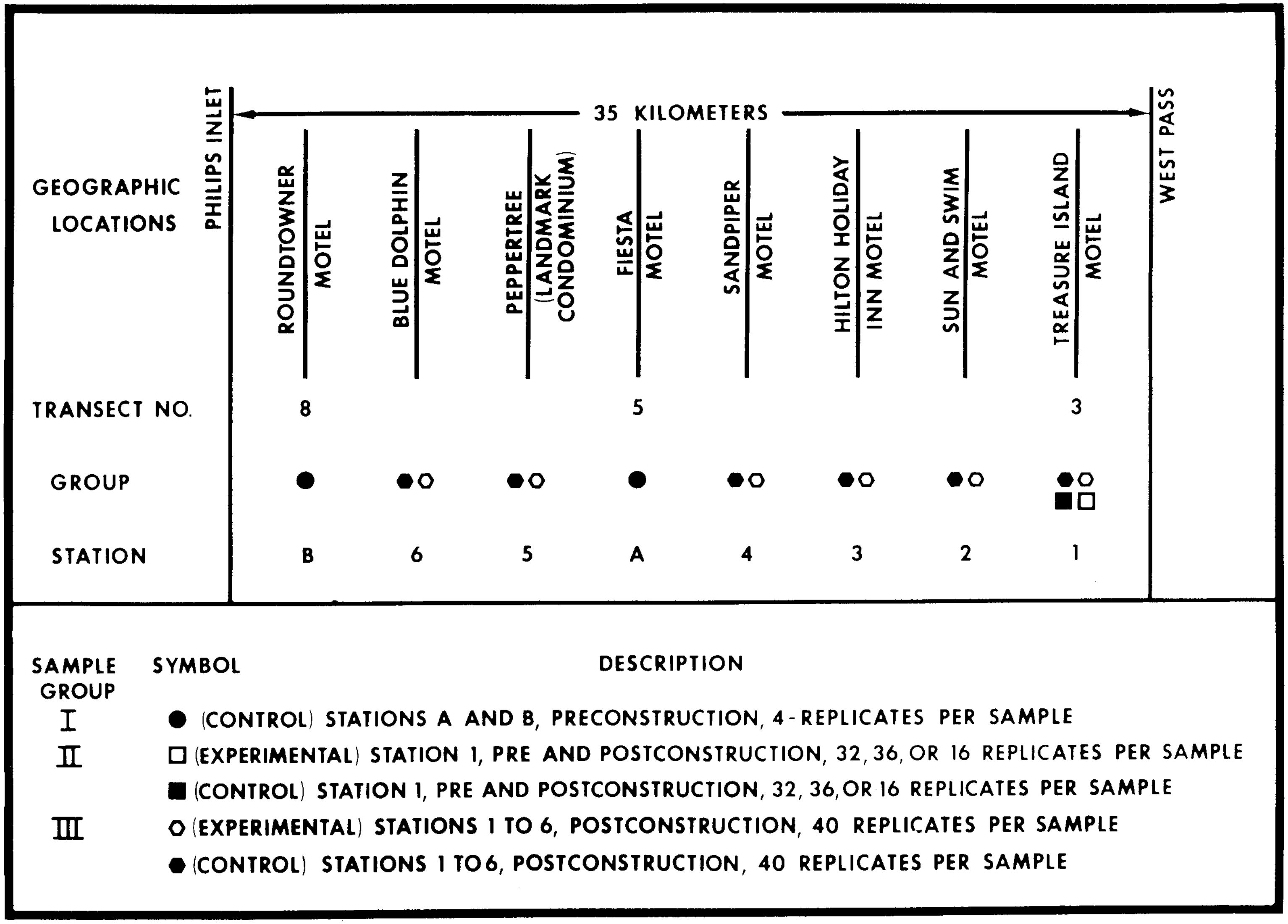


Figure 2. Schematic representation of sampling plan, Panama City, Florida.

Table 1. Water temperature and salinity at stations A and B before the 1974-75 dredging, and at station 1 before and after the 1976 dredging for beach nourishment at Panama City Beach, Florida.

Station	Date	Water Temp. (°C)	Salinity (ppt)
	1974		
A	18 Nov.	21.0	34.5
B	18 Nov.	20.8	34.3
	1975		
A	20 Feb	17.4	34.4
B	20 Feb.	17.5	33.9
A	20 May	26.2	32.2
B	20 May	26.0	32.2
A	12 Aug.	28.3	26.2
B	12 Aug.	28.5	26.1
1	1976		
(before)	Apr.	20.2	33.3
	May	20.2	34.9
	June	25.7	32.3
	July	28.0	33.3
	Aug.	27.0	35.3
	Sept.	27.8	32.6
	Oct.	24.9	33.1
	Nov.	18.0	33.2
	Dec.	12.5	34.1
1	1977		
(after)	Jan.	12.4	33.3
	Feb.	9.0	34.3
	Mar.	14.3	34.4
	Apr.	22.4	33.5
	May	21.8	34.3
	June	25.7	32.1
	July	27.5	33.6
	Aug.	29.0	35.3
	Sept.	27.7	32.6
	Oct.	25.0	33.1
	Nov.	-	-

Table 2. Textural and statistical properties of sediments in control (undredged bottom) and experimental (borrow pit) samples taken 1 year after dredging at stations 1 to 6 along the 9-meter depth contour off Panama City Beach, Florida, July 1977.

Station	Textural			Statistical			
	Granule (pct)	Sand (pct)	Silt-clay (pct)	Mean grain size (phi)	Std. dev. (phi)	Skewness	Kurtosis
1							
Control		99.70	0.30	2.45	0.45	-0.19	1.18
Experimental		98.64	1.36	2.50	0.53	-0.00	1.39
2							
Control		99.65	0.35	2.45	0.44	-0.18	1.15
Experimental		99.80	0.20	2.43	0.48	-0.19	1.21
3							
Control		99.88	0.12	2.21	0.62	-0.32	1.11
Experimental	0.92	98.96	0.11	1.75	1.06	-0.46	0.82
4							
Control		99.86	0.14	2.24	0.61	-0.31	1.16
Experimental	0.08	99.81	0.11	2.01	0.83	-0.41	0.95
5							
Control		99.86	0.14	2.31	0.59	-0.33	1.34
Experimental		99.86	0.14	2.26	0.58	-0.28	1.11
6							
Control	0.34	99.52	0.14	2.11	0.76	-0.40	1.09
Experimental	0.14	99.76	0.11	2.31	0.61	-0.34	1.39

Table 3. Species in dominant phyla (listed alphabetically) that were numerically abundant at one or more base-line or control stations offshore Panama City Beach, Florida, November 1974 to November 1977.

MOLLUSCA

Acteocina candei
Cylichnella bidentata
Diastoma varium
Ervilia concentrica
Lepton sp.
Lucina multilineata
Natica pusilla
Periploma margaritaceum
Pitar simpsoni
Strigilla mirabilis
Tellina texana
Tellina versicolor

ANNELIDA

Armandia agilis
Armandia maculata
Brania wellfleetensis
Ceratonereis irritabilis
Chone sp.
Dispio uncinata
Eteone lactea
Glycera americana
Goniada littorea
Haploscoloplos foliosus
Lumbrineris cruzensis
Lumbrineris tenuis
Lumbrineris tetraura
Magelona riojai
Magelona sp.
Mesochaetopterus sagittarius
Nephtys bucera
Nephtys picta
Onuphis eremita oculata
Onuphis nebulosa
Owenia fusiformis
Paraonides lyra
Paraonis fulgens
Paraprionospio pinnata
Prionospio cristata
Rullierinereis mexicana
Scolelepis texana
Scoloplos armiger
Spio pettiboneae
Spiophanes bombyx
Unidentified Oligochaete

ARTHROPODA

Acanthohaustorius sp.
Albunea paretii
Ampelisca abdita
Ampelisca verrilli
Cyclaspis varians
Cyclaspis sp.
Erichthonius sp.
Lepidactylus sp.
Monoculodes sp.
Oxyurostylis smithi
Processa hemphilli
Protohaustorius sp.
Pseudohaustorius sp.
Pseudoplatyischnopus sp.
Synchelidium sp.
Unidentified Ostracod

Table 4. Species richness, abundance, diversity (H'), and equitability (J') and base-line stations offshore Panama City Beach, Florida, November 1974 to July 1976.

Station	Date	Replicates per sample (No.)	Species (No.)	Individuals per m^2 (No.)	H'	J'
A	Nov. 1974	4	15	2,064	1.9	0.7
	Feb. 1975		27	3,008	2.2	0.7
	May 1975		41	4,784	2.8	0.8
	Aug. 1975		43	3,888	3.1	0.8
Avg.			32	3,436	2.5	0.8
Range			15 to 43	2,064 to 4,784	1.9 to 3.1	0.7 to 0.8
B	Nov. 1974	4	27	3,808	1.9	0.6
	Feb. 1975		26	3,984	2.3	0.7
	May 1975		28	5,344	2.3	0.7
	Aug. 1975		47	5,248	3.0	0.8
Avg.			32	4,596	2.4	0.7
Range			26 to 47	3,808 to 5,344	1.9 to 3.0	0.6 to 0.8
1	Apr. 1976	32	67	1,506	2.5	0.6
	June 1976	36	94	1,902	3.5	0.8
	July 1976	36	120	7,178	3.1	0.6
Avg.			94	3,529	3.0	0.7
Range			67 to 120	1,506 to 7,178	2.5 to 3.5	0.6 to 0.8
Overall						
Avg.			49	3,883	2.6	0.7
Range			15 to 120	1,506 to 7,178	1.9 to 3.5	0.6 to 0.8

Table 5. Species richness, abundance, diversity (H'), and equitability (J') at control stations offshore Panama City Beach, Florida, August 1976 to November 1977.

Station	Date	Replicates per sample (No.)	Species (No.)	Individuals per m^2 (No.)	H'	J'
1	10 Aug. 1976	16	72	5,576	2.4	0.6
	18 Aug. 1976		80	5,500	2.8	0.6
	24 Aug. 1976		84	4,836	2.9	0.6
	1 Sept. 1976		74	3,080	2.9	0.7
	8 Sept. 1976		83	2,260	3.4	0.8
	21 Sept. 1976		89	3,128	3.0	0.7
	4 Oct. 1976		87	3,116	3.3	0.7
	18 Oct. 1976		77	3,912	2.6	0.6
	1 Nov. 1976		67	3,020	2.6	0.6
	1 Dec. 1976		74	3,080	3.0	0.7
	5 Jan. 1977		56	1,724	3.0	0.8
	2 Feb. 1977		53	1,516	3.1	0.8
	1 Mar. 1977		64	2,360	3.1	0.7
	1 Apr. 1977		57	2,632	3.1	0.8
	2 May 1977		55	2,572	2.7	0.7
	1 June 1977		55	1,976	3.3	0.8
	5 July 1977		64	3,264	3.1	0.7
	2 Aug. 1977		80	5,168	3.0	0.7
	1 Sept. 1977		70	3,572	2.9	0.7
	3 Oct. 1977		64	2,112	2.8	0.7
	1 Nov. 1977		72	2,904	3.0	0.7
Avg.			70	3,205	3.0	0.7
Range			53 to 89	1,515 to 5,576	2.4 to 3.3	0.6 to 0.8
1	11 Jul. 1977	40	99	3,365	3.2	0.7
2	15 Jul. 1977	40	112	3,750	3.4	0.7
3	25 Jul. 1977	40	105	4,326	3.2	0.7
4	26 Jul. 1977	40	74	4,050	2.9	0.7
5	27 Jul. 1977	40	57	1,408	3.0	0.7
6	28 Jul. 1977	40	66	2,483	3.0	0.7
Avg.			86	2,817	3.1	0.7
Range			57 to 112	1,408 to 4,326	2.9 to 3.4	0.6 to 0.8
Overall						
Avg.			74	3,119	3.0	0.7
Range			53 to 112	1,408 to 5,576	2.4 to 3.4	0.6 to 0.8

Table 6. Species richness, abundance, diversity (H'), and equitability (J') at experimental stations offshore Panama City Beach, Florida, August 1976 to November 1977.

Station	Date	Replicates per sample (No.)	Species (No.)	Individuals per m^2 (No.)	H'	J'
1	10 Aug. 1976	16	20	324	2.0	0.7
	18 Aug. 1976		38	976	2.2	0.6
	24 Aug. 1976		60	2,136	2.6	0.6
	1 Sept. 1976		38	1,612	2.1	0.6
	8 Sept. 1976		47	1,344	2.7	0.7
	21 Sept. 1976		45	924	2.9	0.8
	4 Oct. 1976		85	2,440	3.7	0.8
	18 Oct. 1976		46	1,124	2.9	0.8
	1 Nov. 1976		55	2,044	2.5	0.6
	1 Dec. 1976		54	3,540	2.3	0.6
	5 Jan. 1977		36	2,192	1.8	0.5
	2 Feb. 1977		44	2,212	1.9	0.5
	1 Mar. 1977		62	3,732	2.6	0.6
	1 Apr. 1977		52	3,144	2.2	0.6
	2 May 1977		54	1,656	2.8	0.7
	1 June 1977		69	3,256	3.2	0.8
	5 July 1977		49	1,964	2.7	0.7
	2 Aug. 1977		70	2,920	3.2	0.8
	1 Sept. 1977		32	440	2.9	0.8
	3 Oct. 1977		61	1,588	3.1	0.8
	1 Nov. 1977		54	1,220	2.9	0.7
Avg.			51	1,942	2.6	0.7
Range			20 to 85	324 to 3,732	1.8 to 3.7	0.5 to 0.8
1	11 July 1977	40	81	2,422	2.9	0.7
2	15 July 1977	40	114	3,862	3.5	0.7
3	25 July 1977	40	98	4,037	3.3	0.7
4	26 July 1977	40	94	2,587	3.4	0.8
5	27 July 1977	40	80	2,644	2.9	0.7
6	28 July 1977	40	83	3,034	3.4	0.8
Avg.			92	3,101	3.2	0.7
Range			80 to 114	2,422 to 4,037	2.9 to 3.5	0.7 to 0.8
Overall						
Avg.			60	2,200	2.8	0.7
Range			20 to 114	324 to 4,037	1.8 to 3.7	0.5 to 0.8

Appendix 5

Excerpts from: Padan, J.W. 1977. New England Offshore Mining Environmental Study (Project NOMES) U.S. Dept. of Commerce, NOAA: 139 p.

Summary of:

Padan, J.W. 1977. New England Offshore Mining Environmental Study (Project NOMES) U.S. Dept. of Commerce, NOAA: 139 p.

Location: Atlantic Ocean, Massachusetts Bay off Boston.
Mine area. Cobble stations D2, D3 and C6.
Reference cobble area C11
Other stations - finer sediments
Water depth: 20m.

Equipment: SCUBA diving.
Grab - not specified.
Collection Period: 1973

Site Characteristics: Cobble areas only - No data extractable

Biological Characteristics:

	Species		**Abundance/m^2**
Sample station	Inverts.	Motiles	Motiles
D2	31	31	1,640
D3	113	101	4,120
C6	65	39.23	3,138
C11	89.25	83.25	7,535

Top 5 ranks of the most common motile organisms, based on mean number of animals:

Cobble substrate stations	C6	(D)T2	(D)T3	C11
Number of times sampled	4	1	1	4
See Table 6 for more details	*Euclymene collaris* PS[1]	*E. collaris* PS	*E. collaris* PS	*U. irrorata* CA
	Unicola irrorata CA[2]	*Phyllodoce groenlandica* PE	*E. dispar* PE	*E. collaris* PS
	Exogone dispar PE[3]	*Syllis armillis* PE	*U. irrorata* CA	*E. dispar* PE
	Glycera capitata PE	*G. capitata* PE	*Corophium crassicorne* CA	*Notomastus luridus* PS
	Strongylocentrotus droebachiensis EE[4]	*Tharyx acutus* PS	*Spirorbis spirillum* PS	*Tharyx acutus* PS

PS = Polychaete, Sedentary

CA = Crustacea, Amphipod

PE = Polychaete, Errant

EE = Echinoderm, Echinoid.

Mean ranking of 5 dominant higher order taxa (see Table 7):

Cobble Stations		Sand Stations	
C6	C11	S10	M9
Polychaeta(1.0)	Polychaeta (1.0)	Polychaeta (1.2)	Polychaeta (1.0)
Amphipoda (2.0)	Amphipoda (1.75)	Amphipoda (1.8)	Amphipoda (2.0)
Ophiuroidea (3.0)	Bivalvia (3.25)	Bivalvia (3.0)	Bivalvia (3.0)
Echinoidea (3.75)	Gastropoda (4.0)	Cumacea (5.2)	Cumacea (4.6)
Bivalvia (4.0)	Polyplacophora (5.0)	Anthozoa (5.4)	Isopoda (5.0)

Mean ranking of feeding type (see Table 8):

Cobble	C.6	C.11
	Scraper/Omnivore (1.3)	Scraper/Omnivore (1.0)
	Deposit/Direct (1.6)	Deposit/Indirect (2.5)
	Predator/Epi/Micro (3.0)	Deposit/Direct (3.0)
	Deposit/Indirect (4.0)	Suspension/Filter (4.0)
	Suspension/Filter (5.0)	Predator/Epi/Micro (5.0)
Sand	M.9	S.10
	Deposit/Indirect (1.0)	Deposit/Direct (1.0)
	Scraper/Omnivore (2.0)	Scraper/Omnivore (1.8)
	Suspension/Filter (3.0)	Suspension/Filter (4.0)
	Predator/Epi/Micro (4.3)	Predator/In/General (4.0)
	Predator/In/General (4.8)	Deposit/Indirect (4.2)

SUMMARY

The New England Offshore Mining Environmental Study (Project NOMES) was begun in 1972 in order to resolve the marine environmental impact uncertainties that had inspired at many levels of government legal and de facto moratoriums on marine mining. It was a joint study sponsored by the Commonwealth of Massachusetts and the National Oceanic and Atmospheric Administration. Plans had called for a 1-year study of baseline conditions at a sand and gravel deposit centered in Massachusetts Bay at 40°21'41" N., 70°47'10" W., followed by a period of well-monitored commercial-scale mining. Two years of post-experiment monitoring were planned to document mining-induced changes in the seafloor and water column as well as their subsequent alteration by natural processes.

The project was terminated in July 1973 as a result of the failure of the Commonwealth to arrange for a suitable site for the disposal of the three-quarters of a million cubic meters of sand and gravel to be mined during the planned spring 1974 test. Nevertheless, all principal investigators were funded through a project wrap-up phase, and two were funded long enough to permit them to study baseline conditions in two important aspects of marine life (i.e., benthos, phytoplankton) for a full year.

The purpose of this report is to consolidate and present the findings in such a manner that the NOMES experience can be considered an informational and procedural point of departure for studies preceding the next continental sand and gravel venture, whether it be an experiment or a commercial mining operation. Studies are reported in four areas of oceanography: biological (benthos, phytoplankton, turbidity experiments), geological (bathymetry, stratigraphy, core samples), chemical (nutrients, suspended solids), and physical (temperature and salinity, currents and dispersion, and light penetration).

Over 650 species of benthic invertebrates were sampled by scuba diving at a number of stations arranged in a grid pattern around the test site. The most important result of this part of the project was the documentation of the natural variability in the system. The existence of month-to-month variation at each station was the most consistent finding. From month to month there was up to 100% variation in the number of species at a station. In fact, the species numerically dominant one month frequently were absent from collections in the next month. The species tended to change with substrate type. This is a heterogeneous environment and only a minority of the species appeared to be specialists for substrate type. Indicator species, if it is possible to use them in the future, will most likely have to be selected for each station and not from general substrate types. In a future study of offshore sand and gravel mining, benthic community studies should utilize permanent stations, as was done in NOMES, but the sampling scheme should be altered. A limited number (two to four) of stations should be sampled intensively on a quarterly schedule. Fifteen to twenty replicate samples hould be taken at each station every three months and analyzed separately so hat aggregated distributions can be identified. This may provide a more ealistic picture of community organization and dynamics than monthly samp- ng with fewer replicates would.

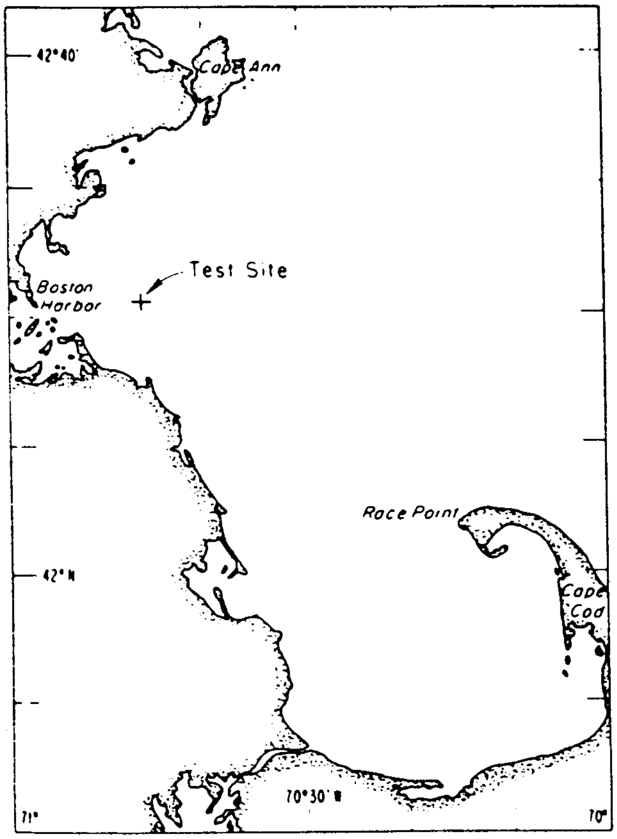


Figure 1. Test site in Massachusetts Bay.

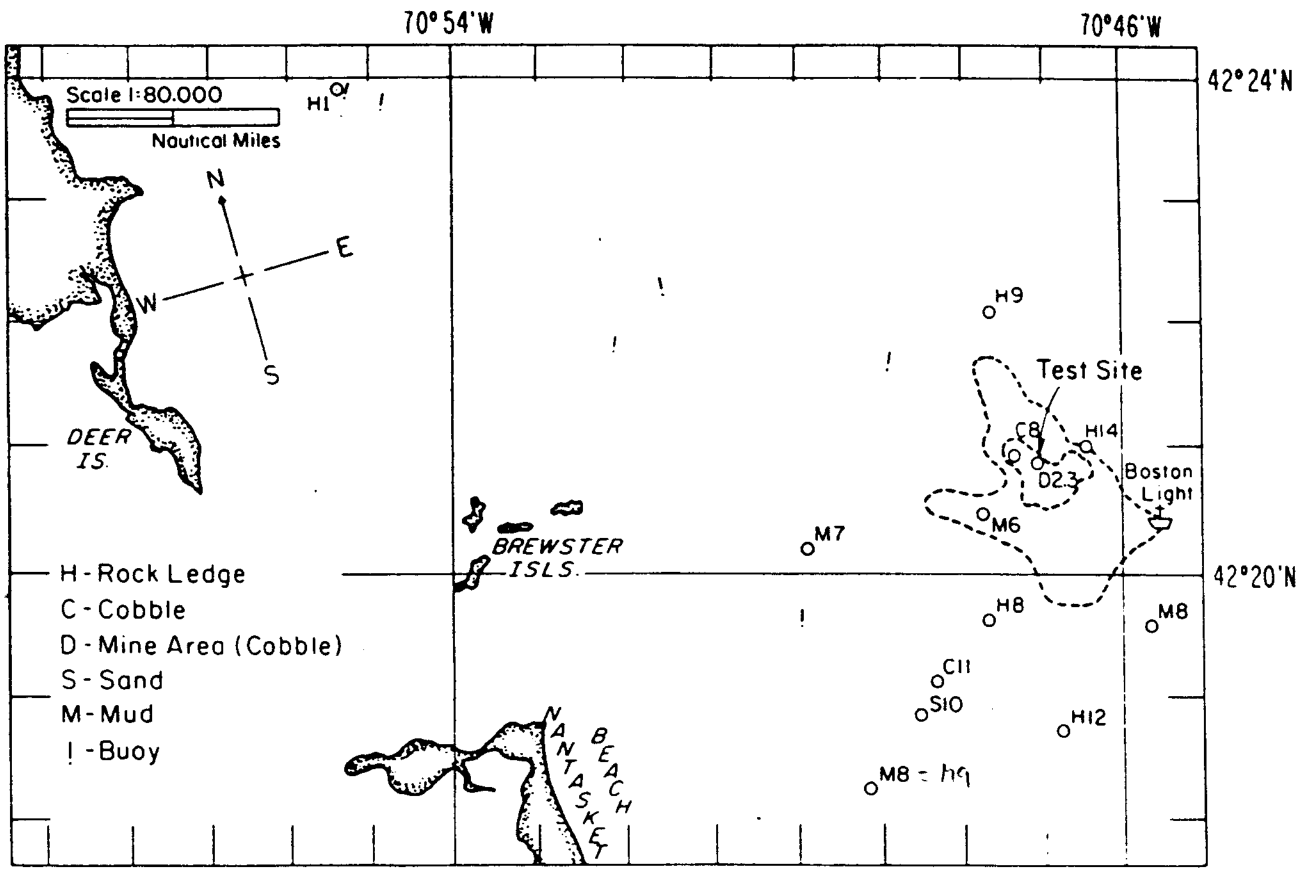


Figure 5. Stations selected for the benthic community study in Massachusetts Bay, identified by substrate type and number.

Table 3. *Characteristics of Permanent Benthic Sampling Stations*

Site	Distance and Direction from Dredge Site	Depth	Substrate	Silt Cover
Hard 1	7 miles NW	15m	large rock outcropping	clean
Hard 8	1.4 miles SSW	17m	cobble and large boulders	moderate silt
Hard 9	1.5 miles NNW	25m	cobble and large boulders	moderate silt
Hard 12	2.5 miles SE	18m	cobble and large boulders	moderate silt
Hard 14	0.5 miles NE	25m	cobble and large boulders	clean
Cobble 6	within dredge area	32m	gravel with large rocks	clean
Cobble 11	2.2 miles SSW	27m	gravel	heavy silt
Mud 6	0.5 miles SW	35m	mud	heavy silt
Mud 7	2.1 miles SW	28m	mud	heavy silt
Mud 8	1.8 miles SSE	40m	gravel with mud matrix	heavy silt
Mud 9	3.25 miles SSW	18m	muddy sand	heavy silt
Sand 10	2.5 miles SSW	23m	sand	moderate silt

Table 4. *Sediment Composition Analyses For The Soft-Substrate Stations in the Benthic Community Study*

Station	Core No.	January 1973 % Sand	January 1973 % Silt	January 1973 % Clay	April 1973 % Sand	April 1973 % Silt	April 1973 % Clay	June 1973 % Sand	June 1973 % Silt	June 1973 % Clay	Mean for All Months % Sand	Mean for All Months % Silt	Mean for All Months % Clay
M6	1				29.0	44.8	26.2	44.1	35.1	20.9			
	2				61.0	24.4	14.6	51.8	32.5	15.7			
	Mean				45.0	34.6	20.4	47.9	33.8	18.3	46.5	34.2	19.3
M7	1	80.1	15.6	4.3	79.5	14.8	5.6	68.5	23.6	7.9			
	2	82.1	14.0	3.9	82.4	11.5	6.1	82.8	11.4	5.8			
	3	77.5	17.1	5.4									
	4	78.7	16.0	5.3									
	Mean	79.6	15.7	4.7	81.0	13.2	5.9	75.6	17.5	6.8	78.7	15.5	5.8
M8	1	65.1	24.8	10.1	54.0	43.9	2.2	67.5	23.8	8.7			
	2	67.7	20.8	11.5	62.6	26.6	10.8	78.9	15.5	5.6			
	3	70.0	19.2	10.8									
	Mean	67.6	21.6	10.8	58.3	35.2	6.5	73.2	19.7	7.2	66.3	25.5	8.2
M9	1				95.4	2.6	2.0						
	2				94.6	3.2	2.2						
	Mean				95.0	2.9	2.1				95.0	2.9	2.1
S10	1				99.2	0.2	0.6	78.7	20.9	0.4			
	2							98.6	0.7	0.7			
	Mean				99.2	0.2	0.6	88.7	10.8	0.5	93.9	5.5	0.6

Table 5. Total Numbers of Species (Parts a. and b.) and of Densities (Part c.) of Benthic Invertebrates

a. Total number of invertebrate species collected on each cruise at each station.

Station	Cruise No.								Mean
	14	15	16	17	18	19	20	21	
H1	51	89	6	6					38.0
H8		87	87	105	146	106	138		111.5
H9		131		99	145				125.0
H12				60	92	64	112		82.0
H14		121	66	92		134	142		111.0
C6		37			81	76	66		65.0
D2			31						31.0
D3				113					113.0
C11				109	78	90	80		89.25
M6	62		67	61	52	79	81		67.0
M7			65	56	29	60	57		53.4
M8			81	73	56	70	68		69.6
M9			78	59		79	88	98	80.4
S10			90	42	58	67	76		66.6

b. Total number of motile species collected on each cruise at each station.

Station	Cruise No.								Mean
	14	15	16	17	18	19	20	21	
H1	31	65	6	6					27.0
H8		57	73	75	104	73	102		80.7
H9		85		77	109				90.3
H12				47	70	54	95		66.5
H14		75	58	67		97	120		83.4
C6		32			73	73	59		59.25
D2			31						31.0
D3				101					101.0
C11				101	75	83	74		83.25
M6	52		56	55	42	72	77		59.0
M7			57	52	26	57	50		48.4
M8			77	68	48	64	65		64.4
M9			71	56		72	82	83	72.8
S10			86	42	49	62	74		62.6

c. Total numbers/m^2 of motile species for each cruise for each station.

Station	Cruise No.								Mean
	14	15	16	17	18	19	20	21	
H1	4517.0	7182.1	528.0	1148.0					3343.8
H8		3616.2	10728.9	6295.9	13938.9	11146.2	8427.4		9025.6
H9		3080.8		7814.4	7611.4				6168.9
H12				3096.0	12236.8	4394.1	11513.0		7810.0
H14		2446.2	2816.0	3896.2		7374.6	5043.6		4315.3
C6		479.6			4465.0	3497.5	4112.9		3138.8
D2			1640.0						1640.0
D3				4120.0					4120.0
C11				5715.0	2427.5	11140.0	10859.5		7535.5
M6	2231.6		735.7	3262.3	1039.1	2030.9	5792.8		2515.4
M7			643.9	920.0	305.5	1254.6	762.0		777.2
M8			2977.0	2046.1	336.4	639.7	2139.6		1627.8
M9			2666.8	2426.4		3961.5	5410.4	7397.2	4372.5
S10			2261.1	1415.9	1123.8	1914.7	1690.4		1681.2

Table 6. Rankings of the Most Common Motile Benthic Species, Based on the Mean Number of Animals and Grouped by Sampling Station Substrate Type

Hard Substrate Stations:	H1	H8	H9	H12	H14
Number of Times Sampled:	3	6	3	4	5
Spirorbis spirillum	3	1	1	1	1
Spirorbis borealis		2	2	2	2
Caprella septentrionalis	1	3		4	4
Modiolus modiolus	2	4			
Ischyrocerus anguipes	9	5	5	8	9
Pontogeneia inermis	7	6		3	
Ophiopholis aculeata		7	6		6
Tonicella rubra		8	8	7	10
Achelia spinosa		9			
Cucumaria frondosus		10			
Jassa fulcata	4				
Caprella linearis	8				
Lacuna pallidula	6				
Nereis pelagica	5				
Lepidonotus squamatus	10				
Spirorbis violaceus			7		
Musculus niger			9		
Sympleustes glaber			3		8
Metopella angusta			4		
Strongylocentrotus droebachiensis			10	6	5
Pectinaria granulata				9	
Anomia simplex				10	7
Lacuna vincta				5	
Balanus balanoides					3

Cobble Substrate Stations:	C6	T2	T3	C11
Number of Times Sampled:	4	1	1	4
Euclymene collaris	1	1	1	2
Unicola irrorata	2		3	1
Exogone dispar	3	7	2	3
Glycera capitata	4	4	10*	
Strongylocentrotus droebachiensis	5		8	
Phyllodoce mucosa	6		7	8
Ischnochiton alba	7		10*	
Spio setosa	8	10		
Corophium crassicorne	9		4	
Euchone rubrocincta	10	9		7
Phyllodoce groenlandica		2		
Syllis armillis		3		
Tharyx acutus		5		5
Owenia fusiformis		6		6
Pholoe minuta		8		
Spirorbis spirillum			5	
Spirorbis borealis			6	
Moelleria costulata			9	
Notomastus luridus				4
Aricidea jeffreysii				9
Nephtys ciliata				10

	Mud			Sand	
Soft Substrate Stations:	M6	M7	M8	M9	S10
Number of Times Sampled:	6	5	5	5	5
Ninoe nigripes	1	1	2		
Maldane sarsi	2				
Spio setosa	3		1		
Sternaspis scutata	4				
Nucula delphinodonta	5		9		
Scoloplos fragilis	6	3	5	7	
Travisia carnea	7				
Edotea montosa	8	2	4		
Pholoe minuta	9	10	3	6	
Periploma papyratium	10				
Diastylis sculpta		4		8	10
Nephtys ciliata		5			6
Owenia fusiformis		6		1	
Modiolus modiolus		7		2	3
Photis reinhardi		8		4	
Nassarius trivittata		9			
Thracia myopsis			6		
Asarte undata			7		
Cerastoderma pinnulatum			8		
Paraonis gracilis			10		
				3	2

Table 7. Mean Ranking of Numerically Dominant Taxonomic Groups, Arranged According to Substrate Types

Taxonomic Group	Hard Substrate H1	H8*	H9	H12	H14
Polychaeta	2.5	1.0	1.0	1.0	1.0
Amphipoda	1.25	2.5	2.0	2.25	2.8
Bivalvia	2.0	3.7	2.0	3.75	2.8
Gastropoda	3.7	4.7	5.0	4.0	4.6
Asteroidea	4.0	5.0	6.0	6.75	9.2
Ophiuroidea	5.5	6.2	3.5		5.75
Polyplacophora	9.5	6.8	6.2	4.25	6.0
Holothuroidea	6.5	7.25	11.3	10.0	11.0
Pantopoda	7.0	7.8	8.3	9.5	9.5
Isopoda	8.0	8.0	10.5	10.25	10.5

	Cobble Substrate C6*	C11
Polychaeta	1.0	1.25
Amphipoda	2.0	1.75
Ophiuroidea	3.0	9.0
Echinoidea	3.75	7.5
Bivalvia	4.0	3.25
Polyplacophora	5.25	5.0
Gastropoda	5.5	4.0
Anthozoa	7.0	8.0
Brachyura	7.0	10.0
Sipunculida	7.0	

	Mud Substrate M6*	M7	M8	M9
Polychaeta	1.0	1.0	1.0	1.0
Bivalvia	2.0	2.8	2.4	3.0
Isopoda	3.2	2.8	2.8	5.0
Amphipoda	4.3	4.2	3.8	2.0
Gastropoda	4.8	5.8	5.8	6.2
Cumacea	5.2	4.4	5.4	4.6
Anthozoa	7.0	7.0	7.2	6.2
Brachyura	7.0	8.0	8.0	8.0
Asteroidea	7.0	8.0	7.3	8.0
Aplacophora	7.25		5.0	

	Sand Substrate S10*	M9
Polychaeta	1.2	1.0
Amphipoda	1.8	2.0
Bivalvia	3.0	3.0
Cumacea	5.2	4.6
Anthozoa	5.4	6.2
Gastropoda	5.6	6.2
Isopoda	6.8	5.0
Polyplacophora	7.0	
Echinoidea	7.4	7.25
Holothuroidea	7.5	9.3

Table 8. Mean Ranking of Feeding Types, Grouped According to Substrate Types

	Hard Substrate				
Feeding Types*	H1	H8	H9	H12	H14
Supension/Filter[1]	2.0	1.0	1.0	1.0	1.0
Scraper/Omnivore[2]		2.0	2.0	2.3	2.0
Suspension/Predato[3]	1.5	3.6	5.0	4.3	3.3
Predator/Epi/Micro[4]	3.0	4.0	4.0	4.3	4.8
Scraper/Herbivore		5.8	5.5	4.5	5.0
Predator/Epi/Macro[5]	2.5	5.8	6.0	6.5	8.0
Deposit/Indirect[6]		6.2	5.0	5.0	5.5
Parasite		7.8	7.5	8.8	9.8
Deposit/Direct[7]		8.8	8.5	10.3	9.2
Predator/In/General[8]		10.2	10.5	8.8	9.5
Predator/Epi/Scraper[9]	3.0	10.8	9.5	10.0	10.0
Predator/In/Mollusc[10]		12.0	12.0	11.8	10.0

	Cobble Substrate	
	C6	C11
Scraper/Omnivore	1.3	1.0
Deposit/Indirect	4.0	2.5
Deposit/Direct	1.6	3.0
Suspension/Filter	5.0	4.0
Predator/Epi/Micro	3.0	5.0
Predator/In/General	6.0	5.3
Scraper/Herbivore	7.0	7.5
Suspension/Predator	8.3	8.0
Predator/Epi/Macro	9.3	8.0
Parasite	11.0	9.3
Predator/In/Mollusc	9.3	10.0
Predator/Epi/Scraper	10.3	10.3

	Mud Substrate		
Feeding Types	M6	M7	M8
Deposit/Direct	1.6	6.0	5.4
Deposit/Indirect	1.8	3.2	1.8
Predator/In/General	2.6	1.0	3.0
Suspension/Filter	4.2	3.0	2.8
Scraper/Omnivore	5.0	2.8	3.6
Predator/Epi/Micro	5.6	5.4	4.6
Predator/In/Mollusc	6.6	7.6	9.2
Suspension/Predator	7.6	6.8	8.0
Predator/Epi/Macro	7.6	7.2	8.0
Scraper/Herbivore	7.8	7.6	7.2
Parasite	8.2	7.2	8.4
Predator/Epi/Scraper	8.2	7.6	9.0

	Sand Substrate	
	M9	S10
Deposit/Direct	6.3	1.2
Scraper/Omnivore	2.0	1.8
Suspension/Filter	3.0	4.0
Predator/In/General	4.8	4.0
Deposit/Indirect	1.0	4.2
Predator/Epi/Micro	4.3	5.8
Predator/In/Mollusc	6.8	7.0
Predator/Epi/Macro	8.3	8.4
Suspension/Predator	8.8	8.6
Scraper/Herbivore	8.8	8.8
Predator/Epi/Scraper	8.8	9.0
Parasite	8.5	9.2

* Key
1 filters suspended particles
2 bites or rasps attached plants and animals
3 captures suspended animals
4 predator on small motile epifauna
5 predator on large motile and sessile epifauna
6 sorts out small particles of sediment to ingest
7 ingests sediment as it burrows
8 nonspecialized predator on infauna
9 rasping predator on sessile epifauna
10 predator on infaunal molluscs

*Table 13. Species Characteristic of Specific Substrate Types, Ranked According to the Total Number of Individuals per Square Meter**

Substrate Type:		Hard						Cobble					Mud					
Station Number:		H1	H8	H9	H12	H14		C6	T2	T3	C11		M6	M7	M8	M9	S10	
Rank	Species						Total Animals					Total Animals						Total Animals
1	Spirorbis violaceus		+	+	+	+	622.8											
2	Lacuna pallidula	+	+	o		o	454.9											
3	Eualus fabricii	+	+	+		+	208.5											
4	Tonicella marmorea	o	+	+	+	+	174.9											
5	Maldanopsis elongata		+	+	+	+	144.8											
6	Idotea phosphorea	+	o				96.4											
7	Amphitrite cirrata		+	+	o	+	89.7											
8	Janira alta			+		o	54.0											
9	Polycera lessonii	+					56.1											
10	Proboloides holmesi		+	o			42.3											
11	Mitrella rosacea			+		+	36.8											
12	Nicolea venustula				+		25.6											
13	Potamilla reniformis		o	+		o	16.1											
14	Colus stimpsoni					+	14.7											
15	Aequipecten irradians		o			+	13.4											
16	Mitrella dissimilis			+			13.3											
1	Asterias rubens	+	+	+			338.7			o		2.5						
1	Lacuna vincta		+	+	+	+	1237.4						o		o			1.5
2	Anomia aculeata	o	+	+	+	+	394.3								o			2.5
3	Velutina laevigata	+	+	+	+	+	103.1								o		o	1.6
4	Nymphon grossipes	o	+	o	o	o	101.0						o					0.7
5	Acmaea testudinalis	+	+	o	+	+	83.4						o		o			5.0
6	Clymenella torquata		o	+		+	34.6										o	2.5
1	Tonicella rubra	+	+	+	+	+	2081.3				o	3.3	o					2.5
2	Alvania castanea	o	+	+	+	+	657.4	o			o	5.0	o					0.7
3	Dodecaceria concharum	+	+	+	+	+	355.4				o	2.5	o					0.7
4	Musculus discors		o	+		+	208.1	o			o	5.8		o	o			2.5
5	Cirratulus cirratus		+	+	+	+	105.2				o	3.3	o					0.7
6	Flabelligera affinis		+	+	o	+	65.5	o			o	5.0				o		0.8
7	Corophium bonelli		+	+		o	49.6				o	5.0					o	0.8
1	Lunatia immaculata							+			+	46.4						
2	Polycirrus eximius										+	12.5						
3	Odontosyllis fulgurans										+	10.5						
1	Syrrhoe crenulata			o			2.7	+		+	o	55.0						
2	Monoculodes tuberculatus		o				5.3	o		+	+	40.0						
3	Lumbrineris tenuis				o		3.2	o			+	37.5						
1	Scolelepides viridis										+	27.5					o	0.8
2	Lora pleurotumania										+	20.5	o		o	o	o	5.5
1	Erichthonius rubricornis					o	2.7	+		+	o	42.5					o	0.8
2	Phoxichildium femoratum		o				2.7	+			+	33.3			o			1.4
3	Anonyx sarsi		o				2.7	o			+	15.0					o	1.7
4	Lora turricula		o				2.7				+	10.0					+	2.7
1	Maldane sarsi												+	o	+	o		1844.5
2	Thracia myopsis												+	+	+	o		326.5
3	Chiridotea tuftsi												o	+			+	194.1
4	Tellina agilis													o		+	+	147.3
5	Cyathura polita												+		o			49.1
6	Anachis haliaecti												+	o				25.9
7	Hippomedon propinquus												+	o	o		o	20.8
8	Apistobranchus tullbergi												+	o	o			19.5
9	Eudorella trunculata													+	+			16.7
1	Sternaspis scutata	o					2.3						+	o	o		o	1238.6
2	Artica islandica		o				2.7						+	+	+	+	o	310.0
3	Axinopsis orbiculatus					o	5.3						+	+	+	+		165.8
4	Edotea triloba		o			o	5.4						+	+		o		35.7
5	Ptilanthura tenuis		o				5.3						+		+			31.2
6	Chaetoderma nitidulum				o		4.0						o		+			27.5
1	Spiophanes bombyx										o	3.3				+	+	314.9
2	Nephtys picta							o				5.0	o			+	+	90.9
3	Halcampa duodecimcirrata										o	2.5				+		40.8
4	Praxillura ornata										o	3.3			+			11.7
1	Lampros quadriplica					o	2.3				o	2.5		o		+	+	100.2

* Data from all cruises and all stations were used.
Note: + indicates 10 or more animals per station.
o indicates less than 10 animals per station.

The aquarium turbidity studies noted above were to have been conducted in a Massachusetts Bay aquarium complex as well. Other laboratory investigations were to have involved effects of the discharge plume on phytoplankton, benthic algae, zooplankton, and finfish.

3.4.2 Experimental Mining

The mining test had been scheduled for a 6-week period in late spring 1974. This period was selected to coincide with the sensitive "bloom" period of phytoplankton to learn whether or not mining would have any impact on this phenomenon.

The dredge selected for the field operation was the 27,000-metric-ton "Hydrobarge" *Ezra Sensibar* (fig. 4). The 155-m-long, 23-m-wide hopper-type barge is both self-loading and -unloading and has a capacity of 12,000 m^3. Mining is accomplished through suction provided by two 84-cm centrifugal dredge pumps amidships. Valving directs the incoming slurry (composed of about 10 m^3 of water for each cubic meter of aggregate) to individual hoppers. Suspended sediments are allowed to overflow the hoppers as each is filled with aggregate.

The bathymetry of the selected site is such that excavations were possible over the full range of deposit depths of 3 to 6.7 m--typically about 4.6 m. A total of three-quarters of a million cubic meters of material was to have been removed over the 6-week experimental period from a deposit distributed over approximately 25 hectares. The dredge was to have conducted three 2-hr operations every 2 days. About 14 hr may have been required between operations for transit, offloading, and return, depending on the distance to the discharge point.

Mining operations were to have been monitored to determine the change in bottom topography, the solids content, size distribution and volumetric overflow of suspended sediment, and the progress of the sediment concentration in the resulting plume of material discharged from the barge. The silt

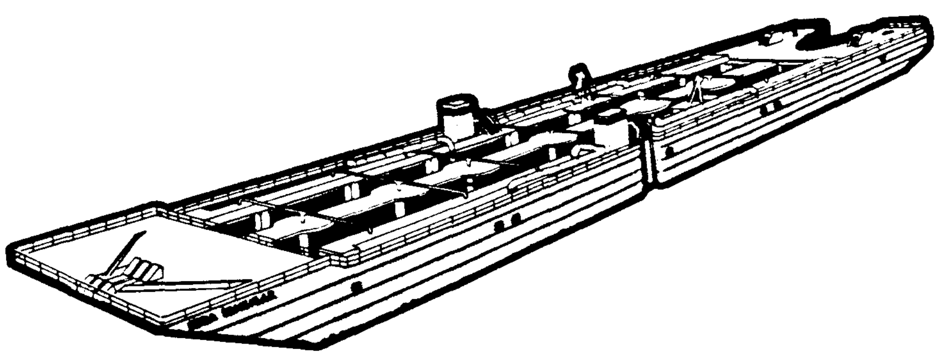


Figure 4. Hydrobarge Ezra Sensibar.

5) In none of the experiments did the 10-day LC50, LC20, or LC10 values bear any predictable mathematical relationship to one another. This illustrates the necessity for studying the tolerance of the most sensitive members of a population.

6) Tolerance to suspended bentonite seemed to be correlated with normal habitat of the organisms, but no phylogenetic correlations were apparent. No species living primarily in close association with mud bottoms was found to be sensitive. All sensitive test species were either invertebrates occurring predominantly on sandy bottoms or in fouling communities, or fish not intimately associated with the bottom.

7) The results indicate that the biological impact of high concentrations of suspended solids would be less severe in winter than in summer. The typically higher dissolved oxygen levels would increase the survival ability of all species studied. Low temperatures would increase the suspended-solids tolerance of the invertebrates, but slightly decrease that of the fish. However, this slight reduction would likely be offset by the increased tolerance at high dissolved oxygen levels.

8) The primary emphasis of this study was mortality of adult macrofauna. It cannot be overemphasized that low mortality of adults in 10 days does not imply the absence of ecologically significant effects. Reduced reproductive success, in terms of spawning adults, eggs, larvae, or juveniles, may be of greater ecological importance than the death of part of the existing population.

4.2 Geological Oceanography

This section discusses the characteristics of the seafloor in the test area, stratigraphy of the upper strata as revealed through subbottom profiling, and sediment properties based upon analyses of vibracores. A prime objective of Project NOMES was a consideration of the potential of test mining to release trace metals or other pollutants to the water column. Additional objectives included the delineation of the deposit in adequate detail to assure that it was commercial in character and that a prediction could be made as to the nature of the discharge plume at the point of discharge from the hydraulic dredge.

4.2.1 Bathymetry

The bathymetric measurements obtained during subbottom profiling, which are discussed later, revealed an irregular bottom topography with NNW.-trending ridges interspersed with circular and eliptical depressions (fig. 19). The area to be excavated during the planned test mining (shaded area in fig. 19) had a relief of 3.4 m and so was considered a realistic choice for operation of the hydraulic dredge.

The shape of the seafloor is characteristic of an area that has experienced glacial scouring and sediment deposition, as well as post-glacial stream channeling and subsequent modification of bottom contours by advancing post-glacial seas.

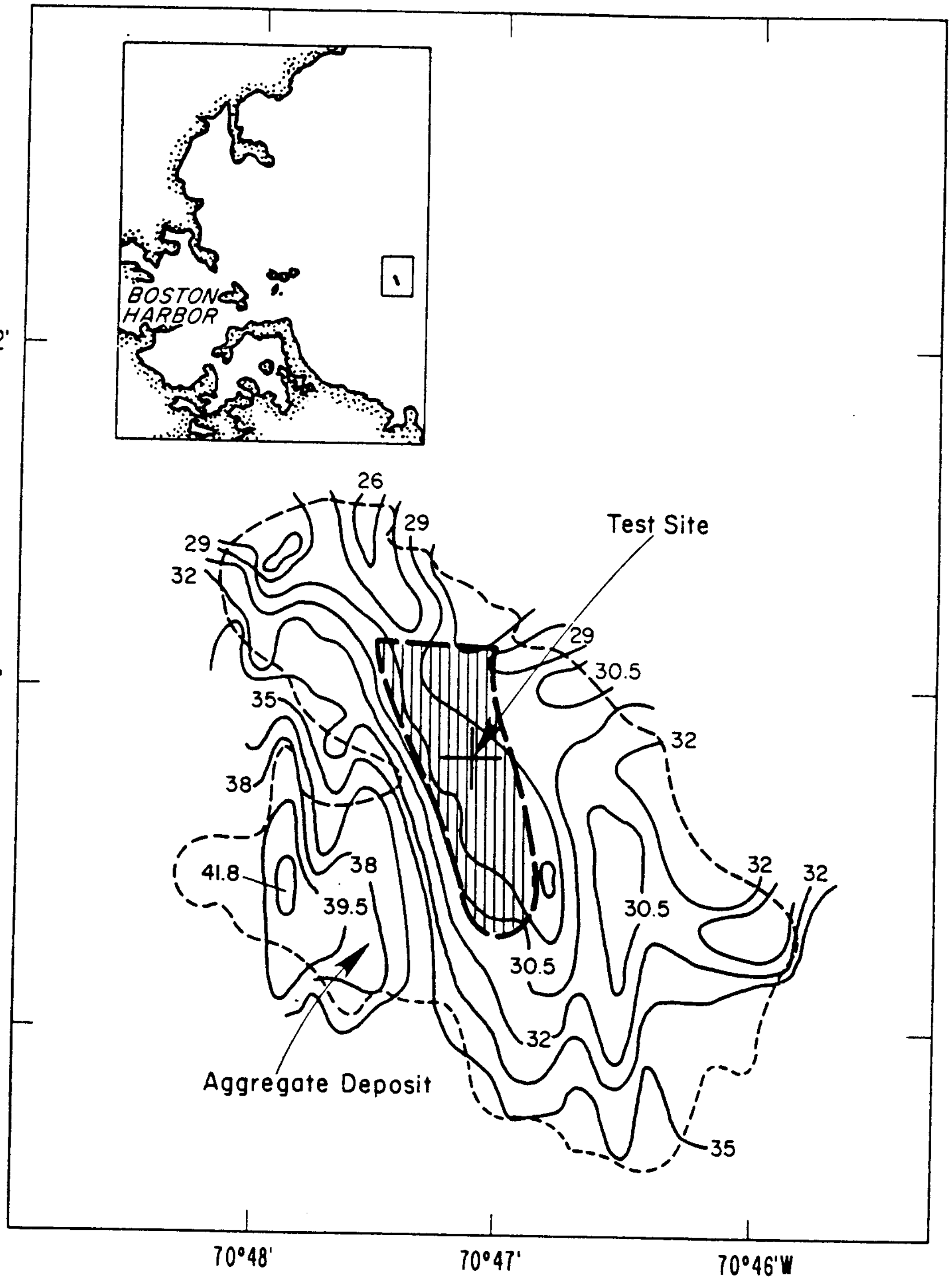


Figure 19. NOMES Project area and area of planned test mining. Contours in enlarged section show water depths in meters, referenced to high water.

4.2.2 Stratigraphy

A pre-NOMES survey conducted for the Massachusetts Division of Mineral Resources in early 1972 located the NOMES sand and gravel deposit through subbottom profiling, side-scan sonar, and two 12-m vibracores. In August 1972, 37 additional subbottom profiles were run, and 31 4-m vibracores were drilled in the vicinity of the deposit. Figures 20 and 21 show the locations of the core sites and subbottom profile tracklines.

For the purpose of identifying those areas within the NOMES deposit that offered characteristics with the best potential for test mining (i.e., thickness of aggregate, commercial quality of sediment, water depth at mean high water, and distance to glacial till outcroppings) three sediment distribution maps were prepared: surficial, subsurface (-1.5 m), and subsurface (-3 m). Core analysis data, reported below, augmented the geophysical records in the preparation of the maps.

The surficial sediment map (fig. 22) was produced from subbottom profiling records, core sample analyses, and information from television observations, as well as diver samples and observations. Classification of sediment types was based on the scheme shown in Table 21, which was modified from a system in use in the Gulf of Mexico (Louisiana Wild Life and Fisheries Commission, 1971). From figure 22 it can be seen that the seafloor in the test site area consists of a patchwork of mixtures of sand, gravel, mud, and glacial till.

Table 21. Sediment Classification

	% Gravel	% Sand	% Mud
Gravel	75 - 100	0 - 25	0 - 25
Sandy Gravel	33.5 - 75	12.5 - 50	0 - 33.5
Muddy Gravel	33.5 - 75	0 - 33.5	12.5 - 50
Sand	0 - 25	75 - 100	0 - 25
Gravelly sand	12.5 - 50	33.5 - 75	0 - 33.5
Muddy Sand	0 - 33.5	33.5 - 75	12.5 - 50
Mud	0 - 25	0 - 25	75 - 100
Gravelly Mud	12.5 - 50	0 - 33.5	33.5 - 75
Sandy Mud	0 - 33.5	12.5 - 50	33.5 - 75
Till	Mixture of boulders, cobbles, gravel, sand, mud		

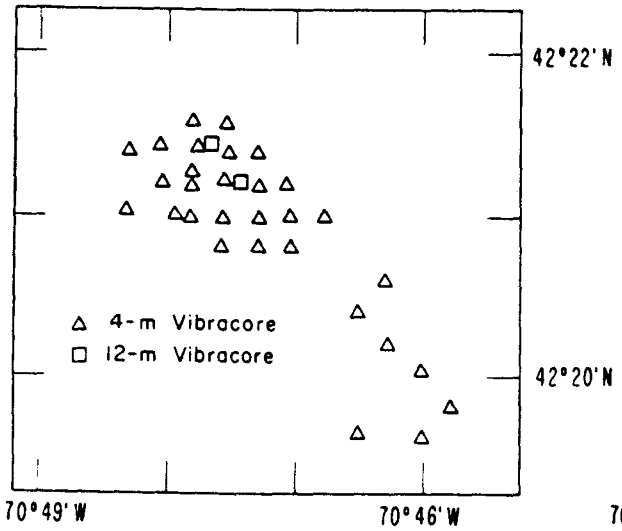


Figure 20. Locations of the vibracores taken in the NOMES site for NOAA (4-m) and for the Massachusetts Division of Mineral Resources (12-m).

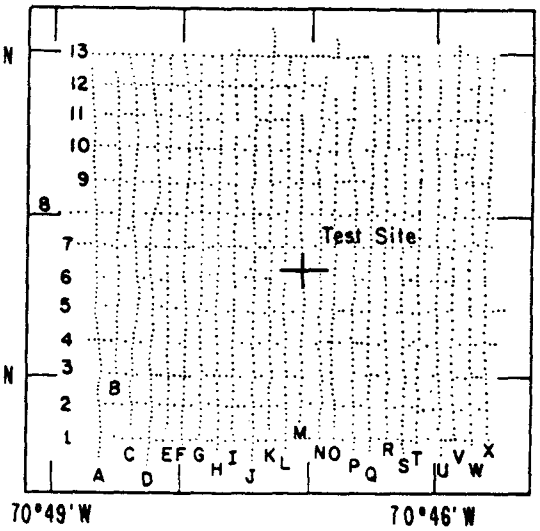


Figure 21. Ship tracks of the subbottom profiles.

The sediment distribution 1.5 m beneath the seafloor (fig. 23) is similar to that of the seafloor in that sandy gravel and gravelly sand are still distinct; also the muddy area remains in the northeast corner of the deposit. The overall size of the deposit is smaller, however.

The sediment distribution 3 m beneath the seafloor (fig. 24) shows a greatly diminshed area of sandy gravel. The extent of glacial till, which underlies most of the test site area, becomes more evident.

The subbottom profiling records, coupled with the core analyses, permitted an estimate of the thickness of the area to be mined (fig. 25). It appeared that the deposit contained over 5 million cubic meters of sand and gravel, considerably more than the three-quarter million planned for excavation during the mining test.

Although the main interest in the stratigraphy of the NOMES area was the upper few meters, the subbottom profiling records revealed several distinct formations: Carboniferous Cambridge argillite, undifferentiated Pleistocene glacial drift, two Pleistocene marine "clays," and Holocene sand and gravel (fig. 26). The section lines used to develop figure 26 are shown in figure 27.

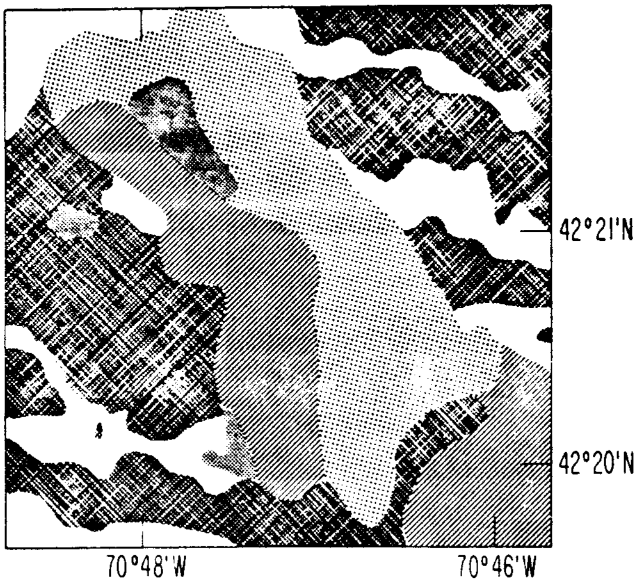


Figure 22. Surficial sediment distribution in NOMES Project area.

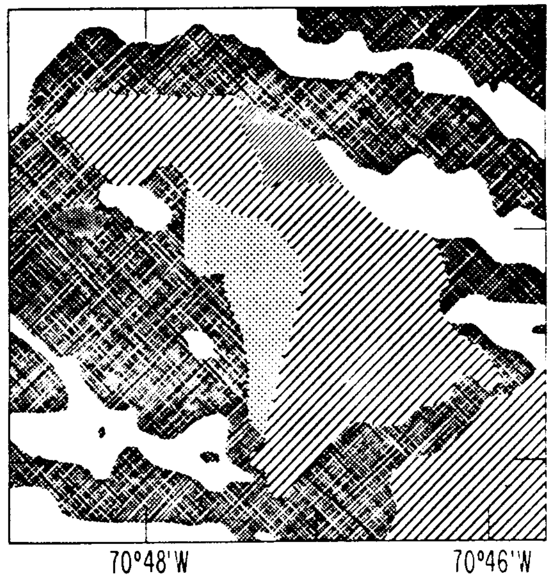


Figure 23. Subsurface (-1.5 m) sediment distribution in NOMES Project area.

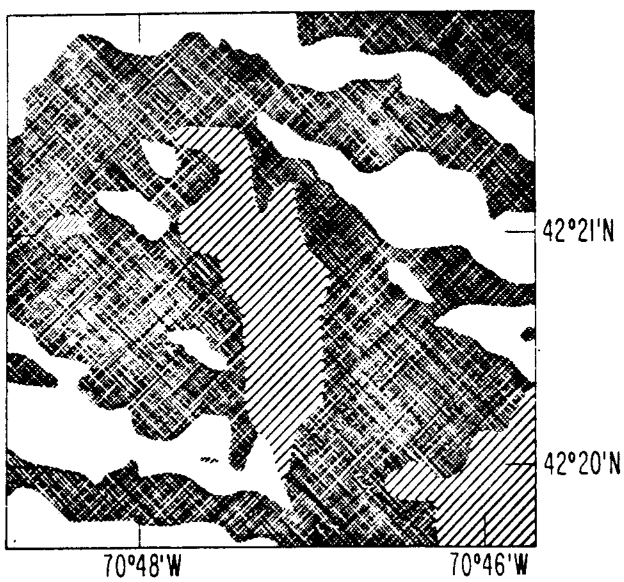
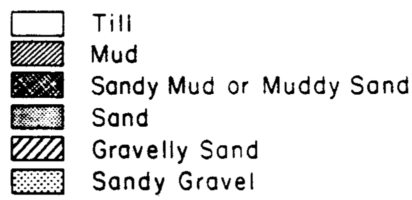


Figure 24. Subsurface (-3 m) sediment distribution in NOMES Project area.



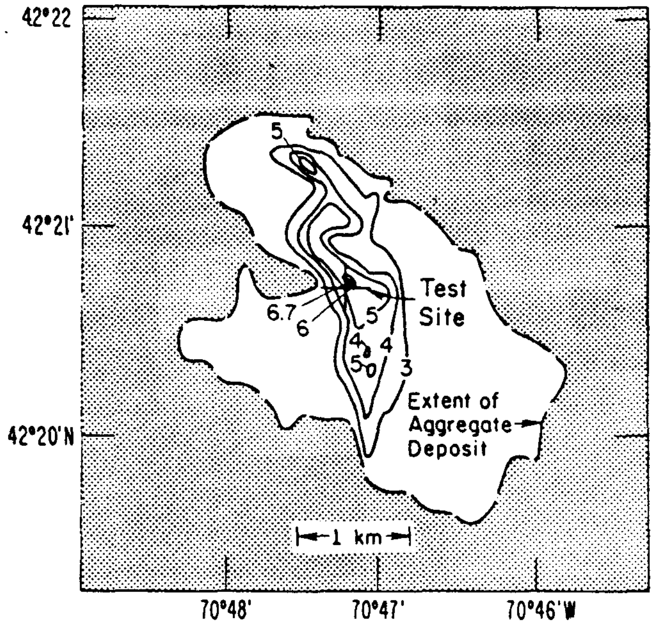


Figure 25. Aggregate isopach map of the experiment area (deposit contoured in meters).

The Cambridge argillite outcrops on several Boston Harbor Islands and is believed to underlie the NOMES area as bedrock. It is overlain by Pleistocene glacial till, a heterogeneous mixture of boulders, gravel, sand, silt, and clay ranging in thickness from a thin veneer to nearly 30 m. Two marine clays, separated by an erosional uncomformity, overlie the glacial till.

The "NOMES deposit" appears to be a gradational feature resting on, and yet geologically part of, the upper marine clay.

4.2.3 Core Analyses

Of the 31 cores acquired by vibratory coring (fig. 20), 10 were selected for detailed laboratory characterization. Mineralogy, chemistry, and trace metal properties were examined.

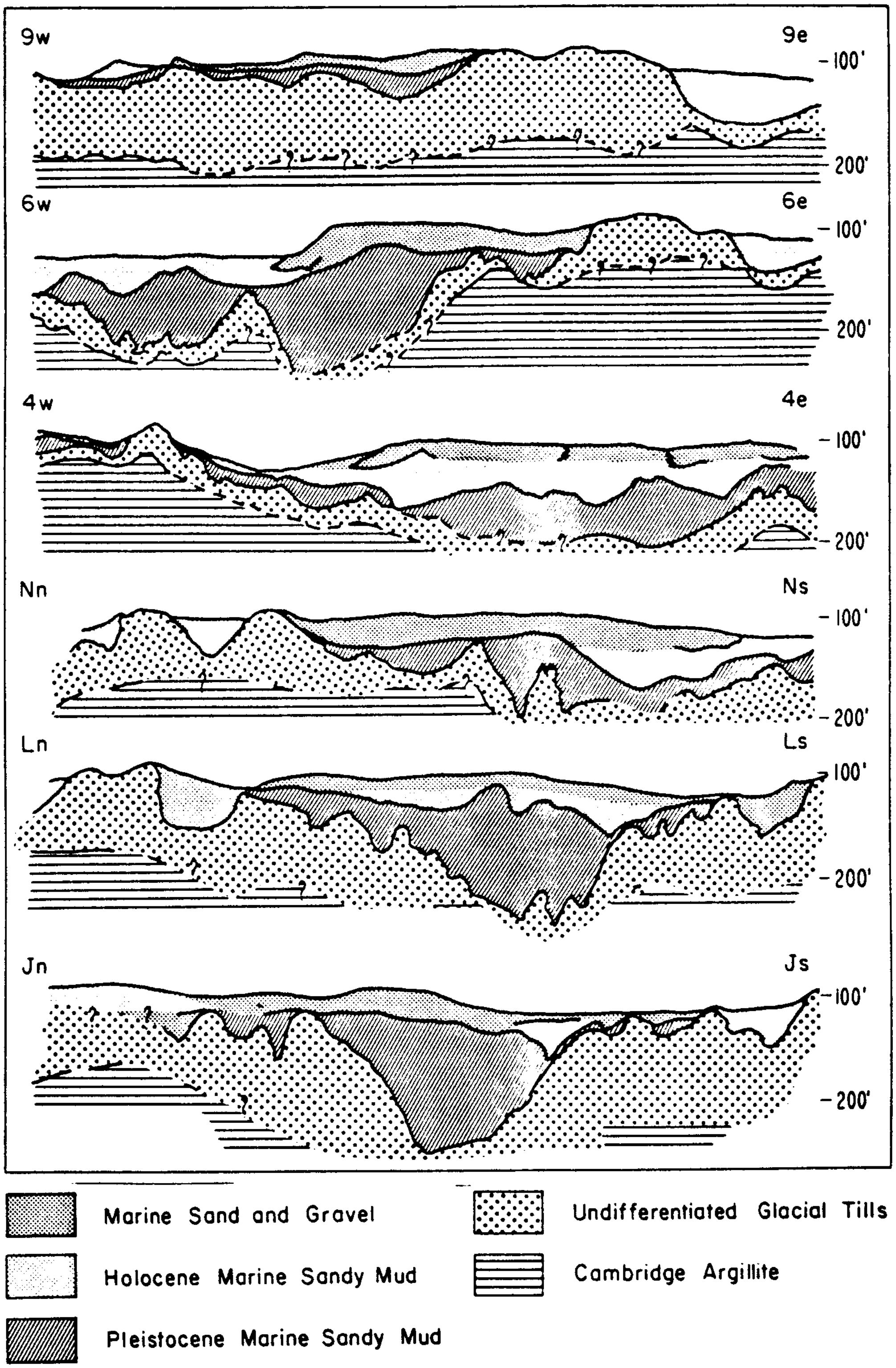
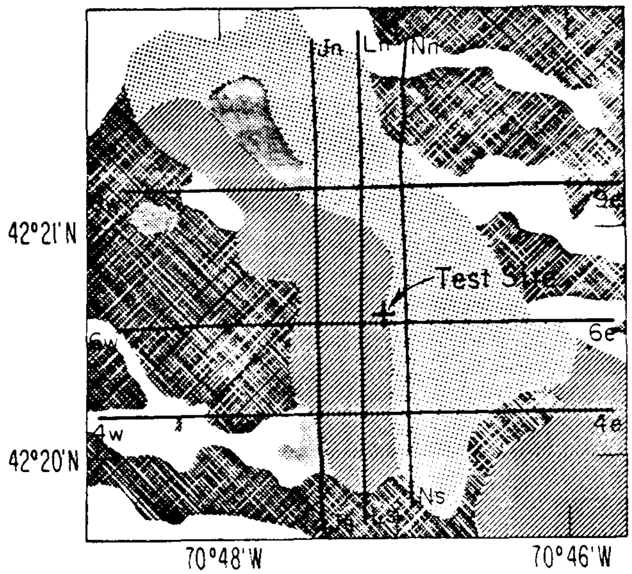


Figure 26. Selected geological cross sections through the NOMES site.

Figure 27. Locations of tracklines used as a basis for cross sections in Figure 26.



Mineralogy

The general appearance of the -10, +230 mesh material from several strata of all 10 cores was similar; therefore, only a single description is given. The particles were subrounded to subangular. The predominant minerals and their percentages were as follows:

Feldspar, 25-30%	(Primarily plagioclase and some orthoclase)
Quartz, 20-30%	(50% clear-to-milky, and 50% stained dull yellow)
Hornblende, 15-20%	
Mica, 5-10%	(Biotite and muscovite)

In addition, the minor minerals included some opaques, garnet, tourmaline, and possibly olivine. There were a few rock fragments that appeared to be granitic grains. The organics included about 5% shell fragments plus *Foraminifera* tests.

The predominant -230 mesh mineral was quartz.

Sedimentological characteristics are not included in this report but generally reveal what we would expect from a heterogeneous glacial deposit: very poorly sorted sediments.

Table 22. Chemical Analyses of Core Strata[a]

Stratum Number	Depth (Inches)	Color	Description	-230 Mesh (%)	COD[b] (g/kg)	Organic Carbon[c] (%)	CEC[d] (meq/100g)	Sulfide[e] (mg/kg)	Phosphorus[f] (mg/kg)	Oil &[g] Grease (mg/kg)
				Core 7-I-1						
7-I-2-1-1	0-20	2.5YN/4	Sand-fine to medium coarse. Gravel-to 1.5 inches. Shell Fragments-very coarse.	3.54	30.8	1.15	61.4	<0.05	1.2	<50
7-I-2-2-1	20-37	2.5YN/4	Fine sand-no gravel.				62.0			
7-I-2-2-2	37-44	2.5YN/4	Fine sand & ∿15% 0.75" gravel.				32.0			
7-I-2-3-1	44-54	2.5YN/4	Coarse sand & ∿15% clay.				24.9			
7-I-2-3-2	54-70	2.5YN/4	Fine gravel & ∿10% clay. Becoming gravelly to 0.5".				27.4			
7-I-2-4-1	70-80	5Y5/2	Clay layer with intermittent, discontinuous sand lenses.				15.4			
7-I-2-4-2	80-85	5Y5/2	Medium fine sand.				20.5			
7-I-2-4-3	85-102	5Y5/2	Clay layer with intermittent, discontinuous sand lenses.		8.6	0.32	11.0			
7-I-2-5-1	102-132	5Y5/2	Clay layer with intermittent, discontinuous sand lenses.				11.3			
				Core 7-K-1[a]						
7-K-1-1-1	0-14	5Y4/2	Fine sand.	4.40	30.7	1.15	43.1	0.19	--	--
7-K-1-1-2	14-56	5Y4/2	Coarse sand and gravel to 2". Gravel becoming very coarse to 3". (Excellent fill material.)				26.0			
				Core 7-M-1[a]						
7-M-1-1-1	0-9	5Y5/2	Fine sand with few shells. Becoming coarse sand.	3.81	26.2	0.98	49.9	<0.05	1.9	<50
7-M-1-1-2	9-13	5Y5/2	Coarse sand and gravel to 0.75"; well graded.				41.4			
7-M-1-1-3	13-29	5Y5/2 ↓ 2.5YN/4	Coarse gravel to 2.5"; very well graded. Small amount of clay.				25.2			
				Core 8-I-1[a]						
8-I-1-1-1	0-12	5Y5/1	Fine sand and shell fragments.	4.50	36.3	1.36	53.6	0.86	3.4	<50
8-I-1-1-2	12-30	5Y5/1	Sand and gravel to 2". Well graded; sand becoming coarse.				61.2			
8-I-1-2-1	30-39	5Y5/2	Sand and gravel to 1.5". Well graded. Some shell fragments.				57.1			
8-I-1-2-2	39-50	2.5Y5/2	Fine sand and shell fragments.		33.9	1.27	68.5			
8-I-1-2-3	50-60	2.5Y5/2	Becoming gravel to 2". Shell fragments to 0.5".				56.3			

Table 22. (Continued)

Stratum Number	Depth (Inches)	Color	Description	-230 Mesh (%)	COD[b] (g/kg)	Organic[c] Carbon (%)	CEC[d] (meq/100g)	Sulfide[e] (mg/kg)	Phosphorus[f] (mg/kg)	Oil &[g] Grease (mg/kg)
				Core 8-K-1[a]						
8-K-1-1-1	0-11	5Y5/2	Well graded sand and gravel to 2".	4.12	44.7	1.68	50.4	0.15	2.4	--
8-K-1-1-2	11-22	5Y4/1	Gravel as above but sand becoming finer.				32.5			
8-K-1-2-1	22-41	2.5YN/4	Medium coarse sand and gravel to 2". Fine sand layers of 2-3" with small shell fragments and slight color change from light to dark gray.				27.5			
				Core 8-M-2[a]						
8-M-2-1-1	0-18	5Y4/2	Sand and gravel to 1.5", well graded.	0.94	55.3	2.07	61.3	0.36	2.0	<50
8-M-2-1-2	18-40	2.5Y4/2	Sand with 10-15% gravel and large shell fragments.				34.0			
8-M-2-2-1	40-74	2.5Y4/2	Very coarse sand-no gravel-large shell fragments.				65.0			
8-M-2-3-1	74-84	2.5Y4/2	Considerable clay and silt		37.2	1.40	17.0	1.8		
8-M-2-4-1	84-110	2.5Y4/2	Silty clay.		29.9	1.12	15.8	0.84		
				Core 8-O-1[a]						
8-O-1-1-1	0-28	5Y6/2	Excellent sand and gravel to 2.5" Well graded.	2.30	14.7	0.55	35.0	0.48	0.90	<50
				Core 9-I-1[a]						
9-I-1-1-1	2-38	5Y5/1	Fine sand and ~25% gravel to 1.5". Heavy shell fragments.	5.00	33.6	1.26	57.7	0.34	14.	<10
9-I-1-3-1	38-45	2.5YN/5	Silty clay and fine sand.				28.6			
				Core 10-G-1[a]						
10-G-1-1-1	0-10	5Y5/1	Old beach sand.	2.32	17.1	0.64	30.3	1.4	2.5	--
10-G-1-1-2	10-18	5Y5/1	Coarse sand and gravel to 1.5". Well graded.				30.0			
				Core 11-E-1[a]						
11-E-1-1-1	0-23	2.5YN/4	Clayey sand and ~20% gravel to 1.5" with shell fragments. Changing to less gravel.	14.7	17.5	0.66	54.0	0.37	1.5	<5
11-E-1-2-1	23-83	2.5YN/5	Very stiff silty clay with occasional fine sand lenses.				11.8			

(a) All results based on oven dry weight (103°-105°C)
(b) Chemical Oxygen Demand of -230 mesh material.
(c) Calculated from COD results.
(d) Cation Exchange Capacity of -230 mesh material. These results are high in some cases. See text.
(e) Based on "grab" samples taken prior to screening.
(f) Total phosphorus after destruction of organic matter--based on -230 mesh material.
(g) Freon extractable from -230 mesh material.

ideal dredge material is considered to be 40% sand and 60% gravel. Impurities normally consist of clay, silt, fine sand, and shells. Their significance will be discussed below, but generally 5% impurities is considered a maximum for a deposit to be mineable.

Both question (1) and question (2) are answered by probing the deposit with a large-diameter (about 77 cm.) drill sampling tool. This provides a bulk sample which, although not undisturbed, is adequate for deposit evaluation. Sometimes bulk sampling is done by the actual mining of small quantities of sediment. In either case, the amount of material removed from the deposit is limited to a small amount under terms of the UK prospecting license.

There is no indication of any adverse environmental impact associated with the steps in the exploration phase: bathymetry, acoustic sub-bottom profiling, drill sampling, and bulk sampling by mining vessel. However, the final two steps, because thay are conducted by vessels at anchor, could pose a navigation hazard. In addition, the final step could provide a miniature version of the impact associated with the mining phase.

Excavation

Sand and gravel are economically mined from the seafloor in several ways: clam-shell barge, bucket-ladder dredge, and suction dredge. The clam shell technique is gradually phasing out as uneconomic in Europe, where deposits are mined far from shore by large ocean-going hopper dredges, but it supplies over one-half of Japan's production, where numerous small dredges mine fairly close to shore. The bucket ladder dredge is best suited for digging hard bottom formations. The hardware (not to mention the great capital investment) required is not needed for most sand and gravel deposits. In addition, the dredge is relatively unstable for ocean operations in most parts of the world.

The bulk of the 80-vessel UK marine mining fleet consists of suction hopper dredges. Cargo capacities range from about 500 to about 10,000 tons. The trend is toward larger and larger dredges to reduce the cost per unit of material dredged.

Recovery of sand and gravel is done by use of one or more high-head centrifugal pumps dredging a slurry of solids from the seafloor (up to about 30 meters beneath the ocean surface) through a suction pipe. The slurry, about 10% solids, is fed to the hopper(s) where most of the solids remain. The excess water flows overboard, along with fine particles trapped in suspension.

Some dredges recover from a single point while at anchor. This results in the creation of a pit 10 or more feet deep initially, and finally, a pockmarked deposit (fig. 3, p. 7). Some dredges recover while drifting with the changing tidal current, while at anchor. This results in the creation of a crescent-shaped trench about one meter deep. Eventually, the deposit becomes laced with overlapping crescent-shaped trenches. Other dredges recover while drifting unanchored.* This results in numerous shallow trenches, each about 30 cm. in depth (fig. 3).

Most UK mining operations are governed by the tides, operating on a 24-hour cycle whereby the dredges take advantage of high tides for leaving and returning to normally shallow-water cargo discharge points in estuaries or rivers. Generally, a dredge leaves port at the start of ebb tide, steams to its lease area, fills its hopper in a matter of 1 to 3 hours, returns on the flood tide, discharges in 1 to 2 hours, and leaves for sea--all within 24 hours. If the draft of the dredge is not a critical factor, and the lease area is not too far away--130 km. is not uncommon--the cycle may then occupy less than 24 hours.

The majority of deposits worked in the UK are relatively near shore (within 30 km.), comparatively close to market, generally in 20 to 30 meters of water, and from 1 to 10 meters thick.

The mining operation can impact the environment in a variety of ways as described in this report. The main UK fears concern damage to the coastline and to marine life. Interference with navigation and communications is minimized by not permitting mining within 0.8 km. of shipping lanes, submarine cables, pipelines, and marker buoys.

Coastal erosion can be caused in four ways: (1) slumping of the beach profile; (2) changing wave refraction patterns; (3) reduced protection from big waves by the removal of offshore banks; and (4) the removal of material normally part of the onshore-offshore sediment transport budget. The UK has sufficient experience to be able to avoid coastal problems from marine mining.

The main enigma concerns the effect on marine organisms of the turbidity plume and resultant blanket of fines. However, the industry has gone on for so long (since 1926) that there is no way to gain a "before" characterization of marine communities. Therefore, the main focus has been on insuring that mining does not occur on known spawning grounds, such as the clean gravel substrate where herring spawn (International Council for Exploration of the Sea, 1975).

Shipboard Treatment

Most dredges utilize a coarse-grid steel framework across the opening of the suction head. This prevents large rocks from entering the suction pipe. In addition, the coarser sizes are screened off and rejected after passing through the pump. At the other end of the particle size distribution

* It has been predicted that the cutterhead pipeline dredge may find application in the United States, in those cases where mining is done within a few kilometers from shore (National Research Council, 1975). This would in effect transport the discharge plume to shore.

spectrum, fine material is washed overboard, as described in this report. All sizes in-between are retained in the hopper if the market demand coincides with the composition of the deposit. Usually this is not the case and so newer dredges are equipped with vibrating screens whereby all or part of the material--usually the sand fraction--is dumped back into the ocean. On the average, the ratio of sand to gravel mined in the UK is about 70:30. An average market mix requires about 40:60, so gravel dredges frequently dump overboard 2 to 3 tons of sand for every ton of gravel recovered.

Specialized large-capacity dredges of advanced design are being developed in increasing numbers. Such dredges are equipped with highly automated shipboard treatment plants capable of producing a wide range of washed and sized aggregate products at sea and then transporting the cargo to distant ports and unloading a desired sized product or special mix with an automated self-discharging system.

There is no knowledge of the impact of shipboard treatment. But inasmuch as no chemicals are utilized, there are probably but two effects: (1) the dumping of large volumes of sand onto the lease area with a gravel/sand substrate; and, (2) the washing overboard of a greater percentage of fines. The former would alter the bottom habitat but not cause a turbidity plume. The latter would add to the initial turbidity plume problem, but eliminate the washing problem at shoreside.

Transportation to Shore

During transit from dredge site to discharge port, the aggregate settles in the hopper(s) and water is drawn off and pumped overboard. The amount of water lost by this means can be about 10% by weight of the total load. Some very fine particles, in suspension because of the motion of the dredge, are lost overboard in this process.

Shoreside Processing

Shore-based support facilities for the dredges include wharves, stockpiling and processing facilities, and treatment plants. The exact arrangement depends upon the nature of the unloading technique, the processing required to produce marketable aggregate, and the treatment required to clean up waste water.

Some dredges pump ashore with either shore-based pumps or shipboard pumps. In either case the hopper full of sand and gravel is reflooded with river water, and the resultant slurry drawn through a duct in the bottom of the hopper and then into a discharge pipe. From there it is pumped into a large settling tank or pond. The overflow water passes through several stages of settling tanks before it is clean enough to return to the river (or estuary).

Dry discharging is accomplished by clam-shell grabs, elevators and belt conveyors, or scraper-buckets. Self-discharging by scraper buckets, coupled with over-the-side conveyor belts, has been well received in the UK as the most efficient and economical system available. With this system, scraper buckets are rapidly hauled up ramps at the forward part of the hopper and then emptied into an elevated hopper which feeds an over-the-side conveyor belt that carries the material ashore.

Shoreside sand and gravel treatment plants are located near dockside cargo-discharge points, where the material is washed and screened into appropriate sizes which then commonly are blended in specified proportions for local markets.

Excessively large stones are crushed for sale as crushed stone. The remaining sand and gravel is washed (just as it is in inland operations), as it is screened into desired sizes, in order to remove excessive fine material which interferes with the cement-aggregate bond in concrete.

Most UK plants utilize recirculated water for washing, although some use water pumped from a river or estuary. If the water is to be discharged into the environment, and not recycled, large settling tanks are used for cleaning up the water.

Standards have been developed in the UK for salt and shells--two obvious impurities in sea-won aggregate. The sole concern with shell, based on tests by the British Standards Institution, the Greater London Council, and others, involves excessive amounts of hollow shell that reduce concrete strength.

Although salt is thought to accelerate the rate of curing--at the expense of strength--the salt water content of sea-won aggregate is not considered to be a problem. The washing required to remove the fines also removes enough salt that no extra washing is required.

Present UK specifications for sea-dredged aggregates are based largely on standards developed by the Greater London Council, as summarized below:

1) The sodium chloride content of the fine and coarse aggregate must not exceed 0.10% and 0.03%, respectively, by weight of dry aggregate.

2) The total sodium chloride content derived from the aggregates can exceed the above amounts as long as it is not greater than 0.32% by weight of the cement in the mix.

3) Shells that are hollow or of unsuitable shape, in quantities sufficient to adversely affect the permeability or other qualities of the concrete, shall not be permitted.

4) The shell content of the aggregate shall not exceed the following allowable dry-weight percentages of shell: 2% in the $1^1/_2$-inch fraction, 5% in the $^3/_4$-inch fraction, 15% in the $^3/_8$-inch fraction, and 30% in the sand (minus $^3/_{16}$-inch) fraction.

The above specifications, which were said to be subject to amendment at the time of their release (1968), have generally prevailed throughout the industry. However, thay have become somewhat more definitive with respect to shell, and less rigid in the case of sodium chloride content. By late 1970, limits set forth by such bodies as the Greater London Council for the new London Bridge contract have been generally accepted by industry in the London area as well as in most other dredging areas in the UK. These standards are as follows:

Fraction	Maximum % by Weight	
	Shell	Sodium Chloride
$1^1/_2$-inch straight	2	0.1
$^3/_4$-inch straight	5	0.1
$^3/_4$-inch graded	10	0.1
$^3/_8$-inch sand	15	0.1
$^3/_{16}$-inch sand	30	0.2

Transportation to Market

Truck transport has been used in the UK to connect the shoreside processing facilities with urban market outlets. In addition, ready-mixed-concrete plants are now being located alongside sea dredging discharge points.

A recent trend has been the establishment of secondary distribution centers in inland metropolitan areas. These secondary centers are supplied by rail from the primary dredge discharge points, using special rail aggregate-container cars.

Appendix 6

Excerpts from: Jewett, S.C., L.A. Gardner, P.C. Garvin, and C.E. Sweeney. 1991. Nome Offshore Placer Project (Western Gold Exploration and Mining Company, Limited Partnership. Nome, Alaska) ENSR Consulting & Engineering. Doc. Num. 7235-010.

Summary of:

Jewett, S.C., L.A. Gardner, P.C. Garvin, and C.E. Sweeney. 1991. Nome offshore placer project. (Western Gold Exploration and Mining Company, Limited Partnership. Nome, Alaska). ENSR Consulting & Engineering. Document Number 7235-010.

Location: Bering Sea, Norton Sound off Nome, Alaska.
Collection period: September 1985 - June 1990.

Table 1. General Site Characteristics and Changes:

Gravel percentages (>2 mm) present at Cobble and Sand sites

	Stations	Cobble	Sand
Post-Dredging	R6	42.07-97.04	0.12-13.04
Dredge Impact	R7	50.94-86.11	0.02-24.07
Pre-Dredging	D8	34.2	-
Controls	C2	29.22-92.81	0-18.60
	C3	51.93-61.15	0.03-27.60
	S2	42.39-98.36	0.41-23.75
	S3	53.37-61.82	0.42-9.50

Table 2. Biological Characteristics:

Cobble data 1990

	R6 (mined 1986)	R7(mined 1987-1990)	S3	C3
Total # of Taxa	63	38	84	83
Average density (= indiv/m^2)	746	408	1497	3997
Average Biomass (g/m^2)	104.2*	0.6	27.2	32.5

* High biomass due to presence of sea urchin *Strongylocentrotus droebachiensis*.

(Table 2 cont.) Sand data 1990 (dredging initiated at R6 in 1986, and at R7 in 1987)

	R6	R7	S3	C3
Total # of Taxa	67	30	81	67
Average density (# indiv/m^2)	1975	328	7113	1768
Average Biomass (g/m^2)	20.4	1.0	13.8	21.9

Station R7 cobble
(dredging initiated nearby in 1987)

	Gravel %	Number of organisms/m^2	Number of species	Biomass/m^2
1987 (Dredging occurring)	50.94	60.2	57	17.3
1988	79.86	363	34	0.6
1990	86.11	403	38	0.6

Station S3 cobble/C3

	Gravel %	Number of organisms/m^2	Number of species	Biomass/m^2
1986	55.28	3243	79	106.8
1987	56.45	2703	76	21.1
1988	53.37/ 51.93	2462/ 1007	75/ 64	17.0/ 26.5
1989	57.07	1317	70	1.6
1990	61.82/ 61.13	1497/ 3997	84/ 83	27.2/ 32.5

Station R6 cobble

	Gravel %	Number of organisms/m^2	Number of species	Biomass/m^2
1988	75.17	578	32	0.7
1989	42.07	997	49	4.4
1990	97.04	746	63	104.2

(Table 2 cont.) Station R6 sand

	Sand %	Number of organisms/ m^2	Number of species	Biomass/m^2
1987	93.94	160	21	0.8
1988	86.37	1253	53	7.2
1989	99.47	1117	48	13.6
1990	98.38	1975	67	20.4

Station C3 sand

1987	97.61	1595	66	35.3
1988	72.09	845	56	10.4
1989	98.60	1050	63	19.6
1990	97.18	17.68	67	21.9

Table 3. Year and depth of dredging

STATION	DEPTH (m)	YEAR DREDGED
R6	10.7 to 12.2	1986
R7	10.7 to 12.2	1987 through 1990*
D8	18.3	1988
C2	7.0 to 7.6	control Station not dredged
C3	10.7 to 12.2	control Station not dredged
S2	7.0 to 7.6	Subsistence Station not dredged
S3	10.7 to 12.2	Subsistence Station not dredged

* Station R7 was dredged in 1988 and was located in the area affected by dredging in 1987, 1989 and 1990

Table 4. Most abundant species (numbers/m^2) at cobble stations

Station	June 1986		June 1987		June 1988		June 1989		June 1990	
C-2 - Cobble	Cerebratulus spp. (N)	68	Ischyrocerus spp. (CA)	632	D. craterodmeta (EO)	87	Mytilus edulis (MB)	425	H. arctica (MB)	200
7.0 - 7.6 m	Diamphioda craterodmeta (EO)	45	Travisia pupa (P)	45	Pholoe minuta (P)	78	Autolytus sp. (P)	220	Myriochele oculata (P)	102
	Clinocardium californiense (MB)	42	Hiatella arctica (MB)	23	Cerebratulus spp. (N)	67	Ischyrocerus spp. (CA)	63	C. californiense (MB)	67
	Strongylocentrotus		Glycinde spp. (P)	22	Autolytus sp (P)	63	Lamprops quadriplicata (CC)	50	Glycinde spp. (P)	35
	droebachiensis (EE)	37	Bathymedon spp. (CA)	22	Glycinde spp. (P)	60	Cerebratulus spp. (N)	42	Cerebratulus spp. (N)	22
	Glycinde spp. (P)	28								
S2-Cobble	Cerebratulus spp. (N)	102	T. alternata (P)	140	D. craterodmeta (EO)	168	Onchidoris muricata (MG)	105	M. occulata (P)	182
7.0 - 7.6 m	Spirorbis spp. (P)	50	Spirorbis spp. (P)	138	Cerebratulus spp. (N)	118	Glycinde spp. (P)	92	C. californiense (MB)	70
	Typosyllis alternata (P)	47	H. arctica (MB)	72	P. minuta (P)	82	Tellina lutea (MB)	80	Glycinde spp. (P)	68
	C. californiense (MB)	45	Cerebratulus spp. (N)	53	C. californiense (MB)	47	P. minuta (P)	60	Magelona sacculata (P)	62
	Spirorbis abnormis (P)	30	S. abnormis (P)	52	Autolytus prismaticus (P)	32	D. craterodmeta (EO)	47	T. lutea (MB)	47
C3 - Cobble					D. craterodmeta (EO)	213			M. oculata (P)	2285
10.7 - 12.2 m					M. oculata (P)	115			D. craterodmeta (EO)	297
					C. Californiense (MB)	77			Glycinde spp. (P)	163
					Tharyx secundus (P)	67			Cerebratulus spp. (N)	145
					Yoldia spp. (MB)	67			C. californiense (MB)	95
S3 - Cobble	D. craterodmeta (EO)	317	D. craterodmeta (EO)	317	D. craterodmeta (EO)	253	Polydora sp. (P)	412	D. craterodmeta (EO)	353
10.7 - 12.2 m	T. alternata (P)	277	T. alternata (P)	277	P. minuta (P)	225	M. oculata (P)	145	M. oculata (P)	287
	Ampharete acutifrons (P)	213	A. acutifrons (P)	213	Cerebratulus spp. (N)	207	Cerebratulus spp. (N)	68	Glycinde spp. (P)	147
	P. minuta (P)	197	P. minuta (P)	197	A. acutifrons (P)	197	Echiurus echiurus alaskanus (EO)	40	Cerebratulus spp. (N)	65
	M. oculata (P)	163	M. oculata (P)	163	T. secundus (P)	167	P. minuta (P)	35	C. californiense (MB)	48
							Diastyllis alaskensis (CC)	35		
R6 - Cobble					D. craterodmeta (EO)	110	Autolytus sp. (P)	273	D. craterodmeta (EO)	272
Dredged in 86					Yoldia spp. (MB)	103	M. edulis (MB)	117	M. oculata (P)	103
10.7 - 12.2 m					C. californiense (MB)	68	Onchidoris muricata (MG)	83	C. californiense (B)	25
					P. minuta (P)	42	D. craterodmeta (EO)	53	S. droebachiensis (EE)	22
					Spio filicornis (P)	32	H. arctica (MB)	45	Spirobis spp. (P)	22
									Cerebratulus spp. (N)	22
R7 - Cobble			Cerebratulus spp. (N)	110	P. minuta (P)	75			C. californiense (MB)	197
Dredged 87-90			D. craterodmeta (EO)	70	C. californiense (MB)	37			D. craterodmeta (EO)	87
10.7 - 12.2 m			T. alternata (P)	38	D. craterodmeta (EO)	23			Atylus collingi (CA)	18
			Heteromastus filiformis (P)	35	Yoldia spp. (MB)	23			Ischyrocerus spp. (CA)	10
			Glycinde spp. (P)	35	Mya sp. (MB)	15			M. oculata (P)	10

CA = Crustacean, amphipod, CC = Crustacean, cumacea, EE = Echinoderm, Echinoid, EO = Echinoderm, ophiuroid, MB = Mollusc, bivalve, MG = Mollusc, gastropod, N = Nematean, P = Polychaete.

Table 5. Most abundant species (numbers/m^2) at sand stations

Station	Sept 1985		June 1986		June 1987		June 1988		June 1989		June 1990
C2 - Sand	Spiophanes bombyx (P)	337	M. sacculata (P)	635	M. sacculata (P)	395	M. sacculata (P)	887	M. sacculata (P)	780	M. sacculata (P)
	Magelona sacculata (P)	327	Spiophanes bombyx (P)	295	Travisia pupa (P)	120	M. lama (MB)	248	T. lutea (MB)	632	Glycinde spp. (P)
	Macoma lama (MB)	235	T. lutea (MB)	272	M. lama (MB)	92	S. bombyx (P)	202	Glycinde spp. (P)	317	Scoloplos armiger (P)
	Echinarachnius parma (SD)	168	Macoma lama (MB)	265	T. lutea (MB)	85	Siliqua alta (MB)	148	M. lama (MB)	187	T. lutea (MB)
	Tellina lutea (MB)	157	Glycinde spp. (P)	152	S. bombyx (MB)	68	T. pupa (P)	143	S. bombyx (P)	187	S. bombyx (P)
S2 - Sand	M. sacculata (P)	830	M. sacculata (P)	262	M. sacculata (P)	570	Spisula polynyma (MB)	543	M. sacculata (P)	720	M. sacculata (P)
	M. lama (MB)	177	S. armiger (P)	60	S. bombyx (P)	178	T. lutea (MB)	90	T. lutea (MB)	627	T. lutea (MB)
	S. armiger (P)	137	Diastylis alaskensis (CC)		T. lutea (MB)	120	E. parma (SD)	60	S. bombyx (P)	360	S. armiger (P)
	T. lutea (MB)	128	Cerebratulus spp. (N)	48	Euhaustorius eous (CA)	87	Cerebratulus spp. (N)	60	Glycinde spp. (P)	278	Myriochele oculata (P)
	Glycinde spp. (P)	93	Lamprops quadriplicata (CC)	47	Acanthostepheia behringiensis (CA)		S. Alta (MB)	50	Macoma spp. (MB)	270	S. bombyx (P)
						65					
				32							
C3 - Sand					M. sacculata (P)	202	M. oculata (P)	203	Glycinde spp (P)	207	M. oculata (P)
					M. oculata (P)	130	S. armiger (P)	73	M. sacculata (P)	130	M. sacculata (P)
					S. bombyx (P)	127	Glycinde spp (P)	73	S. polynyma (MB)	127	Glycinde spp. (P)
					T. pupa (P)	125	M. sacculata (P)	60	Apistobranchus ornatus (P)	105	D. craterodmeta (EO)
					E. parma (SD)	117	Yoldia spp (MB)	53	T. lutea (MB)	47	S. armiger (P)
S3 - Sand			M. oculata (P)	308	S. bombyx (P)	465	M. oculata (P)	1027	T. lutea (MB)	332	M. oculata (P)
			Cerebratulus spp (N)	278	M. oculata (P)	280	E. parma (SD)	512	E. parma (SD)	308	S. bombyx (P)
			Typosyillis alternata (P)	145	Heteromastus filiformis (P)	268	Glycinde spp. (P)	327	Glycinde spp (P)	232	Glycinde spp. (P)
			Glycinde spp. (P)	140	M. sacculata (P)	157	H. filiformis (P)	302	D. caterodmeta (EO)	212	T. lutea (MB)
			D. alaskensis (CC)	82	E. parma (SD)	123	Cistenides granulata (P)	207	Machaironyx muelleri (CA)	193	Diamphiodea. craterodmeta (EO)
R6 - Sand	Dredged 1986				D. alaskensis (CC)	57	Tharyx secundus (P)	360	M. sacculata (P)	223	M. oculata (P)
					L. quadriplicata (CC)	20	M. oculata (P)	225	T. lutea (MB)	213	M. sacculata (P)
					Glycinde spp (P)	15	Cerebratulus spp.(N)	105	S. polynyma (MB)	183	Glycinde spp. (P)
					A. behringiensis (CA)	10	H. filiformis (P)	97	Glycinde spp. (P)	72	S. armiger (P)
					Nephtys longosetosa (P)	7	Glycinde spp. (P)	55	Spisula sp. (MB)	55	A. ornatus (P)
					Campylaspis umbensis (CC)	7					
R7 - Sand	Dredged 1987						Pholoe minuta (P)	93	Glycinde spp. (P)	30	D. craterodmeta (EO)
							Nephtys sp. (P)	22	Hiatella arctica (MB)	22	Glycinde spp. (P)
							Mya sp. (MB)	22	Mytilus edulis (MB)	20	D. alaskensis (CC)
							Clinocardium californiense (MB)	18	M. sacculata (P)	13	M. sacculata (P)
							Monoculodes sp. (CA)	17	Molgula sp. (T)	13	M. oculata (P)

CA = Crustacean, amphipod, CC = Crustacean, cumacea, EE = Echinoderm, Echinoid, EO = Echinoderm, Ophiuroid, MB = Mollusc, bivalve, MG = Mollusc, gastropod, N = Nemertean, P = Polychaete, T = Tunicate.

Table 6

Shannon Diversity Index (H'), Simpson's Index (D), species richness, denisty (indiv./m^2), biomass (g/m^2), and number of taxa of benthic invertebrates collected from sand (s) and cobble (c) near Nome, Alaska during 1985 through 1990.

	Year	Sand Stations						Cobble Stations						
		C2s	S2s	C3s	S3s	R6s	R7s	C2c	S2c	C3c	S3c	R6c	R7c	D6c
Shannon (H')	1990	TBD	TBD	2.54	1.38	2.15	2.36	TBD	TBD	1.68	2.83	2.46	1.71	NS
Simpson (D)				0.83	0.42	0.69	0.85			0.56	0.87	0.80	0.67	
Species richness				7.53	8.38	7.53	4.94			8.51	9.27	7.87	4.43	
Density (indiv./m^2)				1768	7113	1975	328			3997	1497	746	408	
Biomass (g/m^2)				21.9	13.8	20.4	1.0			32.5	27.2	104.2	0.6	
No. Taxa				67	81	67	30			83	84	63	38	
Shannon (H')	1989	2.34	2.70	2.88	3.47	2.65	2.90	2.17	3.25	NS	2.44	2.27	NS	NS
Simpson (D)		0.84	0.89	0.90	0.96	0.88	0.93	0.78	0.93		0.79	0.81		
Species richness		5.80	7.33	7.85	10.13	6.47	6.24	6.06	10.40		8.31	5.59		
Density (indiv./m^2)		2813	3591	1050	3427	1117	530	1208	1088		1317	997		
Biomass (g/m^2)		62.2	76.1	19.6	47.4	13.6	0.9	23.5	7.2		1.6	4.4		
No. Taxa		57	71	63	92	48	40	55	76		70	49		
Shannon (H')	1988	2.34	2.18	2.96	3.24	2.42	2.44	3.22	2.69	2.82	3.12	2.20	2.64	3
Simpson (D)		0.82	0.72	0.91	0.92	0.84	0.84	0.94	0.88	0.90	0.94	0.84	0.89	0
Species richness		5.10	6.04	7.58	9.69	6.60	4.96	8.52	7.53	7.78	8.81	4.50	5.08	14
Density (indiv./m^2)		2437	1277	845	5050	1253	357	995	740	1007	2462	578	363	5780
Biomass (g/m^2)		93.9	4.9	10.4	30.8	7.2	0.3	35.4	14.2	26.5	17.0	0.7	0.6	101
No. Taxa		44	47	56	93	53	34	62	54	64	75	32	34	134
Shannon (H')	1987	2.60	2.51	3.22	3.11	2.28	NS	1.81	2.74	NS	3.13	NS	3.09	NS
Simpson (D)		0.86	0.82	0.94	0.92	0.83		0.57	0.90		0.93		0.93	
Species richness		5.93	6.92	8.48	8.49	4.21		7.54	6.75		8.98		8.58	
Density (indiv./m^2)		1208	1497	1595	2485	160		1030	752		2703		602	
Biomass (g/m^2)		59.9	39.4	35.3	58.8	0.8		12.6	51.6		21.1		17.3	
No. Taxa		43	52	66	66	21		59	48		76		57	
Shannon (H')	1986	2.40	2.56	NS	2.89	NS	NS	3.06	2.70	NS	2.50	NS	NS	NS
Simpson (D)		0.86	0.84		0.91			0.94	0.90		0.83			
Species richness		4.46	5.46		7.86			6.35	5.58		9.01			
Density (indiv./m^2)		2193	707		1767			495	448		3243			
Biomass (g/m^2)		91.5	17.1		10.8			77.0	30.6		106.8			
No. Taxa		34	36		61			43	39		79			
Shannon (H')	1985	2.40	2.21	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Simpson (D)		0.88	0.78											
Species richness		4.19	4.55											
Density (indiv./m^2)		1289	1438											
Biomass (g/m^2)		33.4	41.3											
No. Taxa		32	37											

NS = Not Sampled
TBD = To be determined

Table 7

Example of WestGold's Waste Discharge Permit and Effluent Monitoring Requirement 1990

Process Tailings Launders (Discharge 003)

1. The combined discharge of the process tailings launders shall be limited and monitored by the Permittee as specified below:

Effluent Characteristics	Discharge Limitations		Monitoring Requirements	
	Average	Maximum	Sampling Method and Frequency	Monthly Reporting Values
Flow (MGD)	35	45	Estimate: 3 times per day	Average monthly: maximum daily
Settleable Solids small fraction (m^3/hr)	--	413	Grab: 3 times per day	Average monthly: maximum
Suspended Solids (mg/L)[1]	15,000	30,000	Grab: 3 times per day	Average monthly: maximum
Arsenic (µg/L)[2,3]	234	1,242	Grab: 2 times per week	Average monthly: maximum
Cadmium (µg/L)[2,3]	167.4	774	Grab: 2 times per week	Average monthly: maximum
Copper (µg/L)[2,3]	52.2	52.2	Grab: 2 times per week	Average monthly: maximum
Lead (µg/L)[2,3]	100.8	2,520	Grab: 2 times per week	Average monthly: maximum
Mercury (µg/L)[2,3]	0.45	37.8	Grab: 2 times per week	Average monthly: maximum
Nickel (µg/L)[2,3]	149.4	1.350	Grab: 2 times per week	Average monthly: maximum
Zinc (µg/L)[2,3]	1,548	1,710	Grab: 2 times per week	Average monthly: maximum

1/ Suspended solids is defined herein as the combination of clay and silt particles.

2/ Metal concentrations shall be measured and reported as both total recoverable and total dissolved metals. EPA may reduce the monitoring requirements after the development of a substantial, reliable record of metals concentrations in the discharge plume.

3/ Total recoverable and total dissolved metals shall be measured in accordance with EPA-approved methods which meet the requirements of 40 CFR Part 136 to achieve detection limits for (or at least) As (1 µg/L), Cd (1 µg/L), Pb (1 µg/L), Hg (0.05 µg/L), Ni (1 µg/L) and Zn (8.6 µg/L).

2. There shall be no discharge of dredge material from the tailings process launder to waters of less than 8 m depth at MLLW.

3. The average daily discharge of process tailings shall not exceed 10% solids, of which no more than 15% shall be silts and clays.

Table 8

Example of WestGold's Waste Discharge Permit and Effluent Monitoring Requirement 1990

Gold Table Sluice Tailings Launder (Discharge 004)

1. The discharge shall be limited and monitored by the Permittee as specified below:

Effluent Characteristics	Discharge Limitations		Monitoring Requirements	
	Average	Maximum	Sampling Method and Frequency	Monthly Reporting Values
Flow (MGD)	--	0.34	Estimate: daily	Average monthly: maximum daily
Suspended Solids (mg/L)	15,000	30,000	Grab: daily	Average monthly: maximum
Copper (μg/L)[1,2]	52.2	52.2	Grab: 2 times per week	Average monthly: maximum
Mercury (μg/L)[1,2]	0.45	37.8	Grab: 2 times per week	Average monthly: maximum

1/ Metal concentrations shall be measured and reported as both total recoverable and total dissolved metals. EPA may reduce the monitoring requirements after the development of a substantial, reliable record of metals concentrations in the discharge plume.

2/ Total recoverable and total dissolved metals shall be measured in accordance with EPA-approved methods which meet the requirements of 40 CFR Part 136 to achieve detection limited for (of at least) Cu (1 μg/l), and Hg (0.05 μg/l).

OCS Report
MMS 95-0003

Marine Mining Technologies and Mitigation Techniques

A detailed analysis with respect to the mining of specific offshore mineral commodities

July 1996

Executive Summary

Contract No. 14-35-0001-30723

MMS U.S. Department of the Interior
Minerals Management Service

Office of International Activities and Marine Minerals (INTERMAR)

DISCLAIMER

TABLE OF CONTENTS

1.0 Introduction

This report was commissioned by the Minerals Management Service (MMS), U.S. Department of Interior (DOI). The MMS is responsible for the regulation of mineral exploration and development on submerged Federal Lands of the U.S. Outer Continental Shelf (OCS). Environmental protection is an integral part of the mandate of the MMS, and regulatory requirements exist for the enactment of mitigation measures during the conduct of all offshore mineral exploration and development activities. In keeping with the requirements of the National Environmental Policy Act (NEPA) and Council of Environmental Quality (CEQ) regulations, the MMS performs environmental analysis and assessment of proposed offshore mineral developments on a case-by-case basis. This document provides the MMS with practical guidance in prescribing mitigation measures for future marine mining developments on the U.S. OCS.

1.1 Purpose and Objectives

The purpose of this study was to undertake a detailed analysis of available and proposed marine mining technologies and mitigation techniques with respect to the mining of specific mineral commodities on the U.S. Outer Continental Shelf.

The objectives of the study were:

(1) To develop realistic scenarios for marine mining activities that are likely to occur on the U.S. OCS within a ten-year time span

(2) To make predictions of the environmental impacts associated with the marine mining scenarios

(3) To establish guidelines for mitigation of the anticipated environmental impacts

(4) To perform cost-benefit analyses of available and proposed techniques for mitigation of the environmental impacts of marine mining

(5) To formulate recommendations as to the most appropriate mitigation techniques for the scenarios and similar marine mining developments.

1.2 Project Team

To meet the above stated objectives, a multi-disciplinary team was formed consisting of environmental scientists and marine mining and dredging specialists. The Project Team consisted of four principal groups, or nodes, which included a Management node, a Mining Engineering node, a Physical Environmental Effects node and a Biological/Chemical Environmental Effects node.

The Management node was based at C-CORE - Centre for Cold Ocean Resources Engineering, Memorial University of Newfoundland, Canada. The Mining Engineering node was led by Richard Garnett, Ph.D., C.Eng., an international mining consultant based in Oakville, Ontario, Canada. The Physical Environmental Effects node was headed by Laurie Davidson, M.Sc., Physical Oceanographer and President of Seaborne Information Technologies Ltd., located in St. John's, Newfoundland, Canada. The Biological/Chemical Effects node was directed by Derek Ellis, Ph.D., R.P.Bio., Professor of Biology at the University of Victoria, Canada, and Principal of Derek V. Ellis Ltd., marine environmental consultants.

This report was authored primarily by the node leaders. Supporting contributions were made by Tom Pederson, Ph.D. (environmental chemist; University of British Columbia), Jack Littlepage, Ph.D. (pelagic biologist; University of Victoria), Robert Jantzen (dredging engineer; Jantzen Engineering Co., Inc.), Donald Hodgins, Ph.D. (physical oceanographer; Seaconsult Ltd.), and Laurence Davis, M.Sc. (Project Manager and marine geoscientist; C-CORE).

1.3 Approach and Methodology

1.3.1 Marine Mining Scenarios

A variety of mineral commodities exist on the U.S. OCS and are potential targets for future exploitation. These include sand resources suitable for beach nourishment, marine aggregates, heavy minerals, precious metals, phosphorites, and others. Their exploitation will inevitably result in environmental impacts that will vary in degree depending on factors such as the scale of operation, the extraction technology used, and the nature of the geological and environmental setting.

The fundamental questions dealt with in this study were: what are the likely environmental impacts associated with mining of specific mineral commodities on the U.S. OCS, and how might those impacts be mitigated in a cost-effective manner? These questions are addressed through analysis of a number of marine mining scenarios detailing the scale of operation, extraction technology, and environmental setting of marine mining operations targeting a range of mineral commodities.

The mining scenarios were developed in close consultation with the MMS, and were selected based on the following criteria:

(1) Potential for near-term development: only mineral commodities likely to be exploited within a ten-year time span were considered. Other mineral commodities were excluded on the basis of market and technological constraints.

(2) Commodity resource information: much of the available information pertaining to the distribution of mineral commodities on the U.S. OCS is regional and lacks sufficient resolution to derive reserve or even resource estimates. However, there is sufficient detail

to at least target general areas of interest (scale of kilometres) and sometimes more specific areas.

(3) Proximity to markets and market demand: the proximity to the commodity market, and the market demand, are important considerations for all potential marine mining developments. The MMS provided valuable advice with respect to market requirements, which helped considerably in determining the most appropriate site-selections for the mining scenarios.

(4) Availability of environmental data: a final but secondary consideration in selecting the marine mining scenarios was the availability of local environmental data. Where environmental data were sparse or lacking, it was possible to make appropriate generalizations about distributions of biological assemblages and about likely ecological responses based on regional information and knowledge of the habitat.

A total of five marine mining scenarios were selected and developed in detail. These include:

(1) Precious metal mining, Alaska - bucket ladder dredge
(2) Precious metal mining, Alaska - underwater miner
(3) Marine aggregate mining, Massachusetts Bay
(4) Heavy mineral mining, offshore Virginia
(5) Beach nourishment, Ocean City, Maryland

The first scenario is a case history of a large-scale placer gold mining operation offshore Nome, Alaska, carried out by Western Gold Exploration and Mining Company (WestGold) Limited Partnership during the late 1980's. Though the scale of operation and use of a bucket-ladder dredge are not likely to be repeated in any future offshore mining activities in the region, the scenario is highly instructive in that it documents real experience with the practice of marine mining environmental impact mitigation. It is also the only large-scale marine mining development to occur in U.S. waters to date.

The second scenario, which involves precious metals mining using an underwater mining vehicle, is based on actual production trials carried out towards the end of the WestGold project life. The two mining methods are at opposite ends of the spectrum in terms of scale of operation and precision of extraction, and therefore provide a useful contrast of the effects of using different extraction techniques to mine the same mineral commodity.

Offshore aggregate mining, the subject of the third scenario, is thought to be a likely prospect in the near-term. The first markets to be served by such an industry will probably be the greater-metropolitan areas of Boston and New York. Recognizing that marine aggregate resources in the region are potentially widespread, the choice of a location in Massachusetts Bay for a hypothetical aggregate mining operation was based mainly on the availability of environmental information. A comprehensive baseline environmental study was carried out in the early 1970's in preparation for an experimental offshore aggregate mining project. The experiment did not proceed, but the baseline environmental information gathered serves as a useful resource for this study.

Although the baseline study provides what is still perhaps the most complete site-specific assessment of aggregate resources in the region, it reveals that the geology of the site under consideration is not particularly conducive to economic dredging operation. The sediments are poorly sorted and contain, on average, higher proportions of silt and clay than are normally desirable for an aggregate target. Therefore, the hypothetical marine aggregate mining operation presented in this report represents a worst case scenario both environmentally and economically. As a marginal operation the aggregate mining scenario is a sensitive monitor of the economic costs of mitigation.

The fourth scenario, also hypothetical, involves the dredging of heavy mineral sands in Federal waters off Virginia Beach, Virginia. In this case the site selection for the scenario was based mainly on commodity resource information. Concentrations of industrial heavy minerals are known to exist offshore Virginia as well-sorted placer deposits. The geology and environmental setting are thought to be representative of most areas on the U.S. OCS where heavy minerals could be targeted. Any proposal for offshore mining development in the area would have to address potential conflicts with other uses, including commercial fishing, ocean dumping, and military practice.

The fifth scenario considers the use of sand resources in Federal waters (seaward of the state boundary) for beach nourishment. The site selected for the scenario, Ocean City, Maryland, has undergone repeated coastal restoration projects, the most recent was in the fall of 1994. Borrow sites have moved progressively offshore and the need for sand resources from Federal waters appears imminent.

1.3.2 Mitigation Analysis

One of the key objectives of this study was to develop recommendations as to the most appropriate techniques for mitigation of environmental impacts associated with mining of specific mineral commodities on the U.S. OCS. The recommendations are derived from analysis of a broad range of available and proposed mitigation measures with consideration given to their relative cost, effectiveness and practicality. The selection of mitigation techniques for analysis was based upon the environmental impacts and mitigation guidelines, or objectives, identified for each of the mining scenarios.

1.4 Structure of the Report

Section 2, Environmental Issues, provides a detailed overview of the environmental impacts of marine mining with special emphasis on key issues relevant to the marine mining scenarios. Issues relating to modelling, and to environmental monitoring and quality assurance/quality control (QA/QC) protocols, are also introduced and discussed in the context of environmental impact mitigation.

The marine mining scenarios are presented in Section 3. Details are provided of their environmental settings, the commodity resource characteristics, and the extraction and processing methods. Predictions of the potential environmental impacts of each extraction technology are provided along with guidelines for mitigation of those impacts.

In Section 4, techniques for mitigation of the environmental impacts of marine mining are reviewed and in Section 5 these are applied in detail to the marine mining scenarios. Recommendations are made as to the most appropriate selection of mitigation measures for each mining scenario. A summary and recommendations are presented in Section 6.

2.0 Summary of Environmental Issues

Physical environmental processes affect marine mining operations in two ways. Firstly, these processes constrain or control the actual conduct of the mining operation, and thus are significant in determining the potential environmental impacts of the operation. Factors exercising control over mining operations may vary in importance with the mode of mining, but in most instances include wind, waves, currents and ice. Temperature, precipitation and water level are usually of secondary interest, except possibly in locations where unusually high tides or tidal ranges might impose operating constraints. Seasonal as well as short time scale changes in these conditions combine to determine both the annual operating season for a mining activity, and dictate the viability of particular operations or activities on a particular day.

Principal sources of potential environmental impact resulting from mining operations include processes such as the physical disruption of the seabed, the deposition of disturbed and/or mined materials over undisturbed portions of the seabed, and the dispersion of particulate material through the water column. Thus, the second physical environmental issue is the role of physical processes in determining the distribution and motion of this particulate load through the water column, the timing and location of the deposition of this load on the seabed, and the possible resuspension and redeposition of unconsolidated materials after initial deposition on the sea floor. The magnitude and variability of horizontal currents, as well as the grain-size distribution of the particulates and the particulate cohesive properties, ultimately dictates the residence time in the water column, and the range of horizontal transport of the particles before they are eventually redeposited on the seabed.

Marine organic matter in seabed deposits fuels a suite of bacterially-mediated post-depositional (diagenetic) reactions in which the organic material is progressively degraded as oxidants are consumed. The reactions yield a number of products which may have direct or indirect environmental implications for mining.

Organic matter represents a highly reduced form of carbon which is rich in electrons, and is therefore a primary energy source. Over most of the seabed, marine organic materials are degraded by aerobic bacteria, wherein oxygen is the terminal electron acceptor in the reaction $CH_2O + O_2 = CO_2 + H_2O$. Where oxygen is absent, the bacterial community takes advantage of other electron acceptors, which (in thermodynamic order) include nitrate, manganese and iron oxides and sulphate. Thus, aerobes are succeeded by nitrate-reducing bacteria, and later by sulphate-reducing bacteria as long as degradable organic matter remains. This suite of reactions leads to a biogeochemical zonation in sediments. Anoxia results where oxygen supply via advection or diffusion is exceeded by demand of aerobes and by inorganic consumption of oxygen by a reaction with reduced species such as Fe^{2+}. Anoxic conditions at relatively shallow depths (a few centimetres or less) are typical in most coastal and inner continental shelf sediments.

Benthic (seabed) organisms are the base feedstock for fishery and wildlife resources such as seabed feeding fish, diving waterfowl and marine mammals, and also contribute to the larval biodiversity of the water column. Their populations allow calculations of biodiversity, and biodiversity can be used as a yardstick for gauging environmental impact. Biodiversity is measured by (1) how many different kinds of organisms are present (*Species diversity*), and (2) the relative numbers of each (*Numerical diversity*) .

Two sets of risks arise from dredging operations: (1) extraction risks (i.e. removal of habitat material with some surrounding disturbance), and (2) discharge risks (i.e. deposition of discharged tailings). Extraction removes sediment habitat and the organisms living within the sediment (infauna), or on it (epifauna). The burrowing forms are relatively immobile and cannot swim away from the cutting face of the mining excavation. These benthic organisms include fish and prawn resource species that maintain burrows, and many species of smaller creatures which can function as feedstock for resource species.

Epifauna come in two forms. The mobile epifauna generally live on the surface of the deposits. They may be able to remove themselves from the immediate dredge area. Examples include flatfish, crabs, sea cucumbers and sea urchins (almost immobile), scallops, and other resource species. The other epifaunal forms are sessile, and are attached to large cobbles, boulders or rock outcrops. They are generally attached so firmly that they are only removed if their host substrate is removed. In general, seabed mining will have an impact on resource species, their feedstock and habitat.

A discharged tailing slurry will fall through the water column, with some dispersion of fines), and will eventually reach the seabed as a density current. After initial impact, the tailing will spread in some pattern as a seabed dispersal field. During this spread, deposition occurs, with coarser particles settling before the finer. Large amounts of tailings may smother and kill organisms over a broad area. Smothering kills benthic organisms by preventing them from breathing or feeding. In general the ability of benthos to avoid smothering, or to burrow up faster than smothering deposits can settle, is not known.

Natural annual fluctuations in biodiversity (both number of species, and number of organisms) are enormous. Such natural fluctuations cause great difficulty in describing ambient faunas and environmental impact on benthos. This applies to measuring biodiversity before dredging operations start, assessing changes derived from the dredging operations, and assessing the progress of recolonisation after dredging.

Spatial differences in biodiversity on uniform deposits means that the fauna of Dredging (Test) and nearby Reference sites will inevitably differ to some extent from natural causes, and from year to year. There may be no cost-effective way to obtain accurate and precise biodiversity estimates of benthos with different and varying patchiness. Crude quantitative estimates may have to be accepted.

After a deposit is mined the seafloor is recolonised by benthic organisms. Times for recovery of a reasonable biodiversity depends on the sediment type. Fine-grained tailings may need only 1 year before achieving a recovery level biodiversity, medium-grained deposits 1 - 3 years, and coarse-grained deposits 5 or more years.

During marine mining a number of general impact mitigation objectives are desirable:

Water column:

- minimize elevations of surface water turbidity

Seabed:

- minimize dredge course overlaps and gaps
- minimize return of tailings outside dredge footprint
- leave surface of similar grade
- no release of contaminants
- no anoxic dredge furrows
- recovery to a successional community within time scale of: silts - 2 years, sands - 3 years, gravels - 5 years
- avoid sensitive areas - endangered species, isolated breeding grounds, etc.

Fisheries and Wildlife Resources:

- avoid sensitive habitats, such as finfish and shellfish spawning grounds, and wildlife migration staging grounds or intense migration routes
- design quiet vessels to Best Practical Technology

3.0 Summary of Mining Scenarios

Five marine mining scenarios are discussed. Details of the marine conditions affecting the location of each scenario are provided. The scenarios provide details on all aspects of the mining operations, including the extraction technologies, dredged material processing methods, and effluent types and constituents. Information relating to the geological and environmental settings is also provided. At the end of each scenario predictions of environmental impact are given, potential mitigation objectives are identified, and criteria for appraising the mitigation method are proposed.

1) Precious metal (gold) mining offshore Alaska using a bucket ladder dredge

This scenario is a discussion of actual experiences during a gold mining operation offshore Nome. Dredging for gold has been attempted several times this century but only WestGold achieved a significant production using a bucket ladder dredge from 1986 through 1990. The exploration efforts and the environmental research of WestGold are fairly well documented in various publications. Much of the experimental work on reducing the environmental effects of the WestGold dredging is applicable to other forms of dredging. Therefore the Nome bucket ladder dredging project constitutes a very useful scenario for study. Dredging was carried out using the world's largest ocean-going bucket ladder dredge, the BIMA. During the years 1987-1990 the dredge recovered on average 775 mg gold/m^3. There were extensive pre- and post-dredging surveys to measure the impact of mining.

In general terms the sand bed biodiversity started to recover within 1 year of dredging. A few new species entered the fauna and later disappeared, but there is no clear successional pattern. By 1990, four years after dredging at one sample station, the biodiversity was clearly back in the range of the reference stations. Cobble bed biodiversity appears to have recovered more slowly. The number of species remained as high as the reference stations, or almost so, even 1 year after dredging. However, the number of organisms showed a reduction barely reaching the lower end of the year to year range at the reference stations.

The one fishery species monitored in detail was the red king crab (*Paralithodes camtschatica*). It was found that crabs move locally over distances which allowed them to transfer between dredged and undredged areas. Their movements prior to dredging were apparently random, although crabs often have seasonal shifts with depth. Crabs were fished from both dredged and undredged areas, with more competition by boats for fishing sites in the dredged than the undredged areas.

Water column impact was limited to a turbidity plume extending from the dredge discharge points. Seabed disturbance was caused by the dredge cuts and deposition of tailings. Dredge footprints were substantially smoothed by wave and current action within 3-5 years, even on the coarsest gravel/cobble habitat. A level of biodiversity encompassing several tens of species and several hundred organisms/m^2 had recolonized the impacted areas within 3-5 years, with recovery slower on coarser fraction gravel and cobble habitat.

2) Precious metals mining offshore Alaska using an underwater mining vehicle

An underwater miner (UWM) constitutes the opposite extreme of a large bucket ladder dredge: it has a comparatively very low throughput, is limited in terms of the depth to which it can dig below the seabed, and has the ability to be very selective in its extraction, both laterally and vertically. Dilution is minimal but unit volume costs are high. A bucket ladder dredge, by contrast, relies for its economic success on its digging power and its high throughput, resulting in a low unit volume cost. It is very non-selective, laterally and vertically, and a surficial deposit worked by it is heavily diluted in grade.

WestGold deployed a UWM in the Nome area of Alaska in the summer of 1989. This was the first recorded time that such a piece of equipment had been used for an offshore mineral recovery program other than remotely operated collectors in the earlier deep ocean manganese nodule projects. The UWM used was the "Tramrod", model 250, developed and manufactured by Alluvial Mining of the United Kingdom.

The "Tramrod" is deployed from an ocean-going barge with a draught of 1.5 m. The UWM is placed on, and recovered from, the seabed by a truck-mounted 210 tonne-capacity crane. Mined sediments, to a maximum of 0.25 m in particle size, are suctioned through a 25 cm intake and pumped to surface through a 0.305 m internal diameter floating pipeline.

3) Marine aggregate mining in Massachusetts Bay with a trailing-suction hopper dredge

The deposit is located within the 3 mile limit offshore from Boston. It is part of a complex mixture of glacial products similar to that offshore Nome, Alaska consisting of glacial till, a heterogeneous mixture of boulders, gravel, sand, silt, and clay ranging in thickness from a thin veneer to nearly 30 m. Two clay units overlie the glacial till and the deposit appears to be a gradational feature resting on the upper clay unit. The lithology changes rapidly over short horizontal distances and with each vertical meter below the seabed. The potential dredge area reportedly comprises about 5.25 million m^3 of sand and gravel in water depths of less than 18 m. Assuming that 100% extraction is achieved, then the deposit's productive life is 2.9 years. The minimum required project life is 10 years, preferably 20 years or more. Therefore, in practice, additional or alternative dredging sites will have to be found before the project is started. Mining would be by means of a large ocean-going trailing suction hopper dredge equipped with twin trailing drag-arms. Production would be in the order of 18,000 metric tonnes of aggregate per day.

The fauna of the Massachusetts Bay area were documented in a large study during the summer of 1973. The biodiversity was rich and variable with differences between epifauna on hard rock (including on exposed cobble surfaces) and the burrowing infauna. There are habitats of hard, cobble, sand and mud substrates. Over 650 species were sampled. The number of species per station ranged dramatically, from 31 to 146 per station, as did the number of organisms/m^2, from 305 to over 11,000. The species complexes found on different substrate types differed but statistical correlation with deposit type was not possible. The temporal variation was enormous from month to month, making the use of dominant species only possible at specific site locations that cannot be generalised to a substrate level.

Benthic communities directly in the path of the dredge will be destroyed. The benthos in undredged areas between the furrow lines will be affected by increased turbidity and sedimentation. The impacts will depend on the depth of sediment that accumulates and depth of the furrows.

Unlike mining scenarios where most of the sediment extracted is returned to the environment, in mining aggregates a substantial percentage of the particular size fraction is removed. This will change the particle size characteristics of the deposits remaining. The larvae which recolonise the altered environment will then reflect these changes. It is probable that the silt/clay fractions will increase in the dredged area because the coarser sediments are to be retained by the dredging process.

Soft-bottom communities should recover faster than communities found on coarse sediments, or the epifauna on cobbles and boulders. Expected times to recovery, based on other studies, are suggested to be 1+ years on deposits with least cobbles, with slower recovery where substantial numbers of cobbles are removed.

Environmental impact mitigation objectives should include:

(1) reduction of dredge-derived turbidity through improved outfall design and vessel operations

(2) possible development of alternative enhancement uses for under-sized and over-sized fractions

(3) return of fines to dredge footprint.

4) Heavy minerals dredging offshore of Virginia Beach, Virginia using a cutter suction dredge

The heavy mineral deposit is contained in sand. Total heavy mineral (THM) concentration averages about 3% with values up to 3.65% in the uppermost metre. THM content decreases steadily with increasing depth below the seabed, and the incremental THM content, on average, falls to slightly less than 3% (the grade most probably required in such an offshore operation) at a depth of 4 m. The deposit would be mined using a cutter suction dredge on either a floating pontoon or jack-up platform. Throughput would be in the range of 113,000 to 151,000 litres of slurry per minute, with approximately 95% of dredged sediments returned to sea as effluent.

It is expected that biodiversity will be high on these sands, as is usual at this latitude and water depth. At this site prior human disturbance has probably introduced contaminants or otherwise rendered the ground unsuitable or even dangerous for dredging. There are dump-sites indicated on hydrographic charts and the area is in the proximity of a Navy firing range. The benthos will probably show localised impact from such prior uses. This will need determining by site-specific baseline surveys.

Extensive pre-dredging sampling will be needed to show if there are areas of recent disturbance with little benthos, stable areas with a normal variability of the fauna, and areas in which elevated levels of benthos may occur due to enhancement effects of the nearby disturbance. The site's close proximity to the City of Virginia Beach may pose further stresses to the environment from sewage, storm drain run off and industrial run off. Existing status of fishery and fish-nursery sites would need documenting.

Mining-related impact will be from a combination of the removal of substrate and smothering from the large amounts of tailings. Benthos directly in the path of the dredges will be destroyed. Surrounding benthos will be affected by sedimentation and turbidity. Trenches formed by the cutter head will develop as will elevated areas. Impacts will be extensive as experienced at the WestGold bucket-ladder dredge operation, with time to recovery determined by the nature of the deposit and energy level of the site. Smoothing of the seabed should occur from natural wave action. In general terms recovery on sand beds can be expected within 3 - 5 years but the exact composition of the fauna will vary from place to place, and may not resemble the original populations. Monitoring the nature of the recovery due to mining may be difficult because the area already may be affected by other anthropogenic influences, and these may continue to affect the site.

Environmental impact mitigation objectives should include:

(1) minimization of surface turbidity

(2) reduction of benthic impact by constraining tailings discharge to dredge footprint and nearby

(3) possible development of alternative enhancement projects.

5) Beach nourishment at Ocean City, Maryland, using a cutter suction dredge pumping sand ashore or, alternately, a trailing-suction hopper dredge transporting sand to a nearshore pumping station

Ocean City's beach is eroded at a rate of about 1 m per year and requires replenishment, by agreement with the authorities, every 2 - 3 years. The site is selected so as to provide sand of the size and type normally found on the adjacent beach that is to be renourished. A previously used site 3.2 km offshore is now exhausted. In 1988 the sailing distance was 4.2 km from the hopper dredge pump-out shoreline connection to the dredging site where 77% of the available 3.06 million m^3 of sand was in more than 15.3 m of water. The borrow site used in 1994 was 8 km from shore where the water depths are > 15.3 m. The 1.2 - 1.5 m cut bank of sand is underlain by mud and clay which must not be disturbed.

Generally, if the borrow area is less than 5 - 6 km from the beach, a cutter suction and pipeline are used. If the distance is greater than 5 - 6 km a hopper dredge is employed. Pipeline deployment over greater distances is possible but is dependent upon the prevailing sea conditions at the site. A cutter suction dredge is more productive than a large hopper dredge because the latter cannot approach close to the beach with the prevailing water depths. An additional factor at Ocean City is the difficult entry and the depth of water at the entrance to, and within, the harbour that restricts the size of hopper dredge which may enter to take shelter from severe storms.

Sand-bed benthos is characteristically of high biodiversity, with many species scattered through major taxa, and dynamic in the sense of species changing relative numbers from year to year. Species diversity ranged up to more than 100 per unit area investigated. Numerical diversity ranged up to more than $7000/m^2$.

The immediate impact from mining will be formation of borrow pits. The depth, width and length of the borrow pits could be regulated to maintain current flow so that they do not become settlement basins with consequent anoxia, sulphur-reducing chemistry, and reduced biodiversity. There will be an immediate loss of virtually all the benthic species present. Mining-related seabed disturbance may release nutrients and uncover and displace feedstock species temporarily providing extra food for bottom-feeding resource species. Fishing may improve temporarily downcurrent of the dredging area and continue for some months afterwards. Benthos may also show a temporary increase in biodiversity downstream from the dredge site.

The mining footprint probably will start to smooth, and biological recolonisation to start, within weeks of closure. If closure is during an annual larval settling period, recolonisation will be most rapid, and may be demonstrable within days of closure. It is to be expected that moderate biodiversity will have reformed within 1 year.

Environmental impact mitigation objectives should include:

(1) minimizing cut-face turbidity, thereby preventing upwelling to surface

(2) planning the location, depth, width and length of dredge courses to minimize the risk of anoxic borrow-pits developing.

4.0 Summary of Mitigation of the Environmental Impacts of Marine Mining

The main environmental effects of marine mining that occur and which must be minimized or reduced to acceptable limits are:

(1) the creation of water turbidity

(2) the release and spread of contaminants

(3) the distribution of sediments outside the dredge footprint

(4) changes to the seabed lithology and profile

Any one or more of four possible requirements of mitigation may be applicable to a marine dredging operation. Each of the four approaches requires a procedure, alone or in combination with others, to be successful:

(1) to avoid completely any environmental impact through location-based, time-based, or scale-based constraints on the dredging, alone or in combination

(2) to remove or lessen a cause or effect, and thereby to minimize the unavoidable environmental impact, through: (a) restrictions on the dredge discharges and certain operating techniques, and (b) the requirement that the best and most suitable technology is available

(3) to remediate the environmental impact through post-dredging activities

(4) to compensate for the environmental impact through alternative enhancement of a similar or related environment.

5.0 Summary of Application of Mitigation Techniques

1) Precious metal (gold) mining offshore Alaska using a bucket-ladder dredge

Monitoring of the tailings plume during the mining operation was carried out from the collection of samples from tailings launder and gold room effluent, and from sea water up-current and down-current from the dredge. WestGold and its consultants employed a 3-dimensional water quality and sediment plume computer model referred to as Disposal from a Continuous Discharge (DIFCD) and developed by the U.S. Army Corps of Engineers Waterways Experiment Station. It was used in conjunction with a Wave Current Sediment Resuspension Prediction (WCSRP) model. The DIFCD and WCSRP computer programs proved to be invaluable in predicting the plume creation behaviour of the tailings discharge.

A large variety of mitigation techniques were considered and many were tried over the 1986 to 1990 operation period of the BIMA dredge. The most important was the control of the tailings effluent discharge so as to minimize the degree and extent of sea water turbidity. The optimal design developed from four years of dredge-operating experience comprised fitting the existing 1.8 m-diameter header pipes with cones that terminated in a flanged collar of 0.50 m diameter. A straight circular steel pipe was attached to the flange and extended vertically down to within about 0.5 m of the water surface. A flexible hose of the same diameter was affixed to the steel pipe and extended 2.7 m below the water surface. Several other configurations were considered but were not employed. They were discarded in the design stage after operating experience quickly demonstrated their impracticality under the prevailing marine and dredging conditions. They included multiport systems, a form of controlled surface discharge and flexible stinger pipe designed to lie on the seabed.

2) precious metals mining offshore Alaska using an underwater mining vehicle

A number of location-related restrictions applied to the operation that were designed mainly to protect migrating salmon. Dredging could not take place:

(1) within 30 m of the low water mark

(2) within 1.6 km of the mouth of a river used by migrating salmon

(3) in water depths of less than 5 m.

Compared with the large-scale bucket ladder dredge the use of a selective, small scale operation allowed greater flexibility in mitigating the deleterious effects of the effluent discharges. The use of an underwater miner also served to mitigate the important impact of changing seabed profile caused by dredging.

A novel outfall design, consisting of two large troughs fixed along both sides of the treatment plant barge, was used by WestGold to collect and discharge the jig tailings effluent. The trough was perforated along its base to provide discharge ports so that the slurry was released as a series of small point discharges. The slurry may be discharged in the sea either from above or may be fed down a series of flexible hoses, with quick-coupling disconnect fittings, capable of discharging at various depths above the seabed. Diffusion of the effluent around the barge perimeter, coupled with the low gradient of the flexible subsea hoses, minimized the turbulent kinetic energy of the discharge. This approach was made especially practical by the comparatively low throughput rate of the underwater mining vehicle.

3) marine aggregate mining in Massachusetts Bay with a trailing-suction hopper dredge

Seabed Lithology and Mitigation. Repeated excavation of aggregate within a dredge course eventually may reveal different lithologies. As the workable deposit thins through repeated removal of sediments, high-spots in the underlying sequences are eventually exposed. These may be hard bedrock or glacial clay similar to that below the aggregate source in Massachusetts Bay. To the dredge operator such exposure raises the possibility of unwanted cargo contamination. Over-dredging has other effects. Local fishing may be affected if boulders become exposed since the potential for damaging trawling gear is increased. A layer of the original substrate should be left on the seabed to increase the ability of the original benthic communities to recolonize.

The mitigative solution is two-fold. Either avoid such concentrations of glacial sediments, or apply restrictions to the extent that aggregate may be removed only from the top of the vertical sediment sequence.

Seabed Profile and Mitigation. Even if some care is taken by the avoidance of an excessively repetitive dredge course and direction, trailer suction hopper dredging does not always yield a sufficiently flat seabed profile. After final excavation the seabed surface frequently contains too many peaks and valleys because the drag-heads have a tendency to track the previous excavation. The objective of dredging should be to plane, rather than to trench, the seabed. Operators should attempt to dredge courses adapted to the seabed geology, even if the courses are oriented across tidal flow. Ideally, the courses should be adapted to the contours of equal sediment thickness.

Water Quality Mitigation

Overflow Mitigation: Operational Technique. A practical mitigative technique is to delay the commencement of dredge hopper overflow. This is achieved by emptying all water out of the hopper before starting to pump any sediments on board. Water is discharged directly overboard as the dredge pump is primed. A switching mechanism is then used to direct the slurry to the hopper once sediments are entrained in the pumping system. As a result overflow does not occur until the hopper is filled to within 60-70% of its dredged material capacity. The time during which sediment-laden waters are released to the sea is thereby substantially reduced.

Overflow Mitigation: Re-cycling. The drag-heads of some trailing suction hopper dredges are equipped with water jets that are designed to assist in the liberation of compacted sediments when dredging hard ground. A small percentage of the hopper overflow water can be pumped to the drag head jets instead of using clean seawater, reducing slightly the total volume of sediment-laden overflow.

Overflow Mitigation: Hopper Design. The level of the aggregate surface in a loaded dredge hopper always must be above the load line in order to prevent surplus water from being transported to shore in addition to the solids. This can be achieved by modifying the shape of the hopper to keep much of the contents above the load line. Alternatively, special compartments may be employed on either side of the hopper.

Overflow Mitigation: Overflow Collection. An anti-turbidity measure proposed for hopper dredging is to install compartments on both sides of the dredge. These are designed to intercept and temporarily retain the overflow, allowing partial settling of suspended silts within them. However, there are potentially serious, practical, limitations:

(1) the retention time needed for substantial settling to occur

(2) the need, at intervals, to dispose of the accumulated silts

(3) the significantly reduced hopper capacity caused from the loss of vessel space by incorporating settling compartments.

Overflow Mitigation: Effluent Discharge. A relatively simple technique for handling hopper overflow, called an anti-turbidity overflow system (ATOS), has been developed in Japan. The overflow collection system is streamlined to minimize the entrapment of air bubbles in the overflow water. Removal of the air bubbles, which otherwise make the particles buoyant and prolongs settling, allows the fines to settle at a faster rate.

4) Heavy minerals dredging offshore of Virginia Beach, Virginia using a cutter suction dredge.

Water Quality Mitigation: Cutter-Generated Turbidity

Operational Mitigation. Several operational controls are recommended for the reduction of sediment resuspension. Most involve the manner of excavation. Very thick single-pass cuts should be avoided, because the cutter-head tends to become buried. As a result more sediment is excavated and dislodged than the suction can successfully entrain, leading to high levels of suspension. A thick deposit is best excavated by means of several horizontal slices, each layer of excavation being a single thin cut depth.

In other places it may be more economical to excavate and remove most of the sediments very roughly in a single cut. Final clean-up to the base of the pay zone may be delayed until later in the operation. However, the loosened sediments, while awaiting clean-up, may be at risk of suspension.

Where the mining plan involves dredging to a few meters below the seabed within a defined block the operation should proceed without excavating vertical walls in each cut. The sides should be inclined sufficiently so as to inhibit the slumping of loose sediments into the cut. The final walls of a cut should be terraced by reducing the area of cut with each successively deeper slice. On a smaller scale the formation of distinct cuts should be minimized. The dredge should be swung and advanced so as to cover equally all the seabed within the block. The cutter-head should be advanced by increments that are sufficiently small to ensure that very close concentric arcs are described on the seafloor with each swing of the cutter.

Design Mitigation. The cutter-head's suction should be sufficiently powerful to collect all the sediments it disturbs. Pick-up capability could be increased by including water jet booster systems or ladder-mounted submerged pumps. The cutter-head may be designed in such a way that the suction is brought closer to the sediments thereby improving the chances of entrainment. Differences in shape are particularly important if the cutter-head is not completely buried in the sediments.

The acute angle between the base of the cutter tooth and the upper surface of the sediments is referred to as the rake angle. Proper design of the cutter with an appropriate rake angle is an important mitigation factor. If the rake angle is too large, a gouging action throws soft, fine-grained sediments outward. If the rake angle is too small, however, resuspension occurs through impact.

Water Quality Mitigation: Plant Effluent

The most obvious water turbidity is created by the surface discharge of slurry effluents as tailings from the treatment plant. Mitigation may be attempted by:

(1) minimizing the possibilities of re-digging of the settled tailings through operational procedures

(2) improving the nature of the effluent by de-sliming, dewatering or degassing

(3) optimizing the manner in which effluent is discharged by employing sub-surface discharge and/or discharge diffusion

(4) modifying effluent behaviour in the sea by the use of flocculants.

Operational Mitigation. The mine plan should be designed to avoid significant encroachment of the dredge on the boundaries of a mining block which previously has been dredged and the surface of which is now covered with tailings. The deliberate exclusion of areas of low-grade ground from a first dredge course, on the assumption that they may be dredged as part of a subsequent program, should be avoided.

De-sliming and Dewatering. Separation of the effluent flow into its component parts of solids and water allows the materials to be discharged into the sea with less impact. The solids are not held suspended in the water by the boiling action which otherwise is evident. The water, although containing some fines, is more rapidly diluted by the surrounding sea water. De-sliming and dewatering systems include hydrocyclones, hindered settling classifiers, bucket-wheels and screws and dewatering screens.

Degassing. It is not known whether methane or hydrogen sulphide are present in seabed sediments offshore Virginia in the vicinity of the mining site. If either gas does occur degassing equipment should be employed downstream of the dredge pump to prevent depriming. Both the pump and degasser must be installed underwater because the water depth is greater than 10 m. To limit water column turbulence associated with released gases the installation of a conduit from the degasser to the surface is necessary to allow gases to be vented to the atmosphere.

Effluent Discharge Design. Surface water turbidity and the deposition of tailings on the seabed can be controlled to a significant extent by using a sub-surface discharge. Such an arrangement would consist of a reinforced rubber pipe attached to the vessel. It may be deployed in any attitude ranging from vertical to near horizontal. A reduced effluent discharge velocity could be achieved by fitting the end of a discharge pipe with a flared opening. This modification may require some experimentation to achieve the optimum arrangement.

Flocculants. The use of flocculants comprises the only means available of speeding the settlement of entrained silts. Flocculants have two effects. Firstly, because they are flocculated fine sand and silt are deposited together, thus preventing the natural separation of the two fractions that occurs naturally during settling. Secondly, the deposited silt is increased in volume by the entrapment of water. However, volumetric increase should be minimal if the correct amount of flocculant is used.

Seabed Profile and Mitigation

Operational Procedures. The creation of elevated ridges of tailings on the seabed along the dredge course, especially at its start, may be minimized during operations in several ways:

(1) a sufficiently wide cut face must be dredged

(2) the dredge must not be restrained by sidelines which are so short as to cause it to angle excessively

(3) the dredge must not be angled deliberately and unnecessarily into the corners of the cut face

(4) the gaining of depth at the start of a deep cut must be undertaken at a slow rate

Discharge Control of the Trommel Oversize. Every effort should be made at sea to re-mix the oversize and the undersize. This involves discharging the screen oversize as closely as possible to the solids produced as the cyclone product, without causing unnecessary turbulence.

Alternative Enhancement. Considerable potential exists for alternative enhancement initiatives when dredging for heavy minerals. In particular, the undersize tailings can be pumped ashore, if needed, for beach renourishment, the remediation of contaminated areas, and the creation of wetlands.

5) Beach nourishment at Ocean City, Maryland, using a cutter suction dredge pumping sand ashore or, alternately, a trailing-suction hopper dredge transporting sand to a nearshore pumping station

Prevention of Coastal Erosion. To avoid the possibility of erosion both the local hydrodynamic conditions and the sediment characteristics of the deposit being dredged must be considered. Wave refraction analyses and wave transformation modelling are a necessary input to a study. Prevention of erosion may be achieved by adopting a correct licensing procedure and by restricting the operation of a dredge to specified water depths and/or areas.

6.0 General Recommendations

General recommendations derived from the analysis presented in this report include:

(1) the use of Best Available Technology should be practiced with any marine mining operation. The use of Best Available Technology is not only beneficial environmentally but in most cases improves operational efficiency and is therefore of value to the operator.

(2) numerical modelling is a useful and cost-effective tool in the development of effluent discharge systems, the design of environmental monitoring programs, and the assessment of the potential risk of coastal erosion. Modelling should be implemented as part of any mining project that involves substantial discharge of effluents at sea, or of projects that may potentially affect coastal stability.

(3) well-designed environmental monitoring programs with appropriate QA/QC are a necessary component of any marine mining project. Monitoring ensures that regulatory constraints are observed, and also provides the operator with ongoing guidance as to the level of effort needed to meet those constraints.

(4) operational constraints of location, time and scale need to be determined before the initiation of any mining project, so that the economic viability of the project can be realistically assessed. From an operational and economic perspective, constraints on operations that are based on random occurrences such as sightings of particular species in the mining area are detrimental and potentially very costly. The possible implications of such constraints should be carefully considered.

(5) mitigation can in some cases be achieved cost-effectively through changes in operational procedures, such as the planned order and distribution of dredge courses or the depth and width of cut. The planning of any new marine mining venture should take into consideration the range of operational mitigation techniques presented in this report.

(6) many technology-based mitigation techniques, such as sub-surface tailings discharge systems, dewatering and degassing systems, and onboard feed monitoring systems, measurably reduce the impacts associated with a mining operation and can be implemented at reasonable cost. The implementation of these techniques should be considered for any future offshore mining development.

(7) the potential for alternative enhancement projects should be explored during the planning stages of future marine mining developments. For example, consideration should be given to the possibility of using tailings produced by a heavy mineral mining operation for beneficial purposes, such as beach nourishment or the creation or restoration of coastal wetlands.