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THE ECOLOGICAL CONSEQUENCES OF DREDGING AND DREDGE SPOIL DISPOSAL IN CANADIAN WATERS

BY

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NATIONAL RESEARCH COUNCIL OF CANADA

NRCC ASSOCIATE COMMITTEE ON SCIENTIFIC CRITERIA FOR ENVIRONMENTAL QUALITY

THE ECOLOGICAL CONSEQUENCES OF DREDGING AND DREDGE SPOIL DISPOSAL IN CANADIAN WATERS

Prepared for the Subcommittee on Water

by

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SUMMARY

This document summarizes current knowledge of the ecological consequences of dredging and dumping on aquatic ecosystems in Canada. The review does not intend to establish the significance of this industrial activity in comparison to natural changes in ecosystems. Erosion and sedimentation resemble dredging and dumping qualitatively. Quantitative relationships can usually only be established in relatively closed systems. The local impact of dredging and disposal may be appreciable, and hence its immediate relevance and scale must be determined by lacustrine or coastal ecosystem managers. This document provides a perspective on research priorities that highlights the type of information required to upgrade knowledge for these people to use. The decision as to which ecosystem should receive the most immediate attention must be made by a variety of officials, including scientists.

In 1979, 19.6 x 10^6 m^3 of dredged materials were disposed of in Canadian coastal waters. Over the period 1975 to 1979, 2.5 x 10^6 m^3 were disposed of in Canadian sectors of the Great Lakes. Types of dredging apparatus include draglines, clamshells, and suction dredges, which account for the largest volumes. Dumping is accomplished with barges, hopper vessels, and pipelines.

Research on the ecological effects of dredging elsewhere in the world can usually be only partially applied to the Canadian situation, except in obvious cases where U.S. waters are contiguous. The available information from elsewhere is often not appropriate because of differences in impact, in local species composition, and ecosystem characteristics. Much of the research to date was not designed to address ecological impacts. For example, the biological research conducted by the U.S. Army Corps of Engineers Dredged Material Research Program focussed on polluted sediments and how to deal with them (e.g. U.S Army Corps of Engineers 1980). The "Gold Report" (Anonymous 1975b) was another major consolidation of knowledge, in this case pertaining to freshwater dredging and disposal. Nevertheless, a review of these extensive programs and others indicated that there has been little progress in understanding and predicting changes in ecological systems, which must be the basis for rational decisions to protect renewable resources. Bioassay and bioaccumulation approaches are necessarily designed primarily to protect human health, and cannot easily be related to the populations and communities of ecological systems.

The major impact of Canadian dredging is the physical disruption of ecosystems. Since the ecosystems themselves are so poorly understood, more emphasis is required on ecological research than on laboratory testing. Much of the dredging and dumping in Canada results in either frequent physical disruption on a small scale (≤1 ha) (e.g. Atlantic fishing ports), or large-scale suction dredging (e.g. Fraser

River annual dredging or Beaufort Sea artificial island construction, typically ≥ 10 ha). These latter projects move millions of cubic metres of water and sediment through dredges each year. The vast majority of fish and invertebrates entrained in suction dredges are fatally injured or are buried in spoil piles. This disruption is occurring mainly in the nearshore zone, where juvenile fish rear and migrate. The physical effects of dredging and dumping are not necessarily directly proportional to the volumes moved, as sensitive habitats such as salmon spawning beds can be seriously affected by small dredging operations.

There are limited data on the effects of dredging and dumping on production systems (primary, secondary) supporting fish and wildlife. Data on the effects of dredged material on algal primary production show that excessive turbidity, often associated with dredging and dumping, has little effect on phytoplankton but nearshore algae (e.g. kelp beds) can be damaged by disposal. Marshes are susceptible to smothering. Effects on secondary production by zooplankton and zoobenthos have been poorly investigated. The structure of benthic communities is usually changed by dredging and dumping, primarily because of changes in sediment type. Depending on the thickness and dispersal of dumped material, burial can permanently immobilize benthic organisms. In coastal waters, the rate of colonization by mobile animals that live on the surface of the sediment (e.g. shrimp) is rapid if the water quality is not permanently impaired. Colonization of sedentary organisms by pelagic larvae, often hardier species than those originally present, is variable (time scale of months or years) and is dependent on site-specific factors such as local sedimentation, water current velocity, and depth. There is some evidence that recolonization in lakes is much slower.

Sediments in industrial harbors in Canada sometimes contain assorted heavy metals, nutrients (nitrogen, phosphorus), organic pollutants, and wood wastes. When these types of sediments are removed by dredging and dumped elsewhere, there are concerns that these substances contained in sediments may be taken up by biota and hence may endanger human health. Finer sediments, which disperse further, accumulate more chemicals, and have greater dissolved oxygen demand than coarser material, pose more risk than sands and gravel.

In spite of much research in Canada and elsewhere, the remobilization and bioavailability of chemicals from dumped sediments are not clearly understood. Feeding ecology of invertebrates and sediment geochemistry (minerology) are major areas requiring further study. Laboratory experiments and bioassays with sediments from Halifax Harbour showed some uptake of polychlorinated biphenyls by the bivalve *Macoma balthica*, but no mortality. Similar results were reported with this bivalve and sediments from New Brunswick harbors containing cadmium. The burrowing speed of *M. balthica* was inhibited by sediments from the vicinity of a shipyard in Vancouver Harbour. The toxicity of eight individual organochlorine compounds was tested with an Atlantic coast shrimp (*Crangon* *septemspinosa*), and it was found that the organochlorines were about 10 to 80 times less toxic in sediment than in water. Shoreline vegetation at Lake St. Clair, Ontario, may have accumulated mercury from sediments which were placed in a containment structure. In lakes there is concern that nutrients released by dredging can lead to the stimulation of algal blooms and eutrophication. Experiments with lake simulator columns have demonstrated this possibility.

One of the most promising ecological approaches for investigating the effects of dredging and dredge spoil disposal involves material budgets and models. This technique has been used in the Great Lakes in the context of phosphorus release from dredging operations, and at Alberni Inlet, British Columbia, in the context of dissolved oxygen depletion due to wood waste disposal. Recently, there has been a comprehensive study of the sources and transport modes of a wide variety of metals and other chemicals in the Great Lakes (Anonymous 1982). Both natural and industrial pathways were considered. Models and budgets encourage an examination of the whole system. Even "bookkeeping" tabulations could lead to simple management models which could be used to plan dredging and disposal for major harbors. From a resource species viewpoint, it should be emphasized (Section 5.2.2) that there are few benthic production data available for Canadian coastal waters and lakes for use in models. Once baseline production data are available, it might be possible to evaluate ecosystem performance under the impact of dredging and dumping. Performance criteria such as growth parameters have been suggested elsewhere (ACMRR/IABO 1976) but have not been regularly used. Most benthic monitoring programmes, both in Canada and elsewhere, use standard procedures involving determination of numbers of species, number of individuals, and biomass.

A variety of experimental techniques are available for investigating the physical, chemical, and biological effects of sediment disposal. Chemical and biological effects resulting from Lake Ontario sediments containing nutrients were studied by means of lake simulator columns, which were instrumented using temperature control to provide stratification. A somewhat similar approach was taken with sediments contaminated with wood waste from Alberni Inlet, B.C. Lysimeters were used to examine the solubility of organic compounds and hydrogen sulfide in water overlying sediments. Hydraulic or physical models were used to predict the stability of dredged sand and mud at disposal areas on the Fraser and Miramichi estuaries, respectively. River and tidal currents were the major physical forces considered. Wave action was studied separately using numerical models.

Until techniques and data become available for modelling impacts, and until benthic remobilization is understood, the procedures for choosing dumpsites, justifying existing locations, and deciding whether or not dredging will affect the environment and/or resources will have to be qualitative. Choosing a new dumpsite should take into account the nature of the material to be dumped, the local physical features of the water body (depth, dispersion characteristics), the projected time span of dumping, and the resource species present. The existing locations and dumping practices should be justified through monitoring programs encompassing features such as those shown in Appendix Table II.0. The monitoring of potentially deleterious substances in biota at dumpsites is essential. Information on timing of fish migration, such as data given in Table 6-1, is needed to reduce the impact on fish populations. In summary, the impact of dredging and dumping must be examined using strategies that are ecosystem-specific and take into account ecological processes and local species composition.

RECOMMENDATIONS

The following recommendations, put forth from an ecological perspective, are suggested research areas that are particularly pertinent to Canadian waters. They are not ranked in order of priority.

1. Except for a few relatively well known commercial species, the data base for the timing of fish migrations in Canadian waters is very poor. Fish behavior, especially of the more vulnerable juvenile stages, is poorly understood, and basic biological data such as locations of spawning grounds are often not available. To help develop engineering techniques and avoid killing fish through uptake into suction dredges, and to assist in locating dumpsites, it is recommended that:

   RESEARCH ON FISH MIGRATIONS AND SPAWNING BEHAVIOR BE ACCENTUATED. SPECIAL EFFORT IS NEEDED IN NORTHERN AREAS, WHERE THE PUBLISHED DATA BASE IS SMALL AND DREDGING VOLUMES ARE LARGE BY CANADIAN STANDARDS.

2. Current techniques for locating dumpsites involve site-specific surveys and local knowledge to avoid conflicts with resources (e.g. shellfish). This is probably the only way that small isolated dredging projects that will occur only once can be scrutinized. However, for major harbors that require frequent, large-scale and repetitive dredging, it is recommended that:

   COMPREHENSIVE MANAGEMENT MODELS BE FORMULATED FOR MAJOR HARBORS TO PLAN THE DISPOSAL OF DREDGED MATERIAL IN THE LONG TERM. ASPECTS SUCH AS SURFACE AREA AT SPECIFIC DEPTHS, BURIAL OF POTENTIALLY DELETERIOUS SUBSTANCES, AND HABITAT DEVELOPMENT PROSPECTS, COULD BE CONSIDERED USING PHYSICAL OR HYDRAULIC MODELS. NUMERICAL MODELS ARE NEEDED TO PREDICT DISPERSAL OF CHEMICALS AND BUDGETS FOR MATERIALS (E.G. NUTRIENTS, DISSOLVED OXYGEN), ESPECIALLY IN COASTAL WATERS.

3. The evaluation of the hazards of dumping dredged material is currently conducted with bulk analyses of sediments, sometimes in conjunction with bioassays, data on dispersal, and infrequently with data on bioaccumulation from previous disposal or from natural sources. To gain information on the physical, chemical and biological fate of dumped materials, especially bioaccumulation, it is recommended that:

DATA BE OBTAINED ON PATHWAYS AND LEVELS OF COMPOUNDS AND ELEMENTS IN A WIDER VARIETY OF FISH AND INVERTEBRATES AT DUMPSITES AND AT REFERENCE SITES, IN ORDER TO DELINEATE ANY DIFFERENCES BETWEEN DUMPSITE AND BACKGROUND CONDITIONS.

4. It is possible to estimate the area on the bottom of a water body affected by dredging and dumping activity, and hence losses of benthic animal biomass and changes in community structure can be calculated. However, interpreting these losses in terms of productivity and effects on commercially important fish stocks is not possible because of the lack of basic understanding of aquatic ecosystem processes. It is recommended that:

BASIC ECOSYSTEM RESEARCH TO ESTABLISH THE IMPORTANCE OF LOSSES OF BENTHIC PRODUCTION FOR FISH BE ACCELERATED. THESE STUDIES WILL REQUIRE INTENSIFICATION OF STUDIES ON THE BASIC BIOLOGY AND POPULATION ECOLOGY OF BENTHIC INVERTEBRATES, ESPECIALLY IN NEAR-SHORE ZONES. WITHOUT SUCH DATA, IT IS NOT POSSIBLE TO EVALUATE THE MERITS OF CONCENTRATING A DUMPSITE IN A RESTRICTED AREA AND THEREBY SACRIFICING LOCAL BIOTA IN PREFERENCE TO SPREADING DUMPED MATERIAL OVER A WIDE AREA.

5. Dredging and disposal of sediment containing fine particulate material and wood wastes can lead to the release of hydrogen sulfide and reductions in dissolved oxygen. However, the dispersion, rates of microbial activity, dissolved oxygen utilization, and sulfide production when this material is introduced to water are largely unknown. It is therefore recommended that:

RESEARCH BE CONDUCTED TO EXAMINE THE MICROBIAL, CHEMICAL, AND DISPERSIVE ASPECTS OF DUMPING DREDGED MATERIAL RICH IN FINE PARTICULATE MATERIAL AND/OR WOOD.

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1.0 INTRODUCTION

Canada's extensive coastal waters, lakes, and rivers are used as internal highways, exits, and entrances for cargoes shipped to and from the rest of the world. Ports are often located in estuaries, acknowledged to support some of the most productive ecosystems in the biosphere. Many Canadian shorelines are relatively young from a geological perspective and hence sediments from rivers are filling waterways at a variety of rates, ranging up to several metres per year, for example, in the Fraser River in British Columbia. To keep ports open, dredging and subsequent disposal of the sediment are required, thus creating conflicts with human settlements, renewable resources, and their supportive ecosystems.

This review summarizes our current knowledge of the ecological consequences of dredging and open water dumping on aquatic ecosystems in Canada. In recent years, passage of federal legislation, the Ocean Dumping Control Act (Anonymous 1975a), has focussed attention on the issue and has led to considerable investigation of the impact of dumping. The Canada-U.S. Great Lakes Water Quality Agreements (1972 and 1978) have served a similar function. A number of bibliographies listing or summarizing the national and international literature have recently been published (see, for example, Allen and Hardy 1980; Anonymous 1975b; Bernard 1976; Windom 1976; Morton 1977; Baram *et al.* 1978; Bezanson *et al.* 1979; Conlan and Byers 1979), but no synthesis of the problem as it pertains to Canadian waters is available.

This document examines the literature pertinent to Canadian waters; literature dealing with Alaska and the continental United States to approximately 40°N was considered whenever insufficient data to completely develop concepts or problems were found in the Canadian literature. Research from northern Europe and Asia was considered, as was all work deemed sufficiently important for general or universal application. Literature searches using computer-stored data bases were also conducted. The extensive reports of the Dredged Material Research Program of the U.S. Army Corps of Engineers were reviewed (U.S. Army Corps of Engineers 1980). Documents prepared for international agencies (e.g. GESAMP 1975) were also examined.

Deleterious effects associated with dredged material disposal may be classified into physical and chemical aspects, each with very different ecological consequences. The relative importance of the two varies depending on industrial circumstances at the individual ports across Canada. On the Atlantic coast, physical disruption of benthic ecosystems has a major impact, as the small ports and fishing harbors are subjected to frequent dredging of sand due to infilling by the prevailing coastal currents (McLean and MacGregor 1976). For example, over the period 1950 to 1974, Richibucto, New Brunswick, ranked 34th (out of 50 Atlantic ports) in quantity removed, but was second in frequency of dredging (43 jobs). Construction relating to oil exploration in the Beaufort Sea involves the pumping of millions of cubic metres of water and sediment (Arctic Laboratories Ltd. 1979). In recent years the annual weight of dredged sediment in the lower Fraser River has been about 3.5 x 10^6 tonnes (Anonymous 1978).

Large-scale dredging and dumping at industrial harbors can release potentially deleterious materials into the pelagic and benthic ecosystems, and hence both physical and chemical problems arise. In Lake St. Clair, for example, mercury in dredged sediments could have been introduced to fish habitats and therefore required construction of a containment structure to hold the material (Brooksbank 1980). In British Columbia coastal waters, dredging often involves the disposal of waste material rich in wood, with attendant potential problems of decreases in dissolved oxygen and possible fish kills in estuaries.

The geographic distribution of dredging activity on the Atlantic (Figure 1-1) and Pacific (Figure 1-2) coasts and in the Great Lakes (Figure 1-3) shows that on a volume basis, the disruption matches the distribution of industrial centers. In 1979, the volume of dredged material disposed of in Canadian coastal waters (Ocean Dumping Control Act permits) was 19.6 x 10^6 m^3. One of the largest dredging projects in Canada in recent years was conducted in 1979 and 1980 on the Beaufort Sea coast, where 8.8 x 10^6 m^3 were dredged to make an overwintering harbor for drill ships (Albery *et al.* 1981). In addition, numerous artificial islands have been constructed in the Beaufort Sea by dredging (Figure 1-4). It must be kept in mind that this document does not attempt to examine the significance of these industrial activities in comparison to the significance of natural processes. Although natural processes are responsible for the relocation of large quantities of material, the local impact of man-made dredging and disposal may also be appreciable.

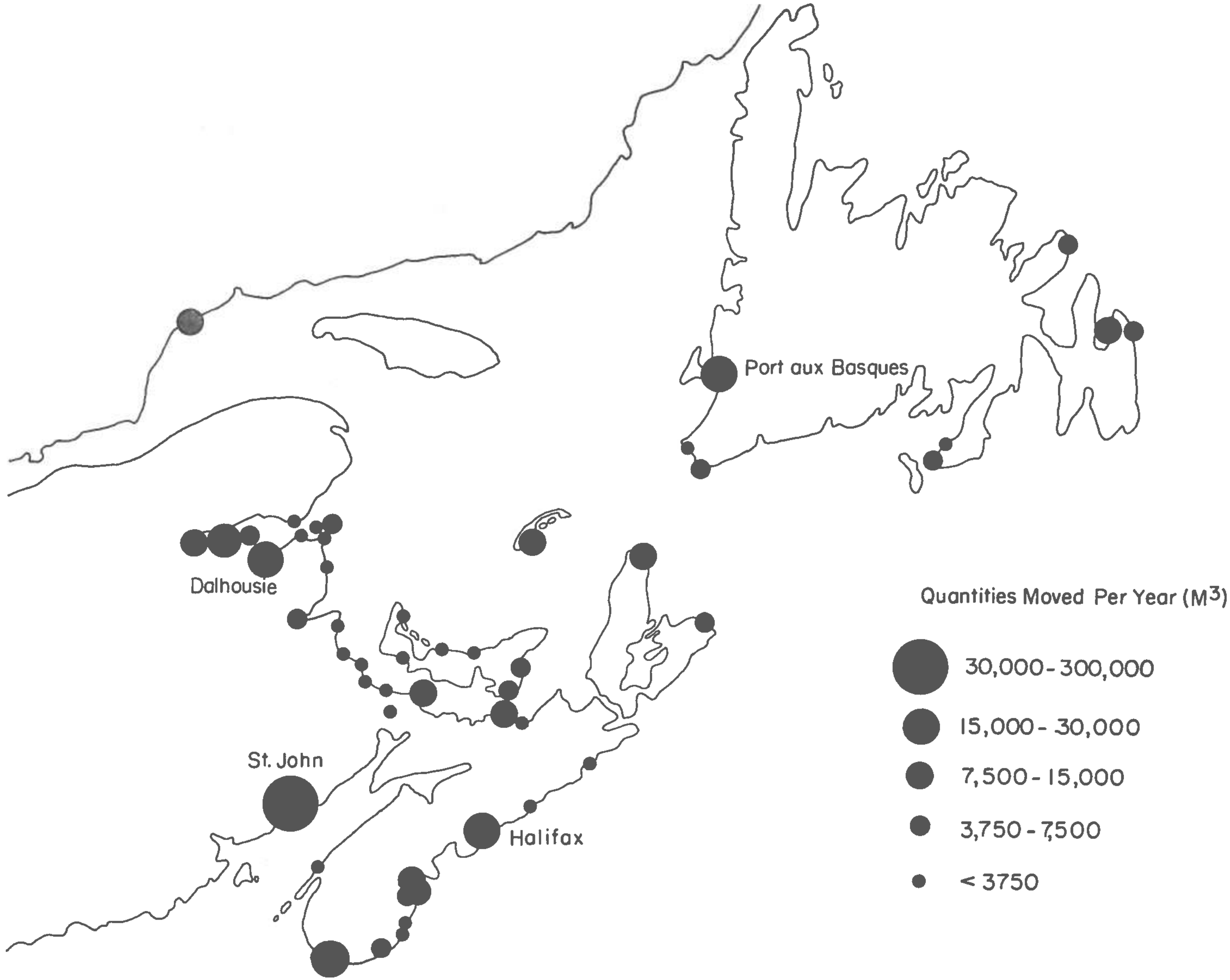


Figure 1-1. Geographic distribution of dredging and dumping activities on the Atlantic coast of Canada (from McLean and MacGregor 1976).

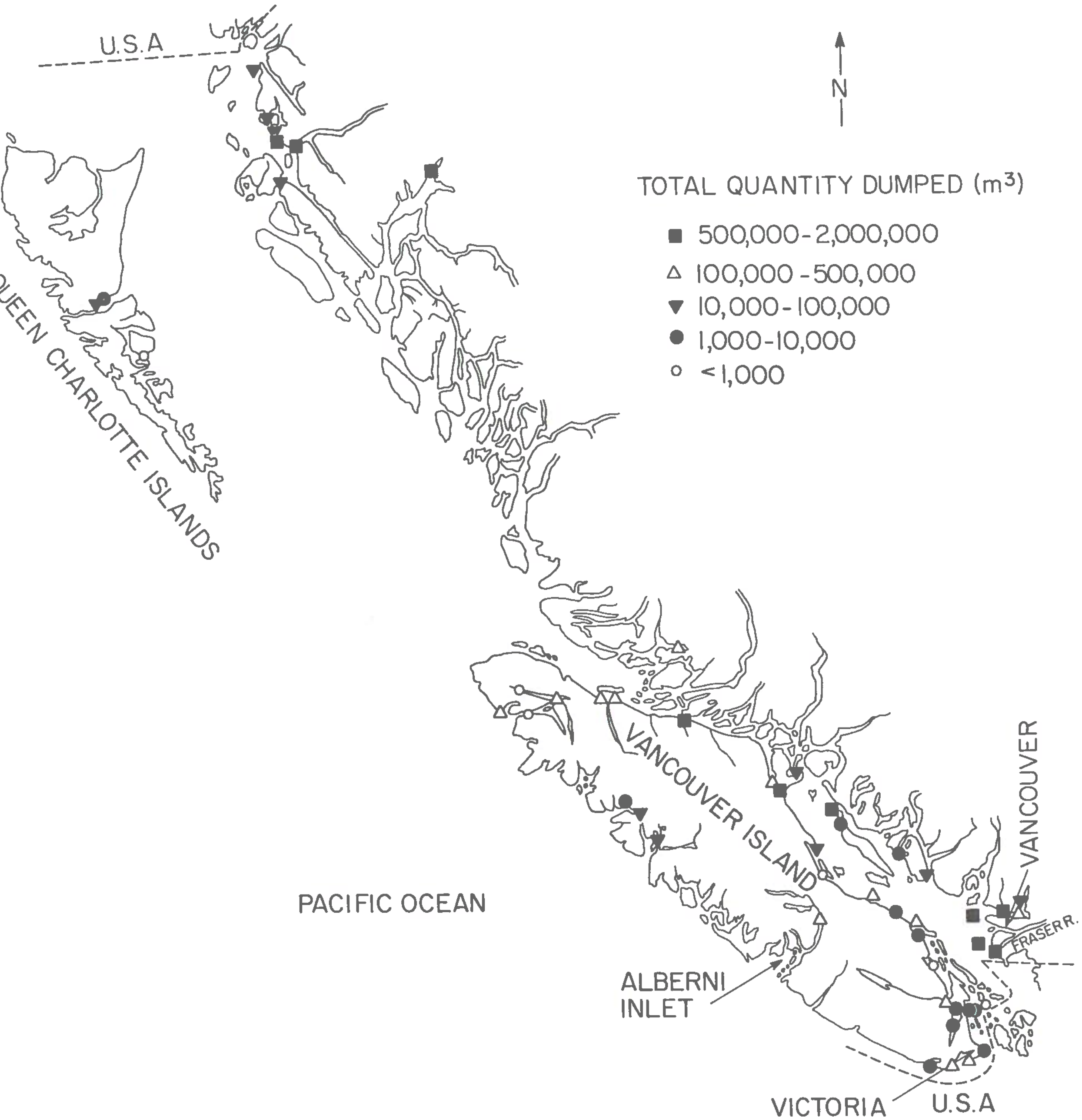


Figure 1-2. Geographic distribution of dredging and dumping activities on the Pacific coast of Canada [total quantities shown] (from Ward and Sullivan 1980).

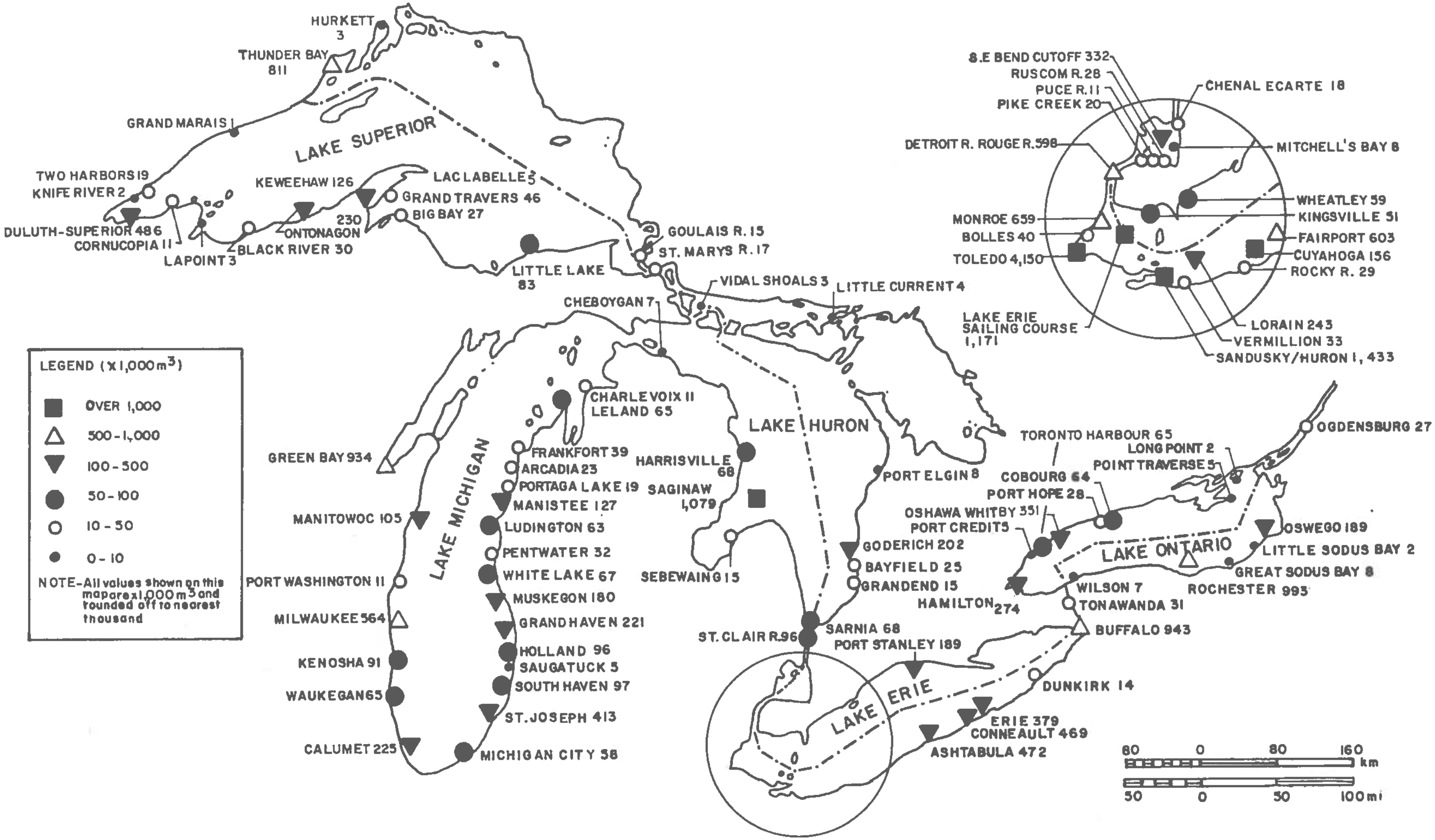


Figure 1-3. Geographic distribution of dredging and dumping activities in the Great Lakes (1975-1979) (from Beach 1981).

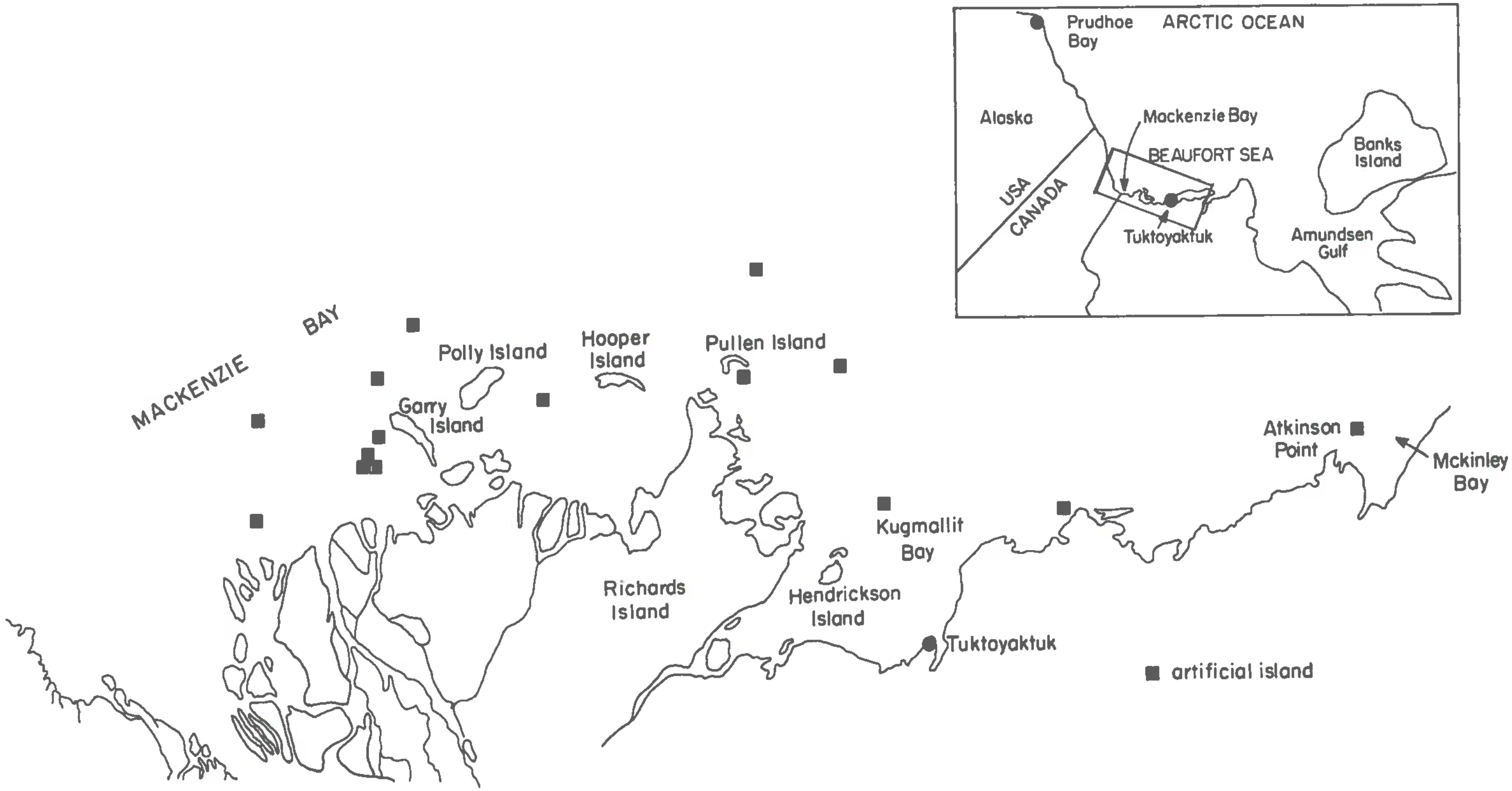


Figure 1-4. Geographic distribution of artificial islands constructed by dredging over the period 1974 to 1976 in the southern Beaufort Sea (from Slaney 1977).

2.0 DREDGING AND DUMPING OPERATIONS

2.1 DREDGING

Sediments are removed from the bottom of bodies of water, and subsequently out of navigable channels, using a wide variety of vessels and techniques. (A glossary of relevant terms appears in Appendix I.O.) The relationship between the gross categories of sediment type and apparatus used for removal is demonstrated in Figure 2-1. Clamshell and cutter dredging operations have the capacity to remove the widest variety of sediment types. Because of the large variation in sizes, it is difficult to describe in detail the typical dredge used in Canadian waters. Some of the simplest techniques for shallow waters (e.g. in rivers and lakes) involve the use of draglines, where a shore-based machine drags material from the center of a water body onto the shore or to an area which does not impede navigation. In small streams, bulldozers may be used. A variant of the dragline operation, the clamshell, is frequently used to move material or to load barges. The clamshell is an opening/closing bucket device lowered into the water, usually from a floating crane.

Major dredging operations usually involve suction (hydraulic) dredging. In this procedure hydraulic pumps are used to lift unconsolidated sediments (usually mud or sand) from the sea or lake bed. In instances where the material is to be moved relatively short distances (e.g. less than 1 km), the sediments are pumped in a slurry through floating pipelines. During recent dredging operations for construction of artificial islands in the Beaufort Sea, floating pipelines of up to 5 km were used. For dredging operations which require movement of large amounts of material over longer distances, hopper dredges are usually used. These are ships which load dredged material into their holds or hoppers through suction lines or draggerheads lowered to the seabed. When the hoppers are full, the vessel travels to the dumpsite, where the contents of the hopper are discharged. A variety of cutting heads are installed on the suction ends of hydraulic lifting apparatus. These rotating devices serve to release sediments from their natural, semi-consolidated state into a slurry which can be dumped.

2.2 DUMPING

Obviously, the method used for release of dredged material depends on the device initially used for removing it. When material is dumped into barges from clamshells, dredge spoils are pushed off the barge using front-end loaders or bulldozers, or self-emptying (bottom-opening) barges may be used. Hopper dredges usually discharge with the latter technique. An example of such a dredge appears in Figure 2-2. Suction dredges discharging through floating pipelines empty the sediment/water slurry directly, either below or above the water surface.

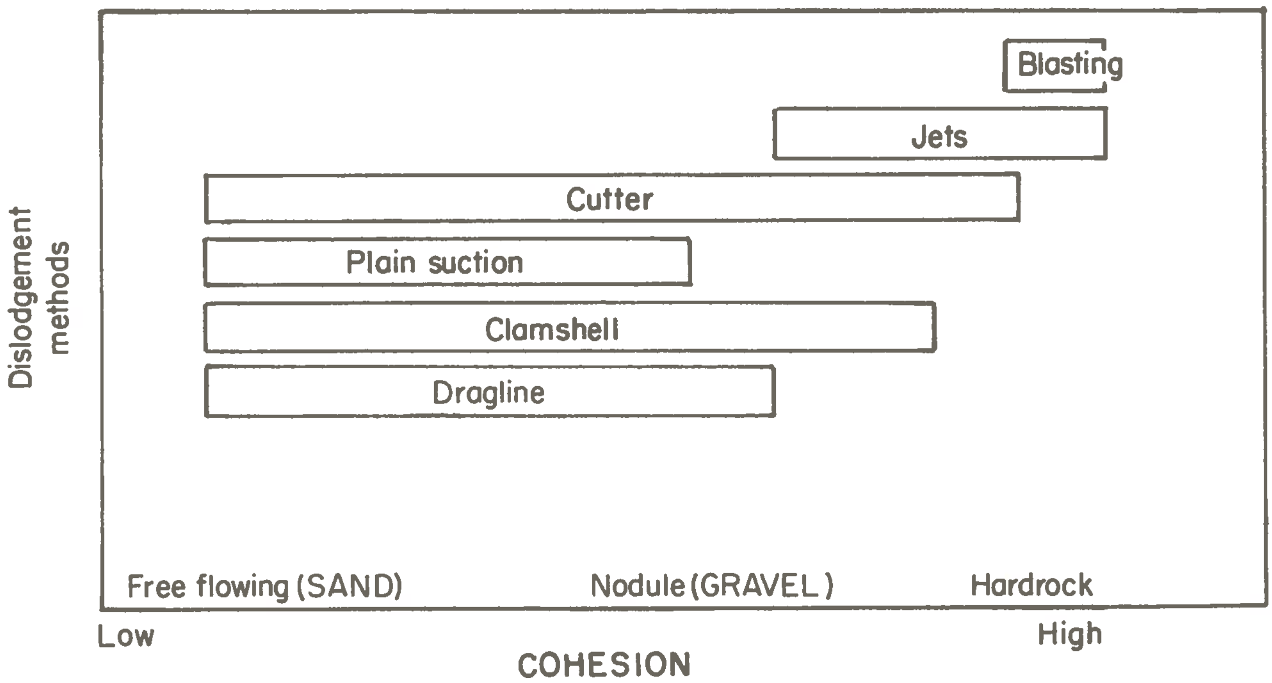


Figure 2-1. Methods used in dredging materials of differing cohesion (from Baram *et al.* 1978).

Fig. 2-2 Photograph of hopper dredge discharging dredged material off Port Hawkesbury, Nova Scotia, August 1975. Photo courtesy MacLaren Atlantic Ltd. (from MacLaren Atlantic Ltd. 1975).

2.3 SPOIL CHARACTERISTICS

The characteristics of spoil dredged from harbors located near estuaries reflect river hydraulics and local oceanography. For example, in the Fraser River estuary, British Columbia, sand (approximately 500 µm in diameter) is the major constituent dredged, as the bed load of the river is mainly composed of this material (Table 2-1). The finer silts and clays are part of the washload (somewhat comparable to the suspended load) and rarely have to be dredged from the main shipping channels of this river. At estuaries where the river gradient is less steep, heavier material such as sand and gravel is deposited further upriver, beyond the limit of navigation. The finer material (silt, clay) is deposited in the estuary harbor, where it must be dredged. In many of the smaller harbors of Atlantic Canada, sand moves into harbors through the action of longshore currents (McLean and MacGregor 1976); similar phenomena occur in the Great Lakes.

Lake sediments frequently consist of fine material rich in organic matter, with extremely slow settling rates. Gravel sediments in upper reaches of rivers are highly mobile because of currents. These sediments are sometimes used directly as construction materials (e.g. in concrete or as road beds) or are moved to improve navigation of shallow-water craft. Major conflicts have arisen because of the potential disruption of fish spawning habitat, especially in British Columbia, specifically the Fraser River (see Boyd 1975).

One of the common types of industrial waste in the sediments of Canadian harbors is that derived from wood-processing industries (sawmills, pulp mills, and log storage). Wood fragments, bark, fibers and waste paper are lost to the aquatic environment. Wood waste is frequently dredged in estuaries such as the Fraser in British Columbia (Table 2-1) and the Miramichi in New Brunswick (Rashid and Reinson 1979).

The specific gravity (usually 1.0 to 1.5) and size of the wood debris (1 mm to more than 1 m) are important attributes, as the former determines sinking rate and the latter influences rates of microbial attack, which in turn control oxygen demand. When the more labile carbohydrates (e.g. hemicelluloses) are removed from the wood particles by bacteria, the remaining lignin is extremely refractory and, from an ecological point of view, is an inert substance. Inorganic material (e.g. sand) from natural sedimentation is often mixed with the wood wastes (Table 2-1) and sinks at different rates when dumped with the wood.

Dredging and dumping of substances such as Hg, Cd, and PCBs in sediments near industrial sites can pose risks to human health and aquatic ecosystems. Table 2-2 shows analyses of sediment samples from Halifax Harbour, obtained in a survey before dredging. Because of the complex behavior of chemicals in sediments during dredging and after dumping, both

Table 2-1. Sediment characteristics from representative dredging and disposal operations in the lower Fraser River, British Columbia, 1975 to 1979 (data from Ocean Dumping Control Act permit applications).

Location	Number of operations	Volume moved ($m^3 \times 10^3$)	Percent sediment <63 µm (mean (range))	Percent loss-on-ignition (mean (range))
Adjacent to sawmills or wood products docks	7	55	53(3-86)	5.8(1.0-15.6)
Main navigation channel (south arm)	3	1003	0	1.5(0.4-5.6)

Table 2-2. Analyses of five sediment samples from an area in Halifax Harbour destined for dredging (data from Packman 1982).

Sample site	Cd	Cu	Pb	Zn	Hg	Oil	PCB	Organic carbon	Inorganic carbon	Gravel	Sand	Silt	Clay
	$(mg\ kg^{-1})$						$(mg\ kg^{-1})$	(%)	(%)	(%)			
A	2.14	281.0	344.0	540.0	1.60	230.0	1500.0	67.6	4.3	1.86	15.62	43.83	38.69
B	2.01	418.0	576.0	736.0	10.30	280.0	1500.0	66.2	0.1	7.65	33.08	30.61	28.66
C	1.68	149.0	596.0	436.0	5.94	51.0	940.0	69.9	3.0	4.07	23.44	49.30	23.19
D	1.68	253.0	428.0	493.0	6.48	84.0	22000.0	57.1	3.4	2.14	22.81	50.30	24.75
E	0.43	80.0	177.0	172.0	8.79	44.0	410.0	20.8	0.8	2.51	59.41	23.94	14.14

the analytical methods and concentration limits for allowing aquatic disposal of these types of sediments are controversial. Although definitive information is not available, regulations and guidelines have been put forth for both marine and freshwater disposal in Canadian waters. Tables 2-3 and 2-4 deal with the concerns of the Ocean Dumping Control Act (Anonymous 1975a) and the Ontario Ministry of the Environment (1979), respectively. Bulk analyses, elutriate tests (U.S. Army Corps of Engineers 1976) and bioassay procedures (EPA 1978) are part of the testing schemes for setting these types of regulations. However, results are very dependent on chemical reactions which in turn vary with ambient water properties. Other problems include extrapolating from freshwater to marine situations, accounting for natural background, and assessing the availability of specific chemicals to biota. Some of these issues are examined in the following sections.

Table 2-3. Classification of substances under the Ocean Dumping Control Act (Canada)[a] (from Waltor 1978).

Classification	Compounds	Comments
Schedule I substances[b]	- Organohalogen compounds - Mercury and mercury compounds - Cadmium and cadmium compounds - Persistent plastics and other persistent synthetics - Crude oil, fuel oil, heavy diesel oil, lubricating oils, hydraulic fluids, and any mixtures containing any of them - High-level radioactive wastes or other high-level radioactive matter that may be prescribed - Substances in whatever form produced for biological and chemical warfare	Dumping prohibited except in special circumstances
Schedule II substances	- Arsenic, lead, copper, zinc, beryllium, chromium, nickel, vanadium, and their compounds - Organosilicon compounds - Cyanides - Fluorides - Pesticides and their by-products not listed in Schedule I - Containers and scrap metal - Radioactive wastes or other radioactive matter not listed in Schedule I - Substances that by reason of their bulk would interfere with fishing	Restricted
Schedule III substances	- Substances not listed above	Permits required

[a] Allowable limits for various substances are given in Appendix IV.

[b] See Swiss *et al.* (1980) for a review of these substances.

Table 2-4. Ontario Ministry of the Environment guidelines for sediment disposal (from Ontario Ministry of the Environment 1979).

Material	Allowable levels (percents are calculated on weight basis)
Volatile solids (loss-on-ignition)	6%
Chemical oxygen demand	5%
Total Kjeldahl nitrogen	0.2%
Total phosphorus (as P)	0.1%
Iron	10,000 mg kg^{-1}
Oil and grease	1500 mg kg^{-1}
Zinc	100 mg kg^{-1}
Ammonia	100 mg kg^{-1}
Lead	50 mg kg^{-1}
Chromium	25 mg kg^{-1}
Copper	25 mg kg^{-1}
Nickel	25 mg kg^{-1}
Arsenic	8.0 mg kg^{-1}
Mercury	0.3 mg kg^{-1}
Cadmium	0.1 mg kg^{-1}
Cyanide	0.1 mg kg^{-1}
PCBs	0.05 mg kg^{-1}

3.0 PHYSICAL EFFECTS

3.1 TURBIDITY

The physical characteristics of dredged material determine its fate after dumping, especially the rate at which it returns to the bottom. The sinking rate of particles is strongly dependent on their size, shape, and specific gravity. In estuaries, Stokes Law (see Appendix III.0), which is often invoked to explain the behavior of particles, is not applicable, and instead flocculation becomes an important process (Kranck 1974). In freshwater, turbulent diffusion has been found to be a major process controlling sedimentation.

When particles remain in the water column for a significant time, water transparency is reduced by turbidity and the concentration of suspended material is increased in comparison to natural levels. There are important exceptions to the latter situation, especially at estuaries such as the Fraser (Milliman 1980) and Mackenzie (Pelletier 1975) where the suspended sediment levels are naturally high. With most types of sediments, surface clarity is rapidly restored, usually within an hour after dumping. For example, settling experiments with sediments and wood wastes from the vicinity of a pulp mill in Nova Scotia followed this time scale (Figure 3-1).

In general, sand and gravel disposal does not cause turbidity, whereas the dumping of mud and silt can lead to an increase in suspended material. For example, sand dredged from the Fraser River and dumped from a hopper dredge in the Strait of Georgia sank very rapidly (Wong *et al.* 1976). Similar behavior would be expected from gravels. In contrast, mud and silt dispersed by a large suction dredge in the Beaufort Sea formed a turbidity plume which could be detected up to about 3 km downstream of the dumping operations (Slaney 1977) (Figure 3-2). The author commented that with tidal rotation of the turbidity plumes over the time required to build the artificial island, the total area affected could approach 63.4 km^2. In Alberni Inlet, the vertical distribution of turbidity was modified after the dumping of dredged material (Dobrocky Sea Tech Ltd. 1974a) (Figure 3-3). The dispersion of suspended material following dumping near Bronte Harbour, Lake Ontario, was found to be very dependent on wind-generated surface currents (Chemex 1973b) (Figure 3-4). In all cases, the duration of excess turbidity was variable in time and space, and especially subject to tide, river runoff, and wind effects.

3.2 REDISTRIBUTION OF DUMPED MATERIAL

The depth and location at which dredged material of any description is dumped are very important for determining the physical forces contributing to redistribution after dumping. Material dumped in shallow

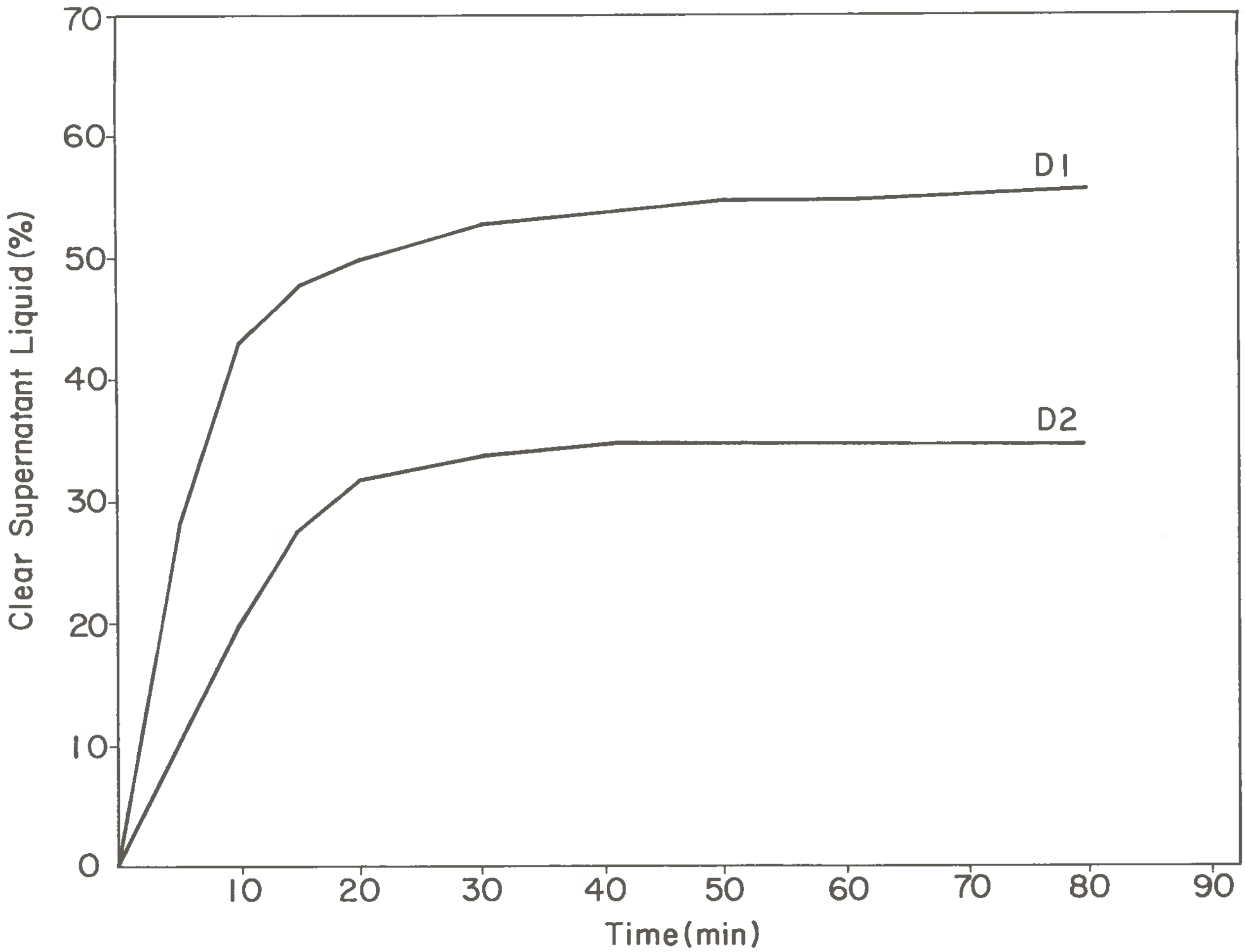


Figure 3-1. Time for restoration of water clarity in laboratory tests with dredged material from the vicinity of a pulp mill at Port Hawkesbury, Nova Scotia (from MacLaren Atlantic Ltd. 1975). D1, D2 are samples from two stations in the harbor.

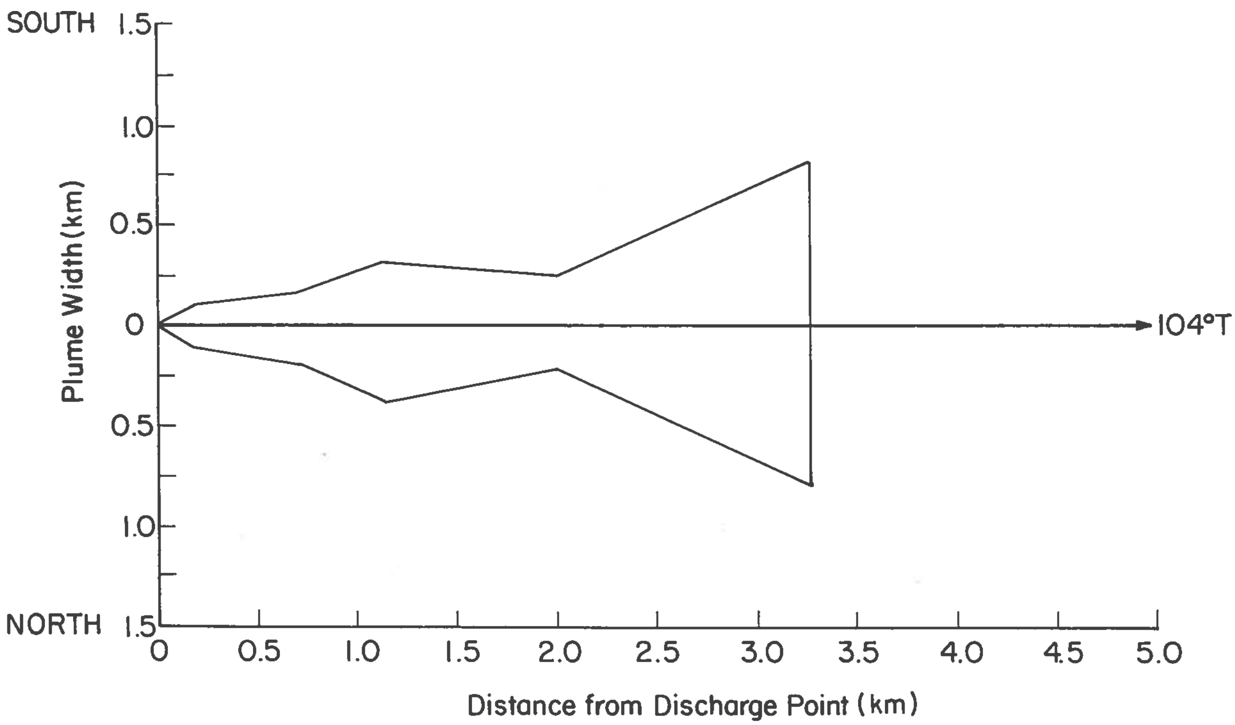


Figure 3-2. Surface turbidity plume from dredging to create an artificial island in the Beaufort Sea (Arnak L-30, August 5, 1976) (from Slaney 1977).

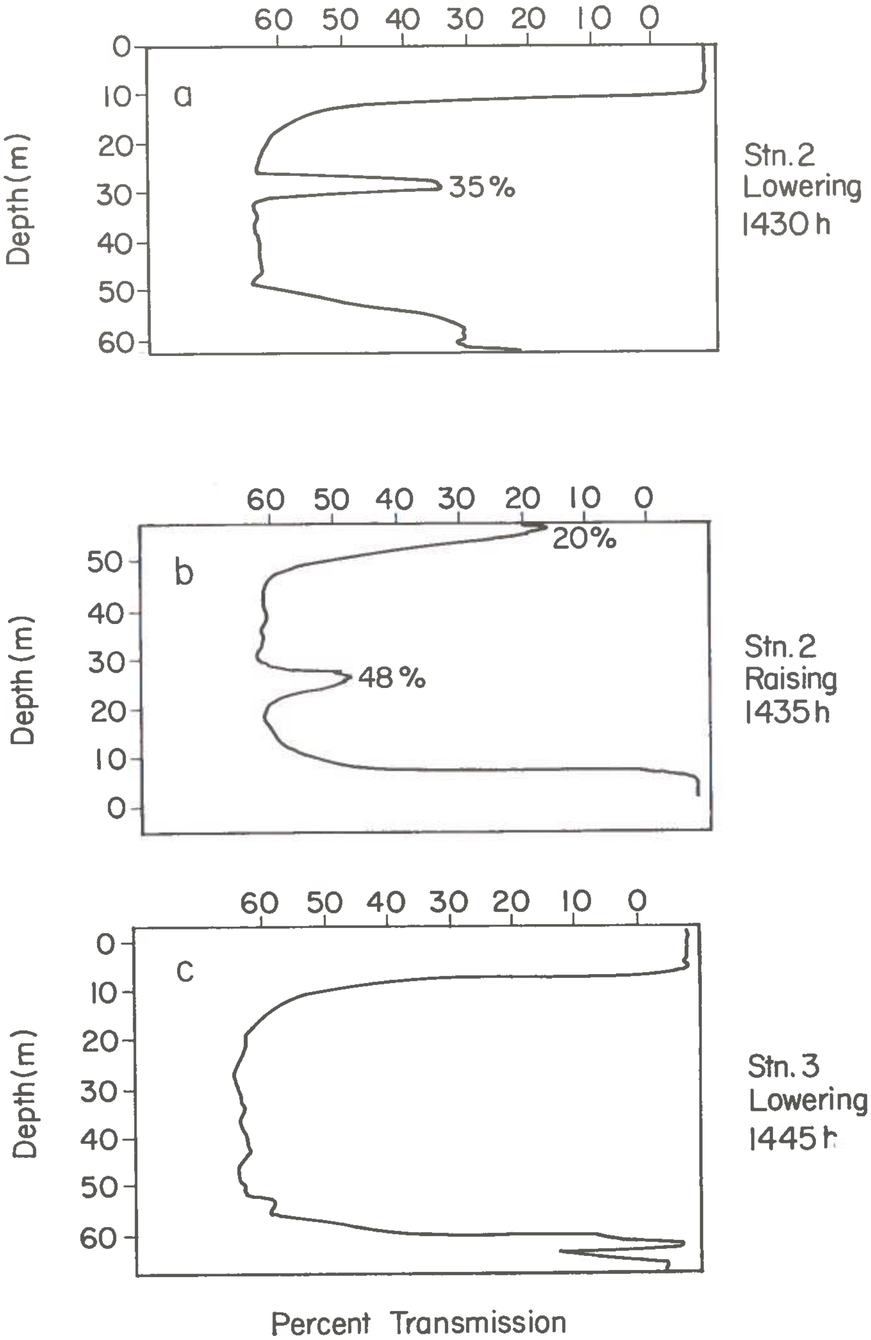


Figure 3-3. Vertical distribution of turbidity at the Alberni Inlet dumpsite, December 17, 1973. Stations 2 and 3 are similar; turbidity measured with transmissometer (a) 125 min after dumping; (b) 130 min after dumping; and (c) 140 min after dumping. Lowering indicates descent of instrument, raising indicates ascent. (From Dobrocky Sea Tech Ltd. 1974a.)

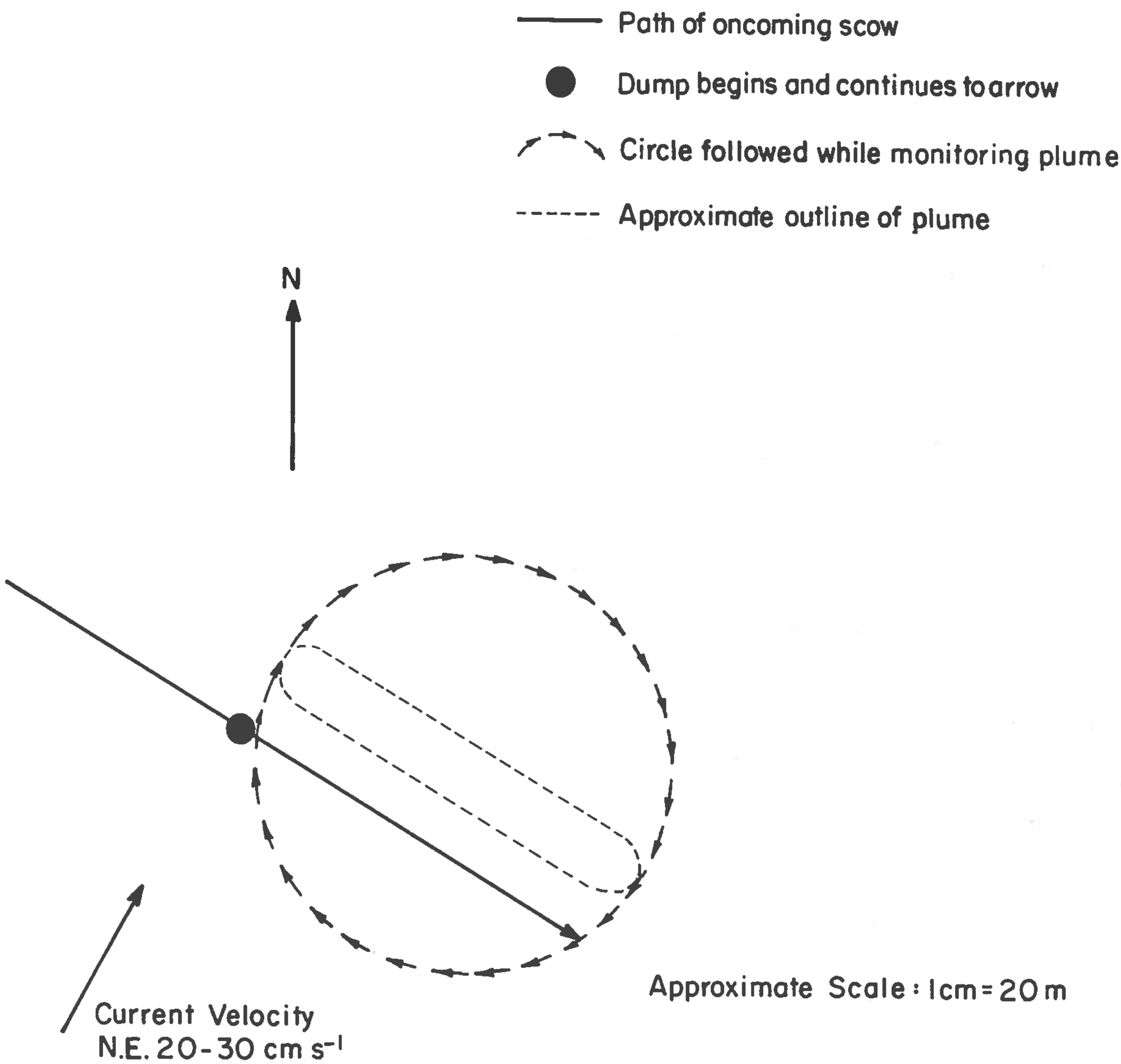


Figure 3-4. Turbidity plume developed by dumping near Bronte Harbour, Lake Ontario (from Chemex 1973b).

water on an open coast may be subjected to erosion from wave action and longshore currents. If local longshore currents are not considered, dredging may be ineffective in improving channel conditions, as shown by Reinson and Frobel (1981) in their studies on the barrier islands off northeast New Brunswick. Material dumped outside an estuary may in fact move back into a harbor through the action of bottom currents, as was shown for St. John, New Brunswick, by Neu (1960), whose work prompted movement of the dumpsite outside the harbor (away from the action of bottom currents). After about a decade of disposal, transport of the dumped material out into the Bay of Fundy is evident from trace metal distributions in sediments (Figure 3-5). This indicates that the new dumping location does not result in movement of material back into the harbor. Sly (1977) pointed out that the majority of sediments dredged annually in Port Stanley, Lake Erie, (about 50,000 m^3 a^{-1}) come from outside the harbor, and input from a creek entering the harbor was only about 10% of the total volume. Material dumped in a river becomes part of the natural bedload and may slump back into channels. Dumping in tide-swept channels, as occurs in several locations in British Columbia (e.g. in Porlier Pass, near Crofton), widely disperses the dumped material.

Once again, the size and specific gravity of the material are major factors determining its mobility on the floor of the water body (see Appendix III.0). Gravel (20-55 mm) moved distances of 1-5 m in a 3-month study carried out in New Zealand (Gillie and Kirk 1980). If local currents are weak, dredging pits and/or dumped material will persist over several years, as has been observed in the North Sea (de Groot 1979). In Arctic waters, movement of sediment by ice-scouring may transport material (Slaney 1977). Suspended material is more subject to the vagaries of surface circulation and can generally travel further from a dumpsite.

3.3 BOTTOM TOPOGRAPHY

The aim of navigational dredging is to modify and deepen water bodies, so effects can be detected by observing depth differences on hydrographic charts. The rates at which the original bottom topography is restored by natural sedimentation and sediment movement are influenced by local geological processes. In estuaries and rivers, for example, large freshets, which occur periodically, can move sediment into harbors much faster than "average" rates would suggest. Some appreciation of the time required to fill in dredged harbors can be obtained by examining frequency of dredging records. For example, Richibucto Harbour in New Brunswick had to be dredged 43 times in 24 years.

Dredging to make artificial islands for oil drilling platforms in the Beaufort Sea has created some unusual deep borrow pits where sediment was removed with suction dredging. These deep holes are developed around the perimeter of the constructed island (Slaney 1977) (Figure 3-6).

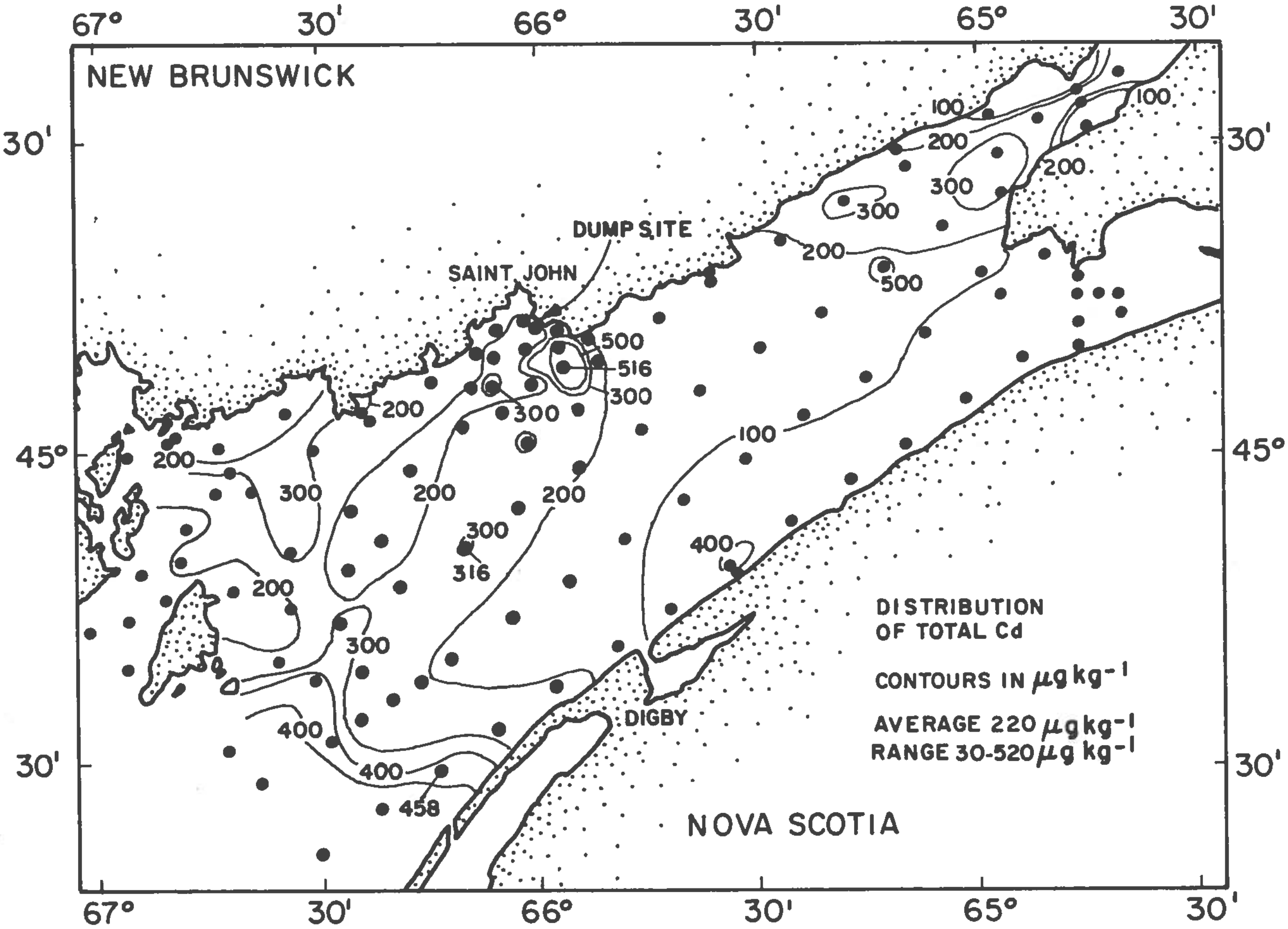


Figure 3-5. Distribution of cadmium in sediments in the Bay of Fundy (from Loring 1979). The dispersal pattern of cadmium away from the dump site at St. John Harbour is shown by contour lines. The dots represent sampling sites.

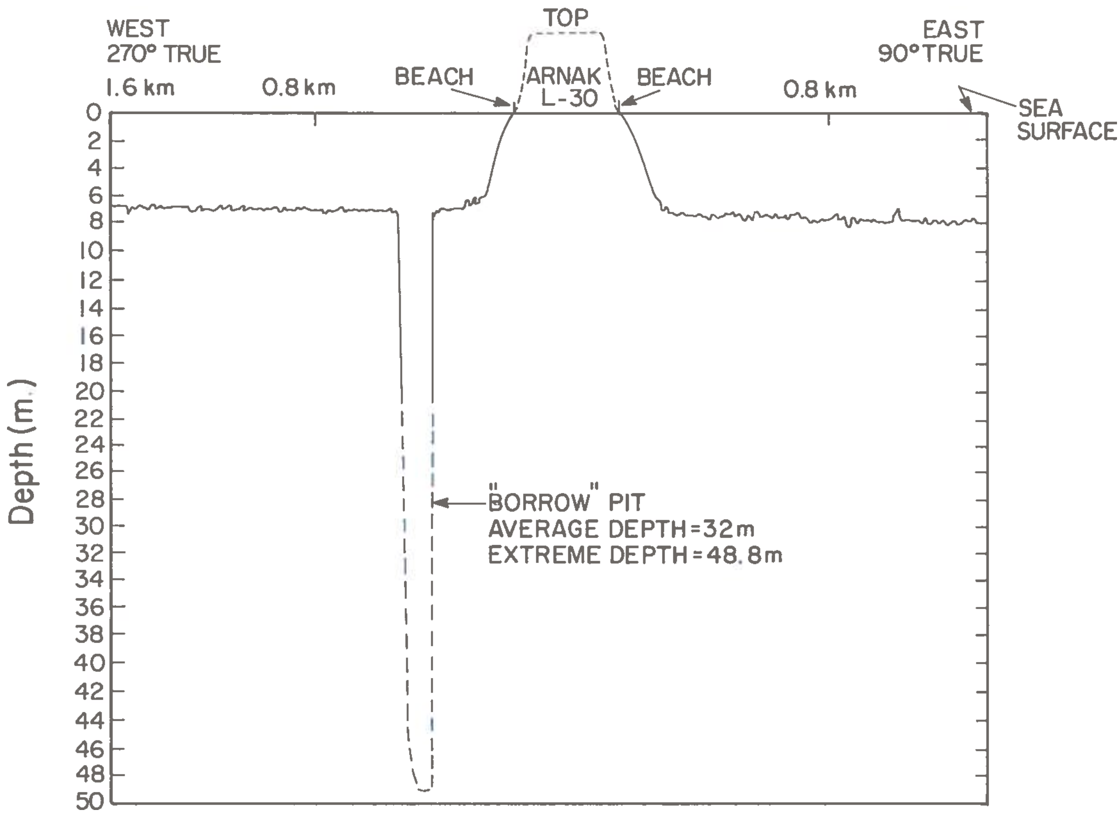


Figure 3-6. Borrow pit created by dredging to create an artificial island in the Beaufort Sea (Arnak L-30) (from Slaney 1977). Representative profile of the dredging pit and artificial island construction.

Dumping alters the topography at dumpsites, usually resulting in increased elevations. The magnitude, both vertically and horizontally, of the topographic alterations is dependent on depth, amounts disposed, local currents, and the navigation aids used in locating a specific dumpsite. The elevation and steepness of the underwater mound of sediment are dependent on the amount of vessel drift while dumping, and the dispersion of material while sinking through the water column. A study of a dumpsite near Thunder Bay, Lake Superior, used side-scan sonar to detect the horizontal dispersion of dumped material. Spoil disposed of within 12 to 18 months of the survey was detectable within 50 to 100 m of the dumpsite (30-m depth). There was little evidence of movement of older material (Sly 1977). At a dumpsite (60 m) in Alberni Inlet, British Columbia, elevations increased by 1 to 3 m over a dumping season (November 1977 to February 1978; 129,000 m^3 disposed of). At a deep (300 m) dumpsite in the Strait of Georgia (Point Grey dumpsite, just outside Vancouver Harbour), submersible observations showed little evidence of spoil accumulation, but large concrete blocks and other types of solid waste were plainly visible (Hoos 1977).

3.4 CHANGE IN PARTICLE SIZE DISTRIBUTION

Change in the particle size distribution of bottom sediments after dumping and dredging is almost inevitable unless both sites are characterized by uniform sediment type, both horizontally and vertically through the sediment column. Dumping sand from Fraser River channels into this river's estuary, for example, does not result in changed sediment type because sands are widespread at the river mouth (Pharo and Barnes 1976). However, as an example of the more common situation, Packman (1980) found coarser material at the Point Grey dumpsite in the Strait of Georgia (Figure 3-7). Observations from a submersible showed that concrete chunks, hardpan, rubble and wood wastes were more common in the northeast sector of the dumpsite, which was closest to Vancouver Harbour where much of the dredging occurs. Sediments from Lake Ontario, examined by Chemex (1973a) before and after dredging, showed a change in mean grain size in Bronte Harbour (Table 3-1). However, no change was observed at Port Stanley.

If the dredge spoil is rich in wood waste, which is generally lighter than the accompanying inorganic sand or mud, some fractionation might be expected as the material falls through the water column. It was possible to delineate a dumpsite used by the forest industry in northern New Brunswick by analyses of lignin in sediments (Figure 3-8). The exact composition of sediment at a dumpsite depends on its particular history. At the Alberni Inlet dumpsite, spoils with wood waste are overlain with cleaner material dredged from unpolluted sediments. In some circumstances (see Section 6.3), this capping procedure dumping style can be used to advantage, for example, to seal in contaminants.

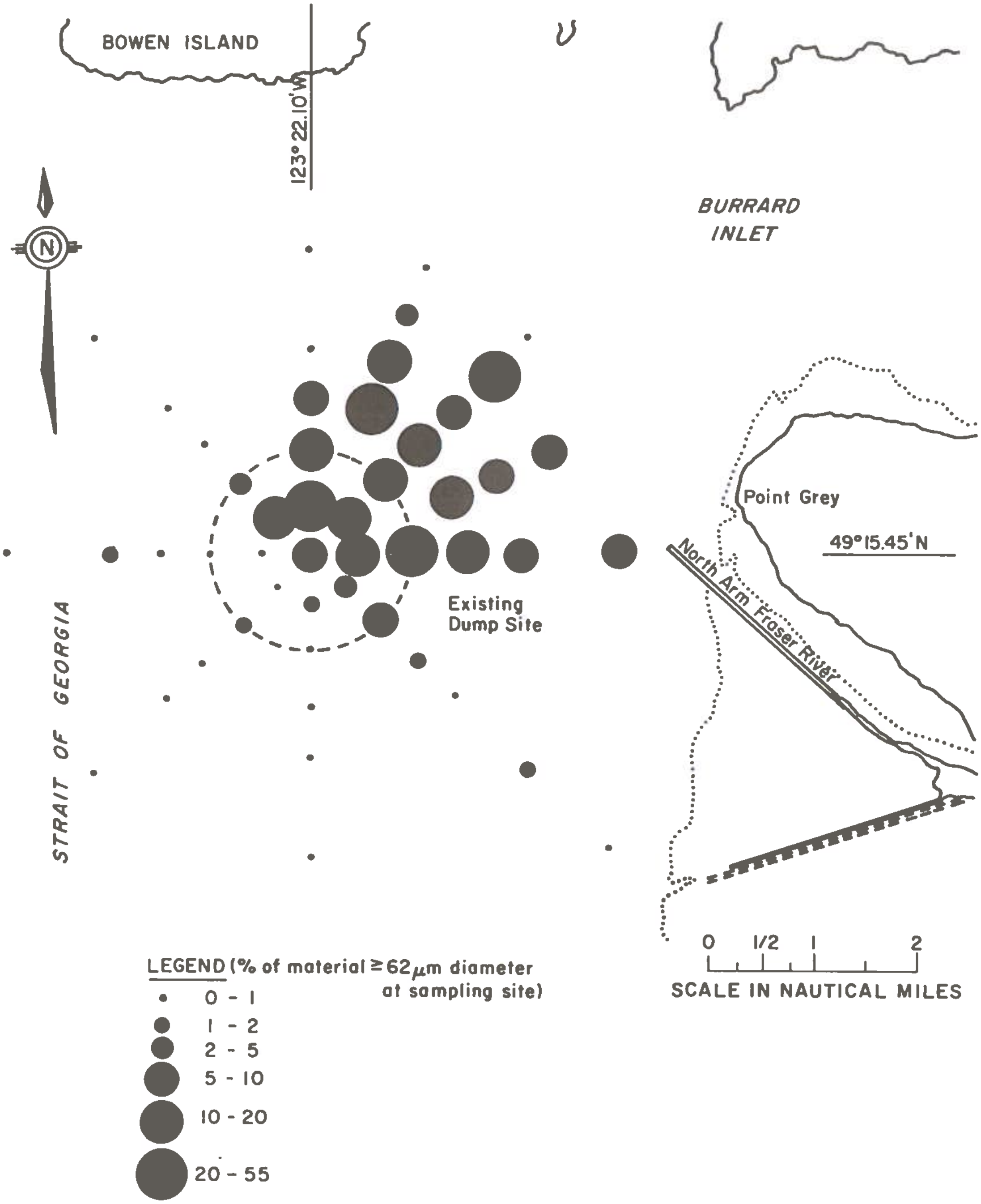


Figure 3-7. Distribution of material ≥ 62 μm in diameter at the Point Grey dumpsite offshore from Vancouver (from Packman 1980).

Table 3-1. Comparison of sediment characteristics (mean grain size, μm) before and after dredging in Bronte Harbour, Lake Ontario (from Chemex 1973a).[a]

Station	Before (Sept. 11, 1973)	After (Nov. 22, 1973)
1	190	55
2	72	19
4	95	15
8	145	24
9	125	8

[a] Only data from the upper 5 cm of cores are considered.

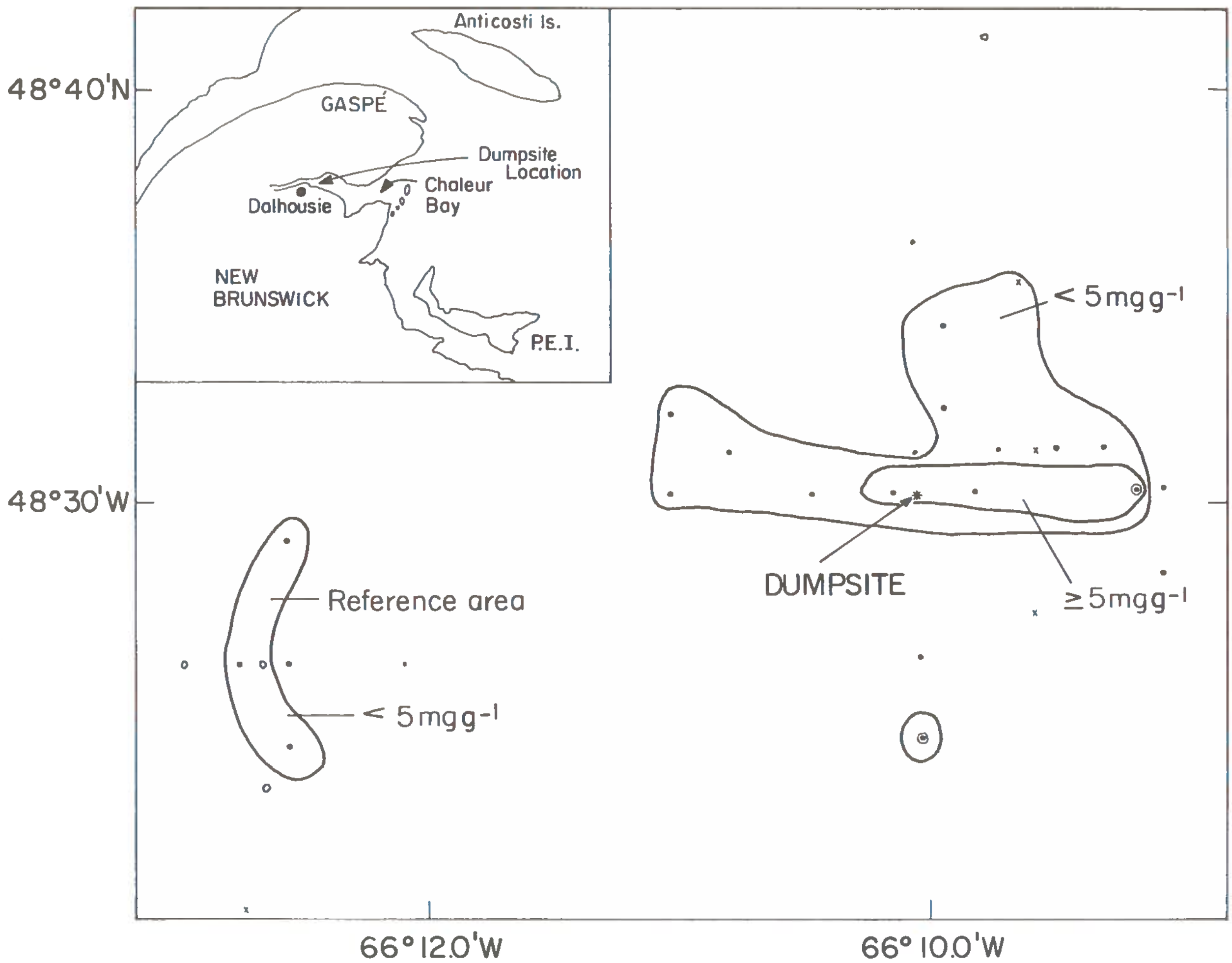


Figure 3-8. Delineation of the Dalhousie (Chaleur Bay), New Brunswick, dumpsite using distribution of lignin in sediments. Dots represent station locations (from MacLaren Marex Inc. 1979b).

4.0 CHEMICAL EFFECTS

4.1 DISSOLVED OXYGEN DEPLETION

A large quantity of data on dissolved oxygen (D.O.) values in relation to dumping has been obtained before, during, and after various episodes of disposal of dredge spoil at Alberni Inlet, British Columbia. Because the fjord's bottom waters naturally display near anoxic conditions (Bell 1976) (D.O. values as low as 1.0 mg L^{-1} were recorded before dumping began), the prospect of further decreases in D.O. due to dumping is of concern. A number of laboratory studies have also been recently conducted using the wood-polluted sediments from the area. Other enclosed water bodies in British Columbia where dumping occurs also show D.O. deficiency (e.g. Cousins Inlet, Packman *et al.* 1975; Howe Sound, Levings 1980). On the Atlantic coast, naturally depressed D.O. values have been recorded in the upper St. John River estuary, New Brunswick (Burns 1978), and at Petpeswick Inlet, Nova Scotia (Hoos 1972). Dredge spoils with D.O. demand dumped in a situation where D.O. is naturally depressed should be of concern.

There is some evidence of localized D.O. depression during and after certain dumping events in Alberni Inlet, British Columbia. However, there are physical oceanographic processes that must be accounted for in any evaluation of the data. Monitoring was conducted at the dumpsite (60 m) and adjacent control stations in December 1973 (Dobrocky Sea Tech Ltd. 1974a), July 1974 (Dobrocky Sea Tech Ltd. 1974b), and February 1975 (Dobrocky Sea Tech Ltd. 1975). In the last sampling, the authors concluded that statistically significant differences in D.O. existed between the dumpsite and a control station about 500 m distant. At two depths, 20 and 30 m, D.O. percent saturation values were 51.4 versus 58.0% and 27.9 versus 34.5%, respectively. Interpretation of these data must be made with the recognition that internal tides with a period of 12 h are probably operating in the bottom water of the inlet (Bell 1976; Dobrocky Sea Tech Ltd. 1978), and so observations made 1 month apart on different tidal stages are not necessarily comparable.

Laboratory studies on the D.O. demand of sediments containing wood waste were conducted by Econotech (1977) using Alberni Inlet sediments. Observations from lysimeters (laboratory columns: 76 cm in diameter with 38 cm spoil topped by 10 cm seawater) showed that at 8°C and about 3.5 mg D.O. L^{-1}, oxygen uptake by dredge spoil ranged from 0 to 23 mg O_2 m^{-2} s^{-1}. These data agree with *in situ* observations using a modified belljar (Dobrocky Sea Tech Ltd. 1977) and calculations based on stoichiometry of the wood waste (Seakem 1977). There was a clear relationship between volatile solid and lignin content and oxygen consumption in the initial stages of lysimeter experiments (Econotech 1977), but after 6 months the relationship was less clear (Econotech 1978a) (Figure 4-1). A subsequent study by Econotech (1978b), also using

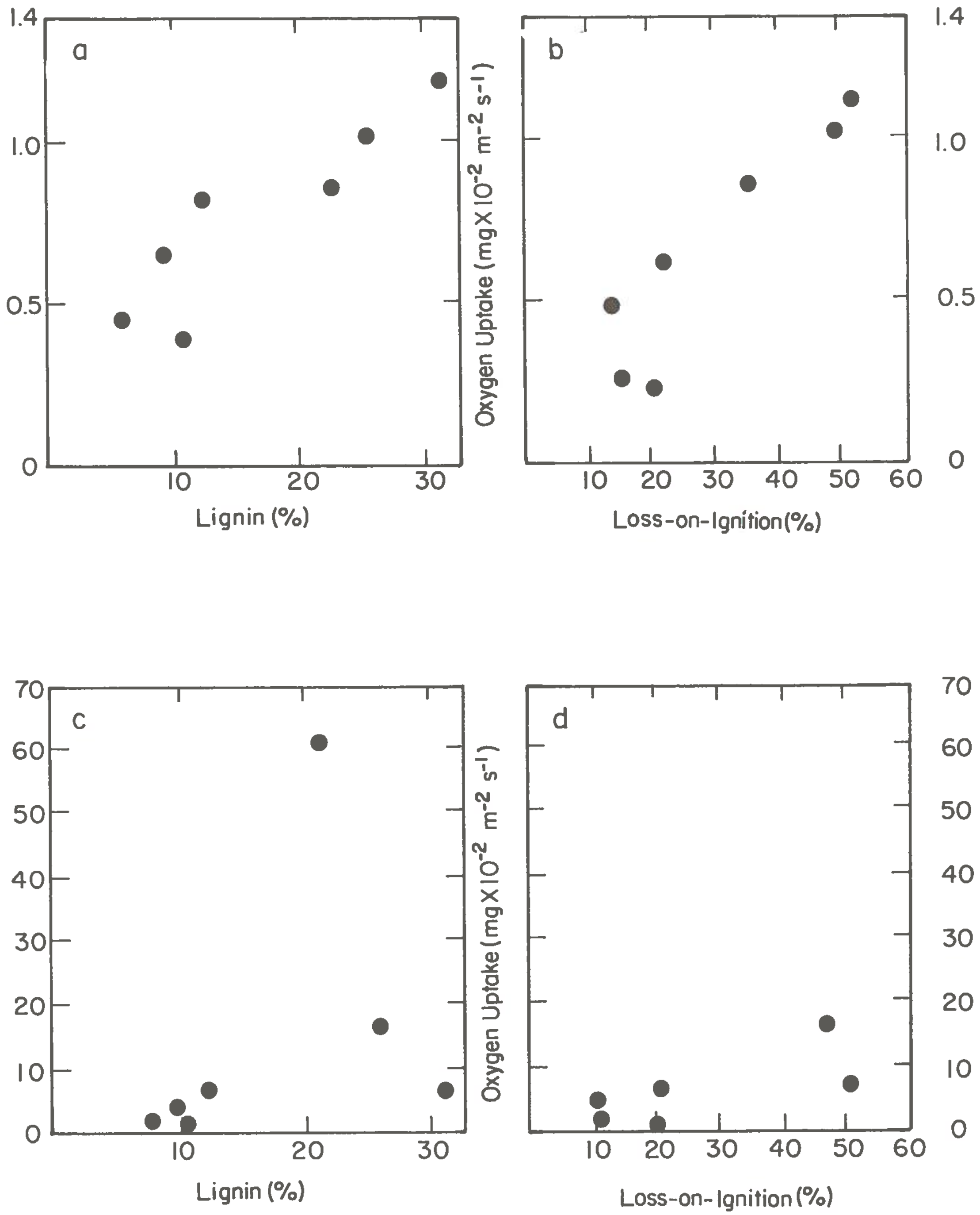


Figure 4-1. Dissolved oxygen uptake of sediments from six dredge and dump locations from Alberni Inlet, British Columbia, with respect to percentage lignin and loss-on-ignition. (a), (b): After 1 month in lysimeter (DO of overlying water 8 mg L^{-1}); (c), (d): after 6 months in lysimeter (DO of overlying water 8 mg L^{-1}) (from Econotech 1977, 1978a).

lysimeters and dredge spoil with wood waste, investigated the effect of placing sand over the spoil. D.O. uptake was significantly reduced (Figure 4-2).

D.O. conditions with "clean" dredge spoil and disposal in current-swept or non-confined areas are likely to be quite different from those observed at Alberni Inlet. The shallow, wave-swept waters of the Beaufort Sea, for example, showed no evidence of D.O. depression during dredging and disposal of sand for artificial island construction. D.O. values near the bottom (about 5 m) varied from 6.0-12.8 mg L^{-1} ("pre-dredging", July 29-30, 1976) to 8.0-12.0 mg L^{-1} ("post-dredging", September 4-6, 1976). The general variations in D.O. conditions appeared to be governed more by the daily and seasonal variations in weather and water body characteristics than by the dredging conditions (Slaney 1977).

Available data on D.O. in freshwater disposal projects show little evidence of reduction. During dredging at both Port Stanley and Bronte Harbour in the Great Lakes there was no marked decrease in D.O. levels (Chemex 1975).

4.2 CHEMICAL RELEASE FROM SEDIMENTS

4.2.1 HYDROGEN SULFIDE

The release of hydrogen sulfide from sediments is a common occurrence, especially in harbors utilized by the forest industry where waste wood accumulates. It is produced as a by-product of the bacterial decomposition of organic matter, and is often implicated in fish kills (see Section 4.3.1).

There are few data from Canadian waters documenting the concentration of dissolved H_2S during dredging and/or dumping operations. In almost all reports dealing with sediments rich in wood waste, however, observers report H_2S by the "smell test" (e.g. Hourston and Herlinveaux 1957; Dobrocky Sea Tech Ltd. 1974a). Because of this compound's solubility variations with temperature, D.O., and pH levels, many investigators involved in monitoring studies do not attempt to measure levels of this compound. A recent study by Econotech (1978b) measured levels of D.O. and H_2S at estuarine (Squamish Harbour) and river (Fraser) dreding locations in British Columbia. D.O. levels at the surface and bottom (6 m) ranged from 4.0 to 11.0 mg L^{-1}; most values were over 7.5 mg L^{-1}. H_2S concentrations were usually less than 0.2 mg L^{-1}. The worst conditions for D.O. and H_2S were recorded in the water draining from the barge onto which dredge spoils were being loaded. At the marine site, D.O. and H_2S values were 0.3 and 16.0 mg L^{-1}, respectively, while at the Fraser River location concentrations of 5.3 and 37.4 mg L^{-1}, respectively, were recorded in the drain water.

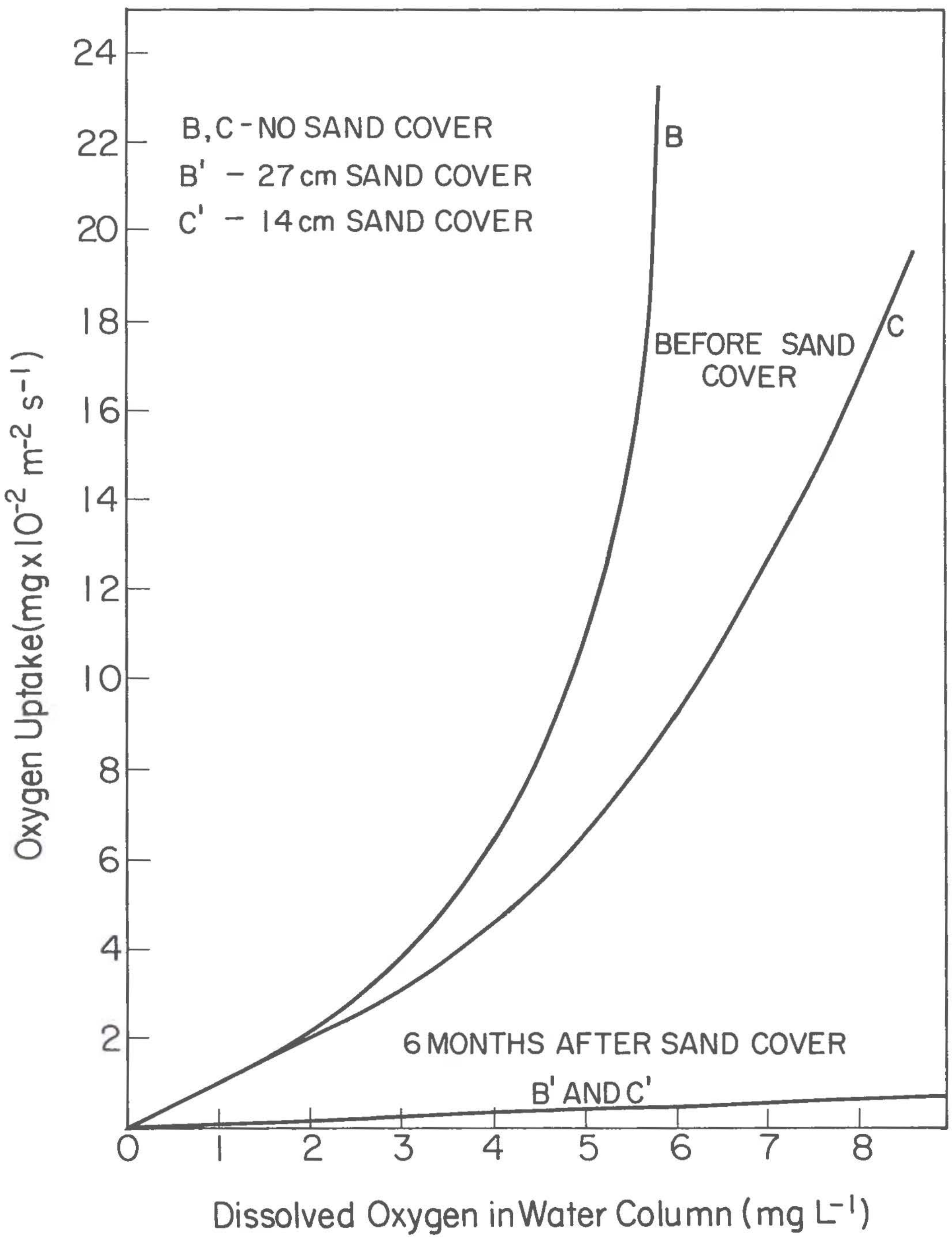


Figure 4-2. Dissolved oxygen uptake with respect to dissolved oxygen in water column of two lysimeters containing sediments, including wood waste, from Alberni Inlet, British Columbia (from Econotech 1978b).

Bella *et al.* (1972) carefully examined the concentrations and role of sulfides at an estuarine mud flat in Oregon, U.S.A. At one station, wood debris was present, so the data may be extrapolated to some dredge-spoil circumstances. As shown in Figure 4-3, the sulfide concentrations varied inversely with D.O. levels, and ranged up to 12 mg L^{-1}.

Relationships between H_2S and D.O. were examined in laboratory studies of leachates from dredged material collected in Alberni Inlet, in which lysimeters were used (Econotech 1978a). As shown in Table 4-1, material from dredge sites, especially in the vicinity of a pulp mill dock, showed consistently low D.O. levels (0-2.9 mg L^{-1}) and very high H_2S concentrations (up to 167 mg L^{-1}). These data give an impression of the levels that could be released upon dredging. Under laboratory conditions (8°C, salinity ∿28 ppt), the concentrations of D.O. and H_2S varied inversely throughout the study. Data from material recovered at the dumpsite area showed considerably more variation in D.O., but D.O. values were generally higher and H_2S concentrations lower (Table 4-1). This was probably because the dumpsite sediment contained less organic material. Interestingly, total organic carbon levels increased during the period of the experiment in all the sediments tested (Table 4-1), possibly because of increased bacterial populations or because the bacteria were removing the more refractory material (hemicellulose, etc.) from the wood in the sediment.

4.2.2 NUTRIENTS

Because of the possible hazards of eutrophication, a number of studies in freshwater systems have focussed on the release of phosphorus and nitrogen from sediments (Golterman 1977; Lean and Charlton 1975). In coastal waters, eutrophication due to dredging and dumping does not seem to be a problem, except in parts of the world where large amounts of sewage sludge (e.g. New York Bight, U.S.A. (Botton 1979) and the North Sea (Norton 1976)) are dumped. There is apparently no sludge dumping in Canadian waters, except for sewage released from melted ice (spring breakup) at some Arctic settlements.

Excessive amounts of nitrogen and phosphorus in lake sediments originate mainly from sewage and agricultural runoff. Nutrients that arrive on the lake floor through a variety of routes (e.g. via rivers, direct sedimentation, as phytodetritus, and as fecal material from zooplankton) are adsorbed onto sediments, and can be resuspended through dredging and/or dumping.

The main source of Canadian data on this topic originates from the dredging impact studies conducted in Lakes Ontario and Erie (Chemex 1973a, 1975; Sly 1977). At Port Stanley and Bronte Harbour, there were significant increases in phosphorus levels in composite water (pooled samples from several stations obtained at five depths in the water column)

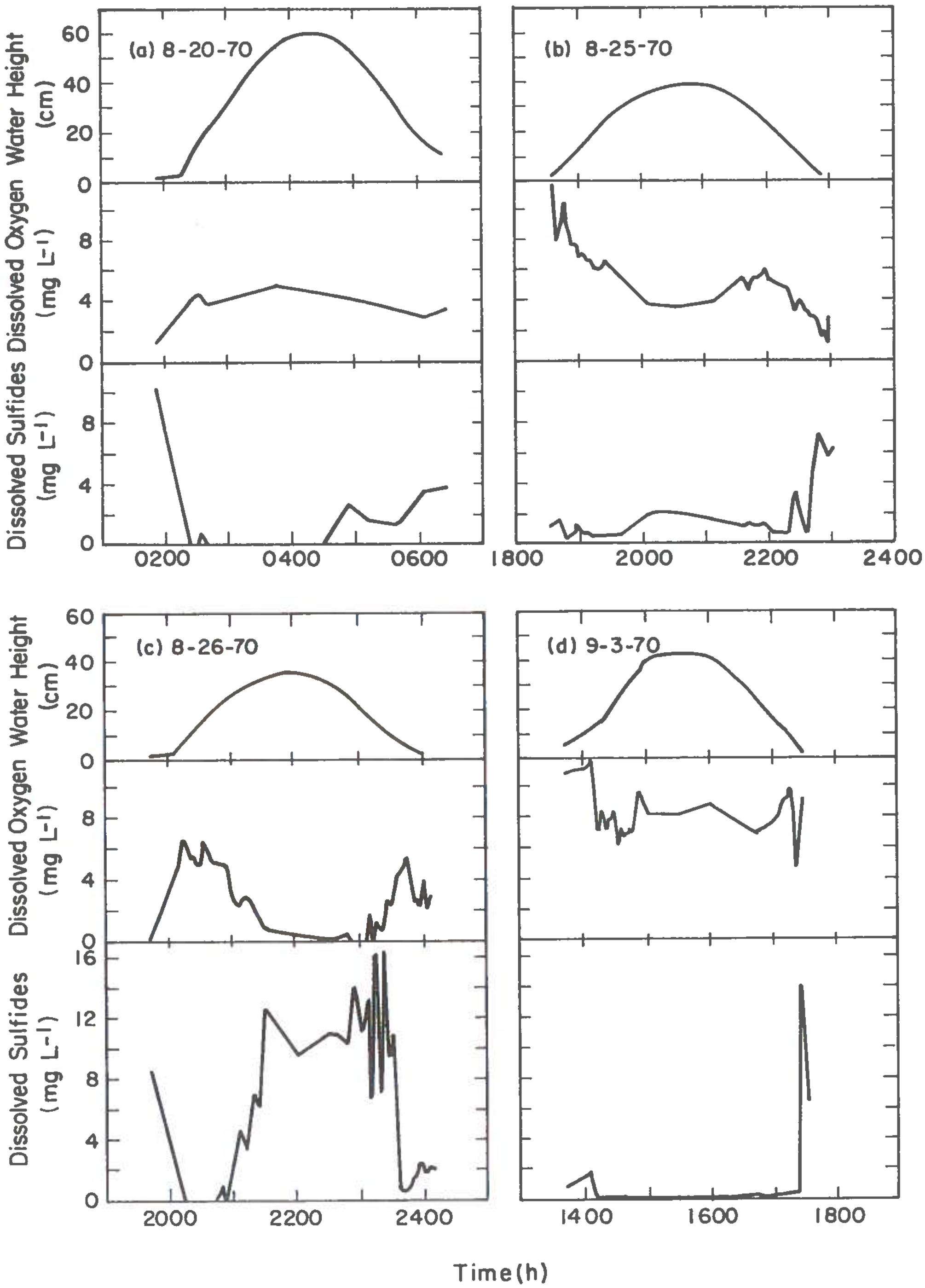


Figure 4-3. Changes in dissolved oxygen, dissolved sulfides, and water height over a period of two weeks (8-20-70 to 9-3-70) at an Oregon, U.S.A., tidal flat having wood-containing sediments (from Bella *et al.* 1972).

Table 4-1. Characteristics of sediments and leachates from five frequently dredged sites and the dumpsite at Alberni Harbour, British Columbia (from Econotech 1978a).

	Sediment					Leachate		
Sample	Sawdust (%)	Total organic carbon (%)	Biological oxygen demand (BOD) (ppm)	Lignin (%)	Volatile solids[a] (%)	Dissolved oxygen (DO) (mg L^{-1})	Hydrogen sulfide (mg L^{-1})	pH
Dredged site A	2.2	3.5	955	9.2	13.7	0	0.9	7.2
B	1.9	13.2	4185	21.6	36.0	0	167.0	7.2
C	13.4	15.3	2965	25.5	47.8	0	5.1	7.4
D	2.8	5.4	1990	12.5	21.6	0	0.9	7.5
E	14.2	18.3	2865	31.1	50.2	0	0.1	7.1
Dumpsite	2.1	5.3	1250	8.4	14.7	2.1	0.1	7.4
Control	0.7	4.8	1730	11.7	21.1	4.9	0.2	7.5

[a] Average of five replicates from a bulk sample.

and pore water at the dredge- and dumpsites (Table 4-2). Reactive phosphorus generally showed the greatest increase, rising in composite water from 3.0-6.0 $\mu g\ L^{-1}$ before disturbance to 17.5 $\mu g\ L^{-1}$ during dumping. Subsequent studies in October 1974, also at Port Stanley (Chemex 1975), showed that at the time of dumping, orthophosphate levels at the surface were greater than 1000 $\mu g\ L^{-1}$, but had diminished or been diluted to undetectable levels after 15 min. The authors felt that at the prevailing pH and D.O. levels, much of the phosphate would be adsorbed onto settling particulate material or had been removed by scavenging of ferric oxides and hydroxides.

Lake column simulators, somewhat analogous to the lysimeters used in the wood waste studies mentioned previously (see Section 4.1), were also used in the Port Stanley work (Chemex 1975). These devices, approximately 1 m in diameter and 4.7 m in height, held 3530 L of lake water, and were fabricated from stainless steel. Sampling ports were located at depths of 0.3, 0.9, 1.8, 2.7, and 3.6 m in the columns. The devices were also instrumented for temperature control.

The columns were used in experiments to simulate the release of nutrients and subsequent algal growth after dumping of dredge spoil through the water column. In one phase of the work, 80 kg of dredged sediment from the Port Stanley harbor were dumped into two columns, one mixed, and one stratified by temperature. There was an immediate increase in orthophosphate in both columns (Figure 4-4). In the mixed column, after 3 days, there was no apparent net release of orthophosphate when compared with concentrations before dumping. No visible algal growth was evident. The column that was allowed to stratify showed indications of continued release of orthophosphate during the first 4 days (Figure 4-4). However, concentrations also dropped in this column as a very extensive algal bloom developed. The control columns showed no apparent net changes during the study period. Subsequent measurements at 2-week periods verified that stratification was the key process determining prolonged orthophosphate release and sustained algal growth.

4.2.3 RELEASE AND BIOAVAILABILITY

The cause-effect interrelations occurring from the release of specific chemicals from sediments during and after dredging and dumping have been very difficult to quantify. Compounds which are released may be toxic to resident biota and/or have the potential to biomagnify. Although standard "bulk" analyses often indicate that total concentrations of chemicals in sediments are above background, there is frequently no relationship between the measured levels in sediment and those in biota. The physicochemical form of metals in sediments is also an important factor, and those bound with sulfides have been found to be "unavailable" to biota (e.g. EVS 1981). In addition, there is often a lack of data on

Table 4-2. Average levels of phosphorus in water and sediments at Port Stanley, Lake Erie, during dredging operations in 1973 (from Chemex 1975).

Sample type	Number of Stations	Total phosphorus ($\mu g\ L^{-1}$)	Reactive phosphorus ($\mu g\ L^{-1}$)
Composite water[a]			
Before dredging (Aug. 2)	10	22.2	6.3
During dredging (Sept. 17)	12	27.8	17.5
After dredging (Nov. 5)	5	73.8	29.2
Pore water[b]			
Before dredging	10	65.4	23.0
After dredging	5	151.0	65.0

[a] Composite water indicates a mixture of water from various depths in the water column.

[b] Pore water collected in the 0- to 15-cm segment of cores.

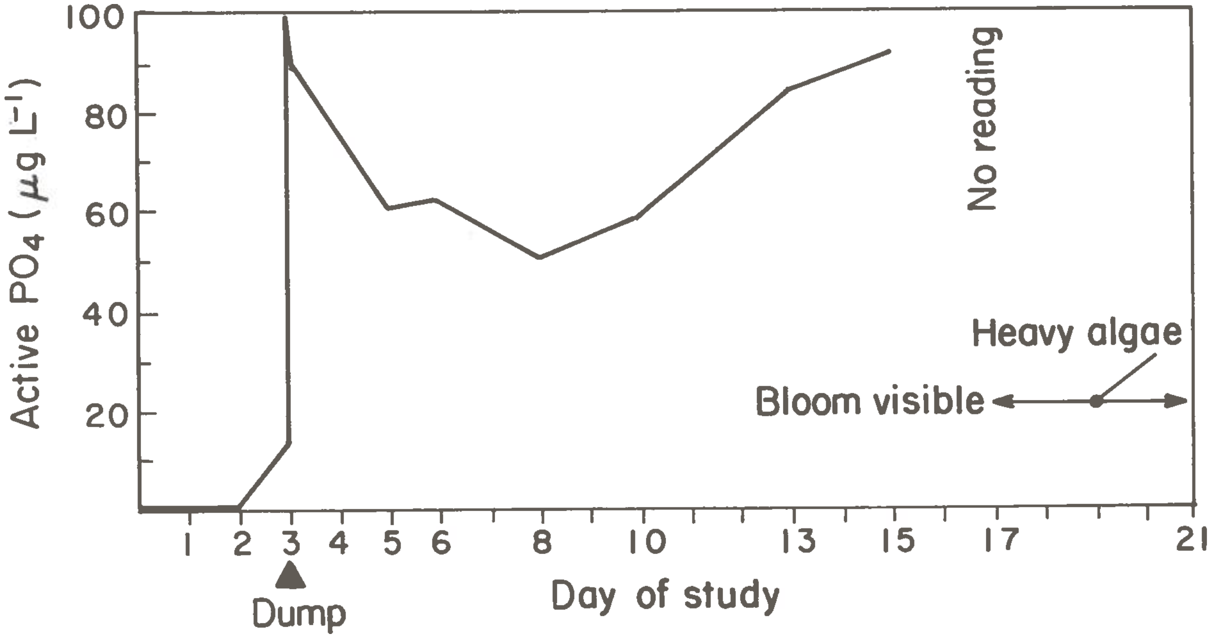


Figure 4-4. Phosphate release and subsequent algal bloom in a lake simulator column containing sediment from Lake Ontario (from Chemex 1975).

background concentrations in space and time. As mentioned previously, in bioassay experiments with sediments containing chemicals, especially metals, it is very difficult to ascribe mortality to particular components. Fujiki *et al.* (1977) showed that sea bream (*Chrysophrys major*), maintained in tanks with sediments containing methylmercury (0.015 mg kg^{-1}), accumulated the compound to a much lesser extent from the sediments than from water or food. Elder *et al.* (1979) showed that polychaetes (*Nereis diversicolor*) living in sediments with PCBs added to them ("spiked" sediment), took up and lost this chemical (Figure 4-5). An equilibrium was reached within 40 to 60 days and a concentration factor of 3.5 was achieved (Figure 4-5). McLeese *et al.* (1980) tested the uptake of another PCB (Aroclor 1254) from spiked, sandy sediments with the polychaete *N. virens*, and found no evidence of equilibrium levels after 32 days' exposure. There was no obvious excretion of PCB by *N. virens* during 26 days' post-exposure.

Laboratory experiments reported by Ray *et al.* (1980) with *Nereis virens* showed that this species accumulated cadmium primarily from the aqueous phase and displayed little excretion of this metal. Accumulation rates (for 1- to 2-g worms) were higher for waterborne than for sediment-borne metal (0.019-2.217 g Cd g^{-1} (dry weight) h^{-1} versus 0.018-0.037 g Cd g^{-1} (dry weight) h^{-1}).

An analytical procedure known as the elutriate test has been developed by the U.S. Army Corps of Engineers (1976) in an attempt to predict biological problems with disposal of chemical-containing sediments. The procedure (Figure 4-6) attempts to simulate conditions in the discharge of a suction dredge, and laboratory results are compared with concentrations of chemicals in water at the disposal site (U.S. Army Corps of Engineers 1976). Elutriate test data from a proposed dredging project in New Brunswick showed an inverse relationship between amount of mercury in sediments and in the elutriate test (compare Tables 7.9 and 7.14 in Philpott 1978). A study of the technique's utility to marine disposal in British Columbia waters was conducted by the Environmental Protection Service (1976b) which concluded the procedure was of limited predictive value. Mercury, cadmium, copper, lead, PCBs, and chlorinated hydrocarbons were not released from sediments in the tests (Table 4-3), but nutrients such as nitrate and phosphate were released. Nutrients were also released in elutriate tests with sediments from Hamilton Harbour, Lake Ontario (Cheam *et al.* 1976). The tests also showed variable results depending on oxygen supply and pH. Research with marine sediments from San Francisco Harbor, U.S.A., showed that the release of metals was related to the pH of the elutriant (Table 4-4) (Serne and Mercer 1975, cited in Bradford and Louma 1980). A strong oxidizing agent was found to release most of the metals. This method provides an alternative method to total dissolution in concentrated acids.

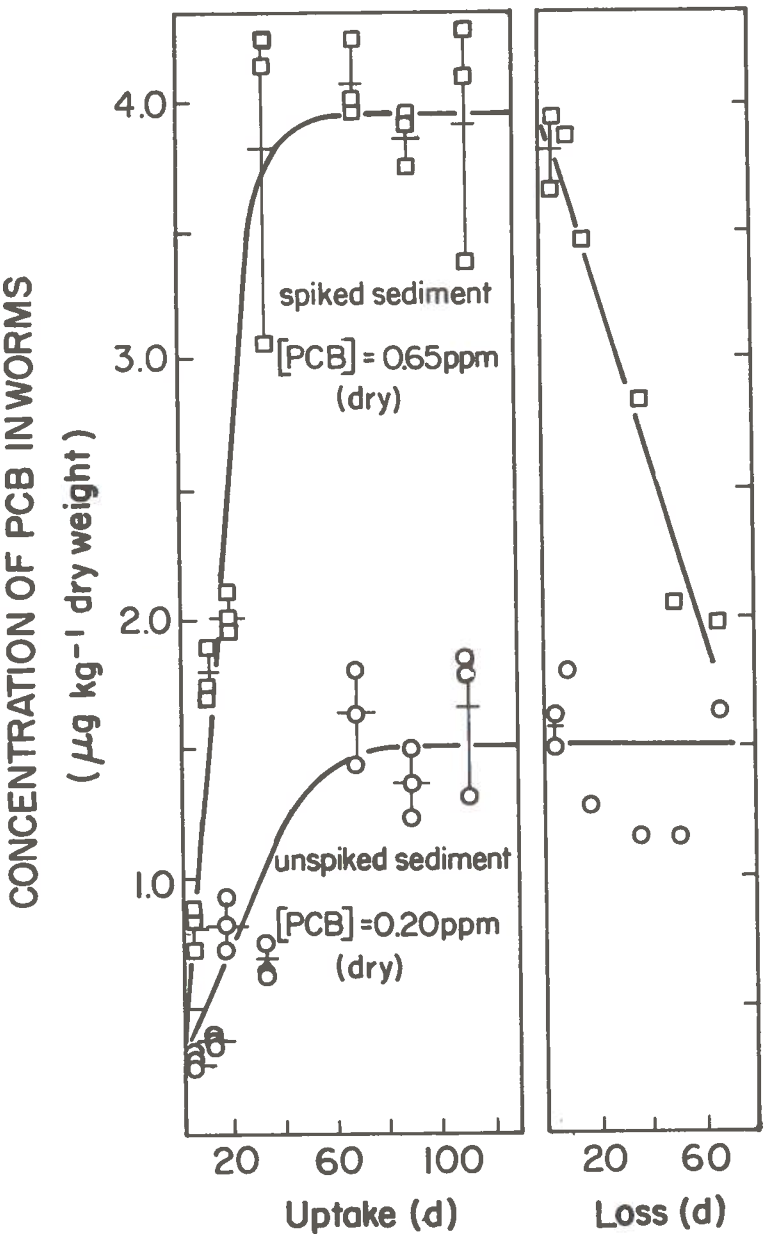


Figure 4-5. Uptake and loss of PCB (Phenochlor DP-5) by *Nereis diversicolor* from sediments. Each symbol represents a composite sample of either 5 or 10 individuals. Horizontal lines intersecting vertical range bars indicate mean concentration, squares indicate spiked sediment, and circles indicate unspiked sediment (from Elder *et al.* 1979).

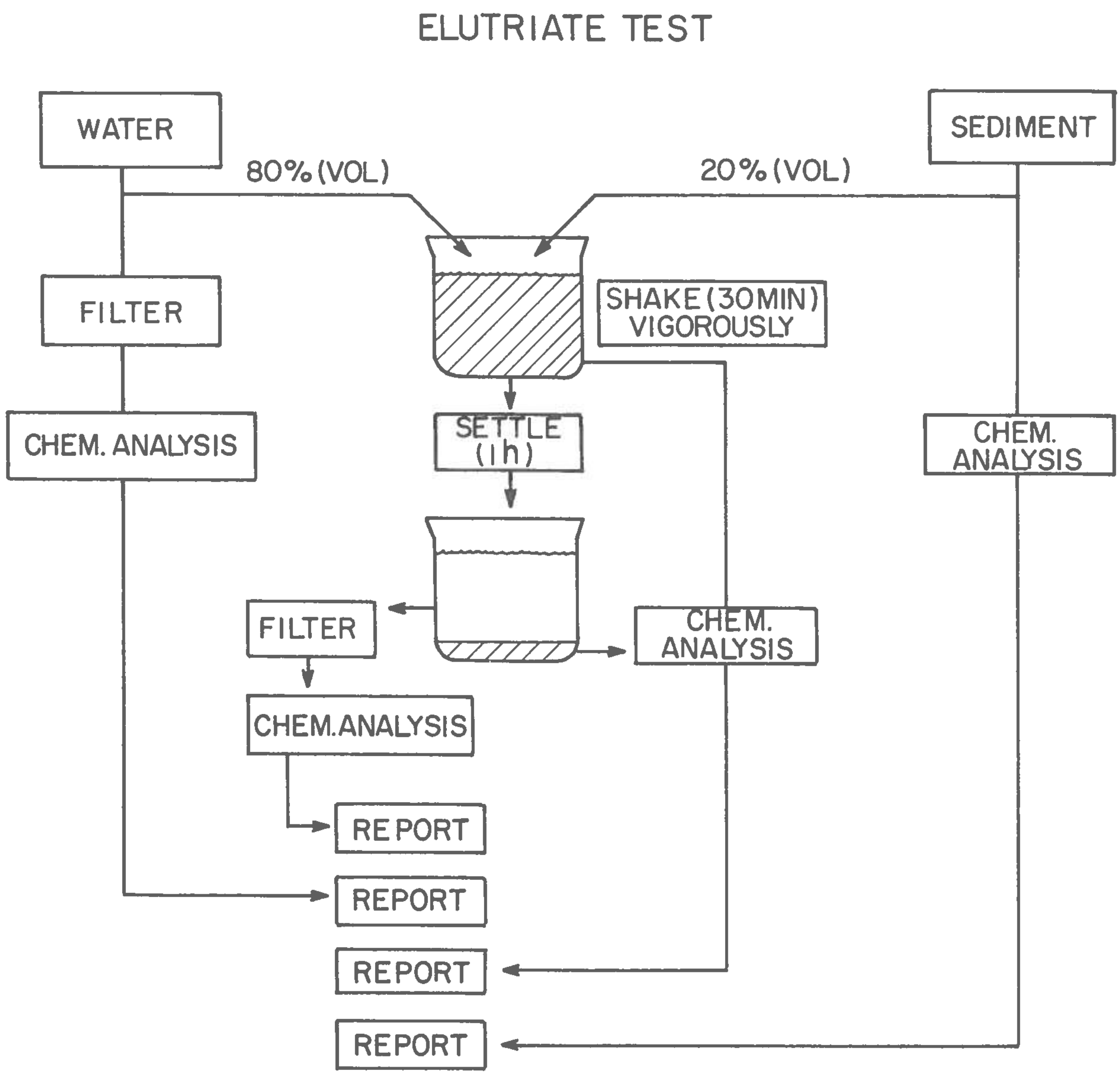


Figure 4-6. Elutriate test methodology as described by Environmental Protection Service, Environment Canada (from Environmental Protection Service 1976a).

Table 4-3. Results of an elutriate test (as specified by the U.S. Army Corps of Engineers) using sediments from False Creek, Vancouver Harbour, British Columbia[a] (from Environmental Protection Service 1976b).

Element	Concentration in sediments ($mg\ kg^{-1}$)	Concentration in elutriate ($mg\ L^{-1}$)
Copper	110.5	0.01
Lead	119.8	0.02
Cadmium	1.6	0.01
Mercury	0.7	0.2

[a] Values shown are averages for 8 stations.

Table 4-4. Release of metals from San Francisco Harbor sediments under various extraction schemes (from Serne and Mercer 1975, cited in Bradford and Louma 1980).

	Percent of metal released						
Extraction treatment	Cd	Cu	Hg	Fe	Mn	Pb	Zn
Centrifugation	1	1	1	1	1	1	1
Strongly reducing (ammonium acetate)	1	1	1	1	5-24	1	1
Weakly reducing (hydroxylamine)	1	1	1	1-4.9	5-24	1	1
Strongly oxidizing (H_2O_2)	50	25-49	25-49	5-24	5-24	25-49	25-49
Strongly reducing (citrate-dithionate)	1	1-4.9	1	25-49	1-4.9	1	1-4.9
Total dissolution (HNO_3, HF, HCl_4)	1-4.9	50	50	50	50	50	50

Murakami and Takeishi (1977) performed elutriate tests with mercury-containing sediments from Minamata Bay, Japan, (297 mg Hg g^{-1}) and showed a dramatic release of the metal into the water at pH levels greater than 10 (Figure 4-7). Macdonald (1979a) applied the selective extraction techniques recommended by Brannon *et al.* (1976) to metal-containing sediments (Fe, Mn, Zn, Cu, Cd, Pb, As, Hg) from Victoria Harbour and False Creek (Vancouver Harbour); the studies showed that the oxidizable and "residual" reservoirs in the sediments accounted for the greatest proportion, but results among metals were highly variable. Loring (1981) estimated the relative bioavailability of metals from eastern Canadian estuarine and coastal environments. For example, he concluded that 12 to 27% of the total Pb present was potentially available, varying regionally and with sediment texture. Fine-grained sediments at the head of the St. Lawrence estuary, the head of the Saguenay fjord, and the lower St. Lawrence contained the highest concentrations of available metals.

Because of the importance of physical-chemical factors, it is essential to consider all those processes which may lead to the release of chemicals during dredging, dumping, and post-dumping (Patrick *et al.* 1977). In shoreline or intertidal circumstances, there is considerable change in microenvironments due to fluctuating water tables and aeration. Laboratory uptake by vascular plants growing in sediments containing cadmium has been shown to vary according to pH and redox potential (Figure 4-8). A study of disposal of dredged material containing cadmium onto the shore in a New York embayment showed clearly that material was available to vascular plants and to animals at lower trophic levels, specifically rushes and blue crabs (Kneip and Hazen 1979).

Field observations of bioaccumulation often show confusing and unpredictable relationships between "total" levels of metals in sediments and in benthic animals. Some of the quandaries may be resolved by detailed attention to the biology and feeding ecology of the species concerned. Analyses of body burdens of benthic animals must correct for animal size, sex, and time of year of collection (Luoma and Bryan 1979). Phelps and Myers (1977) found that benthic organisms utilizing the sediment-water interface and the immediately adjacent water column were better integrators of sediment metal content than were the subsurface feeders (Figure 4-9). Swartz and Lee (1980) and Lee and Swartz (1980) have recently provided an extensive review of the biological processes affecting the distribution of pollutants in marine sediments, including bioaccumulation, trophic transfer, biodegradation, biodeposition, and bioturbation.

Factors such as feeding ecology may explain why the burrowing sea cucumber (*Molpadia intermedia*) showed little evidence of metal accumulation at the Point Grey dumpsite offshore from Vancouver (Thompson

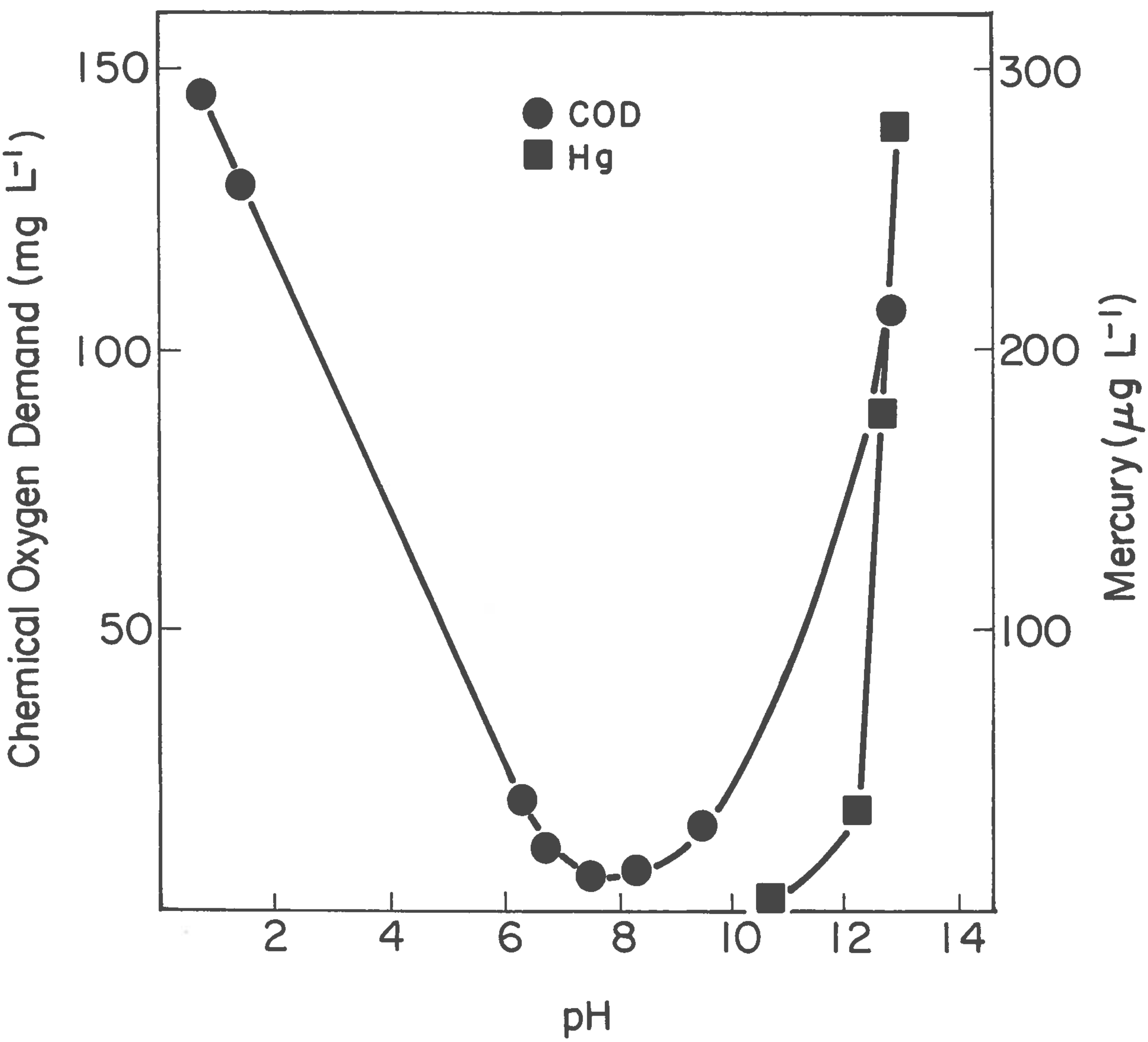


Figure 4-7. Variation in chemical oxygen demand (COD) and release of mercury from sediments from Minamata Bay, Japan, with respect to pH (from Murakami and Takeishi 1977).

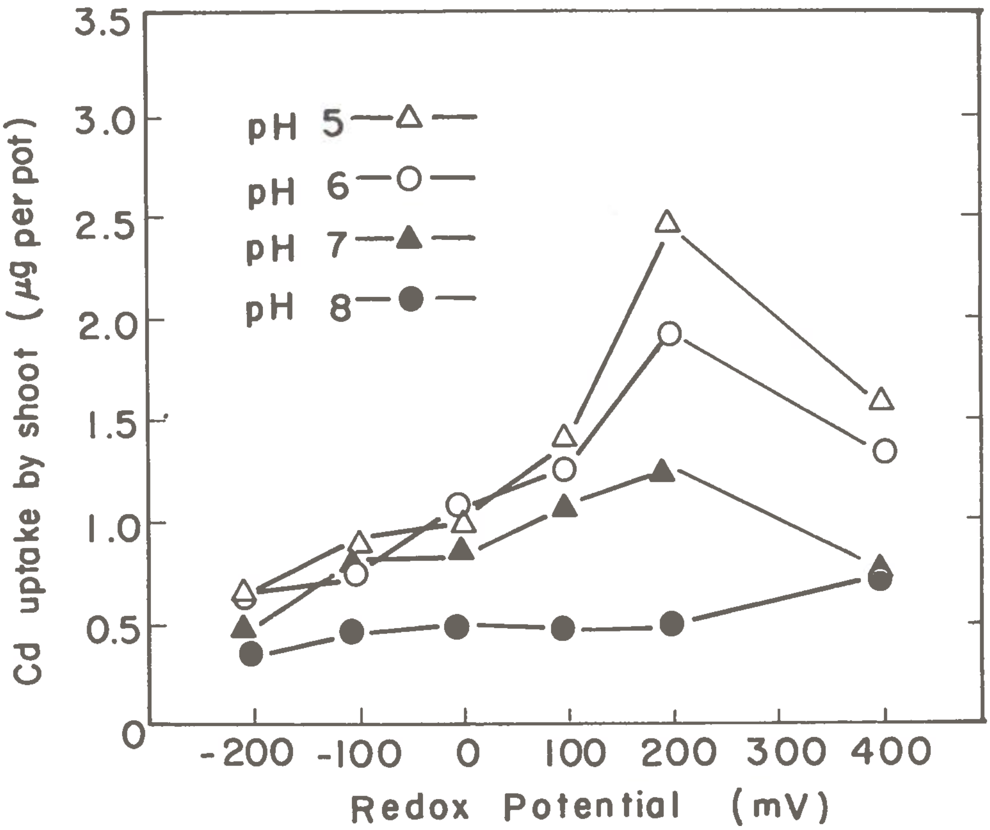


Figure 4-8. Cadmium uptake by *Spartina alterniflora* shoots at various pH levels and redox potential levels (from Patrick *et al.* 1977).

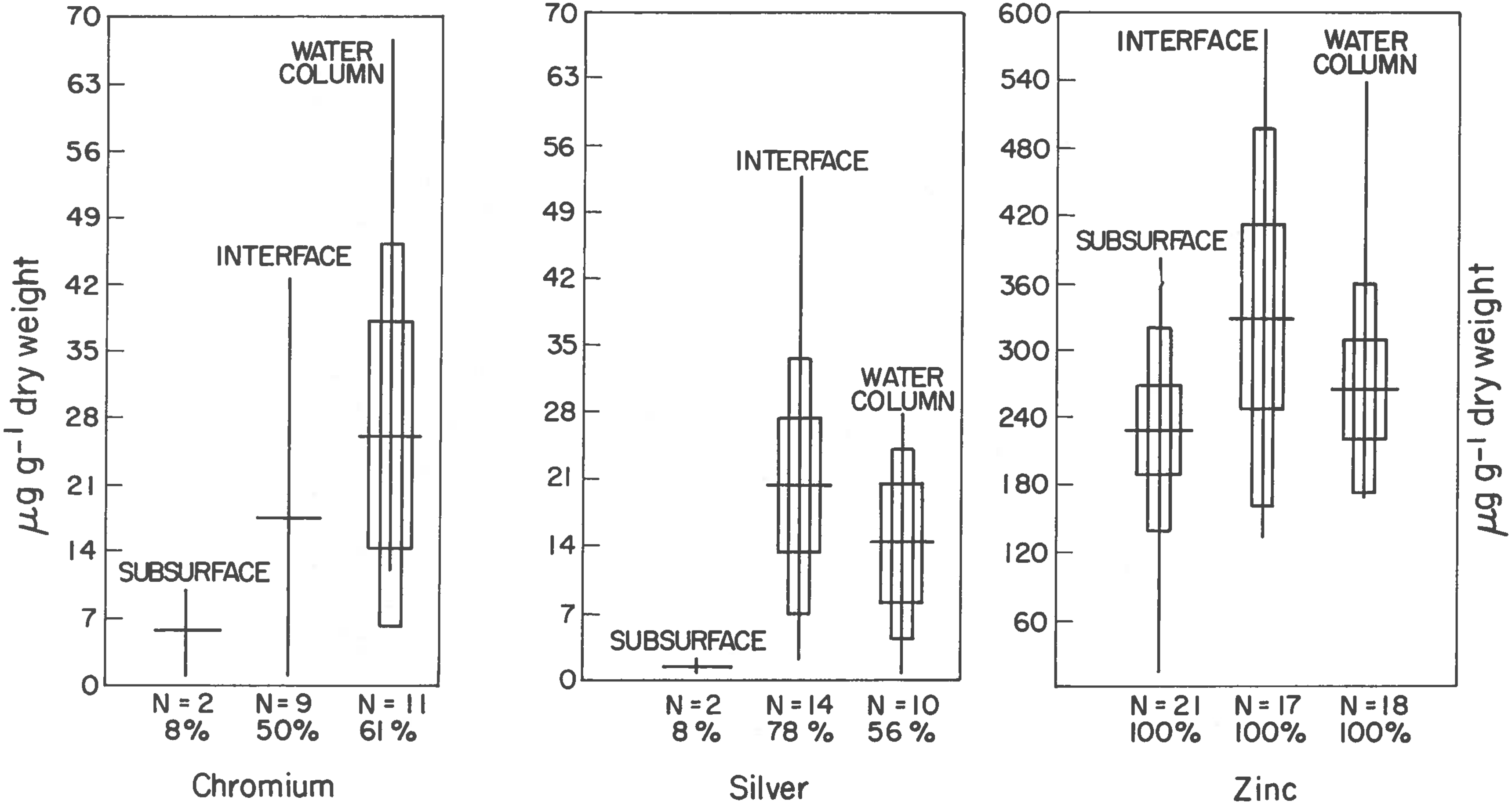


Figure 4-9. Uptake of chromium, silver, and zinc by subsurface feeders, interface feeders, and water column feeders. Subsurface feeders are *Nephtys incisa* and *Glycera dibranchiata* (Polychaeta); interface feeders are *Pherusa affinis* (Polychaeta), *Palaeomenetes pugio* (grass shrimp), *Rithropanopeus harisii* (mud crab), *Yoldia limatula* (bivalve), and *Nassarius obsoletus* (gastropod); water column feeders are *Mercenaria mercenaria*, *Mulina lateralis*, *Enis directus*, and *Mya arenaria* (all bivalves). Note: (i) vertical profiles display means and standard deviations; (ii) N denotes sample size (% data below N indicate number of organisms detected with metal) (from Phelps and Myers 1977).

and Paton 1978), where copper and zinc concentrations appear to be related to the main dumping area (Hoos 1977). In contrast, Pesch *et al.* (1977) reported increased levels of heavy metals in scallops (*Placopectea magellanicus*) from two dumpsites off Delaware Bay on the east coast of the U.S. Silver, copper, and nickel were identified as tags for sewage sludge, and vanadium was a tracer for acid wastes. Sediments from a dumpsite in Chaleur Bay (Dalhousie, New Brunswick) contain cadmium (Figure 4-10), but long-term experimental data or data from organisms at the dumpsite are not available. Eaton (1974) transplanted mussels (*Mytilus edulis*) at the dumpsite to monitor release of metals during dumping. After 1 month, no mercury bioaccumulation was observed. Ray *et al.* (1979), working with *M. balthica* collected from coastal New Brunswick, concluded that the species regulated or excreted copper, zinc, and cadmium, but not lead. Similarly, no bioaccumulation was found for organohalogens and polynuclear aromatic hydrocarbons (McLeese *et al.* 1979).

Uptake and flux of substances in laboratory experiments, as might be expected, are variable and difficult to relate to the field. For example, MacLaren Marex Inc. (1979a) examined cadmium uptake using *M. balthica* and sediments from harbors in New Brunswick. There appeared to be some correlation between metal concentrations in shells of the clams and substrate concentration; however, the authors concluded there was essentially no uptake by the soft tissue of the bivalve in 20-day static bioassays (salinity ∿29 ppt; usually well-oxygenated water). Sharp (1977) and the Environmental Protection Service (1980) found no evidence of uptake (32-day experiment) of metals by *M. balthica* from the sediment of Halifax Harbour, Nova Scotia, but PCBs were accumulated by the clams. Using *M. edulis* and *M. balthica* in laboratory experiments with sediments collected near a Vancouver shipyard, McGreer *et al.* (1981) concluded that Pb and PCBs (especially Aroclor 1254) showed the greatest potential to bioaccumulate. More recent experiments on the Atlantic coast (Parker and Doe 1982) showed that *M. balthica* accumulated Cd from sediments containing 58 $\mu g\ g^{-1}$ of the metal but not from those containing 0.11 or 1.43 $\mu g\ g^{-1}$. Wildish *et al.* (1980) examined the flux of Aroclor 1254 between estuarine sediments and water, and found that the adsorption was much stronger on finer sediments and higher salinities (up to 28%). The authors concluded that their results may be of practical use in predicting PCB concentrations in pore water of settled dredge spoil, provided that the replacement rate of pore water is slow enough to allow establishment of equilibrium conditions. There are no data on the replacement rate of pore water in an actual dumping situation.

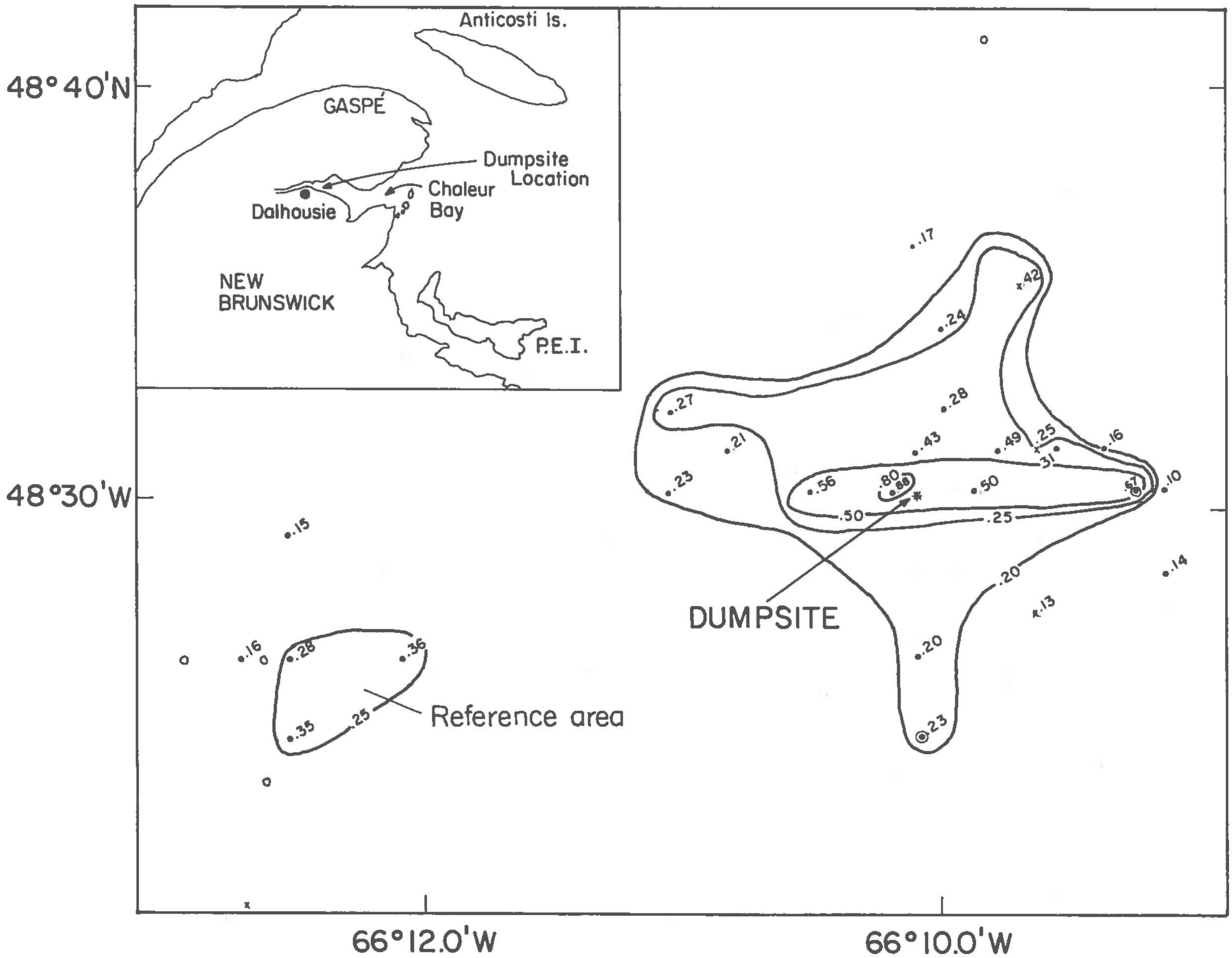


Figure 4-10. Total cadmium levels in surficial sediment (<2 cm) at the Dalhousie (Chaleur Bay), New Brunswick, dumpsite (units in mg kg^{-1}) (from MacLaren Marex Inc. 1979b).

4.3 TOXICITY

Observations of the toxic effects of dredging and dumping activities have come from both field and laboratory studies. Toxic effects, in this report, are taken to be chemical effects causing death or debilitation due to substances present in sediment or the associated reduction of water quality. The laboratory approach has been utilized as an aid to regulatory bodies, but because of the complex sediment chemistry involved, there has been little agreement on the standardization of these techniques. For example, in bioassay tests with sediments from Lake Michigan, Hoke and Prater (1980) found more correlation with bulk sediment analyses than with elutriate test results. There are few studies which consider sublethal (physiological, behavioral) effects of chemical-containing sediments. As is the case for most toxicity data, there are problems with extrapolating the results of individual deaths and/or impaired physiology to the population and community level.

4.3.1 FIELD OBSERVATIONS

The field data on toxicity resulting from dredging and/or dumping are restricted mainly to observations of fish kills or mass mortalities of fish. Table 4-5 presents a summary of a fish kill reported during dredging operations in British Columbia coastal waters. The data show that most of the incidents are apparently due to release of hydrogen sulfide during dredging and subsequent deoxygenation of the surrounding waters. Except for the brief report from Alberni Inlet (Hourston and Herlinveaux 1957), there are no supporting data on D.O. at the time of the incident, so the exact cause of death cannot be determined. For chemical reasons mentioned previously (see Section 4.2.1), data on sulfide levels are extremely difficult to interpret. Oxygen levels as low as 3.4 mg L^{-1} (approximately 40% saturation) were reported in the Alberni Inlet observations, but the authors concluded that H_2S was the poison that killed the fish (shiner perch (*Cymatogaster aggregata*) and stickleback (*Gasterosteus aculeatus*)).

As far as is known, there are no observations in Canadian waters of acute lethal toxicity that have been related to the release of heavy metals, PCBs, or similar substances from sediments during dredging and/or dumping. DeCoursey and Vernberg (1975), working in South Carolina, show one of the best examples from elsewhere. There was a good relationship between the mortality of two crustaceans (*Daphnia pulex* and *Palaeomonetes pugio*) and their location in relation to a dredge effluent (Figure 4-11). Organisms within the dredge spoil plume (up to 200 m downstream) died much faster than did those in a control area. Experiments with juvenile chum salmon (*Oncorhynchus keta*) have been conducted by suspending the fish in cages within the influence of a turbidity plume from a suction dredge in Puget South, Washington. Little mortality was observed in 24 different

Table 4-5. Instances of fish kills (>100 fish) resulting from dredging operations in British Columbia (data compiled from fishery officer records and provided by R. Harbo, Department of Fisheries and Oceans 1978).

Location	Date	Species	Comments
Duncan Bay	February 1971	Herring (*Clupea harengus pallasi*)	Log storage area
Neroutsos Inlet	July 1969, 1970	Hake (*Merluccius productus*)	Sulfite pulp mill
Powell River	December 1973, September 1979	Herring (*Clupea harengus pallasi*) Lingcod (*Ophiodon elongatus*)	Log storage area
Shuswap Lake	April 1976	Salmon fry (*Oncorhynchus* sp.)	Very high silt content
Squamish	February 1971	Herring (*Clupea harengus pallasi*)	
Port Alberni	September 1956	Shiner perch (*Cymatogaster aggregata*) Sticklebacks (*Gasterosteus* sp.)	Log storage area Documented in Hourston and Herlinveaux (1957)

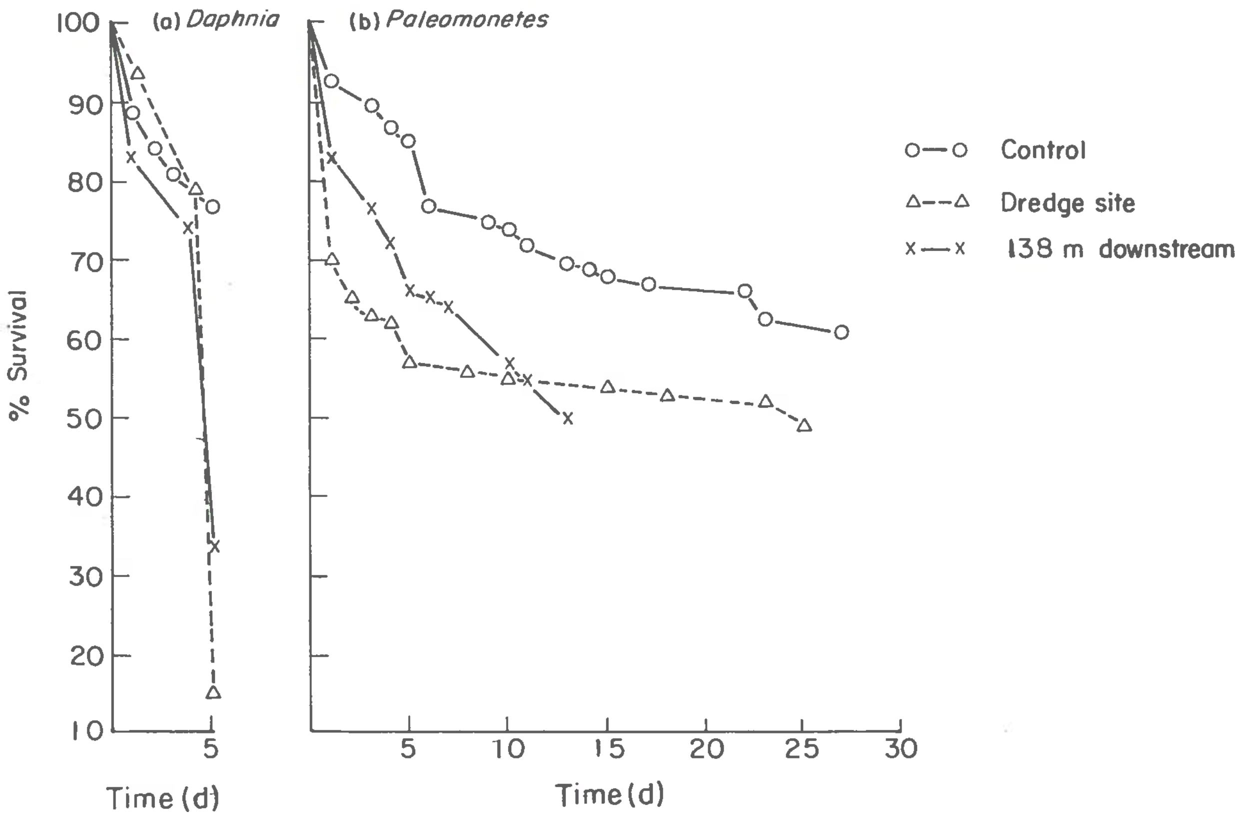


Figure 4-11. Mortality of *Daphnia pulex* and *Palaeomonetes pugio* larvae during *in situ* bioassays in a South Carolina, U.S.A., estuary (from DeCoursey and Vernberg 1975).

7-day bioassays over the period January to July 1977. Static bioassays were also conducted and showed a 96-h LC50 of 15.8-54.9 g sediment L^{-1} (Smith 1978). Some caged fish studies, while more natural than laboratory experiments, are somewhat unrealistic as they reduce the opportunities for the fish to avoid those portions of the water body influenced by the dredged material.

4.3.2 LABORATORY BIOASSAYS

Published laboratory studies involving bioassays with dredged material or sediments of any kind are scarce in the Canadian literature. There has been more activity in recent years because the Ocean Dumping Control Act (Anonymous 1975a) requires that tests be conducted for certain chemicals. Few of these results are published. Because the impact is usually associated with the benthic environment, work has focussed on animals that live on or near the bottom. McLeese and Metcalfe (1980) tested the toxicity of eight individual organochlorine compounds with the Atlantic shrimp *Crangon septemspinosa*, using spiked sediments and seawater (unknown salinity). The authors concluded that the organochlorines were 10 to 80 times less toxic in sediment than in water (Table 4-6). However, sediments with only one chemical substance present are rare, and the bioassay of "composite" samples from the field are more representative of the typical problem.

Bioassays with *Macoma balthica*, a ubiquitous bivalve mollusc, have been performed by Sharp (1977) and McGreer (1979) on the Atlantic and Pacific coasts, respectively. Sharp (1977) found that sediments containing lead (104-385 $\mu g\ kg^{-1}$), copper (119-140 $\mu g\ kg^{-1}$), zinc (130-450 $\mu g\ kg^{-1}$), and DDT (95-108 $\mu g\ kg^{-1}$) did not cause significant mortalities in bioassays with *M. balthica*.

Bioassays using *M. balthica* are routinely employed by Environmental Protection Service personnel on the Atlantic coast to aid in screening sediments for ocean disposal. For example, the toxicity of sediments dredged from the vicinity of shipyards in Halifax Harbour was investigated in 32-day bioassays. The sediment contained cadmium, mercury, lead, zinc, and PCBs, but survival was 87% in the bioassays with 100% sediment (14-16°C, D.O. at 60% saturation) (Environmental Protection Service 1980). McGreer (1979) also did not observe mortalities but did document sublethal effects with *M. balthica* and sediments from the Fraser estuary in British Columbia (see Section 4.3.3).

Given the difficulties in assessing bioavailability (see Section 4.2.3), it is not surprising that efforts to assess the toxicity of sediments are pursued without specific chemical data. Swartz *et al.* (1979) investigated the survival of five estuarine invertebrates in sediments collected from polluted harbors throughout the U.S.A. (Table 4-7). They found that crustaceans, especially the burrowing amphipod *Paraphoxus*

Table 4-6. 96-h LC50s and lethal thresholds for shrimp (*Crangon septemspinosa*) exposed to organochlorine compounds in seawater (20°C) and sediment (10°C) (from McLeese and Metcalfe 1980).

Compound	Seawater tests		Sediment tests	
	96-h LC50 ($\mu g\ L^{-1}$)	Threshold ($\mu g\ L^{-1}$)	96-h LC50 ($\mu g\ L^{-1}$)	Threshold ($\mu g\ L^{-1}$)
Endosulfan	0.2	0.2	6.9	9.0
Endrin	0.6	0.5	47	41
DDT	0.4	0.2	31	20
Dieldrin	0.4	0.5	4.1	2.6
Chlordane	2.0	1.0	120	110
Aroclor 1242	13.0	6.5	>780[a]	-
Aroclor 1254	12.0	0.5	>3400[a]	-
HCB	>7.2[a]	-	>300[a]	-

[a] No mortalities at highest concentration tested.

Table 4-7. Results of sediment toxicity bioassays using sediments from several U.S. harbors and five invertebrate taxa (from Swartz *et al.* 1979).

		Numbers surviving[b]				
Sediment type	Number of experiments	*Protothaca staminea*	*Macoma inquinata*	*Glycinde picta*	*Paraphoxus epistomus*	*Cumacea*
Yaquina Control	2	19.5	19.5	14.0	19.5	15.0
Duwamish Turning Basin	2	20.0	17.0	17.5	4.0[a]	10.5
Duwamish Slip No. 1	2	20.0	13.0[a]	16.0	9.0[a]	7.0
Duwamish Mouth	2	20.0	16.0	17.0	17.0	11.5
Elliott Bay	2	20.0	17.5	15.5	12.0[a]	6.0
Puget Sound	2	20.0	16.5	14.0	17.5	8.0
Yaquina Control	2	20.0	18.5	19.5	19.0	17.0
Coos Bay Station I	2	20.0	19.5	20.0	18.5	13.0
Coos Bay Station II	2	20.0	19.5	18.5	18.5	16.0
Coos Bay Station III	2	20.0	19.5	18.5	18.5	16.5
Coos Bay Station IV	2	20.0	19.5	19.0	18.0	18.0
Yaquina Control	2	19.5	20.0	20.0	20.0	18.5
Houston Channel Station I	2	20.0	20.0	20.0	13.5[a]	6.5[a]
Houston Channel Station II	2	19.5	20.0	20.0	13.5[a]	12.0[a]
Houston Channel Station III	2	18.0	20.0	16.0[a]	0.5[a]	4.0[a]
Houston Channel Station IV	2	20.0	20.0	19.5	6.0[a]	9.5[a]
Houston Channel Station V	2	20.0	20.0	17.0[a]	7.0[a]	13.0
Yaquina Control	5	20.0	20.0	18.4	18.2	20.0
Bailey Creek	5	20.0	17.0[a]	17.6	12.2[a]	14.4[a]
Yaquina Control	5	20.0	20.0	17.2	18.4	16.2
Skipanon River	5	20.0	19.4	19.6	16.6	14.4
Yaquina Control	5	20.0	19.8	16.8	18.8	18.4
Raritan River	5	20.0	19.2	17.0	9.4[a]	14.0[a]

[a] $p < 0.05$.

[b] Average per 20 individuals.

epistomus and several species of cumaceans, were most sensitive. They recommended that bioassays be conducted using these crustaceans to determine whether chemical-containing dredge spoil should be dumped. The experiments of Swartz *et al.* (1979) were particularly useful, as they determined that depth of sediment in the chamber used was shallow enough to avoid burial effects.

Other sediment bioassay experiments reported include those of Prater and Anderson (1977), using the freshwater invertebrates *Hexageneia limbata* (mayfly nymph), *Asellus communis* (isopod), and *Daphnia magna* (cladocerans), and of Tsai *et al.* (1979), using the estuarine fishes *Fundulus heteroclitus* (mummichog) and spot (*Leiostomus xanthurus*) and the soft shell clam (*Mya arenaria*). Using sediments from several stations in Baltimore Harbor, the latter authors developed a relationship between the 24-h LC50 for mummichogs and the species diversity of benthic invertebrates collected at corresponding locations. This relationship was then used to map the "toxicity status" of stations sampled in an extensive benthic survey. A joint publication of the Environmental Protection Agency/U.S. Army Corps of Engineers Technical Committee for Dredged and Fill Material (1977) provides information on the types of sediment bioassays required to determine toxicity. Organisms using habitats affected by the solid, liquid, and suspended phases of sediments are specified (i.e. bivalves, cladocerans, and mysids, respectively).

Experiments concerning the effects of elevated concentrations of suspended sediment on organisms have been recently reviewed by Moore (1977) and Peddicord and McFarland (1978). Earlier studies by Davis and Hidu (1969) showed that larvae of bivalves were sensitive to silt concentrations (Figure 4-12). Kirbøe *et al.* (1981) concluded that silt had no effect on hatching success of Atlantic herring (*Clupea harengus*) eggs but their experiments considered only suspended material. Messieh *et al.* (1981) found that sediment deposited onto the spawn of this species increases egg mortality. EVS (1982) found that the demersal eggs of Pacific cod (*Gadus macrocephalus*) were very sensitive to deposition of Victoria Harbour sediment, which was toxic even when eggs were covered to a depth of 1 mm. Lobster larvae (*Homarus americanus*) were found by Cobb (1976) to be sensitive to small quartz particles (30-55 μm). Mortality in laboratory experiments was directly associated with increasing concentrations of the small particles. Death appeared to result from respiratory interference associated with an accumulation of particles about the gill filaments. Schubel *et al.* (1974, cited in Moore 1977) found that suspended sediments in concentrations of 1000 mg L^{-1} affected egg hatching success in yellow perch (*Perca flavescens*), striped bass (*Morone saxatilis*), and white perch (*Morone americana*). However, another publication by these authors (Auld and Schubel 1974, cited in Moore 1977) mentioned that similar concentrations of suspended matter did not affect

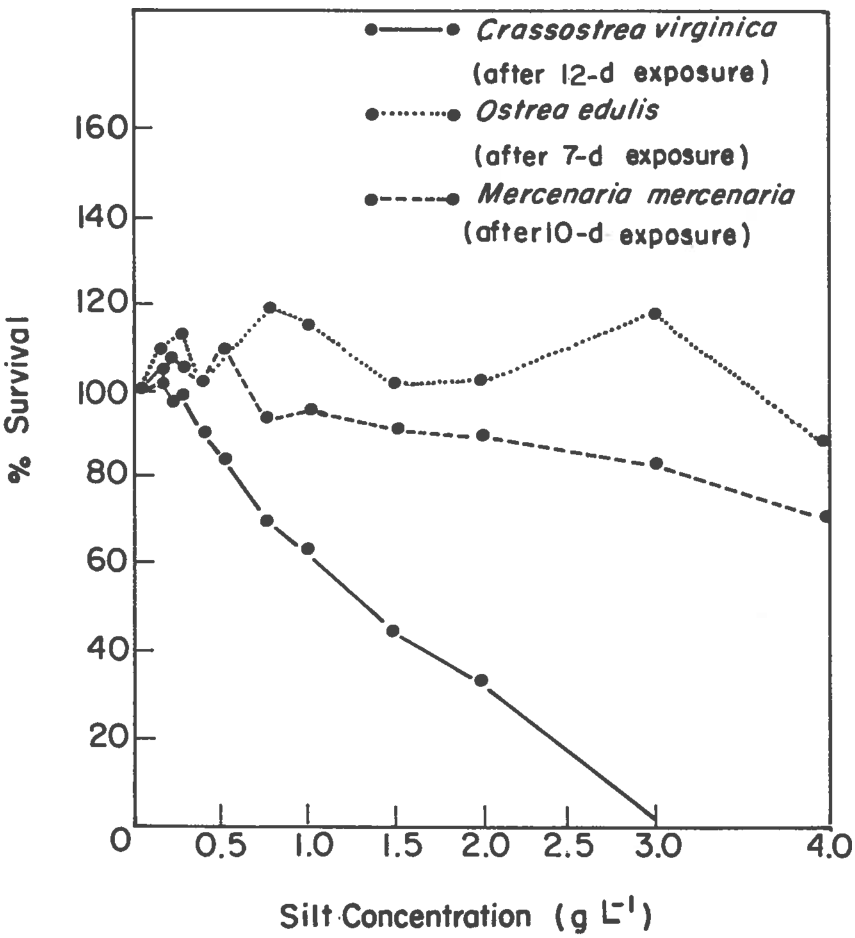


Figure 4-12. Survival of the larvae of three species of bivalve molluscs in seawater suspensions containing various concentrations of silt (from Davis and Hidu 1969).

eggs of yellow perch, blueback herring (*Alosa aestivalis*), and American shad (*A. sapidissima*). Studies of the effects of suspended sediment on a variety of organisms, including crayfish, freshwater clams, insect larvae, shrimp, mussels, tunicates, crabs, and fish, by Peddicord and McFarland (1978), showed mortalities when concentrations were in the "tens of grams" per litre range. The authors stated that these concentrations might be reached in the layer of "fluid mud" that can result from dumping of very fine sediments. O'Neal and Sceva (1971) recorded fluid mud dispersing over the bottom during a hydraulic dredging operation in Bellingham Harbor, Washington.

The toxicity of leachates from dredged material rich in wood waste collected from Alberni Inlet (also used in lysimeter experiments; see Section 4.1) was studied in bioassay experiments by EVS Consultants Ltd. (1977). The study showed that leachates from sediments near a pulp mill and a log storage area were acutely toxic to sand shrimp (*Crangon* sp.). The authors suggested that a variety of toxic components, including H_2S, ammonia, phenolics, fatty acids, and resin acids, were responsible for the observed mortality. In addition, the water in the test chamber could not be aerated to oxygen levels acceptable for bioassay, and the sediment displayed high levels for BOD and COD.

Two experimental studies, one in Alaska and one in Washington, are also particularly relevant to the problem of disposal of dredge spoil and wood debris. In the latter study, Servizi *et al.* (1969) examined the toxicity of sediments from Bellingham Bay to sockeye salmon (*Oncorhynchus nerka*) smolts. Fish were distressed at 0.5% sediment concentration (Table 4-8). As noted in the lysimeter experiments with material from Alberni Inlet, the sediments exhibited a very high oxygen demand. However, Servizi *et al.* (1969) concluded that H_2S poisoning rather than dissolved oxygen deficiency was responsible for mortality in the bioassays. Buchanan *et al.* (1976), working with leachates from Alaska wood, found that spruce extracts were more toxic to pink shrimp adults and larvae (*Pandalus borealis*) and crab larvae (*Cancer magister*) than were hemlock extracts. For crab larvae, for example, the 96-h LC50 for spruce was 530 mg L^{-1} compared to >1000 mg L^{-1} for hemlock. Pink salmon fry (*Oncorhynchus gorbuscha*), on the other hand, showed an opposite tolerance (96-h LC50s of 100-120 mg L^{-1} and 56 mg L^{-1} for spruce and hemlock, respectively).

4.3.3 SUBLETHAL EFFECTS

Behavioral observations were made by Chang and Levings (1976) with several Pacific benthic organisms and sediments representing dumped material (sand, wood debris, etc.). They also observed the effects of sediments dredged near pulp mills. In the laboratory, the shrimps (*Pandalus danae* and *Crangon alaskensis*) showed impaired burrowing activity with wood wastes (Table 4-9), but the squat lobster *Munida quadrispina* used wood as cover, showing how inert material could add heterogeneity

Table 4-8. Toxicity of sediments from Bellingham Harbor, Washington, to sockeye salmon (*Oncorhynchus nerka*) smolts (from Servizi *et al.* 1969).

Sediment concentration (%)	Mortality (%)	Time to death or end of bioassay (min)	Initial hydrogen sulfide concentration (mg L^{-1})	Final dissolved oxygen concentration (mg L^{-1})	Behavior of fish
2.0	100	15	3.13	5.7	Distressed until death
1.0	100	25	2.15	5.6	Distressed until death
0.5	0	85	0.90	3.2	Distressed for 7 min
0.1	0	90	0.24	5.0	No distress evident
0.05	0	95	0.10	4.9	No distress evident
0.0	0	95	0.00	5.5	No distress
2.0	100	15	4.40	-	Distressed until death
1.0	100	25	2.40	-	Distressed until death
0.5	0	60	1.22	-	Distressed for 10 min
0.1	0	60	0.30	-	No distress evident
0.0	0	60	0.00	-	No distress

Table 4-9. Results of choice tests with modified sediments using shrimp (*Crangon alaskensis*)[a] (from Chang and Levings 1976).

Number in mud	Number in alternate substrate	At boundary	Not burrowed	Number of trials	Probability
1	28 (sand)	0	1	30	0.001
25	4 (woodchips	1	0	30	0.001
3	7 (woodchips on mud)	3	0	13	0.17
22	4 (wood debris)	4	0	30	0.001
6	9 (pulp mill fiber)[b]	0	2	17	0.30
27	0 (pulp mill fiber)[c]	0	1	28	0.001

[a] Data indicated are burrow locations after 24 h.

[b] Inactive pulp mill.

[c] Active pulp mill.

to the habitat. Pottle and Elner (1982), in laboratory tests, showed that lobsters (*Homarus americanus*) preferred gravel, so that changes in sediment composition could affect this species habitat. Gannon and Beeton (1971) successfully used the burrowing amphipod *Pontoporeia affinis* in choice test experiments with sediments from Lake Michigan. These laboratory experiments consisted of presenting the amphipod with a choice of several types of sediments, characterized by various concentrations of chemicals. This approach was also followed by Pollutech Pollution Advisory Services Ltd. (1974) who used sediments from Hamilton, Portsmouth, and Oshawa Harbours with several invertebrates, including amphipods and midge fly larvae. There were problems with mortality in controls in the latter experiments. The authors concluded that the test organisms demonstrated a preference for specific sediments but the preference was not related to chemical content. McGreer (1979) found that the burrowing behavior of *Macoma balthica* was slowed in Fraser estuary sediments containing heavy metals (Figure 4-13). McGreer *et al.* (1981) tested sediment collected from a shipyard in Vancouver Harbour and found that burrowing of *M. balthica* was inhibited when compared to a control substrate.

Laboratory studies of Atlantic herring (*Clupea harengus*) behavior showed that juveniles of the species demonstrated avoidance responses to suspended sediment. For a fine sediment of 4.5-μm median particle diameter, the threshold concentration was 19.5 mg L^{-1}, and for a coarser sediment containing 30% sand, the concentration was 35.5 mg L^{-1} (Wildish *et al.* 1977).

Laboratory studies of sublethal effects using striped bass (*Morone saxatilis*), showed that oxygen consumption rates at high levels of swimming activity were reduced in the presence of Fuller's earth (0.79 g L^{-1}) or river sediments (1.31 g L^{-1}) (O'Connor *et al.* 1977). Other sublethal effects included gill tissue disruption, intensified mucus production on the gill, and a decrease in the respiratory surface area. Exposure to sublethal suspended solids increased the microhematocrit, hemoglobin level, and red blood cell count in white perch and three other Atlantic estuarine fish species. The toadfish (*Opsanus tau*), a benthic species, showed no significant respiratory response to Fuller's earth or natural sediment.

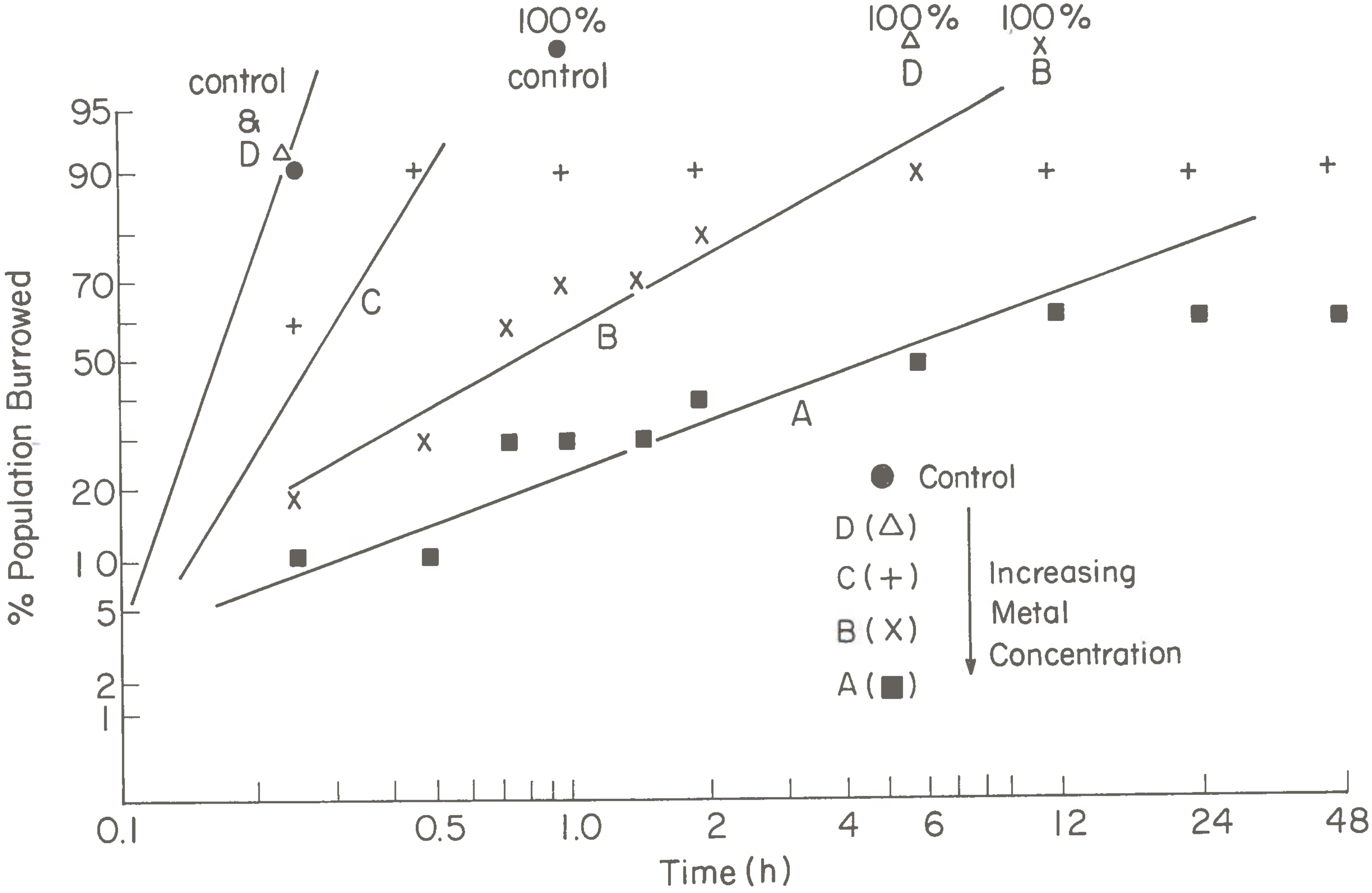


Figure 4-13. Burrowing rates for *Macoma balthica* in sediments from Iona Island sewage outfall, Fraser River Estuary, British Columbia. Ranges for various metals (mg kg^{-1}) in sediment are Cu 13-150, Pb 3-74, Zn 41-172, Cr 34-90, Ag 0.4-1.0, Hg 0.04-0.46, Cd 0.4-1.4, Fe 19,000-36,000 (from McGreer 1979).

5.0 ECOLOGICAL EFFECTS

5.1 DIRECT EFFECTS

The direct impact of dredging and dumping can be evaluated relatively easily, especially when the dumping has occurred in the intertidal zone or in shallow waters where effects can be viewed directly or with the aid of SCUBA. In direct effect cases, organisms are often killed outright or permanently immobilized by physical alterations to the habitat.

5.1.1 SEDIMENT REMOVAL

Two of the most common concerns relating to lake or river dredging activities in Canada are the destruction of fish spawning beds and the death of juvenile fish due to entrainment in suction dredge devices. Engineering operations performed to keep river channels navigable (e.g. Harrison River) (Anonymous 1967), or for the removal of gravel for construction purposes or for pipeline crossings (Whitehead 1978), may result in disruption of salmonid spawning beds. Since salmonids need sufficient clean gravel for spawning, the impact is clear and obvious in all three cases. Atlantic herring (*Clupea harengus*) and sand eel (*Ammodytes marinus*) spawn on gravel of specific size, so alteration of sediments could be expected to be a concern for these species (Anonymous 1975c, 1977). Mortalities related to entrainment during suction dredging have an obvious effect on fish populations. In an experiment where marked chum fry (*Oncorhynchus keta*) were inserted into a suction dredge operating in the Fraser River, an overall mortality rate of 98.8% was observed. For every fry recovered (dead or alive), 22 were buried in the dredge spoil (Dutta and Sookachoff 1975). Some of these problems may also arise in marine dredging projects, and certainly many marine invertebrates, including commercial crabs (Stevens 1981) and shrimps, taken in by suction dredges are killed. Thousands of small fishes, such as the sand lance (*Ammodytes hexapterus*), important in coastal food webs, can be killed by dredging in the lower Fraser estuary (Table 5-1). Some benthic animals may survive clamshell dredging. DFO (1981) examined the mortality of juvenile chinook salmon (*O. tshawytscha*) at three British Columbia harbors where clamshell dredging was occurring. The authors concluded that dredging of highly organic bottom sediments can cause mortality within 40 m of the dredging operation, in an area where water exchange is poor.

The benthic fauna in dredged areas are usually different from those in adjacent shallow areas due to the removal of sediment habitats and the obvious depth differences. At Port Stanley, dredging resulted in an 85% reduction of the benthic community. Oligochaetes were reduced (2 weeks post-dredging) from an average abundance of 503,700 m^{-2} to

Table 5-1. Estimated entrainment of fish and invertebrates into a hopper dredge operating on the lower Fraser River (March 17 to June 2, 1975; St. Mungo Bend to Sandheads) (from Dutta 1976).

Species	Estimated entrainment into hopper dredge
Eulachon (*Thaleichthys pacificus*)	98,384
Sand lance (*Ammodytes hexapterus*)	74,074
Shrimp (*Crangon* sp.)	26,598
Chum (*Oncorhynchus keta*)	15,730
Flounder	9438
Sockeye (*O. nerka*)	9152
Dogfish (*Squalus acanthias*)	6006
Crab (*Cancer magister*)	2860
Sculpin	2002
Sturgeon	572
Hake (*Merluccius* sp.)	286

57,820 m^{-2} and chironomids from 4853 m^{-2} to 292 m^{-2} (Chemex 1973a). Cazemier (1977) examined the benthic communities in dredged sand pits in the Netherlands and found that the abundance of fish food organisms (midge larvae, oligochaetes) was reduced in the deeper parts of the depressions. No data were given on the frequency of dredging in the pits that were studied.

5.1.2 BURIAL AFTER DUMPING

Direct burial of sedentary invertebrates after dumping of dredge spoil has been documented by many authors (e.g. Nichols *et al.* 1978; Maurer *et al.* 1978). In some instances, where the sediments are deposited in a thin layer (e.g. less than 10 cm), burrowing invertebrates (e.g. polychaete worms, McCauley *et al.* 1976) are able to move up through the material to reestablish contact with the sediment-water interface. The thickness of material which will cause permanent burial is dependent on the size and behavior of individual species, in addition to the physical and chemical factors involved in the deposition of material. Chang and Levings (1978), in laboratory studies with large invertebrates (the heart cockle (*Clinocardium nuttallii*) and the Dungeness crab (*Cancer magister*)), found that the critical depth of burial with Fraser River sand was about 20 cm. Goodwin (1975) observed that adult geoducks (*Panope generosa*), a large subtidal bivalve, could extend their siphons through 50 cm of dredge spoil. King (1977) studied the small crustacean *Cumella vulgaris* (Cumacea) in the laboratory, and found that sedimentation rates greater than 2.5 mm min^{-1} were needed to bury 50% of *C. vulgaris* with the deposition of 4 cm of sediment. Nichols *et al.* (1978) developed "overburden stress", a measure relating bulk density and burial depth which could be used to predict permanence of burial, assuming the behavior of organisms was known.

The effects of silt and sand deposition by various construction practices on fish habitats have been a major concern in several areas of Canada. If confinement techniques are used for disposal in shallow water, there is obviously permanent burial of habitat that may not be compensated for by the creation of deeper water by dredging. Effects on river habitats and spawning beds are well known and are described in a number of publications (e.g. McDonald and Shepard 1955; Shea and Mathers 1978; Whitehead 1978). Estuaries are now receiving recognition as important fish habitats for juvenile salmonids in British Columbia. Levings and Moody (1976) observed that the estuarine sedge (*Carex lyngbyei*) at the Squamish estuary had not fully recovered from silt spilled from a dredging operation 4 years previous to the study. Where the silt was less than 10 cm thick, recovery was faster.

5.1.3 PHYSICAL EFFECTS IN THE WATER COLUMN

Organisms in the water column through which dredge spoil has passed can be affected by direct physical effects on filter-feeding apparatus (e.g. zooplankton). Pelagic populations could also be displaced in the water column by entrainment in the sinking dredge spoil, but this is likely to be a very transitory effect (Maurer *et al.* 1978). However, Slaney (1977) observed no impairment of the filtration rate of zooplankton (Figure 5-1) when exposed to a dredge spoil plume from artificial island construction in the Beaufort Sea.

5.2 INDIRECT EFFECTS

As mentioned previously (see Section 4.3), conclusions based on laboratory experiments, especially those dealing with toxicity, are difficult to translate to the population or community. Since it is at these levels that effects impinge on resources which affect human health and/or the economy, there is a growing realization that impact evaluation and monitoring strategy must be ecosystem-specific. The following discussion therefore deals with documented effects of dredging and dumping on processes for specific ecosystems.

5.2.1 PRIMARY PRODUCTIVITY (PHOTOSYNTHESIS)

Since photosynthesis is one of the major production mechanisms, there has been considerable concern directed toward evaluation of impacts on this process. For marine phytoplankton, which move with water masses past dredge and dumpsites, the impact on primary productivity seems to be relatively small and temporary. The influence of turbidity by reducing light available for primary productivity has been examined during dredging and dumping activity at the Mackenzie delta on the Arctic coast (Slaney 1977). The shading effects of dredged sediment plume (see Section 3.1) were found to be very similar to those of the natural sediment of the Mackenzie River (Figure 5-2). Since phytoplankton cells are able to assume "resting stages" under low light conditions (Stockner and Antia 1976), effects of light limitation due to dredge plume turbidity must be temporary.

On the other hand, benthic algae, which assume major importance in certain littoral systems (e.g. kelp beds, intertidal zones) can be severely affected by disposal of dredge spoil. Daly and Mathieson (1977) compared the algal communities at a New England rocky shore partially invaded by drifting sand. The authors concluded that the intertidal seaweed populations at the sandy site showed a lower number of perennials and fewer species than did adjacent rocky shores. The U.S. Army Corps of Engineers (1978) found that dredge spoils dumped on a wave-swept rocky beach in Oregon resulted in direct scouring, smothering, and possibly toxic effects on intertidal algal communities which were dominated by

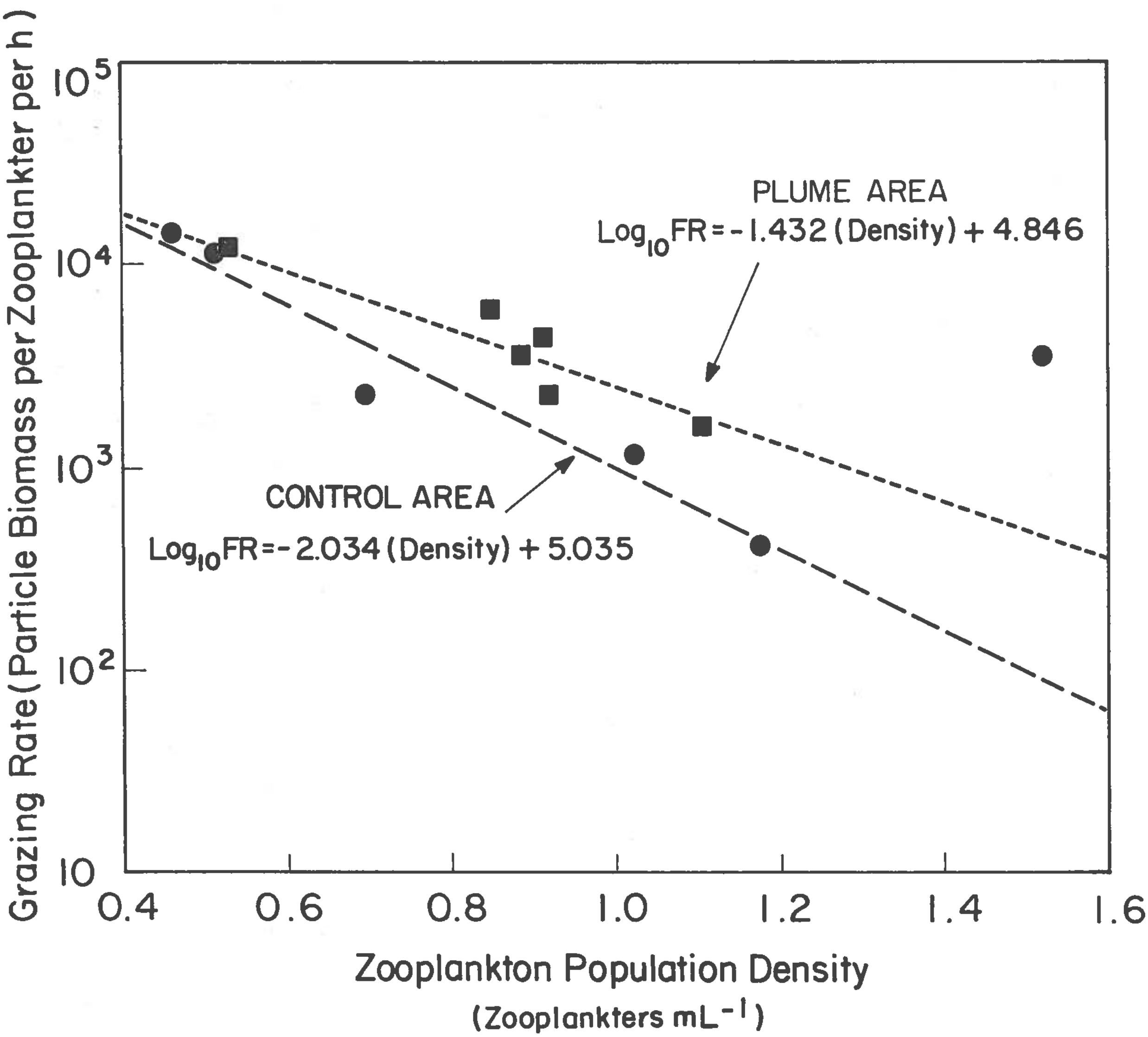


Figure 5-1. Feeding rates of zooplankton from a station within a turbidity plume created during the construction of an artificial island in the Beaufort Sea (Arnak L-30, August 11, 1976) compared with rates at a control location (from Slaney 1977).

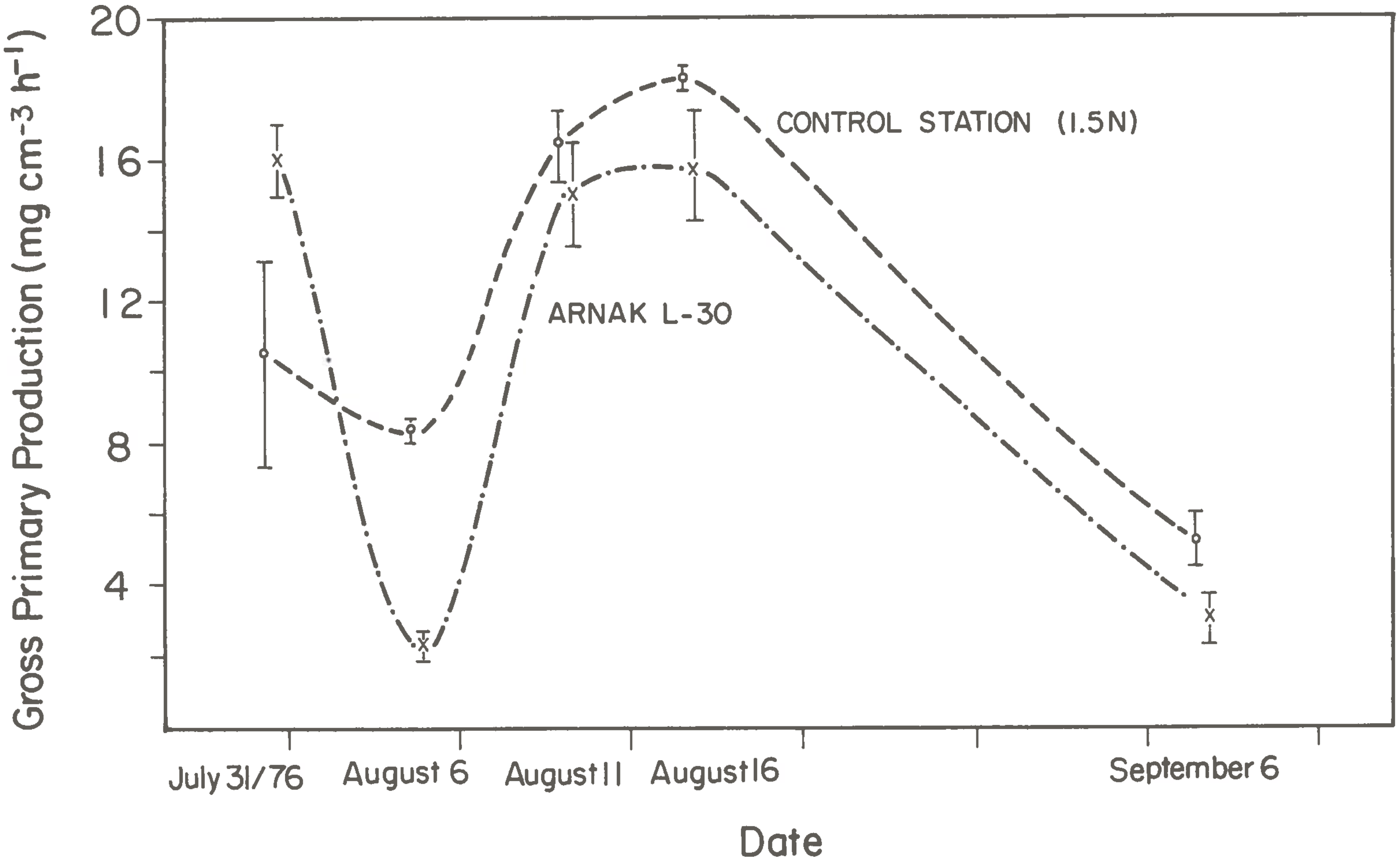


Figure 5-2. Gross primary production from a station within a turbidity plume created during the construction of an artificial island in the Beaufort Sea (Arnak L-30) compared with that at a control location. 1.5N indicates 1.5 nautical miles (2.8 km) north of the artificial island (from Slaney 1977).

Hedophyllum sessile. Effects on the bull-kelp (*Nereocystis leutkeana*) were less conclusive, as the authors felt that the smothering of plants by spoil disposal had to be viewed in balance with the potential creation of scoured settling sites for *Nereocystis* sporophytes. It is clear that disposal of dredged material in habitats for benthic algae can lead to local and possibly permanent reductions in littoral primary productivity. Effects can be indirect; for example, the modification of elevations on beaches could result in habitats not usable by algae or marsh plants because of changed submergence/emergence ratios.

Nutrient release from sediments may occur as a result of dredging and disposal in freshwaters (see Section 4.2.2) and can lead to eutrophication of confined parts of lakes. Enhanced chlorophyll levels were observed after certain dredging operations in Lake Ontario (Chemex 1975). Lake simulator columns showed algal growths following dumping of dredged material (see Section 4.2.2). Because of restricted circulation in some lakes and the "closed" nature of their ecosystems, there is more risk for disruption of natural photosynthetic patterns than in marine systems.

5.2.2 SECONDARY PRODUCTIVITY (ZOOPLANKTON, ZOOBENTHOS)

Because zooplankton generally move past dredge and dumpsites with advective water masses, the loss of plankton populations might be expected to be proportional to the rate of movement, assuming that entrainment led to mortality in the immediate area. Production losses are assumed to be proportional to the amount of biomass taken out of the ecosystem by mortality. However, if particularly sensitive or important life history stages of species are involved (e.g. gravid females), more than simple proportional effects may be involved.

Due to burial or serious modification of sediments, the loss of entire segments of benthic populations occurs whenever bottom material is dredged and dumped. This loss is often computed using biomass data on an areal basis for the portions of the sea floor involved. For example, Slaney (1977) calculated that about 19 ha and 15,000 kg of wet weight biomass would be lost by construction of an artificial island in the Beaufort Sea. There are no published data on the rate or magnitude of recolonization of the new substrates presented by such islands. In Alberni Inlet, Dobrocky Sea Tech Ltd. (1977) found that subtidal disposal of more than 300,000 m^3, dumped over a 5- to 10-year period, led to the modification of 2 ha of bottom area (Figure 5-3) and substantially changed the structure of benthic communities. Although these losses are small in proportion to the seafloor area at these particular locations, such impacts could be significant in heavily industrialized harbors where habitat may be limiting for resource species. In addition, biomass data alone are not enough for the calculation of productivity. Data on turnover times for the major species are required, and these are available for only a few subtidal species in Canadian coastal waters (e.g. the polychaete *Pectinaria koreni*

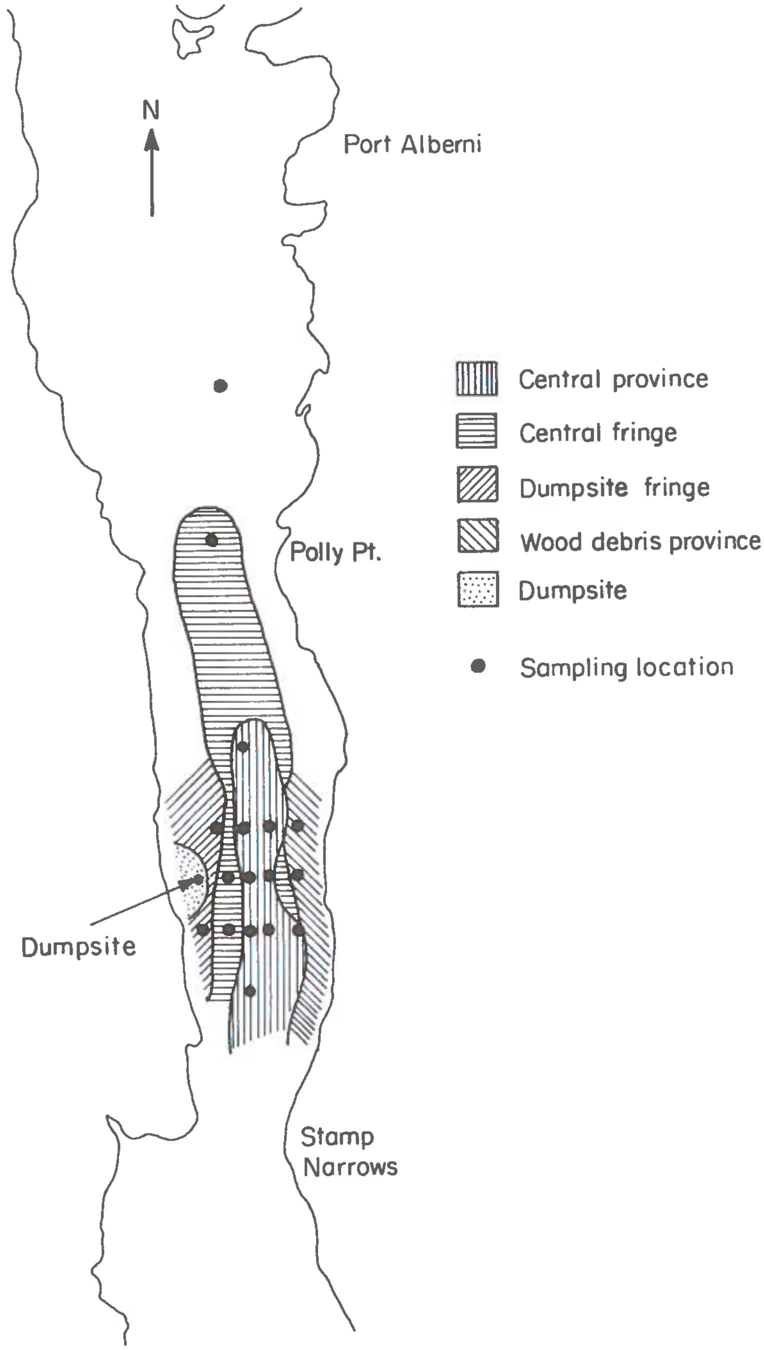


Figure 5-3. Classification of faunal assemblages as deduced from cluster analysis of benthic invertebrate data at the Alberni Inlet, British Columbia, dumpsite (from Dobrocky Sea Tech Ltd. 1977).

in St. Margaret's Bay, Nova Scotia; Peer 1970). Usually, changes in the structure of benthic communities at dumpsites can be measured, for example, by classification or ordination techniques. However, these changes cannot easily be interpreted in terms of the dynamics of the local production system.

5.2.3 BENTHIC RECOLONIZATION

The utilization of disrupted benthic habitats in marine waters has been found to be variable and seems to occur on a weekly or monthly time scale. Other than areas under permanent anoxia, and where dredging and dumping is extremely frequent, most are colonizable. However, the structure of the communities that use dredge and disposal areas is usually different from those initially present. In highly stratified estuaries, the fauna colonizing a dredged channel could be changed because topographic differences would allow penetration of a salt wedge where none was previously present. This was suggested as one possible impact of dredging in Tuktoyaktuk Harbour, N.W.T. (Arctic Laboratories Ltd. 1980).

For adults of mobile organisms, recolonization obviously involves migration to or through an affected area. For example, prawns (*Pandalopsis* sp.) were observed atop wood debris at a dumpsite in Howe Sound, British Columbia, where sedentary infaunal organisms are known to be sparse (McDaniel *et al.* 1977). Durkin and Lipovsky (1977) conducted trawling experiments at test dump sites in the Columbia River, Washington. A series of comparative tests on data from the demersal fish communities (including species richness, diversity, evenness, species per tow, and catch per minute of sampling) revealed a three to six month depressed population of finfish at the experimental test sites. Direct observations (SCUBA) at a dumpsite in Long Island Sound showed that bottom megafauna, such as winter flounder (*Pseudopleuronectes americanus*) and crabs (*Cancer* sp.), used dumped material as habitat within a few weeks of its deposition (Steward 1980). The author suggested that the added relief and/or heterogeneity of the dumped clay attracted the fauna for behavioral reasons. Three species of mobile amphipods, *Eogammarus confervicolus, Paraphoxus millerii,* and *Eohaustorius washingtonianus*, moved into dredged sites at the mouth of the Columbia river, Washington, within 3 months of sediment removal (Sanborn 1975).

For many marine invertebrates, colonization occurs via planktonic larvae from undisrupted populations. A number of factors, including distance of larval drift, sedimentation, and water quality, are dependent on water current speeds. As shown in Table 5-2, a habitat on a current-swept channel is likely to colonize faster than an area at the end of a fjord. At intertidal dumpsites, elevation and stability of the dredged material are key factors governing colonization. Albright and Smith (1976) examined the use of dredged sand by an estuarine amphipod (*Corophium stimpsoni*) at Gray's Harbor, Washington. Because most of the sand was above optimum level for this species, there was little colonization.

Table 5-2. A comparison of parameters influencing recolonization by invertebrates of wood-contaminated sediments at two locations on the coast of British Columbia (from Levings 1976).

Parameters	Swanson Bay	Cousins Inlet (head)
Years since reduction in wood output	52 (complete shutdown)	7 (partial closure)
Years of operation	18 (sulfite/sawmill)	55 (kraft and sulfite)
Shape of wood particles	Coarse sawdust, boards	String-like fibers; fine paper waste
Present oxygen levels in vicinity of wood deposits	2.9-5.0 mg L^{-1}	0.4-2.5 mg L^{-1}
Hydrogen sulfide in sediments	Absent	Present
Depth (m)	45-66	20-90
Currents	Tidal streams; 2-4 kt[a]	Surface currents from river runoff; 1 kt
Stratification (estuarine circulation)	Reduced	Extensive
Natural sediment supply	Moderate (tide swept shell debris and sand)	Low (landslides only)
Sill	Absent	Present (minor amplitude)
Position in relation to open sea (source of larvae)	On a channel between two sounds	Head of a fjord
Recovery status based on infaunal benthos (polychaetes)	Complete (ca. 50 species) but note dominance of a spionid	Incomplete; (ca. 1 species) spionids and capitellids adjacent to azoic portion
Prospect for reestablishment of benthic communities	Good	Poor

[a] kt = knot; 1 knot = 1 nautical mile (1852 metres) per hour.

The dumpsite was useful for shorebirds as a roosting location but not for feeding on the amphipod. It is therefore clear that the physical features are a very relevant aspect in any decision concerning the location of a dumpsite, especially if it is to be abandoned or used only once.

Rates of recolonization differ markedly among marine habitats. In shallow coastal waters, dumpsites are colonized quickly, and some authors state that the changed communities with opportunistic species are more productive than undisrupted ecosystems (Pearson and Rosenberg 1978; Rhoads *et al.* 1978). Table 5-3 shows those species from Alberni Inlet, British Columbia, which are adapted to rapid use of the changing benthic environment at the dumpsite. Sediments at dumpsites are usually characterized by alternate layers of clear and chemical-containing sediments, and faunal change at the dumpsite reflects this. Deep-sea sediments may require more than two years for colonization (Grassle 1977), but some authors have reported colonization in six months (Desbruyères *et al.* 1980).

Freshwater dumpsites show different ecological responses, probably because few freshwater invertebrates reproduce by pelagic larvae. Six weeks after dredging at Port Stanley, oligochaetes and chironomid populations were still reduced to near post-dredging levels (see Section 5.1.1). Near-bottom copepods recolonized the disrupted areas, and average abundance ranged from 132,500 m^{-2} (initial level) to 45,500 m^{-2} (post-dredging). Populations recovered to 102,300 m^{-2} 6 weeks after sediment removal (Chemex 1973a). Five years after a dumpsite in Lake Erie had been abandoned, benthic community structure was different from that at a control location (Sweeney *et al.* 1975).

At sites where material such as concrete blocks, scrap iron, etc., has been dumped, the solid substrates increase the heterogeneity of the benthic habitat. Submersible operations at the Point Grey dumpsite near Vancouver, British Columbia, showed that concrete rubble had served as attachment sites for a variety of sedentary epifauna, especially anemones (*Metridium senile*) (Packman 1980). Before decomposition, large wood debris can also serve as settling sites.

Table 5-3. Life history characteristics of opportunistic species of benthic invertebrates using disrupted sediments of the Alberni Inlet, British Columbia, dumpsite (from Dobrocky Sea Tech Ltd. 1979).

Taxa and association	Lifespan (years)	Fecundity (order of magnitude)	Number of reproductive periods per year	Planktonic larvae	Time in the plankton	Feeding mode	Behavior
"Wood debris fauna"							
Xylophaga washingtona[a]	1	10^4	1?	+?	Months?	Wood eater	Burrows in wood
Nebalia pagettensis[b]	?	?	?	?	?	"Scavenger"	Free swimmer
Limnoria lignorum[b]	1	10	1?	-?	Non-planktonic	Wood eater	Burrows in wood
Oradarea sp. A[b]	?	10	?	-?	Non-planktonic	"Scavenger"	Free swimmer
"Dumpsite fauna"							
Schistomeringos longicornis[c]	1	10^3	1	+	Weeks	Deposit feeder	Burrows in sediment
Capitella capitata[c]	1	10^2-10^4	3	- or +	Non-planktonic or weeks	Deposit feeder	Burrows in sediment
"Dumpsite fringe fauna"							
Trochochaeta multisetosa[c]	1	?	?	?	?	Deposit feeder	Burrows in sediment

[a] Mollusca.

[b] Crustacea.

[c] Polychaeta.

6.0 USEFULNESS OF PRESENT KNOWLEDGE

6.1 TIMING

If the major features of commercial fish movements and life history patterns (e.g. spawning) are known for a particular water body, potential detrimental effects to fish populations can be avoided by restricting dredging and dumping operations to inactive months, and by monitoring.

Entrainment of migrating juveniles into suction dredges can be partially avoided by keeping intakes at depths other than the shallow waters usually occupied by smaller fish. However, data on the vertical distribution of fish are not often available from independent sampling, and as suction dredges entrain fish, data from dredge outfalls are not reliable. This is particularly true in highly stratified estuaries. With the very large capacity suction dredges being used in the Beaufort Sea, there are difficulties in establishing the engineering techniques required to sample fish being entrained (Pelletier and Wilson 1981). The average volume of sediment dredged in McKinley Bay in 1980, for example, was found to be approximately 64,000 m^3 d^{-1} (Albery *et al.* 1981).

Timing restrictions are relatively easy to establish for freshwater and anadromous species where data are available. Table 6-1 shows timing restrictions established by federal d provincial fishery agencies. Spawning ground disruption is of obvious concern, especially for salmonids and other species which have eggs that hatch on or near the bottom. A review of the standard fish textbooks for Canadian waters has shown that almost all freshwater commercial fish have benthic spawning habits (Scott and Crossman 1973). Certain freshwater fish, namely lake whitefish (*Coregonus clupeaformis*), burbot (*Lota lota*), shallow water cisco (*Coregonus artedii*), deepwater sculpin (*Myoxocephalus quadricornis*) and rainbow smelt (*Osmerus mordax*), have benthic larvae (Faber 1970) and would be particularly vulnerable to dredging and dumping effects.

About 30% of the commercial Atlantic and Pacific coast fish (excluding elasmobranchii) use benthic habitats for spawning (Leim and Scott 1966; Hart 1973). Most marine fish usually reproduce by broadcast fertilization and show simple spawning behavior. Crustaceans, such as crabs and lobsters, display complex mating behaviors that could be disrupted by dredging and dumping activity. Generalizations about marine fish spawning habitats are difficult because of the scarcity of data, and so decisions about the timing of dredging and dumping operations usually have to be made on a site-specific basis. On the Atlantic Coast, to avoid conflicts with fishing activity, timing restrictions are also used based on the seasonal appearance and utilization of the various species (Figure 6-1). Ritchie (1970) recommended that dredge spoil disposal in shallow Maryland waters be restricted to late December through

Table 6-1. Examples of timing restrictions on dredging and dumping activities for some species of freshwater and estuarine fish in Canada. This list is not intended to be comprehensive. For many areas and species, data are not available.

Geographic area	Species of concern	Period when dredging/dumping prohibited or time when a species may be more vulnerable to effects	Reference
Insular[a] Newfoundland	Brook trout, brown trout, rainbow trout, salmon, arctic char, smelt, eels	June 15 to September 15	Downey 1978
New Brunswick (Miramichi estuary)		See Figure 6-1	
Labrador[a]	Brook trout, salmon, lake trout, smelt, arctic char, lake whitefish	June 15 to September 1	Downey 1978
Ontario	Whitefish[b]	May 15 to July 15	Loftus 1978
	Rainbow trout, brown trout[c]	March 1 to May 15; September 1 to November 30	
Manitoba	Pike, walleye, sauger[c]	April and May	Whitehead 1978
	Grayling[c]	April 1 to June 15	
	Lake sturgeon[c]	May and June	
	Brook trout, arctic char[c]	August 15 to October 15	
	Lake whitefish, cisco[c]	September and October	
British Columbia			
Fraser River mouth to Sumas River (120 km up river)[d]	Sockeye, pink, coho, chinook, and chum salmon	Suction dredges - March 15 to May 30; recently revised to permit dredging on odd-numbered years as long as water depth ≥4.8 m and the pump is not operated when cutterhead is within ≥1.5 m of the river bottom[e]	Boyd 1975; Payne 1981
Fraser River, Sumas to Hope (120 to 180 km up river)[b,c]	Pink salmon	Clamshell and scraper dredge: January 1 to May 31 in even-numbered years, September 15 to December 31 in odd-numbered years	
Outer Mackenzie delta (NWT)	Broad whitefish, humpback whitefish, lake trout, inconnu	Fall	Percy 1975[f]; Dobrocky Sea Tech Ltd. 1980[g]
	Arctic cisco, arctic char, least cisco	Late fall	
	Arctic flounder, burbot, Starry flounder	Winter	
	Arctic grayling, boreal smelt, northern pike, Pacific herring	Spring	
Central Arctic	Arctic cod[c]	Winter	Bain and Sekerak 1978[i]
	Arctic cod[h]	Summer	

[a] Spawning and migration.

[b] Migration.

[c] Spawning.

[d] Fry and smolt emigration.

[e] Dredge surge valves must be adequately screened.

[f] This report merely summarizes spawning times; no recommendations about dredging impacts are included.

[g] No recommendations about dredging impacts are included; fish catch data from the vicinty of a clamshell dredge site in Tuktoyaktuk Harbour are reported.

[h] Nearshore feeding schools.

[i] This report discusses only biology; no recommendations about dredging impacts are included.

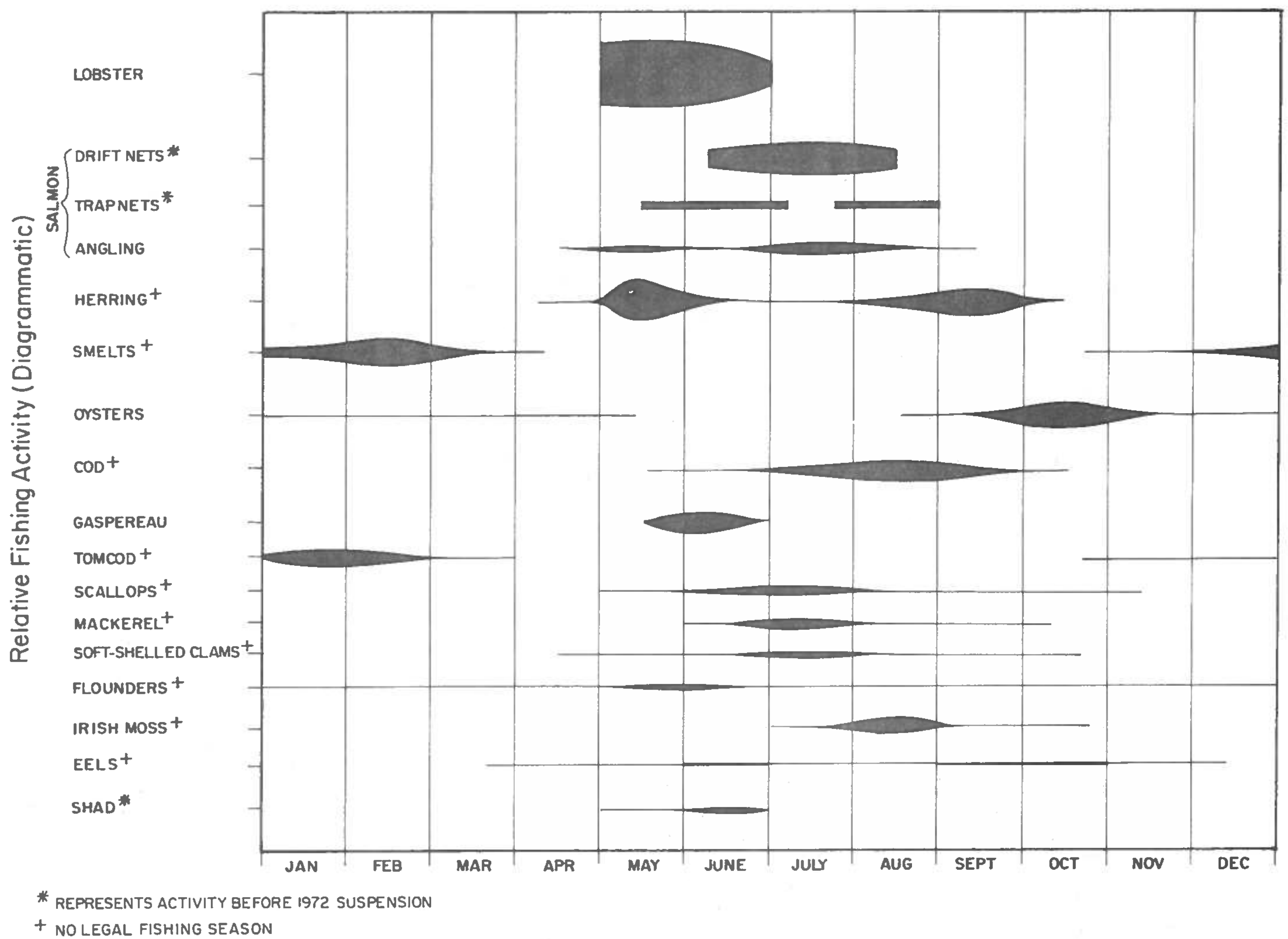


Figure 6-1. Seasonal distribution of fishing effort on various commercial species in the Miramichi Bay, New Brunswick (used in ocean dumping timing restrictions) (from Philpott 1978).

early February, when the fewest species of adult fish are found inshore. In the Beaufort Sea, bowhead and white whales are hunted in summer, and there has been concern about the influence of dredging on their distribution, especially in Kugmallit Bay (Slaney 1978). Studies to date have not shown any significant effect on whale migrations.

6.2 MARINE DUMPSITE LOCATIONS

With passage of the Ocean Dumping Control Act in 1975 (Anonymous 1975a), a systematic procedure was developed to choose new dumpsites or to move the location of previously used sites in the light of new knowledge obtained by monitoring or research (e.g. Appendix II.0). A small committee (Regional Ocean Dumping Advisory Committee (RODAC)) screens the concerns of the proponent biologists, chemists, geologists, Fisheries Officers, and other persons knowledgeable about specific areas. This pooled information is used to decide about each application to dump.

Adequate knowledge of fish resources or critical fish habitat is an important component in locating dumpsites. For example, mapping the location of important mollusc resources (oysters, quahogs, mussels, etc.) in the Miramichi estuary, New Brunswick (Figure 6-2), was very relevant to choosing a dumpsite that would avoid smothering and burial of these sedentary organisms. Fishery surveys in the Beaufort Sea showed that fish are much more abundant in the nearshore shallows (estimated up to 2 km from shore) where anadromous species are reared. Aquatic Environments Ltd. (1977) recommended that dredging be excluded from these latter areas and from the vicinity of bays and lagoons. Interference with fishing operations by dumping (e.g. concrete rubble) is also considered. The Point Grey dumpsite, located 210 to 275 m offshore from Vancouver Harbour, British Columbia, is used instead of shallower locations where shrimp fishing grounds exist. Knowledge of the spawning habitats and behavior of marine fish is generally inadequate, as was pointed out previously. Wherever possible, dumping at known spawning grounds is avoided. Fish spawning behavior is species-specific; for example, the Atlantic cod (*Gadus morhua*) has pelagic eggs, whereas the Pacific cod (*Gadus macrocephalus*) has demersal eggs which sink. The latter species would obviously be more susceptible to dumping effects.

6.3 CHEMICAL ANALYSES OF SEDIMENTS

Present regulations and guidelines in Canada for dredged sediments are based mainly on chemical data from total or bulk analyses, as shown in Tables 2-3 and 2-4. It is obvious from the research reviewed above that much further work is needed to determine the ecological validity of these chemical data. The background or natural levels of chemical substances need to be examined so that budgets for specific areas might be amalgamated, as has been done in the Great Lakes (Anonymous 1982).

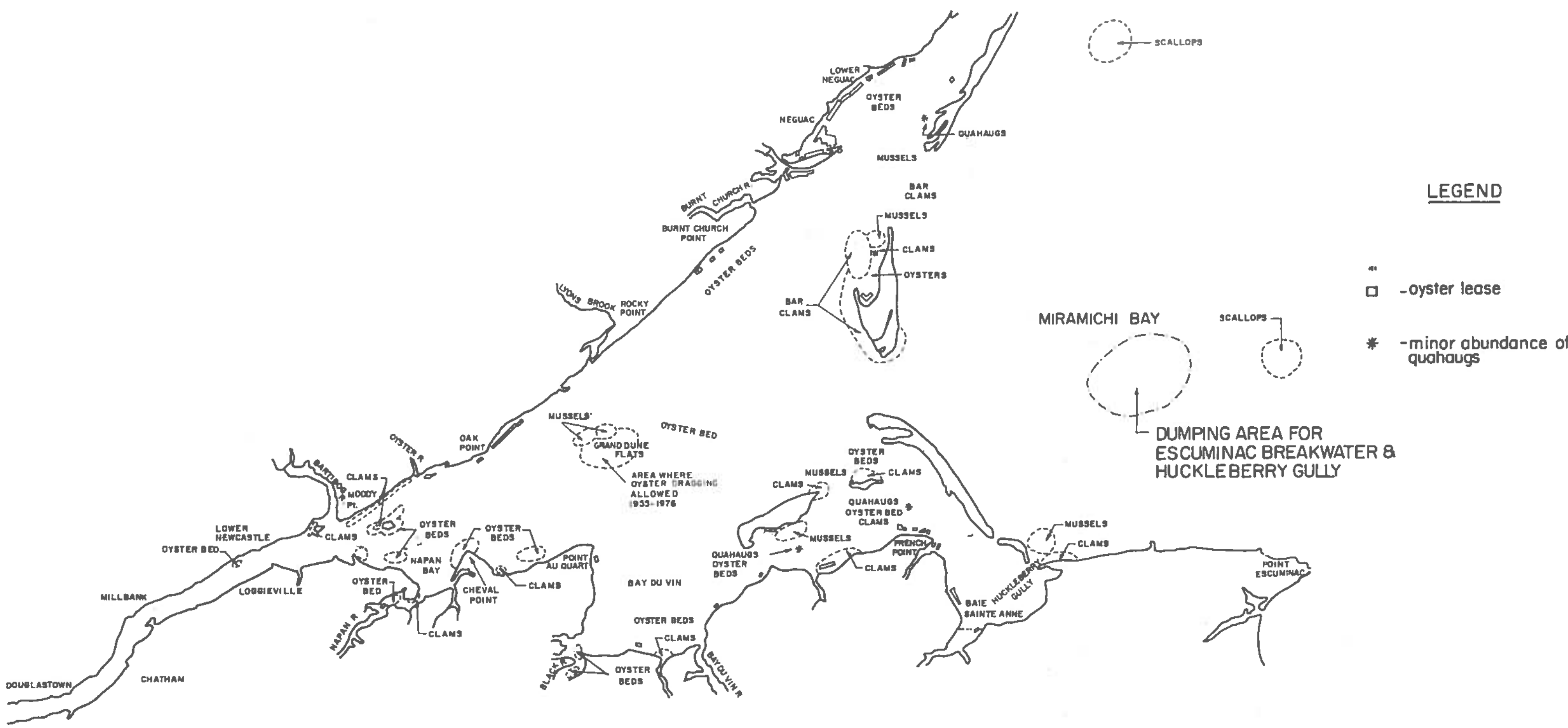


Figure 6-2. Resource map of commercially important bivalves used for dumpsite selection in Miramichi Bay, New Brunswick (from Philpott 1978).

In the interim, ecosystem- or site-specific evaluations and monitoring (Appendix II.0) are needed to avoid potential problems. If dredging and dumping of potentially deleterious material, so defined by present chemical techniques, are needed, ecological factors such as timing, sediment type, and location of dumpsite must be considered. Capping, where dumped sediment is covered with clean dredge soil, is another option. This technique has been applied in Sweden (Thorslund 1975), but not in Canada so far as is known. American workers have recently proposed dumping sediments in pits dug to mine sand near New York (Bokuniewicz 1980). Land disposal or containment may also be necessary. On the Canadian side of the Great Lakes, confined dredge spoil containment areas abutting the shoreline have been constructed in Lake St. Clair, Oshawa, Thunder Bay, and Port Stanley (Beach 1981). This procedure has also been followed with sediments from Vancouver Harbour. To prevent uptake of chemicals into terrestrial or wetland plants, the material should be securely capped, or mobility should be tested with plants grown experimentally in the sediments (Gallagher and Wolf 1980).

Guidelines relating to the disposal of sediments rich in wood wastes and organic material were proposed in 1975 on the Pacific Coast. Sediments with loss-on-ignition ("volatile solids" or LOI) values of more than 10% were to be banned from disposal into marine waters. This guideline originated from observations in Puget Sound, Washington, which showed a drastic change in benthic communities when sediment LOI values exceeded 10% (O'Neal and Sceva 1971). Recent practice has not rigidly followed this recommendation; however, organic content of sediment is an important consideration in an application to dump and is routinely required on the Pacific coast, where the oxygen demand of such material is important because of the oceanographic characteristics of certain fjords. A guideline of 6% LOI has been adopted in the Great Lakes (see Table 2-3).

6.4 MATERIAL BUDGETS, MODELS, AND EXPERIMENTAL ECOSYSTEMS

The decision for allowing dumping or dredging involves consideration of the effects on the whole water body and its sediments, for example, D.O. depletion, buildup of pollutants considered hazardous for human consumption of fishery products, or eutrophication. If removal of sediment from a polluted area (e.g. Belledune Harbour, New Brunswick; see Uthe and Zitko 1980) is required, it would be advantageous to take into consideration the ecological consequences prior to commencement of dumping and dredging. Recently, this has been done on the Great Lakes (Anonymous 1982) for loadings of a variety of metals. This budget approach is practicable in lakes because of the relatively closed nature of the ecosystems, and because the natural geochemistry of the lacustrine system is well known. If it were possible to predict the distributions of metals and organic substances in marine systems with a mathematical model, managers would be provided with a valuable tool. Hall *et al.* (1976) reviewed the sparse literature on this topic, and concluded that only a few models were available at that time, all of which had serious shortcomings. In the following, an example is provided for a site-specific area on the British Columbia coast.

In British Columbia, considerable thought has been devoted to the oxygen budget approach to the problem of reduced dissolved oxygen due to dumping of wood wastes with a high BOD. Oxygen utilization by microbes using wood waste as a substrate is a process which can be linked with oceanographic mechanisms bringing water into the fjords. Most of this work has focussed at the head of Alberni Inlet, British Columbia, where depletions of bottom water D.O. occur seasonally (Bell 1976). Concern was raised about the possibility of ocean dumping activity exacerbating the natural situation. As shown by Levings (1980) in Howe Sound, British Columbia, and by other authors elsewhere (e.g. Rosenberg 1980; Steimle and Sindermann 1978), prolonged reduced D.O. levels can result in the death of sedentary invertebrates and habitat modifications for commercial fish and shrimp. In Howe Sound basin, D.O. levels of less than 0.5 mg L^{-1} persisted over 3 months in 1977, resulting in drastic changes in communities over 24 km^2 (Levings 1980).

The objective of an oxygen budget is to compute, using a mathematical model, the relative magnitude of the sources and sinks of the D.O. in the water body being considered. In lakes, because of their obvious boundaries, such an approach is easier than in the sea. At Alberni Inlet, which is a highly stratified estuary, the bottom water of the Inlet in the vicinity of the dumpsite could be viewed as a compartment with a well-defined upper boundary, namely the halocline. In this compartment, the major source of D.O. is advection or movement of bottom water from the open ocean into the estuary. After these incursions of oceanic water into the Inlet bottom layers, there is vertical and horizontal diffusion of D.O. throughout the bottom waters. There is little *in situ* production of oxygen due to photosynthesis below the halocline because of depth and light relationships.

The standard oceanographic conservation equation (Svedrup *et al.* 1942) is the basis for budget calculations:

$$\frac{\partial c}{\partial t} + u\,\frac{\partial c}{\partial x} + w\,\frac{\partial c}{\partial z} = k_z\,\frac{\partial^2 c}{\partial z^2} + S \qquad (6\text{-}1)$$

where c = dissolved oxygen concentration (D.O.); t = time; u = water velocity (advection) down inlet (i.e. out of the model system); x = distance down inlet; w = velocity upwards through the water column; z = depth positive upwards; k_z = vertical turbulent diffusivity; and

S = sinks for D.O. in the water column. S can be subdivided as follows: S_C = removal of D.O. by decay and respiration in the water column, and S_B = removal of D.O. through benthic routes. An evaluation of the utilization of D.O. per unit time by decomposition of dumped wastes in both the water column and the benthic environment is sought by attempting to balance the equation and by comparing terms.

Use of the model has been hindered by lack of data in two major areas, namely respiration of heterotrophic organisms and velocity for bottom advection. Much of the respiration is accounted for by oxygen-consuming heterotrophic bacteria which live in the water column or in sediments and use organic material (including wood waste) as a substrate. Respiration by microplankton can also account for a sizeable part of the budget (De Souza Lima and Leb Williams 1978). Data from other coastal areas cannot easily be extrapolated to Alberni Inlet, as Seakem (1977) and Macdonald (1979b) found when they attempted to use the model. However, the exercises did bring data together for comparison. For example, benthic respiration measurements using a variety of techniques are available from both the dumpsite and natural sediments (Table 6-2). The dumpsite sediments displayed D.O. demands that were very similar to "natural" materials (4.70 *versus* 3.69 mg m^{-2} s^{-1}), and therefore are a small part of the D.O. sink term. The dumpsite accounts for a limited area of the inlet seabed, especially in comparison with the extensive disrupted areas due to log storage.

Lake simulator columns have been used in experiments to investigate the impact of sediments dumped in Lake Ontario (Chemex 1975) as mentioned previously (see Section 4.2.2). The major shortcoming of this approach for detailed studies and predictions relates to wall effects (i.e. surface-to-volume relationships which are radically different from those in natural ecosystems). In the freshwater systems studied by Chemex (1975), however, the experimental columns did establish the prospects for nutrient release from dredged sediments. The CEPEX (Controlled Ecosystem Pollution Experiments) work in Saanich Inlet, British Columbia, where columns of seawater are isolated using plastic walls, has not been used in work with chemical-containing sediments. Substances in the water column have been emphasized (e.g. Reeve *et al.* 1976). As mentioned previously (see Section 4.1), lysimeters have been used to obtain data on D.O. utilization and H_2S generation with dredged material from Alberni Inlet, British Columbia (Econotech 1977). Probably the most relevant type of *in situ* experimental system for chemical problems relating to ocean dumping is the seabed belljar system developed at Kiel, Federal Republic of Germany (Balzer 1980). This system seals off a portion of the seafloor and has ports to enable introduction of pollutants and subsequent sampling of sediment and/or water. However, the system is also prone to wall effects.

Table 6-2. Oxygen demand of sediments from the dumpsite and adjacent "natural" sediments in Alberni Inlet, British Columbia.

Area	Oxygen demand of sediments ($mg\ m^{-2}\ s^{-1}$)	Source
Dumpsite	5.9×10^{-2}	Shipboard experiments; Macdonald (1979b)
	7.0×10^{-2}	*In situ* measurements; Dobrocky Sea Tech Ltd. (1977)
	1.2×10^{-2}	Laboratory experiments; Econotech (1977)
Adjacent "natural" sediments	5.9×10^{-3}	*In situ* measurements; Dobrocky Sea Tech Ltd. (1977)
	6.8×10^{-2}	Shipboard measurements; Macdonald (1979b)

Hydraulic (physical) and numerical models have been used to predict the physical behavior of dumped dredge spoil. For example, the National Research Council of Canada used a physical model of the Miramichi estuary in New Brunswick to predict the stability of the dredged channel (Willis 1977). While apparently suitable for this task, the model could not predict if sediment dumped along the sides of the dredged channel would retain its integrity, and field studies of sediment characteristics were needed to examine the problem (MacLaren Marex Inc. 1978). The Fraser River model, owned by Western Canada Hydraulics Laboratory, has been used recently to examine the feasibility of marsh development on dredge spoil dumped in the lower Fraser River (Envirocon 1980). In both the Fraser and Miramichi estuaries, post-deposition movement due to wave action was predicted with numerical models using historical records of wind data. Wind-generated currents and their subsequent influence on spoil disposal was also predicted for the McKinley Bay dredging project (Albery *et al.* 1981). Proposed dumpsites in the latter three locations were in shallow water (less than 20 m) and hence subject to waves. Beak Consultants Ltd. (1976) examined three models (Krishnappan 1975; Koh and Chang 1973) which could be used to predict the behavior of dumped material as it falls through the water column (e.g. sinking rates, dispersion). Krishnappan's (1975) model, developed for use in the Great Lakes, was found to be applicable to marine circumstances in coastal British Columbia. Another useful model, for predicting dispersion from barges, was published by Ketchum and Ford (1952). Cederwall and Svensson (1976) presented a numerical model which could be used to predict sediment flushing after dredging, in tidal bays and estuaries, which might help predict the "area of influence" of dredging operations. Bella and Williamson (1980) proposed a conceptual model involving plots of rate of sediment turnover with organic content of sediment as a means of rapidly diagnosing the impact of dredging in estuaries (see Appendix III.0).

A simple model involving the calculation of dispersion in the wake of a ship was used to predict the dilution of barite (drilling mud) in a disposal operation off the west coast of Vancouver Island (RODAC Pacific files, Permit No. 4443-055; May 1976). The dispersion model developed by Farmer and Lemon (1975) was needed to calculate the vertical extent of the ship's wake which then could be used to calculate dilution. Bioassays with coho salmon (*Oncorhynchus kisutch*) found the LC50 was 100 mg L^{-1}, and a factor of 100 times this concentration was sought. The main objective, then, was to calculate the discharge rate of the material in the wake of the ship, steaming at a specified speed. Safe disposal was achieved with a discharge rate of 14.3 t h^{-1} while steaming at 10 kt. Details of calculations are found in Appendix III.0.

Except for Saila's (1976) application of island colonization models, there have been no attempts to predict the time scale of recovery from dumping impacts. The equation used is:

$$T = \frac{2.996}{\lambda A + \mu A} \tag{6-2}$$

where T = time to reestablishment of equilibrium number of species;

λA = the average immigration rate of new species, per species, into a given area where S species are present (i.e. the equilibrium number of species) (assumed constant); and

μA = average extinction rate per species (assumed constant).

Saila (1976) predicted that approximately 11 years would be required for a dredge spoil benthic invertebrate population in New England to reach 95% of its final equilibrium composition of about 75 species. Preliminary results seem to confirm this; after nine years, 52 to 85 species exist in the immediate vicinity of the disposal site (Saila 1980).

7.0 ALTERNATIVES FOR DREDGE SPOIL DISPOSAL IN OPEN WATER

There are a variety of alternatives available for the disposal of dredged material in water, but their feasibility is dependent on the economics of particular circumstances. Alternatives include creation of recreational beaches with sand, and the traditional filling for industrial uses. More recently in the U.S., dredged material from the U.S. Army Corps of Engineers' operations has been used to develop wildlife habitats in the James River, Virginia (Hunt 1978), the Columbia River (Heilman *et al.* 1978), and elsewhere. Biotic communities associated with dredged material have achieved recognition as discrete ecological systems in the U.S. coastal classification schemes (Copeland and Dickens 1974). Use of dredge spoil to create habitat for waterfowl and aquatic birds has been successful in many coastal areas of the U.S. (Landin 1982). However, since shallow water habitat is often in short supply, there is more concern for replacement of fish habitat. Therefore, the volume and surface area of water at specific elevations should be controlled when habitats are constructed (Gonor 1979).

In Canada, alternative disposal techniques have been developed on the Pacific coast and in the Great Lakes. For many years, Public Works Canada has sold dredged Fraser River sand for construction purposes, often at sites remote from the waterfront. For example, over the period June 1980 to June 1981, Public Works Canada pumped approximately 600 x 10^3 m^3 of sand ashore for this purpose. Recently there has been an initiative to use dredged sand for marsh transplant work at the estuary of that river (Envirocon 1980). Dredged material has also been used on the Atlantic coast for beach development in New Brunswick and for road construction in Prince Edward Island. Sixteen million cubic metres of dredged material and trucked fill have been used to construct the Leslie Street Spit in Toronto Harbour, and this headland now covers 160 ha. Embankments or containment structures were recently used to contain sediments dumped onto the Spit, as levels of oils and greases, total phosphorus, PCBs, and heavy metals exceeded Ontario Ministry of the Environment open water disposal guidelines (Griffiths and Winiecki 1981).

In the Canadian sectors of the Great Lakes, over the period 1975 to 1979, 1.4 x 10^6 m^3 of dredged material were placed in confinement, compared to 0.9 x 10^6 m^3 dumped in open water (56% and 37% of the total, respectively) (Anonymous 1982). Many aspects of the long-term impact of confinement are yet to be determined however (Anonymous 1982), and are the subject of ongoing monitoring and research. A pilot project on Lake St. Clair, for example, was conducted from 1973 to 1981, and examined the fate of mercury in sediments which were placed in an impermeable structure. Some plants which began to grow on this "Pilot Island" incorporated the mercury. For example, four and five years after disposal, the roots of *Polygonum* sp. showed elevated levels (303 to 556 ng g^{-1}) of mercury that were two or three times the concentrations in stems and leaves (Wilkins and Associates 1982). Capping with clean material, as has been done in another containment structure along Lake St. Clair, may be a successful technique for the prevention of dispersion of hazardous materials through local ecosystems.

APPENDIX I.0 GLOSSARY

bioavailability - the extent to which a compound or element may be taken up by biota.

borrow pit - location from which sediment is dredged, often to raise elevations elsewhere for industrial purposes (e.g. docks, artificial island construction).

broadcast fertilization - reproductive procedure in which eggs are fertilized with minimal intervention by parents.

bulk or total chemical analyses - procedure in which a sediment sample is subjected to total chemical destruction, usually through oxidation, before elemental analysis is performed (e.g. heavy metals through atomic absorption spectrophotometry).

clamshell dredging - a technique in which a jawed bucket is dropped to the bottom of a water body and the jaws are closed around material to be moved. The sediment is brought to the surface and usually placed on a barge for subsequent disposal.

classification/ordination - a statistical technique for examining the structure of a biological community; typically a location-species table is manipulated.

cutterhead - rotating mechanism on the intake end of a hydraulic suction dredge; serves to loosen sediments.

draggerhead - mechanism which provides a flattened surface for the intake of unconsolidated sediment into the suction line of a hopper dredge.

dragline - a dredging technique in which a bucket is pulled along the bottom of a water body to move sediment, often to the side of a navigable channel, without bringing the material to the surface.

drilling mud - material used to lubricate drills used in exploring for minerals; typically consists of a barium solution mixed with a bactericide such as pentachlorophenol.

eutrophication - process involving primary production in a water body; excessive production in lakes can lead to an unusually rapid conversion to a terrestrial environment by enhanced sedimentation.

faunal assemblage - a group of animals living in the same place; often used as a synonym for community.

flocculation - a physical-chemical process in which inorganic and/or organic material forms aggregates.

fluid mud - mud discharged from a dredging operation which is not suspended, and flows after dumping as a cohesive fluid.

Fuller's earth - a porous colloidal aluminum silicate (clay).

gross primary production - production of plant material uncorrected for loss of organic material due to respiration.

heterotrophic organisms - organisms which require an energy source for life processes. Typically excludes organisms using chlorophyll to synthesize cellular material.

hopper dredge - a mobile suction dredge which takes material aboard and disposes of it at a site some distance from the dredge site.

hydraulic model - a scale model of a particular river or coastal feature which is used to predict, through observation, the consequences of modified flows and/or geomorphology.

infaunal - benthic fauna living in the substrate and especially in a soft sea bottom.

interface feeders - benthic animals which feed at the sediment-water interface.

internal tides - waves within a water body; often not easily observable at the surface.

lake simulator columns - cylindrical tanks used in laboratory experiments to study eutrophication processes in lakes. Stratification of the water column can be achieved when temperature is controlled along the height of the column.

longshore currents - currents developed by wave action; usually propagated parallel to shorelines.

lysimeter - enclosures used in laboratory experiments to study processes affecting solid-liquid exchanges. A water column is established over sediments or other solid matter (e.g. wood debris). The solubility of substances in sediments (e.g. hydrogen sulfide) in the overlying water can be examined.

material budget - an account of the amount of a specific chemical (e.g. phosphate) in a water body, taking into account both input and output; usually computed when a pollutant is to be introduced through man's activities.

methylmercury - mercury converted through bacterial action to a toxic organic form which can be incorporated into plant or animal tissue.

numerical model - a system of equations used to predict, by modifying values of parameters, the consequences of changes in the physical, chemical, or biological systems of a water body.

phytodetritus - dead or moribund algal cells present after a "bloom" of phytoplankton.

pycnocline - a steep density gradient in the water column.

remobilization - a term applied to the process whereby heavy metals and other contaminants can be released from sediments and become available to biota during or after dredging and dumping.

seabed belljar - equipment used for sealing off an area of the benthic environment in order to measure chemical or biological changes in the enclosed sediment and/or overlying water.

selective extraction - chemical procedure to remove chemical substances from sediments; typically a series of reductants or oxidants are used in increasing concentrations.

side-scan sonar - echo sounding technique which gives data on bottom elevations to both sides of a towed transducer.

submergence/emergence ratio - the proportion of time a particular elevation on a tidal shore is submerged under water or exposed to the atmosphere.

subsurface feeders - benthic animals which feed, typically by ingesting sediment, below the sediment-water interface.

suction dredge - a type of dredge which moves unconsolidated sediment by pumping it mixed with water; the material is usually returned to the water a short distance from the dredge, which is temporarily anchored.

suspended load - small particles of sediment lifted far from the bottom by moving water; the material is suspended for long periods and is distributed through the whole body of the current.

turbidity - the cloudiness in a liquid caused by the presence of finely divided and suspended material; often measured with a transmissometer, which measures the attenuation of light due to scattering by the suspended material.

wall effects - an inherent problem involved in artificially sealing off a portion of a natural water body; because of the drastic change in surface area:volume relationships, chemical and microbiological processes occur at vastly different rates than under natural circumstances.

washload - that part of the total sediment load composed of extremely small particles; the material is normally washed into and through the river reach under consideration.

water column feeders - benthic animals which feed in the water above the sediment-water interface.

APPENDIX II.0 ESSENTIAL MONITORING DATA FOR DUMPSITES

BIOLOGICAL

Feature	Rationale	Techniques, comments
Contamination of biota	Routine inspections of commercial catches by Fisheries and Oceans only include commercial species from major fishing grounds. However, other species are sometimes eaten. Also valuable as indicators, and frequently utilized as such by Environmental Protection Service monitoring procedures.	Dumpsite usually not at fishing grounds, therefore more likely noncommercial species affected.
Benthic community data	Most sensitive community.	Except for mobile megafauna, smaller animals reflect impact and/or recovery first; grabs, trawls, photography (with SCUBA in shallow waters).
Carbon/nitrogen	Reflects organic waste and suitability of sediment as food for benthos.	Preferably from vertical sections in cores.

GEOLOGICAL/CHEMICAL

Feature	Rationale	Techniques, comments
Sedimentation rates	Can use data to estimate burial problems, dispersion rates, and as a check on volumes dumped.	Sediment traps, survey rods (need to use SCUBA), radiographs from frozen cores can distinguish interfaces between natural and dumped material (see Alther and Wyeth 1980).
Contaminant data in sediments	Amounts in sediment essential for budget information.	Reference sediments, currently being developed by NRC, should be used (Jamieson 1980).
Bioavailability	Should be correlated with sampling for contaminants in biota.	Major area for research.

PHYSICAL

Feature	Rationale	Techniques, comments
Disposal and movement of dumped sediment after reaching bottom	Need to know magnitude of spreading at a dumpsite.	Current meters, seabed drifters (see Stehman and Bezanson 1976; programme in place at certain Atlantic dumpsites); side-scan sonar; echo sounding (see Alther and Wyeth 1980); use of heavy metals as tracers (e.g. Saint John, N.B.; see Figure 3-5).
Advection of dumped material	Suspended material can be trapped on pycnoclines and moved by currents.	High frequency echo sounding (see Orr 1980).

APPENDIX III.0 FORMULAE RELEVANT TO OCEAN DUMPING

III.1 A POSSIBLE MODEL FOR DISPERSION OF DREDGED MATERIAL BEHIND A MOVING SHIP

$$R = \frac{QVh_f}{Q_\tau} \qquad \text{(III-1)}$$

where R = required rate of discharge *per unit width* of ship's beam from shipboard holding tanks ($cm^2\ s^{-1}$);

Q = required concentration to protect biota (from bioassay results) (ppm);

Q_τ = concentration in holding tanks;

V = ship's velocity ($cm\ s^{-1}$); and

h_f = vertical extent of the ship's wake (cm) (see Farmer and Lemon 1975 for details of calculation).

III.2 STOKE'S LAW TO ESTIMATE SINKING RATE

$$V = \frac{1}{18} \frac{(P_s - P)g\ D^2}{\mu} \qquad \text{(III-2)}$$

where V = free-falling velocity ($cm\ s^{-1}$);

P_s = density of the sediment particle ($g\ cm^{-3}$);

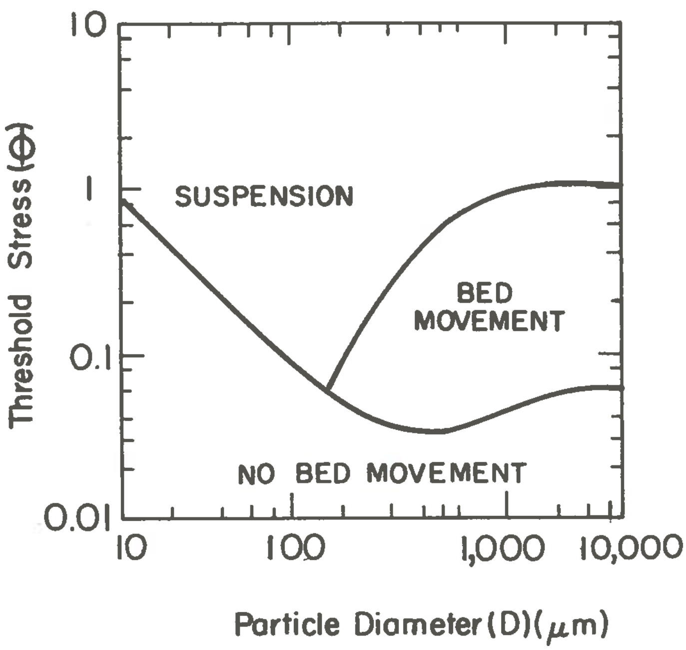
P = density of the water ($g\ cm^{-3}$);

g = acceleration due to gravity ($cm\ s^{-2}$);

D = particle diameter (cm); and

μ = viscosity of water ($g\ cm^{-1}\ s^{-1}$).

III.3 SHIELDS AND BAGNOLD CRITERIA FOR MOVEMENT OF BED MATERIAL (from Allen 1970)



$$\theta = \frac{\tau_o}{(P_s - P)g\,D} \qquad \text{(III-3)}$$

where θ = dimensionless threshold stress criterion;

τ_o = shear stress (dynes cm^{-2});

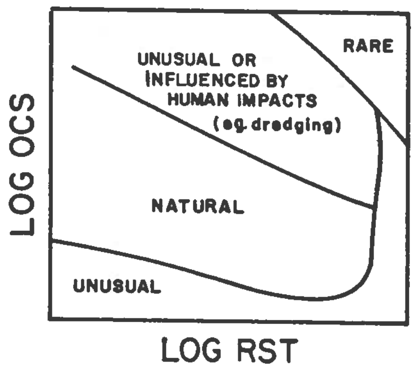
P_s = density of sediment (g cm^{-3});

P = density of water (g cm^{-3});

g = acceleration due to gravity (cm s^{-2}); and

D = particle diameter (cm).

III.4 PREDICTIONS FOR ASSESSING THE IMPACT OF DREDGING IN ESTUARIES



Schematic plot of Bella and Williamson (1980) for predicting the impact of dredging in estuaries. RST = rate of sediment turnover within the upper portions of a sediment; OCS = organic content of the upper portion of a sediment.

The theoretical rationale for expecting a functional relationship between OCS and RST is as follows:

$$OCS = f\left(\frac{1}{RST}, \frac{1}{F_o}, I_o D_o\right) \qquad \text{(III-4)}$$

where OCS and RST are as above and;

F_o = hydraulic flushing rate (primarily advective transport) of suspended organics away from the sediment's location;

I_o = input rate of organics to the sediment's location; and

D_o = decay rate of organics.

- D_o is assumed to be near zero as OCS is primarily refractory;
- OCS is assumed to vary directly, but not necessarily linearly, with I_o; and
- F_o can be interpreted as the probability of a suspended organic particle being removed from a given location, with its magnitude depending upon the settling velocity.

APPENDIX IV.0 MAXIMUM QUANTITY OR CONCENTRATION FOR SCHEDULE I SUBSTANCES UNDER THE OCEAN DUMPING CONTROL ACT (CANADA) (from Anonymous 1975a)

Material	Maximum Quantity or Concentration
Mercury or mercury compounds	Solid phase - 0.75 mg kg^{-1} Liquid phase - 1.5 mg kg^{-1}
Cadmium or cadmium compounds	Solid phase - 0.6 mg kg^{-1} Liquid phase - 3.0 mg kg^{-1}
Persistent plastics	4% by volume, suitably comminuted
Crude oil, fuel oil, etc.	Any quantity that yields less than or equal to 10 mg kg^{-1} of n-hexane-soluble substances.
High level radioactive wastes	Any substance with a concentration in curies per unit gross mass (in megagrams) not exceeding (a) 10 Ci/t for α-active waste of half-life >50 years, (b) 10^3 Ci/t for β/γ-active waste, excluding tritium, (c) 10^6 Ci/t for tritium.
Organohalogen compounds	That quantity not exceeding 0.01 parts of a concentration shown to be toxic to marine, animal and plant sensitive organisms in a bioassay sample and test carried out in accordance with procedures established or approved by the Minister.

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