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AN ASSESSMENT OF THE ENVIRONMENTAL EFFECTS OF DREDGED MATERIAL --ETC(U)
MAR 76 J P KEILLOR, R A RAGOTZKIE DACW37-74-C-0013

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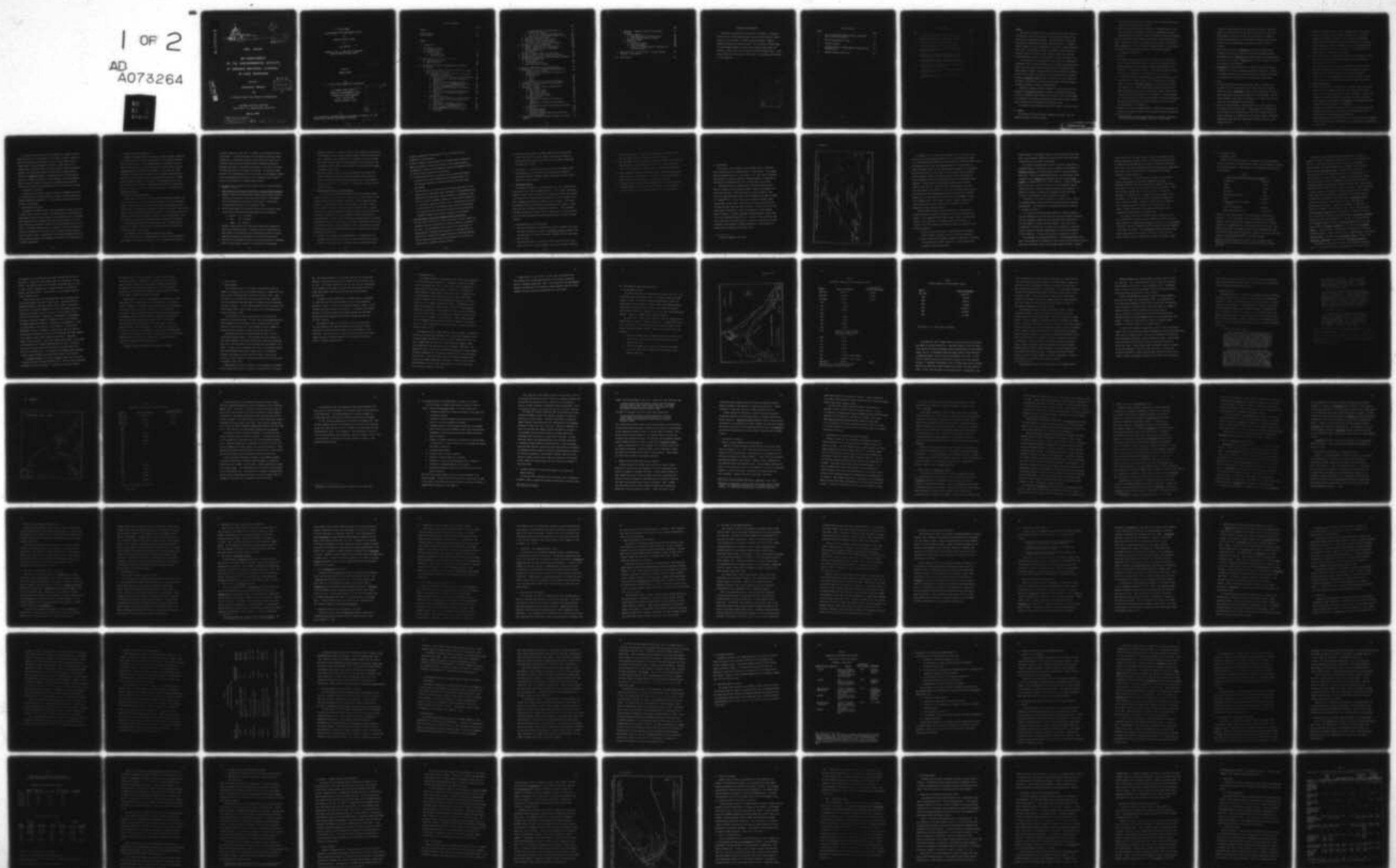

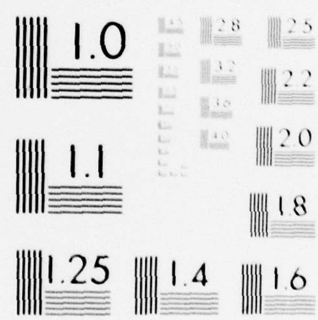

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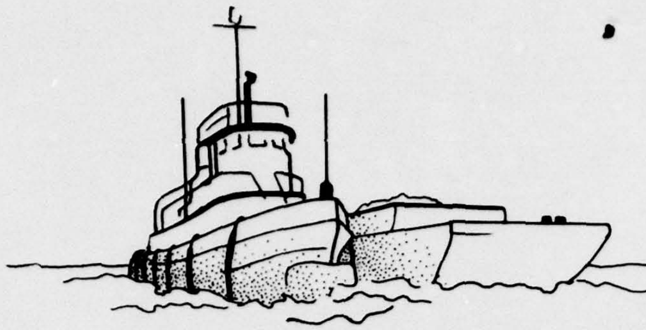

FINAL REPORT

AN ASSESSMENT OF THE ENVIRONMENTAL EFFECTS OF DREDGED MATERIAL DISPOSAL IN LAKE SUPERIOR

Volume I

Summary Report

By

J. Philip Keillor and Robert A. Ragotzkie

MARINE STUDIES CENTER
UNIVERSITY OF WISCONSIN, MADISON

March, 1976

FINAL REPORT

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A REPORT TO THE U.S. ARMY CORPS OF ENGINEERS
FROM THE MARINE STUDIES CENTER

Volume 1

SUMMARY REPORT

By

J. Philip Keillor and Robert A. Ragotzkie

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Table of Contents

Page

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This report was prepared by Philip Keillor and Robert A. Ragotzkie. Philip Keillor is the program manager for the interdisciplinary research project. He has a Master's degree in Ocean Engineering. Robert A. Ragotzkie directed the research project. He is Professor of Meteorology and Environmental Studies, Director of the Marine Studies Center and Director of the University of Wisconsin Sea Grant College Program. Linda Parker edited the five volumes of this report. The graphics were prepared by Jana Fothergill.

List of Figures

List of Tables

Summary

The results are based on field and supporting laboratory studies of the regions of the lake in and near the Duluth-Superior harbor and the North Entry of the Keweenaw Waterway. The report deals primarily with the effects of trace metals (primarily mercury and zinc) in dredged material dumped on or near known benthic communities in these two regions of the lake. The biological effects of turbidity, arsenic, petroleum residues and other pollutants of Lake Superior harbors have not been assessed, because they were not included in the contracted scope of work.

In carrying out this investigation, field studies were conducted in cooperation with the Aquatic Research Group of Michigan Technological University and with Michael Sydor of the University of Minnesota-Duluth. These studies included 1) the description and areal mapping of sediments, and their trace element characteristics and the macro-benthic organisms, especially *Pontoporeia affinis*, and 2) the description and evaluation of the dynamic characteristics of the water environment including sediment transport, turbidity, currents and wave effects.

Supporting laboratory studies included 1) the determination of the responses of *Pontoporeia affinis* to sublethal concentrations of mercury and zinc in sediments under controlled conditions, and 2) the development of a procedure for accurately determining the pollutional status of sediments in terms of trace elements including heavy metals.

The details of these studies are given in volumes 2-5 of this report.

A. Results

The results of the entire study, summarized in Volume 1, are conveniently grouped under two questions:

1. Are the trace metals present in Duluth-Superior and Keweenaw sediments a threat to man and the lake ecosystem?

2. What are the possible effects of disposal of dredged material in Lake Superior compared to the effects of natural sedimentation processes?

Both questions are relevant to other Lake Superior harbors and probably to other Great Lakes harbors where the same metals and lake organisms are found. This report contains an assessment of some specific environmental effects expected from in-lake disposal of dredged material in Lake Superior. The results of the investigation support the following conclusions:

In response to question 1:

1. Mercury

a. The highest concentrations of mercury and other metals are found in the fine clay-size fraction (less than two micron particles) of the harbor sediments and lake sediments. Mercury concentrations of 0.1-0.4 mg/kg[1] in the clay-size fraction can be considered natural concentrations at Duluth-Superior, characteristic of local soils.

b. In controlled laboratory experiments mercury added to sediments in an available form at concentrations of 2.15-3.35 mg/kg, had an adverse effect on groups of Pontoporeia affinis; an important food source for Lake Superior fish. These animals experienced reduced activity and their body burden of mercury was multiplied by several orders of magnitude during five days exposure to the sediments. The same tendency for reduced activity and multiplied body burden of mercury was observed during controlled tests with two day exposures to 0.65-1.15 mg/kg of available mercury in the sediments.

c. Disposal in the lake of dredged material, containing concentrations of mercury at 0.6 mg/kg or higher in the clay-size fraction characteristic

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[1] Concentrations in sediments and organisms are based on dry weight. One milligram/kilogram (mg/kg) = one part per million (ppm).

of benthic community habitats, may have adverse effects on the benthic animals in the lake similar to the effects observed in the laboratory. These effects are most likely to occur if the material is dumped in areas of the lake where it will be available to benthic animals before dilution by normal sedimentation or dispersion by wave action and currents.

d. The effects of mercury on Pontoporeia activity and body burden may already be occurring at certain lake locations near Duluth-Superior where some groups of Pontoporeia and sediment samples have concentrations of mercury up to 2 mg/kg in Pontoporeia and 1.2 to 4.2 mg/kg in the clay size fraction of the sediments.

e. Pontoporeia with high concentrations of mercury may be a major source of mercury to fish and to the human consumers of these fish. Analysis of selected pelagic fish and bottom feeding fish indicates that mercury is concentrated in higher orders of the Lake Superior food chain.

2. Zinc

a. In controlled laboratory experiments, zinc, added to sediments in an available form at concentrations of 58.5-123.5 mg/kg had an adverse effect on groups of Pontoporeia, lowering their activity and increasing their body burden during five days exposure to the sediments. The laboratory sediments more readily released zinc in a soluble form than the harbor and lake sediments that were tested.

b. Harbor and lake sediments at Duluth-Superior have similar tendencies to release zinc in a soluble form. Dredged material, containing zinc with availability and concentrations in the fine fractions similar to natural sediments, will probably add no additional stress to the benthic communities unless there are synergisms with other pollutants in the dredged material.

c. Sediment containing 58 mg/kg or more of soluble zinc in the clay-size fraction will probably have an adverse effect on the Lake Superior benthos in areas where the metal will be available to the benthic communities before being diluted by normal sedimentation or dispersed by wave action and currents. Sediments from the lake and harbor with higher concentrations of zinc may have zinc in less available, non-soluble forms as indicated by our analysis.

d. Zinc concentrations of 140-230 mg/kg in the clay-size fraction of sediments can be considered natural concentrations at Duluth-Superior, characteristic of local soils.

e. There are signs of zinc pollution in sediments from the old Superior dumpsite and nearby areas of the lake at Duluth-Superior, with zinc concentrations as high as 360 mg/kg in the clay-size fraction.

f. Analysis of zinc in *Pontoporeia* and fish showed no evidence of higher concentrations in the higher orders of the Lake Superior food chain.

3. Other Trace Elements

a. Copper is found at high concentrations in sediments along the north and west coasts of the Keweenaw Peninsula. The sources of much of this copper are the stampsand deposits at Freda and Redridge. There is some evidence, collected by Michigan Technological University scientists, which suggests that populations of *Pontoporeia* in the Keweenaw area are adversely affected by copper in the sediments.

b. Concentrations of copper at more than twice the background value, were detected in sediments from some harbor and nearshore lake sites at Duluth-Superior, indicating cultural pollution.

c. Copper concentrations of 65-88 mg/kg in the clay-size fraction of sediments can be considered natural concentrations at Duluth-Superior, characteristic of local soils.

Our study indicates that mercury in sediments is a potential health hazard to man in this area because of the ability of aquatic organisms to take up this metal and concentrate it at successively higher values in higher orders of the Lake Superior food chain. Mercury and zinc in sediments are a potential threat to the Lake Superior aquatic environment because of the demonstrated effect of these metals in depressing the activity of *Pontoporeia affinis*, an important part of the Lake Superior food chain. Copper in sediments at Duluth-Superior and at the Keweenaw Peninsula may be a threat to the aquatic environment but the specific effects of this metal on the benthic organisms in the lake are not known.

In response to question 2:

The answer to this question requires comparisons between the effects of in-lake disposal of dredged material and those of natural processes of sediment movement and deposition. Both qualitative and quantitative differences are considered.

4. Dredged Material Quality

The quality of dredged material from Duluth-Superior harbor varies considerably from one site to another. Some dredged areas of the harbor have predominantly medium to coarse sand with low concentrations of trace metals while other areas have sediments with very large percentages of silt and clay and high concentrations of trace metals associated with the fine fractions. If polluted dredged material is dumped in the lake, the effects on the lake environment will be qualitatively different than the effects of natural sediment inputs. Even disposal of unpolluted dredged material can have an adverse effect on the ecosystem if the material is placed directly on benthic populations.

5. Effects on Benthic Communities

Disposal of dredged material over densely populated benthic communities will cause burial and possibly high mortality of the organisms within the area of rapid settling. If the dredged material is primarily coarse to medium sand, there will be a long-term loss of suitable habitat for *Pontoporeia affinis* which prefers fine sediments. Trace metals or other pollutants in dredged material dumped on or near benthic communities will be more directly available to these organisms than pollutants in dredged material dumped nearshore, or pollutants in the sediment load of rivers which discharge into the lake. The increased availability of some metals may have an adverse effect on the benthic communities as indicated by our behavioral bioassays.

6. Quantities of Dredged Material

If most dredged material from Duluth-Superior harbor were placed in the lake, the quantities would be measureable additions to the total sediment-budget. The 90,000 cubic yards of material placed near Minnesota and Wisconsin Points from maintenance dredging in 1975 was 41 percent of the estimated annual sediment input from Douglas County streams. Lake disposal of new work dredging at 1963 levels would equal 61 percent of the average annual input from shoreline erosion between Superior Entry and Bark Point, Wisconsin.

At the Keweenaw Waterway, the 88,450 cubic yards of dredged material placed in the lake in 1973 was equal to 40 percent of the estimated net littoral transport for that year.

7. Long Residence Time for Flushing Conservative Pollutants

Any in-lake disposal of dredged material is likely to add pollutants to Lake Superior. Dissolved, biologically inactive pollutants may remain in the water column for a long time. Pollutants in particulate form settle to the bottom. If these pollutants are not metabolized they may remain indefinitely. Every effort should be made to reduce the quantities of pollutants entering the lake recognizing that although Lake Superior responds very slowly to conservative pollutants, a long time is required for these pollutants to be flushed from the lake. If contained, harbor disposal of all dredged material is not possible, the environmental effects of in-lake dredged material disposal can be reduced by careful quality control and by selection of suitable disposal areas.

B. Recommendations For Reducing Environmental Effects of Dredged Material Disposal in the Lake

1. Modifications to the Present Criteria for Evaluating Harbor Sediments

a. Chemical analysis of harbor sediment samples should include the determination of trace metals in the clay-size fraction of the sediment. The local background concentration of each metal in the sediment fraction should be used as a "no pollution" value.

b. The following ranges of values should be used as no pollution values in the clay-size fractions of Duluth-Superior harbor sediments:

   a. Mercury: 0.1 - 0.4 mg/kg
   b. Zinc: 140 - 230 mg/kg
   c. Copper: 65 - 88 mg/kg

c. Sediments containing more than the maximum background concentration should be considered polluted. Background values of trace metals at other harbors on Lake Superior may be different from those at Duluth-Superior, and should be considered on an individual harbor basis.

d. There may be considerable variations in the characteristics of sediments within a single harbor area which is classified as non-polluted, moderately polluted, or heavily polluted. Some sediments may be polluted or unpolluted silt and clay while other sediments nearby may be primarily sand. Guidelines used to determine the suitability of harbor sediments for in-lake disposal should include consideration of variations in the percentage of fine sediments and variations in sediment pollution within a classified harbor area.

e. Some form of quality control should be developed for use aboard the dredge to determine whether to use lake or harbor disposal when the dredge is operating within harbor areas approved for in-lake disposal. This monitoring function is essential in harbors where sediment quality is highly variable.

2. In-Lake Disposal Sites at Duluth-Superior

The most likely adverse environmental effects of dumping dredged material in Lake Superior will occur in disposal areas where there are water intakes, densely populated benthic communities, or fish spawning grounds. Disposal of dredged material should be restricted to near-shore areas as far as possible from water intakes and productive benthic areas. Disposal at these sites, where frequent wave-generated turbidity occurs, would result in dilution of potentially harmful pollutant concentrations by erosion and sedimentation. However, even with dilution, dredged material with higher than background values of trace metals will place an additional cultural load of the metal on the total lake environment. This is particularly a problem with mercury because of its demonstrated effects on the benthos and concentration by the food chain.

a. In-harbor, or preferably, contained disposal is recommended for all dredged material, particularly material containing pollutional concentrations of mercury or other trace metals with a demonstrable effect on aquatic organisms or the potential for long residence time, or accumulation in the ecosystem.

b. If harbor disposal is not possible for all dredged material because of adverse environmental effects on the harbor, the following sites are recommended for reducing the likelihood of adverse environmental effects on the lake from the presence of trace metals:

1) Dredged material which is primarily coarse to medium sand should be placed either near the Duluth Entry of Minnesota Point or in the nearshore lake waters of Wisconsin Point for possible beach nourishment.

2) The area which is less likely to be disturbed by deposition of fine dredged material than other areas considered, is the nearshore region between and including Areas 7 and 9 (Figure 4) off Dutchman's Creek. This is an area of frequent turbidity and sparse benthic communities, far from water intakes and shipping lanes. Dredged material placed in this region will be resuspended by wave action and transported by currents, with the fine material being diluted periodically by suspended sediment from coastal erosion and river discharges.

3. <u>In-Lake Disposal Sites at the Keweenaw Waterway, North Entry</u>

a. The main source of pollution in this area appears to be the copper-rich stampsands from the beach deposits at Freda and Redridge, southwest of the Entry. The environmental effects from the in-lake disposal of dredged material containing these stampsands can be reduced by (a) stabilizing or removing the stampsand deposits at Freda and Redridge and (b) nearshore disposal where the stampsands will be likely to follow historic sediment dispersal patterns.

b. Annual nearshore disposal of dredged material from the outer half mile of the North Entry channel appears to have some influence in reducing shoreline erosion north of the Entry, at McLain State Park, and should be continued.

c. Lake disposal of dredged material from the Lily Pond channel should be avoided unless the expected adverse environmental effects of alternative disposal strategies appear greater than the anticipated effects of in-lake disposal.

4. Restricted Disposal

One possible strategy for in-lake disposal is to cover moderately polluted material with "clean" dredged material. This is called "restricted disposal" by EPA. Restricted disposal of moderately polluted spoil appears to be impractical at Duluth-Superior because of the long distances (17-25 km) to disposal areas beyond the depths of wave influence. The adverse environmental effects on the benthic community could be severe, as these deep areas have relatively high population densities. At the Keweenaw Waterway suitably deep disposal sites are located only 6 km from the North Entry, but the environmental effects would be similar to those at Duluth-Superior.

C. Recommendations for Future Research

1. Additional experiments are needed with mercury to determine the extent of uptake and behavioral changes in Pontoporeia affinis exposed to low concentrations (.6-1 mg/kg) of mercury in sediments for periods longer than five days.

2. Bioassay experiments are needed with other, potentially toxic trace metals such as lead, copper, cadmium, and other pollutants identified

in Great Lakes harbors. Since two or more pollutants often exist in the same harbor, synergistic effects need to be explored.

3. Future studies of sediment quality in harbors other than Duluth-Superior should include a multi-element analysis of the clay-size fraction in local soils and sediment to determine local background concentrations.

4. Harbors should be surveyed and sediment samples analyzed by appropriate methods such as atomic absorption, in order to provide detailed maps of harbor areas which bear evidence of trace metal pollution.

5. A quality control method needs to be developed for on-board monitoring of dredged material quality on a scow load basis if in-lake disposal is to be used at harbors with large variations in sediment quality.

I. Introduction

This report is an assessment of environmental impacts associated with in-lake disposal of dredged material in Lake Superior. This assessment was requested by the St. Paul District, U.S. Army Corps of Engineers. Authorization for such environmental assessment studies is contained in the National Environmental Policy Act of 1969 (Public Law 91-190).

Environmental impact statements (EIS) have been prepared by the Corps of Engineers for Lake Superior harbors requiring maintenance at a level which may have a significant effect on the environment. Lake Superior harbors maintained by the Corps of Engineers are shown in Figure 1. Statements[1] for a few of these harbors (Keweenaw Waterway, Grand Traverse Bay, Big Bay Harbor, Saxon Harbor, Cornucopia and Port Wing) included some data from lake sediment samples. But none of the EIS contained enough information to assess the effects of in-lake dredged material disposal. In their assessment of Duluth-Superior harbor (used in the EIS), National Biocentrics, Inc. referred to the possibility that toxic concentrations of metals found in the harbor sediments may be made available to lake organisms through dredging and in-lake disposal of dredged material (National Biocentrics, 1973).

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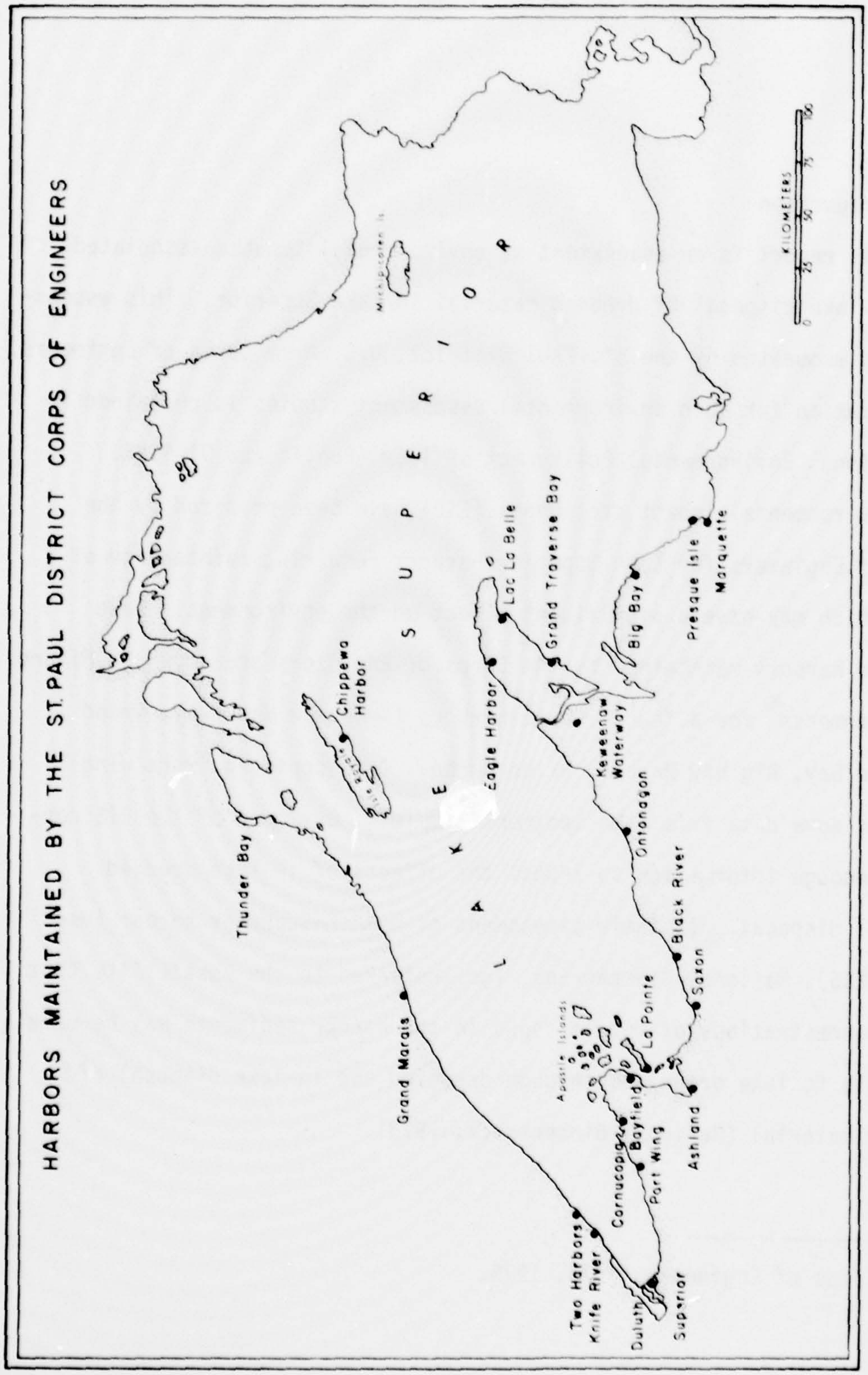
[1]Corps of Engineers, 1974, 1975.


HARBORS MAINTAINED BY THE ST. PAUL DISTRICT CORPS OF ENGINEERS
LAKE SUPERIOR
Thunder Bay
Chippewa Harbor
Isle Royale
Michipicoten Is.
Grand Marais
Two Harbors
Knife River
Duluth
Superior
Cornucopia
Port Wing
Bayfield
Apostle Islands
La Pointe
Ashland
Saxon
Black River
Ontonagon
Keweenaw Waterway
Eagle Harbor
Lac La Belle
Grand Traverse Bay
Big Bay
Presque Isle
Marquette
KILOMETERS
0 25 50 75 100

In September of 1973, our interdisciplinary team of scientists at the University of Wisconsin-Madison began work on an environmental assessment of in-lake dredged material disposal at Duluth-Superior and the northern coast of the Keweenaw Peninsula near the Keweenaw Waterway. Our purpose was to gather information about the lake and Waterway environments, to investigate some possible effects of trace metals on lake organisms and to consider several alternate methods of in-lake disposal in order to provide the Corps of Engineers with an authoritative basis for an environmental impact statement. Several groups of investigators worked to carry out the purpose of this project. Coastal erosion and sedimentation processes were investigated by our geologists. Their work included a beach nourishment experiment at the Keweenaw Waterway and a description of sediment movement in this area based on the distribution of stampsands, a unique local sediment tracer. Their report, Volume 2, contains textural and mineralogical descriptions of beach and lake sediments along the Keweenaw coast and at Duluth-Superior.

The environmental impact of metal availability to organisms has not been previously studied in the context of Great Lakes dredging and dumping. Prior dredging-related studies either focused on water quality effects or were conducted in salt-water estuaries and harbors. An important part of our project was designed to obtain some answers to the following questions:

1. Are the trace metals present in Duluth-Superior and Keweenaw harbor sediments a threat to man and to the lake ecosystem?
2. What is the Corps of Engineers potential contribution, as compared to contributions by natural processes, in making trace metals available to the lake ecosystem?

Several groups of investigators worked to obtain answers to these questions and to assemble information on the biological and trace element characteristics of the benthic environment.

The biologists designed and ran a set of sublethal experiments to determine effects of mercury and zinc in sediments on the behavior of Pontoporeia affinis, an important benthic animal in the Lake Superior food chain. They also investigated the effects of these metals on the susceptibility of Pontoporeia to predation by slimy sculpin (Cottus cognatus), a common benthic fish in Lake Superior. In order to evaluate harbor conditions and the alternatives for in-lake disposal, benthic sampling was done in the harbor and the lake near Duluth-Superior. In addition, a survey of shorebirds was conducted in both study areas. The work of the biological group is reported in Volume 3.

Information on the dynamic processes of coastal currents, flow in the Keweenaw Waterway and wave activity were obtained by our physical oceanographers. The information on these dynamic physical processes is included in Volume 4.

Soil scientists did trace element analysis of benthic organisms, fish and sediments from the harbor and lake and from laboratory bioassays. They also developed a method for identifying abnormal concentrations of trace elements in harbor and lake sediments. Their work on the availability of soluble zinc in harbor and lake sediments to water was used to relate the laboratory experiments with zinc-enriched sediment to lake conditions. The work of this group is reported in Volume 5.

Our assessment of environment effects of in-lake dredged material disposal in Lake Superior was conducted for the St. Paul District Office of the U.S. Army Corps of Engineers under contract number DACW37-74-C-0013. Related studies were carried out under separate contracts by personnel at the Michigan Technological University (MTU) in Houghton and the University of Minnesota at Duluth (UMD) and are recorded in separate reports (MTU, 1975; Sydor, 1974, 1975). Coordination of the contract work at these three institutions was the responsibility of the Marine Studies Center, University of Wisconsin-Madison.

Following their 1973 environmental assessment of ten Michigan harbors on Lake Superior, the Aquatic Research Group at MTU evaluated biological, chemical and geological features of the benthic environment in the lake near the Keweenaw Waterway North Entry in 1974. Their sampling extended some 40 km along the coast and into the Waterway in an investigation of seasonal and spatial changes in the environment. Dr. Michael Sydor at UMD investigated the effects of water circulation patterns, turbidity, currents and the influence of wind on these phenomena in the waters off Duluth-Superior. The reports of these investigators are referenced throughout the five volumes of this environmental assessment report.

This summary volume draws together evidence gathered by all of the research groups in order to make a combined assessment of environmental effects of dredged material disposal in the lake. The alternatives in section V and their attendant effects are based on the data assembled in the other four volumes. The recommendations and conclusions stated here include some which are based on the results of more than one group's research, and are, therefore, not found in the other volumes.

II. Environmental Setting

A. Geographic Setting

Because of the unique character of Lake Superior, the environmental effects of dredging and dredged material disposal must be subject to rigorous and critical evaluation. Some features of Lake Superior are given in the following table:

Table 1

Some Physical Characteristics of Lake Superior*

Surface area	82,000 km^2
Length	565 km
Breadth	258 km
Mean depth	148 m
Maximum depth recorded	406 m
Volume	12,200 km^3
Length of shoreline (including islands)	4,800 km
Area of drainage basin	210,000 km^2
Annual mean outflow rate	2,100 m^3/sec.

Relative to area, Lake Superior is the largest body of fresh water in the world. It is an oligotrophic lake with exceptionally high water quality. Total dissolved solids average less than 60 mg/kg.* The concentration of suspended solids is less than one mg/kg in mid-lake. Lake Superior constitutes the headwater of the entire Laurentian Great Lakes. The relatively small amount of outflow, as compared to the size of the lake, results in a calculated flushing** time of about 183 years.

*Data from the Great Lakes Pilot (1974), Corps of Engineers (1969).

**Flushing time is calculated by dividing the lake volume by the annual mean flow.

Biologically, Lake Superior has been characterized as a "desert" because of the lake's low nutrient levels and hence, its low biological productivity. The original fauna, typical of a sub-arctic oligotrophic lake, have been significantly altered by the invasion from the ocean of the sea lamprey (Petromyzon marinus). Further changes have been consciously brought about by human interventions via the stocking of various species of trout and salmon. Changes in the lower trophic levels, namely the algae and benthic invertebrates may also be occurring due to man-induced changes in sedimentation patterns and pollution. However, these changes are almost certainly local rather than lakewide. Despite alterations of species composition, the overall biological productivity and standing crop of both plants and animals has remained and will probably continue to remain low, as compared to other Great Lakes. Pontoporeia affinis, a burrowing crustacean, is one of the most widely distributed and abundant benthic creatures. Species of oligochaetes (sludge worms), sphaeriids (fingernail clams), chironomids (fly larvae) and nonburrowing crustacean Mysis relecta are part of the benthic invertebrate community. The sculpins (family Cottidae) and longnose suckers (Catostomus catostomus) represent the major bottom-feeding fish. Pelagic fish include American smelt (Osmerus mordax), lake trout (Salvelinus namaycush), burbot (Lota lota), whitefish (Coregonus clupeaformis), and lake herring (Coregonus artedii). Several species of fish have been introduced into the lake by government agencies. These include brown trout (Salmo trutta), rainbow trout (Salmo gairdneri) and coho salmon (Oncorhyncus kisutch), chinook salmon (Oncorhyncus tshawytscha), and pink salmon (Oncorhyncus gorbuscha).

Lake Superior is sub-arctic in terms of its temperature characteristics. It stratifies very late in the heating season (July) and only small amounts of its surface area ever exceed 15°C, and then for only a few months. Although the lake seldom freezes over completely, the bays, harbors and nearshore areas are ice-covered from December until as late as June. Shore ice sometimes has a protective effect, shielding the beaches from winter storms. At other times, ice in movement along the coast increases erosion.

Our two study areas, the Keweenaw Peninsula and the Western Basin near Duluth-Superior, contrast in several ways. Extending along the Keweenaw Peninsula, an uplifted highland marks a break in the earth's crust which is called the Keweenaw Fault. Along the northern coast, this highland rises steeply from the lake floor with lake depths of 240 m within 3 km of the coast. Adjacent to, and southwest of the Waterway, the bottom slopes more gradually to depths of 40 m, 6-9 km offshore. The Keweenaw Peninsula shoreline, in the area of the Waterway, is scenic with tree-topped cliffs and sand or cobble beaches. Some shoreline development in terms of cottages or resorts exist, and 16 km south of the Waterway the smokestacks and ruins of the Redridge and Freda stamping mills remain as signs of past copper mining activity. Stampsand deposits from these mills have high residual metal content and are found on the beaches and in offshore sediments along this coast. The entire coastline is exposed to the activity of waves and winds moving over 80 to 210 km of open water. In the summer, the Keweenaw current develops, flowing swiftly northeast along the northern coast of the Peninsula.

The Keweenaw Waterway is a natural waterway except for the last few kilometers near and including the North Entry. This area was excavated and completed during the late 1800's. The opening of the Entry affected the adjacent littoral zone, providing an escape for sand from the littoral drift system. Completion of the Waterway also provided an avenue into Lake Superior for fine-grained, suspended material which was generated in the Waterway drainage area. This action provided a new source of nutrients and pollutants to the lake from the flushing of the channel caused by the seiche of the lake.

Duluth-Superior is an active international port at the tip of the long western arm of Lake Superior. The offshore water is relatively shallow, reaching 40 m in depth 14 km east northeast of Duluth-Superior. Wind-driven currents near Duluth-Superior form into eddies which occasionally circulate sediment-laden water over a large area offshore. The Minnesota coastline north of Duluth is characterized by basaltic bedrock and boulders weathered from glacial till. The southern, Wisconsin coastline has sandy beaches and steep banks of red clay. Between these two contrasting coasts, a long-sandy bar formed across the mouths of the St. Louis and Nemadji Rivers due to westward[1] movement of sediment in the south shore littoral transport system. This formation, beginning when the lake was at a lower level, created the present Superior Bay, Minnesota and Wisconsin Points.

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[1] Westward-movement toward the west, southwest, northwest.

B. Harbor Setting

1. Duluth-Superior

Duluth-Superior harbor is the largest Lake Superior center of commercial shipping with a total maritime commerce of roughly 36 million metric tons in 1974 (Seaway Port Authority of Duluth, 1974). These Twin Ports are a shipping point and trade center for bulk commodities serving an extensive area from Canada to the Rockies and from Nebraska to central Wisconsin. In 1973, there were 2630 arrivals of vessels with drafts greater than 12 feet, coming to pick up or to discharge cargo (Corps of Engineers, 1973).

The major portion of the cargo moving out of the Twin Ports consists of iron ore and grain. In 1974, iron ore and concentrate shipments amounted to 28 million metric tons. Exports of grain in 1974 totaled 3.4 million metric tons, and shipments of grain to other U.S. Great Lakes ports amounted to roughly one million metric tons.

The economic picture for the Duluth-Superior harbor is one of significant projected growth. At the present time, port commerce in total annual tonnage is far below the 70 million metric tons during the peak days of the high-grade iron ore shipments from the Minnesota iron ranges. A major source of outbound cargo (coal) is expected to develop when the Burlington-Northern coal handling facility is completed. Shipments are expected to total nine million metric tons per year initially, with the prospect of eventually reaching 18-24 million metric tons annually (NBI, 1973).

Future growth in iron ore shipments is also expected, as evidenced by the current construction of a taconite shipment facility in Allouez

Bay. The planned reopening of the Lakehead terminal will increase the shipment of petroleum from this port to roughly one million metric tons per year. With larger shipments of iron ore, coal, and oil contributing to the commerce of the harbor, it may be able to once again reach its former peak tonnage level and provide some increased employment opportunities.

The number of harbor-related jobs in Duluth-Superior is estimated at 2,500-3,000 out of a total 1970 labor force of 53,100 (National Biocentrics, 1973). This does not include a substantial number of local residents who serve as crews on lake vessels. In addition, the largest employers in Duluth and Superior (the Duluth, Mesabe and Iron Range Railway and Fraser Shipyards) are directly dependent upon the port for their viability.

The commercial aspects of the harbor are not its only assets. The scenic beauty of the lake and harbor and the presence of ocean-going vessels and lake carriers attract tourists and boaters to the Twin Ports. The two cities are a major tourist attraction in the Upper Midwest and have a large percentage of the recreational small boat traffic in the Lake Superior Basin.

2. Keweenaw Waterway

The Keweenaw Waterway was purchased by the United States Government in 1891 and has been maintained as a commercial waterway by the Army Corps of Engineers ever since. At the present time, the Waterway is used chiefly by recreational boaters cruising its 32 kilometers of water bordered by steep, wooded bluffs and low hills. Commercial use of the Waterway includes occasional transits by the smaller lake carriers seeking to avoid mid-lake navigation around the tip of the peninsula or as a harbor-of-refuge from storms. The Waterway is also used by a few commercial fishing boats, survivors of a once numerous commercial fishing fleet. The National Park Service uses the Waterway as a base for the "Ranger", a vessel used to transport visitors to Isle Royale, 80 km northwest of the peninsula. A total of 668 passages under the Houghton-Hancock bridge were made for commercial and pleasure vessels in 1973, including 69 ore boats and tankers passing through the Waterway (Wright, 1974).

The Keweenaw Waterway has declined as a port in tonnages of commodities shipped and received since 1963 (NBI, 1973). Total port tonnage declined from approximately 473,000 metric tons in 1963 to 86,000 metric tons in 1969. Between 1969 and 1974, port traffic fluctuated between 63,000 and 137,000 metric tons per year (Corps of Engineers, 1969-1974). The tonnages of cargo on ships passing through the Waterway has ranged between 45,000 and 364,000 metric tons per year during the 24 year period between 1950 and 1974. In the most recent period of 1971-1974, through traffic varied from 118,000-228,000 metric tons/year. In terms of total traffic, the 264,000 metric tons carried in the Waterway in 1974 was less than half the yearly tonnages in 1961-1964.

A steady decline in port traffic of coal, coke, and lignite since 1963 combined with the depressed economies of the region to cause the decline in Waterway useage (NBI, 1973). While ships still use the Keweenaw Waterway, the majority of Lake Superior shipping passes by the tip of the Keweenaw Peninsula enroute to Duluth-Superior or other ports.

III. Description of Corps Project Activity

A. Duluth-Superior Harbor

The Corps of Engineers has maintained this harbor since 1872. Initially there were two separate harbors. These were united as a single project in 1896. The channel maintenance and deepening project has grown greatly since that time. By 1950, channel maintenance dredging included the Duluth Harbor Basin, the East Gate Basin, the Superior Front Channel, Allouez Bay, Howards Bay, St. Louis Bay and the Minnesota Channel. A map of the harbor area is shown in Figure 2.

The statistical history of this project in terms of cubic yards of dredged material removed is shown in Tables 2 & 3. Through 1967, 75 percent of this material (41 million cubic yards) had been dumped in Lake Superior (Corps of Engineers, 1974). The two major offshore dump sites have been:

1. A one mile diameter area, located 105 degrees from North, 1-1/2 miles (2.4 km) from the Duluth Ship Canal South Pier to the center of the area.
2. A one mile diameter area, located 10-30 degrees from North, 2 miles (3.2 km) from the Superior North breakwater to the center of the area.

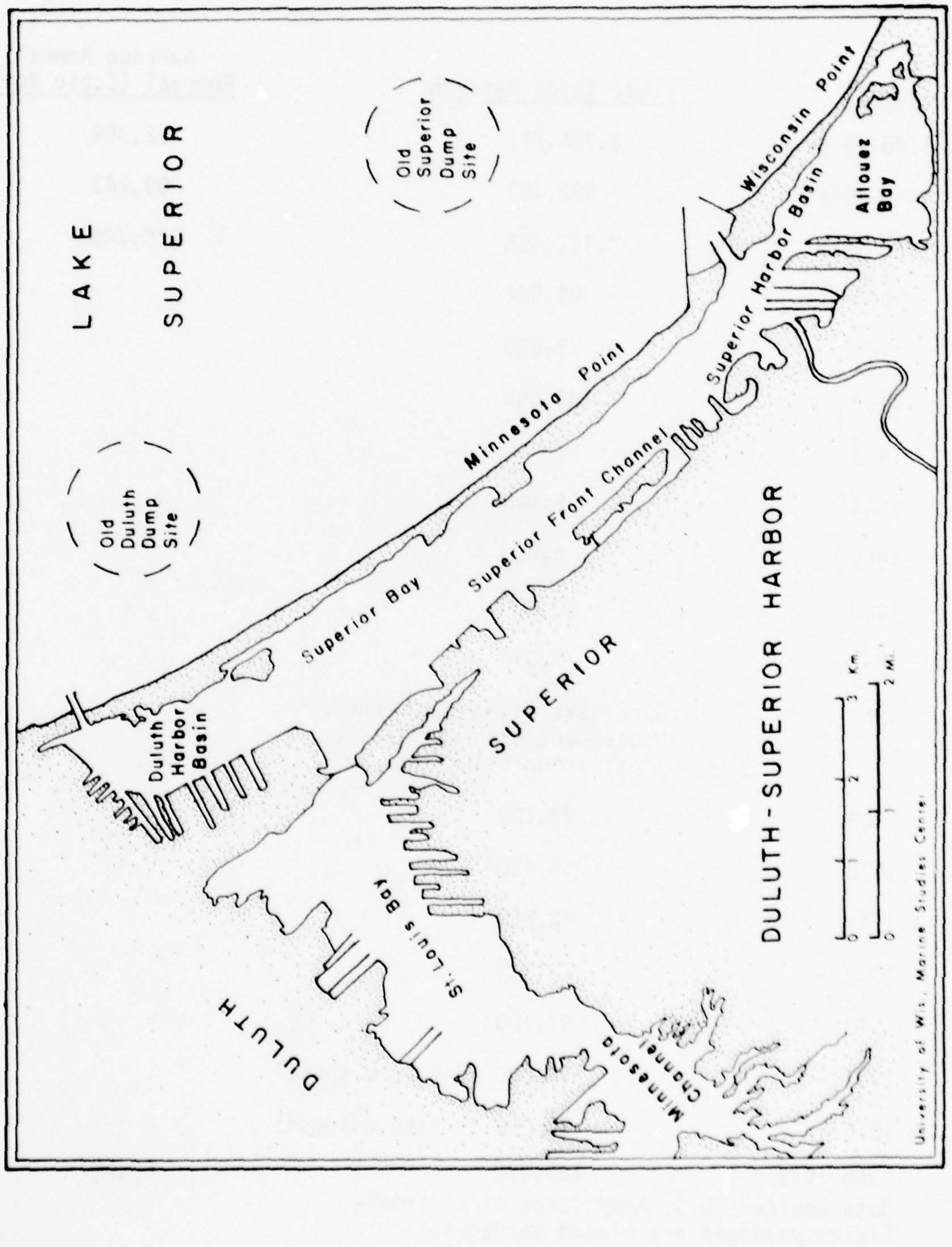
LAKE SUPERIOR
Old Superior Dump Site
Old Duluth Dump Site
Wisconsin Point
Allouez Bay
Superior Harbor Basin
Minnesota Point
Superior Front Channel
Superior Bay
Duluth Harbor Basin
SUPERIOR
DULUTH-SUPERIOR HARBOR
St. Louis Bay
DULUTH
Minnesota Channel
0 1 2 3 Km.
0 1 2 Mi.
University of Wis. Marine Studies Center

Table 2

Maintenance Dredging at Duluth-Superior Harbor

Year(s)	Cubic Yards Removed	Average Annual Removal (Cubic Yards)
1898-1939	3,786,711	92,359
1940-1949	992,427	99,243
1950-1959	2,157,455	215,745
1960	85,582	
1961	75,820	
1962	100,055	
1963	---	
1964	9,400	
1965	4,200	
1966	20,000	
1967	72,590	
1968	Open-lake disposal stopped. Subsequent disposal in the 21st Avenue Slip area.	
1969	29,100	
1970	255,430	
1971	42,550	
1972	73,900	
1973	97,100	
1974	14,000 in-lake disposal	
1975	90,000 in-lake disposal	
1966-1975	680,670	68,067

Data Source: U.S. Army Corps of Engineers
Listed yardages are placed yardages.

Table 3

New Work Dredging at Duluth-Superior Harbor

Year(s)	Cubic Yards Removed
Thru 1939	41,445,130
1955	480,932
1956	540,013
1962	100,000
1963	2,545,015
1964	1,847,891
1965	471,080

Data Source: U.S. Army Corps of Engineers

From 1968 until 1974, dredged material, classified by EPA as polluted, was dumped in the 21st Avenue Slip. Unconfined dumping in the 21st Avenue Slip area was an interim arrangement, made by the Minnesota Pollution Control Agency, the U.S. Environmental Protection Agency (EPA) and the Corps until a contained disposal facility could be constructed on the site. In 1974, the 21st Avenue Slip was not available for disposal, and little dredging was done. In November and December a total of 14,000 cubic yards of dredged material was removed from harbor channels and placed in the lake (Whiting, 1976). In May, 1975 the harbor was re-sampled by EPA. Subsequently, some areas of the harbor were reclassified as unpolluted, and dredge material from these areas was declared suitable for in-lake disposal. Other areas were reclassified as moderately polluted and dredging from these areas were suitable for restricted[1] in-lake disposal. Some areas were classified as heavily polluted and dredged material from these areas had to be confined (EPA, 1975). During the spring and summer of 1975, the Corps of Engineers used 58,000 cubic yards of dredged material for beach nourishment on the lake side of Wisconsin Point, and 32,000 cubic yards for nourishment of Minnesota Point (Mueller, 1975).

Maintenance and permit dredging in the Duluth-Superior Harbor is performed by dipper, clamshell and hydraulic dredges which load the dredged material into bottom dump scows. The scows (or barges) are towed one at a time by a tugboat to the dump site while the dredge fills another barge. Approximately 150,000 cubic yards of sediment will be removed annually in the entire harbor during future maintenance dredging (Corps of Engineers, 1974). Roughly one third of the material is removed by permit dredgers. Nearly all permit dredging is associated with maintenance dredging of dockside and slip areas and is performed by private contractors for the dock or slip owners. Corps of Engineers maintenance dredging in the Duluth-Superior Harbor is presently performed primarily by the dipper dredge GAILLARD and the clamshell dredges COLEMAN and DK-20 in conjunction with tugs, tenders and bottom dump scows. Maintenance dredging at Duluth-Superior is done to maintain depths of 32 feet at breakwaters, 28 feet at pier heads and 27-28 feet in main channels and basins.

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[1]The polluted material will be covered with clean dredged material.

Sediments dredged from the Duluth-Superior Harbor consist of sand, silt and clay. It is likely that most of the silt and clay represents bedload deposition from the St. Louis and Nemadji rivers. The Nemadji River is known to carry a heavy sediment load during the spring run-off and during periods of persistent or heavy rainfall.

A total of 54,800,000 cubic yards of material has been dredged by the Corps since 1896 (Corps of Engineers, 1974). An estimated 85% of this material was removed as new work while the Corps was participating in the conversion of the harbor from a small ship canal to a network of channels totaling 17 miles, extending from Big Bay Island in the St. Louis River to Allouez Bay at the east end of Superior Bay. Confined disposal of polluted dredged material is being planned for this harbor. A large site at the Erie pier location is currently being studied as a possible location for a disposal facility.

In addition to maintenance dredging activities in the Duluth-Superior Harbor, the St. Paul District maintains breakwaters and piers at the Duluth Ship Canal and at the Superior Entry. The Corps of Engineers has established various permanent facilities in the Duluth-Superior Harbor. They maintain their Lake Superior Area Office in Duluth at Canal Park next to the Duluth Ship Canal. A new visitors center and shipping museum is operated by the Corps adjacent to their office at Canal Park. The Corps also operates and maintains a Vessel Yard and repair facility for the various pieces of dredge and attendant equipment on the harbor side of Minnesota

Point south of the Duluth Ship Canal. The Vessel Yard comprises several repair and maintenance buildings as well as a pier and dock where various types of floating equipment can be tied up.

B. Keweenaw Waterway

The Keweenaw Waterway is located on the Keweenaw Peninsula of northern Michigan and connects the open waters of Lake Superior with Keweenaw Bay (Figure 3). The 22 mile long waterway utilizes a natural river, a natural lake and a man-made canal. It was developed as a shorter and safer shipping route between Marquette and Ontonagon, Michigan. The Waterway was first completed as a commercial venture in 1873 by the Lake Superior and Portage Ship Canal Company. It was purchased by the United States Government in 1891 and has been maintained by the Army Corps of Engineers since that time. The following paragraphs describe some of the areas maintained by the Corps:

Upper Project, Upper Entrance

The section identified as the Upper Entrance is also variously known as the North, West and/or Superior entrance. It is totally man-made and extends from the head of Portage Lake at Boston Creek 3 1/2 miles northward to the pier-heads of the two breakwaters which protect the Upper Harbor entrance. Project elements in this area include two breakwaters and two steel revetments as well as a maneuvering basin, a mooring basin (harbor-of-refuge) with mooring piers, and channel dredging operations.

The north-south oriented Upper Entrance section has two rubble-mound breakwaters which define the eastern and western Upper Harbor limits. The breakwaters situated to the east and west of the harbor are 2,385 and 2,645 feet in length, respectively, with 50-foot diameter pierheads. At the shore, the structures are 3,700 feet apart. Offshore they converge and the distance between them diminishes to form a 500-foot wide entrance between the pierheads. Other structural facilities in the Upper Entrance section are steel revetments along both the east and west shore of the waterway. The eastern revetment extends 8,288 feet from the harbor to the south end of the Lily Pond harbor-of-refuge. The shorter western revetment extends 4,832 feet from the southern portion of the harbor to a point 1,000 feet north of the Lily Pond harbor-of-refuge.

Commercial and pleasure craft-accommodating features of the Upper Entrance section include a maneuvering area, a mooring area and a 2 1/2 mile maintained channel of varying depth and width. Extending landward from the breakwater pierheads is a 3,000-foot long channel and maneuvering basin. Project depths in this area range from 32 feet at the pierheads to 25 feet in the protected harbor. The widths of the channel and basin are 500 feet at pierhead, 1,000 feet in center of harbor, constricting to 300 feet at southern harbor boundary.

Lily Pond Harbor-of-Refuge

A 3,600-foot channel, 25 feet in depth and 300 feet wide, links the upper harbor to the mooring basin in the Lily Pond harbor-of-refuge. Lily Pond Harbor, approximately 50 acres in size, is 3,300 feet long, 25 feet deep and 800 feet wide. There are mooring piers, protected by fender pilings, adjacent to the east revetment. The piers can accommodate year around ship dockage. (Corps of Engineers, 1974).

Most recent Corps activities have involved breakwater repair and continued maintenance dredging in the Upper Entry Section. It is anticipated that annual maintenance dredging to achieve control depth will be required indefinitely in this area. The record of maintenance dredging since 1892 is shown in Table 4.

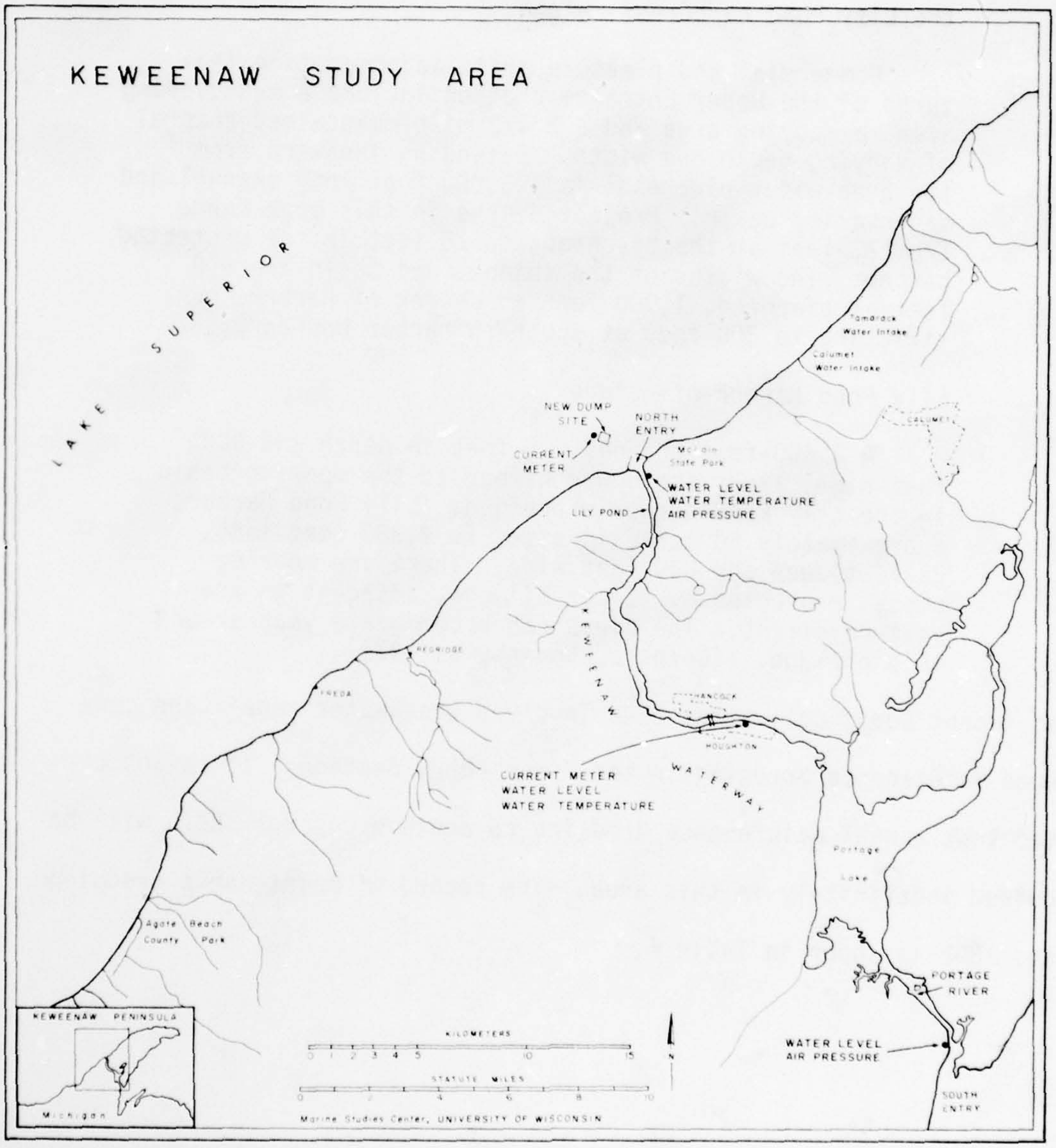
KEWEENAW STUDY AREA
LAKE SUPERIOR
Tamarack Water Intake
Calumet Water Intake
CALUMET
NEW DUMP SITE
NORTH ENTRY
CURRENT METER
McLain State Park
WATER LEVEL
WATER TEMPERATURE
AIR PRESSURE
LILY POND
KEWEENAW WATERWAY
HANCOCK
HOUGHTON
CURRENT METER
WATER LEVEL
WATER TEMPERATURE
Portage Lake
Agate Beach County Park
PORTAGE RIVER
WATER LEVEL
AIR PRESSURE
SOUTH ENTRY
KEWEENAW PENINSULA
Michigan
KILOMETERS
0 1 2 3 4 5 10 15
STATUTE MILES
0 2 4 6 8 10
N
Marine Studies Center, UNIVERSITY OF WISCONSIN

Table 4

Maintenance Dredging in the Keweenaw Waterway

Year(s)	Cubic Yards Removed	Average Annual Removal (Cubic Yards)
1892-1939	2,197,901	46,764
1940-1949	769,626	76,963
1950-1959	262,652	26,265
1960	2,099	
1961	---	
1962	33,045	
1963	8,560	
1964	44,310	
1965	9,225	
1966	---	
1967	---	
1968	---	
1969	---	
1970	---	
1971	48,300	
1972	75,300	
1973	88,450	
1974	96,450	
1975	63,800[1]	

Source: U.S. Army Corps of Engineers

[1] MTU, 1975.

Dredging operations in the Keweenaw Waterway from 1891 through 1973 have removed 20,726,806 cubic yards of sediment (Corps of Engineers, August, 1974). This figure is in excess of the totals for all other St. Paul District Lake Superior ports with the exception of Duluth-Superior. The majority of the Keweenaw dredging has been associated with new construction projects in the Upper Entrance, Lily Pond/Portage River harbors-of-refuge and Princess Point cutoff sites. Corps records indicate that as of fiscal year 1972, maintenance dredging accounted for less than three million cubic yards of the total material removed from the Waterway.

The amount of annual maintenance dredging in the Waterway varies greatly from year to year as Table 4 indicates. In recent years, most of it has been done in the Upper Entry and Lily Pond harbor-of-refuge areas. Sediments dredged from the Waterway consist mainly of sand, silt, clay and stampsand from defunct copper ore processing operations. These sediments have been moved and deposited in the channel by littoral drift, wave action, waterway flow and propeller wash from passing ships.

Corps of Engineers maintenance dredging in the Keweenaw Waterway is presently performed by the dipper dredge GAILLARD, in conjunction with various tugs, tenders and dump scows. Dredged sediments are placed, by the dipper dredge into bottom dump scows for removal from the dredge site to the disposal area. Past practice for disposal of Keweenaw Waterway spoil has involved dumping the material into Lake Superior one mile northwest of the Upper Entry in depths of sixty feet or more.

Sand dredged from the area between the Upper Entry breakwaters has been used for beach nourishment[1] on the McLain State Park shoreline north of the Upper Entry. For beach nourishment, the scows are towed to a minimum water depth of twelve feet before the bottom doors are opened.

In 1970, the entire Waterway was classified as polluted by EPA. More detailed sediment sampling in the northern most 2.5 miles of the Waterway during 1972 showed that the 1/2 mile of channel inside the Upper Entry was unpolluted (EPA, 1972). As of November 8, 1974, the entire 2.5 mile section was reclassified by EPA as unpolluted (Corps of Engineers, 1975). This is the area where all Waterway maintenance dredging is likely to occur during the next ten years.

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[1] replacement of beach sand removed by littoral drift or storm waves.

IV. Environmental Effects of Dredged Material Disposal in the Lake

Earlier studies of dredging and disposal, primarily in marine waters, indicate that possible impacts of in-lake disposal are:

1. Increased availability of harbor pollutants to lake water and to aquatic organisms.
2. Disruption of benthic communities with some mortality due to burial or to the disturbance of sediments.
3. Increased amounts of fine sediment periodically re-suspended during storms and re-distributed to other areas with resulting degradation of water quality and possible adverse effects on aquatic organisms.
4. Changes in sediment texture and mineralogy on or near the dump site resulting in a loss of habitat or an improvement of habitat for benthic communities.
5. Increased oxygen demand.
6. Increased level of organic material.
7. Changes in primary production of plankton.
8. Impairment of larval or egg development due to changes in substrate and suspended particles in the water.
9. Impairment of feeding, respiratory and excretory activity of aquatic organisms.

The first four possible impacts on this list are considered in the following pages. The remaining five items on the list were not included in the scope of work under our contract, and may or may not be effects of dredged material disposal in Lake Superior.

Prior sampling of Lake Superior harbors has shown many of them to be polluted with mercury and zinc.[1] Much of our research focused on the availability of mercury and zinc to organisms, on the behavioral effects of these two metals in laboratory bioassay experiments and on the presence of metals in a variety of species in the lake ecosystem.

Our mapping of benthic communities near Duluth-Superior provided information needed to assess the potential disruption of these communities by in-lake disposal. Michigan Technological University's Aquatic Research Group provided similar information for the Keweenaw Waterway and Upper Entry area of the lake. Analysis of sediments at both sites provided data needed to assess the potential increase in fine sediments and the possible changes in sediment texture and mineralogy which could occur on a dump site in the lake. The sedimentation study at the Keweenaw Peninsula also provided information on sediment transport patterns and beach erosion. Data on currents, waves and other physical processes provided some additional information on suspended sediment movement and possible dredged material dispersal. The following assessment of environmental effects, based on the few intensive studies mentioned here, adds new information on how benthic animals respond to some pollutants and on the aquatic environment in both study areas.

A. Increased Availability of Harbor Pollutants to Lake Water and Aquatic Organisms

In 1967 and 1968, the Buffalo District Office, Corps of Engineers, directed a study of dredging and disposal alternatives at 37 Great Lakes

[1] See discussion on page 45.

harbors from Lake Michigan to Lake Erie. During their study they concluded:

> it became apparent that the sampling program could not generate sufficient data to make a definite determination of the effects of dredging operations on water quality, particularly at open-lake disposal areas (Corps of Engineers, 1968).

The Board of Consultants assisting in the study decided that:

> in-lake disposal of heavily polluted dredgings must be considered presumptively undesirable because of its long-term adverse effects on the ecology of the Great Lakes (Corps of Engineers, 1968).

This conclusion was largely based on bioassay experiments at the University of Wisconsin-Milwaukee designed to determine toxic effects of the pollutants in the dredgings on benthic animals in the lake (Gannon and Beeton, 1971). We have taken a similar approach to our research, focusing primarily on bioassays and on sediment analysis. Our bioassays were designed to measure subtle, sublethal effects of metals on behavior of Pontoporeia affinis, a benthic crustacean which is an important link in the food chain of the Lake Superior ecosystem. Sublethal effects, such as behavioral changes, are indicative of changes in the health of the organisms. These changes may affect the viability of the aquatic community.

1. Pathways for Pollutants Entering the Ecosystem

Harbor pollutants are thought to be available to aquatic systems primarily in soluble form, and secondarily, as solid exchangeable phase material on organic or inorganic particles. Direct chemical analysis of water samples has largely failed to detect significant, increased availability of soluble pollutants in open-lake disposal situations, except on very small time and space scales (Corps of Engineers, 1968). However, rapid dilution or burial of the soluble pollutants during dumping can account for failure to observe an effect. Soluble pollutants in the interstitial water between particles may remain available to benthic animals burrowing in the sediment or ingesting the particles. Soluble pollutants in lake water may also be taken up directly by fish.

Another pathway for pollutants to enter the aquatic ecosystem is through the ingestion of contaminated organic or inorganic particles by benthic organisms. *Pontoporeia affinis* apparently feed on organic matter and bacteria in the sediments and ingest inorganic particles while feeding. Pollutants associated with the particulate material enter the *Pontoporeia* and can then be transferred to animals higher in the food chain (Volumes 3 and 5).

2. Availability of Mercury

a. Mercury in Harbor Sediments at Duluth-Superior

Sampling of Duluth and Superior Harbor Basins[1] by EPA (1970, 1973), National Biocentrics, Inc. (1972, 1973) and the University of Wisconsin-Superior (1973) indicated mercury concentrations in the sediments of 1-5 milligrams of mercury per kilogram (mg/kg)[2]. In May, 1975, EPA re-sampled the Duluth and Superior Harbor Basins' sediments using a combination of bulk sediment analysis and elutriate tests. Bulk sediments contained less than 0.1 to 0.2 mg/kg, well below EPA's guideline of 1 mg/kg for unpolluted sediment. In EPA's 1975 survey, some parts of the outer harbor had clean sediments. Sediments from other areas were relatively

[1]The results of this sediment sampling are summarized in EPA, 1975.

[2]One mg/kg is equivalent to one part per million (ppm), used in Volumes 3 and 5. For comparative purposes mg/kg is used consistently in this section. All listed metal concentrations are based on dry weight.

unpolluted, except for the presence of mercury. Certain sections on the fringes of the navigation channel were classified as heavily polluted, based on the earlier sampling surveys.

Our 1973 harbor samples had total sediment concentrations in agreement with the 1975 EPA findings (Volume 5, Table 4 p. 17-22). Five samples of dredged material were collected May 22-29, 1975 from scows operating with the dredge D.D. GAILLARD in the Superior Entry area. These samples had mercury concentrations ranging from less than 0.01 to 0.06 mg/kg in the total sediments (Volume 5, Table 4 p. 32-35). All of these sediments are within the current EPA guideline for sediment unpolluted with mercury.

b. Concentrations in the Fine Fractions of Sediments

Mercury, like most of the 22 elements we analyzed, is found at higher concentrations in the fine fractions of sediments than in the coarser fractions. The fine sediments have a greater capacity for trace element adsorption than do the larger particles. For example, sample S-III-1 from the harbor had 0.99 mg/kg in the clay-size fraction and 0.14 mg/kg in the total sediment sample (Volume 5, Table 4). The clay-size fraction consists of particles less than 2 microns (0.002 mm) in diameter. These particles are very mobile in the environment. As a result, concentrations of most trace elements in this fraction of sediment samples from an area like Duluth-Superior will be very similar--indicating the widespread dispersion of sediments from a common source (or sources). Some elements used by man, like mercury, will occasionally appear at higher than normal concentrations in the clay-size fraction of a sample. The mercury concentration in the clay-size fraction of sample

S-III-1 was 2.5-5 times as high as the mercury concentration in the same fraction of local soils--indicating probable pollution at this site in the harbor.

Other harbor sediments in our 1973 sampling had similar enrichment in the fine fraction. In five out of six samples, the clay-size fraction contained 0.27-0.99 mg/kg of mercury, while the total sediment concentrations were less than 0.24 mg/kg. Only sample S-IX had lower concentrations of mercury in the clay-size fraction: 0.074 mg/kg. The percentage of clay-size material in these samples ranged from 2.9-24 percent by weight (Volume 5, p. 55). Three of five scow samples (with 3-7% clay-size material) had concentrations of 0.58-0.97 mg/kg mercury in the clay-size fraction but had only 0.02-0.06 mg/kg mercury in the total sediments.

Analysis of the clay-size fraction will provide a good indication of cultural (or man-made) pollution. This method is described in Volume 5, Section II. If fine dredged material polluted with mercury is dumped in the lake, the material will eventually settle out in deep areas populated by benthic animals. As a consequence, mercury may be available for uptake by animals such as *Pontoporeia affinis*.

c. Mercury Uptake in *Pontoporeia affinis*

The literature review in Volume 3 identifies *Pontoporeia affinis* as an important animal in the lower orders of Great Lakes food chains. *Pontoporeia* demonstrated a remarkable ability to take up mercury in laboratory accumulation experiments. When living *Pontoporeia* were placed on sediment containing high values of mercury (3.5-4 mg/kg), they increased their body burden of mercury from 0.1 mg/kg to more than 10 mg/kg in one week and to 40 mg/kg in two weeks--a multiplication of 100-400 times original values, assuming uniform initial body burdens in the animals (Volume 3, p. 94). Similar results were observed at lower sediment concentrations in the behavioral experiments. Two days' exposure to sediments containing 0.65-1.15 mg/kg resulted in a 50-100 times increase in body burden from 0.1 mg/kg at the start to 5-10 mg/kg at the end of the experiment. Five days' exposure to sediments with 2.15-3.35 mg/kg produced a body burden of up to 100 mg/kg: a 1000 fold increase (Volume 3, p. 82).

After each of the laboratory experiments, the Pontoporeia were placed on clean sediment for three days to permit removal of contaminated sediment from the gut. The body burden of mercury measured was the total mercury on the exoskeleton and in the flesh of the Pontoporeia.

There are differences between the experimental situation, the harbor and the lake which affect interpretation of the uptake study. These differences are discussed in Volume 3, Section III,D. The form of mercury, route of uptake and extent of methylation in the laboratory experiments may have been different than in the lake and harbor. Possible mechanisms of mercury uptake include: direct ingestion, bacterial intake, chemical leaching in the gut, adsorption to the exoskeleton. The relative amounts of soluble, insoluble, and exchangeable phase mercury in the lake sediments may differ from the primarily soluble mercury used in the laboratory. The laboratory sediments were washed Lake Superior sand with a noticeable, but unmeasured, quantity of fine sediment and detritus remaining after washing. The unknown quantities of organic matter included periphyton which developed during the experiment. The Trout Lake water used in the laboratory had slightly different chemical characteristics than did Lake Superior water (Volume 3, p. 68). The hardness and pH were similar.

We conclude that Pontoporeia can multiply their body burden of mercury by two or more orders of magnitude on sediments containing 0.6 mg/kg or more of mercury over a few days time, if the mercury is in an available form.

d. Effect of Mercury on Pontoporeia Activity

A change in animal behavior, caused by an introduced substance (like mercury), is commonly regarded by biologists as an indication of a change in the health and potential well-being of the animal. Mercury was noted to have an effect on Pontoporeia behavior during two sets of experiments described in Volume 3. In both sets of experiments, behavior of Pontoporeia on mercury-enriched sediment was compared to behavior of "control" Pontoporeia on natural sediments--with other tank conditions being the same for both. The number of active animals and their rates of activity were used as indices of behavior. In one group of experiments, Pontoporeia had statistically significant lower activity rates and lower numbers active than the controls did during a five-day exposure to sediments containing 2.15-3.35 mg/kg of mercury.[1] Mercury concentrations in these Pontoporeia increased from 0.1 to as much as 100 mg/kg at the end of the five days. Another set of experiments showed that Pontoporeia exposed to a lower concentration of mercury (0.65-1.15 mg/kg) for a shorter period (two days) had lower activity rates than did the control Pontoporeia, but the differences between exposed and unexposed animals in these experiments were between the 70 and 80% confidence level, and therefore they were not regarded as statistically significant. Mercury concentrations in these Pontoporeia had increased from 0.1 to 10 mg/kg (maximum) by the end of the two days.

Interpretation of the results of these experiments must take into account the differences between lake, harbor and laboratory sediments mentioned in the description of mercury uptake by Pontoporeia. Mercury can be even more toxic to animals when it is methylated. The amount of methyl

[1] Differences in activity were significant at $p = .02$, x^2 test.

mercury in the laboratory, lake or harbor sediments was not determined. We conclude that Pontoporeia can experience reduced activity and take up large amounts of mercury as a result of short-term (two-five day) exposure to sediments containing 0.6 mg/kg or more of available mercury. We interpret this as an adverse environmental effect.

During the bioassay, the Pontoporeia were subject to predation by sculpin for 24 hours. In 21 tests, using single sculpins, no apparent effect of mercury on Pontoporeia vulnerability to predation was determined. The low number of sculpin used and the unknown variability in their feeding habits limit the significance of these predation experiments.

The description and results of these laboratory experiments with Pontoporeia are discussed more thoroughly in Volume 3, Section III.

e. Mercury in Pontoporeia from the Lake.

Pontoporeia were collected from 11 stations in the lake near Duluth-Superior. Groups of 10-70 animals per station were analyzed for trace metals. These Pontoporeia had widely varying concentrations of mercury: 0.024-2.0 mg/kg (Volume 5, p. 118). The highest mercury concentrations were found in 40 animals collected from station MP near the south end of Minnesota Point. However, ten Pontoporeia at station 45, 19 km from the harbor had concentrations almost as high as station MP: 1.7 mg/kg of mercury. Pontoporeia in groups of 19-85 per station were collected from 11 locations near the Keweenaw Waterway. These animals had 0.14-1.0 mg/kg of mercury. The animals with the highest concentrations were collected close to the Upper Entry. The reasons for variations in the body burden of mercury in Pontoporeia within these two areas are unknown.

In both the Duluth-Superior and Keweenaw areas, there are Pontoporeia with concentrations of mercury that were considerably above the body burdens (0.1 mg/kg) of the Pontoporeia used as controls in the bioassay, but that were less than the 5-10 mg/kg and 12-100 mg/kg final concentrations in the laboratory animals which experienced behavioral changes. In three of seven lake sampling stations where the Pontoporeia in the lake had high body burdens of mercury, the sediments also had high concentrations of mercury. However, at two locations, high mercury sediments contained Pontoporeia with low mercury concentrations. The uncertainty of any correlation between sediment and Pontoporeia mercury concentrations may be due to differences in metal availability, animal mobility, or other unknown factors.

Pontoporeia could be a major source of mercury to fish through the aquatic food chain in some locations where sediment concentrations of mercury are high.

f. Biomagnification of Mercury in the Aquatic Food-Chain

Analysis of selected gamefish (whitefish, lake trout and burbot) and bottom feeding fish (suckers and sculpin) showed that mercury concentrates at higher values in higher orders of the Lake Superior food chain (Volume 5, p. 135). This biomagnification is an indication that pollution of Lake Superior by mercury-bearing sediments may lead to adverse effects throughout the ecosystem and may make mercury available to people who consume fish. The samples of flesh from the whitefish and lake trout had concentrations of mercury (converted to a wet weight basis) that exceed the 0.5 mg/kg limit set by the Food and Drug Administration (Volume 5, p. 104).

g. Mercury in Lake Sediments and Nearby Soils

Analysis of lake sediments showed that the clay-size fraction has variable concentrations of mercury near Duluth-Superior. Five lake sediment samples out of 13 samples had 0.17-0.67 mg/kg, three samples had 1.2-2.7 mg/kg and one sample (collected off Minnesota Point) had 4.22 mg/kg (Volume 5, Table 4).

The natural background level of mercury in the clay-size sediment fraction in the Duluth-Superior area is probably 0.1-0.4 mg/kg based on analysis of soil samples from nearby banks, from the minimum values found in lake sediments, and from lake sediment cores. Lake sediments in the Duluth-Superior area with higher than background concentrations of mercury in the clay-size fraction indicate probable cultural (man-made) pollution (Volume 5, p. 75-85).

h. Conclusions: Environmental Effects of Mercury

Short-term (two-five day) exposures of Pontoporeia to available forms of mercury at concentrations of 0.6 mg/kg and higher in sediments are likely to depress the activity of the animals and multiply their body burden of mercury. Increased amounts of mercury in Pontoporeia probably multiply up the food chain. Pontoporeia are an important element in the diet of Lake Superior fish. However, part of the uptake in fish may come from other food organisms and from the water. Mercury uptake by fish from Pontoporeia may already be occurring off Duluth-Superior in areas presently showing signs of mercury pollution in the sediments, and high values of mercury in some Pontoporeia.

Processes of re-suspension and advection cause fine sediment to settle out in deep water where the sediments are available to burrowing benthic animals. Mercury values of 0.1-0.4 mg/kg in clay-size dredged material can be considered natural concentrations in the Duluth-Superior area--adding no abnormal metal burden to the benthic system and providing some dilution if it is dumped in areas with higher existing mercury concentrations. Dredged material having concentrations of mercury 0.6 mg/kg or higher in the clay-size fraction may have some adverse effect if it is dumped in areas where the material becomes available to benthic animals before dilution by normal sedimentation occurs. Dredged material dumped in near-shore high energy zones with sparse benthic populations will likely be diluted with fine sediments from erosional and sedimentation processes before harmful concentrations reach the benthic communities. However, even with dilution, dredged material with higher than background values of mercury will place an additional cultural load of mercury on the lake environment.

3. Availability of Zinc

a. Zinc in Harbor Sediments at Duluth-Superior

EPA's 1975 analysis of Duluth-Superior sediments showed a wide range of zinc concentrations in whole sediment samples from 9-275 mg/kg in the Duluth Harbor Basin and 73-240 mg/kg in the Superior Harbor Basin. Earlier sampling (referenced on page 29) produced a similar range of values. EPA uses a range of concentrations for zinc guidelines. Harbor sediments with less than 90 mg/kg are considered unpolluted. Concentrations greater than 200 mg/kg indicate heavy pollution. Concentrations in between these values are considered by EPA to be moderately polluted (Robert Bowden, EPA, personal communication). Our harbor samples from 1973 and dredged material samples from 1975 contained total sediment concentrations of zinc within the range of EPA's 1975 samples.

b. Concentrations in the Fine Fractions of Sediments

Analysis of our harbor samples (S-III to S-IX) showed that zinc, like mercury, has the highest values in the fine sediments. Total sediment concentrations of zinc were 36-156 mg/kg but clay-size concentrations were higher, varying from 166-530 mg/kg (Volume 5, p. 17-22). The clay-size fraction was 3.6 to 24% of the total sample weight. Similar tendencies toward higher concentrations of zinc in the fine sediments can be seen in the three scow samples that had a measurable clay-size fraction (Table 7, page 62).

c. Zinc Uptake in Pontoporeia affinis

In the laboratory, Pontoporeia experienced an increase in their body burden of zinc when placed on sediments containing an initial zinc concentration of 128 mg/kg. Body burdens[1] increased from 90-100 mg/kg, initially, to 185 mg/kg at the end of two weeks (Volume 3, p. 95). Concentrations of zinc in the sediments decreased to 100 mg/kg over this period. Accumulation of zinc during two-day and five-day behavioral experiments showed similar increases in body burden (Volume 3, p. 90).

d. Effect of Zinc on Pontoporeia Activity

Zinc had an apparent effect on Pontoporeia activity in one of two sets of controlled behavioral experiments (Volume 3, Section III). Pontoporeia had a significantly lower rate of activity, as compared to control animals, when placed on sediments containing 58.5-123.5 mg/kg of zinc for five days. The number of active animals was the same in both control and zinc-enriched tanks. Zinc concentrations in the affected animals were 92-146 mg/kg at the end of five days, as compared to concentrations of 83-99 mg/kg in control animals. In shorter experiments

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[1] The initial sample was a composite of 30 (male and female). The final sample after two weeks was a composite of 20 females.

using sediment concentrations of 68-99.5 mg/kg of zinc and only two days exposure, there were no significant differences in activity or in number of active individuals, as compared to controls. Zinc concentrations in these Pontoporeia after two days were 89-150 mg/kg as compared to 65-79 mg/kg in the control animals (Vol. 3, p. 84). At the end of the two-day and five-day experiments, a 24 hour exposure to sculpin resulted in greater consumption of Pontoporeia in tanks with zinc-enriched sediment than in the control tanks, suggesting increased predation susceptibility of Pontoporeia to sculpin. However, the small sample size (15 sculpin) limits the significance of these results. The short (24 hours) exposure of the sculpin to the Pontoporeia and sediments did not yield a detectable change in metal concentrations in the sculpin.

e. Zinc in Pontoporeia from the Lake

The same groups of Pontoporeia from the Duluth-Superior and Keweenaw areas that were analyzed for mercury were also analyzed for zinc. The Pontoporeia from Duluth-Superior had fairly uniform body burdens which were within the zinc concentrations range of 65-99 mg/kg found in Pontoporeia used as laboratory controls during the bioassay. Pontoporeia from the Keweenaw area had a broader range and slightly higher concentrations of zinc: 63-142 mg/kg (Volume 5, p. 121-123). The animals with the highest body burden came from K7, a station 8 km west of the Upper Entry. A small fraction of the zinc (about 10%) was associated with the ingested sediments in the Keweenaw Pontoporeia.

f. Biomagnification of Zinc in the Aquatic Food Chain

Analysis of zinc in fish and Pontoporeia showed no indication of increased concentrations at higher levels in the Lake Superior food chain (Volume 5, p. 133).

g. A Comparison of Zinc Availability in Different Sediments

The results of tests comparing the availability of zinc in harbor, lake and bioassay sediments are described in Volume 5 (p. 94-98). These results show that all of the harbor and lake sediments tested have about the same tendency to release zinc in a soluble form. The in-lake disposal of dredged material from these harbor sites will not significantly change the concentration of soluble zinc in the water column or in the interstitial water, if placed in the areas from which our lake sediment samples were collected. Sediments used for the behavioral experiments in the bioassay released soluble zinc at concentrations hundreds of times greater than the soluble zinc concentrations obtained from lake, harbor and laboratory control sediments. There was a much smaller increase of zinc in the exchangeable phase of the behavioral study sediments. The increase in Pontoporeia's body burden of zinc during these experiments may have been due to the increase in soluble zinc.

h. Zinc in Lake Sediments and Nearby Soils

Analysis of the clay-size fraction in soils from Wisconsin red clay cliffs near Superior, lake sediments and a sediment core suggests that a zinc concentration of 180 mg/kg is an approximate background value in this size fraction for the Duluth-Superior area. A minimum value of 140 mg/kg and a maximum value of 230 mg/kg represent the range of possible background values determined for zinc in the clay-size fraction at Duluth-Superior (Volume 5, p. 75-83). Lake sediment samples from 13-21 km off Minnesota Point showed little or no indication of zinc pollution based on the 180 mg/kg background value (Volume 5, page 78). However, some sites less than 5 km from Minnesota Point (including three stations in the old Duluth disposal area) appear to be polluted with zinc with concentrations as high as 360 mg/kg in the clay-size fraction. A sediment core (S-2) collected 13 km from Minnesota Point had 201-233 mg/kg of zinc in the clay-size fraction of the top five centimeters and 154-191 mg/kg of zinc at depths of 25-33 cm (Volume 5, p. 71-74).

i. Conclusions: Environmental Effects of Zinc

As with mercury, the differences between laboratory conditions and lake conditions qualify our conclusions. The bioassays demonstrated that zinc in an available form in sediments can reduce the activity of Pontoporeia affinis and that they can increase their body burden of zinc during a short exposure of less than one week. Dredged material containing zinc with availability and concentrations in the fine fractions similar to natural sediments will probably add no additional zinc-related stress to the benthic communities. Dredged material containing high values of soluble zinc would have an adverse effect on the benthos and add an additional cultural load to an environment which shows signs of zinc pollution in some areas near Duluth-Superior.

4. Synergisms With Other Metals

It is possible for metals in combinations to have a greater adverse effect on organisms than the effect of each metal separately. The literature review in Section I,C of Volume 3 represents some synergisms which have been observed in studies of aquatic animals. Synergisms were not measured in the bioassay, and probably were of little importance in the experiments. Zinc concentrations in sediments used for controls and for mercury experiments were 13-26 mg/kg. Mercury concentrations in sediments used for controls and for zinc experiments were .01-.05 mg/kg. These concentrations are in the lower part of the range of total sediment concentrations found in the lake sediments.

5. Other Trace Elements and Pollutants

One potentially important pollutant that we did not analyze is lead. This element must be analyzed by atomic absorbtion. Our work focused on elements which can be measured by neutron activation techniques. Lead has been found in Duluth-Superior harbor sediments at total sediment concentrations ranging from less than 5 to 80 mg/kg (EPA, 1975). The EPA guideline concentration is 50 mg/kg.

Copper and arsenic were found at concentrations more than twice background values in some of the Duluth-Superior harbor and nearshore sediments (Volume 5, p. 47). These higher concentration are an indication of cultural influence. We found no evidence of biomagnification of copper, chromium, arsenic, cobalt or selenium in the food chain. Copper concentrations were relatively high in Pontoproeia (44-238 mg/kg) but much lower in the flesh of fish that were analyzed (Volume 5, p. 134). Variations in flesh concentrations of copper between sampled fish species was small, with values ranging from 1.9 to 2.7 mg/kg.

Duluth-Superior harbor has other pollutants which may have effects on the lake ecosystem. Phosphorous, oil-grease, volatile solids, chemical oxygen demand and nitrogen have been found in harbor sediments at levels greater than EPA guidelines. These data are summarized in the 1975 EPA report on the harbor. An assessment of the effects of these pollutants was beyond the scope of this contract. Additional research is needed to determine what effects these pollutants may have on the lake ecosystem.

6. Pollutants at the Keweenaw Waterway

The northern 2.5 miles of the Waterway was sampled by EPA in 1972. The first half mile of the channel inside the North Entry was classified as unpolluted. The other section was judged to be polluted with zinc and total Kjeldahl nitrogen (TKN). Copper is the dominant metal in local sediments, but no guidelines have been set by EPA for this element. Michigan Technological University's (MTU's) Aquatic Research Group sampled sediments in the Waterway and the adjacent coastal waters. They found total sediment concentrations of copper varying from 9-1310 mg/kg in the lake with an average of 117 mg/kg. All of their analyses were of total sediments only. Waterway sediments had a narrower copper range of 103-866 mg/kg but had a higher average value of 425 mg/kg. Background values of copper in Lake Superior sediments are about 30 mg/kg in the total sediment sample (MTU, 1975).

Zinc concentrations in MTU's lake sediment samples varied from 4-69 mg/kg with an average of 20 mg/kg. Zinc concentrations in the Waterway appear to be higher. Samples had 14-116 mg/kg of zinc, averaging 39 mg/kg. Some of these samples were within the range of 90-200 mg/kg of zinc, regarded by EPA as moderately polluted.

Most of the enriched levels of zinc and copper are attributed to large lakeside deposits of stampsands (tailings) from copper ore processing plants at Freda and Redridge, 13-18 km southwest of the North Entry. At Redridge, approximately 15 million metric tons of ore containing residual copper averaging 2500-3000 mg/kg was dumped in the lake or on the beach between 1895 and 1922. At nearby Freda, additional ore was processed and some Redridge stampsands re-processed between 1923 and 1968. Approximately 45 million metric tons of ore was processed at

Freda and Redridge during the period 1895-1968 and most of this material was either dumped in the lake or deposited on beaches at these two locations (MTU, 1975). The strong influence of these stampsands on coastal sedimentation near the Waterway is shown in maps of metal concentrations, sediment texture and mineralogy (Volume 2; MTU, 1975; Moore, 1975).

Analysis of local sediments for pollution parameters (other than metals) indicates that this region is little influenced by presently active sources of cultural pollution, judging by the EPA sediment guidelines. MTU analyzed lake and Waterway sediments for total volatile solids (TVS), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), and total phosphorous (TP). Values of TVS, COD and TP in Waterway sediments were within EPA guidelines. A maximum value of 1067 mg/kg for TKN in the Waterway slightly exceeded the EPA criteria of 1000 mg/kg (MTU, 1975).

Chemical analysis of 54 dredged material samples from the outer half mile of the North Entry channel showed that maximum values of TVS, COD, TP, and zinc were below the EPA criteria (MTU, 1975). Maximum TKN (1141 mg/kg) was slightly above the EPA criteria of 1000 mg/kg. The maximum copper concentration of 662 mg/kg was less than the maximum concentrations of copper in sampled channel and lake sediments. The Lily Pond area had the highest concentrations of TVS, COD, TKN, and the highest mean copper values compared to other channel areas (MTU, 1975). However, the maximum TVS, COD, and TKN values were all equal or lower than the EPA criteria in this area where fine sediments settle. There was no analysis of trace elements in the fine fractions of Waterway or adjacent lake sediments and no comparisons to background values in local soils to determine pollutional levels.

7. Pollutants at Other Lake Superior Harbors

The previous descriptions of pollutants in Keweenaw Waterway and Duluth-Superior Harbor sediments show that types and concentrations of pollutants vary from harbor to harbor. Natural, background values of trace elements may also vary from harbor to harbor. Aquatic organisms are generally considered to have adapted to local, natural conditions. Therefore, any evaluation of dredged material for potential adverse impacts on the ecosystem should consider the ratio of pollutant in the material to local, background concentrations.

Earlier sampling surveys in Lake Superior harbors indicate zinc is a pollutant at Presque Isle, Ashland and Ontonagon harbors (Corps of Engineers, 1974). Ontonagon, Big Bay and Cornucopia are harbors with mercury pollutants in the sediments (Corps of Engineers, 1974, 1975). Our evidence of mercury and zinc-induced effects on the behavior of Pontoporeia is applicable to these harbor areas, provided the concentrations of these metals in harbor or lake sediments exceed background values. An assessment of the effects of dredged material disposal on the lake ecosystem at these harbors requires benthic data from nearby areas of the lake. Earlier sampling of these harbors did not include enough benthic data to permit an informed assessment of the disruption of benthic communities by in-lake disposal at these sites.

B. Disruption of Benthic Communities

In-lake disposal of dredged material can have a disruptive influence on the relatively immobile benthic community. The disruption may include:

1. Temporary limited disruption due to a transient cloud of turbidity in areas adjacent to settling material.

2. Temporary or permanent loss of habitat on the dump site due to textural or chemical changes.

3. Burial and mortality of the existing benthic community on the dump site and adjacent areas.

Disruption of benthic communities can be observed by sampling the benthos before and after disposal of material on a controlled site. No in-lake dumping experiments were done at Duluth-Superior; therefore, predictions of benthic disruption must be inferred from information on the benthic community briefly described in the following section. An in-lake dumping experiment was done near the Keweenaw North Entry.

1. Benthic Communities Near Duluth-Superior

Densities and distributions of Pontoporeia, Oligochaetes (aquatic worms), Chironomidae (insect larvae) and Sphaeriidae (small clams) at Duluth-Superior are shown on maps in Volume 3, Section II. Average densities of Pontoporeia collected near Duluth-Superior for all collection dates (1973-1975) and all stations (2.5-140 m depths) were $278/m^2$. Other studies cited in Volume 3, Section II show average densities of Pontoporeia vary from $153/m^2$ in eastern Lake Superior to $878/m^2$ near the Apostle Islands. Differences in time of year and station depths may account for some of the data variation between these three areas.

The absence of Pontoporeia at some nearshore stations at Duluth-Superior in July, 1974 but not in September and October suggests an offshore migration in midsummer when nearshore waters are warmer. Pontoporeia were found at two stations in the harbor: stations IV and IX with densities of $19/m^2$ and $172/m^2$, respectively (Volume 3, p. 61). Station IV is in the South Channel of St. Louis Bay. Station IX is located at the entrance of Allouez Bay. These animals are considered to have a low tolerance for pollution. Their presence in the harbor may indicate that some areas of the harbor are relatively unpolluted or that these animals drifted into the harbor with the occasionally strong ship canal currents. The literature reviewed in Volume 3 indicates that Pontoporeia prefer fine sediments with detritus. This may be one reason for the higher populations in deeper areas offshore as compared to populations in shallower nearshore areas. Their absence in a narrow coastal strip, 1 km wide off the points may be due to a combination of unsuitably coarse substrate and high wave energy.

Chironomidae and Oligochaetes were abundant off the Superior Entry in July, September and October of 1974. The May, 1975 sampling showed complex distribution patterns with high concentrations off the Duluth and Superior Entries. Some species may be intolerant to pollution. Other species of these animals are known to concentrate in areas with high nutrient discharge. Their high numbers near the Entries indicate the influence of harbor-lake water exchange at these points. Very high concentrations of Oligochaetes are located near the Duluth sewage outfall in the harbor (Volume 3, p. 61).

2. Benthic Communities Near the Keweenaw Waterway North Entry

Pontoporeia are slightly more numerous near the Keweenaw Waterway North Entry, as compared to their numbers in the Duluth-Superior area. In MTU's sampling, considering all sample stations and three sampling periods: early summer, midsummer, and early fall, *Pontoporeia* averaged 331/m^2 (MTU, 1975). *Pontoporeia* were the most abundant organism in MTU's samples -- making up 67% of the total number of organisms present. Highest distributions of *Pontoporeia* were found in the deep area north of the North Entry. The highest number of *Pontoporeia* in a single sample was 270 (5100/m^2). Their abundance generally increases with distance offshore. Highest densities of *Pontoporeia* were found at depths of 50-55 m. Densities and percent occurrence were low at depths of 20 m or less off the North Entry and also off the stampsand deposits at Freda-Redridge. Statistical analysis indicated that the population of *Pontoporeia* is negatively correlated with sediment color, copper and possibly zinc (MTU, 1975). This animal is generally absent in the Waterway. A new offshore dump site was sampled before and during the period of dumping. Benthic sample analysis showed a reduction in the percent occurrence of *Pontoporeia* on this site, which may be attributable to the dumping (MTU, 1975).

Chironomidae are the second most abundant benthic organism in the Keweenaw area, constituting about 10% of the total organisms in MTU's sampling offshore. There is some indication that the organic content of the sediment controls Chironomidae distribution (MTU, 1975). Chironomidae include a number of species with different habitat preference. MTU's distribution maps show a bimodal distribution with population density peaks nearshore and peaks offshore in deep water.

Oligochaeta are also a diverse group of species, making up 10% of the total organisms in MTU samples. They are not abundant in the deep area north of the North Entry.

The abundance of Chironomidae and Oligochaeta did not appear to be affected by dredged material dumped offshore. However, the differing habitat preference of some species of these animals may have obscured any changes that did occur. Both Chironomidae and Oligochaeta are important members of the Waterway's benthic community; in MTU's samples, they constituted 50% and 43% of the total organisms, respectively. A reduced abundance of Chironomidae in dredged areas appeared to be caused either by physical removal or by the creation of an unfavorable habitat. Abundance in adjacent undredged areas remained the same (MTU, 1975).

MTU analyzed distributions of 15 benthic species from the Keweenaw area and found small numbers of 19 additional taxa. Analysis of total organism abundance indicated highest numbers in the deep area north of the North Entry and in deep water west of Agate Beach (Figure 3). The maximum abundance of total organisms appeared to be at depths of 38-53 m. A relatively barren area extended from Freda-Redridge offshore and along the coast to the east of these stampsand deposits.

3. Conclusions

Dumping of dredged material in areas of the lake which are densely populated by benthic organisms will probably cause high mortality of these animals within the area of rapid solids settling. If the dredged material is coarse to medium sand, there will likely be a permanent loss of suitable habitat, particularly for Pontoporeia which display a preference for fine sediments. Benthic areas adjacent to the area of highest sedimentation will experience lesser disruption from the dispersing cloud of dredged material, depending on the dynamics of the descending material. After dumping occurs, the cloud will expand due to entrainment of fluid as the material descends from the barge. When the cloud encounters a sharp temperature gradient (thermocline) or the bottom, horizontal spreading will occur (Volume 4, p. 8, 9). During the descent, solid particles begin settling out of the cloud on to the bottom below. The area beneath the dumping barge receives the heaviest sedimentation. However, local currents and turbulence, as well as thermal stratification cause spreading of the finer material out in all directions and increase the dispersal of fines over the benthic community. Fine material settling on the bottom may have a continuing effect on the benthic community if the depth is shallow enough for wave-induced water motion to re-suspend the material.

Disposal in shallow, high energy areas will avoid direct burial of nearshore populations of Chironomidae and other species. The effect of the fine dredged material moving into deeper areas and settling on denser, offshore communities will probably be similar to natural sedimentation processes, unless the fine fractions in the dredgings are polluted.

Disposal alternatives described in Section V consider the possibility of benthic community disruption by direct burial, dredged material re-suspension and transport of fine material from shallow water dump sites.

C. Changes in Sediment Texture and Mineralogy

Most potential dump sites off Duluth-Superior are subject to some sediment re-suspension from wave action and transport by currents. Sediment texture in a given area reflects the amount of energy recently present in that area. Areas of coarse sediment are generally areas exposed to high energy. Areas of fine sediment are usually identified with low energy regimes. Extensive sorting of sediments is another indication of strong wave and current activity. When dredged material is more poorly sorted and finer(or coarser) than sediments on available offshore dump sites, a textural match is not feasible.

In some situations like Duluth-Superior and the Keweenaw Waterway, nearby rivers or eroding coastlines cause large amounts of sediment to enter the lake (Table 5). Dredged material dumped in nearshore waters and the new sediments from these sources move towards sites where the particles will settle out in equilibrium with the dynamic forces of water motion. Adverse environmental effects may be caused by creation of new substrate surfaces unsuitable for benthic animals or spawning fish. Beneficial effects could result from the introduction of a substrate with more nutrients available to the benthic community. Dumping dredged material in locations where existing sediments and the material have equivalent textural and compositional characteristics insures that the substrate and its degree of mobility would remain the same. This matching of sediments and dredged material should reduce some of the adverse effects. It may also eliminate some beneficial effects of disposal.

Table 5

Estimates of Sedimentation

In The Western Lake Superior Region

Annual Rate (metric tons/year)	Source	Suspended Sediment or Total Sediment	Reference
132,000	1973 Corp of Engineers Maintenance Dredging at Duluth-Superior Harbor[3]	Total	Corps of Engineers[2]
345,000	1970 Dredging at Duluth-Superior Harbor[3]	Total	Corps of Engineers[2]
300,000	Douglas County Streams	Total	Sydor (1975)
100,000-300,000	Resuspension of bottom sediments in the Duluth-Superior area.	Suspended	Sydor (1975)
1,000,000	All Wisconsin Rivers	Suspended	Dudley (1973)
3,400,000	1963 Corps of Engineers New Work Dredging at Duluth-Superior Harbor	Total	Corps of Engineers[2]
5,600,000[1]	Shoreline erosion: Superior Entry to Bark Point, Wisconsin	Total	Hess (1973)

[1] Hess gives an estimate of 3.8 million cubic yards/year for the past 28 years. The tonnage figure here is based on a rough estimate of 1.48 metric tons/cubic yard.

[2] These tonnage figures are based on 1.36 metric tons/cubic yard of placed material listed in a record of dredging quantities prepared 10/30/67 by the Lake Superior Area Office for the OCE Pollution Study, Buffalo District Office.

[3] All dredged material was placed in the harbor disposal site.

The Aquatic Research Group at MTU studied the effects of poorly sorted dredged material dumped on a new dump site off the Keweenaw Upper Entry in 1974. Analysis of dump site sediments showed evidence that fine sand in the material spread lakeward after being dumped on the coarser grained sand and gravel at the dump site (MTU, 1975). Our divers noticed large mounds of sediment on this dump site soon after the dumping was terminated. These mounds were also observed on our side scan sonar in September, 1974. Seven months later, in June, 1975, we repeatedly towed divers on an underwater sled over the dump site, but failed to find any trace of these mounds. Wave action and currents probably dispersed the dredged material.

D. Increased Amounts of Fine Sediment in the Lake

Some Duluth-Superior harbor sediments contain large amounts of silt and clay. Sediments collected by EPA in 1975 had 2-44% silt and clay in areas classified for unrestricted in-lake disposal. Sediment samples from areas designated for restricted in-lake disposal had 40-78% silt and clay. Keweenaw spoil was primarily fine sand with some silt and clay.

In-lake disposal of fine sediment could extend the size or duration of turbidity plumes which occasionally occur off Duluth-Superior and the Keweenaw Waterway due to runoff, coastal erosion and re-suspension of sediments by wave action. The turbidity cloud associated with a descending mass of dumped material can be expected to spread rapidly in a horizontal direction. The very mobile, clay-size fraction in this material advected by currents could remain suspended for days, increasing the turbidity level of adjacent waters as it disperses. However, our observations indicate visible surface turbidity from a single scow dumping lasts up to five hours. High turbidity due to natural turbidity events at Duluth-Superior returns to normal levels in three to six days (Sydor, 1975).

The effects of turbidity from fine sediments on the ecosystem of Lake Superior are not known. Studies in marine ecosystems, referenced in Volume 2, suggest that items 5-9 listed at the beginning of this section IV, are some possible effects. Dr. William Swenson, University of Wisconsin-Superior, is currently studying the effects of turbidity on nearshore fish populations in Lake Superior near Duluth-Superior.

E. A Quantitative Comparison of Dredged Material Disposal and Natural Sedimentation

The potential magnitude of any environmental effects attributable to in-lake disposal is determined by the quantity as well as the quality of the material available for in-lake disposal. Both dredging and in-lake disposal activities should be viewed in the context of natural sedimentation processes. In the following sections, possible dredged material disposal in the lake is compared to inputs of sediment from streams, coastal erosion, and littoral transport. Comparisons are made in terms of tonnages, or in the analysis of turbidity: time.

1. Duluth-Superior

The potential quantitative contribution of dredged material to local sedimentation is significant at Duluth-Superior. Estimates of sedimentation from various sources are listed in Table 5. Annual maintenance dredging tonnages are sometimes more than the estimated annual load of total sediments carried by Douglas County streams, including the St. Louis and Nemadji

Rivers which empty into the harbor. The volume of dredging required by a major channel deepening project could be on the same order of magnitude as annual shoreline erosion from this region. This can be seen by comparing the large volume of "new work" dredging done by the Corps in 1963 to the estimated annual shoreline erosion from Superior Entry to Bark Point.

Quantitative comparisons must take into account sediment size and percentages of the different size fractions. The fine clay-size fraction was 0-24% of the total sample in 17 of our lake and harbor samples with an average of 7% by weight. In 13 samples collected by EPA in 1975 from areas classified for unrestricted in-lake disposal, the silt and clay ranged from 2-44% of the samples, averaging 20%. Harbor areas classified for restricted in-lake disposal had 40-78% silt and clay in eight samples, with an average of 61%. These fine materials are very mobile and may distribute over broad areas offshore.

The quantitative impact of in-lake disposal on local turbidity conditions can be demonstrated by comparing the duration of lake plumes to duration of scow plumes. Sydor (1975) estimates an annual occurrence of three to five large turbid plumes (each containing 5×10^4 metric tons of fine material) due to major storm events and six to ten smaller plumes (each containing roughly 10^4 tons of fine material). Assume that the duration of strong winds is 1.5 days during major plume events and 0.5 days during smaller plume events (See p. 96 in Volume 4). The dispersion of suspended material following a storm results in turbidity at Duluth-Superior dropping to near normal levels in approximately four days (Sydor, 1975). Based on these assumptions, the number of days each year when turbidity from lake plumes is higher than normal may approach 72 days.

In 1975, the Corps deposited 58,000 cubic yards of dredged material in the lake, near Wisconsin Point, averaging 1800 cubic yards per day (3 trips/day at 600 cubic yards per trip). The disposal activity required roughly 97 barge trips. We have observed surface turbidity from a single scow dumping to be visible for up to five hours after dumping. Assume that the turbidity from a dumping scow decreases in five hours to the same turbidity level that is reached four days after a storm - induced lake plume develops. The duration of turbidity from in-lake disposal at Wisconsin Point in 1975, based on the above assumptions, was 20 days. This is 28% of the estimated duration of storm-induced turbidity. From a quantitative point of view, it appears that the disposal of dredged material in the lake will add significantly to the duration of turbid conditions but over a much smaller area than the turbid lake plumes.

The amount of fine material in the four major and eight smaller plume events described above is estimated at 280,000 metric tons. Assume that 20% of the total dredged material placed in the lake at Duluth-Superior in 1975 was fine material similar in texture to the suspended material in the lake plumes. Also assume that 75% of the material in the lake plumes is new material introduced by natural coastal processes (Sydor, 1975). The 24,480 metric tons of fine sediment in the dredged material may have been 12% of the new material suspended in lake plumes at Duluth-Superior in 1975. Using the same assumptions for harbor maintenance dredging at 1970 levels; the percentage would be 42%, for new work dredging at 1963 levels; 323%, if all dredged material were placed in the lake. It seems unlikely that all dredged material would in the future be placed in the lake and not all the fines in dredged material can be expected to go into suspension during disposal. Nevertheless, fine silt and clay in dredged material can be a significant, quantitative addition to the lake if in-lake disposal is adopted as a strategy for maintenance and new work dredging activity.

2. The Keweenaw Waterway

Maintenance dredging at the Keweenaw Waterway North Entry is required almost every year to remove material deposited in the Waterway by the littoral transport system. Comparisons between dredging and the littoral system are shown in Table 6. The amount of sediment moving into the Waterway is a significant fraction of the material in the littoral transport system. Disposal of this sediment nearshore can be considered a simple return to the littoral system.

3. Other Lake Superior Harbors

The average annual quantities of potential dredged material are lower at the other ports as compared to Duluth-Superior and the Keweenaw Waterway. Port Wing (32,700 cubic yards) and Ontonagon (140,000 cubic yards) are the only other ports that had more than 10,000 cubic yards of harbor sediments removed between 1971 and 1974 in the St. Paul District (Corps of Engineers, 1974, 1975).

Table 6

Comparisons of Sedimentation Processes in Lake Superior Near the Keweenaw Waterway - North Entry

Annual Rate (cu. yds./yr.)	Source	Suspended or Total Sediment	Reference
26,265	Corps of Engineers Maintenance Dredging in the Waterway (average annual rate from 1950-1959)	Total	Corps of Engineers (1973)
88,450	1973 Corps of Engineers Maintenance Dredging in the Waterway	Total	Corps of Engineers (1973)
226,718 gross* 184,226 net*	Littoral Transport based on observation from 5/26/72-11/9/72 (167 days)	Total	Littoral Environment Observation Program (LEO, 1972)
365,000	Net transport extrapolated to an annual rate		Corps of Engineers
200,759 gross 87,670 net	Littoral Transport based on observation from 7/12/73-12/4/73 (145 days)	Total	LEO, (1973)
220,000	Net transport extrapolated to an annual rate		

*Gross transport is the total amount of sediment moved into and out of the observed littoral area. The net transport is the difference between the volumes of sediment moving up and down the coast. The LEO data gives a lower limit to the littoral transport since the periods of observation do not include many periods of storms, and cover less than half of the year.

V. Alternatives, Modifications and Recommendations

The alternatives for dredged material disposal are:

1. Contained or uncontained disposal on land.
2. In-lake dumping in deep areas beyond the re-distributing influence of wave action.
3. In-lake dumping in areas where the dredged material is texturally and chemically compatible with the sediment.
4. In-lake dumping nearshore for widespread dispersal or beach nourishment by wave and current action.
5. Dredged material disposal directly on the beach.

The desirability of any one alternative depends upon the nature of the dredged material and a combination of factors which must be considered. These factors are:

1. Proximity to water intakes.
2. Distance from the harbor and from shipping lanes.
3. Possibility of re-suspension and transport due to local currents and wave action.
4. Local turbidity conditions.
5. Environmental effects, including disturbance of benthic communities.
6. Economic feasibility.

The previous assessment of environmental effects emphasized the need for careful evaluation of disposal alternatives using the best criteria available. There are several criteria in the present EPA guidelines which should be modified.

A. Modified Criteria for Evaluating Dredged Material

1. Analysis of Fine Sediment

Analysis of our sediment samples shows that trace metals have the highest concentrations in the clay-size fractions of sediments. Other pollutants may show a similar tendency to concentrate in the finest fraction of harbor sediments. Chemical analysis of these sediments should include analysis of pollutant concentrations in either the pan-size or the finer, clay-size fractions.

Analysis of the clay-size fraction will give the best indication of cultural influences as compared to natural background values for each element. This recommendation and the justification for it are discussed more completely in Volume 5, Sections I and II. The clay-size fraction is also important because of its high mobility and eventual settlement in deep areas where benthic populations are relatively abundant.

2. Recommended Metal Concentration Guidelines for Dredged Material

a. Mercury

At Duluth-Superior, 0.2 mg/kg mercury in the clay-size fraction of sediments is the approximate background value determined from surface lake sediments, from a sediment core and from nearby coastal soils. Natural surface enrichment in the sediments and natural variations in local soils indicate a possible range of 0.1-0.4 mg/kg for background concentrations of mercury in the clay-size fraction. Sediments containing these concentrations should not be considered polluted with mercury. The evidence for these values is discussed in Volume 5 (pp. 75-85). Sediments containing more than the maximum background concentration of mercury in the clay-size fraction are probably polluted, and may cause adverse environmental effects if dumped in the lake.

A value of 0.6 mg/kg mercury or higher in the clay-size fraction of dredged material, harbor and lake sediments is a concentration of mercury sufficient to cause adverse effects in the lake ecosystem if the mercury is in an available form. The value was selected for three reasons. First, this concentration is 1.5-6 times the natural background value, strongly indicative of pollution. Second, a change in Pontoporeia activity was noted in the laboratory when the animals were exposed to sediments containing 0.6 mg/kg mercury. The behavioral change did not occur in Pontoporeia placed in control tanks without the mercury. We assume that a concentration of mercury at 0.6 mg/kg in the clay-size fractions of fine lake sediments will also be available to Pontoporeia in the lake and may produce similar results. We do not know how much of the mercury in Duluth-Superior harbor sediments is methylated or in an available form. These factors may influence the magnitude of behavioral changes or the exposure time required before adverse effects occur in the ecosystem. Third, the evidence of Pontoporeia ability to multiply their body burden of mercury in a short time of two weeks or less, plus the evidence of biomagnification of mercury up the aquatic food chain suggests that guidelines for mercury should be held close to background values in order to reduce additions of this metal to the lake. Guideline values for sediment mercury at Duluth-Superior should be between 0.4 and 0.6 mg/kg in the clay-size fraction.

For other areas of Lake Superior, the above values for mercury are recommended unless the local background values are higher. In such an event, the background value in the clay-size fraction should be used as a "no-pollution" value. Surficial lake sediments may not give reliable background levels because they are subject to previous pollution. Analysis of selected lake sediments, sediment cores and soils from local coasts and watersheds should be used to determine background concentrations of metals in other areas.

b. Zinc

At Duluth-Superior, 180 mg/kg zinc in the clay-size fraction of sediments is the approximate background concentration based on analysis of the same sediments and soils used to determine mercury values. As with mercury, natural surface enrichment and natural variability in sediment sources indicate a possible range of 140-230 mg/kg for background concentrations of zinc in the clay-size fraction of sediments from this area. Sediments containing more than the maximum background concentration of zinc should be considered polluted. Background values at other harbor locations may be different, depending on local soil conditions.

c. Copper

At Duluth-Superior, a copper concentration of 75 mg/kg in the clay-size fraction of sediments is the approximate background concentration. The range in background values is probably 65-88 mg/kg. These values are based on the same samples that were analyzed for mercury and zinc. Sediments containing more than the maximum background value should be considered polluted. Background values at other harbors may be quite different from those at Duluth-Superior.

3. Consideration of Fine Sediment Percentages

The potential for adverse environmental effects from metals in the fine sediments depends partially on the amount of this sediment in the dredged material. Trace metals have the highest concentrations in the fine sediments. There will be more pounds of metals entering the aquatic system in sediment with a high percentage of fines than in sediment which is mainly sand. Nine of 11 sediment samples we collected from Duluth-Superior harbor contained clay-size material ranging from 3-24% of sample weights. A small percentage of fine mercury-bearing sediment dumped in the nearshore shallows can be expected to disperse with other fine sediments discharged from local rivers, eroded from the coasts or re-suspended by waves and currents. The mercury-bearing dredged material will be diluted with natural sediments under these circumstances. Fine sediments dumped in deep waters may not experience dilution by natural sedimentation for several weeks or months, increasing pollutant availability to the benthos.

EPA's 1975 sampling of Duluth-Superior harbor included 21 samples from areas re-classified for some form of in-lake disposal. The pan fraction in these samples varied from 2-78% of each sample. The fine sand varied from 4-6%. Coarse to medium sand ranged from 16-90%. These wide variations suggest that within an area classified as polluted or moderately polluted, there may be some material unsuitable for in-lake disposal and other material which has beneficial uses, such as coarse to medium sand for beach nourishment.

Guidelines used to determine the suitability of dredged material for in-lake disposal should include consideration of the percentage of fine sediments in the harbor sediments being dredged. This may require some on-board testing of dredged material on a scow load basis during dredging.

B. Suitability of Duluth-Superior Harbor Sediments for In-Lake Disposal

A set of five dredged material samples collected from the Superior Harbor Basin in May, 1975 demonstrates the previous point that sediment from a single classified area may have different potentials for adverse and beneficial environmental effects in the lake. Table 7 shows the textural characteristics and the concentrations of mercury, zinc and copper in these sediments.

Table 7

Some Textural And Chemical Characteristics Of
Selected Dredged Material From Superior Harbor Basin

Sediment Size (Percentage by Weight)

Date	Sample Number	Medium to Coarse Sand[1]	Fine Sand[4]	Pan Fraction (Silt and Clay)[2]	Clay-Size Fraction[3]
5/21/75	H6	38.3	25.7	36.0	6
5/22/75	H7	26.6	30.1	43.3	7
5/23/75	H8	95.1	3.5	1.4	-
5/27/75	H9	92.2	7.0	0.8	-
5/29/75	H10	77.6	11.6	10.8	3

Metal Concentrations (mg/kg)

	Mercury		Zinc		Copper	
Sample Number	Total Sediment	Clay-Size Fraction	Total Sediment	Clay-Size Fraction	Sediment	Clay-Size Fraction
H6	.058±.003	.829±.006	71±3	194±3	28.3±.2	75.8±.5
H7	.038±.007	.58 ±.02	70±1	180±12	26.6±.2	71.3±.5
H8	<.01	---	32.3± .8	---	12.3±.1	---
H9	<.01	---	24±1	---	12.5±.1	---
H10	.02 ±.01	.97 ±.01	32±3	195±5	11.6±.1	78.5±.6

[1] Particles 0.25 mm diameter (2ϕ) or larger.

[2] Particles smaller than 0.074 mm (3.76ϕ) diameter.

[3] Particles smaller than 0.002 mm (2 microns) diameter which are part of the pan fraction.

[4] Particles between 0.25 mm and 0.074 mm diameter

Samples H8-H10 indicate an area (dredge cuts 8-13) which seems to be texturally suitable for beach nourishment since more than 75% of the material is compatible with mean grain-size on or near the beach at Minnesota Point (Volume 2, p. 19). In one of these three samples (H10), mercury is above background levels in 3-10.8% of the sediment. We assume that most of the mercury is restricted to the pan fraction which includes the clay-size fraction. The pan fraction will probably settle in deeper areas of the lake whether initial disposal occurs near the beach or in deeper areas of the lake. The small amount of pan fraction fines indicates that the relative adverse effects of turbidity and metal availability from sediments H8-H10 will be low as compared to samples H6 and H7.

Just 600 feet west of dredge cuts 8-13, we collected samples H6 and H7. These samples indicate that less than 40% of the material from dredge cuts 2-7 was suitable for beach nourishment. Also, there was a relatively high percentage of fine sediment (36-43.3%) in which pollutants might be concentrated. The clay-size fraction, while only 6-7% of the total sediment, was high in mercury concentration. These two samples indicate a higher potential for adverse environmental effects due to turbidity and metal availability to benthic organisms than do samples H8-10.

These scow samples came from five different scow-loads on five separate days. This random sampling represents more than just the surface sediments being dredged. These samples do not indicate the sediment variability which exists within a single scow load.

All of these scow samples were taken from an area recently classified by EPA as moderately polluted and suitable for "restricted" open-lake disposal (EPA, 1975). Under current EPA guidelines the following restrictions apply to moderately polluted sediments:

1. The amount of material dredged be minimized.
2. The material be disposed in as restricted an area as possible.
3. The material is covered with material dredged from an unrestricted area.

These restrictions indicate to us a necessity for disposal at depths where re-suspension or bed-load movement of the material is unlikely. Considering the pollutional classification of this part of the harbor, spoil from dredge cuts 8-13 would be unavailable for beach nourishment. Disposal of material from dredge cuts 8-13 in deep water might cause long-term textural changes.

EPA's classification of harbor sediments does not take into account the variations in sediment qualities within a classified area. Some of these differences in sediment characteristics are visible. The scows from which samples H6 and H7 were taken had very noticeable water retention in the hoppers while the scows were being loaded.[1] In contrast, samples H8-10 were collected from scows which had material piles that drained quickly. It may be feasible to develop an on-board testing procedure which evaluates each scow load on the basis of de-watering qualities and sediment texture. A size analysis of dredge spoil samples during loading of a scow could be helpful in deciding whether or not the material is suitable for beach nourishment or some other disposal alternative.

The mean grain size of seven other sediment samples collected in the harbor during this study was finer than that on the outer beaches of Wisconsin and Minnesota Points (Volume 2, p. 19, 24, 32). Dredged material from these areas appears to be unsuitable for beach nourishment, because of its relative fineness. One sample from the Allouez Bay Channel (IX) was coarser than the beach sediments.

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[1] Similar water retention has been noted in some scow loads at the Keweenaw Upper Entry (Photo on p. 39, Volume 1/4; MTU, 1975).

C. Alternate Disposal Sites at Duluth-Superior

The alternatives for dredged material disposal have changed in the past eight years. Until 1967, this material was used to create islands in the harbor, placed onshore, used for beach nourishment on the outer points or dumped offshore. Between 1968 and 1973 disposal was restricted to shallow harbor waters in the 21st Avenue Slip area. In 1974, disposal was not allowed at this location, and the 14,000 cubic yards of dredged material were dumped in the lake. In 1975, all dredged material was dumped in near-shore lake waters at the base of Wisconsin Point, or near Minnesota Point. Resamplingof the harbor by EPA in May, 1975, led to a re-classification of some harbor areas, permitting two forms of in-lake disposal: restricted and unrestricted. Other areas of the harbor remain classified as heavily polluted with confined disposal recommended. Restricted disposal involves burial of moderately polluted material with unpolluted material (EPA, 1975). To be effective, restricted disposal will require sites with low wave and current energy in order to avoid resuspension and removal of the polluted spoil or its protective cover. This requires disposal in deep areas having low current velocities near the bottom, where the sediments are below the influence of surface waves.

1. Offshore Dumping

Dumping of dredged material in deep areas of the lake will result in dispersion of an unknown percentage of the fine sand, silt and clay during the initial descent and collapse of the material on the lake-floor. The suspended material will disperse over a wider area under the influence of water turbulence and currents. Re-suspension of dredged material deposits may occur if sufficient wave energy exists to move the sediment.

The main source of wave energy at Duluth-Superior is wind-driven waves from the east northeast. Figure 32 in Volume 4 shows the approximate depth of wave influence varies from roughly 18 meters (for 20 mile per hour winds blowing more than 13 hours) to 60 meters (for 50 mile per hour winds blowing more than five hours).

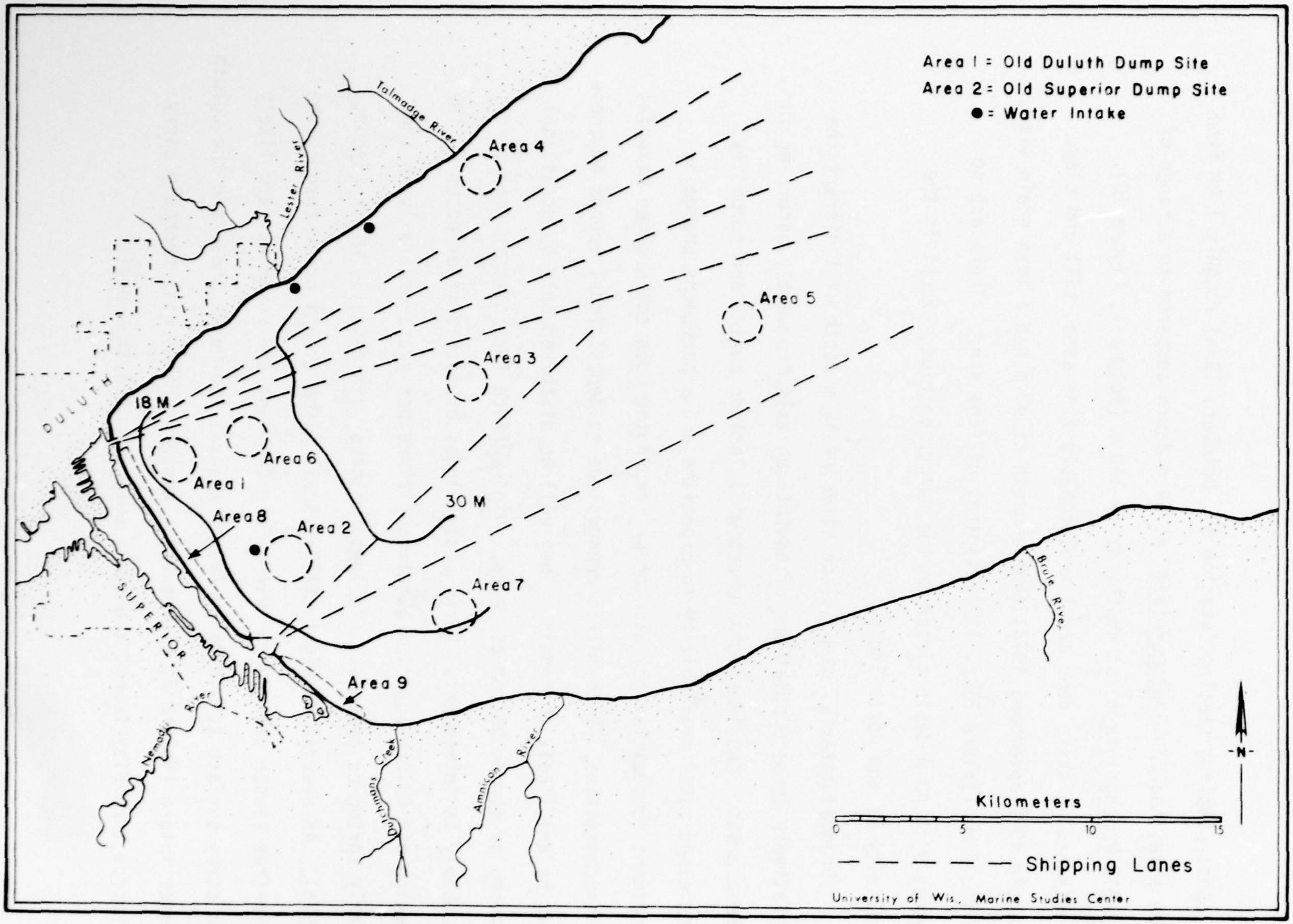
To avoid frequent re-suspension of fine sediments, dump sites deeper than 18 m are required, since east northeast winds occur 10-16% of the time in April, May, and June. In April and May, east northeast winds at the Duluth airport have average wind velocities of 18-20 miles per hour (Volume 4, Figures 18 and 20). Similar average velocities for east northeast winds have been recorded for November, December and February but the frequency of occurrence is lower (4-6%). Lake winds from the east northeast may have velocities considerably higher than the airport winds. Depths of 18 m can be found within 2 km of both Entries. The old dump sites off the Entries had depths of 18-24 m (Areas 1 and 2 in Figure 4). Table 11 in Volume 4 indicates that occasional east northeast storms generate storm waves sufficiently large to cause some water motion at depths approaching 38 m. In order to reduce the possibility of fine sediment re-suspension by waves during these occasional storms, in-lake disposal will require depths of water greater than 38 m.

a. Areas of 40 m Depth

One of the areas closest to the harbor with depths of 40 m is located 14 km from the Duluth entry (bearing 80° true), about seven km southeast of the Duluth water intake, and one km from the nearest shipping lane. This is Area 3 in Figure 4. The benthic population at this site is unknown. Our closest sampling station (station 51, October, 1974) roughly 1 km from the site, had 323 Pontoporeia/m^2 at 54 m depth compared to a range of 82-912 Pontoporeia/m^2 at depths of 44-140 m (Volume 4, Figure 10). Sediments in these deep areas are probably fine sand, silt and clay. Sample 40 (September, 1974) from a depth of 43 m had a mean grain size of 0.17 mm (Volume 2, p. 137), typical of fine sand. There are no areas with 40 m depth closer to the harbor entries, except in the vicinity of the North Shore.

Dredged material disposal on sites of 40 m depth will disrupt the relatively dense populations of benthic animals frequently occurring in these areas. The immediate impact will include burial and turbidity. Increased metal availability to organisms and a permanent change in sediment composition may also occur, depending upon the dredged material characteristics. Bathymetric changes due to depositional mounds at these depths are likely to remain. They will be disturbed only by occasional storms or strong bottom currents. High surface turbidity in Area 3 probably is infrequent. Large scale plumes of turbid water occur in the region off Duluth-Superior about four times per year, generally in the early spring or late fall, following storms with easterly winds (Sydor, 1975). An average of eight smaller-scale plume events occur through the ice-free season each year. Winds from the east and southeast are likely to carry surface turbidity in Area 3 towards the North Shore and the Duluth water intake (Volume 4, Figure 24). Westerly winds will probably carry surface turbidity toward the east, away from Duluth-Superior.

ALTERNATE SITES FOR DREDGED MATERIAL DISPOSAL NEAR DULUTH - SUPERIOR



b. Areas of 60 m Depth

Depths of 60 m or more are required for in-lake dredged material disposal if re-suspension by waves is to be avoided during rare storms when east northeast wind velocities are 50 mph or greater. The frequency and duration of 50 mph winds has not been determined. The closest areas of 60 m depth are a location 1.5 km off the Talmadge River, 17 km from the Duluth Entry (Area 4) and another area 22 km from the Superior Entry on a bearing of 55^{o} (true) (Area 5 in Figure 4).

The environmental effects of dredged material disposal in these areas are probably similar to the effects of disposal at 40 m depths. The Talmadge River site is only 4-5 km from the Duluth water intake. Coastal currents may bring suspended sediment from disposal operations on this site to the intake. The long distances from the harbor may make these 60 m deep disposal areas economically impractical. One alternative is to select a closer site where re-suspension will occur, but where there will be less disruption to the benthic community. There appear to be two areas which fit both of these conditions: Areas 6 and 7 in Figure 4.

c. Area 6 - Off Duluth Entry

Area 6, centered 5 km east of the Duluth Entry, in 24-27 m depths has a low to moderate population of Pontoporeia (100-300/m^2) and Oligochaetes (100-300/m^2) and low populations of Chironomidae and Sphaeriidae. Sediments are muddy sand. Surface current patterns indicate that sometimes there is in this area a counter-clockwise eddy created by winds from the east and southeast (Volume 4, Figure 24), which brings turbid water to the Cloquet water intake, 4.5 km from Area 6. Turbidity in this area is highest from late fall to early summer when the lake is isothermal (Sydor, 1975). Dumping of fine sediment in Area 6 would create initial and periodic turbid conditions that might affect the Cloquet water intake. If this area was used for disposal, burial of a moderately populated benthic community would occur with unknown initial mortality. The extent or rate of repopulation that would occur is not known. A high percentage of coarse to medium sand in the dredged material could permanently change the sediment texture, and probably reduce repopulation of this site.

d. Area 7 - Off Superior Entry

Area 7 (Figure 4) is located 7 km east northeast of the Superior Entry in 15-21 m of water. This area has low populations of Pontoporeia (0-100/m^2), Chironomidae (50-100/m^2) and Sphaeriidae (less than 10/m^2). Oligochaetes are found in moderate abundance (100-300/m^2). Sediments in the area are sand and rock. Surface current patterns indicate that fine dredged material, placed in suspension in this area, would move toward the east with a west wind. Suspended sediment would probably become entrained in an eddy off Superior Entry when east and southeast winds occur. A northwest wind moves surface water in Area 7 into a large clockwise eddy to the north of the area (Volume 4, Figures 22-24). ERTS satellite photos taken during five high turbidity events show relatively low turbidity in Area 7, as compared to adjacent nearshore areas (Sydor, 1975). If Area 7 were used for disposal, burial of a low to moderately populated benthic community would occur. The finer fractions of the dredged material would be resuspended by wave action and carried away in the currents. The bottom sediments in this area are frequently subject to wave action (Volume 4, Section V,E).

2. Beach Nourishment

Possible areas for beach nourishment are shown as Areas 8 and 9 in Figure 4. The following section describes beach nourishment first as a process of deposition on the beach and second as deposition near the beach. The St. Paul District currently uses the latter method.

a. Deposition on Minnesota and Wisconsin Points

Sand derived from the Wisconsin south shore is transported by wave action along the beach and in shallow nearshore water. This longshore sediment transport is the main source of sediment for the outer beaches on both points. The Superior Entry breakwaters interrupt this transport, causing an accreting beach on the Wisconsin side of the breakwater and accelerated erosion on Minnesota Point.

Area 8 is the beach and adjacent waters of Minnesota Point. The one kilometer of this beach adjacent and south of the Duluth Ship Canal has been severely eroded by wave action and blockage of longshore sand transport by the canal structure. In 1963, the Corps of Engineers dumped 270,000 cubic yards of dredge material on the beach to restore it. By 1970 the material had eroded away. There is evidence that fine, poorly sorted material in the deposit moved southward and out into the lake, causing some shoaling. No additional nourishment has been attempted at this site by placement of the dredged material on the beach. An evaluation of beach nourishment in this area is given in Volume 2 (p. 7-14).

Mean grain size on the Minnesota Point beach increases from .22 mm (fine sand) at the Ship Canal to .54 mm (medium sand) halfway towards Superior Entry. Beach material on Wisconsin Point near the Entry is medium sand with a mean grain size of .30-.47 mm. Deposited material containing sand, silt or clay particles finer than the beach sands could create a nuisance because of wind-borne transport or would move offshore due to wave action. Trace metals in the sediments or harbor organisms could become accessible to shorebirds feeding on the dredged material deposits.

b. Nourishment by Deposition Near Minnesota Point

The current method of nourishment used by the Corps of Engineers at Duluth-Superior is to move the loaded scows into shallow water about 4 m deep and dump the load. This method largely avoids the problem of wind-borne fines which occurs with placement of material on the beach. In 1975, the Corps dumped 32,000 cubic yards of dredged material south of the Duluth Ship Canal near Minnesota Point (Mueller, 1975). Nearshore sediments sampled in November, 1972, were mainly fine sand with a mean grain size of .18-.25 mm out to depths of 6 m (Volume 2, p. 19). Beach nourishment of Minnesota Point by nearshore dumping in depths of 0-10 m may be suitable when dredged material which is texturally similar to the beach sediments is used. Finer sand in the dredgings will move offshore, creating shoal areas which absorb some of the wave energy. This reduces the wave effects on the beach. Populations of benthic animals were very low in this area during our May, 1975 sampling. Population densities at four stations within one kilometer of shore were 6-32 Chironomidae/m^2, 6-13 Pontoporeia/m^2 and 19-108 Oligochaete/m^2 (Volume 3, p. 52-54).

Surface current patterns indicate that with east and southeast winds a counter clockwise eddy near the Duluth Ship Canal is present. Some offshore movement of the water near Minnesota Point is indicated during periods of west and northwest winds (Volume 4, Figures 22 and 23). Fine dredged material in suspension because of dumping or wave action will move offshore under any of these wind conditions. There is a possibility of suspended sediments from nourishment operations reaching the Cloquet water intake, 3 km offshore. Subsurface currents below the thermocline (depths greater than 9-24 m) move less frequently toward this intake than do the surface currents. (Sydor, 1975) Extensive, turbid plumes containing resuspended sediment and soil eroded from red clay bluffs along the south shore enter this area during periods of east winds (Sydor, 1975).

c. Nourishment by Deposition Near Wisconsin Point

In 1975, the Corps of Engineers resumed in-lake disposal at Duluth-Superior with nearshore scow dumping at the base of Wisconsin Point. An estimated 58,000 cubic yards of material was placed for beach nourishment (Mueller, 1975).

Nearshore currents in this area move along the shore towards Superior Entry with winds from the east and southeast. Eastward flow occurs with west and northwest winds. Fine, suspended sediments nearshore may enter a complex, large scale eddy in deeper waters offshore with winds from the northwest. With easterly winds, these sediments may move offshore into a smaller clockwise eddy east of Superior Entry, the finest fractions becoming part of a large turbidity plume. Nearshore areas from Wisconsin Point eastward are frequently turbid and have the highest concentrations of suspended solids. Populations of benthic animals appear to be low in this area (Area 9), according to samples collected in May, 1975 at three stations. Within 1 km off shore from Dutchman's Creek to Superior Entry, benthic population densities were: $0/m^2$ for Pontoporeia, $0\text{-}13/m^2$ for

Chironomidae and 19-38/m^2 for Oligochaete (Volume 3, p. 52-54). Water depths in this coastal strip are less than 10 m.

3. Conclusions

Tables 8 and 9 contain a comparison of the disposal sites discussed in the previous section, using a number of qualitative and quantitative factors.

a. Restricted Disposal

Restricted disposal requires accurate placement of both the polluted material and the covering layers of clean material at depths beyond the influence of wave action. The closest areas of suitable depth (60m) are Areas 4 and 5, 17-25 km from the harbor entrances. Accurate placement of dredged material will require electronic position measurements or a buoy array. The long towing distances will increase dredging costs, compared to nearshore disposal. The immediate and long term impact on the benthic communities in the disposal area would be significant, since these areas have relatively high population densities.

b. Beach Nourishment

Beach nourishment in eroding areas of Minnesota and Wisconsin Points is a potentially beneficial use for dredged material consisting of predominantly coarse to medium sand. Nourishment near Minnesota Point may occasionally create turbid water conditions at the Cloquet water intake if substantial amounts of fine sediment in the dredged material move 2-4 km offshore under the influence of winds from the northwest to southeast. Nourishment near Wisconsin Point is less likely to influence intake water quality. Both sites are suitable for short-term, high energy dispersion of small amounts offine-textured sediment. Disposal of predominantly fine

Table 8

Some Features of Alternate Disposal Sites in Lake Superior Near Duluth-Superior

	Historic Dump Sites		Deep Disposal Sites			Sites of Intermediate Depth		Nearshore Beach Nourishment	
Factors	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8	Area 9
Distance* to Closest Municipal/Agency Water Intake (km)	4.7	1.5	7	5	15	4.5	8	2.2-3.8	4.5-7.5
Distance* from Duluth Entry (km)	2.5	--	14	17	24.8	5	--	.5-9	--
Distance* from Superior Entry (km)	--	3.3	12.4	--	22	--	7	.5-9	.5-4.5
Minimum Distance from Nearest Shipping Lanes (km)	.5	1	1	1	2	.5	1.4	--	--
Frequency of Dredged Material Resuspension and Transport	frequent	occasional	occasional	rare	rare	occasional	frequent	frequent	frequent
Frequency of Local Turbidity Conditions	occasional	occasional	occasional	rare	occasional	occasional	frequent but low level	occasional	frequent
Probability of Disturbance to the Benthic Community	low to moderate	moderate to high	high	high	high	moderate	low to moderate	low	low
Anticipated Bathymetric Changes	short-term	short-term	long-term	long-term	long-term	short-term	short-term	brief	brief
Anticipated Changes in Sediment Texture	short-term	short-term	long-term	long-term	long-term	short-term	short-term	brief	brief
Water Depth (m)	20	25	40	60	60	25	20	5	5

* Note: Distances are to the center of the 1.8 km diameter areas: 1-6

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AN ASSESSMENT OF THE ENVIRONMENTAL EFFECTS OF DREDGED MATERIAL --ETC(U)
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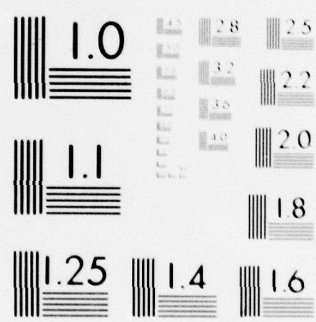


MICROCOPY RESOLUTION TEST CHART

Table 9

A Comparison of Several Possible
Lake Disposal Sites at Duluth-Superior

Qualitative Factor	Disposal Areas 1	2	3	4	5	6	7	8	9
More Than 5 km From Water Intakes			•		•		•		•
Low Probability of Turbid Water Transport to Intakes			•		•		•		
Within 8 km of Duluth Entry	•					•		•	
Within 8 km of Superior Entry		•					•	•	•
Low Probability of Disturbance to the Benthic Community	•						•	•	•
Beach Nourishment Possible								•	•
Desirable Features for Dispersal Strategy:									
Frequent, Local Turbidity From Coastal Processes							•		•
Frequent Sediment Resuspension	•	•					•	•	•
Desirable Feature for a Containment Strategy:									
Low Probability of Dredged Material Resuspension				•	•				

material in these areas will probably cause more turbidity than disposal at deeper sites as the fine sediment moves towards deeper water.

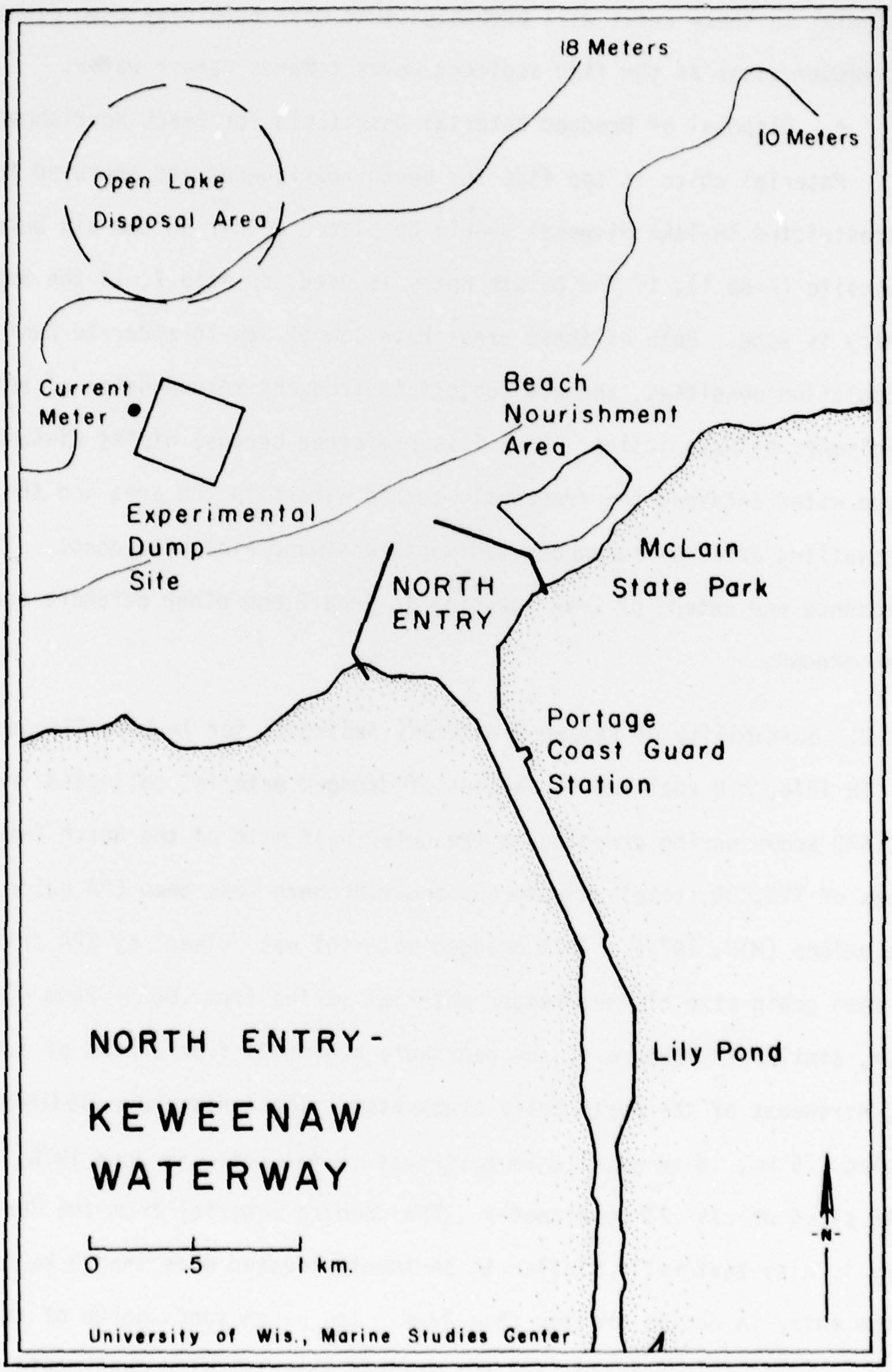
c. Disposal of Dredged Material Unsuitable for Beach Nourishment

Material which is too fine for beach nourishment and approved for unrestricted in-lake disposal should be placed either on the old Duluth dumpsite (Area 1), if the Duluth Entry is used, or Area 7, if the Superior Entry is used. Both of these areas have low or low-to-moderate benthic population densities, and are subject to frequent resuspension of bottom sediments by wave action. Area 7 is preferred because of its distance from water intakes, the frequently turbid waters in the area and the prevailing drift of suspended sediments eastward along the coast. The presence and extent of fish spawning in Area 7 and other offshore areas is unknown.

D. Suitability of Keweenaw Waterway Sediments for In-Lake Disposal

In 1974, MTU analyzed 54 samples of dredged material collected from GAILLARD scows during dredging in the outer half mile of the North Entry. Values of TVS,COD, total phosphorous and zinc were less than EPA guideline values (MTU, 1975). This dredged material was "clean" by EPA criteria. The mean grain size of the dredged material varied from .0625-.25mm diameter, similar in texture to the nearshore sediments from depths of 1.4-8 m, northeast of the North Entry breakwater. These nearshore sediments, sampled .25 km, .6 km and 1.3 km northeast of the entry in June 1975, had mean grain sizes of .14-.25 mm diameter. The dredged material from the North Entry is also texturally similar to sediments located more than 3 km north of the entry in depths greater than 27 m. The beach sands north of the entry are generally coarser than the dredged material with mean grain sizes ranging from .25-8.0 mm diameter.

80 (Figure 5)


18 Meters
10 Meters
Open Lake
Disposal Area
Current
Meter
Beach
Nourishment
Area
Experimental
Dump
Site
McLain
State Park
NORTH
ENTRY
Portage
Coast Guard
Station
Lily Pond
NORTH ENTRY-
KEWEENAW
WATERWAY
0 .5 1 km.
N
University of Wis., Marine Studies Center

In the Lily Pond harbor of refuge, sampled sediments had the highest values of TVS, COD, TKN, copper, and zinc in the 4.5 km of channel sampled south of the North Entry light (MTU, 1975). Values of TVS, COD, and zinc were below the EPA criteria. The maximum value of 1141 mg/kg of TKN slightly exceeded the EPA value of 1000 mg/kg. The highest total sediment concentrations of copper (679-866 mg/kg) were found in the Lily Pond, but less than the maximum concentrations found in the lake (909-1310 mg/kg) (MTU, 1975). Lily Pond sediments appear to be generally finer than other channel sediments and finer than nearshore and beach sediments. Mean grain sizes of sediments sampled at mid-channel in the Lily Pond were .038-.097 mm diameter. Elsewhere in the northern 4.5 km of the Waterway, mid-channel sediments had mean grain sizes ranging from .046-.43 mm (MTU, 1975). Lily Pond sediments are texturally similar to sediments located 4.8 km north of the entry (Volume 2, p. 57).

E. Alternate Disposal Sites Near the Keweenaw Waterway

The Corps of Engineers has used three methods of disposal at the Keweenaw Waterway North Entry area: offshore disposal, nearshore dumping for beach nourishment and on-land disposal. Until 1974, all dredged material was dumped in the lake; in 18 m depths northwest of the Entry (bearing 315°) or placed in 4 m depths adjacent to McLain State Park for beach nourishment. In 1974, 32,650 cubic yards from the outer half-mile channel was used for beach nourishment. A total of 60,800 cubic yards, from the outer channel and the Lily Pond, was placed on a new, experimental offshore dump site, 18 m deep, 1.3 km west northwest of the Entry. An additional 3,000 cubic yards from the Lily Pond was dumped on adjacent land (MTU, 1975).

1. Offshore Dumping

Dredged material can be dumped in shallow areas of the lake where wave action will re-suspend fine-textured sediments in the dredging and where local currents, combined with natural turbulence, will disperse this fine material. Disposal in deep areas will reduce the extent of dispersal and the likelihood of re-suspension.

Wave statistics from Eagle Harbor, 48 km northeast of the North Entry indicate a peak wave length of 113 m occurring one percent of the time from May to December (Volume 4, p. 51). The depth of wave influence (half the wave length), is approximately 56 m for this maximum wave condition. Eagle Harbor's exposure to wind-driven waves is similar to the exposure to wind-driven waves at the North Entry; therefore, these statistics provide an approximate picture of conditions at the North Entry. The Eagle Harbor data also indicate that a maximum wave length of 191 m (and 95 m depth of influence) can be expected once a year.

A wave hindcast for the North Entry, based on wind data from the nearby Portage Coast Guard Station, indicates that wave influence may have occurred as deep as 40 m[1] during some storm events between October, 1973 and July, 1975 (Volume 4, p. 52).

Comparisons of dredged material grain sizes, calculated wave-induced water velocities and published studies of sediment movement indicate that the wave action from the hindcast storm events was sufficient to move

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[1]This depth of 40 m is less than the depth of 56 m derived from Eagle Harbor wave data partly because the hindcast data give the average wave length of the significant waves (the highest 1/3 of the waves present) not the maximum wave length to be found.

unconsolidated portions of dredged material if placed in depths of less than 24 m (Volume 4, p. 53). Observations of the experimental Keweenaw dump site by divers soon after the termination of dumping in the fall and again the following spring suggest that large piles of dredged material at 15-18m depth disappeared during the seven month period.

The wave data provide some information for considering in-lake disposal sites disturbed or undisturbed by wave action. If future disposal options are to include burial of moderately polluted dredged material with "clean" material, a disposal site must be selected where potential re-suspension from wave action is unlikely. Disposal sites at 95 m depths would be free of wave disturbance. Disposal sites 40-56 m deep may experience occasional wave influence. If dispersal of dredged material is desired, nearshore sites in depths of 24m or less should be used.

a. Deep Areas North of the North Entry

The closest area to the North Entry, deep enough (95 m) to avoid wave influence on sediments is located about 6 km north of the Entry in silty sand. Several miles to the west and east of this area, sediments (including stampsands) move offshore from the littoral transport system (Volume 2, p. 67). Sediments in this area are finer than sediments in 54 dredge scow samples from the outer section of the North Entry channel (Volume 2, p. 57, 58, 119). The dissimilarity in texture could cause a permanent change in sediment characteristics if disposal occurred on this site. Fine sediments from the Lily Pond and other Waterway sections might have better textural compatibility. Populations of <u>Pontoporeia affinis</u> and total benthic organisms are high in this general offshore area as compared to other areas nearer the Waterway (MTU, 1975). Disposal operations in this area would probably be immediately disruptive to the benthic community due to burial, turbidity and changes in substrate. If the dredged material is considerably coarser than the existing sediments or if the material contains elements which are toxic to the benthos, the dump site may become a less suitable habitat for a relatively long time until natural sedimentation processes restore the area to predumping conditions. Conversely, organic matter in fine sediment placed on this site might constitute a favorable influence resulting in a short-term increased food supply for benthic animals repopulating the site after deposition has been completed.

Shallower areas of 40 m and 56 m depth are located about 4.8 and 5.5 km north of the Entry, respectively. Both of these areas have fine sand sediments. The finest fractions in the dredged material would be susceptible to occasional disturbance by storm wave action if the material is dumped in these areas. These two areas are texturally similar to dredged material from both sides of the North Entry channel (Volume 2, p. 120). Population densities of Pontoporeia are moderate to high at 40 m and 56 m depths. The highest density of Pontoporeia at depths less than 81 m was an average of 1170 organisms/m^2 for 15 samples from 50-55 m depth (MTU, 1975). Numbers of total organisms/m^2 were also high at these depths. The maximum abundance of organisms was found at 38-53 m depths offshore (MTU, 1975). Disposal operations at these two sites would probably be immediately disruptive to these relatively abundant benthic communities due to burial and turbidity. If the dredged material placed on these sites is generally comparable in quality to the existing sediments, the effects of disposal would probably be short-term and repopulation of the site could be expected after dumping had terminated.

The existing sediments in the three areas described in the preceding paragraphs show less influence from stampsands[1] than the nearshore sediments that move into the North Entry (Volume 2, p. 54). Since there is some evidence that the stampsands have had a negative influence on the nearshore benthic communities due to high copper levels (MTU, 1975), the disposal of material containing large percentages of stampsands may have an adverse effect on the benthic communities in these three deep areas.

Currents have not been measured in these areas. However, three maps of surface temperature gradients showing large scale thermal structure of the Keweenaw Current (Yeske, 1973) indicate that water movements in these three regions may be part of the strong current which develops in the summer months and sweeps along the west and north coast of the Keweenaw Peninsula. If this is true, then fine material, suspended during dumping on these sites would move primarily to the northeast and be widely distributed before settling to the bottom.

The three potential disposal sites described above are located one to two kilometers east of the Houghton to Isle Royale ferry route and about three to four kilometers from other shipping lanes.

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[1] identified by the basaltic lithic fragments characteristic of the stampsands (Volume 2, p. 39, 40).

b. Areas Shallower Than 24 m Depth

Our divers' observations and periodic monitoring of the experimental dump site sediments (MTU, 1975) indicate that disposal of dredged material at depths less than 18 m resulted in movement of the material and fairly rapid dispersal of fine sediments through wave action and local currents. The sediment dispersal patterns shown in Volume 2 (p. 65) indicate that sediments at depths of 15 m or less move in the longshore direction. Dispersal of stampsands from Freda and Redridge beaches has occurred towards the northeast (and the North Entry) and toward the southwest. There is some evidence of coarse sediments moving offshore, southwest and northeast of the Entry and an offshore movement of fine sediment at the Entry.

Fine sediment in suspension during dumping or sediments re-suspended by waves will move longshore with the current. Currents on the experimental dump site west of the Entry (Figure 5) moved predominantly towards the northeast on 43 days out of 60 days in June and July of 1974 (Volume 4, p. 31). A current towards the southwest was predominant eight days out of a 60 day period. If in-lake disposal occurred during northeasterly flow, initial advection of suspended material could be as much as 20 km/day (Volume 4, p. 55). Visual observations of dumping operations on June 3, 1974 suggest that turbidity generated by the dumping process is of short duration. Five hours after dumping, the turbid plume from the dumping was indiscernible (Volume 2, p. 106). Turbidity is common in nearshore areas after storms and heavy rains.

Areas with depths of 24 m are located less than 3 km from the North Entry. A site with 18 m depths, northwest of the Entry (on or adjacent to the old dump site) is texturally similar to dredged material from the northeast side of the Entry channel (Volume 2, p. 120). Two other nearshore areas within 4 km of the Entry having sediment texture compatible with the 1974 dredged material samples, are adjacent to and east of McLain State Park.

Nearshore benthic communities are sparsely populated near the North Entry. The density of Pontoporeia averaged 90 individuals/m^2 at 20-25m depths, 70 individuals/m^2 at 15-20m depths, and 25/m^2 at 10-15m depths. Shallower waters had 10-19/m^2 (MTU, 1975). Numbers of total organisms were also low in these areas throughout the sampling period between June and October 1974.

Disposal of dredged material in these nearshore areas will have an immediate disruptive effect on these sparsely populated communities and a possible delayed effect on more abundant populations offshore as the finer sediments move out into deeper water. The dredged material from the outer portion of the Waterway is similar in overall textural and chemical properties to sediments found in the lake. The environmental effects of this material on the ecosystem are probably similar to the effects of natural sedimentation processes when the material is dumped in the nearshore areas to disperse. Dredged material containing high concentrations of copper, zinc, and other possible pollutants in the fine fraction may cause more serious effects if this material drifts into benthic communities. There is some evidence to suggest that copper in stampsands dumped on the beach at Freda-Redridge has had an adverse effect on the abundance of benthic organisms, particularly Pontoporeia affinis, in some parts of the Keweenaw Area. A reduction in biomass and numbers of organisms was noted in areas where sediments had high copper values (MTU, 1975).

2. Beach Nourishment

All of the beaches studied south of the Entry increased in width from the fall of 1973 to November, 1974 (Volume 2, p. 67-75). North of the Entry, there was abundant evidence of erosion. An exception was a beach at McLain State Park that accreted throughout the study period, possibly because of nourishment from dredged material dumped in nearshore waters as part of the Corps of Engineers beach nourishment effort. This accretion was in contrast to the severe erosion of another McLain State Park beach one kilometer to the northeast. The different angles of the eroding and accreting beaches to the dominant wave directions and the influence of nearshore bathymetric irregularities on wave refraction may explain some of the differences in erosion on these two beaches.

Volume 2 (p. 101), describes a small scale beach nourishment experiment at McLain State Park, adjacent to the north breakwater of the North Entry. One cubic yard of dredge material was placed in the swash zone of the beach. Beach profiles and sediment textural analysis before and after dumping showed that the beach received a considerable portion of fine sediment from the dredged material but that texture and profile returned to pre-nourishment conditions in one day. This experiment showed that it is possible to create a sandy beach temporarily on a gravelly foreshore, but wind and waves soon remove the dredged material.

Dredged material which is finer than the beach sand (during a given season of the year) is not likely to remain if placed directly on the beach. Material dredged in June of 1974 and placed nearshore for beach nourishment would most likely have remained nearshore during the summer months of low wave activity, with eventual movement of the finest material into deep water north of the Entry or along the coast as indicated by Figures 38 and 70 in Volume 2 (page 65, 120). The environmental effects of this transport process are probably similar to those previously described for nearshore disposal at depths less than 24 m deep. The textural similarity of the nearshore sediments sampled in June 1975 to the dredged material placed on this site adjacent to McLain State Park in 1974 indicates that much of the dredged material remains nearshore.

3. Conclusions

Table 10 contains a comparison of the disposal sites discussed in the previous sections, using a number of qualitative and quantitative factors.

a. Restricted Disposal

Restricted disposal of moderately polluted dredged material in the lake near the Keweenaw North Entry would require an area with depths approaching 95 meters. The closest area with this depth is 6 km north of the Entry. This is about the same distance from the dredging site as the 1975 disposal area near Wisconsin Point was from the dredging areas in Superior Harbor. The accurate placement of clean material over polluted material will require a buoy array or electronic positioning. The immediate and long term impact of material dumped on the densely populated benthic community would probably be substantial. This disposal strategy seems undesirable, and should be attempted only if in-harbor disposal of moderately polluted material is not possible.

b. Beach Nourishment

Beach nourishment by nearshore disposal at McLain State Park is a beneficial use of the littoral material which characterizes the outer half mile of the North Entry channel. Fine sediment will disperse, following normal sediment distribution patterns. It may be feasible to extend the nourishment area to the eroding beaches of the park, northeast of the Entry.

c. Disposal of Dredged Material Unsuitable for Beach Nourishment

Material which is too fine for beach nourishment and which is approved for unrestricted in-lake disposal should be placed at depths less than 24 m deep where benthic populations are low and where dispersal of fine sediments will follow similar distribution patterns to the sediment in the littoral drift. The area of the old dumpsite is an obvious choice for continued disposal because of its continuing textural similarity to dredged material from the outer part of the Entry channel.

In-lake disposal of dredged material which is qualitatively different from sediments in the littoral transport system should be avoided if possible to reduce the introduction of pollutants to the lake environment. The sediments from the Lily Pond area appear to be generally finer, with higher copper concentrations than the sediments deposited in other, adjacent areas of the Waterway channel. In-lake disposal of this material should be avoided unless the adverse environmental effects of alternate disposal strategies appear to be greater than the anticipated effects of lake disposal.

Table 10

A Comparison of Disposal Sites at the Keweenaw North Entry

Characteristics	Disposal Areas: 95 m Depth	40 & 56 m Depths	Historic Dump Site	Nearshore at McLain Park
Within 6 km of the Entry	•	•	•	•
Within Normal Littoral Sediment Transport Patterns			•	•
Low Probability of Disturbance to the Benthic Community			•	•
Known Beneficial Uses				•
Sediment Texture Similar to Dredge Material		•	•	•
Desirable Feature for a Dispersal Strategy:				
Frequent Sediment Resuspension			•	•
Desirable Feature for a Restricted Disposal Strategy:				
Low Probability of Spoil Resuspension	•			

VI. Short-term and Long-term Effects of Dredged Material Disposal in Lake Superior

The dredging of harbors and waterways on Lake Superior has gone on for many years and will need to be continued as long as significant shipping is carried on in that lake, therefore, the disposal of spoil is a long-term requirement. The trend in Great Lakes shipping is toward larger, deeper draft ships. This trend suggests that dredging activity at major harbors like Duluth-Superior will increase in the future. The possibility of larger quantities of dredged material in the future increases the importance of economical and environmentally suitable methods and locations for disposing of this material.

At present, the disposal of material in Lake Superior is governed by Federal Water Pollution Control Act Amendments of 1972 (PL 92-500). The Corps of Engineers has authority to regulate in-lake disposal in accordance with guidelines put into effect by the U.S. Environmental Protection Agency (EPA). Since discharges of dredged material into Lake Superior are potentially discharges of pollutants, and are increased loadings of the lake with natural sediment, state regulatory agencies are also involved because of state water quality laws (FWPCA, 1972).

The guidelines are used by EPA to classify harbor areas as; heavily polluted, moderately polluted, or unpolluted, depending on the results of sediment analysis and elutriate tests. The designation "polluted" is defined in terms of concentrations of specific substances in the sediment, chemical conditions in the sediment and the potential release of soluble elements to the water column. There have been very few attempts to determine if the substances (or elements) in the sediments will in fact have short-term or long-term effects on the Lake Superior ecosystem.

In considering lake disposal of dredged material the questions of irreversible damage to the lake or its biota, hazards to human health due to contamination of either the water or fish used for human food, and the creation of major aesthetic nuisances must be addressed. If any of these effects is likely to occur, then the environmental cost of in-lake disposal is clearly too high and is unacceptable.

Lesser effects such as temporary disruption of benthic organisms in limited and local areas, transitory turbidity in offshore areas, or minor and local increases in non-toxic dissolved substances do not fall into the irreversible, human health, or serious nuisance categories and should not be considered as contributing to the long-term impairment of environmental quality or productivity. Dumping of dredged material in critical areas such as fish spawning areas or upcurrent from domestic water supply intakes is clearly unacceptable, but these and similar hazards are easily avoidable by prudent selection of pre-surveyed dump sites, assuming that the locations of water intakes and fish spawning grounds are known.

In-lake disposal of dredged material is an attractive short-term alternative because of the low economic costs associated with this method and because some of the material can be used to temporarily reduce the erosion of nearby beaches. In 1974, the Corps of Engineers estimated that dredging with in-lake disposal cost approximately $2.00 per cubic yard of material and that contained on-land disposal could increase the cost to $6.00-$10.00 per cubic yard. (Corps of Engineers, March, 1974). In-lake disposal was commonly used until 1968, when sediments in some harbors including Duluth-Superior were declared polluted by EPA. Subsequent disposal occurred within this harbor, in an unconfined, shallow water area.

In-lake disposal of dredged material at Duluth-Superior may have contributed to some long range changes in the Lake Superior ecosystem near Duluth-Superior. Our analyses of lake sediments from the old Duluth dumpsite and off the south end of Minnesota Point show evidence of probable trace metal pollution in these areas of past dredged material disposal. However, other areas af far as 19 km from the harbor also show signs of trace metal pollution. It is impossible to identify the sources of these polluted sediments. The evidence indicates only that the presence of human activity in this area has led to an increase in sediment metal concentrations above the background values found in local soils and sediments.

Some of the Pontoporeia from high mercury-bearing lake sediments have high body burdens of mercury (1-2 mg/kg) which are within the range of mercury uptake observed to have an effect on Pontoporeia behavior in the laboratory, indicating that mercury already present in lake sediments near Duluth may be having a long-term adverse effect on the activity and health of the benthic communities in this area. The ability of Pontoporeia to multiply their body burden of mercury, and the high levels of mercury (exceeding FDA levels) in the flesh of game fish which feed on Pontoporeia when the fish are young, are evidence that mercury in sediments may be one source of mercury to people who eat these fish. This transfer of mercury through the food chain is a long-term effect on a time scale of years.

Two sites (19, 21) had high concentrations of mercury in the clay-size sediments (1.23, 1.37 mg/kg) and large numbers of Pontoporeia (684, 804/m^2), but low mercury values in the Pontoporeia (.09, .10 mg/kg). Station 51 (October 1974) had a slightly enriched concentration of .6 mg/kg mercury in the clay-size fraction, a moderate population of 323 Pontoporeia/m^2 and a high concentration of .97 mg/kg mercury in the Pontoporeia. There are several possible conclusions that can be drawn from this evidence:

1. Pontoporeia do not avoid sediments containing high mercury concentrations.
2. The sediment mercury at stations 19 and 21 was in an unavailable form.
3. The Pontoporeia at stations 19 and 21 recently moved into these sites.
4. Some reduction of Pontoporeia population densities occur where there is evidence of mercury uptake as at station 51.
5. The effects of mercury on Pontoporeia behavior and health are less severe in the lake than in the laboratory.

Of these five possibilities, 1, 2, and 4 seem most likely. However, the number of sites sampled is insufficient to develop correlations between mercury concentrations in sediments, mercury concentrations in Pontoporeia, and population densities of this animal. Undoubtedly other characteristics of the benthic habitat are also important factors.

In spite of heavy sedimentation with red clay of low metal content from the adjacent Wisconsin shore, surface sediments near Duluth-Superior remain high in metal concentrations in some areas. This may indicate that the transfer of trace metals from the harbor to the lake sediments is continuing without the assistance of in-lake dredged material disposal or that the dilution of previously-deposited spoil with high metal concentrations by red clay sedimentation is a slow or ineffective process. Pollution from a source outside of the harbor is also a possibility. Unfortunately, there are no earlier data to indicate if there has been an improvement in lake sediment quality since in-lake disposal was suspended in 1968. In any case, existing high concentrations of mercury above background values in some sediments and in some Pontoporeia affinis suggest that polluted sediments are now and will continue to be a long-term source of mercury to the local ecosystem and to man in the Duluth-Superior area. We do not know the areal extent of polluted sediments, the pollutional source(s) or how extensively uptake by Pontoporeia occurs.

In-lake disposal of fine textured material with high metal content should be considered an undesirable addition to the ecosystem. There is some potential for long-term alteration in the organic productivity and health of the benthic communities, which will, in turn, affect the fishes that depend on them for food, and possibly will affect the health of humans who consume fish.

Some of the dredged sediment we analyzed is coarse sand, with essentially background levels of metals. This type of material has the potential for beneficial short-term usage as beach nourishment material and very little possibility of long range adverse effects.

Some dredged material (fine sediment with low metal content) will not fit either of the previous two categories. If placed in the lake, this material may cause some short-term effects due to turbidity, other pollutants such as pesticides, PcBs, petroleum hydrocarbons or temporary disruption of the benthic community. The long-term consequences are not clearly evident at this time. We did not analyze sediments or organisms for pollutants other than trace elements.

With careful material analysis and selection of disposal alternatives some types of dredged material can be placed in the lake at Duluth-Superior with a low risk of long-term consequences. Continued in-harbor disposal (preferably contained disposal) will be required for fine textured, polluted material if the long-term impairment of biological productivity is to be avoided.

In the Keweenaw Waterway area, deposits of stampsands, refuse from copper mills, are the largest source of trace metals. Some 50 million tons of stampsands containing high concentrations of copper (2500 mg/kg or greater) was deposited on the lakeshore at Freda and Redridge, 15 km southwest of the North Entry between 1895 and 1968 (MTU, 1975). Much of this material has moved into the lake and has been distributed in the littoral transport system. The large remaining deposits of stampsands which are spread along 20 km of coast will be a major source of trace metals in this area for decades and possibly centuries to come.

Sparse populations of benthic organisms in coastal areas near Freda and Redridge indicate that the high-copper bearing stampsands may be having an adverse effect on the local ecosystem (MTU, 1975). The known toxicity of copper in other aquatic systems (Marine Studies Center, 1974) is an added reason for concern about the effects of stampsands. Prior use of the lake as a convenient dumping ground for copper tailings was a short-term advantage which is probably having long-term consequences to the lake ecosystem.

Up to the present, littoral material which has moved into the North Entry of the Waterway was dredged and dumped nearshore in depths of 4-20 m--returning the sediment to the littoral and nearshore environment. A halt to this practice will not enhance the lake environment because the stampsands at Redridge and Freda continue to move into the lake and are distributed in the natural littoral transport system. Disposal of dredged material in deep areas, or in-lake disposal of fine textured, polluted sediments from inner portions of the Waterway can be considered as actions which are not similar to natural sediment dispersal processes and are actions with some potential for adverse environmental effects. These effects include permanent changes in substrate by introduction of coarse, littoral material unsuitable for habitat, or effects from exposure of the benthos to polluted sediments. Onshore disposal or nearshore disposal with subsequent littoral dilution would be preferable alternatives to offshore disposal in deep areas. Disposal of dredged littoral material from the North Entry containing large amounts of stampsands in areas beyond the littoral transport zone could also be detrimental. In these areas, stampsands are presently a smaller part of the sediments than in the littoral zone.

Determination of what is detrimental requires some knowledge about the animals in the lake ecosystem. Pollution intolerant organisms like Pontoporeia affinis are sensitive to changes in sediment (and possibly water) quality. Changes in the distributions and trace element body burdens of these organisms can give an early warning of subtle changes in the lake ecosystem. Our benthic sampling and subsequent analysis provide a modest baseline for detecting future changes in trace element concentrations in sediments and Pontoporeia affinis. Bioassays, such as were performed in this study, should be used to interpret the significance of changing lake conditions and to predict the long-term consequences of actions like dredged material disposal. Since our bioassays included only the metals mercury and zinc, the results are more useful for predicting effects of dredged material disposal at Duluth-Superior than at the Keweenaw Waterway, where sediment copper is dominant. Bioassays with sediment copper and Pontoporeia having low body burdens of the metal would give information on the rate of accumulation and the behavioral effects due to copper uptake. This information could provide some insight into what has occurred in coastal areas of the Keweenaw Peninsula where stampsands have been prominent, or what would occur if dredged material with high copper content was placed in new benthic areas where prior exposure to copper was low. Other organisms which may prove useful in bioassays are phytoplankton, zooplankton, fish or birds.

It can be argued that the very addition of solid material to Lake Superior constitutes an undesirable long-term effect. However, most of the material dredged from harbors and waterways was either derived from sediment transport in the lake itself or would have ultimately reached the lake as river-borne sediments if the harbor had never been constructed in the first place. Based on this line of reasoning, in-lake disposal of dredged material is simply the continuation of existing natural processes through human activities. In short, the idea that in-lake disposal of dredged material from existing harbors and waterways will accelerate the filling in of Lake Superior is not defensible.

Due to the immense volume of Lake Superior, it has a very large capacity for diluting and assimilating any material added to it which is a major asset to man's use of the lake. As the nearly pure headwater of the Great

Lakes, Lake Superior also constitutes an important source of diluting water for the other four more heavily used and pollutant-loaded Great Lakes. However, Lake Superior's relatively small watershed combined with its role as the headwater for the entire chain of the Laurentian Great Lakes place special responsibilities on man's contemplated uses of the lake. From the average outflow of the lake and its volume, it can be calculated that the water is replaced once every 183 years. But if some conservative (i.e. dissolved and biologically inactive) material is added to the lake and if this substance undergoes complete mixing within the lake, then it will require nearly 500 years for 95 percent of this substance to be removed at the present mean rate of outflow. In terms of our industrial culture's time scale, the removal from Lake Superior of mixed material such as dissolved pollutants is so slow that additions of pollutants to the lake can be considered an irreversible change.

Conversely, it can be stated that if a small amount of a conservative substance is added to Lake Superior each year, the concentration in the lake will increase very slowly and that it will require 500 years for the lake to reach 95 percent of its ultimate equilibrium concentration. In short, Lake Superior responds very slowly to the addition of any conservative pollutant, but once it is degraded it will require a very long time to cleanse itself.

These characteristics - long flushing time and headwater source - impose special responsibilities to guard against long-term additions of foreign substances to Lake Superior and to monitor water quality with an accuracy and precision barely possible with present day analytical techniques. Bioassays and water quality analysis are two of a variety of techniques and tools which can be used to detect and measure changes in the inherently stable environment of Lake Superior. It is important to note, however, that the availability of these techniques means nothing unless they are used and used systematically. It is further worth noting the elementary and self-evident fact that changes cannot be detected without a baseline from which to start.

It follows from the previous discussion that the maintenance and enhancement of long-term environmental quality and productivity of Lake Superior, however desirable, cannot be ensured by simply setting concentration standards for material being added to the lake. The actual fate and effects of the materials on the lake itself and its biota must be determined. In addition, the imperfections of these short-term measurements must be recognized. The lake and its biota must be kept under surveillance for long-term changes by careful and systematic monitoring of the lake as a whole and of particular regions where local changes may signal future larger scale changes.

The relationship between the short-term use of the lake environment and the maintenance and enhancement of its long-term environment quality and productivity is complex. In the case of Lake Superior, long-term changes are difficult to forecast and almost as difficult to detect even after they have begun. Recognition of this situation points inexorably to the need for extreme care in investigating potential effects of materials added to the lake, some of which are addressed in this report and to the need for on-going monitoring of the lake itself in order to detect unforeseen changes. This admonition applies not only to dredged material but also to the addition of any material to this priceless lake.

VII . Bibliography

VII. BIBLIOGRAPHY

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