

**A PRELIMINARY ASSESSMENT
OF SUBAQUEOUS TAILINGS
DISPOSAL IN MANDY LAKE,
MANITOBA**

MEND Project 2.11.1a-d

March 1990

A Preliminary Assessment of Subaqueous Tailings Disposal in Mandy Lake, Manitoba

Prepared and Funded by:

**British Columbia Ministry of Energy,
Mines and Petroleum Resources
CANMET
Environment Canada
Hudson Bay Mining and Smelting Co., Ltd.**

Prepared by:

**Rescan Environmental Services Ltd.
Vancouver, Canada**

March 1990



EXECUTIVE SUMMARY

A preliminary field assessment of long-term subaqueous disposal of reactive mine wastes in Mandy Lake, Manitoba was conducted as part of the Mine Environment Neutral Drainage (MEND) program. Mandy Lake received approximately 73,000 metric tonnes of high-sulphur-base metal tailings discharged from a single launder into the lake during 1943-1944. An examination of the lake in 1975 found that natural revegetation of tailings in the shallower areas had occurred. The water quality was considered good, and aquatic vertebrates and invertebrates had moved into the tailings area.

Mandy Lake is a small lake (area = 239,000 m²) situated in the Precambrian Shield near Flin Flon, Manitoba. The lake, originally part of Schist Lake, was isolated by construction of a causeway. Mandy Lake is shallow (mean depth = 3.6 m) with a maximum depth of 5.5 m. During the study, lake inflow and outflow was minimal. No thermocline was observed in the water column, but low dissolved oxygen concentrations (anaerobic conditions) were found below 2.0 m depth. The high biological productivity (mesotrophic to eutrophic conditions) of the lake has created sediments with high organic content and high sediment oxygen demand.

Lake water quality was similar at all stations and depths. The lake has moderate hardness with conductivity, dissolved solids, and alkalinity values comparable to other Manitoba lakes. The pH is slightly basic. Chloride, sulphate and reactive silicate concentrations are low. Dissolved metal concentrations are low with minimal differences between surface and bottom samples indicating that metal release from the sediments is minimal. Moreover, higher metal concentrations were found in inflow waters than in the lake itself.

Elevated metal concentrations were found in the lake sediments, particularly for arsenic, copper, lead, mercury and zinc. However, decomposition of the thick organic layer overlying the sediments appears to maintain anoxic conditions, thereby reducing the potential for sulphide oxidation and subsequent release of acid-soluble metals. Detailed petrographic, X-ray diffraction (XRD), X-ray fluorescence (XRF), particle size and leaching analyses were also performed to characterize the sediments.

The results of this detailed analyses indicated an abundance of organic material including diatom frustules. Tailings were dispersed throughout the lake sediments with XRD scans detecting quartz, pyrite, feldspar and chlorite in the sediments. The XRF analyses indicated a possible mineral composition of quartz, plagioclase feldspar, micas, chlorite and pyrite in the sediments. Trace proportions of framboidal pyrite and rare examples of spherulitic chalcopyrite and sphalerite were found. Leaching results using a sequential extraction technique of sediment samples (Station 3) exposed to oxidization indicated high release of cadmium, zinc, nickel, cobalt and manganese in the water-soluble and exchangeable phases. As water quality results did not indicate metals release from the sediment, the results are more indicative of potential release under aerobic conditions. Releases of iron, arsenic, lead and selenium occurred under moderate to strong reducing conditions. Strongly oxidizing conditions released silver, copper, lead, zinc and nickel and the residual phase released aluminum, iron, manganese, arsenic, cobalt, mercury, nickel and zinc. Total concentrations of aluminum and iron were high in the residual fraction followed by lesser amounts of zinc and arsenic.

Lake biota were examined in considerable detail. Benthic invertebrate densities are low and the community is dominated by oligochetes and dipteran larvae. Phytoplankton density and community structure

characterize the lake as mesotrophic to eutrophic with higher densities than two oligotrophic lakes situated nearby. Diatoms are the predominant phytoplankton. Zooplankton densities are slightly lower than other Manitoba lakes and the community is dominated by rotifers, cladocerans and copepods.

Aquatic vegetation in the lake was mapped and samples collected for metals analyses. Since 1975, the vegetation community in the tailings area has become more diverse and comparable to other areas in the lake. Metal levels in pondweeds (*Potamogeton* sp.) are higher in the tailings area. Fish sampling revealed a healthy fish population comprised of northern pike, white sucker, lake whitefish, yellow perch and spottail shiner. Metal levels in fish tissues are generally low compared to other Manitoba lakes and are within background levels observed elsewhere in Canada.

SOMMAIRE

Une évaluation préliminaire sur le terrain de l'élimination subaquatique à long terme de résidus miniers réactifs dans le lac Mandy (Manitoba) a été effectuée dans le cadre du Programme de neutralisation des eaux et du drainage dans l'environnement minier (NEDEM). Environ 73 000 tonnes métriques de résidus à teneur élevée en soufre et en métaux communs ont été déversées d'un unique caniveau dans le lac Mandy en 1943-1944. Un examen du lac en 1975 a permis de constater qu'il y avait eu végétalisation naturelle des secteurs les moins profonds. L'eau était considérée de bonne qualité et des vertébrés et invertébrés aquatiques s'étaient déplacés dans la zone occupée par les résidus.

Le lac Mandy est un petit lac (superficie = 239 000 m²) situé dans le Bouclier précambrien près de Flin Flon (Manitoba). Ce lac faisait à l'origine partie du lac Schist, dont il a été séparé par la construction d'une chaussée. Le lac Mandy est peu profond (profondeur moyenne = 3,6 m) et la profondeur maximale y est de 5,5 m. Pendant la durée de l'étude, les entrées et les sorties d'eau ont été minimales. Aucune thermocline n'a été observée dans la colonne d'eau, mais de faibles concentrations en oxygène dissous (conditions anaérobies) ont été relevées sous la profondeur de 2,0 m. La productivité biologique élevée (conditions de mésotrophes à eutrophes) dans le lac a entraîné la présence de sédiments présentant une teneur élevée en matière organique et une demande d'oxygène élevée.

La qualité de l'eau était la même à toutes les stations et à toutes les profondeurs dans le lac. L'eau du lac est d'une dureté modérée et présente des valeurs de la conductivité, de la concentration en solides dissous et de l'alcalinité comparables à celles de l'eau d'autres lacs manitobains. Elle est légèrement basique. Les concentrations de chlorures, de sulfates et de silicates réactifs sont faibles. Les concentrations de métaux dissous sont faibles et des différences minimales entre ces concentrations dans des échantillons d'eau du fond et de la surface indiquent que des quantités minimales de métaux se dégagent des sédiments. De plus, des concentrations de métaux plus élevées ont été relevées dans l'eau pénétrant dans le lac que dans l'eau du lac même.

Des concentrations élevées de métaux, en particulier d'arsenic, de cuivre, de plomb, de mercure et de zinc, ont été relevées dans les sédiments. Cependant, la décomposition de l'épaisse couche organique recouvrant les sédiments semble maintenir des conditions anoxiques, ce qui réduit le potentiel d'oxydation des sulfures et le dégagement ultérieur de métaux solubles dans l'acide. Des analyses pétrographiques, de diffraction X (XRD), de fluorescence X (XRF), granulométriques et de lixiviation détaillées ont également été effectuées afin de caractériser les sédiments.

Les résultats de ces analyses indiquent une abondance de matières organiques, incluant des frustules de diatomées. Les résidus étaient dispersés dans l'ensemble des sédiments du lac, les balayages par XRD indiquant la présence de quartz, de pyrite, de feldspath et de chlorite dans les sédiments. Les analyses de XRF ont indiqué comme constituants minéralogiques possibles des sédiments le quartz, le feldspath la plagioclase, les micas, la chlorite et la pyrite. On a relevé des traces de pyrite framboïdale et de rares exemples de chalcopyrite sphérolitique et de sphalérite. Les résultats des analyses de lixiviation par une méthode d'extraction séquentielle d'échantillons de sédiments (station 3) exposés à l'oxydation indiquent des dégagements de quantités élevées de cadmium, de zinc, de nickel, de cobalt et de manganèse dans les phases hydrosolubles et échangeables. Puisque les résultats des analyses de la qualité de l'eau n'indiquaient pas la présence de métaux dégagés par les sédiments, ces résultats sont plus indicatifs du

dégagement possible dans des conditions aérobies. Les dégagements de fer, d'arsenic, de plomb et de sélénium s'effectuaient dans des conditions modérément à fortement réductrices. Dans des conditions fortement oxydantes, il y avait dégagement d'argent, de cuivre, de plomb, de zinc et de nickel, et la fraction résiduelle dégageait de l'aluminium, du fer, du manganèse, de l'arsenic, du cobalt, du mercure, du nickel et du zinc. Les concentrations totales d'aluminium et de fer dans la fraction résiduelle étaient élevées et on y relevait des quantités moindres de zinc et d'arsenic.

Le biote du lac a été examiné de manière très détaillée. Les densités d'invertébrés benthiques sont faibles et la communauté est dominée par des oligochètes et des larves de diptères. La structure de la communauté et la densité du phytoplancton sont caractéristiques de celles de lacs mésotrophes à eutrophes. Les densités étant plus élevées que dans deux lacs oligotrophes situés à proximité. Les diatomées sont prédominantes dans le phytoplancton. Les densités du zooplancton sont légèrement inférieures à celles observées dans d'autres lacs manitobains et la communauté est dominée par des rotifères, des cladocères et des copépodes.

La végétation aquatique du lac a été cartographiée et des échantillons ont été recueillis afin d'y doser les métaux. Depuis 1975, la communauté végétale de la zone de résidus est devenue plus diversifiée et comparable à celle d'autres secteurs du lac. Les concentrations de métaux dans les potamots (*Potamogeton sp.*) sont plus élevées dans la zone des résidus. L'échantillonnage ichtyologique a indiqué l'existence d'une population bien portante de poissons composée de brochets, de meuniers noirs, de grands corégones, de perchaudes et de queues à tache noire. Les concentrations de métaux sont généralement faibles dans les tissus de poissons comparativement à ce qu'elles sont dans d'autres lacs manitobains et se situent en deçà des concentrations de fond observées ailleurs au Canada.

ACKNOWLEDGEMENTS

A number of people have made substantive contributions to this project. Clem Pelletier of Rescan Environmental Services Ltd. (Rescan) provided overall project coordination and senior review of the report. Bill Duncan (Rescan) and Shirley French were responsible for water quality sampling, sediment and core sampling, biota and lake morphology work.

Rescan personnel involved in various aspects of the project, included Paul Davidson who assisted with drafting and Janice Kukurudz who patiently wordprocessed this document. Bill Duncan, Gary Birch, Diane Howe and David Flather (Rescan) were responsible for reporting of this work.

We would also like to gratefully acknowledge HBMS for their overall support of the project, particularly Wayne Fraser and for other personnel for their logistical and field support including Steve West, Ron McNeil and Brian Levia. They generously supplied boats, sampling equipment, lab space, accommodations and their time.

TABLE OF CONTENTS

EXECUTIVE SUMMARY.....	i
ACKNOWLEDGEMENTS.....	iii
TABLE OF CONTENTS.....	vi
LIST OF TABLES.....	vi
LIST OF FIGURES.....	vii
1.0 INTRODUCTION.....	1-1
1.1 Objectives and Scope.....	1-1
1.2 Background.....	1-2
2.0 STUDY AREA AND METHODS.....	2-1
2.1 Study Area.....	2-1
2.2 Sampling Stations.....	2-1
2.3 Study Methods.....	2-1
2.3.1 Lake Morphometry.....	2-1
2.3.2 Water Quality.....	2-4
2.3.3 Sediment.....	2-5
2.3.4 Benthic Invertebrates.....	2-7
2.3.5 Phytoplankton.....	2-7
2.3.6 Zooplankton.....	2-7
2.3.7 Fish.....	2-8
3.0 RESULTS AND DISCUSSION.....	3-1
3.1 Lake Morphometry.....	3-1
3.2 Water Quality.....	3-1
3.3 Sediment.....	3-7
3.4 Biota.....	3-21
3.4.1 Benthic Invertebrates.....	3-21
3.4.2 Phytoplankton.....	3-25

3.4.3	Zooplankton.....	3-28
3.4.4	Aquatic Vegetation.....	3-31
3.4.5	Fish.....	3-34
4.0	CONCLUSIONS.....	4-1
	REFERENCES.....	R-1
APPENDICES		
APPENDIX A		
	Dissolved Oxygen and Temperature Profiles for Mandy Lake at Four Stations.....	A-1
APPENDIX B		
	Mandy Lake - Water Quality Data for Lake Stations.....	B-1
APPENDIX C		
	Particle Size Analysis of the Top 2 cm of Sediments.....	C-1
APPENDIX D		
	Petrographic analyses of Top 2 cm of Sediments.....	D-1
APPENDIX E		
	Sequential Extraction Results of Top 2 cm of Sediments.....	E-1
APPENDIX F		
	Chlorophyll <i>a</i> and Quantitative Phytoplankton Data (cells/ml) for Mandy Lake.....	F-1
APPENDIX G		
	Mandy Lake Fisheries Data - Sampled August 22, 1989 by Gill Nets....	G-1
APPENDIX H		
	Metal Analyses of Mandy Lake Fish Tissue Samples.....	H-1

LIST OF TABLES

1-1 Composition of Tailings from Mandy Mine 1-3

1-2 Soluble Constituents in a 1:5 Distilled Water Leach of
Tailings from Mandy Mine..... 1-4

1-3 Acid Generating Potential of Mandy Mine Tailings..... 1-4

1-4 Quality of Inlet and Outlet Water at Mandy Lake..... 1-5

3-1 Summary of Selected Water Quality Parameters - Maximum Values
by Depth in Mandy Lake - 1989 3-5

3-2 Mandy Lake - Water Quality Data for Inflow and Pit Sites 3-6

3-3 Field Observations of Sediments Collected for Benthic
Invertebrates, Metals Analyses and Particle Sizing - Mandy Lake..... 3-8

3-4 Particle Size Distribution for Mandy Lake Sediments 3-8

3-5 X-Ray Fluorescence (XRF) Analysis of Top 2 cm Layer of Sediments
in Mandy Lake..... 3-12

3-6 Total Carbon, Nitrogen, and Sulphur (Dry Weight%) in Surface Sediments
(Top 2 cm) from Mandy Lake Core Samples..... 3-14

3-7 Metals Analyses of Sediment Samples (Top 2 cm) from Mandy Lake
Collected, August 24, 1989 3-15

3-8 Species and Taxa List of Benthic Invertebrates Found in Mandy Lake 3-22

3-9 Counts of Profundal Benthic Invertebrates from Mandy Lake,
Manitoba, August 23, 1989..... 3-23

3-10 Littoral Benthic Invertebrates from Mandy Lake,
Manitoba, August 23, 1989..... 3-26

3-11 Classification of Taxa Encountered from Phytoplankton
Samples from Mandy Lake..... 3-27

3-12 Mandy Lake - Density of Zooplankton Captured in Vertical
and Horizontal Tows (individuals/m³)..... 3-29

3-13 Metal Analyses of Mandy Lake Aquatic Vegetation..... 3-33

3-14 A Summary of Metal Concentrations in Mandy Lake Fish Samples 3-35

3-15 Mean and Highest Metal Concentrations Found in Fish Tissue in Various
Manitoba Lakes..... 3-36

LIST OF FIGURES

2-1 Project Location Map - Mandy Lake..... 2-2

2-2 Sampling Locations - Mandy Lake..... 2-3

3-1 Bathymetric Mapping - Mandy Lake..... 3-2

3-2 Water Column Profiles - Stations 1 and 4..... 3-3

3-3 Sequential Extraction of Mandy Lake Sediments 3-17

3-4 Aquatic Vegetation Mapping - Mandy..... 3-32

LIST OF PLATES

3-1 Photomicrograph of Station 1 sediments using reflective light 3-9

3-2 Photomicrograph of Station 2 sediments using reflective light 3-9

3-3 Photomicrograph of Station 2 sediments using transmitted light 3-10

3-4 Photomicrograph of Station 3 sediments using reflective light 3-10

3-5 Photomicrograph of Station 4 sediments using reflective light 3-11

1 - Introduction

1.0 INTRODUCTION

Surficial deposition of sulphide-bearing mine wastes has been a common disposal practice used by many mines. However, subsequent oxidation of the sulphidic waste can result in the generation of highly acidic drainage waters with concomitant leaching of heavy metals. The deleterious effects on the receiving environment associated with such practices are well documented. The need for environmentally safe, yet economically feasible, disposal of mine wastes has resulted in considerable efforts being directed toward identifying more benign disposal alternatives. Alternatives to land-based disposal of mine waste rock and tailings are based primarily on limiting the exposure of the material to oxygen and the inhibition of autotrophic iron and sulphide oxidizing bacteria. Subaqueous deposition of mine wastes has been identified as a particularly promising disposal alternative. In theory, underwater disposal of reactive mine wastes should suppress sulphide oxidation, however data in support of the above supposition, particularly for freshwater disposal, is sparse. Moreover, a dearth of information exists on the post-depositional chemical behaviour of submerged tailings and the associated impacts on the surrounding aquatic ecosystem. To alleviate these deficiencies in knowledge, a two-phase study of Mandy Lake was commissioned as part of the Mine Environment Neutral Drainage program. The initial phase was a preliminary assessment of existing lake conditions, while the second phase was to address, in more detail the geochemical conditions related to tailings disposal. Reported here are the results from this initial phase.

1.1 Objectives and Scope

Given the above identified gaps in knowledge concerning the efficacy of freshwater subaqueous disposal, the several fold objectives of the present study were as follows:

- To define the present environmental conditions of Mandy Lake;
 - To review and compare previous studies with the present in order to identify the impacts, if any, that have occurred since cessation of subaqueous tailings disposal;
- and

- To evaluate the environmental stability of submerged tailings and assess their contribution, both present and future, to the metals loading in the biotic and aqueous environments.

The field and laboratory study designed to meet the above objectives included a general physical and chemical limnological survey, a biological survey to document the aquatic fauna and flora and geochemical analyses of lake sediments. Preliminary characterization of submerged tailings and sediments involved chemical, mineralogical, elemental, petrographic and particle size analyses. Metals stability and partitioning between the sediment and aqueous-phase was examined through sequential multiple extractions. Although detailed sediment pore-water analyses was not in the scope of the present work, the second phase of the Mandy Lake study (spring 1990) will utilize such analyses to more clearly define the post-depositional reactivity of the tailings deposits.

1.2 Background

A case history by Hamilton and Fraser (1978) examined the natural underwater revegetation of the tailings at Mandy Lake. The report briefly examined the effects that the tailings had on the environment in and around the area of deposition.

The mine was first operated during the years 1917 to 1920, with the ore processed off-site. The ore vein was solid chalcopyrite (>20% copper) with associated gold, silver and other lower grade sulphides. The mine was opened again during 1943 to 1944. During this time, ore was milled on site and an estimated 73,000 metric tonnes were deposited into Mandy Lake in a fan-shaped deposit from a single launder. Some spillage occurred along the shore where it has remained. The deposited tailings gradually slope away from the east shore to about 1 m depth, then drop-off quickly into 5 m deep water. Below the drop-off point, tailings are covered by a black, soft sediment.

Little data are available regarding the original condition of the tailings. The tailings were primarily pyrite with 15 to 17% sulphur and appreciable quantities of zinc and copper. Analysis of the submerged tailings in 1975 indicated minimal oxidation had occurred. The iron was present as iron sulphide and the percentage of iron oxide and sulphate present was low, with shore samples marginally higher (Table 1-1). Analyses of a distilled water leach of the tailings indicated the oxidized shore samples had a lower pH, higher conductivity and a higher concentration of soluble metals than the

Table 1-1
Composition of Tailings from Mandy Mine
(Adapted from Hamilton and Fraser 1978)

Constituent (%)	Mandy Mine	
	Underwater	Shore
Total Iron	17.4	19.8
Iron (Fe ₂ O ₃)	0.8	2.9
Total sulfur	15.5	15.8
Sulfide sulfur	15.4	15.5
Sulphate sulfur	0.03	0.30
Aluminum (Al ₂ O ₃)	8.4	6.7
Silica (SiO ₂)	35.7	37.7
Copper	0.91	2.70
Zinc	4.70	1.60
Lead	0.13	0.12
Cadmium	0.01	<0.01
Calcium	1.04	0.51
Magnesium	1.75	1.03

underwater samples (Table 1-2). The shore and underwater tailings were net acid producers (Table 1-3) with the shore samples having very low acid consuming ability. However, the underwater tailings still had a substantial amount of acid consuming ability indicating minimal acid generation had occurred underwater.

Water samples collected in 1975 and 1976 showed similar water quality in inlet and outlet waters of Mandy Lake, with the outlet waters having higher conductivity and higher iron concentrations but lower sulphate levels (Table 1-4). Water collected above the tailings had higher conductivity and zinc concentrations than the inlet water, and lower zinc concentrations than the outlet waters. Changes in zinc levels in the outlet water did not appear to be attributable to the underwater tailings material.

Vegetation was established on the submerged tailings but not on the tailings exposed to the atmosphere. Species found on the submerged tailings included sedges (*Carex* spp.), riverweed (*Podostemum ceratophyllum*) and spike rush (*Eleocharis* spp.). Over 90% of the shallow sloping tailings area was covered with decaying organic material up to 2.5 cm thick. In other areas of the lake, vegetation consisted of cattails (*Typha latifolia*),

Table 1-2

**Soluble Constituents in a 1:5 Distilled Water Leach
of Tailings from Mandy Mine
(Adapted from Hamilton and Fraser 1978)**

Constituent (mg/kg tailings)	Mandy Mine	
	Underwater	Shore
Iron	0.9	84.3
Copper	0.25	6.23
Zinc	15.5	44
Lead	0.35	1.05
Cadmium	0.05	0.28
Calcium	145	2,590
Magnesium	18	121
Sulphate	240	7,340
pH	6.9	4.9
Conductivity (mmho/cm)	0.4	2.45

Table 1-3

**Acid Generating Potential of Mandy Mine Tailings
(Adapted from Hamilton and Fraser 1978)**

Parameter	Mandy Mine	
	Underwater	Shore
Original pH	6.7	4.4
Total sulfur (kg/tonne)	156	158
Acid production potential (kg/tonne)	475	484
Acid consuming ability (kg/tonne)	52	4
Net acid production (kg/tonne)	424	480

Table 1-4

**Quality of Inlet and Outlet Water at Mandy Lake
(from Hamilton and Fraser 1978)**

Parameter	Sample Source		
	Inlet	Outlet	Above Tailings
pH	7.6	7.7	7.7
Conductivity (mmho/cm)	0.20	0.39	0.26
Copper (mg/L)	0.01	0.02	0.01
Zinc	0.14	0.13	0.20
Lead	0.01	0.01	0.01
Cadmium	0.01	0.01	0.01
Iron	0.11	0.23	0.05
Calcium	22.0	22.5	21.0
Magnesium	5.3	5.5	5.6
Sulphate	28.8	21.7	-

yellow pond lily (*Nuphar variegation*), water smartweed (*Polygonum amphibium*), bullrushes (*Scirpus* spp.) and pondweeds (*Potamogeton* spp.).

Similar animal species were found throughout the littoral areas of the lake. These included leaches, mayfly nymphs, mosquito larvae, nematodes and white sucker fry. No distinctions were determined in the species present in the tailings area and the rest of the lake based on this limited sampling.

This study examined Mandy Lake, Manitoba, which received high-sulphur base metal tailings during 1943 to 1944. These tailings have remained underwater for the past 45 years. A previous study (Hamilton and Fraser 1978) indicated that without expenditures on rehabilitation or site maintenance, the lake had good water quality, supported aquatic animal life and had natural revegetation.

The study provides a detailed field assessment of a lake that has had subaqueous disposal of reactive mine wastes in the past as part of CANMET's Mine Environmental Neutral Drainage (MEND) program. To fully address whether sulphide oxidation of the tailings has been controlled the present field assessment included a general physical and chemical limnological survey, a biological survey to document both aquatic fauna and flora, and sediment geochemical studies.

2 - Study Area and Methods

2.0 STUDY AREA AND METHODS

2.1 Study Area

The study area is located in central Manitoba (Figure 2-1) near the Saskatchewan-Manitoba border. Mandy Lake is an inactive subaqueous tailings disposal site about 5 km south of Flin Flon. Originally a bay off the west side of the northwest arm of Schist Lake, Mandy Lake was enclosed when a causeway was built across the inlet to the Mandy Mine site.

2.2 Sampling Stations

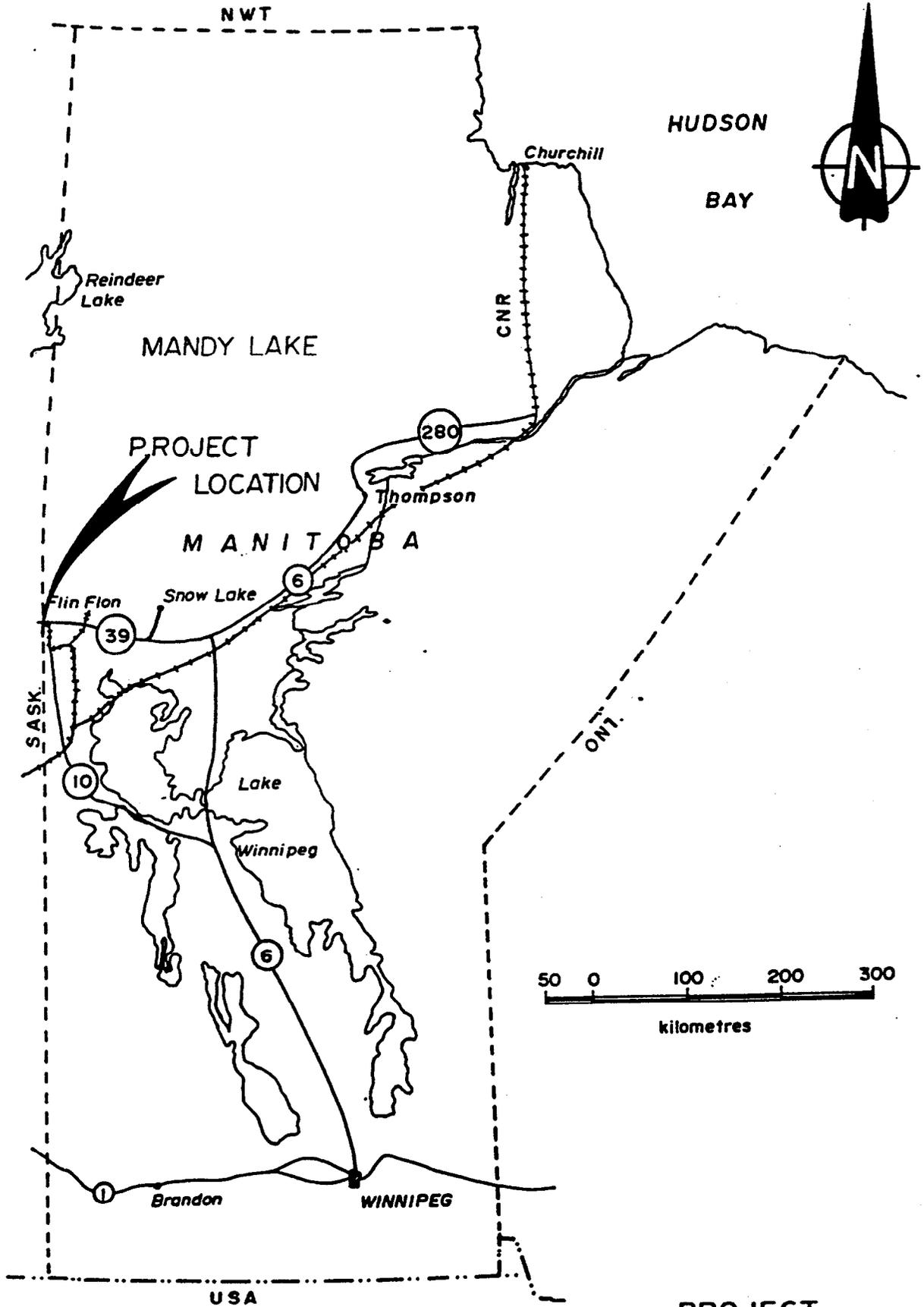
Four primary sampling stations (Stn. 1 to Stn. 4) were located along the central north-south axis of Mandy Lake (Figure 2-2). Water, sediment, benthos, zooplankton and phytoplankton were collected at these four stations. Dissolved oxygen and temperature profiles and Secchi disk transparency measurements were also completed at the primary stations. Two additional stations (Stn. 0 and Stn. 5) were sampled for benthos. Beach seining was carried out at four sites (SN1 to SN4) along the east shore of the lake. Two gill net gangs were set near the middle of the lake off the west (GN1) and east (GN2) shores. Three horizontal net tows (HNT1 to HNT3) for zooplankton were conducted along the north-south axis of the lake.

One inflow station (I1) was sampled at the south end of Mandy Lake. Several outflow culverts exist on the east side of the lake. However, due to the drought conditions experienced for several years prior to the study, no significant discharge was observed. A sample of standing water (P1) from the mining pit on the east side of the lake was also collected.

2.3 Study Methods

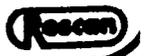
2.3.1 Lake Morphometry

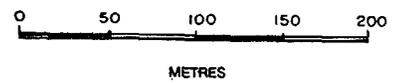
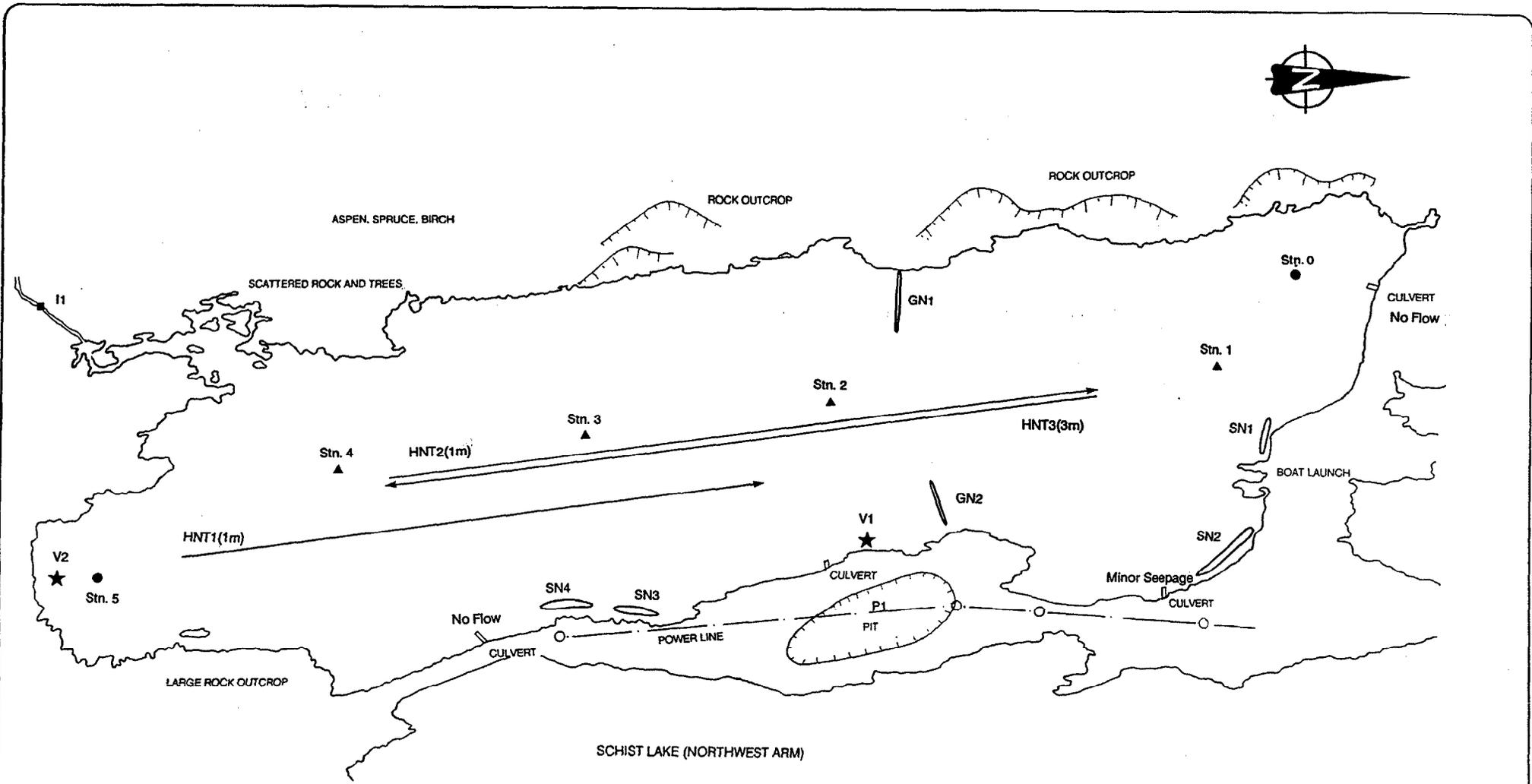
A bathymetric map of Mandy Lake was produced from timed echo soundings along defined transects using a Furano Mark II depth sounder. From the soundings and bathymetric map, a number of morphometric parameters were calculated including



**PROJECT
LOCATION MAP**

Figure 2-1





LEGEND

- ▲ Stn. Water Samples
- Stn. DO/Temperature Profiles
- Stn. Cores/Ponar Grab
- Stn. Benthos
- Stn. Phytoplankton
- Stn. Benthos Only
- HNT Zooplankton (Horizontal)
- SN Seine Netting
- GN Gill Net Set
- I Inflow Site (Water)
- P Pit Site (Water)
- ★ V Vegetation Site

		RESCAN ENVIRONMENTAL SERVICES LTD. VANCOUVER, B.C. CANADA	
		FIG.2-2 SAMPLING STATIONS	
DWG:	PWD		
DATE:	MARCH, 1990	MANDY LAKE	

area, volume, length, mean breadth, mean depth, maximum depth, shoreline length and shoreline development factor (Hutchinson 1957). Lake volume was determined by measuring the area under the lake's hydrographic curve.

2.3.2 Water Quality

Lake water samples were collected on August 23, 1989 at the four primary stations (Figure 2-2) using a teflon lined 5L Go-Flow water sampler. Samples were taken at 4 sample depths (0.5 m below the surface, 1.7 m, 2.7 m and at the bottom). The 1L polyethylene sample bottles and caps were rinsed with sample water prior to filling. To minimize air contact, bottles were carefully filled to the top using a teflon tube attached to the water sampler and inserted into the sample bottle. No preservatives were added to the 1 L bottles which were maintained at 4°C during shipping and handling. Grab water samples were collected from the inflow and pit sites by submerging the sample bottle directly into the water flow. Rate of inflow (L/s) was measured by determining the time to fill a container of known volume.

Water samples were analyzed by Analytical Services Laboratories Ltd. (ASL) of Vancouver, B.C. Samples were analyzed for physical parameters including pH, specific conductivity, turbidity (NTU), total dissolved solids and total suspended solids (volatile and fixed), as well as anions and nutrients including alkalinity, sulphate, chloride, reactive silica, total phosphorus, nitrate/nitrite, ammonia, total dissolved nitrogen and total organic carbon using standard methods (APHA 1985).

Dissolved metals were analyzed by various atomic absorption and emission spectroscopy methods as follows:

- Inductively coupled argon plasma (ICP) emission spectroscopy for higher concentration elements
- Graphite furnace atomic absorption spectroscopy for low concentration elements
- Hydride generation atomic absorption spectroscopy for arsenic
- Cold vapour atomic absorption spectroscopy for mercury

2.3.3 Sediment

Sediment cores were collected at the primary four stations (Figure 2-2) on August 22, 1989 using an 8.8 cm OD lightweight gravity corer (Pedersen et al. 1985). Cores collected in the polycarbonate core liner were capped to retain interface water and sealed with tape. Cores were stored upright at 4 °C during transportation and storage, and were subsequently processed at the University of British Columbia (UBC), Department of Oceanography, Vancouver, B.C. The top 2-3 cm of each core was removed, freeze-dried, mixed and split in half. One half was ground to -200 mesh in a tungsten carbide mill, while the other half was left intact.

Petrographic analysis for mineral identification of intact core samples using polished thin sections were performed by Dr. Jeff Harris, Harris Exploration Services Ltd., North Vancouver, B.C.

A multiple extraction leach test was performed on intact core material from Station 3 by ASL. The test used was similar to those utilized in other aquatic studies (Forstner and Wittman 1983, Engler, Brannon and Rose 1974). In a multiple extraction the mildest extraction is completed first, solids are recovered by filtration and washed, and subsequent extractions, are conducted until the sample has been subjected to an entire predetermined series of extractants. The following extractants were used, and are identified in terms of their anticipated reaction with metals in the solids.

Water Soluble Phase

Distilled water extractant;

Exchangeable Cations

1 molar ammonium acetate at pH 7;

Weak Acid Soluble Phase

1 molar sodium acetate at pH 5;

Easily Reducible Phase

0.1 molar hydroxylamine hydrochloride + 0.01 molar nitric acid at pH 2;

Moderately Reducible Phase

0.2 molar ammonium oxalate + 0.2 molar oxalic acid at pH 3;

Difficultly Reducible Phase

0.5 molar sodium citrate + 0.1 molar sodium dithionite;

Oxidizable Phase

30% hydrogen peroxide + 1 molar ammonium acetate acidified to pH 2.5 with nitric acid;

Total Extractable

Nitric/perchloric/hydrofluoric acid digestion.

Core samples for X-ray diffractometry (XRD) analysis were ground in acetone and dispersed on a glass slide. Samples were scanned using $\text{CuK}\alpha$ radiation at 24 mA and 40 KV. Scans extended from 2θ angles of 4° to 60° for Station 1 (Sample ML-1) and from 4° to 34° for Station 2, 3 and 4 (Samples ML-2, ML-3 and ML-4, respectively). Ground core samples were used for X-ray fluorescence analysis. X-ray fluorescence (XRF) analyses were performed at Cominco Exploration Research Laboratory, Vancouver, B.C. by Dr. J. Harris.

Carbon and nitrogen analyses were measured using Carlo-Erba 1106 CHN Elemental Analyzer at UBC in which the sample was combusted in a stream of oxygen and the evolved CO_2 and N_2 determined by thermal conductivity. Carbon measurements were for total carbon which includes carbonate carbon.

Sulphur analyses were done using a Carlo-Erba NA-1500 CNS Analyzer at UBC. The sample was combusted in oxygen and SO_2 produced was detected by thermal conductivity. The high sulphur content of the samples swamped the N and C channels of the analyzer which required the analysis of these elements by the 1106 CHN instrument.

Bulk sediment samples were collected using a petite ponar dredge from the four primary stations on August 24, 1989. The top 2 cm layer of sediment was collected for particle size and metals analyses. Particle sizing analysis was performed by Golder and Associates Ltd., Vancouver, B.C. using a hygrometer method in accordance with ASTM designation D422-72 "Standard Method for Particle-Size Analysis of Soils".

Metals analyses of the sediments were performed by ASL. Sediments were homogenized and representative portions analyzed. Moisture was determined gravimetrically after drying the sample for 12 hours at 103°C . Subsamples for metals

were digested using a combination of nitric and hydrochloric acids, bulked to volume with deionized-distilled water and metals concentrations in the extract determined. Cadmium and lead were analyzed by direct flame atomic absorption spectrophotometry (AAS). Arsenic was determined by hydride generation AAS, while mercury was determined by cold vapour AAS. Aluminum, antimony, calcium, chromium, cobalt, copper iron, magnesium, manganese, molybdenum, nickel, vanadium and zinc were analyzed by ICP emission spectroscopy.

2.3.4 Benthic Invertebrates

Benthic invertebrate (benthos) samples were collected in triplicate on August 23, 1989 at 6 stations using a petite ponar dredge (0.023 m² sample area). Samples were washed through a sieve bucket with a screen size of 253 μ m. The retained material was preserved in a 10% buffered formalin solution. Benthos were counted and identified by R.D. Kathman Biological Consulting, Sydney, B.C. to the lowest practical taxonomic group.

2.3.5 Phytoplankton

Phytoplankton samples were collected at the four primary stations by bottle casts at 2 depths (0.5 m and 1.7 m) on August 24, 1989. Five hundred ml were collected for phytoplankton identification and preserved with Lugol's solution. Additional samples were collected for chlorophyll *a* analysis. Chlorophyll samples were filtered through a 45 μ m filter and preserved with a saturated MgCO₃ solution. Filters were wrapped in aluminum foil and frozen. Analysis for chlorophyll *a* was completed by ASL using a spectrophotometer method (APHA 1985).

Quantitative phytoplankton analysis to the lowest possible taxonomic level was carried out by Aquametrix Research Ltd., Sydney, B.C. Samples were counted using Utermohl chambers. Organisms in 10 fields of each sample were identified and counted under a 35 power objective lens. All count data have been expressed as cells/ml.

2.3.6 Zooplankton

Vertical net hauls for zooplankton collection were taken at the four primary stations on August 23, 1989 using a Wisconsin zooplankton net with a 12 cm diameter opening and

mesh size of 64 μm . Hauls were brought up from just off the bottom to the surface at a rate of 0.5 to 1 m/s. Three horizontal net tows approximately 500 m in length were taken at either 1 or 3 m depths between August 21-23, 1989. The Wisconsin net was towed at constant velocity of approximately 1 m/s. Zooplankton samples were preserved in 10% buffered formalin.

Quantitative zooplankton analyses were performed by Sy-Tech Research Ltd., Sidney, B.C. Zooplankton were keyed to lowest practical taxonomic level using keys of Pennak (1978), Torke (1974), Torke (1976) and Ward and Whipple (1963).

2.3.7 Fish

Fish were sampled in Mandy Lake on August 21 and 22, 1989 using sinking 2 inch stretch gill nets (45 m long). One gill net was set at each site for soak times of approximately 15 hours. Fish caught in the nets were placed in plastic fish boxes. Species caught included northern pike (*Esox lucius*), lake whitefish (*Coregonus clupeaformis*), white sucker (*Catostomus commersoni*) and yellow perch (*Perca flavescens*). Fish were weighed (± 10 g), measured for fork length (± 5 mm), sexed and stomach contents examined. Samples were then frozen for shipping to ASL.

At the laboratory, selected fish were dissected on clean plastic bags using stainless steel scalpels and a filleting knife. Tissue samples of the dorsal muscle were obtained by removing the skin from the first dorsal fin forward to the gill cover. Tissue was sampled from this area taking special care not to include any bones or skin. Liver samples were also collected from the same fish.

Aging structures (otoliths) were collected from northern pike. Aging analysis was carried out by Aquatic Resources Ltd., Vancouver, B.C.

Representative aliquots of tissue were homogenized and digested using a combination of nitric acid and hydrogen peroxide. The resultant extracts were analyzed for metals as follows:

- Cadmium, copper, lead, nickel and zinc were analyzed by graphite furnace AAS with automatic background correction.
- Arsenic analyzed by hydride generation AAS.

- Mercury analyzed by cold vapour AAS after a potassium permanganate digestion.

Seine netting using a 10 m long pole seine with 1/4 inch mesh was carried out on August 22, 1989. Four sites (Figure 2-2), 10 to 20 m in length, were sampled parallel to the shore to determine if additional fish species were present. In addition to yellow perch, spottail shiners (*Notropis hudsonius*) were caught in the seine net. Invertebrates caught in the seine net were retained for identification.

3 - Results and Discussion

3.0 RESULTS AND DISCUSSION

3.1 Lake Morphometry

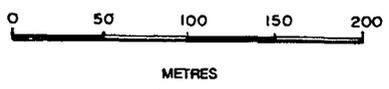
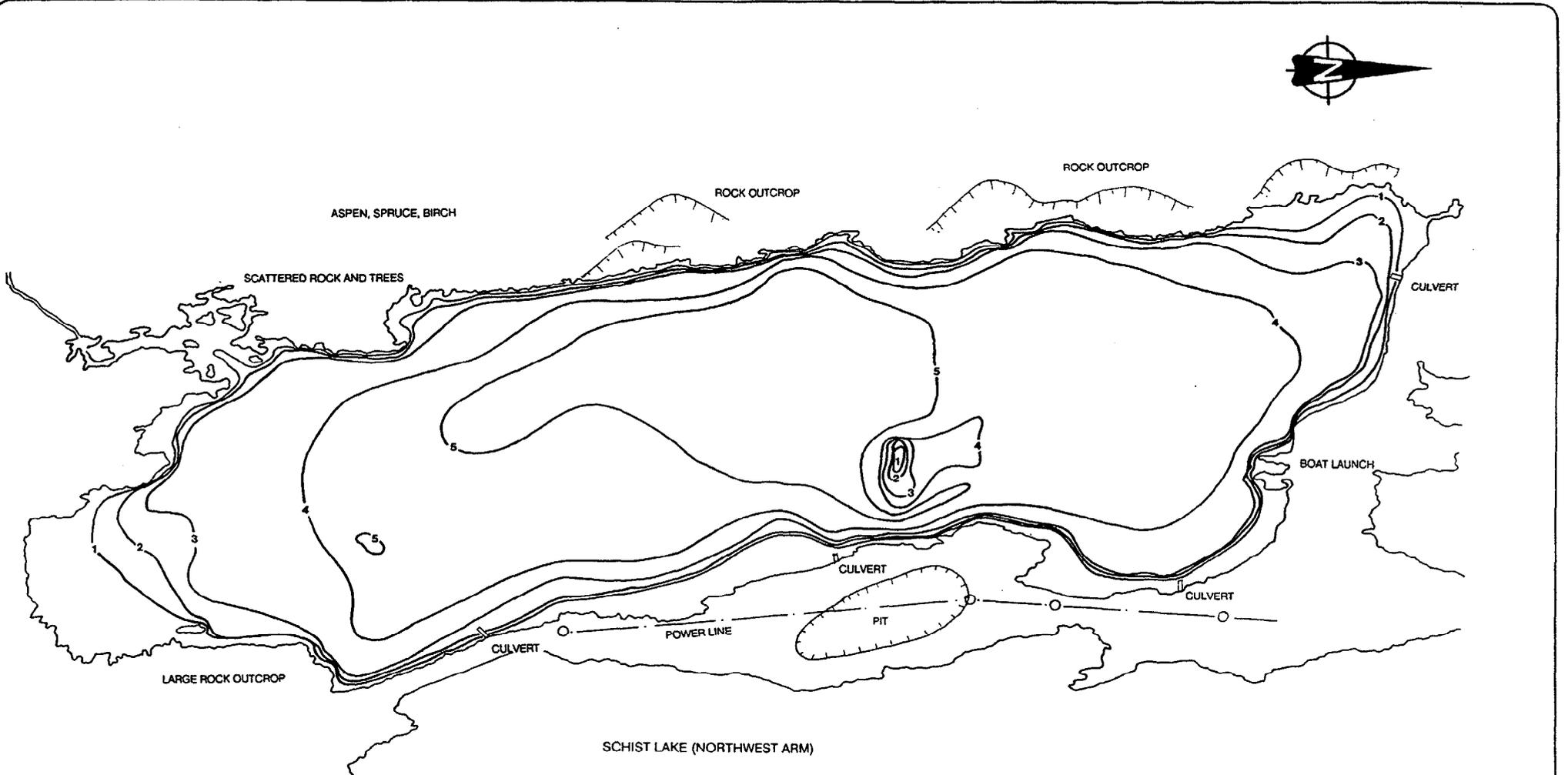
Mandy Lake (Figure 3-1) is a small, shallow lake approximately 1,070 m long and 220 m wide with a mean depth of 3.6 m and a maximum depth of 5.5 m. The lake was formed when a bay of the northwest arm of Schist Lake was isolated by construction of a causeway. The total area enclosed was 239,000 m² and lake volume is currently 853,000 m³. The lake receives drainage from Phantom Lake to the west and has culverts draining to the east into Schist Lake. During the study, lake inflow was minimal and discharges were limited to seepages near the Schist Lake culverts. The lake has 3,200 m of shoreline and a shoreline development factor of 1.8; a value of 1.0 would indicate a circular lake (Hutchinson 1957). The lake is roughly rectangular in shape.

3.2 Water Quality

Water column profiles of temperature, dissolved oxygen, turbidity, conductivity and pH indicate similar water quality at the four lake stations (Figure 3-2). Turbidity, conductivity and pH varied little with water depth or between stations. Temperature profiles do not indicate the presence of thermocline in the lake (Figure 3-2; Appendix A). However, a clinograde oxygen curve was observed with decreasing oxygen concentrations to anaerobic conditions below 2.0 m depth (Figure 3-2; Appendix A). The 2 m oxycline suggests that only approximately 50% of the lake volume was usable by the fish population. Secchi disk transparency ranged from 1.2 to 1.35 m.

Results of water quality testing at the four lake stations indicated similar water quality at all sampled depths (Appendix B). The lake is moderately hard with a hardness of approximately 87 mg/L as CaCO₃. The lake is nearly neutral pH (approximately 7.1), with alkalinity of approximately 77 mg/L as CaCO₃. Sulphate and chloride concentrations were low, approximately 17 mg/L and 4 mg/L, respectively.

Conductivity varied slightly from 174 to 191 μ mhos/cm; dissolved solids were approximately 160 mg/L, while suspended solids and fixed volatile solids were low (<5 mg/L). Turbidity was generally low and was likely caused by plankton suspended in the water column. Concentrations of nutrients varied slightly between stations and ranged



LEGEND

Mean Breadth (\bar{b})	223 m
Length (l)	1070 m
Maximum Depth (zm)	5.5 m
Mean Depth (\bar{z})	3.6 m
Area (A)	239,000 m ²
Volume (V)	853,000 m ³
Shoreline (L)	3,200 m
Shoreline Development (SLD)	1.8

Rescan	RESCAN ENVIRONMENTAL SERVICES LTD. VANCOUVER, B.C. CANADA	
	FIG. 3-1 BATHYMETRIC MAPPING	
DWG: .P.W.D.		MANDY LAKE
DATE: MARCH, 1990		

pH	5	0	5	0	5	0	5
Conductivity	100	0	100	0	100	0	100
Turbidity							
Temperature							
Dissolved O ₂	0	10	0	10	0	10	0

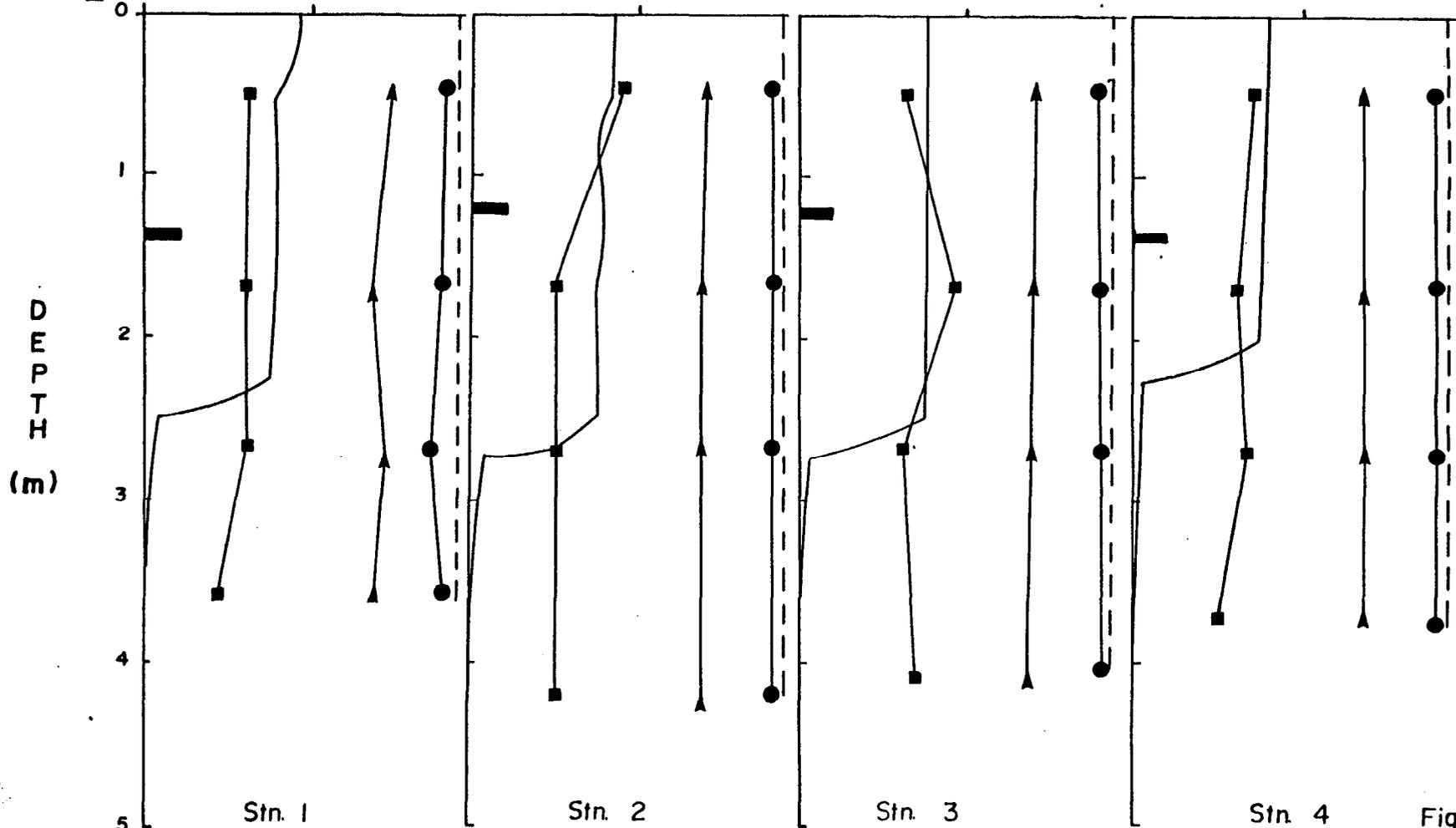


Figure 3-2

WATER COLUMN
PROFILES
MANDY LAKE

— Dissolved O₂ (mg/L) —■— Turbidity (NTU) ← pH
 - - - Temperature (°C) —●— Conductivity (µmhos/cm) — Secchi (m)

from 0.025 to 0.048 mg/L for total phosphorus, from 0.14 to 0.18 mg/L for nitrate - nitrite nitrogen, from 0.31 to 0.54 mg/L for total dissolved nitrogen, and <0.005 mg/L for ammonia. Total organic carbon was approximately 8 mg/L at all sites. Reactive silicate ranged from 1.5 to 2.2 mg/L. The differences between surface and bottom samples for these parameters were minor (Table 3-1).

Dissolved metal concentrations were generally low with only arsenic, copper and zinc being consistently above detection limits. Arsenic concentrations ranged from 0.0064 to 0.0092 mg/L, copper concentrations were 0.004 to 0.007 mg/L, and zinc concentrations ranged from <0.005 to 0.011 mg/L. Copper concentrations were consistently above water quality guidelines (CCREM 1987), while aluminum and cadmium exceeded guidelines only occasionally (Table 3-1). The slightly higher maximum metal concentrations found near the bottom occurred infrequently with no consistent pattern between stations. The heavy metal concentrations (Cu, Zn, Pb, Cd and Fe) and conductivity found in the bottom samples were lower than recorded from water collected above the tailings in 1975 (Table 1-4). Release of metals from the sediments appears to be minimal.

The inlet water from Phantom Lake (Table 3-2) had similar chemistry compared to the lake stations with higher concentrations of cadmium (0.0005 mg/L), copper (0.013 mg/L) and zinc (0.16 mg/L). The pit water had generally poor water quality with a lower pH (5.78), higher conductivity and dissolved solids, high sulphate concentrations (656 mg/L), higher chloride levels, high reactive silicate levels (14.8 mg/L) and generally higher metal levels (Table 3-2). Cadmium, copper, manganese, nickel and zinc concentrations were also elevated in this sample. Due to the diffuse nature of the outflow seepages, no samples were collected.

Copper, zinc, calcium and magnesium concentrations, and the conductivity values in the inlet waters of the present study (Table 3-2) were comparable to those found in 1975 (Table 1-4); while lead, cadmium, iron and sulphate concentrations were lower than those observed in 1975. Metal levels in the inflow sources may be contributing to lake water concentrations more than the release of metals from bottom sediments.

Table 3-1
Summary of Selected Water Quality Parameters - Maximum Values by Depth in Mandy Lake - 1989

Parameter	Depth (m)		CCREM (1987) Aquatic Life Guidelines ^a
	0.5 (surface)	3.6-4.2 (Bottom)	
pH (lab)	7.03-7.58	7.00-7.04	6.5-9.0
Conductivity	185	191	none
Dissolved Solids	160	170	none
Suspended Solids	5.0	4.0	10 mg/L
Turbidity	9.2	6.9	none
Alkalinity	77.6	77.6	none
Hardness (calc)	86.5	87.4	none
Sulphate	16.4	17.6	none
Chloride	4.3	4.3	none
Dissolved Metals			
Aluminum	0.005	0.009	0.005
Arsenic	0.0087	0.0087	0.05
Cadmium	0.0002	0.0012	0.0008
Copper	0.004	0.007	0.002
Iron	<0.03	<0.03	0.3
Lead	0.001	0.001	0.004
Manganese	<0.005	<0.005	none
Nickel	<0.001	<0.001	0.065
Zinc	0.006	0.011	0.03

Results expressed as mg/L except for pH, Conductivity (μ mhos/cm) and Turbidity (NTU).
^a Adjusted for hardness of the lake where appropriate.

Table 3-2

Mandy Lake - Water Quality Data for Inflow and Pit Sites

Site Number Date Sampled Flow	P1 (Pit) Aug 24/89 Standing	I1 (Inlet) Aug 24/89 6 L/S
Physical Tests		
pH (lab)	5.78	7.05
Conductivity	1300.	180.
Dissolved Solids	1170.	150.
Suspended Solids	29.0	52.0
Fixed Volatile Solids	14.0	27.0
Turbidity	40.4	20.0
Anions & Nutrients		
Alkalinity	3.2	74.3
Sulphate	656.	15.1
Chloride	34.0	5.0
T-Phosphorous	0.057	0.076
NO3/NO2	0.010	0.14
Ammonia	<0.005	<0.005
T-Dissolved Nitrogen	0.25	0.49
TOC	11.1	8.5
Silicate	14.8	2.3
Dissolved Metals		
Aluminum	<0.005	<0.005
Arsenic	0.0011	0.0078
Cadmium	0.088	0.0005
Copper	0.65	0.013
Iron	<0.03	<0.03
Lead	0.001	<0.001
Manganese	1.45	<0.005
Mercury	<0.00005	<0.00005
Nickel	0.021	<0.001
Silver	0.0001	<0.0001
Zinc	43.3	0.16
Calcium	154.	22.8
Magnesium	49.9	6.39
Potassium	4.53	1.37
Sodium	19.5	3.58

Results expressed as milligrams per litre except for pH, Conductivity (μ mhos/cm), and Turbidity (NTU)

< = Less than

NO3/NO2 = Nitrate/nitrite nitrogen

T = Total

TOC = Total Organic Carbon

3.3 Sediment

Field descriptions of Mandy Lake sediments that were collected in the deeper areas using the ponar dredge indicated the presence of organic material in the deposited tailings (Table 3-3). These observations are in agreement with those reported by Hamilton and Fraser (1978) who noted that 90-95% of the shallow submerged tailings were covered by a 2.5 cm thick layer of organic debris while deeper areas were composed of soft black sediment. Detailed particle size analyses (Appendix C) of the sediment samples revealed that the percentage of sand and silt sized material varied considerably between samples, however the percentage of clay in each sample generally remained at approximately 5% (Table 3-4). An exception, however, was the sediment sample from Station 5 which had significantly less sand and more silt and clay-sized material than the other four samples.

Petrographic analyses of sediment samples (Appendix D) indicates a predominantly organic origin ranging from 75 to 81 % organic material and 10 to 20% silicates (predominantly, quartz with lesser chlorite, biotite and/or sericite, and minor amounts of hornblende, carbonate and other silicates.) Sulphides generally comprise 2 to 5% of the total (principally pyrite with traces of sphalerite, chalcopyrite and possibly arsenopyrite). Photomicrograph plates are presented with detailed captions for each sample (Plates 3-1 to 3-5). Tailings material is not a major component in these samples. Station 2, closest to the old dumping area has the highest proportion of mineral material (approx. 25%) and Station 4 the lowest (approx. 12%), but the general character of the four samples is similar, suggesting lake-wide dispersal of tailings material. All sediments analyzed contained abundant diatom frustules. Trace proportions of framboidal pyrite and rare examples of spherulitic forms of chalcopyrite and sphalerite were noted. X-ray diffractometry (XRD) analyses of the sediments indicated the presence of quartz, pyrite, and chlorite, with all samples exhibiting diffraction tracing signatures of amorphous organic material. XRD scans are capable of detecting crystalline components occurring in amounts of a few percent or more.

X-ray fluorescence analyses (XRF) of the sediments for major constituents and % loss on ignition (LOI) are presented in Table 3-5. The average percentage of lithophile elements are expressed in the conventional oxide form. These data can be recalculated to provide an approximation of the most likely mineralogical composition. This is done by assuming that the Na_2O (plus part of the CaO) is combined with the SiO_2 and Al_2O_3

Table 3-3

Field Observations of Sediments Collected for Benthic Invertebrates, Metals Analyses and Particle Sizing - Mandy Lake

Station Number	Date	Time	Depth (m)	Field Observations
0	23/08/89	16:04	1.5 - 1.8 m	Coarse and fine black organic material. Surface was grey-black, underlain by grey-brown material over sand.
1*	23/08/89	15:45	4.2 m	Dark black mud composed of fine organic material.
2*	23/08/89	15:15	4.8 m	Dark black mud composed of fine organic material. Some lumps (old mine tailings?).
3*	23/08/89	14:35	4.8 m	Black-brown clay/silt material.
4*	23/08/89	13:45	4.2 m	Black-brown clay/silt material with fine organic material.
5*	23/08/89	12:40	1 - 1.5 m	Highly variable: 1) heavy organic debris, dark brown to black with odour; 2) Grey clay/silt with root material; 3) black to brown with organic material (some twigs).

* Analyzed for metals and particle size

Table 3-4

Particle Size Distribution for Mandy Lake Sediments

Station	Sand (%)	Silt (%)	Clay (%)
1	45	50	5
2	20	75	5
3	35	60	5
4	50	45	5
5	5	85	10

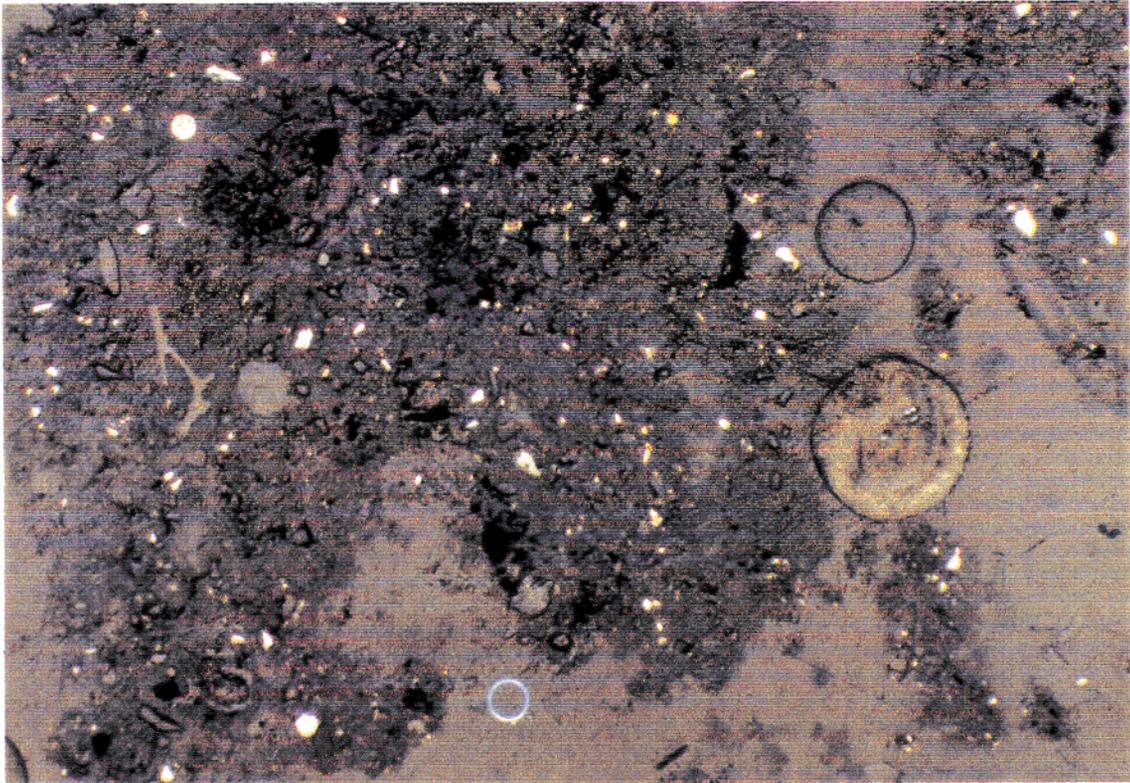


Plate 3-1: Photomicrograph of Station 1 sediments (ML-1) using reflective light (Scale 1 cm = 42 microns). Note relative abundance and even distribution of fine, angular pyrite particles, few spherulitic pyrite bodies (e.g., top left; bottom left centre), and angular quartz grains (grey with dark rims up to 30 microns).

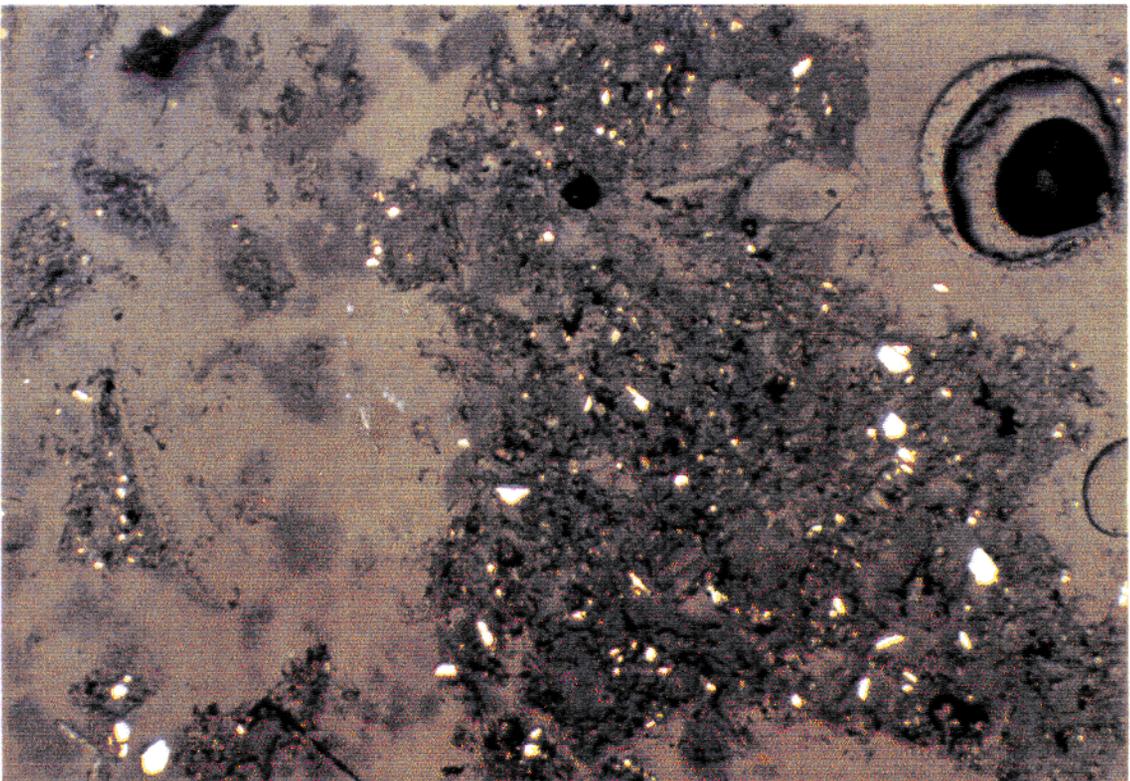


Plate 3-2: Photomicrograph of Station 2 sediments (ML-2) using reflective light (Scale 1 cm = 42 microns). Note perceptibly coarser and more abundant sulphides (angular pyrite up to 20 microns) than in Station 1.

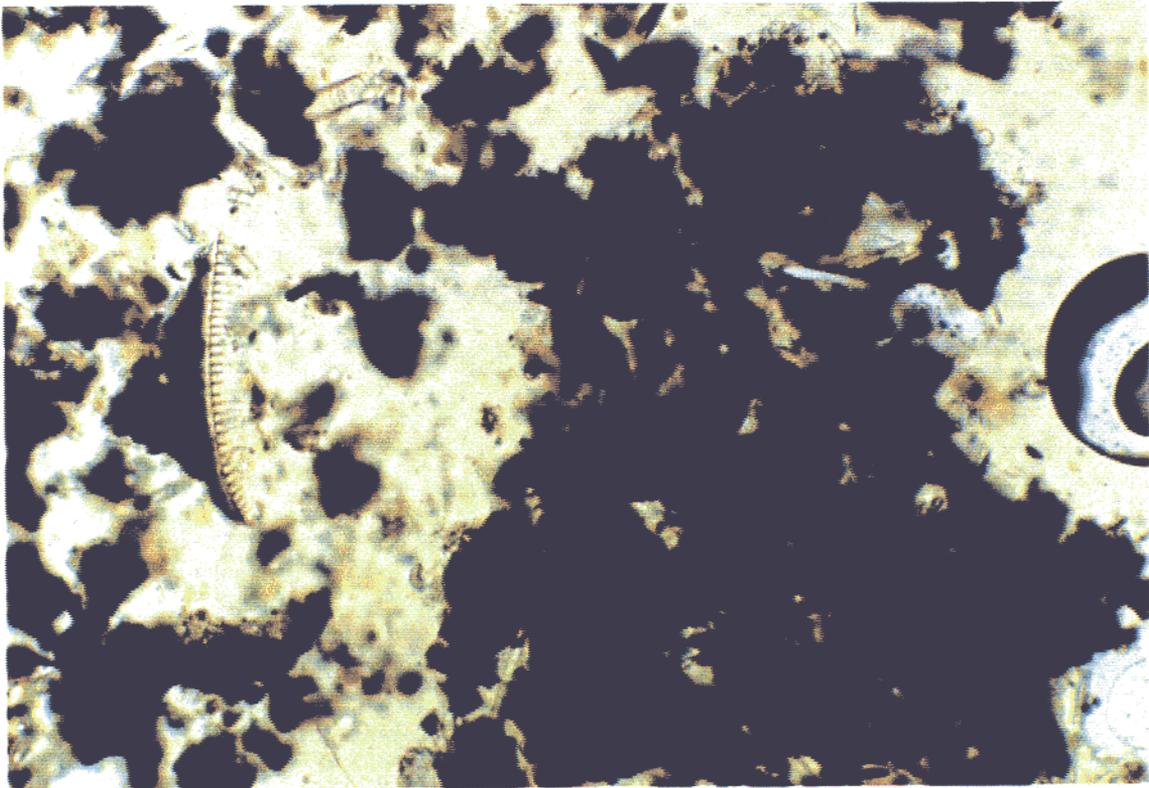


Plate 3-3: Photomicrograph of Station 2 sediments (ML-2) using transmitted light (Scale 1 cm = 42 microns). Note biogenic forms and dark brown, sub-opaque organic material (speckled with pyrite and possibly Fe hydroxides).

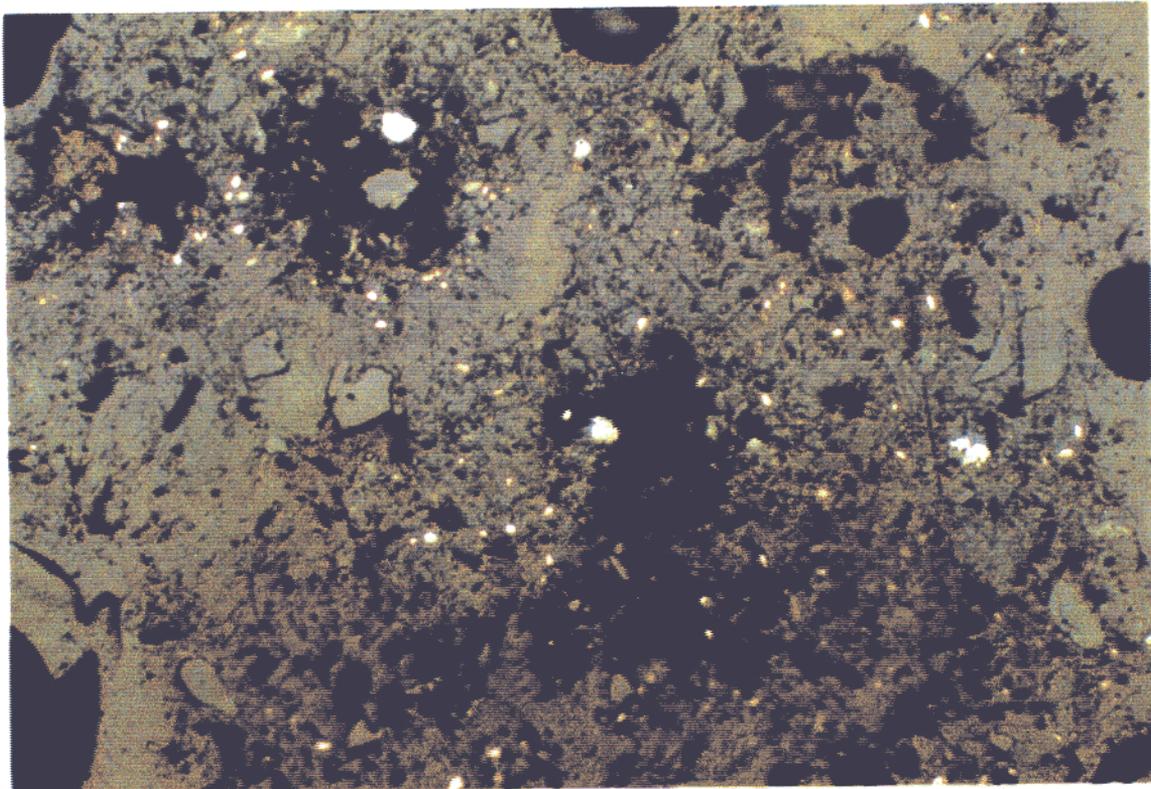


Plate 3-4: Photomicrograph of Station 3 sediments (ML-3) using reflective light (Scale 1 cm = 42 microns). Note evenly distributed pyrite specks and rare coarser particle up to 20 microns in a tenuous organic matrix, and relative abundance of quartz grains (light grey; moderate relief) up to 50 microns.

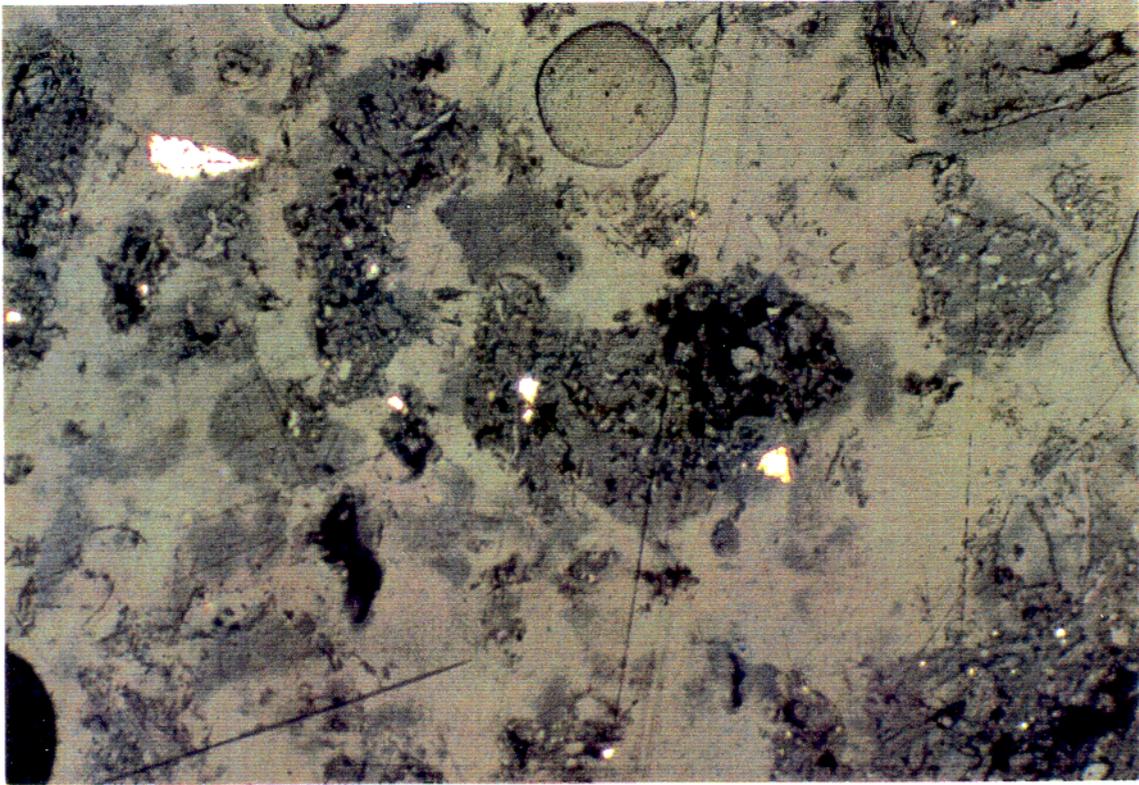


Plate 3-5: Photomicrograph of Station 4 sediments (ML-4) using reflective light (Scale 1 cm = 42 microns). Note lower sulphide and quartz content than ML-1, ML-2 and ML-3. Sulphides (including chalcopyrite; yellowish, near centre) are sparse discrete, coarse grains with the exception of a few, tiny pyrite specks in the organic clump (bottom right).

Table 3-5

**X-Ray Fluorescence (XRF) Analysis of Top 2 cm Layer of Sediments in Mandy Lake
(Values as %)**

Sample ID	Major Constituents											LOI	% Total
	CaO	K ₂ O	P ₂ O ₅	SiO ₂	Al ₂ O ₃	MgO	Na ₂ O	Fe ₂ O ₃	TiO ₂	MnO	Ba		
ML-1 (1)	1.53	1.98	0.17	41.77	12.17	2.91	1.16	11.16	0.48	0.08	0.04	24.30	97.76
ML-2 (2)	1.64	1.87	0.17	40.93	11.98	3.07	1.08	12.87	0.49	0.09	0.04	23.20	97.43
ML-3 (3)	1.67	2.03	0.17	42.96	12.34	2.92	1.27	10.59	0.52	0.08	0.04	23.61	98.20
ML-4 (4)	1.90	1.80	0.17	39.61	10.67	2.25	1.40	7.59	0.46	0.09	0.04	32.70	98.68
Mean	1.6	2.0	0.17	41.3	11.8	2.8	1.2	10.6	0.49	0.09	0.04	26.0	-

() Indicates station number.

as plagioclase feldspar; the MgO (plus part of the Fe_2O_3) is combined with SiO_2 and Al_2O_3 as chlorite; the K_2O is combined with SiO_2 and Al_2O_3 as chlorite; K_2O is combined with SiO_2 and Al_2O_3 as the micas (sericite and muscovite), and with the addition of some Fe for biotite; and the S is combined with Fe as pyrite and pyrrhotite. Unused SiO_2 is assumed to be free quartz. The remainder is presumably made up of organic matter, combined H_2O , excess Fe as $\text{Fe}(\text{OH})_3$, other sulphides, carbonates, etc. Thus the average composition for the samples are as follows: quartz (18.8%), plagioclase (16.5%), micas (16.0%), chlorite (9.6%), pyrite (9.1%) and remainder (30%).

These XRF results differ from the petrographic analyses which indicated a total mineral content of 19% while XRF indicated 70%. The optically observed abundance (weight percentage) of mineral grains versus organic matrix may have been biased due to an underestimation of the organic component. Moreover, the silica content may include that portion of the organic debris formed by diatom frustules. The samples show substantial contents of Al_2O_3 and Na_2O suggesting plagioclase is a major component of the gangue material. This material is difficult to distinguish optically from quartz in particulate material. Thus it appears the optically determined quartz is a mixture of quartz and plagioclase in various proportions. The XRD peak at 27.8° is likely due to plagioclase. Analyzed levels of K_2O and MgO indicated the presence of micas (sericite) and chlorite, however, XRD did not confirm the presence of micas. It is possible the K-bearing phase is K-feldspar.

Total carbon, nitrogen and sulphur analyses were also performed on the top 2 cm of sediments (Table 3-6). The carbon:nitrogen ratio of collected sediments remained at approximately 10:1. Due to the considerable quantity of organic material in these sediments, a significant percentage of the sulphur is expected to be in the organic fraction in proteinaceous material.

Metal analyses of the sediments indicated that all had elevated metal levels, specifically, arsenic, copper, lead, mercury and zinc (Table 3-7). Arsenic concentrations ranged from 1032 mg/kg to 6550 mg/kg, with the highest concentration in the sediment from Station 5. Similarly, the highest concentrations of the other metals of concern were observed in sediment from Station 5, while sediments from Stations 1 through 4 were consistently lower in overall metal concentration and levels were relatively consistent between these samples. The results are in agreement with the particle size distributions in that

Table 3-6

Total Carbon, Nitrogen, and Sulphur (Dry Weight %) in Surface Sediments (Top 2 cm) from Mandy Lake Core Samples

Station	Carbon (%C)	Nitrogen (%N)	Sulphur (%S)
1	9.22	0.94	5.51
2	8.41	0.85	6.59
3	9.44	0.95	4.26
4	14.8	1.25	2.58

sediment from Station 5 had significantly more fine grained material than any of the other samples. It has been widely observed that heavy metals accumulate in the finer fractions (Forstner and Wittmann 1983). This is a result of adsorption reactions that bind metallic ions onto the surfaces of clays and secondary minerals such as Fe, Mn and Al hydroxides. Because surface area is inversely proportional to particle size, invariably metal concentrations increase in the finer material. Despite the very high observed metal concentrations in the sediments, it does not appear that these sediments are a significant *in situ* source of soluble metals under reducing conditions. Presumably, the thick organic layer on the surface of the tailings substrate enhances oxygen consumption, thereby reducing the potential for sulphide oxidation and concomitant release of acid-soluble metals. In addition, strong bonding occurs between metallic cations and the coordinating functional groups (e.g. carboxyl-COOH, thiol-SH, phenolic-OH, amino-NH₂, etc.) found in organic material (Evans 1989), thereby increasing the metal retention capabilities of these sediments.

The methodology used for the sequential extraction of sediment from Station 3 is outlined in Section 2.3.3. Eight (8) different extractions were used to assist with the determination of the metal associations with this sediment. Although the discussion below deals with several metals of environmental concern, some general comments can be made regarding the expected speciation of metal forms in the tailings sediment.

The concentration of metals in the water-soluble phase is usually quite low, representing only those ions which are loosely bound to the surface of the sediments. Similarly the

Table 3-7

**Metals Analyses of Sediment Samples (Top 2 cm)
from Mandy Lake Collected, August 24, 1989**

Element	Detection Limit	Sampling Station					
		Station 1	Station 2	Station 3	Station 3 ¹	Station 4	Station 5
Aluminum %	0.005	3.39	3.16	3.23	3.22	2.92	2.36
Antimony	15	<	42	34	35	<	44
Arsenic ²	0.02	1,710	2,620	1,460	1,450	1,032	6,550
Cadmium ²	0.10	97.3	71.6	84.7	80.8	92.9	71.3
Calcium %	0.005	0.77	1.01	0.73	0.79	1.00	2.07
Chromium	2.0	46.3	38.4	50.9	54.9	51.9	4.23
Cobalt	2.0	126	173	121	115	95.9	294
Copper	1.0	3,410	3,000	3,140	3,060	3,137	3,720
Iron %	0.005	7.32	9.94	6.52	6.75	5.53	14.7
Lead ²	2.0	737	681	636	612	670	840
Magnesium	0.005	1.59	1.83	1.54	1.51	1.41	2.16
Manganese	0.50	618	705	603	607	695	1,014
Mercury ²	0.005	2.62	3.84	2.89	2.55	3.96	4.41
Molybdenum	5.0	<	<	<	<	<	<
Nickel	2.0	37.3	25.4	37.1	35.6	40.4	10.4
Vanadium	2.0	50.1	34.2	47.5	50.3	47.8	29.0
Zinc	0.10	26,500	24,500	24,000	22,000	26,201	31,780

Results are expressed in milligrams per dry kilogram of sediment except where otherwise stated.

< = Less than detection limit stated

% = Percent weight basis (w/w)

1 = Duplicate

2 = Parameters analyzed by specific atomic absorption spectrophotometry techniques.

exchangeable cation phase which represents those metals adsorbed to the surfaces of sediment by electrostatic or coulometric forces, usually does not have a large proportion of metals associated with it. Nonetheless, cation exchange is an important metal scavenging mechanism (e.g. Hg^{2+} and Cd^{2+}) and maybe more significant in sediments with high clay content. However, because the positively charged metals are relatively weakly held to the surfaces they can be easily exchanged by other cations. The use of excess ammonium ions in the extractant effectively displaces these weakly held metals from the surface exchange sites.

The weak acid soluble phase is generally resigned to carbonates, whereby the metal ions are liberated by the dissolution of metal carbonate or host carbonate at pH 5.0 with the subsequent release of CO_2 . Some Cu, Zn and Fe(II) oxides and hydroxides are also marginally soluble at this pH.

The easily and moderately reducible phases will include primarily amorphous manganese and ferric oxides hydroxides respectively. Their solubility is greatly increased in acid solution by the reduction from the higher to lower oxidation state. Heavy metals such as As, Cr, Cu, Cd and Pb which have co-precipitated with these amorphous hydroxides or are covalently bound to their surface would be liberated simultaneously.

The difficulty reducible phase is often termed the non-silicate iron phase and includes those crystalline forms of ferric and manganese oxides and hydroxides (e.g. $\beta\text{-FeOOH}$). Metals which have co-precipitated or participated in lattice substitutions would be released during this extraction.

The oxidizable phase includes species which are rendered soluble in acid solution by oxidation with hydrogen peroxide. Most metal sulphides and organic metals compounds are included in this category.

Sequential extraction results are presented in Appendix E for Station 3 (duplicate samples) and Figure 3-3. The sampling and storage of the sediments, and the actual extraction method used did not exclude the potential for atmospheric oxidation of the sample to occur. Thus the results obtained by the procedure are more representative of potential for metal release should reducing conditions in the bottom of Mandy Lake change to more oxidizing. The water quality did not indicate any substantial metal (88%), Zn (78%), Ni (60%), Co (43%) and Mn (32%) were noted in the water soluble

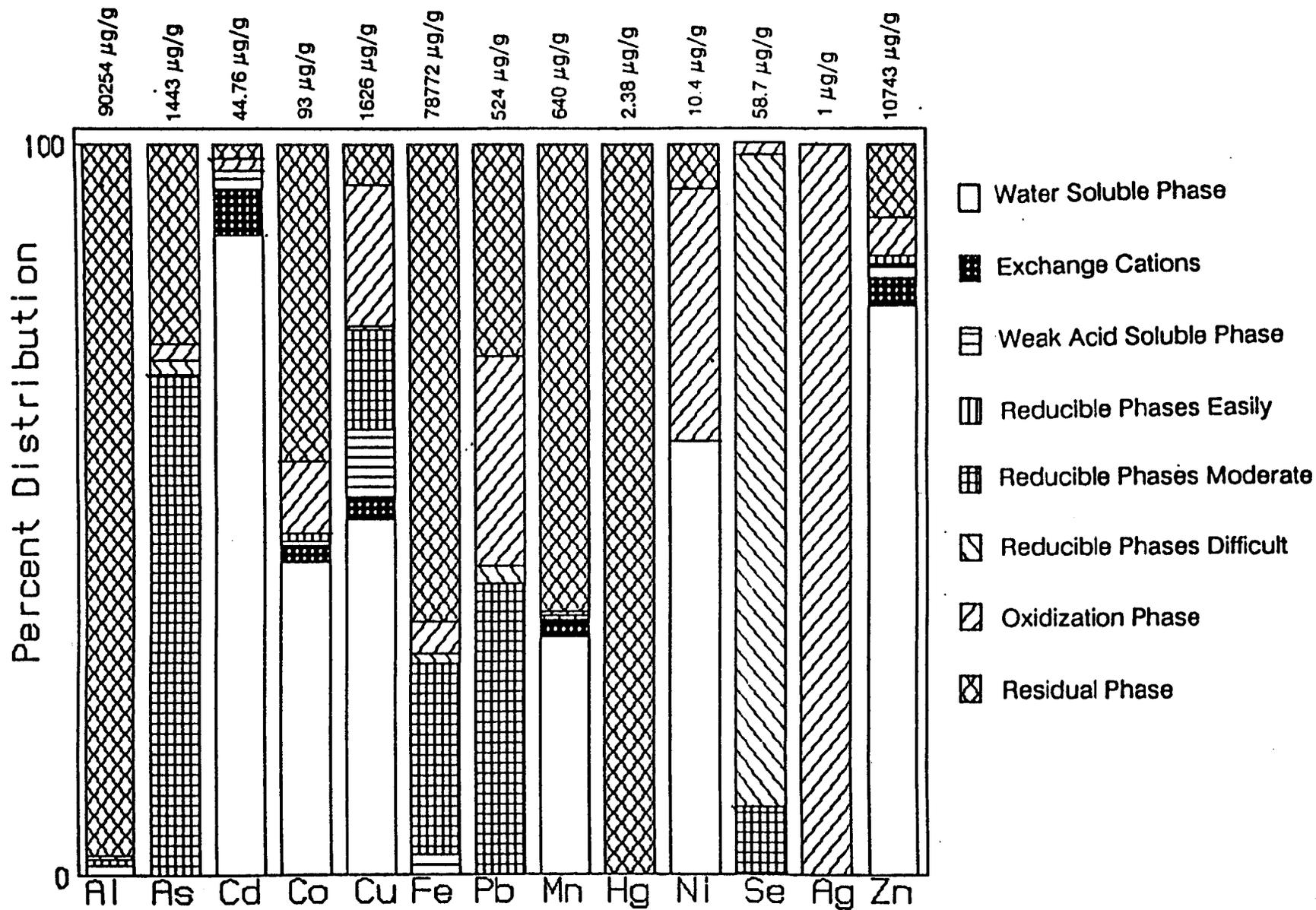


FIGURE 3-3 SEQUENTIAL EXTRACTION OF MANDY LAKE SEDIMENTS

phase of the extraction process with minor releases (from 1 - 5% of total releases) of Al and Fe. In the exchangeable phase, moderate release (from 5 - 20% of the total releases) of Cd (6%) and minor releases Cu, Zn and Mn occurred. The water soluble and exchangeable phases represent loosely bound metals that may be readily released to the surface waters (Forstner and Wittman 1983). The weak acid phase released moderate amounts of Cu (9%) and minor releases Cd, Fe and Zn.

As previously stated, easily and moderately reducible phases will include amorphous manganese and ferric oxides and hydroxides, respectively. Only minor amounts of Fe were released in the easily reducible phase. Higher releases of As (69%) and Fe (24%) occurred in the moderately reducing phase with moderate releases of Cu (13%) and Se (9%), and minor releases of Al and Zn.

In the difficulty reducing phase, high releases of Se (90%) occurred as well as minor releases of As and Pb.

The oxidizable phases includes species which are rendered soluble in acid by oxidization with hydrogen peroxide. This phase was characterized by high release of Pb (30%), Ni (35%) and Ag (100%); moderate releases of Co (10%), Cu (19%) and Zn (5%); and minor releases of As, Fe and Se.

The residual phase was characterized by high releases of Al (97%), As (27%), Co (43%), Fe (66%), Pb (29%), Mn (64%) and Hg (100%); moderate releases of Ni (6%) and Zn (10%); and minor releases of Cd.

To summarize, by metals:

- **Aluminum** showed very low availability in all extractants and was mainly found in the residual phase (97%). Total aluminum concentration was very high in the sample (70,530 $\mu\text{g/g}$).
- **Arsenic** showed very low availability in all extractants except the moderately reducible phase (69%) indicating association with amorphous ferric hydroxides. The remainder was associated with the residual fraction (27%). Total arsenic concentration was elevated in the sample (1,650 $\mu\text{g/g}$).
- **Cadmium** was associated with the water soluble (88%) and exchangeable phases (6.3%). Total cadmium concentrations of the samples was 49.2 $\mu\text{g/g}$.

- **Cobalt** was associated with the water soluble (43%) and oxidizable (10%) phase with the remainder in the residual fraction (43%). Total cobalt concentration was 116 $\mu\text{g/g}$.
- **Copper** was associated with the water soluble (49%), oxidizable (19%) and moderately reducible (13%) phases. Total copper concentration was elevated (1,636 $\mu\text{g/g}$).
- **Iron** was released in the moderately reducible phase (24%) by the reduction of amorphous ferric hydroxides but the majority was found in the residual phase (66%). Total iron concentration was very high (85,053 $\mu\text{g/g}$).
- **Lead** was released (40%) in the moderately reducible phase a significant proportion of Pb indicating that was specifically adsorbed onto Fe/Mn hydroxides. Approximately was released 30% in oxidizable phase and the remainder in the residual fraction (29%). Total lead concentration was elevated in the sample (510 $\mu\text{g/g}$).
- **Manganese** was released primarily in the water-soluble phase (33%) with the remainder in the residual fraction (64%). Total manganese concentration of the sample was 573 $\mu\text{g/g}$.
- **Mercury** was only detected in the residual fraction (100%) at a concentration of 2.95 $\mu\text{g/g}$.
- **Nickel** was readily available under water soluble (62%) and oxidizable (32%) conditions the total Ni concentration in sample was 16.0 $\mu\text{g/g}$.
- **Selenium** was primarily associated with the non-silicate iron phase (91%) with the total concentration in the sample of 54.5 $\mu\text{g/g}$.
- **Silver** was released under oxidizing conditions (100%) and was only present in trace amounts ($<0.30 \mu\text{g/g}$).
- **Zinc** was present in the water-soluble phase (77%), slightly but only soluble under oxidizing conditions (5%) with some being retained in the residual fraction (10%). Total zinc concentration of the sample was high (13,415 $\mu\text{g/g}$).

High releases of Cd, Co, Cu, Mn, Ni and Zn were noted in the water-soluble phase. Releases of Fe, As, Pb and Se occurred under moderate to strong reducing conditions. Arsenic and lead form strong complexes with Fe-oxides and hydroxides and their

association with this phase is not unexpected. Oxidation with 30% H_2O_2 releases organically bound metals and metal sulphides. Metals released from this phase included Ag, Cu, Pb, Zn and Ni. As Mandy Lake sediments have high organic content and a low percentage of metal sulphides, the above results indicate a considerable amount of metal bonding to organic matter in these sediments. The residual phases had high releases of Al, Fe, Mn, As, Co and Mg with moderate releases Ni and Zn. The residual fraction was composed primarily of Fe and Al with lesser amounts of Zn and As. The relatively large percentage of certain metals released in the water-soluble fraction is difficult to explain in relation to the observed water quality in Mandy Lake. With the exception of Cu, dissolved metal concentrations were lower suggesting minimal transfer of metals from the sediment phase to the aqueous phase. However, the results from the represented extraction indicates that the sediments have a significant proportion of Zn, Cu, Cd, Co and Ni in a readily soluble form. Post-collection oxidation of the sample both biological and chemical, could partially explain the water solubility. As Mandy Lake sediments contain significant quantities of organic carbon, pre-analysis mineralization of organically complexed metals may have resulted in their release upon re-wetting. Several heavy metals, including copper, cadmium, zinc, nickel, cobalt and manganese, are known to participate in complexation reactions with humic substances; the extent of retention being somewhat dependent upon the functional groups being available for metal complexing (Evans, 1989). Bacterial and fungal oxidation of the organic matter could have reduced the metal retaining ability of the sediments. The rate of oxidation of organic material in Mandy Lake and the subsequent release of organo-metal associations would be limited by the rate of diffusion of O_2 into these sediments. Although anaerobic heterotrophs oxidize organic carbon, the efficiency and rate of oxidation is much lower because of a lower energy yield gained from using alternate electron acceptors (NO_3^- , Mn^{4+} , Fe^{3+} , SO_4^{2-}). Moreover, laboratory temperatures are conducive to rapid growth and mineralization. This fact, coupled with an adequate supply of O_2 , for both carbon and sulphide oxidation gives credence to the supposition of laboratory induced erroneous results. To obviate this potential problem and to confirm the above results, future work is being conducted by Rescan with considerable sample quality control. Immediately upon collection, sediment samples are being frozen with dry-ice and are to be maintained frozen until analyses. In addition, sample preparation will be conducted under a nitrogen atmosphere to exclude the potential for significant oxidation of the sample prior to analyses. Detailed analyses of interstitial waters is also

being carried out on Mandy Lake cores as was performed on Buttle Lake sediment cores (Rescan, 1990).

3.4 Biota

3.4.1 Benthic Invertebrates

The invertebrate taxa found at Mandy Lake are presented in Table 3-8. The profundal benthic invertebrate community was dominated by oligochaetes (tuberficid worms) and dipteran larvae (chironomids and *Chaoborus punctipennis*) due to the low oxygen content of the profundal zone (Table 3-9). The mean number of individuals ranged from 87 to 1174 individuals/m². The mid-lake stations showed the highest densities with a lake-wide mean of 533 individuals/m².

The densities of benthos are higher in Mandy Lake compared to oligotrophic Trout and Cliff lakes, near Flin Flon, Manitoba (Wilson 1984). The benthic community of these lakes was dominated by clams and chironomid larvae with densities ranging from 19 to 1165 individuals/m², and mean lake densities of 385 and 351 individuals/m² for Trout and Cliff lakes, respectively. *Chaoborus* larvae were less abundant in these lakes. Higher mean densities of profundal benthos, ranging from 3277 to 5592 individuals/m², were found in Southern Indian Lake in northern Manitoba (Wiens and Rosenberg 1984). The benthos of Southern Indian Lake were comprised of four main taxa: Diptera (mainly chironomids), Amphipoda, Oligochaeta and Pelecypoda (mainly sphaerids). Anderson Lake, a second Manitoba lake studied as part of the MEND program (Rescan 1990), had a slightly lower lake-wide mean density of 519 individuals/m² than Mandy Lake, with a community dominated by dipteran larvae and sphaerid clams, and no oligochaetes.

The variability in community composition and numbers of benthic invertebrates probably results from the heterogeneity of the lake bottom and the different feeding and habitat requirements of each species. For example, tuberficid worms feed in organic rich surficial sediments and can tolerate anaerobic conditions for extended time periods (Wetzel 1975), while *Chaoborus* larvae feed on small benthic animals or migrate off the sediments and feed on pelagic zooplankton. Sample stations varied in depth and

Table 3-8

Species and Taxa List of Benthic Invertebrates
Found in Mandy Lake

INSECTA

ODONATA

Aeshnidae

Aeshna

TRICHOPTERA

Phryganeidae

Phryganea

Molannidae

Molanna

Hydroptilidae

DIPTERA

Chaoboridae

Chaoborus (Sayomyia) punctipennis

Ceratopogonidae

Bezzia

Chironomidae

*Procladius**Tanypus**Corynoneura**Cricotopus-Orthocladius**Heterotrissocladius**Nanocladius**Psectrocladius**?Thienemanniella**Chironomus**Endochironomus**Glyptotendipes**Tanytarsus*

ANNELIDA

OLIGOCHAETA

TUBIFICIDA

Tubificidae

Limnodrilus claparedianus

Immature with bifids

Immature with hairs

Naididae

Dero digitata

ARTHROPODA

CRUSTACEA

DECAPODA

Astacidae

Cambarinae

MOLLUSCA

GASTROPODA

LYMNOPHILA

Physellidae

Physella

Planorbidae

Helisoma anceps

MESOGASTROPODA

Valvatidae

Valvata

Table 3-9 (cont'd)

Taxa	Ponar Samples																	
	0-1	0-2	0-3	1-1	1-2	1-3	2-1	2-2	2-3	3-1	3-2	3-3	4-1	4-2	4-3	5-1	5-2	5-3
Mollusca																		
Gastropoda																		
Planorbidae																		
<i>Hellsome anceps</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Mesogastropoda																		
Valvatidae																		
<i>Valvata</i> sp.	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Number of Taxa	6	5	0	4	2	5	2	5	1	2	2	4	0	3	3	0	2	3
Total Number of Individuals	14	13	0	7	2	6	6	22	20	31	6	44	0	4	3	0	2	4
Total Number of Taxa by Site	8			6			7			6			4			3		
Mean Number of Individual by Site	9.0			5.0			16.0			27.0			2.3			2.0		
Mean Number/m²	391			217			696			1174			100			87		

substrate characteristics; substrates ranged from clay/silts to fine and coarse organic material. Station 0, a shallow station with higher oxygen concentrations and variable substrate characteristics, had the highest number of taxa including snails, naidid oligochaetes and additional chironomid species.

Naidid oligochaetes are most abundant at the sediment-water interface, while tubificids burrow into the top 2 to 4 cm of sediment occasionally reaching as deep as 15 cm (Wetzel 1975). Tubifid burrowing activity can cause bioturbation, disrupting the sediment-water interface which can then alter the rates of chemical exchange between sediments and overlying waters. Such activity contributes to the heavy metals release through liberation of interstitial water, and concomitant excretion of faeces and transport of anaerobic sediment into aerobic surface layers (Forstner and Wittmann 1983).

Littoral invertebrates were collected incidentally while seining for fish (Table 3-10). This sample should not be considered complete since the large mesh size of the fish nets excluded many of the smaller invertebrate species. The aquatic invertebrates caught are not necessarily associated with the sediments but are common in littoral zones. Two additional orders and five additional families (Cambarinae, Aeshidae, Phryganeidae, Mollanidae and Physellidae) were found.

3.4.2 Phytoplankton

The various phytoplankton taxa collected in Mandy Lake are presented in Table 3-11. Chlorophyll *a* values ranged from 12.8 to 22.9 mg/m³ (Appendix D). At any given station the chlorophyll *a* value was the same or higher for the 0.5 m depth versus the 1.7 m depth. Chlorophyll *a* values and phytoplankton taxa and densities encountered (Appendix D) are good indicators of meso-eutrophic conditions (Wetzel 1975). The abundant diatom population (Bacillariophyceae), particularly *Asterionella formosa*, *Fragilaria crotonensis* and *Synedra*, the abundance of green algae species (Chlorophyta), blue-green algae (Cyanophyta), and euglenophytes (Euglenophyceae) are typical of mesotrophic to eutrophic conditions. Although no taxa were present in unusually high numbers, *Trachelmonas* spp. were moderately high at most stations.

Phytoplankton were generally evenly distributed throughout the lake. The average phytoplankton density of Mandy lake was 6714 cells/ml compared to average densities

Table 3-10

Littoral Benthic Invertebrates from Mandy Lake, Manitoba,
August 23, 1989

Taxa	Seine #2	Seine #4
Anthropoda		
Crustacea		
Decapoda		
Astacidae		
Cambarinae	0	1
Insecta		
Odonata		
Aeshnidae		
<i>Aeshna</i> sp.	1	0
Trichoptera		
Phryganeidae		
<i>Phryganea</i> sp.	0	1
Mollanidae		
<i>Molanna</i> sp.	0	1
Diptera		
Chironomidae		
Pupae	0	1
Larvae:		
<i>Corynoneura</i> sp.	1	1
<i>Cricotopus-Orthocladius</i> sp.	2	21
<i>Heterotrissocladius</i> sp.	1	0
<i>Nanocladius</i> sp.	0	1
<i>Psectrocladius</i> sp.	0	3
? <i>Thieneanniella</i> sp.	0	2
<i>Endochironomus</i> sp.	0	2
<i>Glyptotendipes</i> sp.	0	4
<i>Tanytarsus</i> sp.	0	5
Mollusca		
Gastropoda		
Lymnophila		
Physellidae		
<i>Physella</i> sp.	0	3
Total Number of Taxa	4	12
Total Number of Individuals	5	46

Table 3-11

**Classification of Taxa Encountered from
Phytoplankton Samples
from Mandy Lake**

<p>DIVISION CHRYSOPHYCOPHYTA CLASS BACILLARIOPHYCEAE ORDER PENNALES <i>Asterionella formosa</i> <i>Fragellaria crotonensis</i> <i>Fragellaria virescens</i> <i>Synedra radians</i> <i>Tabellaria fenestrata</i> ORDER CENTRALES <i>Coscinodiscus subtilus</i> <i>Rhizosolenia ariensis</i></p> <p>CLASS CHRYSOPHYCEAE ORDER OCHROMONADALES <i>Mallomonas</i> sp. indet.</p> <p>DIVISION EUGLENOPHYCOPHYTA ORDER EUGLENALES <i>Euglena</i> sp. 1 <i>Phacus</i> sp. <i>Trachelomonas</i> sp. 1 <i>Trachelomonas</i> sp. 2 <i>Trachelomonas</i> sp. 3</p> <p>DIVISION PYRRHOPHYCOPHYTA ORDER PERIDINIALES <i>Peridinium</i> sp. indet.</p> <p>DIVISION CRYPTOPHYCOPHYTA <i>Cryptomonas</i> sp. indet.</p> <p>DIVISION CYANOCHLORONTA ORDER OSCILLATORIALLES <i>Anabaena</i> sp. indet. <i>Apanothece</i> sp. indet. <i>Lyngbya</i> sp. <i>Loefgrenia</i> sp. <i>Spirolina major</i></p> <p>ORDER CHROOCOCCALES <i>Chroococcus</i> sp. indet. <i>Coelosphaerium</i> sp. indet. <i>Gomphosphaeria</i> sp. indet. <i>Merismopedia punctata</i></p>	<p>DIVISION CHLOROPHYCOPHYTA ORDER CHLOROCOCCALES <i>Closteridium</i> sp. indet.</p> <p>ORDER CHLORELLALES <i>Ankistrodesmus falcatus</i> <i>Coelastrum microsporum</i> <i>Dictyosphaerium pulchellum</i> <i>Scenedesmus bijuga</i> <i>Scenedesmus obliquus</i> <i>Scenedesmus quadricauda</i></p> <p>ORDER VOLVOCALES FAMILY CHLAMYDOMONADACEAE Chlamydomonadaceae spp. indet. <i>Haematococcus</i> sp.</p> <p>ORDER ULOTRICHALES Chlorophyte filament 1</p> <p>ORDER ZYGNEMATALES FAMILY ZYGNEMATACEAE <i>Spondylosium</i> sp. indet.</p> <p>FAMILY DESMIDIACEAE <i>Cosmarium biocculatum</i> <i>Cosmarium</i> sp. indet. <i>Staurastrum</i> sp. indet.</p> <p>ORDER OEDOGONIALES <i>Oedogonium</i> sp. indet.</p> <p>ORDER RHIZOCHRYSIDALES <i>Chrysidiastrum</i> sp. indet.</p>
--	---

of 7.5 and 12.8 cells/ml in Trout and Cliff lakes, respectively (Wilson 1984). Trout and Cliff lakes are oligotrophic to ultra-oligotrophic lakes near Flin Flon, Manitoba and are by diatoms with the virtual absence of chlorophytes. Mandy Lake is classified as mesotrophic to slightly eutrophic based on nitrogen and phosphorous values in the water column (Wetzel 1975). Anderson Lake had a slightly lower average phytoplankton density of 4346 cells/ml and similar algae species but no blue-green algae. Phytoplankton were unevenly distributed throughout Anderson Lake due to differences in lake morphometry and tailings discharge into the lake. Chlorophyll *a* values were lower, ranging from 0.66 mg/m³ near the discharge to 10.1 mg/m³ furthest from the discharge, which represents generally lower primary productivity in Anderson Lake relative to Mandy Lake.

3.4.3 Zooplankton

A diverse zooplankton community was found at Mandy Lake with densities ranging from 17,513 to 32,536 individuals/m³ (Table 3-12). The community was dominated by rotifers (Rotatoria), cladocerans (Cladocera), and copepods (Copepoda) with minor representation of trematode flatworms (Turbellaria), nematodes (Nematoda), chironomids (Chironomidae) and phantom midges (*Chaoborus* sp.). While higher densities of rotifers, cladocerans and copepods were found at Station 1, the zooplankton were generally evenly distributed throughout the lake. Anderson Lake had zooplankton densities ranging from 1441 to 80,000 individuals/m³ with the lowest values found at the tailings outfall (Rescan 1990).

Rotifer densities were generally low (Wetzel 1975), ranging from 8.2 to 22.5 individuals/L, and included representatives from two families, Testudinellidae and Asplanchidae (*Keratella* sp.). The density of cladocerans ranged from 2.7 to 7.1 individuals/L, while copepods ranged from 5.2 to 9.1 individuals/L. The densities of cladocerans and copepods combined are lower than those found in Southern Indian Lake, Manitoba, which showed densities of 10 to 200 individuals/L, and average densities of 40 to 76 individuals/L (Patalas and Salki 1974). Anderson Lake had rotifer densities ranging from 0.15 to 27.3 individuals/L, cladoceran densities ranging from 0.06 to 8.9 individuals/L, and copepods densities from 0.98 to 43.8 individuals/L (Rescan 1990). This high variability is attributed to differences in the lake's morphometry and tailings input.

Table 3-12

Mandy Lake - Density of Zooplankton Captured in Vertical and Horizontal Tows (individuals/m³)

Station Number		1	2	3	4
Date		23/08/89	23/08/89	23/08/89	23/08/89
Depth (m)		3.5	4.35	4	3
Time		16:00	15:06	14:47	14:15
Tow		VNH	VNH	VNH	VNH
Volume (m ³)		0.119	0.148	0.136	0.102
Split		0.0625	0.125	0.125	0.25
TAXON					
TURBELLARIA		134	0	0	0
NEMATODA		0	54	0	0
ROTATORIA					
Testudinellidae		0	0	0	0
Asplanchnidae		21916	8162	8294	8392
<i>Keratella</i> sp.		538	0	0	0
CLADOCERA					
<i>Diaphanosoma brachyurum</i>		0	0	0	0
<i>Bosmina longirostris</i>		2958	3676	5941	1922
<i>Alona costata</i>		269	0	235	431
<i>Graptoleberis testudinaria</i>		134	0	0	0
<i>Leptodora kindti</i>		269	0	412	118
Cladoceran embryos		403	432	471	275
COPEPODA					
<i>Epischura lacustris</i>	Vlf	0	0	0	0
<i>Diaptomus oregonensis</i>	Vlf	134	54	118	39
	Vlm	0	0	59	0
	V	0	270	588	0
Calanoid copepodites	IV	538	162	412	196
	III	134	0	0	353
	II	0	0	0	39
	I	0	0	0	0
<i>Topocyclops prasinus</i>	Vlf	0	0	0	0
<i>Eucyclops macrurus</i>	Vlf	0	0	0	0
Cyclops	Vlf	0	108	0	78
	Vlm	0	0	0	118
	V	134	0	0	39
Cyclopoids	I-IV	2017	2865	6000	3333
Copepod nauplii		2958	1730	1882	902
INSECTA					
Chironomid larvae		0	0	59	39
Chaoborus larvae		0	0	59	0
TOTALS (individuals/m³)		32536	17513	24530	16274

VNH = Vertical net haul
 HNH = Horizontal net haul

Table 3-12 (cont'd)

Station Number		HNT1	HNT2	HNT3
Date		23/08/89	23/08/89	23/08/89
Depth (m)		3.5	4.35	4
Time		16:00	15:06	14:47
Tow		HNH	HNH	HNH
Volume (m ³)		3.39	5.085	7.797
Split		0.125	0.0625	0.0313
TAXON				
TURBELLARIA		0	0	0
NEMATODA		0	0	0
ROTATORIA				
Testudinellidae		19	0	0
Asplanchnidae		345	318	340
<i>Keratella</i> sp.		9	0	0
CLADOCERA				
<i>Diaphanosoma brachyurum</i>		5	0	0
<i>Bosmina longirostris</i>		57	535	524
<i>Alona costata</i>		5	9	8
<i>Graptoleberis testudinaria</i>		0	0	0
<i>Leptodora kindti</i>		64	3	66
Cladoceran embryos		0	19	0
COPEPODA				
<i>Epischura lacustris</i>	Vlf	2	0	0
<i>Diaptomus oregonensis</i>	Vlf	0	0	4
	Vlm	0	0	0
	V	0	0	4
Calanoid copepodites	IV	9	3	29
	III	2	0	20
	II	0	0	0
	I	0	0	0
<i>Topocyclops prasinus</i>	Vlf	0	3	20
<i>Eucyclops macrurus</i>	Vlf	2	0	0
Cyclops	Vlf	2	0	0
	Vlm	0	0	0
	V	0	0	0
Cyclopoids	I-IV	47	132	57
Copepod nauplii		35	195	107
INSECTA				
Chironomid larvae		0	0	4
Chaoborus larvae		0	0	0
TOTALS (individuals/m ³)		603	1217	1183

VNH = Vertical net haul
 HNH = Horizontal net haul

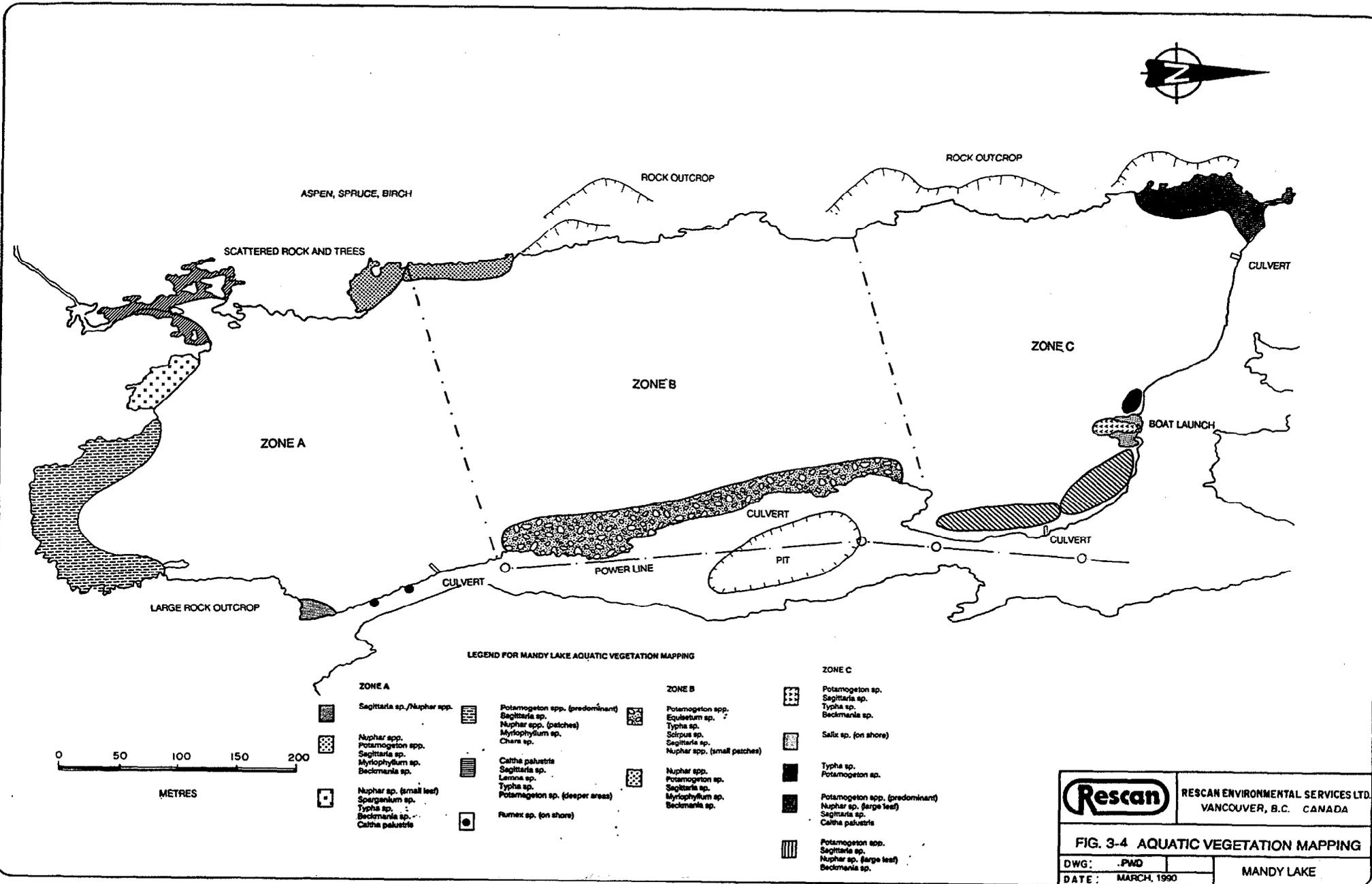
3.4.4 Aquatic Vegetation

Aquatic vegetation is well established in the littoral zones of Mandy Lake including the submerged tailings area near the pit (Figure 3-4). Common genera found in the littoral zone included *Typha*, *Scirpus*, *Potamogeton*, *Sagittaria*, *Nuphar*, *Beckmania* and *Myriophyllum*.

The areas of littoral development around the lake correspond to the 1-2 m depth contour on the bathymetric map (Figure 3-1). The absence of littoral vegetation along the west shore and southeast corner are the result of steep drop-offs in depth. The littoral area over the tailings in Zone B (Figure 3-4) has been colonized by species previously considered intolerant (Hamilton and Fraser 1978). This area which previously supported sedges, riverweed and spike rush, now supports a healthy growth of pondweed (*Potamogeton* spp.), bullrushes (*Scirpus* sp.), pond lilies (*Nuphar* spp.), cattails (*Typha* sp.), horsetails (*Equisetum* sp.) and *Sagittaria* sp. The settlement and development of an organic mat at this site appears to have provided the base for establishment of plant species previously intolerant of tailings sediments. The high primary productivity of the lake appears to be contributing to its natural recovery.

Metal analyses of aquatic vegetation revealed 2 to 10x higher levels of arsenic, cadmium, copper, lead, mercury, nickel and zinc in *Potamogeton* sp. from the tailings (Site V1) as opposed to the south end of the lake (Site V2) (Table 3-13). The largest increases were observed in declining order of arsenic, zinc, cadmium, copper, lead, mercury and nickel. *Typha* sp. collected only at the tailings site (Site V1) had elevated concentrations of arsenic, copper and zinc.

Aquatic vegetation from Anderson Lake generally had lower or similar metal concentrations in their tissue (Rescan 1990). Aerial leaves of *Typha* sp. growing adjacent to a tailings seepage area in Anderson Lake contained lower levels of arsenic, cadmium, copper, mercury and zinc, and comparable concentrations of lead and nickel. In an area furthest from the active tailings discharge in Anderson Lake, the arsenic, cadmium, copper, lead and zinc levels in *Typha* sp. were lower still, however, the nickel concentration (2.50 $\mu\text{g/g}$ - dry weight) was higher. In this area, the metal levels in *Potamogeton* sp. were comparable to the uncontaminated site in Mandy Lake, with the exception of nickel which was again higher (3.75 $\mu\text{g/g}$ - dry weight).



ASPEN, SPRUCE, BIRCH

SCATTERED ROCK AND TREES

ROCK OUTCROP

ROCK OUTCROP

CULVERT

ZONE C

ZONE B

ZONE A

BOAT LAUNCH

CULVERT

PIT

POWER LINE

CULVERT

CULVERT

LARGE ROCK OUTCROP

LEGEND FOR MANDY LAKE AQUATIC VEGETATION MAPPING

ZONE A

- Sagittaria sp./Nuphar spp.
- Nuphar spp., Potamogeton spp., Sagittaria sp., Myriophyllum sp., Beckmannia sp.
- Nuphar sp. (small leaf), Sparganium sp., Typha sp., Beckmannia sp., Caltha palustris

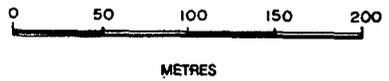
- Potamogeton spp. (predominant), Sagittaria sp., Nuphar spp. (patches), Myriophyllum sp., Chara sp.
- Caltha palustris, Sagittaria sp., Lemna sp., Typha sp., Potamogeton sp. (deeper areas)
- Rumex sp. (on shore)

ZONE B

- Potamogeton spp., Equisetum sp., Typha sp., Scirpus sp., Sagittaria sp., Nuphar spp. (small patches)
- Nuphar spp., Potamogeton sp., Sagittaria sp., Myriophyllum sp., Beckmannia sp.

ZONE C

- Potamogeton sp., Sagittaria sp., Typha sp., Beckmannia sp.
- Salix sp. (on shore)
- Typha sp., Potamogeton sp.
- Potamogeton spp. (predominant), Nuphar spp. (large leaf), Sagittaria sp., Caltha palustris
- Potamogeton spp., Sagittaria sp., Nuphar spp. (large leaf), Beckmannia sp.



	RESCAN ENVIRONMENTAL SERVICES LTD. VANCOUVER, B.C. CANADA	
	FIG. 3-4 AQUATIC VEGETATION MAPPING	
DWG: .PMD	MANDY LAKE	
DATE: MARCH, 1990		

Table 3-13

Metal Analyses of Mandy Lake Aquatic Vegetation

Site	Date	Site Description	Plant Species	Tissue Samples	Metal ($\mu\text{g/g}$ - dry weight)						
					As	Cd	Cu	Pb	Hg	Ni	Zn
V1	24/08/89	East side (Zone B) across from pit	<i>Potamogeton</i> sp. (oval leaf)	Leaves, stems	80.3	3.80	98.8	12.1	0.30	2.50	1205
			<i>Typha</i> sp.	Leaves	3.50	0.20	6.50	1.10	0.065	0.50	208
V2	23/08/89	South end (Zone C) south of Str. 5	<i>Potamogeton</i> sp. (oval leaf)	Leaves, stems	8.0	0.45	15.3	2.95	0.075	1.15	129

With aquatic vegetation recolonizing the tailings area, the uptake of metals from the tailings may be remobilized through seasonal vegetation die-off and subsequent decomposition. Thus the aquatic vegetation may actually increase metal levels into the water and increase metal availability to other biota.

3.4.5 Fish

Fish species caught in Mandy Lake included northern pike (*Esox lucius*), lake whitefish (*Coregonus clupeaformis*), white sucker (*Catostomus commersoni*) yellow perch (*Perca flavescens*) and spottail shiner (*Notropis hudsonius*) (Appendix E). Only the pike were aged and all aged pike were mature. Male pike ranged from 4 - 12 years of age; females were 7 - 9 years old. There were no obvious relationships between age or size and most metal concentrations in the tissues. The possible exceptions are copper and mercury in northern pike where an increase in size and age may correspond to increased metal concentrations in the tissues (Appendix F). Sample sizes, however, were deemed inadequate for statistical tests of such relationships. Metal concentrations in fish tissues from Mandy Lake are summarized in Table 3-14. In almost all cases, observed metal levels in Mandy Lake fish are within background levels for freshwater fish in Canada.

Arsenic was not detectable in any of the fish species caught in Mandy Lake, and cadmium was not detectable in lake whitefish (Table 3-14). In other Manitoba lakes, especially those impacted by mine tailings, arsenic is found at greater than 0.2 ppm (Table 3-15). Cadmium has often not been detectable in fish tissue from Manitoba lakes, whether affected by mine tailings or not (Table 3-15). Both arsenic and cadmium tissues concentrations from Mandy Lake are comparable or even less than background levels observed elsewhere in Manitoba and the rest of Canada (Table 3-15, Demayo et al. 1979, Reeder et al. 1979a).

The concentrations of copper observed in Mandy Lake fish are similar to those found in the same species in Manitoba lakes unaffected by mine operations (Table 3-15), and are generally less than levels found in Great Lakes fishes (Demayo and Taylor 1981). Copper concentrations in fish muscle from Mandy Lake were highest in white sucker (Table 3-14), which may be related to this species' bottom feeding lifestyle.

Lead is a highly toxic metal, and is usually found at background levels of <0.5 ppm wet weight in fish muscle in Canada (Demayo et al. 1980). In other Manitoba lakes, lead has

Table 3-14
A Summary of Metal Concentrations
in Mandy Lake Fish Samples

Fish Species	Tissue Type	Metal (ppm - wet weight)						
		As	Cd	Cu	Pb	Hg	Ni	Zn
Lake Whitefish	Muscle (n=2) ^c	<0.2	<0.005	0.098-0.124 ^a	<0.01-0.014	0.004-0.009	0.014-0.018	4.6-5.44
White Sucker	Muscle (n=3)	<0.2	0.005 ± 0.005 ^b (<0.005-0.006)	0.19 ± 0.041 (0.16-1.84)	0.043 ± 0.055 (<0.01-0.106)	0.013 ± 0.0130 (0.0042-0.028)	0.065 ± 0.0272 (0.048-0.096)	5.37 ± 0.960 (4.26-5.98)
Northern Pike	Muscle (n=3)	<0.2	0.008 ± 0.0056 (0.004-0.018)	0.2 ± 0.13 (0.098-0.428)	0.02 ± 0.016 (0.008-0.0192)	0.08 ± 0.040 (0.0194-0.128)	0.04 ± 0.021 (0.01-0.06)	11.1 ± 9.35 (5.12-27.6)
	Liver (n=2)	<0.2	0.026-0.142 ^b	6.54-11.04	0.0148-0.015	0.022-0.044	0.01-0.022	28.4-29.0

a Range
b Mean ± standard deviation (range). Note - below detectable limit measurements are taken as detectable limit for calculations
c Sample size
Metal concentrations in tissue wet weight were calculated for comparison purposes by applying a factor of 0.2 to dry weight measurements from Appendix F

Table 3-15

**Mean and Highest Metal Concentrations
Found in Fish Tissue in Various Manitoba Lakes
Mean Followed by (Maximum)**

Lake	Lake Status	Metal (ppm - wet weight)						
		As	Cd	Cu	Pb	Hg	Ni	Zn
Northern Pike								
Burge Lake ¹	Background	0.12 (0.17)	<0.01 (0.01)	0.24 (0.52)	0.01 (0.02)	0.18 (0.29)	0.10 (0.12)	5.82 (18.3)
Rice Lake ²	Tailings Releases	0.03 (0.08)	<0.1 (0.2)	0.91 (2.0)	0.87 (2.5)	0.54 (1.12)	<0.61 (2.0)	3.54 (4.6)
Snow Lake ³	Stockpile Drainage	0.07 (0.26)	<0.1 (<0.1)	0.47 (0.80)	0.61 (1.0)	0.31 (0.45)	0.68 (1.0)	5.5 (7.7)
Herblet Lake ³	Tailings Releases	0.47 (2.20)	<0.1 (<0.1)	0.18 (0.3)	<0.51 (0.6)	0.36 (0.65)	<0.53 (0.6)	5.3 (8.2)
Gods Lake ⁴	Background	0.02 (0.03)	<0.1 (<0.1)	0.15 (0.50)	0.53 (0.80)	0.30 (0.51)	<0.5 (<0.5)	6.53 (9.0)
	Tailings Releases	0.04 (0.09)	<0.1 (<0.1)	0.48 (0.90)	0.52 (0.80)	0.29 (0.52)	<0.5 (0.5)	4.55 (8.4)
Trout Lake ⁵	Background	0.11 (0.31)	<0.1 (<0.1)	0.27 (0.5)	<0.5 (<0.5)	0.35 (0.68)	<0.5 (<0.5)	4.75 (7.8)
Cliff Lake ⁵	Background	0.08 (0.11)	<0.1 (<0.1)	0.35 (0.5)	<0.5 (<0.5)	0.32 (0.44)	0.52 (0.7)	6.16 (11.6)

1 Rescan Environmental Services Ltd. 1989

2 Beck 1984B

3 Beck 1984A

4 Beck 1982

5 Wilson 1984

Table 3-15 (cont'd)

Lake	Lake Status	Metal (ppm - wet weight)						
		As	Cd	Cu	Pb	Hg	Ni	Zn
Lake Whitefish								
Burge Lake ¹	Background	0.15 (0.31)	<0.01 (0.1)	0.42 (0.88)	0.02 (0.10)	0.12 (0.21)	0.10 (0.14)	5.82 (18.3)
Snow Lake ³	Stockpile Drainage	0.11 (0.33)	<0.01 (<0.1)	0.23 (0.5)	0.55 (1.0)	0.12 (0.25)	<0.5 (<0.5)	4.1 (7.1)
Gods Lake ⁴	Background	0.04 (0.08)	<0.1 (<0.1)	0.29 (0.80)	<0.5 (0.5)	0.06 (0.10)	<0.5 (<0.5)	5.71 (7.4)
	Tailings Releases	0.08 (0.19)	<0.1 (<0.1)	0.15 (0.50)	<0.5 (<0.5)	0.11 (0.26)	<0.5 (<0.5)	3.86 (5.4)
Trout Lake ⁵	Background	0.19 (0.76)	<0.1 (<0.1)	0.24 (0.4)	<0.5 (<0.5)	0.13 (0.22)	<0.5 (<0.5)	3.99 (5.7)
Cliff Lake ⁵	Background	0.03 (0.05)	<0.1 (<0.1)	0.45 (0.6)	<0.5 (<0.5)	0.02 (<0.02)	<0.5 (<0.5)	5.33 (6.4)
White Sucker								
Rice Lake ²	Tailings Release	<0.02 (<0.02)	<0.01 (<0.01)	0.58 (0.9)	0.60 (0.7)	0.30 (0.42)	0.56 (1.0)	3.45 (4.5)
Snow Lake ³	Stockpile Drainage	0.05 (0.27)	<0.13 (0.6)	0.43 (0.7)	<0.5 (0.5)	0.04 (0.09)	<0.5 (0.5)	4.0 (4.7)
Herblet Lake ³	Tailings Release	0.15 (0.46)	<0.1 (0.1)	0.32 (0.7)	<0.5 (0.5)	0.07 (0.13)	<0.52 (0.8)	4.6 (6.1)
Gods Lake ⁴	Background	0.03 (0.06)	<0.1 (<0.1)	0.44 (0.80)	<0.5 (<0.5)	0.06 (0.10)	0.57 (1.80)	3.72 (7.2)
	Tailings Release	0.05 (0.09)	<0.1 (<0.1)	0.17 (1.0)	<0.5 (<0.5)	0.17 (0.35)	<0.5 (<0.5)	4.98 (6.6)
Trout Lake ⁵	Background	0.04 (0.08)	<0.1 (<0.1)	0.36 (1.0)	<0.5 (0.5)	0.05 (0.11)	<0.5 (<0.5)	6.19 (10.0)

1 Rescan Environmental Services Ltd. 1989

2 Beck 1984B

3 Beck 1984A

4 Beck 1982

5 Wilson 1984

often not been detectable in lake whitefish and white suckers, but has been found at >0.5 ppm in northern pike from lakes impacted by mine tailings discharge (Table 3-15). In Mandy Lake, lead concentrations in northern pike tissues are even less than those observed in the lake whitefish and white suckers (Table 3-14). Lead concentrations in all three fish species are within background ranges observed elsewhere in Canada and are below the recommended fish content level for human consumption of 0.5 ppm (Demayo et al. 1980).

The recommended safe limit for mercury in edible fish in Canada is 0.5 ppm wet weight. Background concentrations in Canadian freshwater fish are usually <0.5 ppm (Reeder et al. 1979). Mercury concentrations in fish from Mandy Lake were all within background levels (Table 3-14). Of the three species examined, however, northern pike show the highest mercury concentrations in the muscle. Predatory fish usually exhibit higher mercury levels than other species (Reeder et al 1979b). Other Manitoba lakes, both impacted and not impacted by mine tailings, showed much higher levels of mercury in fish tissues (Table 3-15).

Nickel concentrations in fish from Mandy Lake were typically <0.1 ppm (Table 3-14). This is less than reported as background levels in other Manitoba lakes (Table 3-15) and elsewhere in Canada (<0.17 ppm wet weight; Taylor et al. 1979).

Zinc is an essential element that is bioaccumulated to relatively high levels, especially by omnivorous and bottom feeding fish (Taylor and Demayo 1980). It is, therefore, surprising that the highest concentrations observed in Mandy Lake fish were in predatory northern pike (Table 3-14). The concentrations observed in Mandy Lake pike muscle were on average about 2x the concentrations found in pike from other Manitoba lakes (Table 3-15). Concentrations found in Mandy Lake whitefish and suckers are similar to those levels observed in other Manitoba lakes. The levels of zinc in Mandy Lake fish however were well within background levels found in Great Lakes fish and are within the recommended levels for human consumption (100 ppm wet weight; Taylor and Demayo 1980).

4 - Conclusions

4.0 CONCLUSIONS

Examination of water quality in Mandy Lake indicated that the overall water quality in the lake was good and that metals release from the sediments appears to be minimal. The metal levels in water samples taken directly above the bottom sediments were lower than those collected above shallow tailings in 1975.

Although sediment metal levels are elevated, in those areas where tailings were deposited, the organic layer covering these sediments appears to be effectively reducing oxygen concentrations at the water-sediment interface thereby providing an effective barrier to metal release. The high productivity of the lake maintains low O₂ levels in the sediments through decomposition of the organics. Organic-metal complexes may also limit the release of metals to the water column.

Sequential extraction studies on tailings sediments resulted in the release of certain metals from the water-soluble phase. Post-collection oxidation of the sample may partially explain these releases.

Benthic invertebrates are well established in the lake with the number of taxa likely limited by the low oxygen content of the profundal zone.

The diverse phytoplankton community was evenly distributed throughout the lake and species present and densities are indicative of meso-eutrophic conditions.

The diverse zooplankton community was dominated by rotifers, cladocerans and copepods.

The limited littoral zone of the lake is well colonized. The area of shallow tailings has become colonized by species which were previously intolerant to the sediment conditions. The elevated metal concentration in pondweed collected over tailings sediments indicates that some metal cycling is occurring in the vegetation. As the littoral zone of many lakes are extensively colonized, it is imperative that subaqueous disposal systems be designed so that deposition occurs in the deeper depositional areas without vegetative growth. Root respiration from vegetation growing on tailings may supply enough oxygen to oxidize sulphides with concomitant metal solubilization and potential plant uptake. Moreover, depositing tailings at depth would prevent

transportational process from resuspending tailings sediments and would allow for more rapid sealing of the deposits with a reducing organic layer.

Metals do not, however, appear to be bioaccumulating in the fish. A healthy fish population exists in Mandy Lake with metal levels comparable or lower than those observed in other Manitoba lakes.

The reasonably diverse and abundant biotic communities observed in Mandy Lake indicates that the lake has rehabilitated naturally and it appears likely it will continue to do so.

References

REFERENCES

- APHA. 1985. Standard Methods for the Examination of Water and Wastewater. American Public Health Association. Washington, D.C.
- CCREM. 1987. Canadian Water Quality Guidelines. Prepared by Task Force on Water Quality Guidelines of the Canadian Council of Resource and Environment Ministers, March 1987.
- Demayo, A., M.C. Taylor, and S.W. Reeder. 1979. Guidelines for Surface Water Quality. Vol I. Inorganic Chemical Substances. Arsenic. Environment Canada, Inland Waters Directorate, Water Quality Branch, Ottawa, 13 p.
- Demayo, A., M. C. Taylor, and S. W. Reeder. 1980. Guidelines for Surface Water Quality. Vol I. Inorganic Chemical Substances. Lead. Environment Canada, Inland Waters Directorate, Water Quality Branch, Ottawa, 36 p.
- Demayo, A., and M. C. Taylor. 1981. Guidelines for Surface Water Quality. Vol I. Inorganic Chemical Substances. Copper. Environment Canada, Inland Waters Directorate, Water Quality Branch, Ottawa, 55 p.
- Engler, R.M., J.M. Brannon, and J. Rose. 1974. A Practical Selective Extraction Procedure for Sediment Characterization. Presented at Symposium on Chemistry of Marine Sediments, National American Chemical Society Meeting, Atlantic City, N.J., August 12, 1974.
- Evans, L.J. 1989. The Chemistry of Metal Retention by Soils. Environ. Sci. Technol. 23: 1046-1056.
- Forstner, U., & G.T.W. Wittmann. 1983. Metal Pollution in the Aquatic Environment, Springer-Verlag, New York.
- Hamilton, R. and W.W. Fraser. 1978. A Case History of Natural Underwater Revegetation: Mandy Mine High Sulphide Tailings. Reclamation Review. 1:61-65.

- Hutchinson, G.E. 1957. *A Treatise on Limnology*. John Wiley & Sons, Inc. New York, New York.
- Patalas, K. and A. Salki. 1984. Effects of Impoundment and Diversion on the Crustacean Plankton of Southern Indian Lake. *Can. J. Fish. Aquat. Sci.* 41(4): 613-637.
- Pedersen, T.F., S.J. Malcolm and E.R. Sholkovitz. 1985. A Lightweight Gravity Corer for Undisturbed Sampling of Soft Sediments. *Can. Jour. of Earth Sci.* 22: 133-135.
- Pennak, R.W. 1978. *Fresh-Water Invertebrates of the United States*. 2nd Edition. John Wiley & Sons.
- Reeder, S.W., A. Demayo, and M.C. Taylor. 1979a. Guidelines for Surface Water Quality. Vol. 1. Inorganic Chemical Substances. Cadmium. Environment Canada, Inland Waters Directorate, Water Quality Branch, Ottawa, 19p.
- Reeder, S. W., A. Demayo, and M. C. Taylor. 1979b. Guidelines for Surface Water Quality. Vol I. Inorganic Chemical Substances. Mercury. Environment Canada, Inland Waters Directorate, Water Quality Branch, Ottawa, 16 p.
- Rescan Environmental Services Ltd.. 1990. A Preliminary Assessment of Subaqueous Tailings Disposal in Anderson Lake, Manitoba. Prepared for CANMET/Environment Canada.
- Taylor, M. C., A. Demayo, and S. W. Reeder. 1979. Guidelines for Surface Water Quality. Vol I. Inorganic Chemical Substances. Nickel. Environmental Canada, Inland Waters Directorate, Water Quality Branch, Ottawa, 12 p.
- Taylor, M. C., and A. Demayo. 1980. Guidelines for Surface Water Quality. Vol I. Inorganic Chemical Substances. Zinc. Environmental Canada, Inland Waters Directorate, Water Quality Branch, Ottawa, 52 p.
- Torke, B.G. 1974. *An Illustrated Guide to the Identification of the Planktonic Crustacea of Lake Michigan With Notes on Their Ecology*. Special Report No. 17. University of Wisconsin.

- Torke, B.G. 1976. A Key to the Identification of Cyclopoid Copepods of Wisconsin, With Notes on Their Distribution and Ecology. Research Report 88. Department of Natural Resources, Wisconsin.
- Ward, H.B. & G.C. Whipple. 1963. Fresh Water Biology. 2nd Edition. John Wiley & Sons.
- Wetzel, R.G. 1975. Limnology. W.B. Saunders Co. Philadelphia, Pa.
- Wilson, D. 1984. A Background Study of Trout (Embury) and Cliff Lake. Manitoba Environment and Workplace Safety and Health, Water Standards and Studies Report. #84-7. 40 pp.

**Dissolved Oxygen and Temperature
Profiles for Mandy Lake at
Four Stations**

Table A-1

Station	1		2		3		4	
Date	23/08/89		23/08/89		23/08/89		23/08/89	
Time	21:10		20:40		20:05		19:25	
Secchi (m)	1.35		1.20		1.20		1.35	
Max z (m)	3.6		4.3		4.2		3.8	
	DO	TEMP	DO	TEMP	DO	TEMP	DO	TEMP
	(mg/L)	(°C)	(mg/L)	(°C)	(mg/L)	(°C)	(mg/L)	(°C)
Depth (m)								
0.25	8.65	18.9	8.3	18.8	7.8	18.9	8.25	19.0
0.50	8.0	18.9	8.25	18.9	7.7	18.9	8.25	19.0
0.75	7.9	19.0	7.95	19.0	7.7	18.9	8.2	19.0
1.00	8.1	19.0	7.9	19.0	7.6	18.9	8.1	19.0
1.25	8.0	19.0	8.0	19.0	7.6	18.9	8.15	18.9
1.50	7.9	18.9	7.8	19.0	7.7	18.9	8.15	18.9
1.75	7.9	18.9	7.8	19.0	7.7	18.9	8.15	18.9
2.00	8.1	19.0	7.7	19.0	7.8	18.9	7.8	18.8
2.25	7.8	19.0	7.7	19.0	7.7	18.9	0.60	18.8
2.50	0.40	18.8	7.6	19.0	7.7	18.9	0.30	18.8
2.75	0.10	18.8	0.25	19.0	0.25	18.9	0.10	18.8
3.00	0.10	18.8	0.10	18.8	0.10	18.8	0.075	18.8
3.25	0.05	18.8	0.10	18.9	0.10	18.8	0.075	18.8
3.50	0.05	18.8	0.075	18.9	0.05	18.8	0.075	18.8
3.75	-	-	0.06	18.9	0.05	18.8	0.075	18.8
4.00	-	-	0.05	18.9	0.05	18.7		
4.25	-	-	0.05	18.8	-	-		
4.50	-	-	-	-	-	-		

**Mandy Lake - Water Quality Data for
Lake Stations**

Table B-1

Site Number	ML 1A	ML 1B	ML 1C	ML 1D
Date Sampled	Aug 23/89	Aug 23/89	Aug 23/89	Aug 23/89
Time	21:10	21:05	21:00	20:52
Depth (m)	0.5	1.7	2.7	3.6
Physical Tests				
pH (lab)	7.58	7.05	7.15	7.02
Conductivity	185.	182.	174.	181.
Dissolved Solids	160.	160.	160.	160.
Suspended Solids	3.0	2.0	2.0	2.0
Fixed Volatile Solids	3.0	1.0	2.0	2.0
Turbidity	6.3	6.0	5.9	4.5
Anions & Nutrients				
Alkalinity	76.5	75.4	77.6	77.6
Sulphate	16.4	17.0	16.6	16.9
Chloride	4.3	4.2	4.2	4.2
T-Phosphorous	0.033	0.026	0.025	0.042
NO ₃ /NO ₂	0.14	0.14	0.14	0.14
Ammonia	<0.005	<0.005	<0.005	<0.005
T-Dissolved Nitrogen	0.38	0.40	0.44	0.39
TOC	8.0	8.0	7.9	8.1
Silicate	1.7	1.6	1.7	1.8
Dissolved Metals				
Aluminum	<0.005	<0.005	0.005	<0.005
Arsenic	0.0086	0.0094	0.0087	0.0083
Cadmium	0.0002	<0.0002	<0.0002	0.0012
Copper	0.004	0.006	0.005	0.004
Iron	<0.03	<0.03	<0.03	<0.03
Lead	0.001	<0.001	0.003	<0.001
Manganese	<0.005	<0.005	<0.005	<0.005
Mercury	<0.00005	<0.00005	<0.00005	<0.00005
Nickel	<0.001	<0.001	<0.001	<0.001
Silver	<0.0001	<0.0001	<0.0001	<0.0001
Zinc	0.006	0.007	0.006	0.006
Calcium	24.2	23.8	23.8	23.9
Magnesium	6.35	6.16	6.24	6.44
Potassium	1.86	1.87	1.86	1.82
Sodium	3.58	3.50	3.47	3.49

Results expressed as milligrams per litre except for pH, Conductivity (μ mhos/cm) and Turbidity (NTU)

< = Less than

T = Total

NO₃/NO₂ = Nitrate/nitrite nitrogen

TOC = Total Organic Carbon

Table B-2

Site Number	ML 2A	ML 2B	ML 2C	ML 2D
Date Sampled	Aug 23/89	Aug 23/89	Aug 23/89	Aug 23/89
Time	20:35	20:30	20:20	20:15
Depth (m)	0.5	1.7	2.7	4.3
Physical Tests				
pH (lab)	7.07	7.01	7.03	7.04
Conductivity	178.	186.	185.	187.
Dissolved Solids	160.	160.	170.	170.
Suspended Solids	4.0	4.0	2.0	4.0
Fixed Volatile Solids	4.0	2.0	2.0	4.0
Turbidity	9.2	5.4	5.3	5.4
Anions & Nutrients				
Alkalinity	77.6	77.6	76.5	75.4
Sulphate	16.6	16.8	16.1	17.2
Chloride	4.2	4.2	4.2	6.6
T-Phosphorous	0.031	0.040	0.032	0.036
NO ₃ /NO ₂	0.15	0.16	0.16	0.18
Ammonia	<0.005	<0.005	<0.005	<0.005
T-Dissolved Nitrogen	0.34	0.34	0.31	0.35
TOC	7.9	8.1	8.1	8.1
Silicate	2.2	1.5	1.7	1.7
Dissolved Metals				
Aluminum	<0.005	<0.005	0.005	0.009
Arsenic	0.0087	0.0091	0.0086	0.0086
Cadmium	<0.0002	<0.0002	<0.0002	<0.0002
Copper	0.004	0.004	0.004	0.007
Iron	<0.03	<0.03	<0.03	<0.03
Lead	<0.001	<0.001	<0.001	<0.001
Manganese	<0.005	<0.005	<0.005	<0.005
Mercury	<0.00005	<0.00005	<0.00005	<0.00005
Nickel	<0.001	<0.001	<0.001	<0.001
Silver	<0.0001	<0.0001	<0.0001	<0.0001
Zinc	0.006	0.009	0.006	0.008
Calcium	23.6	24.1	24.2	23.7
Magnesium	6.27	6.53	6.28	6.10
Potassium	1.83	1.79	1.81	1.82
Sodium	3.37	3.49	3.35	3.41

Results expressed as milligrams per litre except for pH, Conductivity (μ mhos/cm) and Turbidity (NTU)

< = Less than

T = Total

NO₃/NO₂ = Nitrate/nitrite nitrogen

TOC = Total Organic Carbon

Table B-3

Site Number	ML 3A	ML 3B	ML 3C	ML 3D
Date Sampled	Aug 23/89	Aug 23/89	Aug 23/89	Aug 23/89
Time	19:57	19:49	19:42	19:38
Depth (m)	0.5	1.7	2.7	4.2
Physical Tests				
pH (lab)	7.07	7.06	7.04	7.05
Conductivity	181.	184.	187.	186.
Dissolved Solids	160.	160.	160.	160.
Suspended Solids	2.0	5.0	3.0	4.0
Fixed Volatile Solids	2.0	4.0	2.0	4.0
Turbidity	6.2	9.2	6.3	6.9
Anions & Nutrients				
Alkalinity	77.6	77.6	77.6	77.6
Sulphate	16.1	17.2	16.5	17.6
Chloride	4.3	4.2	4.2	4.3
T-Phosphorous	0.024	0.020	0.048	0.045
NO3/NO2	0.15	0.16	0.16	0.17
Ammonia	<0.005	<0.005	<0.005	<0.005
T-Dissolved Nitrogen	0.33	0.33	0.32	0.31
TOC	8.2	8.2	8.4	8.1
Silicate	1.8	1.7	1.7	1.6
Dissolved Metals				
Aluminum	<0.005	<0.005	0.005	<0.005
Arsenic	0.0087	0.0092	0.0080	0.0079
Cadmium	<0.0002	<0.0002	<0.0002	0.0002
Copper	0.004	0.004	0.004	0.004
Iron	<0.03	<0.03	<0.03	<0.03
Lead	<0.001	0.001	<0.001	<0.001
Manganese	<0.005	<0.005	<0.005	<0.005
Mercury	<0.00005	<0.00005	<0.00005	<0.00005
Nickel	<0.001	<0.001	<0.001	<0.001
Silver	<0.0001	<0.0001	<0.0001	<0.0001
Zinc	0.006	0.006	<0.005	0.007
Calcium	23.4	23.4	24.2	23.3
Magnesium	6.17	6.31	6.54	6.23
Potassium	1.85	1.80	1.84	1.87
Sodium	3.35	3.37	3.38	3.32

Results expressed as milligrams per litre except for pH, Conductivity (μ mhos/cm) and Turbidity (NTU)

< = Less than

T = Total

NO3/NO2 = Nitrate/nitrite nitrogen

TOC = Total Organic Carbon

Table B-4

Site Number	ML 4A	ML 4B	ML 4C	ML 4D
Date Sampled	Aug 23/89	Aug 23/89	Aug 23/89	Aug 23/89
Time	19:10	19:00	18:30	18:00
Depth (m)	0.5	1.7	2.7	3.7
Physical Tests				
pH (lab)	7.03	7.02	7.02	7.00
Conductivity	185.	187.	183.	191.
Dissolved Solids	160.	160.	160.	160.
Suspended Solids	5.0	3.0	2.0	1.0
Fixed Volatile Solids	3.0	3.0	1.0	1.0
Turbidity	7.4	6.5	7.0	5.5
Anions & Nutrients				
Alkalinity	77.6	77.6	77.6	76.5
Sulphate	16.2	17.0	16.5	16.3
Chloride	4.3	4.2	5.6	4.2
T-Phosphorous	0.038	0.041	0.045	0.043
NO ₃ /NO ₂	0.18	0.17	0.17	0.16
Ammonia	<0.005	<0.005	<0.005	<0.005
T-Dissolved Nitrogen	0.32	0.36	0.54	0.54
TOC	8.0	8.0	8.0	8.3
Silicate	1.2	1.5	1.8	1.9
Dissolved Metals				
Aluminum	0.005	<0.005	<0.005	<0.005
Arsenic	0.0085	0.0064	0.0080	0.0087
Cadmium	<0.0002	<0.0002	<0.0002	<0.0002
Copper	0.004	0.004	0.004	0.004
Iron	<0.03	<0.03	<0.03	<0.03
Lead	0.001	<0.001	<0.001	0.001
Manganese	<0.005	<0.005	<0.005	<0.005
Mercury	<0.00005	<0.00005	<0.00005	<0.00005
Nickel	<0.001	<0.001	<0.001	<0.001
Silver	<0.0001	<0.0001	<0.0001	<0.0001
Zinc	<0.005	0.009	0.010	0.011
Calcium	23.7	23.6	23.1	24.0
Magnesium	6.69	6.57	6.47	6.68
Potassium	1.84	1.85	1.83	1.85
Sodium	3.36	3.31	3.24	3.38

Results expressed as milligrams per litre except for pH, Conductivity (μ mhos/cm) and Turbidity (NTU)

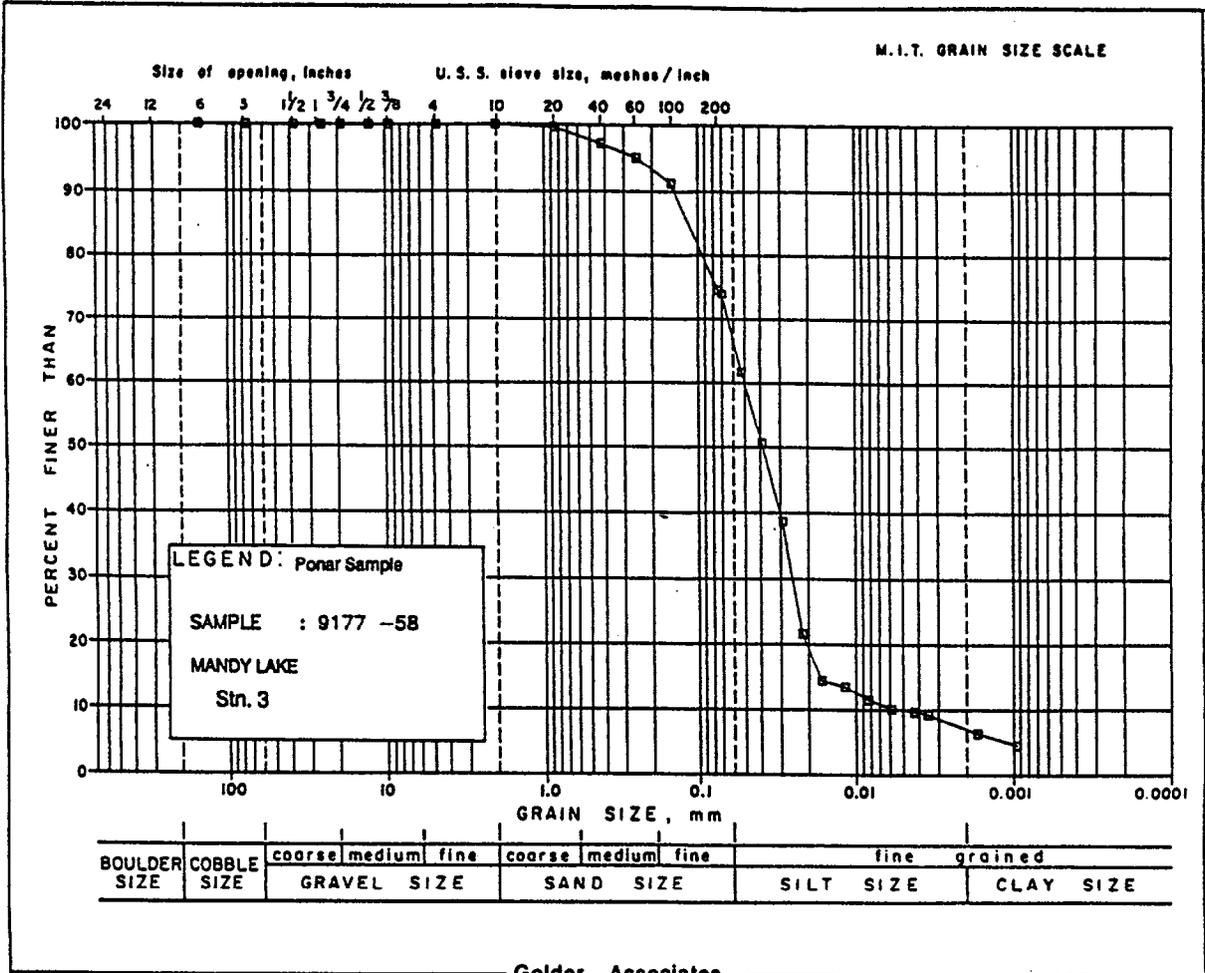
< = Less than

T = Total

NO₃/NO₂ = Nitrate/nitrite nitrogen

TOC = Total Organic Carbon

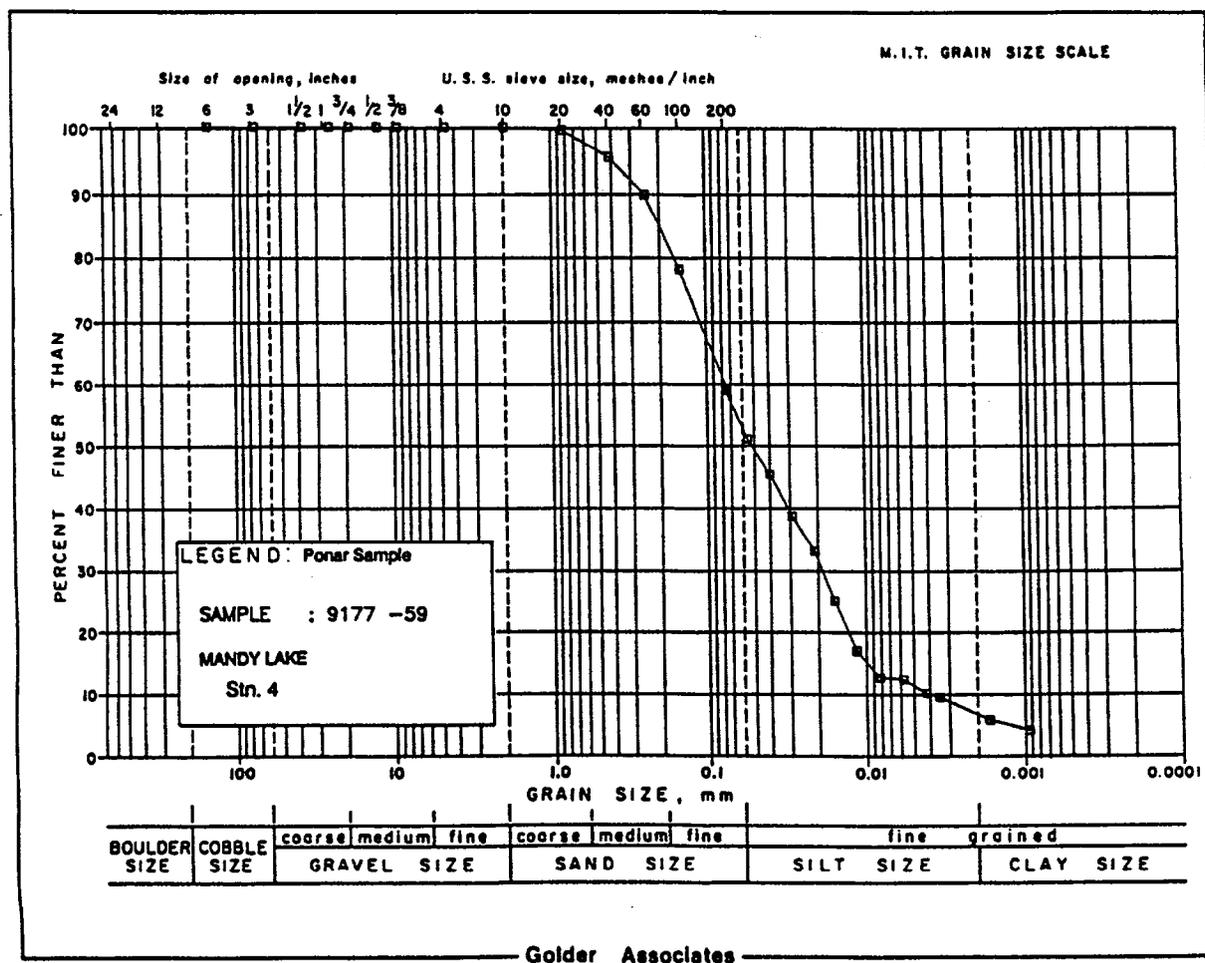
**Particle Size Analysis of the
Top 2 cm of Sediments**



GRAIN SIZE DISTRIBUTION

Figure C 3

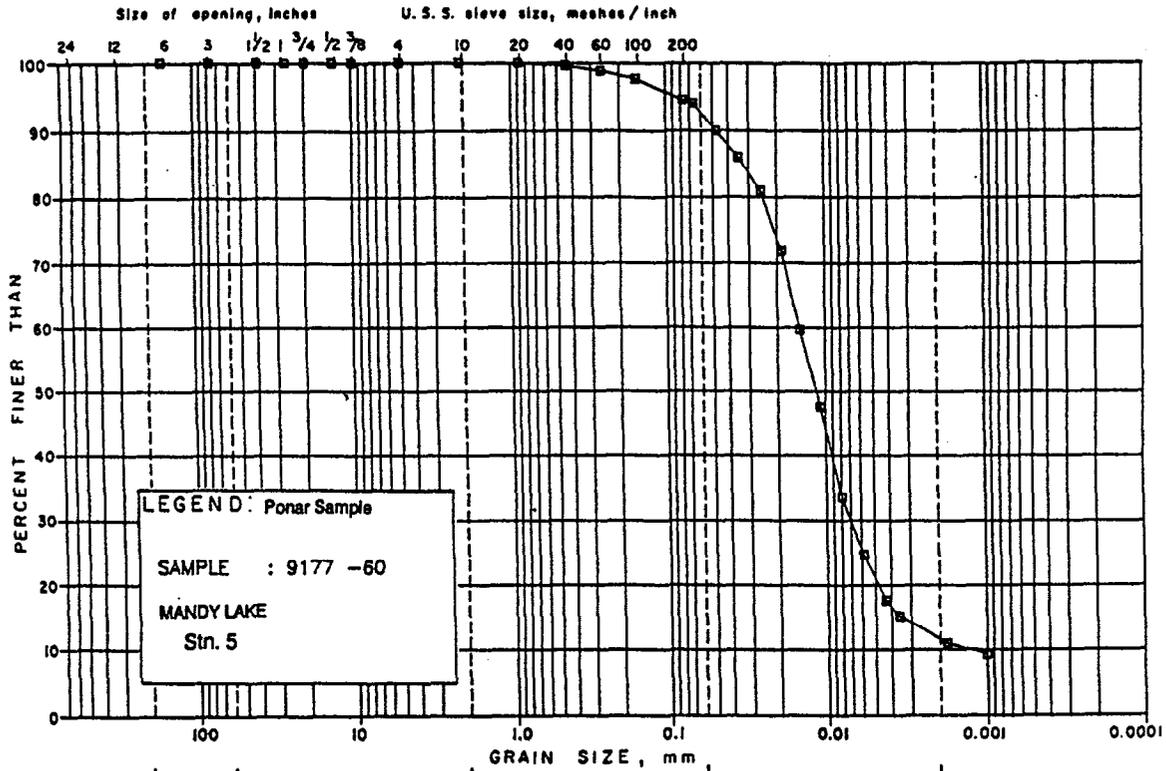
Golder Associates



GRAIN SIZE DISTRIBUTION

Figure C 4

Golder Associates



**Petrographic Analyses of
Top 2 cm of Sediments**

Sample: ML-1

Constituents	Estimated Mode (%)
Organic Material	79
Clastic Sulfides	3
Pyrite Framboids	trace
Quartz	13
Sericite)	
Biotite)	4
Chlorite)	
Hornblende	1
Carbonate	trace

This sample is made up predominantly of fragments of loosely consolidated, fibrous/pellety, brown organic material. Biogenic skeletal forms and cellular vegetal debris are common.

The silicates consist predominantly of quartz, as angular particles, 10 - 70 microns in size. In addition, there is a significant component of micaceous minerals, generally as tiny individual flakes 5 - 15 microns in size. Minor proportions of hornblende, carbonate and miscellaneous silicates are also present.

Estimation of the modal percentages of the silicates is difficult, owing to their small grain size and the obscuring effect of the brown to sub-opaque organic material within which they are intimately dispersed. Estimates in terms of percentages by weight could be significantly low, especially since the organic phase is highly porous and of low bulk density. This same comment applies to all the ML-series samples.

Sulfides occur as rather evenly dispersed, angular specks, 2 - 25 microns in size (rarely to 50 microns), incorporated within the organic matrix. They are predominantly pyrite, but minor sphalerite and rare traces of chalcopyrite and possible arsenopyrite are also recognizable. Interestingly, pyrrhotite could not be positively identified. These sulfides (together with the silicate constituents) presumably represent redistributed slimes from the old tailings dumping activity. They are fresh, and show no sign of oxidation.

The sample also includes a very minor component of pyrite (and pyrrhotite?) framboids, as sparsely scattered individuals, 10 - 25 microns in size.

Sample: ML-2

Constituents	Estimated Mode (%)
Organic Material	75
Clastic Sulfides	5
Pyrite Framboids	trace
Quartz	14
Sericite)	
Biotite)	5
Chlorite)	
Carbonate	1

This sample is identical in all essential respects to ML-1 (q.v.).

Apparent slight differences are a significantly greater abundance of clastic sulfides (in the same grain size range as in ML-1) and a slightly higher proportion of silicates (including minor carbonate).

The sulfides appear to be almost entirely pyrite.

Sphalerite and chalcopyrite are notably rare.

Of the 4 ML samples, this one appears to have the highest percentage of admixed, tailings-derived material.

Sample: ML-3

Constituents	Estimated Mode (%)
Organic Material	82
Clastic Sulfides	3
Pyrite Framboids	trace
Quartz	11
Biotite)	
Sericite)	4
Chlorite)	
Hornblende	trace
Carbonate	trace

This sample is essentially identical to ML-1 (q.v.)

The sparse, but evenly dispersed, clastic sulfides are mainly pyrite, with traces of sphalerite. Chalcopyrite appears virtually absent.

Sample: ML-4

Constituents	Estimated Mode (%)
Organic Material	88
Clastic Sulfides	2
Pyrite Framboids	trace
Quartz	8
Biotite)	
Sericite)	2
Chlorite)	
Hornblende	trace

This sample is of similar general type to the other ML samples, but has a notably lower sulfide content. Strangely, the proportion of chalcopyrite in these very minor sulfides appears relatively higher than in the other ML samples.

The clastic silicate component also appears proportionately low, though it is of similar mineralogy to the other samples.

**Sequential Extraction Results of
Top 2 cm of Sediments**

Table E-1

Sequential Multiple Extraction of Surface
Sediments (top 2 cm) from Mandy Lake (Station 3; Sample ML-3)
Mandy Lake Duplicate A

Parameter	Detection Limit (µg/g)	Water Soluble Phase	Exchange Cations	Weak Acid Soluble Phase	Reducible Phases			Oxidizable Phase	Residual Phase	Mass Balance (ug/g)	Total Digestion
					Easy	Moderate	Difficult				
Aluminum	4.00	1440	<	116	<	854	105	239.5	87500	90254	70530
	%	1.6	0.0	0.1	0.0	0.9	0.1	0.3	96.9	100.0	
Arsenic	4.00	<	<	<	<	995	26.9	33.9	388	1443	1650
	%	0.0	0.0	0.0	0.0	68.9	1.9	2.4	26.8	100.0	
Cadmium	0.20	39.3	2.80	1.04	<	<	<	0.8	0.75	44.76	49.2
	%	87.9	6.3	2.3	0.0	0.0	0.0	1.8	1.7	100.0	
Cobalt	0.30	39.6	2.02	0.78	<	0.81	<	9.4	40.0	93	116
	%	42.8	2.2	0.8	0.0	0.9	0.0	10.1	43.2	100.0	
Copper	0.20	790	56	1511	2.10	218	8.0	316	84	1626	2014
	%	48.6	3.5	9.3	0.1	13.4	0.5	19.4	5.2	100.0	
Iron	0.50	1370	4.08	1030	1043	19225	1098	3300	51702	78772	85053
	%	1.7	0.0	1.3	1.3	24.4	1.4	4.2	65.6	100.0	
Lead	1.00	<	<	<	<	209	11.7	154.5	150	524	510
	%	0.0	0.0	0.0	0.0	39.8	2.2	29.5	28.5	100.0	
Manganese	0.10	206	13.0	1.76	0.24	2.47	1.61	5.1	410	640	573
	%	32.2	2.0	0.3	0.0	0.4	0.3	0.8	64.0	100.0	
Mercury	0.010	<	<	<	<	<	<	<	2.38	2.38	2.95
	%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	
Nickel	0.40	6.19	<	<	<	<	<	3.59	0.60	10.4	16
	%	59.6	0.0	0.0	0.0	0.0	0.0	34.6	5.8	100.0	
Selenium	0.04	<	0.10	0.09	0.10	5.15	52.5	0.80	<	58.7	54.5
	%	0.0	0.2	0.2	0.2	8.8	89.4	1.4	0.0	100.0	
Silver	0.30	<	<	<	<	<	<	1.00	<	1.0	<
	%	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	100.0	
Zinc	0.10	8400	412	199	34	98	<	570	1030	10743	13415
	%	78.2	3.8	1.8	0.3	0.9	0.0	5.3	9.6	100.0	

Results are expressed as micrograms per dry gram of sediment followed by % of total.
Molybdenum was not detectable in the sample.

Table E-2

**Sequential Multiple Extraction of Surface
Sediments (top 2 cm) from Mandy Lake (Station 3; Sample ML-3)
Mandy Lake Duplicate B**

Parameter	Detection Limit (µg/g)	Water Soluble Phase	Exchange Cations	Weak Acid Soluble Phase	Reducible Phases			Oxidizable Phase	Residual Phase	Mass Balance (ug/g)	Total Digestion
					Easily	Moderate	Difficult				
Aluminum	4.00	1335	<	125.2	<	922	156	232	86140	88910	70860
	%	1.5	0.0	0.1	0.0	1.0	0.2	0.3	96.9	100.0	
Arsenic	4.00	<	<	<	<	1005	57	17.5	390	1470	1620
	%	0.0	0.0	0.0	0.0	68.4	3.9	1.2	26.5	100.0	
Cadmium	0.20	35.4	2.78	0.52	<	<	<	1.47	0.8	40.96	49.0
	%	86.5	6.8	1.3	0.0	0.0	0.0	3.6	1.8	100.0	
Cobalt	0.30	37.2	2.30	0.76	<	0.51	<	9.0	45.0	95	101
	%	39.3	2.4	0.8	0.0	0.5	0.0	9.4	47.5	100.0	
Copper	0.20	770	61	157	2.02	226	11.6	296	78	1602	2000
	%	48.1	3.8	9.8	0.1	14.1	0.7	18.5	4.9	100.0	
Iron	0.50	1295	4.20	1040	1110	20600	1522	3365	51500	80436	78085
	%	1.6	0.0	1.3	1.4	25.6	1.9	4.2	64.0	100.0	
Lead	1.00	<	<	<	<	223	17.5	162	143	546	570
	%	0.0	0.0	0.0	0.0	40.9	3.2	29.7	26.2	100.0	
Manganese	0.10	190	14.3	1.88	0.3	2.45	1.80	4.48	395	610	630
	%	31.1	2.3	0.3	0.0	0.4	0.3	0.7	64.8	100.0	
Mercury	0.010	<	<	<	<	<	<	<	2.45	2.45	2.90
	%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	
Nickel	0.40	6.2	<	<	<	<	<	3.19	0.60	9.98	16.0
	%	62.0	0.0	0.0	0.0	0.0	0.0	32.0	6.0	100.0	
Selenium	0.04	<	0.10	0.16	<	5.20	62	0.88	<	68.3	55.0
	%	0.0	0.1	0.2	0.0	7.6	90.7	1.3	0.0	100.0	
Silver	0.30	<	<	<	<	<	<	0.60	<	0.6	<
	%	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	100.0	
Zinc	0.10	7800	446	200	35	99	<	555	1060	10195	13100
	%	76.5	4.4	2.0	0.4	1.0	0.0	5.4	10.4	100.0	

Results are expressed as micrograms per dry gram of sediment followed by % of total.
Molybdenum was not detectable in the sample.

**Chlorophyll a and Quantitative
Phytoplankton Data (cells/ml)
for Mandy Lake**

Table F-1

Site	1-A	1-B	2-A	2-B
Date	24/08/89	24/08/89	24/08/89	24/08/89
Time	12:20	12:15	11:55	11:35
Depth (m)	0.5	1.7	0.5	1.7
Chlorophyll a (mg/m³)	17.9	17.9	12.8	13.1
Taxa				
<i>Asterionella formosa</i>	61.5	86.1	49.2	37.56
<i>Fragellaria crotonensis</i>	24.6	73.8	209.1	18.78
<i>Fragellaria virescens</i>	-	-	-	-
<i>Synedra radians</i>	258.3	24.6	73.8	676.1
<i>Tabellaria fenestrata</i>	24.6	36.9	-	37.56
<i>Coscinodiscus subtilus</i>	12.3	-	-	-
<i>Rhizosolenia ariensis</i>	-	12.3	12.3	18.78
<i>Mallomonas</i> sp.	24.6	-	24.6	-
<i>Chlorellales</i> sp. Indet.	147.6	147.6	61.5	845.1
<i>Ankistrodesmus falcatus</i>	-	-	24.6	18.76
Chlamydomonadaceae spp. indet.	61.5	98.4	246.0	525.8
Chlorophyta filament 1	36.9	-	24.6	131.5
<i>Coelastrum</i> sp.	-	-	-	-
<i>Cosmarium biocculatum</i>	-	-	-	-
<i>Cosmarium</i> sp.	-	-	-	-
<i>Dictyosphaerium pulchella</i>	-	-	-	-
<i>Euglena</i> sp. 1	-	-	36.9	18.78
<i>Gomphosphaeria</i> sp.	24.6	12.3	24.6	-
<i>Haematococcus</i> sp.	49.2	36.9	12.3	93.9
<i>Oedogonium</i> sp.	196.8	221.4	147.6	225.4
<i>Phacus</i> sp.	73.8	49.2	36.9	56.34
<i>Scenedesmus bijuga</i>	-	-	-	112.7
<i>Scenedesmus obliquus</i>	98.4	-	-	-
<i>Scenedesmus quadricauda</i>	-	49.2	49.2	75.12
<i>Staurastrum</i> sp.	-	-	24.6	-
<i>Spondylosium</i> sp.	-	-	-	56.34
<i>Chrysidiastrum</i> sp.	-	12.3	12.3	-
<i>Anabaena</i> sp.	-	-	-	-
<i>Apanothece</i> sp.	24.6	-	-	56.34
<i>Closteridium</i> sp.	-	-	-	-
<i>Coelosphaerium</i> sp.	-	-	-	-
<i>Lyngbya</i> sp.	258.3	282.9	344.0	1052
<i>Loefgrenia</i> sp.	1439	1316	1697	2058
<i>Spirolinea major</i>	-	-	12.3	18.78
<i>Chroococcus</i> sp.	-	-	-	18.78
<i>Merismopedia punctata</i>	-	-	196.8	1202
<i>Trachelomonas</i> sp. 1	256.7	319.8	110.7	375.6
<i>Trachelomonas</i> sp. 2	269.0	258.3	221.4	244.1
<i>Trachelomonas</i> sp. 3	110.7	98.4	147.6	225.4
<i>Dinobryon sirtularia</i>	12.3	-	12.3	-
<i>Peridinium</i> sp.	12.3	12.3	12.3	-
<i>Cryptomonas</i> sp.	61.5	36.9	73.8	7512
Total	3538.1	3136.4	3871.7	15711.5

Table F-2

Site Date Time Depth (m)	3-A 24/08/89 12:20 0.5	3-B 24/08/89 12:15 1.7	4-A 24/08/89 11:55 0.5	4-B 24/08/89 11:35 1.7
Chlorophyll a (mg/m³)	22.9	18.4	20.7	16.2
Taxa				
<i>Asterionella formosa</i>	49.2	86.1	49.2	49.2
<i>Fragellaria crotonensis</i>	344.4	504.3	479.7	123.0
<i>Fragellaria virescens</i>	-	12.3	-	-
<i>Synedra radians</i>	-	-	-	344.4
<i>Tabellaria fenestrata</i>	24.6	-	36.9	12.3
<i>Coscinodiscus subtilus</i>	-	-	-	-
<i>Rhizosolenia ariensis</i>	12.3	36.9	12.3	-
<i>Mallomonas</i> sp.	-	12.3	-	-
<i>Chlorellales</i> sp. Indet.	381.3	383.6	209.1	1132
<i>Ankistrodesmus falcatus</i>	24.6	49.2	98.4	147.6
Chlamydomonadaceae spp. indet.	147.6	442.8	172.2	295.2
Chlorophyta filament 1	12.3	172.2	36.9	12.3
<i>Coelastrum</i>	-	-	12.3	24.6
<i>Cosmarium biocculatum</i>	12.3	-	-	-
<i>Cosmarium</i> sp.	-	-	-	24.6
<i>Dictyosphaerium pulchella</i>	49.2	-	-	-
<i>Euglena</i> sp. 1	-	-	12.3	24.6
<i>Gomphosphaeria</i> sp.	12.3	-	12.3	12.3
<i>Haematococcus</i> sp.	221.4	98.4	86.1	36.9
<i>Oedogonium</i> sp.	233.7	172.2	233.7	332.1
<i>Phacus</i> sp.	24.6	24.6	61.5	36.9
<i>Scenedesmus bijuga</i>	73.8	123.0	-	49.2
<i>Scenedesmus obliquus</i>	-	-	-	-
<i>Scenedesmus quadricauda</i>	73.8	-	98.4	73.8
<i>Staurastrum</i> sp.	12.3	24.6	86.1	-
<i>Spondylosium</i> sp.	12.3	12.3	12.3	36.9
<i>Chrysidiastrum</i> sp.	-	-	-	-
<i>Anabaena</i> sp.	-	12.3	12.3	-
<i>Apanothece</i> sp.	-	-	-	-
<i>Closteridium</i> sp.	12.3	-	-	-
<i>Coelosphaerium</i> sp.	-	-	24.6	-
<i>Lyngbya</i> sp.	504.3	418.2	553.5	553.5
<i>Loefgrenia</i> sp.	2927	1771	2263	2903
<i>Spirolina major</i>	-	-	-	-
<i>Chroococcus</i> sp.	12.3	73.8	36.9	-
<i>Merismopedia punctata</i>	689.0	1205	393.6	-
<i>Trachelomonas</i> sp. 1	418.2	344.4	405.9	369.0
<i>Trachelomonas</i> sp. 2	307.5	344.4	135.3	184.5
<i>Trachelomonas</i> sp. 3	209.1	233.7	369.0	233.7
<i>Dinobryon sirtularia</i>	-	-	24.6	-
<i>Peridinium</i> sp.	24.6	24.6	-	24.6
<i>Cryptomonas</i> sp.	147.6	172.2	295.2	479.7
Total	6961.6	6754.4	6223.6	7575.9

Mandy Lake Fisheries Data
Sampled August 22, 1989 by Gill Nets

Table G-1

Species	Sample No.	Fork Length (mm)	Weight (g)	Age	Sex	Maturity	Stomach Contents
White Sucker	ML1	310	525	-	M	Mature	Unidentified Fish (6 cm)
White Sucker	ML2	300	475	-	M	Mature	Empty
White Sucker	ML3	310	525	-	M	Mature	Empty
White Sucker	ML4	380	1000	-	M	Spawning	Empty
White Sucker	ML5	290	400	-	F	Immature	Empty
White Sucker	ML6	310	525	-	M	Mature	Empty
White Sucker	ML7	310	525	-	F	Immature	Empty
White Sucker	ML8	310	550	-	F	Egg dev.	Empty
White Sucker	ML9	395	1200	-	F	Spawning	Empty
White Sucker	ML10	350	800	-	F	Spawning	Unidentifiable
White Sucker	ML11*	330	600	-	M	Mature	Empty
White Sucker	ML12	360	800	-	F	Mature	Empty
White Sucker	ML13	420	1000	-	M	Spawning	Empty
White Sucker	ML14	280	460	-	F	Immature	Unidentifiable
White Sucker	ML15	350	750	-	M	Mature	Unidentifiable
White Sucker	ML16	290	430	-	M	Immature	Unidentifiable
White Sucker	ML17	320	500	-	M	Immature	Empty
White Sucker	ML18	340	600	-	F	Egg dev.	Unidentifiable
White Sucker	ML19*	340	600	-	M	Mature	Unidentifiable
White Sucker	ML20*	330	600	-	M	Mature	Empty
White Sucker	ML21	325	500	-	F	Mature	Empty
White Sucker	ML22	360	800	-	F	Spawning	Empty
White Sucker	ML23	340	600	-	M	Mature	Empty

* Analyzed for metal content

Table G-2

Species	Sample No.	Fork Length (mm)	Weight (g)	Age	Sex	Maturity	Stomach Contents
Lake Whitefish	ML24*	295	390	-	M	Immature	Empty
Lake Whitefish	ML25*	410	1000	-	M	Mature	Empty
Northern Pike	ML26	530	1500	-	M	Mature	Fish backbone
Northern Pike	ML27	650	2600	-	M	Spawning	Empty
Northern Pike	ML28	490	900	-	F	Immature	Perch (3.5 cm)
Northern Pike	ML29	610	2000	-	F	Mature	Empty
Northern Pike	ML30*	555	1600	7	M	Mature	Empty
Northern Pike	ML31	535	1400	7	M	Mature	Empty
Northern Pike	ML32	655	2400	8	F	Spawning	Empty
Northern Pike	ML33*	470	1000	-	M	Spawning	Perch (3.8 cm)
Northern Pike	ML34	600	2250	8	M	Spawning	Empty
Northern Pike	ML35	525	1250	-	M	Mature	Empty
Northern Pike	ML36*	545	1400	6	M	Mature	Empty
Northern Pike	ML37	535	1400	-	M	Mature	Empty
Northern Pike	ML38*	115	20	-	U	Immature	Empty
Northern Pike	ML39*	645	2200	12	M	Mature	Empty
Northern Pike	ML40	620	2500	10	M	Mature	Empty
Northern Pike	ML41	675	3500	9	F	Mature	Empty
Northern Pike	ML42	580	2000	7	F	Mature	2 Unidentified Fish (10.5 cm and 11.0 cm)
Northern Pike	ML43	535	1500	4	M	Mature	Unidentified Fish (4 cm)

* Analyzed for metal content

**Metal Analyses of Mandy Lake
Fish Tissue Samples**

Table H-1

Sample Number	Date Sampled	Fish Species	Tissue Type	Metal ($\mu\text{g/g}$ - dry weight)						
				As	Cd	Cu	Pb	Hg	Ni	Zn
ML24	22/08/89	Lake Whitefish	Muscle	<1.00	<0.025	0.49	<0.050	0.046	0.084	27.2
				<1.00	<0.025	0.62	<0.050	0.032	0.090	24.7
ML25	22/08/89	Lake Whitefish	Muscle	<1.00	<0.025	0.50	0.068	0.020	0.068	23.0
ML11	22/08/89	White Sucker	Muscle	<1.00	<0.025	0.92	<0.050	0.036	0.25	29.9
ML19	22/08/89	White Sucker	Muscle	<1.00	<0.025	0.80	0.53	0.021	0.48	21.3
ML20	22/08/89	White Sucker	Muscle	<1.00	0.030	1.20	0.060	0.14	0.24	29.3
ML30	22/08/89	Northern Pike	Muscle	<1.00	0.020	0.72	0.040	0.64	0.24	28.1
ML33	22/08/89	Northern Pike	Muscle	<1.00	0.038	0.67	0.096	0.31	<0.050	25.6
			Liver	<1.00	0.13	32.7	0.074	0.11	<0.050	145
ML36	22/08/89	Northern Pike	Muscle	<1.00	0.027	0.49	0.076	0.42	0.30	44.7
ML38	22/08/89	Northern Pike	Muscle	<1.00	0.088	2.14	0.24	0.097	0.15	138
ML39	22/08/89	Northern Pike	Muscle	<1.00	<0.025	0.92	0.046	0.46	0.32	41.6
			Muscle	<1.00	<0.025	0.96	0.040	0.44	0.24	42.5
			Liver	<1.00	0.71	55.2	0.075	0.22	0.11	142