A PRELIMINARY BIOLOGICAL AND GEOLOGICAL ASSESSMENT OF SUBAQUEOUS TAILINGS DISPOSAL IN BENSON LAKE, BRITISH COLUMBIA

MEND Report 2.11.1c-a

March 1991

A PRELIMINARY BIOLOGICAL AND GEOLOGICAL ASSESSMENT OF SUBAQUEOUS TAILINGS DISPOSAL IN BENSON LAKE, BRITISH COLUMBIA

Prepared and Funded by:

Ministry of Energy, Mines and Petroleum Resources
B.C. Acid Mine Drainage Task Force
Room 105 - 525 Superior Street
Victoria, British Columbia
V8V 1X4

and

CANMET
Environment Canada
Hudson Bay Mining and Smelting Co. Ltd.

Prepared by:

Rescan Environmental Services Ltd.
Vancouver, British Columbia

March 1991

EXECUTIVE SUMMARY

Available evidence suggests that the chemical and biological reactivity of mine tailings is inhibited by storage underwater and thus appears to be a promising alternative to the less environmentally benign practice of land disposal. While impacts on the biotic community resulting from subaqueous disposal have been documented, the duration of these impacts appears to be transitory. To assess the above, we examined the water quality, geochemical conditions of the sediments and biotic communities in Benson Lake near Port Alice, British Columbia. Benson Lake had been used as a tailings repository for approximately eleven years prior to cessation of operations in 1973.

Benson Lake is a small, deep, oligotrophic coastal mountain lake situated in the coastal western hemlock biogeoclimatic zone on the northern end of Vancouver Island. During the period August 1962 through January 1973, the Benson Lake Coast Copper Mine, operated by Cominco Ltd. disposed of its mine tailings by depositing them, under permit, into the deep basin of the lake. As a result, the lake was subject to extended periods during which lake turbidity levels were elevated beyond levels normally found in the lake. Furthermore, tailings fines smothered the lake's profundal sediments thereby eradicating all traces of benthic invertebrate life. Tailings fines were also found in the Lower Benson River. Finally, tailings deposition also resulted in elevated levels of zinc, relative to background control levels, in the water and in the flesh of fish taken from the lake.

In 1973, Cominco Ltd. ceased operations and halted their tailings disposal activities. A subsequent evaluation of the lake, conducted 10 months later, found that colloidal tailings material in the lake's waters had settled and that Benson Lake's clarity had returned to pre-mine conditions. Also, the elevated levels of zinc noted in the water column during active tailings deposition had subsided. However, it was noted that the profundal zone of the lake was still devoid of invertebrate life.

In September 1990, more than 17 years after cessation of tailings disposal, it was found that Benson Lake showed little evidence of the fact that it was the recipient of mine waste.

Physical and chemical water quality sampling conducted at three stations in the lake indicated that lake water was similar in virtually all respects to the waters of a nearby control lake, Keogh Lake. Some differences were noted, however, the differences were attributable to inherent characteristics of Benson Lake's drainage basin and to the presence of a fish farm sited in the control lake. Benson Lake was characterized by higher conductivity, total dissolved solids, alkalinity, calcium and potassium than the control lake, but the levels of each of these parameters reflected their levels in the water flowing into the lake via the Benson and Raging Rivers and Craft Creek. The fish farm on Keogh Lake appeared to be eliciting a fertilization effect that resulted in higher levels of nutrients (phosphorous and nitrogen) and plankton growth in the control lake compared to Benson Lake.

Lake and surface samples of tailings-rich sediments were collected and examined in detail. Metal and petrographic analyses of lake samples indicated that tailings are areally widespread in the lake. A surficial organic layer is accumulating over the tailings which may be helping to prevent benthic effluxes of metals to the overlying water column. Sequential extractions of tailings-dominated lake and land tailings samples revealed that underwater samples did not release any significant quantities of metals from the water-soluble or exchangeable cation phases. In contrast, metals were released in the water-soluble phase of the land tailings sample. Most of the metals appeared to be associated with primarily the unreactive residual phase in both samples. However, a significant quantity of metals were associated with the oxidizable phase (organo-metal complexes, metal sulphides) in the lake tailings sample which was not apparent in the land tailings sample. These preliminary results suggest that the chemical reactivity of the underwater tailings is minimal and that their presence is not degrading the biochemical environment of Benson Lake.

The biota of Benson Lake was examined in considerable detail. It was found that the benthic invertebrate community in the lake had re-established itself to reflect the community structure and organism density typical of oligotrophic lakes throughout Canada and the world. Net phytoplankton densities and community structure were similar to densities and assemblages found in the control lake and in other coastal mountain lakes in British Columbia. Zooplankton species compositions in Benson Lake were also similar to those in the control lake, but their densities were significantly lower in both lakes than in other oligotrophic coastal lakes.

Aquatic vegetation was well established in the littoral zone of the lake particularly along its southern and eastern shorelines. Compared to the control lake, aquatic vegetation in Benson Lake was found to contain elevated levels of arsenic and copper. Arsenic accumulated in both the tops and roots of horsetail (*Equisetum* sp.) and pond weed (*Potamogeton* sp.), while copper only accumulated in the roots of horsetail and in both the tops and roots of pond weed.

Fish sampling confirmed the presence of rainbow trout in both Benson and Keogh Lakes, a species of char in Benson Lake, and cutthroat trout in Keogh Lake. Fish from Benson Lake were significantly larger and had significantly higher condition factors than fish from the control lake. In addition, the concentrations of metals in the flesh of fish from Benson Lake were lower than body metal burden in fish from the control lake, but the concentrations of metals in the livers were higher. However, the concentrations of all metals in the fish from both lakes were within the range of concentrations for the same metals in fish tissues and livers from unpolluted Canadian waters. The stomach contents of fish from Benson Lake suggested that the fish in the lake were incorporating the re-established benthic invertebrate community in their diet.

SOMMAIRE

Selon des données limitées, la réactivité chimique et biologique des résidus miniers serait inhibée lorsque ces résidus sont éliminés sous l'eau. L'élimination subaquatique des résidus pourrait donc constituer une alternative prometteuse à l'élimination sur terre, qui est plus nuisible à l'environnement. Bien que l'on ait documenté les répercussions, sur la biocénose, de l'élimination subaquatique des résidus, ces répercussions semblent être transitoires. Afin de les évaluer, on a examiné la qualité des eaux, les conditions géochimiques des sédiments et la biocénose du lac Benson près de Port Alice, en Colombie-Britannique. Le lac Benson a été utilisé comme bassin de réception de résidus pendant environ 11 ans, avant qu'on ait mis fin aux activités en 1973.

Le lac Benson est un lac oligotrophe, petit et profond, de chaîne côtière qui se situe dans la zone biogéoclimatique côtière de la pruche occidentale, dans l'extrême nord de l'île de Vancouver. Au cours de la période allant d'août 1962 à janvier 1973, la Cominco Ltée. a éliminé les résidus de sa mine de cuivre (Benson Lake Coast Copper Mine) en les déversant, sous licence, dans le bassin lacustre profond. Par conséquent, pendant certaines périodes prolongées, la turbidité des eaux du lac a été plus élevée que la normale. En outre, les particules fines comprises dans les résidus miniers ont couvert les sédiments de la zone profonde du lac, effaçant ainsi toute trace de vie benthique. On a aussi trouvé des particules fines de résidus dans la rivière Benson inférieure. Enfin, le déversement de résidus a fait augmenter, par rapport aux niveaux de fond, les concentrations de zinc dans les eaux et dans la chair des poissons du lac.

En 1973, la Cominco Ltée a cessé ses activités et mis fin à l'élimination des résidus miniers. Une évaluation subséquente du lac, menée 10 mois plus tard, a révélé que les particules colloïdales des résidus dans les eaux du lac s'étaient déposées, et que les eaux avaient retrouvé leur limpidité d'origine. En outre, les fortes concentrations de zinc qui avaient été notées dans la tranche d'eau durant la période de déversement des résidus, avaient baissé. Cependant, on a noté que les zones profondes du lac étaient encore dépourvues d'invertébrés.

En septembre 1990, soit plus de 17 ans après que la société eût arrêté d'y déverser les résidus, le lac Benson montrait peu d'indications qu'elle avait servi de bassin de réception de résidus.
L'échantillonnage de la qualité physique et chimique de l'eau, entrepris à trois stations dans le lac, a révélé que les eaux lacustres ressemblent à presque tous les égards aux eaux du lac Keogh, lac témoin situé à proximité. Or, certaines différences ont été notées, mais elles sont attribuées aux caractéristiques inhérentes du réseau hydrographique du lac Benson et à la présence d'une piscifacture dans le lac témoin. La conductivité, les matières totales dissoutes, l'alcalinité et la teneur en calcium et en potassium sont toutes plus élevées dans le lac Benson que dans le lac témoin, mais les niveaux de chacun de ces paramètres traduisent les niveaux dans les apports d'eaux provenant des rivières Benson et Raging et du ruisseau Craft. La piscifacture du lac Keogh semble avoir un effet fertilisant de sorte que la quantité de substances nutritives (phosphore et azote) et le degré de développement planctonique sont plus élevés dans le lac témoin que dans le lac Benson.

Des échantillons de sédiments lacustres et terrestres riches en résidus ont été prélevés puis examinés en détail. L'analyse des métaux et de la pétrographie des échantillons lacustres indique que les résidus sont très étendus dans le lac. Une couche organique superficielle s'accumule sur les résidus et pourrait aider à empêcher le passage benthique de métaux dans la tranche d'eau sus-jacente. Les prélèvements séquentiels d'échantillons lacustres à prédominance de résidus et d'échantillons de résidus terrestres montre que les échantillons subaquatiques ne libèrent pas de quantités significatives de métaux de la phase hydrosoluble ou de la phase de cations échangeables. Par opposition, il y a libération de métaux dans la phase hydrosoluble de l'échantillon de résidus terrestres. Dans les deux échantillons, la plupart des métaux semblent être associés principalement à la phase résiduelle inerte. Cependant, une quantité significative de métaux est associée à la phase oxydable (complexes organométalliques, sulfures de métaux) dans l'échantillon de résidus lacustres, ce qui n'était pas apparent dans l'échantillon de résidus terrestres. Ces résultats provisoires portent à croire que les résidus subaquatiques ont une réactivité chimique minimale et qu'ils ne provoquent pas la dégradation de l'environnement biochimique dans le lac Benson.

On a examiné en détail le biote du lac Benson. On s'est rendu compte que la communauté d'invertébrés benthiques du lac s'était rétablie de sorte à refléter la structure des communautés et la densité d'organismes typiques des lacs oligotrophes partout au Canada et à travers le monde. Les densités nettes de phytoplancton et la structure des communautés ressemblent à d'autres densités et assemblages qui se trouvent dans le lac témoin et dans d'autres lacs de chaîne côtière en Colombie-Britannique. En outre, la composition des espèces de zooplancton du lac Benson ressemble à celle du lac témoin, mais les densités sont beaucoup moins élevées dans ces deux lacs que dans d'autres lacs oligotrophes côtiers.

La végétation aquatique est bien établie dans la zone littorale du lac, notamment le long des rivages sud et est. La végétation du lac Benson contient des quantités élevées d'arsenic et de cuivre, comparativement à la végétation du lac témoin. L'arsenic s'accumule dans les racines, les tiges et les feuilles du prêle (*Equisetum* sp.) et du potamot (*Potamogeton* sp.) et le cuivre, dans les racines du prêle et dans les racines, les tiges et les feuilles du potamot.

L'échantillonnage de poissons a confirmé la présence de truite arc-en-ciel dans les lac Benson et Keogh, d'une espèce d'omble dans le lac Benson, et de truite fardée dans le lac Keogh. Les poissons du lac Benson sont beaucoup plus grands et ont un coefficient de condition beaucoup plus élevé que les poissons du lac témoin. En outre, les concentrations de métaux dans la chair des poissons du lac Benson sont inférieures à la charge corporelle de métaux des poissons du lac témoin, bien que les concentrations de métaux dans le foie soient plus élevées. Toutefois, les concentrations de tous les métaux dans les poissons des deux lacs se trouvent dans la gamme de concentrations des mêmes métaux dans les tissus et foies de poissons provenant d'eaux canadiennes non polluées. Le contenu des estomacs de poissons du lac Benson porte à croire que la communautés rétablie d'invertébrés benthiques fait partie du régime alimentaire des poissons du lac.

ACKNOWLEDGEMENTS

We would like to gratefully acknowledge the finacial assistance of the British Columbia Ministry of Energy, Mines and Petroleum Resources, Hudson Bay Mining and Smelting Co., Ltd., Environment Canada and CANMET. We would also like to extend our appreciation to Ian Horne of BHP-Utah's Island Copper Mine, for generously providing a work boat and various field supplies.

A number of people have made substantial contributions to the completion of this project. Mr. Clem Pelletier of Rescan Environmental Services Ltd. (Rescan) provided overall project coordination and senior review of the report. David Flather and John Werring (Rescan) conducted all field work and analytical review and reporting. Gratitude is also extended to Ping Lee for his drafting efforts.

TABLE OF CONTENTS

EXECUTIVE SUMMARY i

ACKNOWLEDGEMENTS iv

TABLE OF CONTENTS v

LIST OF TABLES vii

LIST OF FIGURES ix

1.0 INTRODUCTION 1-1

2.0 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 and Hydrology 2-1
  - 2.3.2 Water Quality 2-6
  - 2.3.3 Sediment 2-7
  - 2.3.4 Phytoplankton 2-9
  - 2.3.5 Zooplankton 2-9
  - 2.3.6 Benthic Invertebrates 2-10
  - 2.3.7 Aquatic Vegetation 2-11
  - 2.3.8 Fish 2-11

3.0 RESULTS AND DISCUSSION 3-1

- 3.1 Lake Morphometry and Hydrology 3-1
  - 3.1.1 Morphometry of Benson and Keogh Lake 3-1
  - 3.1.2 Benson Lake Hydrology 3-4
- 3.2 Water Quality 3-4
- 3.3 Sediment and Tailings 3-13
  - 3.3.1 Particle Size Analysis 3-13

3.3.2 Petrographic Analysis 3-14
3.3.3 Sediment Metal Analysis 3-17

3.4 Biota 3-25
3.4.1 Benthic Invertebrates 3-25
3.4.2 Phytoplankton 3-31
3.4.3 Zooplankton 3-35
3.4.4 Aquatic Vegetation 3-38
3.4.5 Fish 3-45

4.0 CONCLUSIONS 4-1

REFERENCES R-1

APPENDICES

APPENDIX A Hydrologic Data A-1

APPENDIX B Water Quality Data B-1

APPENDIX C Particle Size Analysis C-1

APPENDIX D Detailed Petrographic Analysis D-1

LIST OF TABLES

Table

2-1 Extractants and Associated Phases in Sequential Extraction of Sediments 2-10

3-1 Physical and Chemical Water Quality Parameters for Benson Lake and Keogh Lake 3-10

3-2 Water Quality Analysis for Benson and Raging Rivers and Craft Creek 3-11

3-3 Field Observations of Sediments Collected from the Profundal Zone of Benson and Keogh Lake for Benthic Invertebrate, Metals, and Particle Size Analyses 3-14

3-4 Total Carbon, Nitrogen and Sulphur in Surface Sediments from Benson Lake 3-15

3-5 Particle Size Distribution for Benson and Keogh Lake Sediments 3-15

3-6 X-Ray Fluorescence (XRF) Analysis of Top 15 cm Layer of Sediments from Benson Lake 3-18

3-7 Metal Analyses of Sediment Samples from Benson Lake 3-19

3-8 Sequential Extraction of BL2 Tailings from Benson Lake 3-21

3-9 Sequential Extraction of Land Tailings near Benson Lake 3-22

3-10 Densities and Species Compositions of Benthic Invertebrate Communities in Benson and Keogh Lakes in September, 1990 3-26

3-11 Average Numerical Density of Benthic Macroinvertebrates in the Profundal Zone of Several Lakes of Varying Productivity 3-29

3-12 Phytoplankton Taxa found in Benson and Keogh Lakes 3-32

3-13 Densities of the Phytoplankton in the Water Column at Three Sites in Benson Lake, September 1990 3-33

3-14 Densities of Phytoplankton in the Water Column at Two Sites in Keogh Lake 3-34

3-15 Benson Lake - Densities of Zooplankton Captured in Vertical and Horizontal Tows 3-36

3-16 Keogh Lake - Densities of Zooplankton Captured in Vertical and Horizontal Tows 3-37

3-17 Typical Fall Densities of Some Crustacean Zooplankton in a Coastal Lake in British Columbia 3-38

3-18 Concentrations of Specific Metals in Benson and Three Isle Lake Aquatic Vegetation 3-41

3-19 Mean Metal Concentrations in Tops and roots of *Equisetum* sp. from Benson Lake and Three Isle Lake 3-42

3-20 Metal Levels in Sediments Associated with Aquatic Vegetation Samples 3-43

3-21 Mean Metal Concentrations in *Potamogeton* sp. Tops in Benson Lake, Mandy and Anderson Lakes, Manitoba 3-44

3-22 Condition Factors and Stomach Contents of Fish from Benson and Keogh Lakes 3-46

3-23 Metal Body Burden in Fish Tissue and Livers from Benson and Keogh Lakes 3-47

LIST OF FIGURES

Figure

1-1 Project Location Map 1-2

2-1 Benson Lake Project Location and Hydrology Sites 2-2

2-2 Benson Lake Sampling Stations 2-3

2-3 Keogh Lake Sampling Stations 2-4

2-4 Benson Lake Vegetation Sampling Locations 2-12

3-1 Benson Lake Bathymetric Mapping 3-2

3-2 Keogh Lake Bathymetric Mapping 3-3

3-3 Turbidity, Conductivity, pH, Dissolved O_2, and Temperature Profiles for Benson Lake, Station 1 3-5

3-4 Turbidity, Conductivity, pH, Dissolved O_2, and Temperature Profiles for Benson Lake, Station 2 3-6

3-5 Turbidity, Conductivity, pH, Dissolved O_2, and Temperature Profiles for Benson Lake, Station 3 3-7

3-6 Turbidity, Conductivity, pH, Dissolved O_2, and Temperature Profiles for Keogh Lake, Station 1 3-8

3-7 Metals Released in Water Soluble Phase from Land and Submerged Lake Tailings 3-23

3-8 Metals Released in Oxidizable Phase from Land and Submerged Lake Tailings 3-23

3-9 Aquatic Vegetation Mapping 3-39

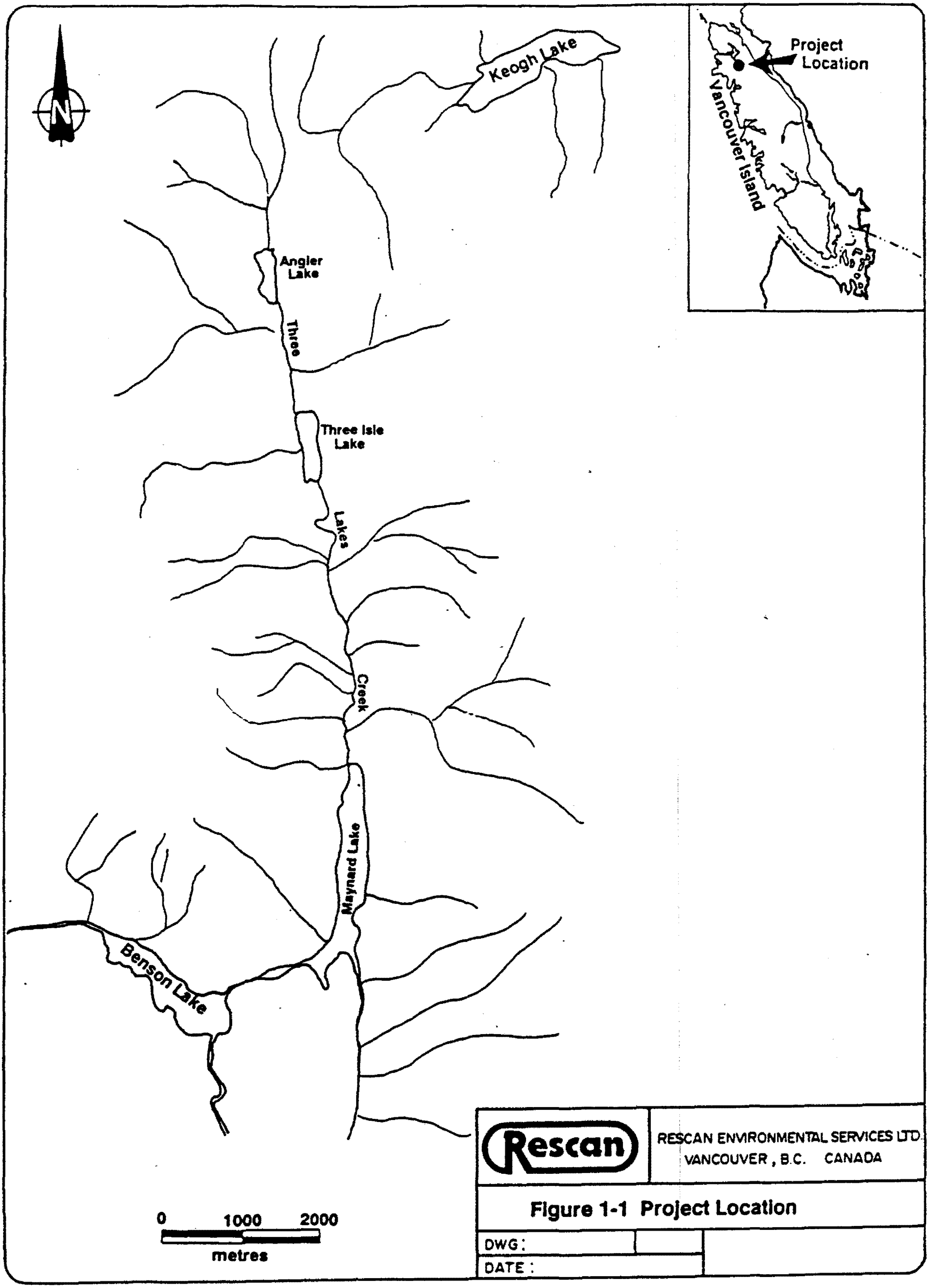
1 - Introduction

1.0 INTRODUCTION

The Benson Lake watershed is located on northern Vancouver Island, about 15 km east of the town of Port Alice and is part of the Marble River drainage (Figure 1-1) . The drainage is primarily surrounded by a coastal western hemlock biogeoclimatic zone. MacMillan Bloedel Limited currently logs the Benson River and Raging River drainages out of their Port McNeil division. Access to the area is therefore excellent along active logging roads.

The area is characterized by limestone karst formations, and has historically been the location of a number of mining operations. The Benson Lake Coast Copper Mine, owned by Cominco Ltd., commenced operations in August 1962 and operated until January 1973. Over the operating period, a total of 3.6 million tons of ore were mined. The underground operation and adjoining concentrator processed 750 to 850 tpd, and discharged the tailings, under permit, into Benson Lake.

Throughout the period of operation of the mine, the lake consistently exhibited increased levels of turbidity caused by the finer colloidal fractions of the tailings remaining in suspension despite the addition of flocculents to enhance particle settling (Hallam *et al.* 1974). Moreover, tailings fines were also found in the Lower Benson River below the lake's outlet. As a direct result of tailings deposition, profundal benthic organisms in Benson Lake were eliminated by the smothering effect of the tailings (Kussat *et al.* 1972). Because of the lack of aquatic benthic invertebrate production in the lake, resident fish were found to be feeding on insects commonly found in the benthic drift (aquatic and terrestrial invertebrates) entering the lake from inlet streams and on adult terrestrial insects deposited on the lake's surface (Kussat *et al.* 1972). Finally, elevated concentrations of zinc (relative to background concentrations) were observed in both Benson Lake water and in the flesh of fish from Benson Lake. However, the metal concentrations in fish were found to be similar to those found in fish from nearby Maynard Lake. Maynard Lake flows into Benson Lake via the Raging River which is dammed for hydroelectric power (Figure 1-1). A study carried out in Benson Lake 10 months after Cominco's operations had ceased, showed an improvement in lake water clarity, although metal concentrations in the water and fish tissue had not changed (Hallam *et al.* 1974). Hallam *et al.* concluded that improvements



RESCAN ENVIRONMENTAL SERVICES LTD.
VANCOUVER, B.C. CANADA

Figure 1-1 Project Location

DWG :

DATE :

JB-R0021

2 - Methods

in lake productivity and benthic invertebrate recolonization could eventually be expected.

The present study is the second stage of a series of field assessments to assess the lake's recovery from subaqueous disposal of reactive mine wastes. The study is part of CANMET's Mine Environmental Neutral Drainage (MEND) program. This work concludes the preliminary assessment of Benson Lake and is a continuation of the 1989-1990 field program completed by Rescan (Rescan, 1990a). The initial stage (1989-1990) included a study of the lake bathymetry and the establishment of staff and crest gauges to examine the hydrology of the area. During the present study additional hydrological work was completed.

This report focuses on the chemical and biological aspects of changes in Benson Lake following subaqueous tailings disposal. Keogh Lake which is located approximately 12 km to the northwest of Benson Lake (Figure 1-1) was used as a control for water chemistry, sediments, and bioto (excluding aquatic macrophytes). Keogh Lake did not have similar aquatic vegetation to Benson Lake and therefore nearby Three Isle Lake was used as control for vegetation analyses. The biota examined included phytoplankton, zooplankton, benthic invertebrates, aquatic macrophytes and fish. The present report lays the ground work for intensive sediment chemistry work proposed for 1991 which will examine, in detail, the pore water and solid-phase chemistry in cores obtained from the lake's bottom.

2.0 METHODS

2.1 Study Area

The study area is located in northern Vancouver Island (Figure 2-1) near the towns of Port Alice, to the west and Port Hardy to the northeast. Benson Lake received tailings from August 1962 through January 1973. Tailings were discharged onto the surface of the lake not at depth.

2.2 Sampling Stations

Three (3) primary sampling stations were established on Benson Lake along a east-west axis (Figure 2-2). Water, sediment, benthos, zooplankton and phytoplankton were collected at each station. Dissolved oxygen, pH, and temperature profiles and Secchi disk transparency were measured at each station. Seine netting was attempted at several locations in Benson Lake but proved unsuccessful. Three (3) gill net sites were therefore employed over the lake.

Water samples were collected at three inflow streams (Benson River, Raging River and Craft Creek) and one (1) outflow stream (Lower Benson River).

One (1) sampling station was established on Keogh Lake and sampled for water, sediments, zooplankton and phytoplankton (Figure 2-3). As with Benson Lake, a dissolved oxygen, pH and temperature profile and Secchi disk transparency were measured at the station. One gill net site was established on Keogh Lake.

2.3 Study Methods

2.3.1 Lake Morphometry and Hydrology

A bathymetric map of Benson Lake was constructed from timed depth profiles taken at a slow speed along predefined transects using a Lowrance X16 Computer Sonar

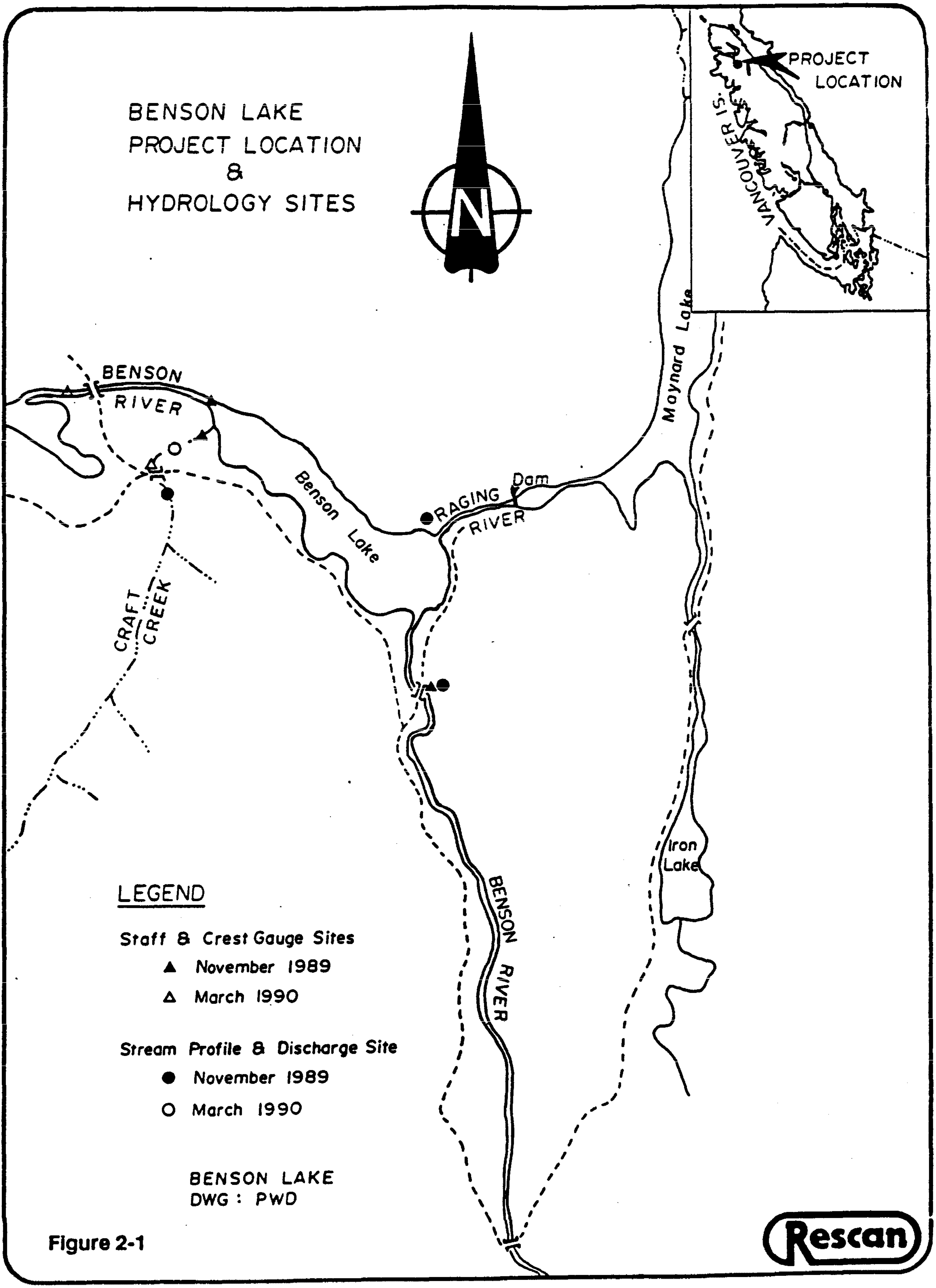


Figure 2-1

DB-R0022

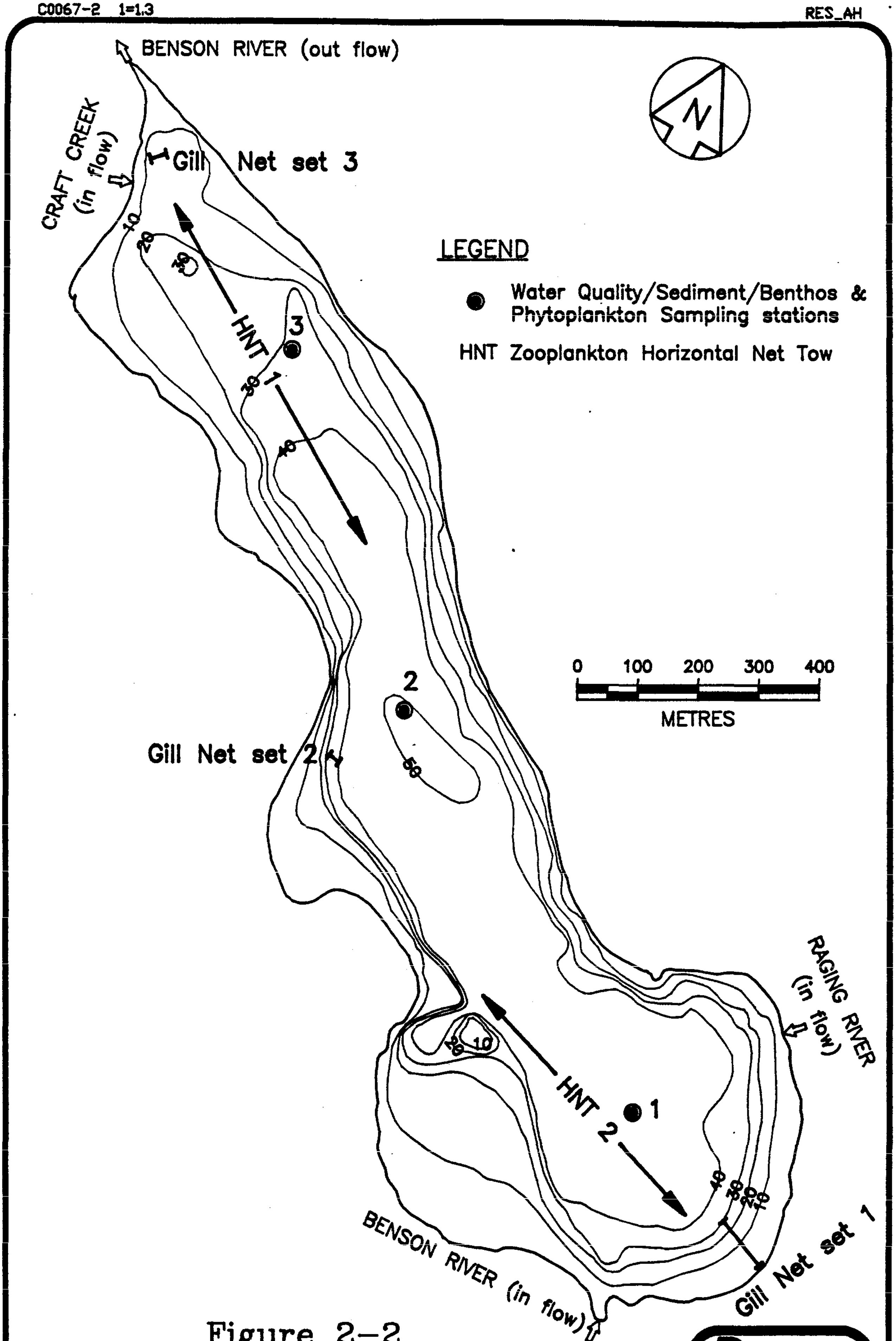


Figure 2-2
Benson Lake Sampling Locations

C0076-3 1=1.4

RES_AH

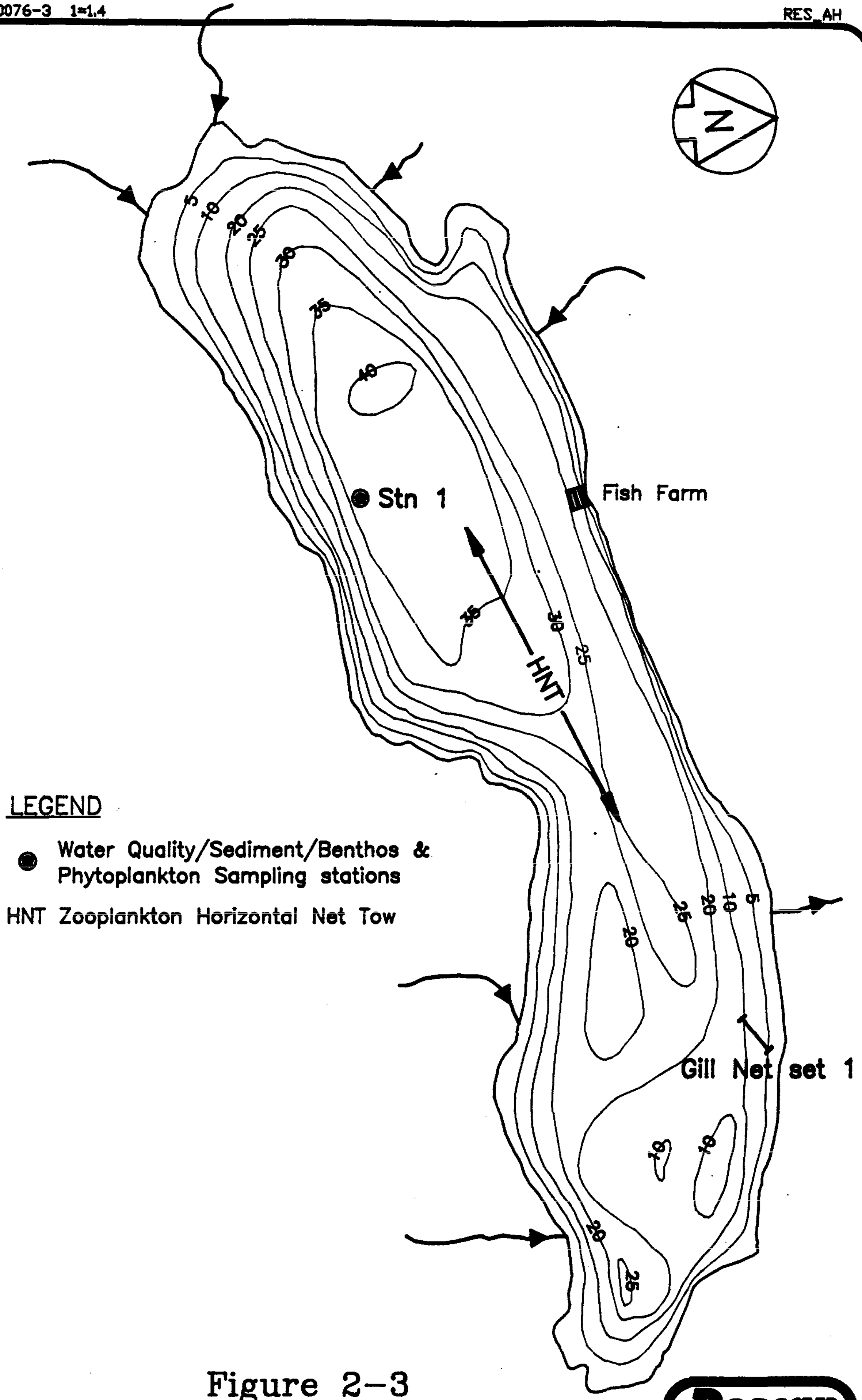


Figure 2-3
Keogh Lake Sampling Stations

Rescan

sounder. Soundings were conducted on November 3, 1989 (Rescan 1990a). From the sounding charts and the resulting bathymetric map, a number of morphometric parameters were calculated (Hutchinson 1957). The calculated parameters included:

- maximum length;
- maximum breadth;
- area;
- volume;
- maximum depth;
- mean depth;
- relative depth;
- shoreline length; and
- shoreline development factor.

Lake volume was calculated as the area under the hypsographic curve.

Staff gauges, consisting of one or more 1 m long water survey gauge plates, were mounted on lengths of 2" x 4" lumber and fixed to stable structures at the waters edge in the Benson River, Craft Creek and Raging River (Figure 2-1). Crest gauges, to measure the maximum stage of the river between readings, were also strapped to each staff gauge. Depth readings to the nearest mm were taken from crest gauges with a tape measure.

In the proximity of each gauge site, stream profile sites were selected. At these sites, the width of the wetted channel was measured to the nearest 10 cm with a surveyor tape. At set intervals of 1 to 3 m, depending on the stream width, depth measurements were taken with a wading rod (to the nearest cm). The data were then used to prepare stream profiles.

Current velocity measurements were taken at 60% of the depth below the surface at each interval along the profile. Velocity was measured with a Marsh McBirney flow meter to the nearest 0.5 cm s^{-1}. This depth approximates the mean velocities at depths <0.76 m (Nielsen and Johnson 1983). Discharge was approximated by summing the products of velocity x depth x interval width for each interval of the profile.

2.3.2 Water Quality

Lake water samples were collected on September 13 and 17, 1990 at three Benson Lake sites and at Keogh Lake using a teflon-lined 5 L Go-Flo (General Oceanics) water sampler (Figures 2-2 and 2-3). Water samples from lake sampling sites were taken at 4 depths in the water column (0.5 m below the surface, 5 to 11 m (variable depending on temperature stratification data), 20 m and 0.5 m off the lake bottom). One litre and 250 ml polyethylene bottles and caps were rinsed with sample water prior to filling. To minimize air contact, bottles for lake samples 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. The 250 ml bottles collected for metals analyses were field filtered using a 0.45 μm filter and preserved with 1:1 nitric acid. Grab water samples were collected from inflow and outflow stream sites at Benson Lake by submerging rinsed sample bottles directly into the water flow. Preservation was as for the lake samples.

Water samples were analyzed by Analytical Services Laboratories (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

Sediments were collected at three stations in Benson Lake and one station in Keogh Lake on September 14, 1990 using a stainless steel Ponar grab sampler (Figures 2-2 and 2-3). The top 2 - 3 cm of sediments were collected and placed in plastic sample cups.

Samples of un-oxidized tailings were obtained from the bottom few centimetres of the Ponar grab sample (at depth of 15 cm) taken at Site BL2 in Benson Lake and from surface samples of tailings disposed on land near the mine site. Sediment and tailing samples were split into four portions. One portion was sent to Dr. Jeff Harris, Harris Exploration Services Ltd., North Vancouver, B.C. for petrographic analysis using polished thin sections for mineral identification and X-ray diffraction (XRD) analysis. A second portion was sent to the University of British Columbia (UBC), Department of Oceanography, Vancouver, B.C. where the samples were freeze-dried and ground to -200 mesh in a tungsten carbide mill for total carbon, nitrogen and sulphur (CNS) and X-ray fluorescence (XRF) analyses. A third portion was sent to Golder Associates Ltd. of Vancouver, B.C. for particle size analysis using a hygrometer method in accordance with ASTM designation D422-72 "Standard Methods for Particle-Size Analysis of Soils". The fourth portion was sent to Elemental Research Inc. (Elemental) of North Vancouver, B.C. for metals analyses. Also, a multiple extraction leach test was conducted on the lake tailings sample and land tailings sample (BL2 Tails and Land Tails).

Samples for petrographic analysis were dried, disaggregated by brief pulverization, dispersed in epoxy on glass slides and prepared as polished thin sections for microscopic study. No slide could be made for the Keogh Lake sample as some property of the sample prevented hardening of the mounting medium. X-ray diffractometer (XRD) scans (Cu Kα radiation) were carried out on unmounted portions of the samples.

Major and minor element concentrations were respectively measured on cast glass and pressed powder discs, using an automated Philips PW 1400 X-ray fluorescence spectrometer equipped with a Rh target anode. Glass discs were prepared using a slight modification of the method of Norrish and Hutton (1969), which eliminated the need to apply specific corrections for matrix absorption effects. Major elements for the Keogh Lake sample could not be determined by XRF as similar matrix problems occur in trying to form the glass disc as were experienced in the petrographics thin sections.

Calibration for both sets of measurements was provided by a wide range of international geochemical reference standards, with discs prepared in the appropriate way, and using the element concentrations recommended by Abbey (1980). Additional metal-rich standards were prepared for the minor element measurements on the tailings-bearing samples, to ensure that a calibration curve could be used which was linear up to and beyond the maximum Zn, Cu or Pb concentration encountered.

Total carbon, nitrogen and sulphur were determined using elemental analysis. Total C and N were measured using a Carlo-Erba 1106 Elemental Analyzer which combusts the sample in a stream of O_2, separates the combustion gases (CO_2 and N_2 reduced from NOx) chromatographically, and measures the gas concentrations (thus C and N contents) by thermal conductivity. Sulphur was determined using a Carlo-Erba NA-1500 CNS Analyzer, which employs the same methodology. The analyzers are calibrated using acetanilide and the NRC marine sediment standards MESS-1 and BCSS-1. Accuracy is excellent; agreement with the recommended values for total C and N was always within analytical precision. The precision of the measurements (1σ, R.S.D.) was about 1.5%, 3% and 3% for C, N and S respectively.

Carbonate carbon was determined on all samples by coulometry using a coulometrics analyzer, which electrochemically measures the CO_2 evolved following addition of HCl to a sample. Concentrations were very low in the natural sediments (typically <0.1 wt. %), but ranged up to 0.8 wt. % in the tailings. Precision of the measurements (1σ, R.S.D.) was better than 3% for the higher carbonate carbon concentrations. Organic carbon was determined by subtracting carbonate carbon from the total C measurements. Precision of the resulting organic C value was about ±5 % (1σ, R.S.D.).

Sediments were homogenized by shaking. A percent solids determination was made on a 1.0 g portion of the sample at 103 °C for 24 hours. For metals analysis 1.0 g of sample was weighed into a 250 ml Phillips beaker to which 4 ml (1:1) HNO_3, 10 ml (1:4) HNO_3 and two drops of concentrated HCl was added. The beaker was covered with a watch glass and refluxed for 30 minutes at 95 °C. The sample was cooled and diluted to 100 ml with deionized distilled water. Analysis was by ICP-MS as per EPA protocol 200.8. To determine sulphate concentration, 5.0 g of solid was weighed into a 250 ml beaker, to this 5.0 g of Na_2CO_3 was added and 100 ml of DIH_2O with a boiling chip. The sample was boiled for 20 minutes. The sample was then cooled and filtered and analyzed as per

"Standard Methods", 16th edition (section 426c). Total organic carbon was determined by dichromate reflux.

A multiple extraction leach test was performed on material from lake (BL2) and land tailings to assess the leachability of metals from tailings exposed to a range of environmental conditions. The test used was similar to those utilized in other aquatic studies (Forstner and Wittman 1983, Engler, Brannon and Rose 1974, Rescan 1990c and Rescan 1990d). 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. Table 2-1 lists the extractants used, and identifies each in terms of their anticipated reaction with metals in the solids.

2.3.4 Phytoplankton

Phytoplankton samples were collected at the three stations on Benson Lake and on one station in Keogh Lake on September 13 and 17, 1990, respectively (Figures 2-2 and 2-3). Two bottle casts were taken at 0.5 m and 5-11 m (variable) depths. Five hundred ml samples 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 μm filter and preserved with a saturated $MgCO_3$ solution. Filters were wrapped in aluminum foil and frozen. Analysis for chlorophyll *a* was completed using an approved spectrophotometric method (APHA 1985).

Qualitative and quantitative phytoplankton analysis was carried out to the lowest possible taxonomic level by Aquametrix Research Ltd., Sydney, B.C. Samples were counted using Utermohl chambers. Organisms in 10 fields of each sample were identified and counted at 350 x magnification. Data are expressed as number of cells ml^{-1}.

2.3.5 Zooplankton

Vertical net hauls for zooplankton collection were taken at three Benson Lake sites and one site in Keogh Lake on September 14 and 17, 1990 respectively using a 13 cm diameter Wisconsin 80 μm mesh plankton net. Hauls were brought up from just off the bottom to the surface at a rate of 0.5 to 1 m s^{-1}. Three horizontal net tows were also

Table 2-1

Extractants and Associated Phases in Sequential Extraction of Sediments

Extraction Phase	Extractant
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.

conducted, two on Benson Lake and one on Keogh Lake on September 14 and 17, 1990 respectively. Horizontal tows were approximately 500 m long at a depth of 1 m and towed at ≈ 0.75 m s^{-1}. Zooplankton samples were preserved in 10% buffered formalin.

Qualitative and 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).

2.3.6 Benthic Invertebrates

Benthic invertebrate (benthos) samples were collected using a Ponar grab sampler at the three Benson Lake sites and the Keogh Lake site (Figures 2-2 and 2-3). Three sub-samples were taken within the grab sampler using a 8 cm diameter cylinder at each site. Samples were then washed through a sieve bucket with a screen mesh size of 253 μm.

The retained material was preserved in a 10% buffered formalin solution. Benthos were counted and identified to the lowest practical taxonomic group.

Surber samples were collected on September 14, 1990 from Benson and Raging rivers using a 1 square foot Wildco Surber Sampler with 1 mm mesh net. Samples were taken in riffle areas and preserved in 10% buffered formalin. Benthos were counted and identified to species.

Fish stomachs were collected from Benson and Keogh Lakes on September 14 and 17, 1990 respectively. Samples were preserved in 10% buffered formalin and the contents of each stomach counted and identified to the lowest practical taxonomic level.

2.3.7 Aquatic Vegetation

The aquatic macrophytes of Benson Lake were surveyed and mapped. Samples of macrophytes and associated sediments were collected from Benson Lake (Figure 2-4) and Three Isle Lake on September 15, 1990. In addition, the sediments in which the plants were rooted were collected using a hand trowel or shovel. Sampled plants were separated into tops and root material and placed in individual plastic zip-loc or whirlpak bags (after a thorough rinsing in site water) and refrigerated.

In the laboratory, plant samples were rinsed lightly with 1% HCl to remove attached surface material and homogenized in a stainless steel blender. Percent moisture was determined gravimetrically on a 1.0 g sample at 103°C for 24 hours. For metals analysis, a 1.0 g sample was weighed into a 60 ml teflon digestion vessel, 2 ml of ultrapure nitric acid was added, and the sealed vessel was then heated to 200°C until digestion was complete. The sample was then diluted to 10 ml using deionized distilled water and metals analysis performed using an inductively coupled plasma mass spectrophotometer (ICP-MS).

2.3.8 Fish

Fish were sampled in Benson and Keogh Lakes on September 13 and 17, 1990 using 2.0 cm mesh sinking and floating gill nets. Gill nets were set at various sites in each lake (Figure 2-2) with soak time of 3 to 6 hours. Captured fish were weighed (±0.1 g), measured for fork length (±1 mm), sexed and dissected to extract stomachs. The

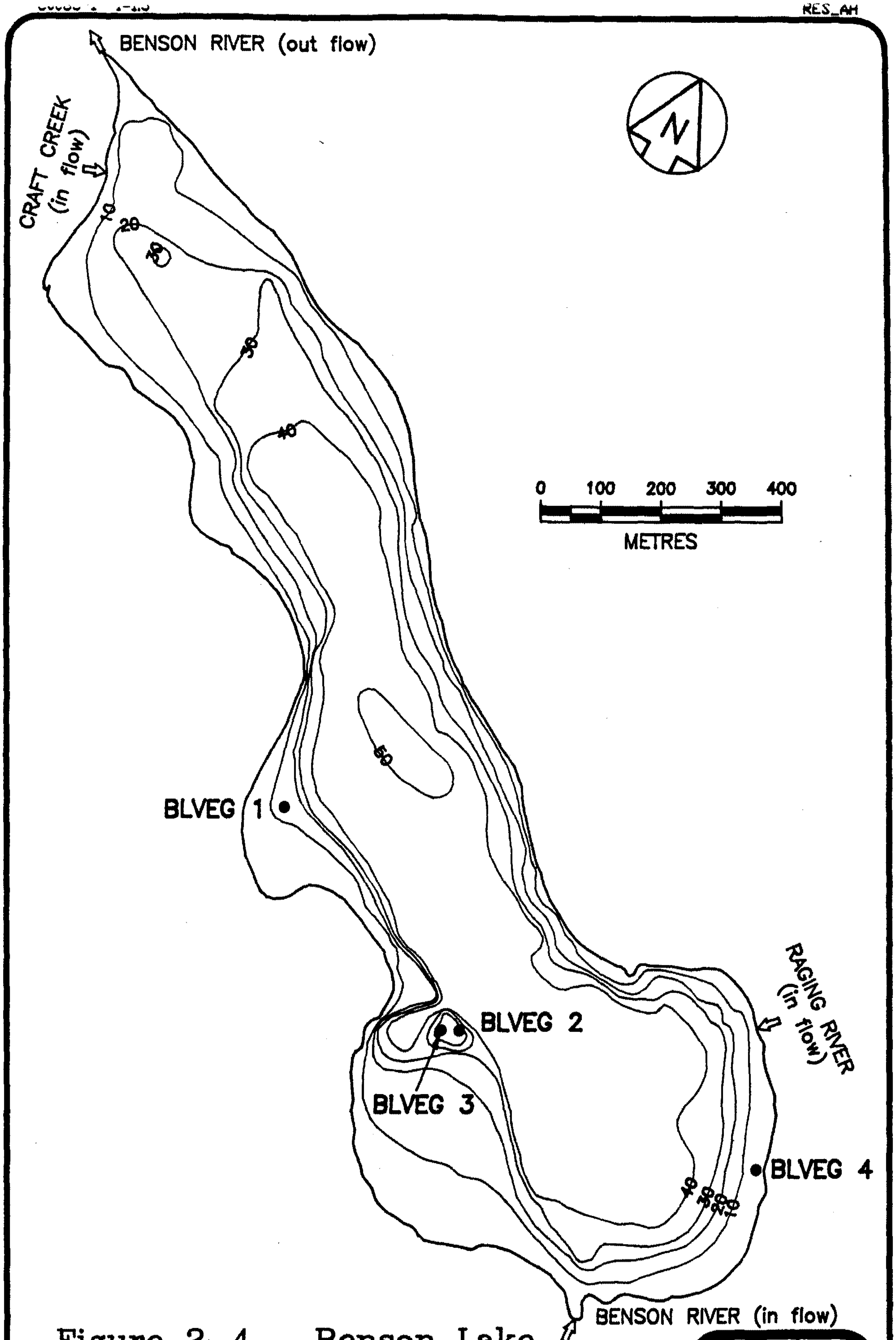


Figure 2-4 Benson Lake Vegetation Sampling Locations

Rescan

stomachs were retained and preserved in 10% buffered formalin. Selected fish were dissected on clean plastic bags using a stainless steel scalpel. Tissue samples of the dorsal muscle were obtained by removing the skin from the first dorsal fin ray forward to the gill cover. A tissue sample was collected from this area taking special care not to include any bones or skin. Liver samples were also collected from the same fish. Tissue samples were frozen and shipped to Elemental. Scales were collected for aging analysis.

Fish tissue samples were homogenized using a mortar and pestle to prevent metal contamination. The percent moisture was determined gravimetrically by weighing 1.0 g of tissue into a small beaker and drying at 103°C for 24 hours. For metals analysis a 1.0 g sample was weighed into a 60 ml teflon digestion vessel, 2 ml of ultra pure nitric acid added and the sealed vessel was then heated to 200°C until digestion was complete. The sample was then diluted to 10 ml with deionized distilled water and metals analysis performed using an inductively coupled plasma mass spectrophotometer unit (ICP-MS).

3 - Results and Discussion

3.0 RESULTS AND DISCUSSION

The following section details the results of physical and chemical analyses of the hydrology, water quality and sediment characteristics of Benson Lake 17 years after the cessation of subaqueous tailings disposal. In addition, the biota (plankton, vegetation and fish) are evaluated to determine whether effects of tailings disposal on community structure and composition are evident.

3.1 Lake Morphometry and Hydrology

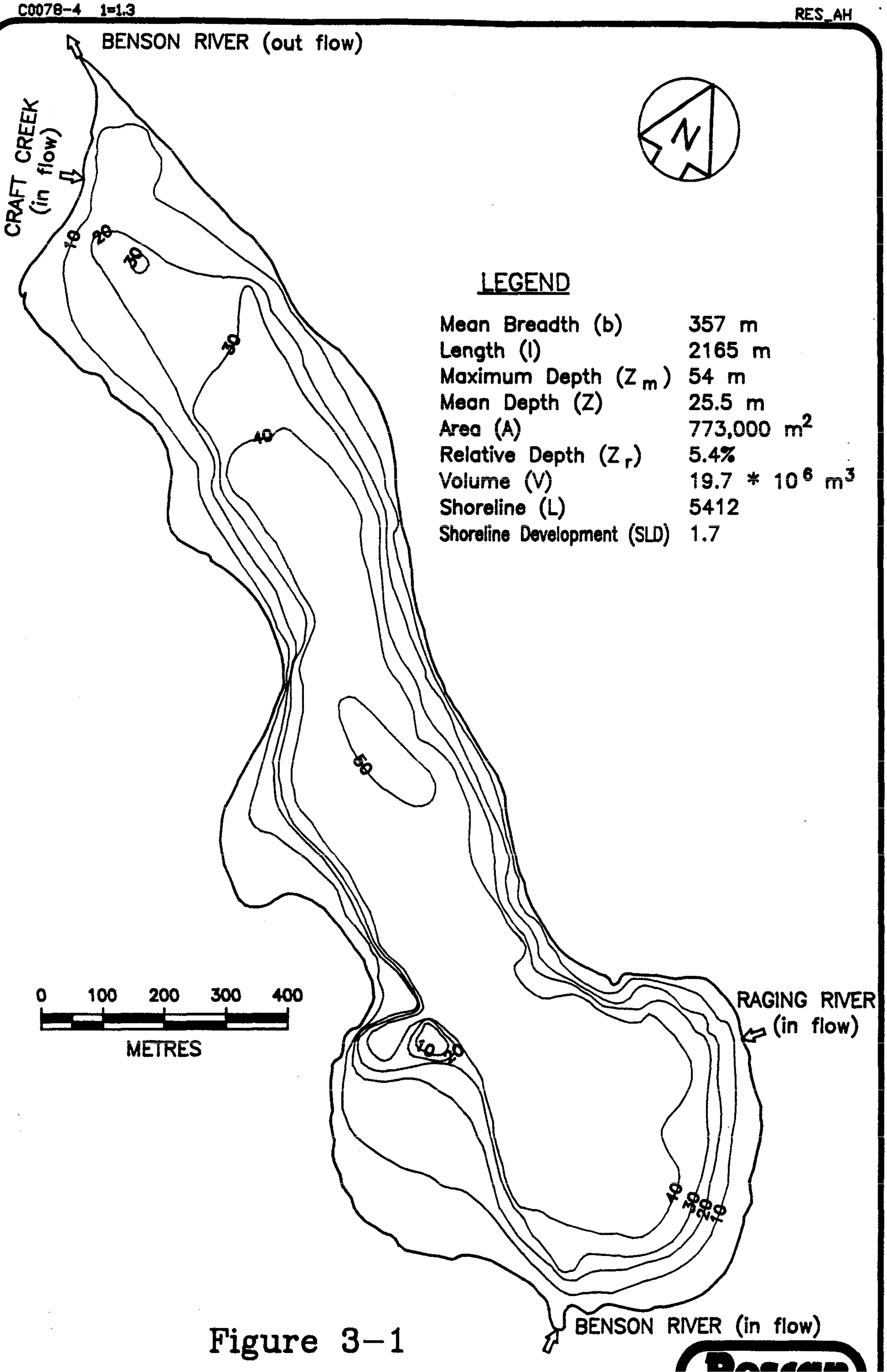
3.1.1 Morphometry of Benson and Keogh Lake

Benson Lake is a small deep lake about 2.16 km long with a mean breadth of 0.36 km, a mean depth of 25.5 m, and a maximum depth of approximately 54 m (Figure 3-1). The total area enclosed is 773,000 m^2 and the lake volume is currently 1.97×10^6 m^3. The lake is one in a series of lakes that lie in an area of moderate relief on the northern end of Vancouver Island. It is oriented in a southeast-northwest direction and is fed from the eastern end by the Benson River and the Raging River. The Raging River flows in the adjacent valley to the east and ultimately drains Maynard Lake which lies to the northeast. The lower Benson River, which drains Benson Lake, flows westward to Kathleen Lake and further to Alice Lake.

Keogh Lake, the control lake, is similar to Benson Lake in size, shape and depth (Figure 3-2) and lies approximately 12 km to the northeast (see Figure 1-1). This lake forms the headwaters of the Keogh River which flows northwestward into Queen Charlotte Strait.

The lake morphometry of Three Isle Lake, used as a control lake for aquatic vegetation analyses, was not examined in detail. However, a preliminary examination found the lake to be relatively shallow (maximum depth less than 12 m) and gradually sloping around its entire perimeter.

C0078-4 1=1.3 RES_AH



LEGEND

Mean Breadth (b)	357 m
Length (l)	2165 m
Maximum Depth (Z_m)	54 m
Mean Depth (Z)	25.5 m
Area (A)	773,000 m^2
Relative Depth (Z_r)	5.4%
Volume (V)	$19.7 * 10^6$ m^3
Shoreline (L)	5412
Shoreline Development (SLD)	1.7

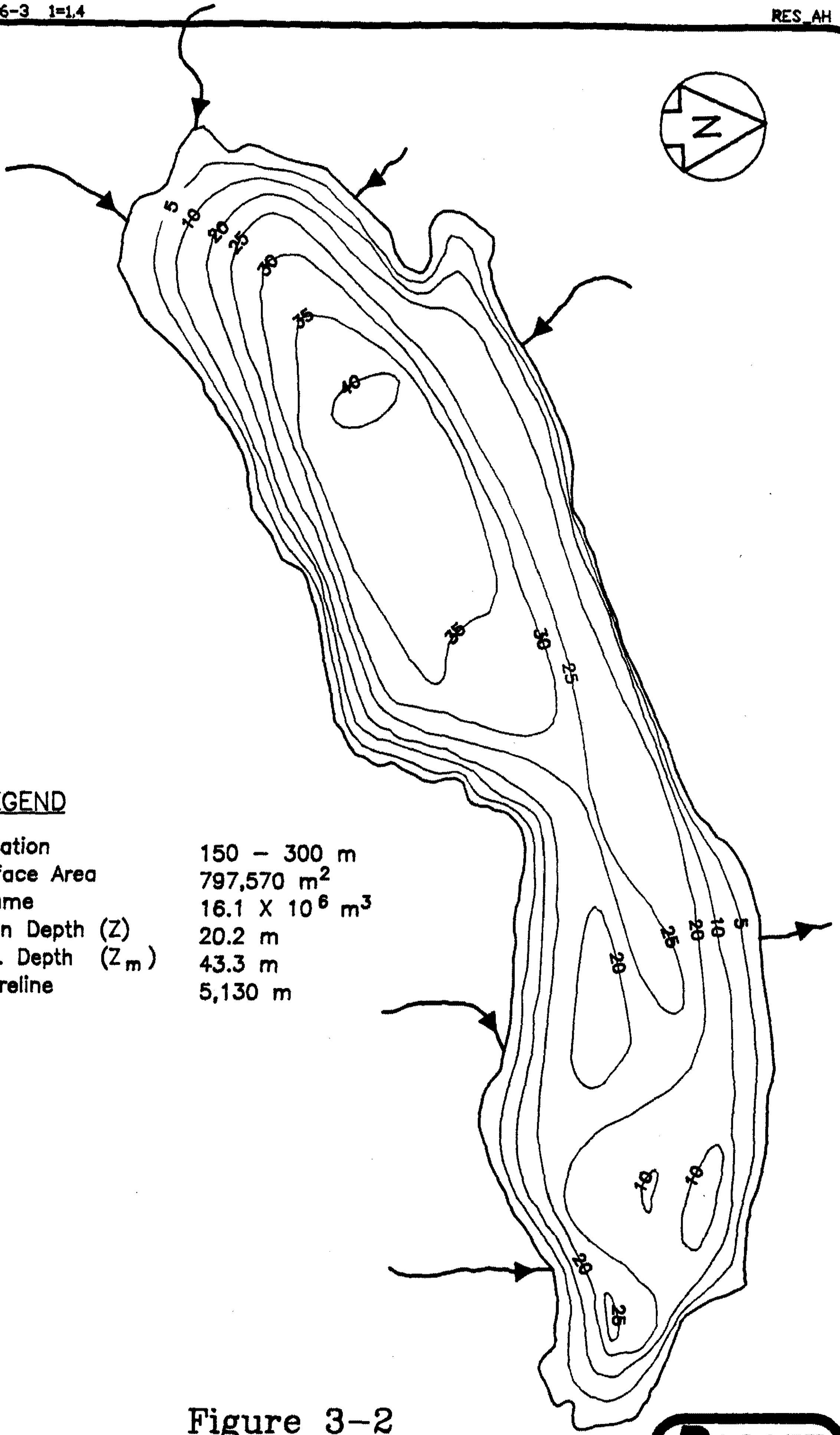
Figure 3-1

Benson Lake Bathymetric Mapping

Rescan

C0066-3 1=1.4

RES_AH



LEGEND

Elevation	150 - 300 m
Surface Area	797,570 m^2
Volume	16.1 X 10^6 m^3
Mean Depth (Z)	20.2 m
Max. Depth (Z_m)	43.3 m
Shoreline	5,130 m

Figure 3-2
Keogh Lake Bathymetric Mapping

3.1.2 Benson Lake Hydrology

While a detailed hydrological investigation of Benson Lake and its associated drainages was not part of the present scope of work, the data collected to date affords some general comments. At the time of this survey (September 13 - 17, 1991), the Raging River, which enters Benson Lake on its eastern end, contributed the greatest amount of inflow (80%) to the lake, followed by the upper Benson River (13.5%) and Craft Creek (6.5%) (Appendix A). Discharge measurements indicated that total surface water inflow (2.08 $m^3 s^{-1}$) was roughly equal to total surface water outflow (1.88 $m^3 s^{-1}$). No measurements of input or loss due to groundwater, evapotranspiration and or precipitation were made.

The hydrology of Benson Lake is also affected by a dam situated on the Raging River at the outlet of Maynard Lake. Since the Raging River contributes the greatest amount of inflow to Benson Lake in late summer, water management strategies that affect water levels in Maynard Lake will also affect water levels and water quality in Benson Lake.

3.2 Water Quality

The summer stratification regime in Benson Lake appeared to be deteriorating with the onset of fall overturn as there was a progressive deepening of the epilimnion with no distinct thermocline evident (Figures 3-3 to 3-5). In contrast, the control lake, Keogh lake, had a distinct thermal discontinuity layer at between 6 and 9 m in depth (Figure 3-6).

Temperature, oxygen, pH, turbidity and conductivity profiles in Benson and Keogh Lakes indicated that the physical properties controlling water quality were similar to a depth of approximately 35 m, both between lakes and at each of the three sampling stations within Benson Lake (Figures 3-3 to 3-5). Below 35 m, there was a progressive reduction in oxygen content at all sites, becoming acute just above the sediments in Keogh Lake. Turbidity levels at Stations 1 and 2 in Benson Lake were slightly higher below 35 m than above this depth (1.1 and 1.6 NTU's, respectively), however, values in the range of those observed essentially represent clear water. Station 3 in Benson Lake and Station 1 at Keogh Lake were not sampled for turbidity, conductivity or pH below 35 m. The observed sharp decline in oxygen concentrations above the sediments in Keogh Lake may, in part, be explained by the fact that an operational fish farm was

Figure 3-3 Turbidity (NTU), Conductivity (μmhos), pH, Dissolved O_2 (mg L^{-1}) and Temperature Profiles for Benson Lake, Station 1

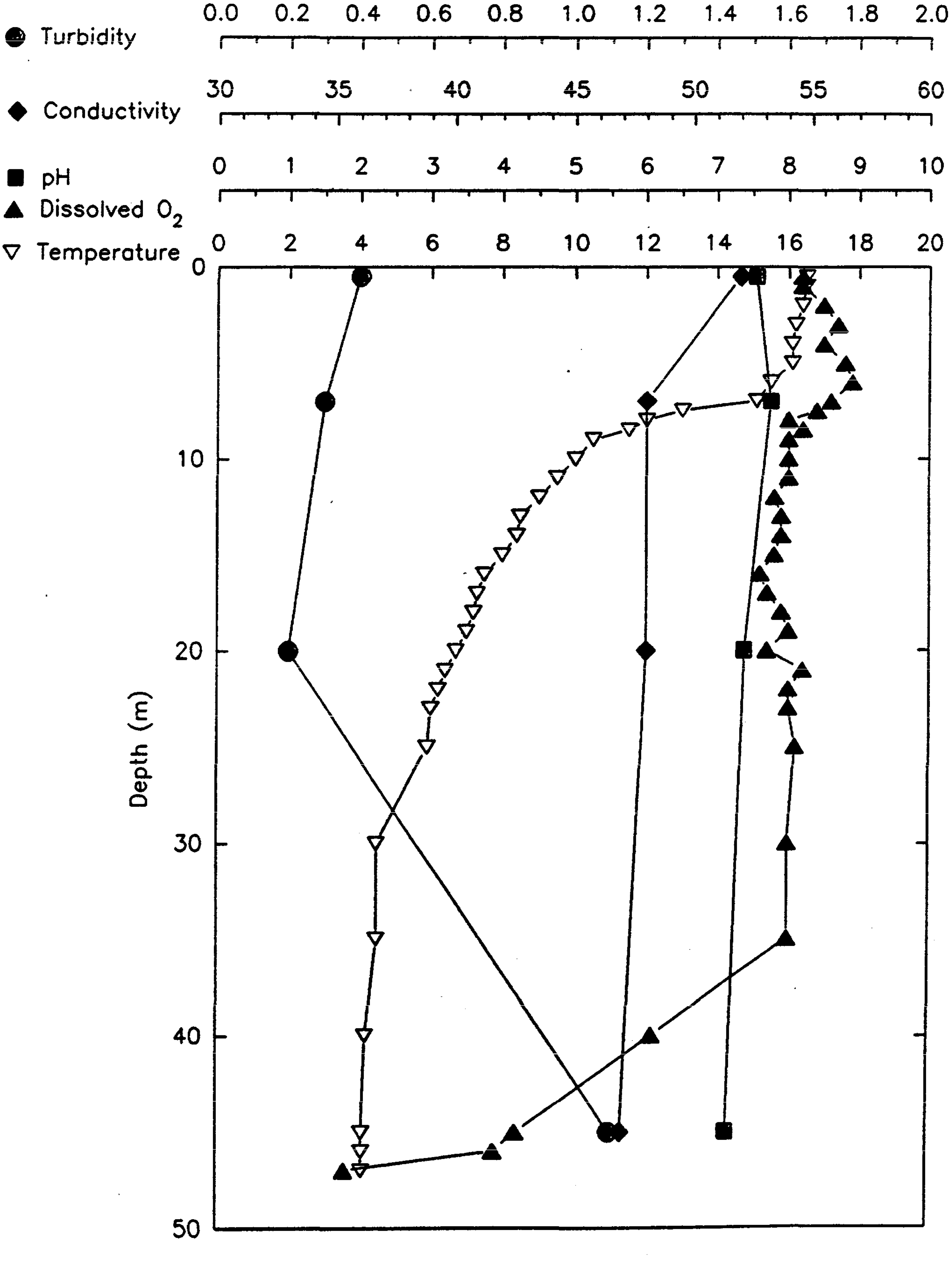


Figure 3-4 Turbidity (NTU), Conductivity (μmhos), pH, Dissolved O_2 (mg L^{-1}) and Temperature Profiles for Benson Lake, Station 2

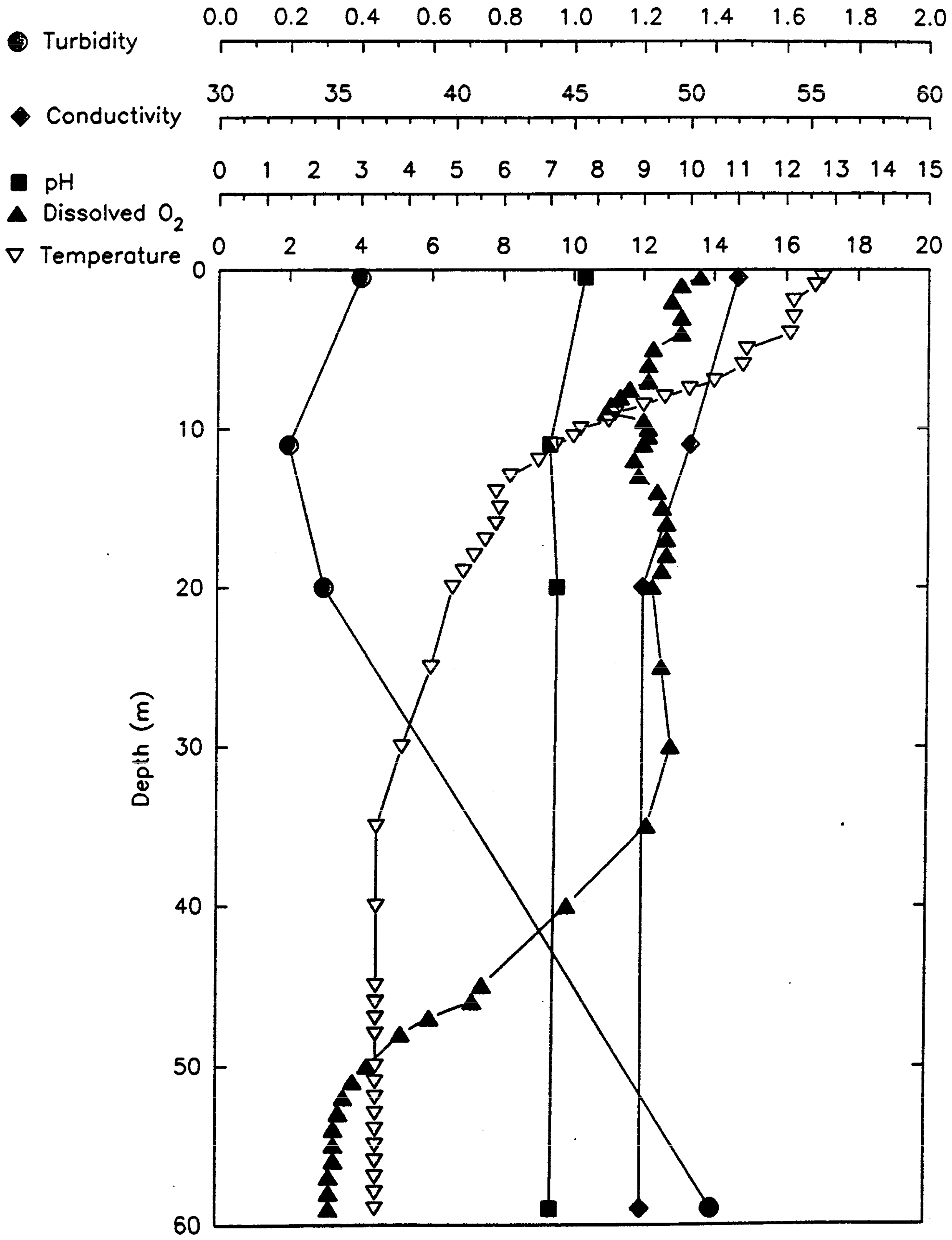


Figure 3-5 Turbidity (NTU), Conductivity (μmhos), pH, Dissolved O_2 (mg L^{-1}) and Temperature Profiles for Benson Lake, Station 3

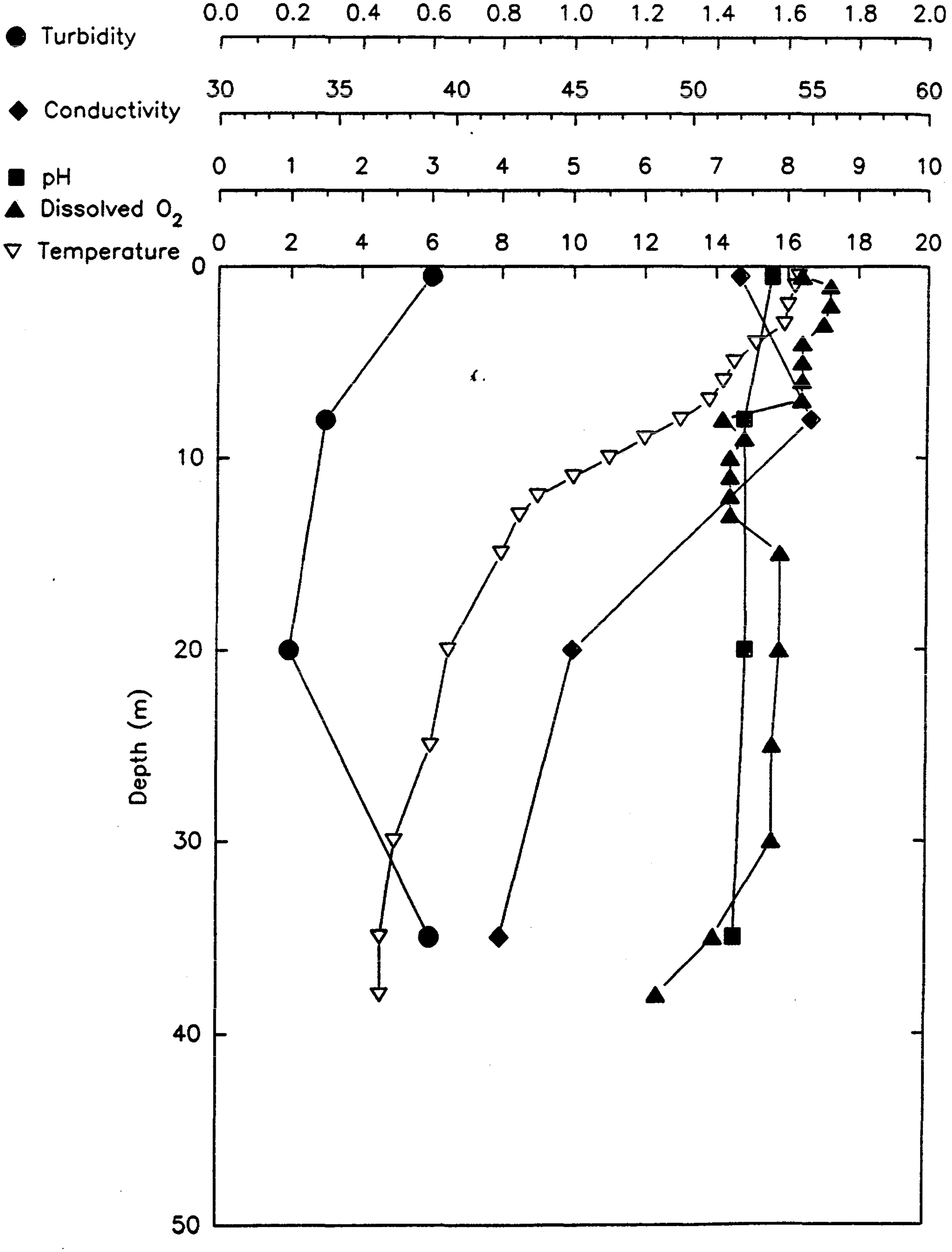
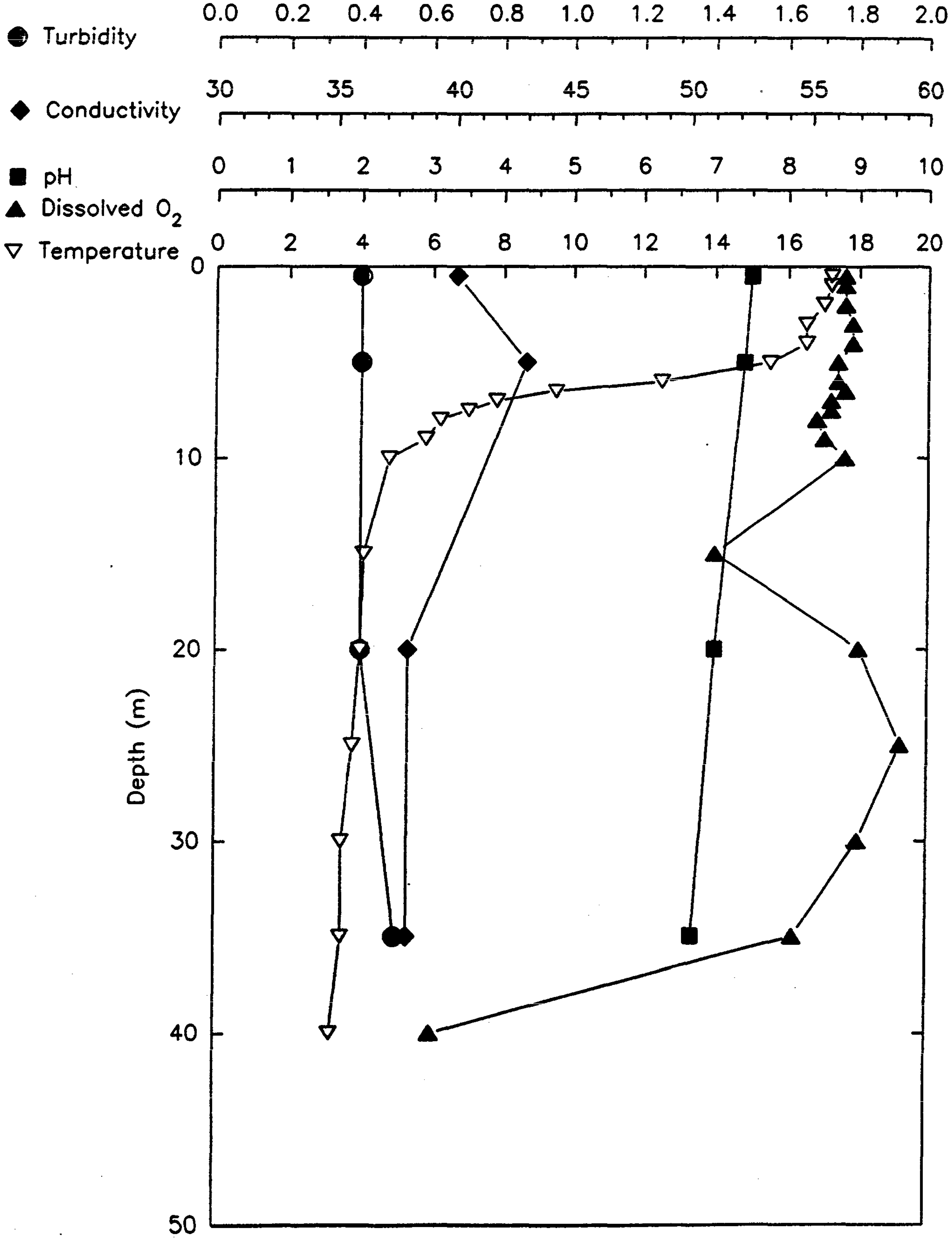


Figure 3-6 Turbidity (NTU), Conductivity (µmhos), pH, Dissolved O_2 (mg L^{-1}) and Temperature Profiles for Keogh Lake, Station 1



located near the sampling station. Fouling of the profundal sediments from uneaten fish food and from fish feces may be increasing the biological oxygen demand at the sediment-water-interface resulting in lower-than-expected oxygen concentrations.

Physical and chemical water quality test results indicated similar water quality at all stations in Benson Lake but there were major differences between Benson and Keogh Lakes (Table 3-1; Appendix B). Both lakes were circumneutral in pH, but Benson Lake water was significantly higher in conductivity (74.7 μmhos), alkalinity (31.8 mg L^{-1} $CaCO_3$) and total dissolved solids (53.5 mg L^{-1}) than Keogh Lake water (comparative values 24.5 μmhos, 7.7 mg L^{-1} $CaCO_3$, and 20 mg L^{-1}, respectively). Keogh Lake water was significantly higher in the nutrient phosphorus (6.5 μg L^{-1} vs 3.3 μg L^{-1}) and in total productivity as measured by the parameters Chlorophyll *a* (0.64 μg L^{-1} vs 0.072 μg L^{-1}), total organic carbon (4.4 mg L^{-1} vs 1.7 mg L^{-1}), and secchi disk transparency (3.5 m vs 6.3 m). All other parameters, including dissolved metals concentrations, were similar between lakes. Finally, the chemical composition of the water entering Benson lake through the inflows was very similar in composition to the lake water (Table 3-2) and reflects the higher conductivity, alkalinity, total dissolved solids and lower nutrient levels mentioned above. Inflow water quality to Keogh Lake was not assessed.

Dissolved metals concentrations in both lakes and in the inflow streams to Benson Lake were generally low with only aluminum, arsenic, copper, and iron being consistently above detection limits (Table 3-2). Aluminum concentrations ranged from 0.015 to 0.046 mg L^{-1}, As from <0.0001 to 0.0005 mg L^{-1}, Cu from <0.001 to 0.003 mg L^{-1}, and Fe from <0.030 to 0.251 mg L^{-1} in Benson Lake. In Keogh lake the respective ranges of values were 0.066 to 0.141 μg L^{-1} for Al, <0.0001 mg L^{-1} (always) for As, 0.002 to 0.003 mg L^{-1} for Cu, and 0.039 to 0.309 for Fe. Aluminum concentrations were consistently above the CCREM guidelines for the protection of aquatic life in both lakes (Table 3-1; Appendix B). The forest podzolic soils in the area are the likely source of soluble aluminum. Decomposition of forest litter releases humic acids that chelate aluminum and enhance its mobility through the soil column and into surface waters. Arsenic never exceeded CCREM guidelines. Copper did so on only two occasions (max. 0.003 mg L^{-1}) and iron did so only once (max. 0.309 mg L^{-1}; see Appendix B).

Differences in the chemical profile of water from surface (0 to 10 m) and mid-water (10 to 20 m) depths were minor in both lakes, but bottom waters (below 20 m) were significantly different with respect to levels of ammonia nitrogen, nitrate/nitrite nitrogen

Table 3-1

Physical and Chemical Water Quality Parameters for Benson Lake (Sept 13, 1990) and Keogh Lake (Sept 17, 1990)*

Parameters		Benson Lake	Keogh Lake	CCREM Receiving** Water Guidelines
Physical Tests				
Conductivity	μmhos/cm	74.7	24.5	
Total Dissolved Solids	(mg/L)	53.5	20.0	
pH		7.56	7.15	6.5 - 9.0
Total Suspended Solids	(mg/L)	3.71	2.47	increase of 10.0 mg/L
Fixed Suspended Solids	(mg/L)	<1	<1	
Volatile Suspended Solids	(mg/L)	2.15	2.25	
Turbidity	NTU	0.51	0.40	
Dissolved Anions (mg/L)				
Alkalinity	$CaCO_3$	31.8	7.65	
Chloride	Cl	0.94	1.1	
Silicate	SiO_2	3.27	3.3	
Sulphate	SO_4	1.16	2.0	
Nutrients (mg/L)				
Ammonia Nitrogen	N	0.020	0.007	
Nitrite/Nitrate Nitrogen	N	0.033	0.037	
Total Phosphorus	P	0.0033	0.0065	
Other Tests (mg/L)				
Chlorophyll	μg/L	0.072	0.64	
Total Organic Carbon	C	1.70	4.37	
Dissolved Metals (mg/L)				
Aluminum	Al	0.028	0.105	0.1
Arsenic	As	0.00025	<0.0001	0.05
Cadmium	Cd	<0.0002	<0.0002	0.0002
Calcium	Ca	11.9	2.45	-
Copper	Cu	0.001	0.002	0.002
Iron	Fe	0.081	0.131	0.300
Lead	Pb	0.001	<0.001	0.001
Magnesium	Mg	1.11	0.72	-
Manganese	Mn	0.05	0.02	-
Mercury	Hg	<0.00005	<0.00005	0.0001
Nickel	Ni	0.001	<0.001	0.025
Potassium	K	0.10	0.035	-
Silver	Ag	<0.0001	<0.0001	0.0001
Sodium	Na	1.13	1.12	-
Zinc	Zn	<0.0005	<0.005	0.03

< = less than

*** Mean values for entire water column (i.e. mean of samples taken at 4 depths. See Appendix B)**

**** For the protection of aquatic life.**

Table 3-2

Water Quality Analysis for Benson and Raging Rivers and Craft Creek

Parameters		Benson Inflow Sep 18/90	Benson Outflow Sep 18/90	Craft Creek Sep 18/90	Raging River Sep 18/90
Physical Tests					
Conductivity	μmhos/cm	105	76.8	124	70.6
Total Dissolved Solids	(mg/L)	90.0	60.0	100	60.0
pH		7.90	7.78	8.03	7.84
Total Suspended Solids	(mg/L)	2.7	4.7	2.7	<1.0
Fixed Suspended Solids	(mg/L)	<1	<1	<1	<1
Volatile Suspended Solids	(mg/L)	2.0	4.0	2.0	<1
Turbidity	NTU	0.20	0.30	0.10	0.50
Dissolved Anions (mg/L)					
Alkalinity	$CaCO_3$	47.5	34.3	55.5	31.5
Chloride	Cl	0.9	0.5	0.6	0.5
Silicate	SiO_2	3.2	3.8	3.3	4.3
Sulphate	SO_4	4.1	2.5	2.6	1.7
Nutrients (mg/L)					
Ammonia Nitrogen	N	<0.005	<0.005	<0.005	<0.005
Nitrite/Nitrate Nitrogen	N	0.120	0.036	0.140	0.023
Total Phosphorus	P	0.003	0.004	0.004	0.005
Other Tests (mg/L)					
Total Organic Carbon	C	0.75	1.64	0.84	1.92
Dissolved Metals (mg/L)					
Aluminum	Al	0.020	0.028	0.056	0.033
Arsenic	As	0.0007	0.0002	0.0004	<0.0001
Cadmium	Cd	<0.0002	<0.0002	<0.0002	<0.0002
Calcium	Ca	18.9	12.5	21.3	10.8
Copper	Cu	0.001	0.005	0.001	0.002
Iron	Fe	<0.030	0.043	<0.030	0.079
Lead	Pb	<0.001	<0.001	<0.001	<0.001
Magnesium	Mg	0.927	1.35	1.66	1.60
Manganese	Mn	<0.005	<0.005	<0.005	<0.005
Mercury	Hg	<0.00005	<0.00005	<0.00005	<0.00005
Nickel	Ni	<0.001	<0.001	<0.001	<0.001
Potassium	K	0.16	0.09	0.14	0.08
Silver	Ag	<0.0001	<0.0001	<0.0001	<0.0001
Sodium	Na	1.40	1.22	1.50	1.20
Zinc	Zn	<0.005	<0.005	<0.005	<0.005

< = less than

and the dissolved metals aluminum and iron (Table 3-1). All other parameters were similar from top to bottom.

Ammonia nitrogen concentrations in the bottom water of Benson Lake (0.096 mg L^{-1}) were an order of magnitude higher than in surface waters (0.005 mg L^{-1}) while nitrate/nitrite levels remained fairly consistent from top to bottom (range 0.21 to 0.46 mg L^{-1}). The observed increases in ammonia, iron and aluminum concentrations and the reduction in the concentration of nitrate/nitrite in the profundal zones of Benson Lake are consistent with the observation that oxygen concentrations near the bottom were reduced (Figures 3-3 to 3-5). Under anaerobic conditions, and with a suitable supply of metabolizable carbon, denitrification can convert nitrates and nitrites to gaseous nitrous oxide and dinitrogen. Moreover, under highly reducing conditions, nitrate and nitrate can be dissimilated to ammonium by fermentative bacteria. Iron and aluminum solubility also increases as the redox potential decreases and the two compounds are liberated from benthic muds (Hutchinson 1957).

In accordance with the observed, rather severe, oxygen depletion in the bottom waters of Keogh Lake (Figure 3-6), dissolved iron and aluminum concentrations increased relative to the well-oxygenated overlying waters. Ammonia nitrogen, on the other hand, was undetectable (<0.005 mg L^{-1}) and nitrate/nitrite was relatively abundant (0.083 mg L^{-1}). In contrast, ammonia nitrogen was present in surface water (0.011 mg L^{-1}), while nitrate/nitrite was not (<0.005 mg L^{-1}; see Table 3-1). The absence of ammonia nitrogen and the prevalence of nitrate/nitrite nitrogen species in the bottom waters of Keogh Lake, at first glance, appears to be anomalous. However, the deep water sample in this lake was taken from a depth of 35 m, which was still in the well oxygenated zone (Figure 3-6). Therefore, it is not surprising that nitrate/nitrite nitrogen was present in this sample in significant concentrations.

Depletion of nitrate/nitrite in the surface waters of Keogh Lake may have been caused by assimilation of this nutrient by photosynthetic processes, leading to the apparent stratification of this form of nitrogen. This hypothesis is supported by the evidence of increased photosynthetic activity, as suggested by the elevated levels of Chlorophyll *a* and total organic carbon relative to Benson Lake. The detectable levels of ammonia nitrogen in the surface waters of Keogh Lake, which in itself is anomalous, may have been caused by excretory products generated by a nearby fish farm.

In conclusion, it can be stated that the water quality in Benson Lake, 17 years after cessation of tailings deposition, was similar to that of the control lake which had not received tailings. Differences in the water quality between the two lakes can be explained, in large part, by the presence of a fish farm in Keogh Lake which appears to be having the effect of enriching lake productivity. Both lakes can be categorized as being oligotrophic on the basis of their water quality. Anaerobic conditions in the deep profundal zones of both lakes are likely due to a high biological oxygen demand resulting from consumption during the oxidation of organic matter. The profundal oxygen depletion in Keogh Lake was more severe than in Benson Lake. This may be attributable to increased bacterial decomposition of detritus from the fish farm.

3.3 Sediment and Tailings

Benthic sediments collected from Benson Lake indicated that the tailings which had once been deposited and dispersed over the lake bottom are presently overlain by a layer of mud and organic material between 2 and 3 cm thick (Table 3-3). The sediment collected at the station nearest the lake's inlet streams (Station 1) contained abundant organic material and significant quantities of poorly decomposed wood chips; probably by-products of active forestry (carried down in surface runoff) which has been going on in the area over the last decade. Below the organic muds, there was evidence of tailings material at all stations, being most prominent at Station 2.

Total carbon, including organic and carbonate forms, nitrogen and sulphur analyses results are presented in Table 3-4. Samples BLSS 1-3 contained significant amounts of organic carbon (6.6 to 7.9%) with much lesser amounts of carbonate-C being present. Total nitrogen concentrations were greatest in those samples with the highest amount of organic-C as expected. Total sulphur concentrations were poorly correlated with organic-C concentrations. Moreover, the highest sulphur concentrations were associated with the tailings samples indicating that the majority of the sulphur in these samples was inorganic. The sediment sample obtained from Keogh Lake (KL-1) was high in organic-C (17%) and contained less sulphur than Benson Lake tailings sediments.

3.3.1 Particle Size Analysis

Particle size analysis of the Benson Lake samples indicated the sediments at Station 1 (BLSS-1) were coarser and contained more fine sand particles (<0.15 mm) than

Table 3-3

Field Observations of Sediments Collected from the Profundal Zone of Benson and Keogh Lake for Benthic Invertebrate, Metals and Particle Size Analyses

Lake	Station Number	Date	Time	Depth	Observations
Benson	1	09/14/90	17:00 hrs	47 m	High organic content. Contained significant quantities of poorly decomposed wood chips. More sand sized particles
	2	09/14/90	17:45 hrs	51 m	Brown to reddish brown mud, 2 cm thick underlain by layer of mixed tailings and mud approximately 8 cm thick. Metallic grey tailings predominant below 10 cm.
	3	09/14/90	18:30 hrs	35 m	Brown to reddish brown organic ooze. Absence of large organic material that was found on site 1 (above). Mud was underlain by coarse gravelly type sediment.
Keogh	1	09/17/90	15:45 hrs	40 m	Chocolate brown coloured organic ooze approximately 10 cm thick underlain by brown to grey clayey material.

sediments at the other sites (Table 3-5; Appendix C). By contrast, sediments at Stations 2 and 3 were composed almost entirely of silt and fine clay particles. The fine sand particles at Station 1 are probably carried into the lake in the runoff from both the Benson and Raging Rivers and deposited in the eastern end of the basin. The land tailings sample had a particle size distribution most similar to that observed at Station 1, being composed primarily of fine sand and silt sized material. The Keogh Lake sample also consisted of fine sand material with similar proportions of clay as compared to the Benson Lake samples.

3.3.2 Petrographic Analysis

Six sediment samples were mounted on glass slides and prepared as polished thin sections for microscopic study. No slide could be made of the sample from Keogh Lake as some property of the sample prevented hardening of the mounting medium. X-ray

Table 3-4

Total Carbon (Organic and Carbonate C) Nitrogen and Sulphur (Dry Weight %) in Surface Sediments from Benson Lake

	Carbon			
Sample ID	Org. C	Carb. C	Nitrogen	Sulphur
BLSS-1	7.51	0.02	0.26	0.14
BLSS-2	7.94	0.02	0.34	0.17
BLSS-3	6.68	0.01	0.29	0.40
BL2 - Tailings	1.76	0.03	0.10	1.20
Land Tailings	0.48	0.00	0.03	2.55
KL-1	17.06	0.01	0.75	0.18

Table 3-5

Particle Size Distribution for Benson and Keogh Lake Sediments

Lake	Sample	Sand %	Silt %	Clay %
Benson	BLSS 1	54	37	9
	BLSS 2	18	72	10
	BL2 Tails	2	82	16
	BLSS 3	13	75	12
	Land Tails	56	40	4
Keogh	KL 1	61	28	11

diffractometer scans (CuKα radiation) were carried out on portions of each of the unmounted samples. Samples BL SS 1, 2, 3 and BL 2 Tailings are all of similar character, consisting of a mixture of mineral grains and a translucent brown to opaque amorphous material which almost certainly represents a veneer of organic-rich ooze and possible Fe-hydroxides on the lake bottom. Estimated proportions of the organic material are generally in the range of 30 to 40%.

The mineral component seems similar in all cases, consisting of various proportions of feldspar (plagioclase), quartz, amphibole, chlorite, garnet, epidote, possible diopside and/or olivine, and Fe-oxides (magnetite and minor hematite). The mineral grains are small (mainly in the range 5 to 100 microns), and identifications and estimates of relative proportions are not of high reliability.

Sulphides were notably sparse, totalling an estimated 0.3 to 0.5%. They consisted of pyrite, pyrrhotite and traces of chalcopyrite, all as liberated particles. The Fe sulphides occasionally showed thin rims of oxidation to limonite, but the chalcopyrite was unoxidized. The proportion of the mineral component (and specifically of sulphides) was not significantly different in the BL 2 Tailings sample than in samples BL SS 1 to 3. The overall mineralogy of the mineral component in the latter samples was also similar to that of BL 2, suggesting that it consists, in all cases, predominantly of redistributed tailings.

The CuKα XRD scans and analyses confirm the salient features of the optically estimated mineralogy. Various small, unidentified peaks (not always the same in each sample) were also present. The brown organic phase, being non-crystalline, did not show up on the XRD traces. The XRD pattern of the Keogh sample showed only a few subdued peaks, suggesting that it consisted largely of organic ooze, with a minimal (quartzo-feldspathic) mineral component. Such a composition may explain its effect on the epoxy used in the attempted mounting.

The sample designated "Land Tailings" was apparently some form of comminuted high grade ore. It contained about 12% chalcopyrite and 20% magnetite. Its mineralogy differed from that of the material whose processing produced the tailings in the lake, as the sulphides are devoid of pyrite or pyrrhotite, and, in the gangue, quartz was strongly dominant over feldspar. X-Ray Fluorescence analyses of the profundal and surficial sediments confirm these findings. The lake samples showed substantial amounts of

Al_2O_3 and Na_2O, indicating that plagioclase was a major component of the gangue material discharged to the lake. Conversely, the sample of land tailings contained significantly less Na_2O and Al_2O_3 with quartz being more dominant (Table 3-6). The chalcopyrite grains appeared relatively fresh, and the strongly oxidized appearance of the sample was probably the result of precipitation of hydroxides from Fe-rich percolating waters.

3.3.3 Sediment Metal Analysis

Metal analyses of four profundal sediment samples from Benson Lake revealed that primarily copper and, to a lesser extent, arsenic were elevated in these sediments (Table 3-7). Sample BL2 had very elevated levels of Cu (1,000 mg Kg^{-1}) as compared to the other Benson Lake samples (230 to 400 mg Kg^{-1}). Iron was also somewhat enriched in BL2. By contrast, levels of Zn appeared to be depleted in BL2 (82 mg Kg^{-1}) as compared to BLSS 1-3 (200 to 220 mg Kg^{-1}). Copper was extremely elevated (24,000 mg Kg^{-1}) in the land tailings sample but had lower concentrations of Zn (58 mg Kg^{-1}), V (48 mg Kg^{-1}) and Ni (13 mg Kg^{-1}) in comparison to the profundal sediments. The Cu concentration in the land tailings greatly exceeded the Pacific Place Guideline level C of 500 mg Kg^{-1}, indicating that the sediments are highly contaminated with respect to this element. Iron was highly enriched in the land tailings sample (27%) and agrees well with the petrographic analysis which indicated the presence of secondary precipitation of Fe-oxides and the high percentage of magnetite.

The profundal sediment sample from Keogh Lake had significantly less Cu and As than that observed in Benson Lake, however more Cr and Ni was present in the Keogh Lake sample.

The methods used for the sequential extraction of sediment from Benson Lake tailings and land disposed tailings are outlined in Section 2.3.3. Eight (8) different extractions were used to assist with the determination of the metal associations with these sediments. 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 3-6

X-Ray Fluorescence (XRF) Analysis of Top 15 cm Layer of Sediments from Benson Lake (Values as %)

	Major Constituents									
Sample ID	Fe_2O_3	MnO	TiO_2	CaO	K_2O	SiO_2	Al_2O_3	MgO	P_2O_5	Na_2O
BLSS-1 (1)	10.31	0.13	1.10	3.85	0.89	46.92	13.99	3.06	0.23	2.58
BLSS-2 (2)	12.26	0.23	1.16	4.12	0.80	42.93	13.73	3.34	0.30	2.20
BLSS-3 (3)	14.03	0.14	1.05	6.48	0.64	43.61	12.42	3.90	0.26	1.89
BL2 - Tailings	22.82	0.24	0.60	11.71	0.39	45.23	8.54	4.87	0.15	1.08
Land Tailings	41.27	0.14	0.37	10.06	0.18	34.05	4.24	2.44	0.05	0.37

( ) Indicates station number.

Table 3-7

Metal Analyses of Sediment Samples from Benson Lake (mg Kg^{-1})

Element	BLSS-1	BLSS-2	BL2-Tailings	BLSS-3	Land Tailings	KL-1
Aluminum %	3.2	3.2	1.6	3.6	0.34	4.91
Antimony	0.21	0.25	0.03	0.26	0.44	0.08
Arsenic	44.0	55.0	61.0	36.0	89.0	7.5
Cadmium	1.5	0.25	0.30	1.2	1.3	0.08
Calcium %	1.4	1.6	7.3	2.2	3.0	1.2
Chromium	55.0	67.0	72.0	91.0	13.0	150.0
Cobalt	38.0	51.0	170	49.0	19.0	65.0
Copper	230.0	320.0	**1000.0**	400.0	**24000**	150.0
Iron %	8.3	9.3	15.0	11.0	**27.0**	6.8
Lead	12.0	11.0	3.2	10.0	18.0	7.1
Magnesium	1.7	1.7	1.2	2.1	0.21	1.0
Manganese	970.0	1600.0	1400.0	940.0	520.0	1900.0
Mercury	0.25	0.16	0.30	0.10	1.0	0.79
Nickel	43.0	48.0	71.0	64.0	13.0	80.0
Vanadium	150.0	160.0	76.0	190.0	48.0	230.0
Zinc	220.0	200.0	82.0	210.0	58.0	150.0

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 and may be more significant in sediments with high clay content or significant quantities of organic matter. 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 and 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 difficultly reducible phase is often termed the non-silicate iron phase and includes those crystalline forms of ferric and manganese oxides and hydroxides (e.g. ß-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 metal compounds are included in this category.

A direct comparison between subaqueous and land-disposed tailings behaviour was examined in sequential extractions of sediments. Results from these experiments are presented in detail in Table 3-8 and 3-9. As can be seen for the underwater tailings sample, very small quantities of metals were released in the water-soluble, exchangeable

Table 3-8

Sequential Extraction of BL2 Tailings from Benson Lake

Parameter	Water Soluble Phase	Exchange Cations	Weak Acid Soluble Phase	Reducible Phases			Oxidizable Phase	Residual Phase	Mass Balance (μg/g)
				Easily	Moderate	Difficult			
Arsenic	0.06	<0.01	<0.01	0.05	0.74	0.02	0.80	29.0	30.62
%	**0.2**	**0.0**	**0.0**	**0.01**	**2.4**	**0.06**	**2.6**	**94.7**	
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.03	0.19	0.22
%	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**13.6**	**86.4**	
Cobalt	0.02	2.6	0.11	0.05	0.21	0.32	5.8	30	39.11
%	**0.05**	**6.6**	**0.28**	**0.13**	**0.54**	**0.82**	**14.8**	**76.7**	
Copper	0.20	0.06	0.04	<0.01	<0.01	0.61	46.0	38.0	84.91
%	**0.23**	**0.07**	**0.05**	**0.0**	**0.0**	**0.72**	**54.2**	**44.7**	
Lead	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.11	0.27	0.38
%	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**28.9**	**71.0**	
Mercury	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.56	0.57
%	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**1.7**	**98.2**	
Nickel	0.15	0.15	0.16	0.03	0.25	0.14	1.1	33	34.98
%	**0.43**	**0.43**	**0.45**	**0.08**	**0.71**	**0.40**	**3.14**	**94.3**	
Zinc	0.10	0.04	0.16	0.12	0.27	0.56	2.2	45	48.45
%	**0.21**	**0.08**	**0.33**	**0.24**	**0.55**	**1.12**	**4.5**	**92.87**	

Results are expressed as micrograms per dry gram of sediment followed by % of total.

Table 3-9

Sequential Extraction of Land Tailings near Benson Lake

Parameter	Water Soluble Phase	Exchange Cations	Weak Acid Soluble Phase	Reducible Phases			Oxidizable Phase	Residual Phase	Mass Balance (µg/g)
				Easily	Moderate	Difficult			
Arsenic	<0.01	<0.01	<0.01	0.02	3.2	1.4	0.02	40	44.64
%	**0.0**	**0.0**	**0.0**	**0.04**	**7.2**	**3.1**	**0.04**	**89.6**	
Cadmium	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	0.07	0.09
%	**11.0**	**0.0**	**0.0**	**0.0**	**11.0**	**0.0**	**0.0**	**78.0**	
Cobalt	0.91	<0.01	<0.01	<0.01	0.50	0.09	0.05	26	27.55
%	**3.3**	**0.0**	**0.0**	**0.0**	**1.8**	**0.33**	**0.18**	**94.4**	
Copper	260	0.52	3.0	0.17	51.0	0.48	160	12000	12475
%	**2.1**	**0.004**	**0.02**	**0.001**	**0.41**	**0.004**	**1.28**	**96.2**	
Lead	<0.01	<0.01	<0.01	<0.01	0.70	0.05	0.38	3.8	4.93
%	**0.0**	**0.0**	**0.0**	**0.0**	**14.2**	**1.0**	**7.7**	**77.1**	
Mercury	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.54	0.55
%	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**1.8**	**98.2**	
Nickel	0.28	<0.01	0.01	<0.01	0.13	0.04	0.05	18	18.51
%	**1.5**	**0.0**	**0.05**	**0.0**	**0.7**	**0.22**	**0.27**	**97.2**	
Zinc	1.0	0.05	0.03	0.02	1.6	0.47	0.22	38	41.39
%	**2.4**	**0.12**	**0.07**	**0.05**	**3.86**	**1.13**	**0.53**	**91.81**	

Results are expressed as micrograms per dry gram of sediment followed by % of total.

Figure 3-7: Metals Released in Water Soluble Phase from Land and Submerged Lake Tailings

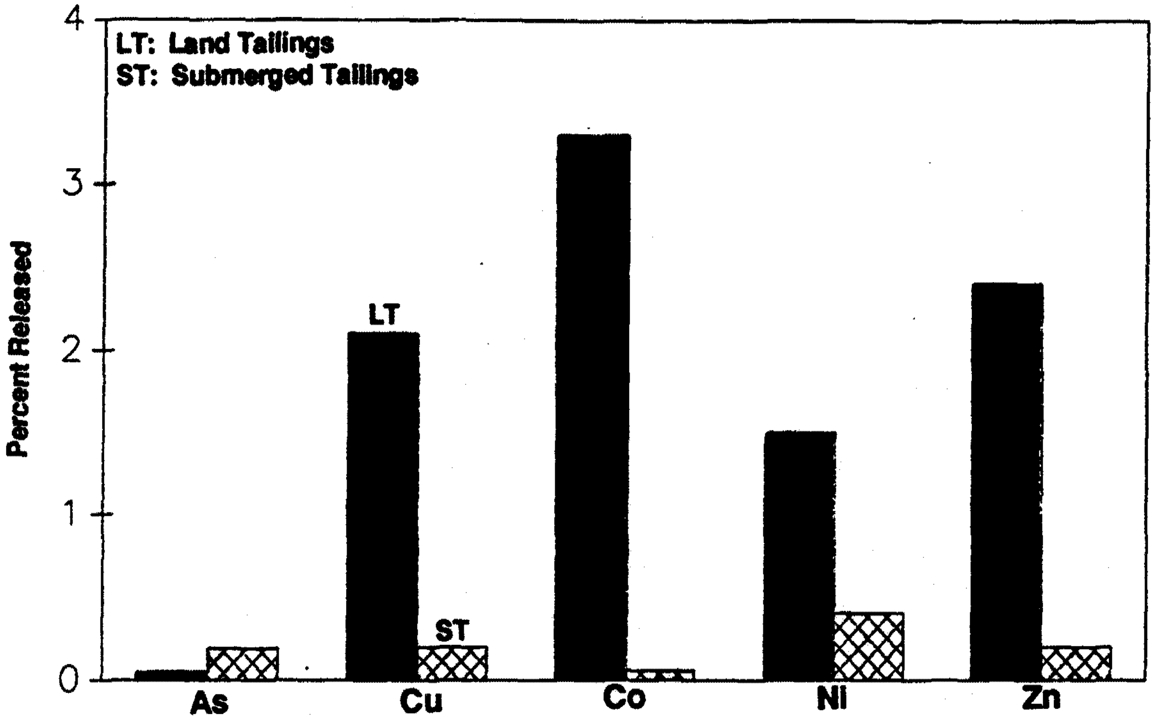
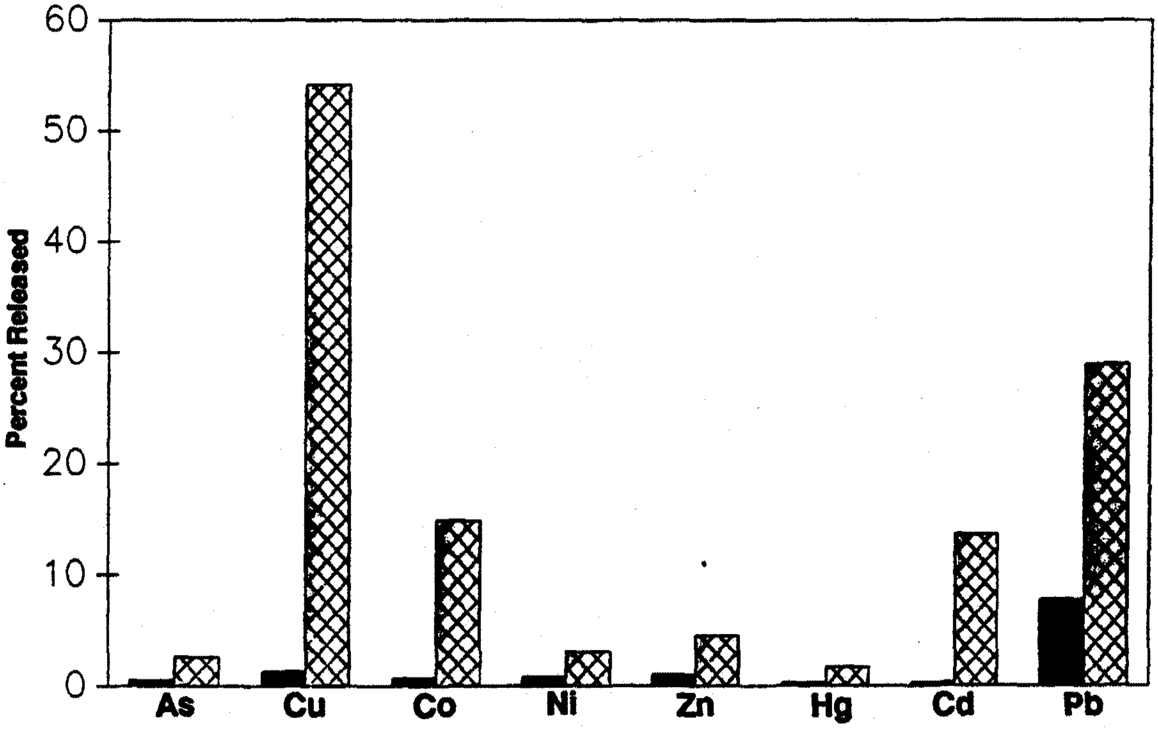


Figure 3-8: Metals Released in Oxidizable Phase from Land and Submerged Lake Tailings



cation and weak acid soluble phase. The exchangeable cation phase released moderate amounts of Co in BL2. In contrast, the moderate releases of Cd, Co, Cu, Ni and Zn occurred in the water-soluble phase of the land tailings (Figure 3-7).

The easily and moderately reducible phases will include amorphous manganese and ferric oxides and hydroxides respectively. Extremely minor releases (< 0.75%) of all metals analyzed occurred in these phases in BL2. Moreover, Cu was not released at all in BL2 in these phases. Moderate releases of As, Cd and Pb occurred in the moderately reducible phase from the land tailings sample, suggesting that these metals are associated with the secondary mineral precipitates. Petrographic analyses revealed that ferric oxides were present in the land tailings sample. Arsenic and lead form strong complexes with Fe-oxides and hydroxides and their association in this phase is therefore not unexpected.

The oxidizable phase includes species which are rendered soluble in acid by oxidation with hydrogen peroxide. For the subaqueous tailings sample, BL2, significant quantities of Cu (54%) and Pb (29%) were released in the oxidizable phase with moderate releases of Cd (13.6%), Co (14.8%), Ni (3%) and Zn (4.5%). This is strongly contrasted by the behaviour of those same metals from the land tailings sample in the oxidizable phase. As can be seen in Figure 3-8, only Pb (7%) was released in any significant quantity in this phase from the land tailings sample. Oxidation of the samples with 30% H_2O_2 releases organically bound metals and metal sulphides. The higher organic-C content of BL2 (1.76%) compared to the land tailings (0.48%) suggests that metal bonding to organic matter may be occurring in these sediments. The attractive forces between metals and organic material range from weak (cation exchange), which results in the ions being readily replaceable, to very strong (complexation, chelation) and thus indistinguishable from chemical bonds (Forstner and Wittmann 1983). The adsorptive capacity of organic material arises from the ionization of functional groups (e.g. COO^-), thus resulting in a negative surface charge capable of binding divalent cations through electrostatic forces. The absence of metal releases in the exchangeable phase in BL2 suggests that strong inner sphere complexes are forming between the metals and the organic material.

The adsorption of metals by organic matter in sediments has been the focus of much research. The typical results of these studies are depicted below, with the extent of retention decreasing from left to right:

Hg = Fe = Pb = Al = Cr = Cu > Cd > Zn > Ni > Co > Mn

at pH 5.8 (Evans 1989).

It can be summarized then that of the metals studied Hg, Fe, and Cu are very strongly retained with Co and Mn the most weakly held (Evans 1989). This may partially explain the moderate release of Co (6.6%) from the exchangeable phase. In both samples however, most of the metals were released in the residual phase with the exception of Cu in BL2 where roughly 50% was released in each of the oxidizable and residual phases (Tables 3-8 and 3-9). Typically, greater than 90% was released in the residual phase suggesting that, in both samples, the metals were largely associated with the biologically unreactive phase.

While interpretation of sequential extractions is not without limitations, they do provide an operational definition of the phases being investigated (Nirel and Morel 1990). Detailed analyses of interstitial waters will be conducted in the summer of 1991 on Benson Lake cores to substantiate and finalize the above conclusions.

3.4 Biota

3.4.1 Benthic Invertebrates

Benthic invertebrates were present in profundal sediments taken from the bottom of Benson Lake in September 1990 (Table 3-10). This is in direct contrast to previous studies which showed that the benthos of Benson Lake was devoid of benthic organisms as a result of deep lake tailings disposal (Kussat *et al.* 1972; Hallam *et al.* 1974).

The mean density of benthic invertebrates in the profundal zone of Benson Lake in September 1990 was 1,044.4 organisms/m^2 (range = 300.0 to 2,400.0, n=3), which was similar to the mean profundal density of around 1,118.7 organisms/m^2 in nearby Keogh Lake (a control). Densities in Benson Lake ranged from a high of 2,400.0 organisms/m^2 at Site 1, in deep water (40 m) near the inlets of the Benson and Raging Rivers, to a low of 300.0 organisms/m^2 at Site 2 in the deepest portion of the lake (50 m). Densities of organisms at Site 3 (433.3 organisms/m^2), near the outlet of the lake, were comparable to those at Site 2, but slightly higher. The benthos in Keogh Lake was sampled at only one location.

Table 3-10

Densities and Species Compositions of Benthic Invertebrate Communities in Benson (B) and Keogh (K) Lakes in September, 1990

	Sample Site (number/square metre)				
Taxon	BL1	BL2	BL3	KL1	KL1
Ephemeroptera (Mayflies)					
Cinygmula sp.				1600	
Epeorus deceptivus				200	
Rithrogena sp.				600	600
Ephemerella coloradensis				200	
Baetis insignificans					200
Plecoptera (stoneflies)					
Sweltsa sp.				400	
Calineuria californica					400
Trichoptera (Caddisflies)					
Unidentified adult				200	
Unidentified pupae				400	
Glossosoma sp.				28400	400
Moselyana sp.				1200	
Hydropsyche sp.					1000
Diptera (true flies)					
Unidentified adult				200	
Unidentified pupae				200	
Chironomid pupae					800
Phaenopsectra sp.	600				
Chironomus sp.			600		
Procladius sp.			200		200
Micropsectra sp.				400	
Polypedilum (*pentapedilum*) sp.				400	6800
Polypedilum (*polypedilum*) sp.					200
Eukiefferiella sp.				600	2800
Cricotopus sp.					600
Cardiocladius sp.					1400
Tanytarsus sp.					1000
Microtendipes sp.					200

Table 3-10 (cont.)

Densities and Species Compositions of Benthic Invertebrate Communities in Benson and Keogh Lakes in September, 1990

Taxon	BL1	BL2	BL3	KL1	KL1
	Sample Site (number/square metre)				
Tipulidae					
Hexatoma sp.				400	
Simulidae					
Simulium sp.					200
Coleoptera (beetles)					
Heterlimnius sp.					200
Ostracoda (bivalves)	1200	400	600		
Hydracarina (hydra)					
Torrenticola sp.					200
Turbelleria (flatworms)					
Tricladida					400
Oligochaeta (segmented worms)					
Limnodrilus sp.	1000	200	400		
Tubifex sp.	600	200	600		
Nais sp.				400	1400
Mollusca (molluscs)					
Pisidium sp.			200		
Nematoda (nematode worms)	8600	400			
Mean # Organisms per site	2400.0	300.0	433.3	2237.5	1000.0
# Taxa per site	5	4	6	16	18
Total # of Taxa		8		30	
Average Lake Density of Organisms		1044.4		1118.7	

The diversity of organisms in Benson Lake was much lower than in the control lake (Table 3-10). The benthic community in Benson Lake was represented by only 8 different taxonomic groups compared to a total of 30 for Keogh Lake. The community in Benson Lake was predominantly made up of burrowing tubificid oligochaetes (*Limnodrilus* sp. and *Tubifex* sp.), nematode worms and the epibenthic ostracod, a small bivalved crustacean that lives on the surface of the sediments (Table 3-10). Only ostracods and oligochaete worms were present at all three sample sites. Some dipteran larvae were present at Sites 1 and 3. In contrast, the benthic invertebrate community in Keogh Lake was predominantly comprised of epi-benthic insect pupae and larvae represented by all of the major insect groups (Table 3-10). Oligochaete worms were also present in Keogh Lake but they were represented by a different genus (*Nais* sp.). Nematode worms and ostracods were not found.

The observed densities of benthic organisms in the profundal zone of both Benson and Keogh Lakes in September 1990 were typical of the size of benthic communities in other oligotrophic lakes in Canada and the world (Table 3-11), suggesting that the recovery of Benson Lake's benthic community may now be complete. The composition of benthic fauna in Benson Lake is typical of lakes which have become organically polluted (despite the fact that all other indicators suggest that the lake is oligotrophic) and/or suffer an acute reduction or elimination of oxygen in the profundal depths (Cook and Johnson 1974; Wetzel 1979). In contrast, the organisms that make up the benthic community structure in Keogh lake (Ephemeroptera, Plecoptera, Trichoptera, and Diptera) are characteristic of shallow water communities which are generally restricted to waters of relatively high oxygen content (Cook and Johnson 1974; Wetzel 1979).
Oxygen depletion in the depths of Benson Lake cannot be ruled out as a factor in determining the benthic community structure in this lake. Hallam *et al.* (1974) reported that oxygen concentrations in the lake after fall overturn were uniform from surface to bottom at 12.0 ppm (100% saturation at 6.0°C). However, on September 13 1990, fall overturn was incomplete. Oxygen concentrations were uniform with depth and slightly undersaturated (average 85% saturation) given prevailing water temperatures (Figures 3-3 to 3-5), but immediately above the sediment water interface, the dissolved oxygen concentration was only 2.9 ppm (24% saturation at 4.5°C) compared to 8.8 ppm (95% saturation at 17.2°C) at the surface. It is common to find an abundance of tubificid

Table 3-11

Average Numerical Density of Benthic Macroinvertebrates in the Profundal Zone of Several Lakes of Varying Productivity

Lake Name	Status	Average Numerical Density of Benthic Fauna ind/m² (range)	Source
Benson Lake	oligotrophic	1044 (300-2400)	This study
Keogh Lake	oligotrophic	1118 (1000-2237)	This study
Lake Borrevann (Norway)	eutrophic	1143-1598	Wetzel 1979
Lake Chud-Pskov (USSR)	oligotrophic	407-1996	
Trout Lake (Manitoba)	oligotrophic	385 (19-1165)	Rescan 1990d
Cliff Lake (Manitoba)	oligotrophic	351 (19-1165)	Wilson 1984
Southern Indian Lake (Manitoba)	eutrophic	3327-5592	Weirs & Rosenberg 1984
Lake Erie (Ontario)	eutrophic		Cook and Johnson 1974
West basin		7500	
Central basin		2400	
Eastern basin		4600	
Lake Superior (Ontario)	oligotrophic	392 (14-1190)	Schelske and Roth 1973
Saginaw Bay (Lake Michigan)	eutrophic	4229	Cook and Risley 1963
Lake Huron (Open Lake)	oligotrophic	720-2000	Teter 1960 Shrivastava 1974
Mandy Lake*	meso-eutrophic	533 (87-1174)	Rescan 1990d
Anderson Lake (Manitoba)**	meso-eutrophic	519 (109-1622)	Rescan 1990c

* Following cessation of tailings disposal after 45 years.

** Tailings are still being deposited in this lake.

oligochaetes, especially *Tubifex* sp., under these conditions of low oxygen saturation (Wetzel 1979).

Another factor which may explain the benthic community structure observed in Benson Lake and the divergent nature of the community structure in Keogh Lake is sediment composition. Among benthic invertebrates, inorganic and organic particle size is important in determining distribution, abundance and growth of these organisms (Cummins and Lauff 1969). Generally, the finer the particles, the smaller the organisms which can live in the interstitial spaces. The sediments in Benson Lake were comprised of extremely fine particles with roughly 80% being finer than 0.1 mm. This sediment composition is conducive to benthic invertebrate communities being dominated by oligochaetes, nematodes, and ostracods (Dr. D. Kathman, pers. comm.) which was observed in the profundal zone of Benson Lake (Table 3-10).

One factor confounding the above analysis is that the oxygen concentrations above the sediments in Keogh Lake were lower (1.1 ppm or 8% saturation at 3.3°C; Figure 3-6) than in Benson Lake, yet the benthic community was comprised of organisms typically found only in well oxygenated environments. Moreover, the diversity of organisms in profundal environments is usually restricted to 4 to 6 species (Cook and Johnson 1974), but in Keogh Lake, the deep-water benthic community contained 30 different species (Table 3 – 10). Many of the species were abundant and have not been documented as occurring in the profundal zone of lakes (Dr. D. Kathman, pers. comm.), and only two classes of which (chaoborus and flatworms) can be classified as profundal organisms. It is difficult to explain the observed data for Keogh Lake benthos except to say that there may be some factor associated with the presence of the fish farm in the lake which is causing typically shallow water insects to deposit their eggs and larvae in open water such that they sink to the bottom. Alternatively, excessive wave action may have stirred up littoral benthic invertebrate communities and resulted in the suspension and deposition of organisms into the deeper portion of the lake.

In summary, it appears that the benthic invertebrate community in Benson Lake has re-established itself to the point where the densities of organisms and the species represented are typical of those found in the profundal zones of temperate, oligotrophic lakes having fine sediments. The profundal benthic invertebrate community in the control lake was atypical and could not be used as a comparison to confirm the normalcy of the benthic recolonization of Benson Lake. It is suggested that the presence of a fish farm in Keogh Lake has affected the benthic community composition in that lake.

3.4.2 Phytoplankton

The phytoplankton assemblages found in the water column of both Benson and Keogh Lakes (Table 3-12) were characteristic of oligotrophic lakes (Hutchinson 1967; Wetzel 1979) and included such indicator organisms as the chrysophyceans (*Acnanthes*, *Dinobryon*), chlorophyceans (*Scenedesmus* spp. and *Chlorococcaceae*), and Pyrrhophytes (*Peridinium*). Numerically, the dominant phytoplankters were the Chlorophyta or green algae, and the Cyanophytes, or Blue-green algae. This type of assemblage is common in coastal lakes in the late summer - early fall (Werring 1986; Wetzel 1979).

The dominant phytoplankton association in Benson Lake was a *Chlorococcaceae-Scenedesmus incrassatus-Anacystis* sp. mix with a minor dominant association of *Gloeocapsa* sp.-*Chlamydomonas* sp-*Crucigenia quadrata*. The dominant phytoplankton assemblage in Keogh Lake was one of *Chlorococcaceae-Euglenophyta* with a minor dominant association of *Achnanthes minutissima-Chlamydomonas* sp.-*Merismopedia* sp.

Densities of phytoplankton at three sites in Benson Lake ranged between 853 and 2,173 cells ml^{-1} (0.8 to 2.2 x 10^6 cells L^{-1}) with a mean lake density of approximately 1529 cells ml^{-1} (1.5 x 10^6 cells L^{-1}; see Table 3-13). In contrast, the mean density of phytoplankton in Keogh Lake (3,263 cells ml^{-1} ; Table 3-14) was approximately twice that of Benson Lake. These values are within the range of densities for fall phytoplankton populations in several oligotrophic coastal lakes in British Columbia (1-10 x 10^6 cells L^{-1}; Werring 1986).

In general, the species composition of the net phytoplankton in Benson Lake in September 1991 was similar to that of the control lake in that the community was dominated by a green algae - blue-green algae assemblage. In addition, densities of algal cells were typical of late summer densities in coastal lakes. Densities of net phytoplankton in Keogh lake were almost twice that of Benson Lake, a phenomenon which may be attributable to the presence of a fish farm (fertilization effect) on Keogh Lake.

Table 3-12

Phytoplankton Taxa Found in Benson and Keogh Lakes

Taxa	Benson Lake	Keogh Lake
CYANOPHYTA		
Anacystis sp.	P	P
Gloeocapsa sp.	P	P
Coelosphaerium sp.	P	P
Dictyosphaerium sp.	P	-
Merismopedia sp.	-	P
CHLOROPHYTA		
Ankistrodesmus sp.	P	-
Chlamydomonas sp.	P	P
Chlorococcaceae*	P	P
Crucigenia quadrata	P	-
Euglenophyta	P	P
Mougeotia sp.	P	-
Scenedesmus incrassatus	P	-
S. bijuga	P	-
Spondylosium sp.	P	-
Staurodesmus sp.	P	-
CHRYSOPHYTA		
Achnanthes minutissima	P	P
Cocconeis sp.	-	P
Diatom	P	P
Dinobryon divergens	P	-
PYRRHOPHYTA		
Peridinium **		
OTHER TAXA***		
Cyst 1	P	P
Cyst 2	P	P
PROTOZOA		
Ciliate	P	-
Verticella sp.	P	-

"P" = denotes the presence of taxa in at least some of the samples with that letter designation, "-" denotes absence.

*** The taxa Chlorococcaceae is a large taxa comprised of many dissimilar genera. All of the Chlorococcaceae counted as such are small coccoid representatives of the group - possibly Chlorococcum.**

**** May be Glenodinium.**

***** The two distinct cysts present in the samples are undoubtedly of algae. It is probable that these cysts are Pyrrhophytes, but they could also be encysted Trachelomonas or Euglenophytes.**

Table 3-13

Densities (# cells ml-1) of the Phytoplankton in the Water Column at Three Sites in Benson Lake September, 1990

	No./Station (Cells ml-1)					
Taxa	BL1A	BL1B	BL2A	BL2B	BL3A	BL3B
CYANOPHYTA						
Anacystis sp.	220.68	275.85	98.08	24.52	288.11	422.97
Gloeocapsa sp.	73.56	0	110.34	18.39	49.04	49.04
Coelosphaerium sp.	0	6.13	0	0	0	0
Dictyosphaerium sp.	6.13	6.13	0	6.13	0	12.26
CHLOROPHYTA						
Ankistrodesmus sp.	0	0	0	6.13	0	0
Chlamydomonas sp.	12.26	134.86	6.13	0	0	0
Chlorococcaceae	766.25	974.67	190.03	177.77	643.65	796.90
Crucigenia quadrata	24.52	0	34.58	0	0	73.56
Euglenophyta	36.78	12.26	0	12.26	0	0
Mougeotia sp.	0	0	0	0	0	0
Scenedesmus bijuga	0	0	0	0	0	0
S. incrassatus	318.76	300.37	300.37	502.66	735.60	753.99
Spondylosium sp.	6.13	0	0	0	0	0
Staurodosmus sp.	0	0	0	0	0	0
CHRYSOPHYTA						
Achnanthes minutissima	0	18.39	0	0	42.91	0
Diatom	0	0	0	76.96	12.26	0
Dinobryon divergens	6.13	6.13	0	0	0	0
PYRRHOPHYTA						
Peridinium	0	0	0	0	12.26	0
OTHER TAXA						
Cyst 1	6.13	6.13	12.26	12.26	6.13	6.13
Cyst 2	18.39	18.39	55.17	18.39	12.26	55.17
PROTOZOA						
Ciliate	0	0	0	0	0	6.13
Verticella sp.	0	0	0	0	0	0
TOTALS	1485	1757	1107	853	1800	2173
MEAN LAKE DENSITY	1529					

Table 3-14

Densities (#cells ml-1) of Phytoplankton in the Water Column at Two Sites in Keogh Lake

	Station	
Taxa	KL1A	KL1B
CYANOPHYTA		
Anacystis sp.	85.82	0
Gloeocapsa sp.	12.26	0
Coelosphaerium sp.	6.13	24.52
Merismopedia sp.	196.16	220.68
CHLOROPHYTA		
Chlamydomonas sp.	202.89	220.68
Chlorococcaceae	1888.04	1158.57
Euglenophyta	1244.39	331.02
Spondylosium sp.	0	0
Staurodesmus sp.	0	0
CHRYSOPHYTA		
Achnanthes minutissima	220.68	465.88
Cocconeis	61.03	24.53
Diatom	49.04	30.65
PYRRHOPHYTA		
Peridinium	6.13	6.13
OTHER TAXA		
Cyst 1	0	12.26
Cyst 2	0	12.26
TOTALS	3960	2507
MEAN LAKE DENSITY	3234	

3.4.3 Zooplankton

The early fall zooplankton community in Benson Lake was numerically dominated by the cladocerans *Holopedium gibberum* and *Eubosmina longispina* (in that order) and by cyclopoid copepods, (Table 3-15). Less dominant organisms included the cladoceran *Daphnia rosea*, the calanoid copepod *Diaptomus franciscansia*, and some rotifers. The cladoceran *Alona* sp. was rare. A similar assemblage was found in Keogh Lake (Table 3-16). However, in the control lake, *Eubosmina longispina* was the numerically dominant cladoceran. Holopedium and daphnia were moderately abundant and present in roughly equal numbers. In addition, a second calanoid copepod, *Epischura nevadensis*, which was not found in Benson Lake was present. Some of the less dominant zooplankters included the predominantly littoral cladocerans *Polyphemus pediculus* and *Scaphaloberis kingii*, and the rotifers. Both Polyphemus and Scaphaloberis are generally rare in coastal lakes, as evidenced by their low number in Keogh Lake. Thus it is not surprising that they did not show up in Benson Lake samples, but that does not exclude their presence there.

Overall densities, and densities of individual zooplankton species, were significantly lower in both Benson and Keogh Lakes than are commonly found during the fall in coastal British Columbia lakes and in other lakes in Canada (Table 3-17). Whereas autumn densities of zooplankton in most lakes are in the range of 20 to 200,000 organisms/m^3, densities of zooplankton in Benson lake only ranged between 272 and 1,823 organisms/m^3 and in Keogh lake between 8,349 and 12,961 organisms/m^3. This discrepancy is probably related to the method used for sampling zooplankton in the study lakes. The plankton net employed only had a 13 cm diameter opening. Small diameter plankton nets such as these set up a bow wave when hauled through the water. Detection of the approaching bow wave elicits an escape response in highly motile species of zooplankton allowing them to escape capture. In addition, smaller, less motile organisms, such as rotifers, can be deflected around the net rather than being drawn into it. As a result, true estimates of zooplankton abundance are often underestimated when these types of nets are used. However, the data for Benson and Keogh lakes are useful in that a comparison of relative, rather than actual, densities between lakes can still be made.

The data indicate that relative abundances of zooplankton in vertical net hauls in Benson Lake were approximately 7 times lower than in Keogh Lake (331 vs 12,961

Table 3-15

Benson Lake - Densities of Zooplankton Captured in Vertical and Horizontal Tows (individuals/m^3)

Station Number		1	2	3	HNT1	HNT2
Date		14/09/90	14/09/90	14/09/90	14/09/90	14/09/90
Depth (m)		47	60	38		
Time		15:00	14:45	15:15	12:55	13:15
Tow		VNH	VNH	VNH	HNT	HNT
Volume (m^3)		0.679	0.532	0.430	7.04	5.1
Split		1	1	1	0.0625	0.0312
TAXON						
ROTATORIA sp.		0	0	5	2	0
CLADOCERA						
Daphnia rosea		6	3	2	17	50
Eubosmina longirostris		49	7	95	31	176
Holopedium gibberum		45	15	21	636	1207
Alona sp.		2	0	0	0	0
COPEPODA						
Diaptomus franciscansis	VIf	2	2	0	0	6
	VIm	2	0	0	0	0
	V	6	0	0	0	13
Cyclopoids	VIf	8	0	5	0	0
	VIm	17	4	12	4	13
	I-IV	111	18	279	50	333
Calanoid copepodites	I-IV	9	11	0	0	19
Copepod nauplii		4	28	58	0	6
OSTRACODA		7	98	2	0	0
NEMATODES		0	4	7	0	0
OLIGOCHAETES		2	21	21	0	0
CHIRONOMID LARVAE		2	23	21	0	0
Total (individuals/m^3)		272	214	508	740	1823
Mean lake Density			VNH 331		HNT 1251	

VNH = Vertical Net Haul
HNH = Horizontal Net Haul

Table 3-16

Keogh Lake - Densities of Zooplankton Captured in Vertical and Horizontal Tows (individuals/m^3)

Station Number		1	2
Date		17/09/90	17/09/90
Depth (m)		40	
Time		15:45	15:30
Tow		VNH	HNT
Volume (m^3)		0.453	3.398
Split		0.0625	0.0313
TAXON			
ROTATORIA sp.		883	414
CLADOCERA			
Daphnia rosea		1095	28
Eubosmina longirostris		5581	5707
Polyphemus pediculus		35	56
Scaphaloberis kingii		35	19
Holopedium gibberum		1095	19
COPEPODA			
Diaptomus franciscansis	VIf	71	18
	VIm	0	9
	V	0	9
Epischura nevadensis	VIf	35	9
	VIm	0	9
	V	35	28
Cyclopoids	VIf	212	452
	V	848	132
	I-IV	2860	1271
Calanoid copepodites	I-IV	0	104
Copepod nauplii		106	85
HARPACTICOIDS		35	0
ACARINA		35	0
Total (individuals/m^3)		12961	8349
Mean Lake Density		1065	

VNH = Vertical Net Haul

HNH = Horizontal Net Haul

Table 3-17

Typical Fall Densities of Some Crustacean Zooplankton in a Coastal Lake in British Columbia

	Density (#/m3)	Source
Rotifer (planktonic)	200 to 300,000	Wetzel 1979
Cladocerons		
Daphnia rosea	4,000 - 5,000	Werring 1986
Halopedium gibberum	500 - 1,000	Werring 1986
Bosmina	20 - 25,000	Werring 1986
Copepods		
Diaptomus sp.	10 - 15,000	Werring 1986
Cyclopoids	5 - 10,000	

organisms/m^3 in Benson and Keogh Lakes, respectively; see Tables 3-15 and 3-16). Horizontal net tows from Benson Lake yielded approximately 4 times fewer organisms.

No comparisons can be made between present and past densities and/or species compositions of zooplankton in Benson Lake as there are no historical data on zooplankton population dynamics available.

In summary, it can be concluded that the zooplankton species composition in Benson Lake in September 1990 was comprised of the same community dominants as in nearby Keogh Lake, the control lake. The assemblages were the same as those which occur in many coastal lakes in B.C. (Northcote and Clarotto 1975) differing only in their co-existing copepod species. Densities of zooplankton were between 4 and 7 times lower in Benson Lake than in the control lake depending on the type of sampling method used. The higher densities in Keogh lake may be related to the apparent fertilization effect of the fish farm discussed previously.

3.4.4 Aquatic Vegetation

Aquatic vegetation is well established in the littoral zones of Benson Lake, particularly along its southern and eastern shorelines (Figure 3-9). A submerged tailings mound is

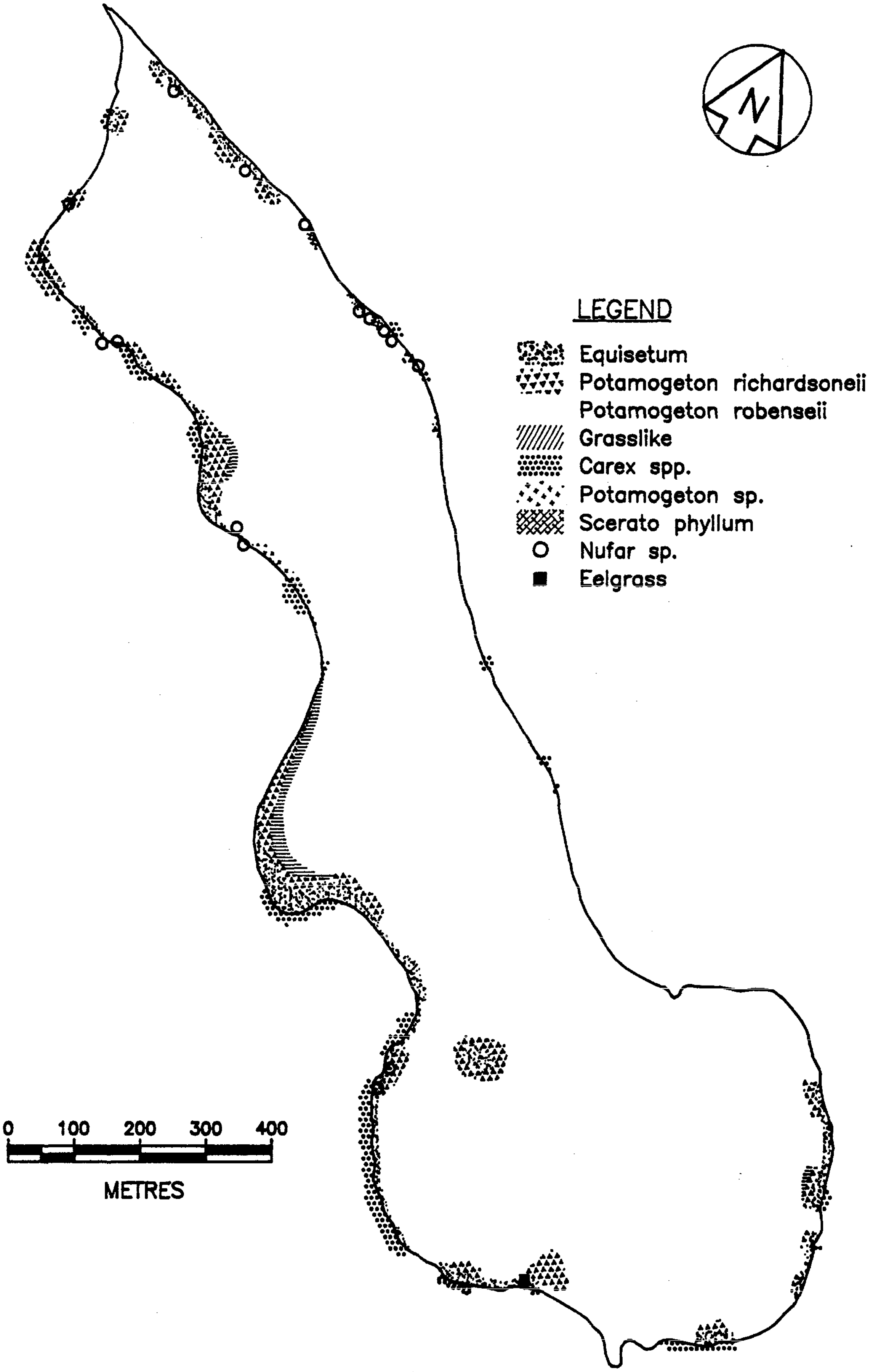


Figure 3–9 Benson Lake Aquatic Vegetation Mapping

Rescan

well populated with the common genera found in the lake. These include, *Equisetum*, *Potamogeton*, *Carex*, *Nufar* and *Scerato*.

Littoral vegetation was absent along much of the north shore of Benson Lake. Shear cliffs and the inflow of the Raging River prevent colonization in this area. The densely populated tailings mound, west of the Benson River inflow, contributes to an organic mat over the surface of the tailings. At the time of the present survey, the tailings mound remained submerged, but by less than 0.20 m of water. While diffusion of oxygen to the surface of the tailings appeared possible, no evidence for such was observed in the sediment samples removed from this area. It is likely that the high organic inputs and subsequent decomposition effectively consume potential oxidants.

Results of metal analyses of aquatic vegetation collected from Benson Lake and Three Isle Lake is presented in Table 3-18 and 3-19. While Keogh Lake was used as the control lake for this study for benthic sediments and water quality analyses, the aquatic vegetation community present in Keogh Lake's littoral zone was too dissimilar to effect meaningful comparisons with the vegetation in Benson Lake. Hence, Three Isle Lake, a small lake north of Benson Lake and in the same drainage basin, was used as a control lake for aquatic vegetation. Three Isle Lake has never received tailings discharge. Many of the species observed in Benson Lake were found in Three Isle Lake, particularly *Equisetum* sp. As previously discussed, metal analyses were performed on both roots and tops of the species collected.

Both *Equisetum* sp. (horsetail) and *Potamogeton* sp. (pond weed) from Benson Lake accumulated significant concentrations of arsenic in their tops and roots (Table 3-18). In particular, the roots of both species had very high levels of arsenic ranging from 100 to 320 $\mu g\ g^{-1}$ in roots of *Equisetum* sp. and from 330 to 2,100 $\mu g\ g^{-1}$ in *Potamogeton* sp.. In contrast, *Equisetum* sp. from Three Isle Lake had low levels of As in both tops and roots (Table 3-18 and 3-19). This is likely due to the much lower As concentrations in the sediments associated with the sampled vegetation in Three Isle Lake (0.01 to 1.9 $\mu g\ g^{-1}$) as compared to Benson Lake (14 to 54 $\mu g\ g^{-1}$) (Table 3-20).

Significantly higher concentrations of Cu were found associated with the roots of *Equisetum* sp. However, copper concentrations in *Equisetum* sp. do not appear to be elevated in the tops. Copper concentrations in the tops of *Equisetum* sp. in Benson Lake did not differ significantly from that observed in Three Isle Lake (5.7 and 4.3 $\mu g\ g^{-1}$

Table 3-18

Concentrations of Specific Metals in Benson Lake and Three Isle Lake Aquatic Vegetation

		Metals $\mu g\ g^{-1}$ (dry tissue)							
Sample Location	Species	As	Cd	Co	Cu	Hg	Ni	Pb	Zn
BL VEG 1	*Equisetum sp.*								
	Tops	3.3	0.08	2.6	7.6	0.02	2.8	0.09	40.0
	Roots	150.0	0.12	4.7	29.0	0.03	4.2	2.7	76.0
	Potamogeton sp.								
	Tops	2.3	0.34	4.6	31	0.04	4.6	0.62	50.0
	Roots	910	0.91	8.8	53	0.07	8.8	3.0	60.0
BL VEG 2	*Equisetum sp.*								
	Tops	0.97	0.14	2.0	4.7	0.02	2.9	0.04	39.0
	Roots	150.0	0.16	5.9	30.0	0.04	9.9	4.1	130.0
	Potamogeton sp.								
	Tops	1.9	0.45	2.0	31	0.13	5.6	1.5	70.0
	Roots	420.0	0.37	17.0	180	0.25	16.0	4.9	86.0
BL VEG 3	*Equisetum sp.*								
	Tops	1.9	0.04	0.53	6.8	0.04	2.4	0.08	29.0
	Roots	100.0	0.58	16.0	380.0	0.09	12.0	3.8	63.0
	Potamogeton sp.								
	Tops	0.50	0.49	1.7	44.0	0.05	3.3	0.09	41.0
	Roots	2100.0	0.16	21.0	44.0	0.16	7.1	0.31	43.0
BL VEG 4	*Equisetum sp.*								
	Tops	2.5	0.04	2.0	3.7	0.02	2.8	0.03	35.0
	Roots	320.0	0.14	8.2	110.0	0.04	3.3	1.1	48.0
	Potamogeton sp.								
	Tops	2.5	0.34	2.0	39.0	0.11	2.8	0.69	45.0
	Roots	330.0	0.32	9.3	110.0	0.05	6.8	8.5	47.0
TIL VEG 1	*Equisetum sp.*								
	Tops	0.29	0.02	3.1	3.1	0.02	3.6	0.03	24.0
	Roots	3.2	0.33	6.3	15.0	0.03	10.0	0.83	63.0
TIL VEG	*Equisetum sp.*								
	Tops	0.16	0.08	5.4	5.4	0.09	4.8	0.33	36.0
	Roots	13.0	0.26	14.0	23.0	0.04	13.0	1.8	55.0

Table 3-19

Mean Metal Concentrations in Tops and Roots of Equisetum sp. from Benson Lake and Three Isle Lake (Control)

	Benson Lake		Three Isle Lake	
Element	Tops	Roots	Tops	Roots
As	**2.2**	**180**	0.23	8.1
Cd	0.08	0.25	0.05	0.29
Co	1.8	8.7	1.2	10.2
Cu	5.7	**138.8**	4.3	38
Pb	0.06	2.9	0.18	2.6
Hg	0.03	0.05	0.05	0.035
Ni	2.7	7.4	4.2	11.5
Zn	35.8	**79.3**	30.0	59

Numbers in bold represent elevated concentrations as compared to control

Values expressed as $\mu g\ g^{-1}$ (dry tissue)

respectively) despite the higher sediment copper concentrations in Benson Lake (110 to 800 $\mu g\ g^{-1}$) compared to that in Three Isle Lake (95 to 100 $\mu g\ g^{-1}$)(Table 3-20).

Conversely, *Potamogeton* sp. in Benson Lake had significantly higher concentrations of Cu in their tops (36.25 $\mu g\ g^{-1}$) than *Equisetum* sp. indicating highly variable results between different species. *Potamogeton* sp. sampled from Benson Lake had higher Cu concentrations in their tops as compared to *Potamogeton* sp. sampled from Mandy Lake and Anderson Lake in Manitoba, both of which are lakes which have been subjected to subaqueous tailings disposal (Table 3-21). All other metals, with the possible exception of Ni, were present in lower concentrations in Benson Lake than in either Mandy or Anderson Lake.

Metal levels in tops and roots of two aquatic macrophytes, *Equisetum* and *Potamogeton*, has been examined from Benson Lake. Roots typically accumulated more metal than

Table 3-20

Metal Levels in Sediments Associated with Aquatic Vegetation Samples

	Metals µg g^{-1} (dry sediment)							
Sample	As	Cd	Co	Cu	Hg	Ni	Pb	Zn
BL VSS *E1	20	0.60	29	180	0.17	37	5.9	180
BL VSS **P1	33	1.0	36	310	0.20	40	9.8	200
BL VSS E2	14	0.51	27	110	0.07	36	5.2	170
BL VSS P2	43	0.38	53	850	0.08	41	7.8	160
BL VSS E3	37	0.68	39	800	0.07	24	6.2	130
BL VSS P3	54	0.73	43	760	0.02	27	7.1	180
BL VSS E4	43	0.60	36	790	0.04	23	5.1	150
BL VSS P4	51	0.72	42	690	0.02	29	8.3	190
TIL VSS E1	0.01	0.07	56	110	0.19	150	1.7	140
TIL VSS E2	1.9	0.08	59	95	0.12	130	3.5	120

* **Sediments associated with** Equisetum sp. **sample at BL VEG 1**
** **Sediments associated with** Potamogeton sp. **sample at BL VEG 1**

the tops and, in some instances, 10^5 times more metal accumulated in the roots. For *Equisetum* sp. collected from Benson and Three Isle Lake, only As was found in greater concentrations in the tops of plants removed from Benson as compared to the control. Arsenic concentrations in the associated sediments were 31 times higher for Benson Lake as compared to Three Isle Lake. While both sediment and root Cu concentrations were higher for *Equisetum* sp. in Benson Lake, the corresponding Cu levels in the plant tops were not significantly greater than that observed in Three Isle Lake for the same species. These observations attest to the fact that plants can accumulate elevated levels of metals in their roots, but that translocation from the roots to the shoots is minimal. In fact, the high levels of some heavy elements in roots may be the result of binding on root exchange sites and/or membrane surfaces and may represent little or no actual uptake (Romney and Wallace 1975).

Table 3-21

Mean Metal Concentrations in Potamogeton sp. Tops in Benson Lake, Mandy and Anderson Lakes, Manitoba

Element	Benson Lake	*Mandy Lake	*Anderson Lake
As	1.8	8.0	6.0
Cd	0.40	0.45	0.29
Cu	36.25	15.3	16.1
Pb	0.73	2.95	2.05
Hg	0.083	0.075	0.035
Ni	4.07	1.15	3.75
Zn	51.5	129	100

* Rescan 1990c, 1990d

Submergent *Potamogeton* sp. from Benson Lake had higher shoot-Cu concentrations than that previously observed in two Manitoba Lakes. Unlike As, the metals Cu, Co and Zn are required in certain enzymatic reactions and hence are typically found in higher concentrations in plant tissues. Such a trend was observed for both plant species sampled.

While excessive metal concentrations are not observed in the shoot material of the plants sampled, the very elevated root concentrations suggest that the roots are concentrating metals from the sediments. This is particularly apparent for arsenic where root metal levels were considerably greater than the surrounding sediments. Previous work (Rescan 1990b) has demonstrated that metal solubility is enhanced in the presence of organic chelating agents. By-products of root respiration (e.g. citrate) are excellent chelating compounds and are capable of forming stable organo-metal complexes. These organo-metal complexes are also known to be potentially bioavailable. Moreover, root respiration may supply sufficient O_2 to oxidize the tailings immediately surrounding the root surface, thereby enhancing the possibility of forming soluble organic complexes. In light of this it would be most prudent to ensure that tailings deposits do not accumulate in the littoral zone where the presence of vegetation could release solid-phase metals.

3.4.5 Fish

Gillnet sets in both Benson and Keogh lakes resulted in the capture of 7 rainbow trout and 1 unidentified salmonid (probably arctic char, *Salvelinus alpinus*) from Benson Lake and 2 rainbow and 1 cutthroat trout from Keogh Lake (Table 3-22).

Fish from Benson Lake were significantly larger, both in mean length ($P_{(t \geq 0.19)} < 0.001$) and mean weight ($P_{(t \geq 0.70)} < 0.001$), and had significantly higher condition factors ($P_{(t \geq 0.19)} < 0.001$) than fish from Keogh Lake. However, due to the small sample size from Keogh Lake (n=3) these data should be interpreted with caution. Furthermore, mature females (5) were captured in Benson Lake but not in Keogh Lake

The stomach contents of fish from both lakes suggest that all fish whose stomachs contained food (with the exception of one fish from Keogh Lake), were feeding, at least partially, on organisms commonly found in the water column and/or in, or on, the benthos in the littoral zone (Table 3-22). Two of the fish from Benson Lake (BL1 and BL5) had been feeding on benthic organisms (the trichopteran *Onocosmecus* sp., gastropods, and bivalves) exclusively.

Metal body burden analyses of fish tissue and liver samples collected from the two lakes show that the mean concentration of all of the metal species examined were higher in the flesh of fish from Keogh Lake (control lake) than from Benson Lake (with the exception of cadmium and cobalt) but were within the range of concentrations for the same metals in fish tissues and livers from unpolluted Canadian waters (Table 3-23). Alternatively, concentrations of arsenic, copper, cobalt, and cadmium were significantly higher in the livers of fish from Benson Lake, suggesting that there may be some bioaccumulation of these metals from the environment. However, the levels of all metals in both the flesh and the liver from all fish sampled from both lakes were below established guidelines for human consumption as set out by the Departments of Health and Welfare Canada and Fisheries and Oceans Canada (Table 3-23; only four metals are regulated to-date. They are arsenic, zinc, mercury and lead [DFO 1985]).

Table 3-22

Condition Factors and Stomach Contents of Fish from Benson and Keogh Lakes

Location (Sample I.D)	Species	Length (mm)	Weight (g)	Sex	Condition Factor (C.F)*	Maturity**	Stomach Contents
Benson Lake							
BL1	RB	192	67	M	0.95	I	28 trichopterons, assorted unidentifed loose stomach contents.
BL2	RB	257	180	F	1.06	M	4 gastropods, 2 trichopterons, loose stomach contents.
BL3	RB	210	110	F	1.19	I	1 nematomaph, 1 chironomid adult, 3 coleoptera, 1 hymenopterm 1 formicad, assorted unidentified insect remains.
BL4	RB	257	180	F	1.06	M	500 cladocerons (Daphnia, Ceriodaphnia), 5 trichopterons, coleopteron, assorted loose stomach contents.
BL5	RB	270	215	F	1.09	M	53 gasotropods, 1 bivalve, 7 trichopterons.
BL6	RB	185	60	M	0.95	I	n/s
BL7	RB	260	195	F	1.11	M	n/s
BL8	UD	245	165	F	1.00	M	n/s
Mean (S.D)		234.5(31.4)	146.5(59.5)		1.05(0.08)		
Keogh Lake							
KL1	RB	195	70	M	0.94	I	empty
KL2	RB	220	95	M	0.89	I	5 arachnids, 2 hemipteron notonectids, 1 hemipteron adult, 1 hymenopteran, unidentified insect remains.
KL3	CT	200	75	M	0.94	I	1 ephemeropteron adult, 1 empheropteron nymph, 3 trichopterons, 3 arachnids, 2 hemipterons, 3 dipteron adult, 1 homopteron, assorted unidentified insect remains.
Mean (S.D)		205(13.2)	80.0(13.2)		0.92(0.03)		

*** CF = Weight (g)/Fork length (mm)^3 x 100,000**
**** I = Immature; M = Mature**

RB = Rainbow Trout
UD = Unidentified

CT = Cutthroat Trout

Table 3-23

Metal Body Burden in Fish Tissue and Livers from Benson and Keogh Lakes

Sample	Species	As	Cu	Co	Ni	Zn	Hg	Cd	Pb
BL1	RB	0.037	0.195	0.026	0.039	3.902	0.024	<0.002	0.020
BL2	RB	0.069	0.193	0.028	0.048	3.252	0.072	<0.002	<0.002
BL3	RB	0.080	0.202	0.017	0.026	3.252	0.022	<0.002	<0.002
BL4	RB	0.022	0.176	0.009	0.007	2.818	0.098	<0.002	<0.002
BL5	RB	0.039	0.210	0.013	0.024	3.035	0.039	<0.002	0.007
Mean (S.D)		0.049	0.195	0.019	0.029	3.252	0.051	<0.002	0.007
KL1	RB	0.059	0.499	0.043	0.152	4.770	0.238	<0.002	0.039
KL2	RB	0.074	0.282	0.007	0.013	3.902	0.076	<0.002	0.054
KL3	CT	0.074	0.199	0.015	0.009	3.469	0.039	<0.002	0.011
Mean (S.D)		0.069	0.327	0.022	0.058	4.047	0.118	<0.002	0.035
BL 1-5 Liver		0.520	32.520	0.210	0.013	21.680	0.061	0.128	0.002
KL 1-3 Liver		0.139	4.770	0.035	0.011	23.848	0.082	0.017	0.002
Background Concentrations in fish flesh from unpolluted sources		0.2-0.5	0.5-1.53	-	0.12-0.17	4.7-17.2	<0.5	<0.06	0.04-1.31
Background concentrations in liver of fish from unpolluted sources		-	1.5-28.0	-	-	11-48	-	<0.06	0.12-3.2
Sources		Demayo et al 1980	Demayo and Taylor 1981	-	Demayo et al 1980	Taylor and Demayo 1980	Reeder et al 1979	Reeder et al 1979	Demayo et al 1980
Cdn. Standard for Human Consumption		3.5	-	-	-	100	0.5	-	10

All values expressed as $\mu g\ g^{-1}$ (ppm) wet weight.
RB = Rainbow Trout
CT = Cutthroat Trout

4 - Conclusions

4.0 CONCLUSIONS

Historical disposal of reactive mine tailings in Benson Lake had an initial negative impact on water quality and biological communities, particularly benthic, within the lake. This impact appears to have been only temporary. The following summarizes the most salient points of the present study which have led to the above conclusion.

Benson Lake water quality has been compared to that of Keogh Lake which has never received tailings discharge. Both lakes are categorized as being oligotrophic on the basis of their water quality. The lakes did not differ significantly in their concentration of dissolved metals of environmental concern. Both lakes have anaerobic conditions near the surface of their profundal sediments. This has been partially attributed to decomposition of organic material in the top 5 cm of the lake sediments. Benson Lake water quality is considered good and any negative impact resulting from previous tailings deposition is no longer apparent.

Detailed petrographic and sediment metal analyses of submerged and land disposed tailings revealed that lake tailings were mineralogically distinct from the land tailings. Both lake and land tailings contained very elevated concentrations of copper. Sulphides, while relatively sparse in the submerged tailings, showed no signs of post-depositional oxidation. The chalcopyrite in the land tailings was also relatively fresh, however, considerable iron-staining in the sample suggested percolation of iron-rich acid waters had precipitated secondary iron oxides.

Sequential extractions performed on the above samples indicated that the land tailings released low levels of metals in the water soluble phase, whereas virtually no metals were released from the same phase in the lake tailings sample. Most metals were associated with the residual, biologically inactive phase in both samples. However, significant quantities (5 to 55%) of metals were associated with the oxidizable phase in the lake tailings sample. These results suggest that considerable binding of metals to organic matter may be occurring in the lake sediments. Thus, metal scavenging by organics may be preventing the efflux of metals from the benthic sediments to the overlying water column.

The observed densities of benthic organisms in Benson Lake were typical of oligotrophic lakes in Canada and elsewhere. The benthic community in Benson Lake appears to have re-established itself to pre-tailings deposition conditions. Phytoplankton and zooplankton densities differed between Benson and Keogh Lakes, with densities being greater in the control lake. These differences are largely ascribable to a fertilization effect on Keogh Lake resulting from operation of a fish farm. The species and densities observed in both lakes were typical of coastal lakes in British Columbia.

Metals, particularly As, were accumulated in the roots, and to a much lesser extent in the tops, of *Equisetum* sp. in Benson Lake as compared to that observed in Three Isle Lake for the same species. This may be a function of the significantly higher sediment As concentrations in Benson Lake. Copper did not accumulate in the tops of *Equisetum* sp. in Benson Lake despite high root-Cu concentrations and high sediment-Cu levels. While aquatic plants are not accumulating metals to harmful levels, the roots are concentrating metals from the surrounding sediments. The potential for forming stable, soluble organo-metal complexes and subsequent release to the water column is therefore enhanced. This potential should be minimized in the future by ensuring that the areal extent of tailings deposition in lakes is confined to the profundal zones, not in the littoral zones of repository lakes.

Analyses of metal body burden in fish from Benson Lake indicated that all metals measured were present within the range of concentrations observed in fish in unpolluted waters. For most metals, fish from Benson Lake had lower tissue metal levels than those from Keogh Lake. These results further support the general observation that impacts related to tailings deposition in Benson Lake were temporary and are no longer apparent.

References

REFERENCES

Abbey, S. 1980. Studies in "standard samples" for use in the general analysis of silicate rocks and minerals, Part 6: 1979 Edition of "Useable" Values.

APHA. 1985. Standard Methods for the Examination of Water and Wastewater. American Public Health Association, Washington D.C.

Cook, D.G and M.G. Johnson. 1974. Benthic macroinvertebrates of the St. Lawrence Great Lakes. J. Fish. Res. Board Can. 31(5): 763-782.

Cook, G.W., and C. Risley. 1963. The distribution of phytoplankton and benthic fauna of Lake Michigan. U.S. Dept. Health Educ. Welfare, Great Lakes - III. Rive Basins Proj., P.H.S. Region V. Chicago. 12 p.

Cummins, K.W. and G.H. Lauff. 1969. The influence of particle size on the microdistribution of stream macrobenthos. Hydrobiologica. 34:145-181.

DFO. 1985. Guidelines for metals in fish for human consumption. Unpublished report. Department of Fisheries and Oceans Canada Fish Inspection Branch, Vancouver, British Columbia.

Demayo, A., and M.C. Taylor. 1981. Guidelines for Surface Water Quality. Volume I - Inorganic Chemical Substances - Copper. Environment Canada, Inland Waters Directorate, Water Quality Branch, Ottawa, Canada.

Demayo, A., M.C. Taylor and S.W. Reeder. 1979. Guidelines for Surface Water Quality. Volume I - Inorganic Chemical Substances - Arsenic. Environment Canada, Inland Waters Directorate, Water Quality Branch, Ottawa, Canada.

Demayo, A., M.C. Taylor and S.W. Reeder. 1980. Guidelines for Surface Water Quality. Volume I - Inorganic Chemical Substances - Lead. Environment Canada, Inland Waters Directorate, Water Quality Branch, Ottawa, Canada.

Engler, R.M., J.M. Brannon and J. Rose. 1974. A practical selective extraction procedure for sediment characterization. Presented at the Symposium on Chemistry of Marine Sediments, National Chemical Society Meeting, Atlantic City, N.J.

Evans, L.J. 1989. Chemistry of metal retention by soils. Environ. Sci. Technol. 23:1047-1056.

Forstner, U. and G.T.W. Wittmann. 1983. Metal Pollution in the Aquatic Environment. Springer-Verlag, New York.

Hallam, R., R. Kussat and M. Jones. 1974. A biological assessment of Benson Lake following cessation of deep lake tailings disposal. Environmental Protection Service Canada (Pacific Region) Surveillance Rpt EPS 5-PR-74-2.

Harvey, P.K., and B.P. Atkin. 1982. The estimation of mass absorption coefficients by Compton scattering: extensions to the use of RhKa Compton radiation and intensity ratios. Am. Mineral. 67: 534-537.

Hutchinson, G.E. 1967. A Treatise on Limnology. Volume II - Introduction to Lake Biology and Limnoplankton. John Wiley and Sons, Inc. New York.

Hutchinson, G.E. 1957. A Treatise on Limnology. Volume I - Geography, Physics and Chemistry. John Wiley and Sons, Inc. New York.

Kathman. D. 1991. Personal communication. Woodward Clyde and Associates. Franklin, Tennessee, U.S.A.

Kussat, R.H., M. Jones and B. Lawley. 1972. A cursory evaluation of the deep lake tailings disposal system at Cominco's Benson Lake operation. Department of the Environment Canada, Fisheries Service Manuscript Report 1972 - 1.

Nielsen, L.A. and D.L. Johnson (eds.) 1983. Fisheries Techniques. American Fisheries Society, Bethesda, Maryland. 468 p.

Nirel, P.M.V and P.M.M. Morel. 1990. Pitfalls of sequential extractions. Wat. Res. 24:1055-1056.

Norrish, K. and J.T. Hutton. 1969. An accurate X-ray spectrographic method for the analysis of a wide range of geological samples. Geochim. Cosmochim. Acts 33: 431-453.

Northcote, T. G., and R. Clarotto. 1975. Limnetic macrozooplankton and fish predation in some coastal British Columbia lakes. Verh. Internat. Verein. Limnol. 19: 2378-2393.

Pennak, R.W. 1978. Freshwater Invertebrates of the United States. 2nd Edition. John Wiley and Sons.

Reeder, S.W., A. Demayo, and M.C. Taylor. 1979. Guidelines for Surface Water Quality. Volume I - Inorganic Chemical Substances - Cadmium. Environment Canada, Inland Waters Directorate, Water Quality Branch, Ottawa, Canada.

Reeder, S.W., A. Demayo, and M.C. Taylor. 1979. Guidelines for Surface Water Quality. Volume I - Inorganic Chemical Substances - Mercury. Environment Canada, Inland Waters Directorate, Water Quality Branch, Ottawa, Canada.

Rescan. 1990a. A Preliminary Assessment of Subaqueous Tailings Disposal in Benson Lake, British Columbia. Prepared for Mine Env. Neutral Drain. Prog. CANMET/Environment Canada.

Rescan. 1990b. Geochemical Assessment of Subaqueous Tailings Disposal in Buttle Lake, British Columbia. Prepared for Mine Env. Neutral Drain. Prog. CANMET/Environment Canada.

Rescan. 1990c. A Preliminary Assessment of Subaqueous Tailings Disposal in Anderson Lake, Manitoba. Prepared for Mine Env. Neutral Drain. Prog. CANMET/Environment Canada.

Rescan. 1990d. A Preliminary Assessment of Subaqueous Tailings Disposal in Mandy Lake, Manitoba. Consultants Report. Prepared for Mine Env. Neutral Drain. Prog. CANMET/Environment Canada.

Romney, E.M. and A. Wallace. 1975. Roots of higher plants as a barrier to translocation of some metals to shoots of plants. *In*: Biological Implications of Metals in the Environment. Fifteenth Annual Hanford Life Sci. Symp. Richland, Wash. USA.

Schelske, C.L., and J.C. Roth. 1973. Limnological survey of lakes Michigan, Superior, Huron and Erie. Univ. Michigan Great Lakes Res. Div. Publ. 17: 1-108.

Shrivastava, H.N. 1974 Macrobenthos of Lake Huron. J. Fish. Res. Board. Can. Tech. Rep. 449.

Taylor, M.C., A. Demayo and S.W. Reeder. 1979. Guidelines for Surface Water Quality. Volume I - Inorganic Chemical Substances - Nickel. Environment Canada, Inland Waters Directorate, Water Quality Branch, Ottawa, Canada.

Taylor, M.C., and A. Demayo. 1980. Guidelines for Surface Water Quality. Volume I - Inorganic Chemical Substances - Zinc. Environment Canada, Inland Waters Directorate, Water Quality Branch, Ottawa, Canada.

Teter, H.E. 1960. The bottom fauna of Lake Huron. Trans. Am. Fish. Soc. 89: 193-197.

Torke, B.G. 1974. An Illustrated Guide to the Identification of the Planktonic Crustaceans 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., and G.C. Whipple. 1963. Fresh Water Biology. 2nd Edition. John Wiley and Sons.

Weirs, A.P., and D.M. Rosenberg. 1984. Effect of impoundment and river diversion on profundal macrobenthos of Southern Indian Lake, Manitoba, Canada. J. Fish. Aquat. Sci. 41(4): 638-648.

Werring. J. 1986. Fertilization of an Oligotrophic Montane Lake Using Frequent Doses of High N:P Ratio Fertilizers: Effects on Phytoplanton and Zooplankton Community Structure. M.Sc.. Thesis, University of British Columbia, Vancouver, B.C.

Wetzel, R.G. 1979. Limnology. W.B. Saunders, Toronto.

Wilson, D. 1984. A background study of Trout (Embury) and Cliff Lakes, Manitoba. Envir. Workpl. Safety Health Wat. Stand. Studies Rep. #84-7: 40 pp.

Appendix A

Hydrologic Data

Table A-1

Estimated Inflow and Outflow Rates To/From Benson Lake September 13-17, 1991

Stream	Discharge ($m^3 s^{-1}$)
Inflow	
Raging River	1.66
Upper Benson River	0.28
Craft Creek	0.14
Total Inflow	2.08
Outflow	
Lower Benson River	1.88
Total Outflow	1.88

Table A-2

Lower Benson River Discharge

Distance from Left Bank (m)	Depth (m)	Velocity ($m\ s^{-1}$)	Discharge ($cum\ s^{-1}$)
0	0	0	0
2	0.2	0.03	0.009
3	0.4	0.06	0.0255
4	0.45	0.11	0.051
5	0.42	0.13	0.0783
6	0.55	0.23	0.13095
7	0.4	0.31	0.154375
8	0.4	0.34	0.098
9	0.54	0.15	0.0564
10	0.45	0.09	0.091575
11	0.55	0.28	0.1175
12	0.67	0.19	0.1281
13	0.72	0.23	0.156375
14	0.68	0.22	0.133
15	0.53	0.16	0.117975
16	0.6	0.23	0.138425
17	0.6	0.26	0.108
18	0.68	0.1	0.0832
19	0.55	0.16	0.083025
20	0.5	0.11	0.05775
21	0.35	0.11	0.0425
22	0.3	0.09	0.014625
Total Discharge			1.875575

Discharge calculated as $\Sigma(D_{L+1}-D_i)*((Dep_{L+1}+D_i)/2)*((V_{L+1}+V_i)/2)$

D = Distance from left bank (m)

Dep = Depth

V = Velocity ($m\ s^{-1}$)

n = wetted width of stream (m)

Table A-3

Raging River Discharge

Distance from Left Bank (m)	Depth (m)	Velocity ($m\ s^{-1}$)	Discharge ($cum\ s^{-1}$)
0	0	0	0
1	0.05	0	0.002875
2	0.09	0.23	0.01505
3	0.12	0.2	0.028875
4	0.25	0.35	0.034225
5	0.26	0.02	0.0408
6	0.28	0.3	0.07425
7	0.2	0.25	0.0348
8	0.1	0.04	0.0225
9	0.28	0.26	0.057
10	0.4	0.34	0.1496
11	0.36	0.54	0.1368
12	0.36	0.18	0.1188
13	0.32	0.48	0.153
14	0.25	0.42	0.1596
15	0.15	0.7	0.095
16	0.36	0.25	0.03825
17	0.25	0.05	0.016775
18	0.35	0.06	0.054
19	0.4	0.3	0.178125
20	0.45	0.65	0.163625
21	0.35	0.12	0.058
22	0.28	0.17	0.026775
23	0.05	0	0
Total Discharge			1.65585
Total Inflow			2.080288

Discharge calculated as $\Sigma(D_{L+1}-D_i)*((Dep_{L+1}+D_i)/2)*((V_{L+1}+V_i)/2)$

D = Distance from left bank (m)

Dep = Depth

V = Velocity (m s^{-1})

n = wetted width of stream (m)

Table A-4

Craft Creek Discharge

Distance from Left Bank (m)	Depth (m)	Velocity ($m\ s^{-1}$)	Discharge ($cum\ s^{-1}$)
0	0	0	0
1	0.2	0	0.001
1.5	0.28	0.02	0.0126
2	0.3	0.19	0.0232
2.5	0.25	0.13	0.01375
3	0.25	0.07	0.013125
3.5	0.2	0.14	0.010125
4	0.2	0.04	0.0035
4.5	0.2	0.03	0.0045
5	0.2	0.06	0.0055
5.5	0.2	0.05	0.0095
6	0.25	0.14	0.021375
6.5	0.15	0.24	0.0165
7	0.1	0.09	0.00375
7.5	0.05	0.03	0.000563
8.4	0	0	0
Total Discharge			0.138988

Discharge calculated as $\Sigma(D_{L+1}-D_i)*((Dep_{L+1}+D_i)/2)*((V_{L+1}+V_i)/2)$

D = Distance from left bank (m)

Dep = Depth

V = Velocity ($m\ s^{-1}$)

n = wetted width of stream (m)

Table A-5

Raging River Discharge

Distance from Left Bank (m)	Depth (m)	Velocity ($m\ s^{-1}$)	Discharge (cum s^{-1})
0	0	0	0
2	0.05	0	0.0005
3	0.18	0.02	0.002875
4	0.24	0.03	0.0042
5	0.22	0.01	0.00575
6	0.03	0.04	0.0078
7	0.28	0.02	0.00725
8	0.04	0.03	0.0136
9	0.45	0.05	0.017
10	0.45	0.03	0.02025
11	0.4	0.06	0.023375
12	0.44	0.05	0.0231
13	0.4	0.06	0.021
14	0.4	0.04	0.022
15	0.55	0.07	0.0285
16	0.5	0.05	0.021
17	0.4	0.03	0.01575
18	0.4	0.04	0.016
19	0.2	0.04	0.012
20	0.25	0.04	0.01125
21	0.2	0.06	0.007875
22	0.2	0.01	0.003
23	0.3	0.02	0.0025
24	0.35	0	0.00325
25	0.35	0.02	0.00525
26	0.5	0.01	0.00425
27	0.5	0.01	0.005
28	0.4	0.01	0.00225
Total Discharge			0.28545

Discharge calculated as $\Sigma(D_{L+1}-D_i)*((Dep_{L+1}+D_i)/2)*((V_{L+1}+V_i)/2)$

D = Distance from left bank (m)

Dep = Depth

V = Velocity (m s^{-1})

n = wetted width of stream (m)

Appendix B

Water Quality Data

Rescan

Table B-1

Water Quality Analysis
Benson Lake - Station 1

Parameters		BL1-A* Sep 13/90	BL1-B Sep 13/90	BL1-C Sep 13/90	BL1-D Sep 13/90
Physical Tests					
Conductivity	µmhos/cm	77.3	77.4	69.1	77.6
Total Dissolved Solids	(mg/L)	55.0	55.0	50.0	55.0
pH		7.29	7.59	7.49	7.36
Total Suspended Solids	(mg/L)	4.0	5.3	4.7	3.3
Fixed Suspended Solids	(mg/L)	<1	<1	<1	<1
Volatile Suspended Solids	(mg/L)	4.0	5.0	5.0	3.0
Turbidity	NTU	0.40	0.30	0.20	1.10
Dissolved Anions (mg/L)					
Alkalinity	$CaCO_3$	33.7	33.7	29.3	34.1
Chloride	Cl	0.6	<0.5	0.8	1.5
Silicate	SiO_2	3.4	3.2	2.6	3.0
Sulphate	SO_4	1.5	1.6	1.1	<1.0
Nutrients (mg/L)					
Ammonia Nitrogen	N	<0.005	<0.005	<0.005	0.085
Nitrite/Nitrate Nitrogen	N	0.029	0.029	0.021	0.028
Total Phosphorus	P	<0.0001	<0.001	<0.001	0.004
Other Tests (mg/L)					
Chlorophyll	µg/L	0.20	<0.01	-	-
Total Organic Carbon	C	1.59	1.54	1.68	1.92
Dissolved Metals (mg/L)					
Aluminum	Al	0.015	0.022	0.037	0.025
Arsenic	As	<0.0001	0.0005	0.0004	0.0005
Cadmium	Cd	<0.0002	<0.0002	<0.0002	<0.0002
Calcium	Ca	12.4	12.2	11.5	12.7
Copper	Cu	<0.001	0.001	0.001	<0.001
Iron	Fe	0.055	0.043	0.036	0.251
Lead	Pb	<0.001	<0.001	0.005	<0.001
Magnesium	Mg	1.33	1.28	0.924	1.10
Manganese	Mn	<0.005	<0.005	<0.005	0.239
Mercury	Hg	<0.00005	<0.00005	<0.0005	<0.0005
Nickel	Ni	<0.001	<0.001	<0.001	<0.001
Potassium	K	0.09	0.09	0.10	0.12
Silver	Ag	<0.0001	<0.0001	<0.0001	<0.0001
Sodium	Na	1.20	1.19	1.10	1.13
Zinc	Zn	<0.005	<0.005	<0.005	<0.005

< = less than
Results expressed as milligrams per litre except for pH, Conductivity (µmhos/cm), Turbidity (NTU) and Chlorophyll (µg/L)
*** Sample Depths: A = 0.5 m, B = 5 - 11 m, C = 20 m, D = 1 meter above bottom.**

Table B-2

Water Quality Analysis
Benson Lake - Station 2

Parameters		BL2-A* Sep 13/90	BL2-B Sep 13/90	BL2-C Sep 13/90	BL2-D Sep 13/90
Physical Tests					
Conductivity	µmhos/cm	76.6	68.8	68.7	78.4
Total Dissolved Solids	(mg/L)	55.0	50.0	50.0	55.0
pH		7.70	7.62	7.59	7.45
Total Suspended Solids	(mg/L)	<1.0	4.0	2.0	10.7
Fixed Suspended Solids	(mg/L)	<1	<1	1.0	<1
Volatile Suspended Solids	(mg/L)	<1.0	4.0	1.0	10
Turbidity	NTU	0.40	0.20	0.30	1.60
Dissolved Anions (mg/L)					
Alkalinity	$CaCO_3$	33.8	29.7	29.0	33.8
Chloride	Cl	0.6	0.7	1.1	1.1
Silicate	SiO_2	3.3	2.6	5.6	3.3
Sulphate	SO_4	1.4	1.3	1.2	<1.0
Nutrients (mg/L)					
Ammonia Nitrogen	N	0.005	<0.005	0.006	0.096
Nitrite/Nitrate Nitrogen	N	0.021	0.046	0.039	0.034
Total Phosphorus	P	0.003	<0.001	0.001	0.012
Other Tests (mg/L)					
Chlorophyll	µg/L	0.01	0.12	-	-
Total Organic Carbon	C	1.54	1.45	1.64	2.01
Dissolved Metals (mg/L)					
Aluminum	Al	0.030	0.034	0.032	0.018
Arsenic	As	0.0003	0.003	0.0003	0.0004
Cadmium	Cd	<0.0002	<0.0002	<0.0002	<0.0002
Calcium	Ca	12.1	11.4	11.0	12.3
Copper	Cu	0.001	0.003	0.001	<0.001
Iron	Fe	0.055	<0.030	0.039	0.215
Lead	Pb	<0.001	<0.001	<0.001	<0.001
Magnesium	Mg	1.30	0.949	0.947	1.10
Manganese	Mn	<0.005	<0.005	<0.005	0.351
Mercury	Hg	<0.00005	<0.00005	<0.00005	<0.00005
Nickel	Ni	<0.001	0.001	<0.001	<0.001
Potassium	K	0.09	0.09	0.10	0.13
Silver	Ag	<0.0001	<0.001	<0.0001	<0.0001
Sodium	Na	1.19	1.08	1.08	1.12
Zinc	Zn	<0.005	<0.005	<0.005	<0.005

< = less than

Results expressed as milligrams per litre except for pH, Conductivity (µmhos/cm), Turbidity (NTU) and Chlorophyll (µg/L)

*** Sample Depths: A = 0.5 m, B = 5 - 11 m, C = 20 m, D = 1 meter above bottom.**

Table B-3

Water Quality Analysis
Benson Lake - Station 3

Parameters		BL3-A* Sep 13/90	BL3-B Sep 13/90	BL3-C Sep 13/90	BL3-D Sep 13/90
Physical Tests					
Conductivity	µmhos/cm	76.5	75.2	67.5	71.5
Total Dissolved Solids	(mg/L)	55.0	55.0	50.0	60.0
pH		7.72	7.78	7.63	7.54
Total Suspended Solids	(mg/L)	3.3	4.0	<1.0	2.0
Fixed Suspended Solids	(mg/L)	<1	<1	<1	<1
Volatile Suspended Solids	(mg/L)	3.0	4.0	<1	2.0
Turbidity	NTU	0.60	0.30	0.20	0.60
Dissolved Anions (mg/L)					
Alkalinity	$CaCO_3$	33.2	32.6	29.4	30.0
Chloride	Cl	0.5	0.7	1.9	1.3
Silicate	SiO_2	3.7	3.3	2.3	3.1
Sulphate	SO_4	1.2	1.4	<1.0	<1.0
Nutrients (mg/L)					
Ammonia Nitrogen	N	<0.005	<0.005	0.006	0.023
Nitrite/Nitrate Nitrogen	N	0.025	0.041	0.036	0.044
Total Phosphorus	P	0.002	0.003	0.003	0.004
Other Tests (mg/L)					
Chlorophyll	µg/L	0.08	<0.01	-	-
Total Organic Carbon	C	1.87	1.64	1.59	1.92
Dissolved Metals (mg/L)					
Aluminum	Al	0.028	0.020	0.046	0.032
Arsenic	As	0.0001	0.0002	0.0003	0.0003
Cadmium	Cd	<0.0002	<0.0002	<0.0002	<0.0002
Calcium	Ca	12.3	12.1	11.3	11.7
Copper	Cu	<0.001	0.001	<0.001	<0.001
Iron	Fe	0.062	0.032	0.047	0.102
Lead	Pb	<0.001	<0.001	0.002	0.001
Magnesium	Mg	1.34	1.09	0.937	1.07
Manganese	Mn	<0.005	<0.005	<0.005	<0.005
Mercury	Hg	<0.00005	<0.00005	<0.00005	<0.00005
Nickel	Ni	<0.001	0.001	<0.001	<0.001
Potassium	K	0.09	0.09	0.10	0.11
Silver	Ag	<0.0001	<0.0001	<0.0001	<0.0001
Sodium	Na	1.19	1.13	1.08	1.08
Zinc	Zn	<0.005	<0.005	<0.005	<0.005

< = less than
Results expressed as milligrams per litre except for pH, Conductivity (µmhos/cm), Turbidity (NTU) and Chlorophyll (µg/L)
*** Sample Depths: A = 0.5 m, B = 5 - 11 m, C = 20 m, D = 1 meter above bottom.**

Table B-4

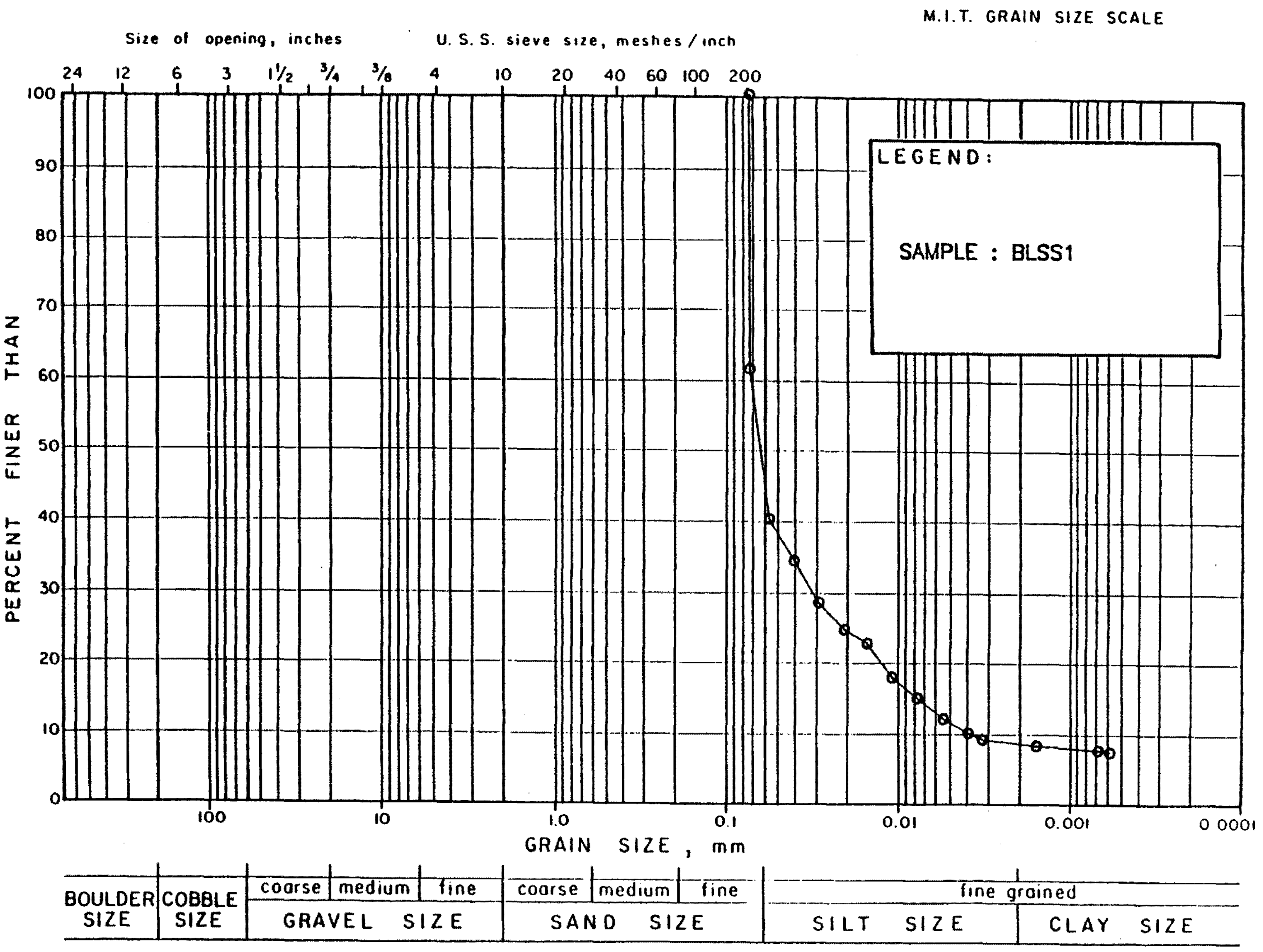
Water Quality Analysis
Keogh Lake

Parameters		KL1-A* Sep 17/90	KL1-B Sep 17/90	KL1-C Sep 17/90	KL1-D Sep 17/90
Physical Tests					
Conductivity	µmhos/cm	25.5	25.3	23.2	24.0
Total Dissolved Solids	(mg/L)	20.0	20.0	20.0	20.0
pH		7.51	7.17	7.05	6.86
Total Suspended Solids	(mg/L)	2.0	3.3	3.3	1.3
Fixed Suspended Solids	(mg/L)	<1	<1	<1	<1
Volatile Suspended Solids	(mg/L)	2.0	3.0	3.0	1.0
Turbidity	NTU	0.40	0.40	0.40	0.50
Dissolved Anions (mg/L)					
Alkalinity	$CaCO_3$	8.2	8.5	6.6	7.3
Chloride	Cl	1.6	0.7	1.1	1.0
Silicate	SiO_2	2.9	3.2	3.9	5.4
Sulphate	SO_4	<1.0	<1.0	1.5	1.5
Nutrients (mg/L)					
Ammonia Nitrogen	N	0.011	0.008	0.005	<0.005
Nitrite/Nitrate Nitrogen	N	<0.005	<0.005	0.056	0.083
Total Phosphorus	P	0.004	0.005	0.004	0.013
Other Tests (mg/L)					
Chlorophyll	µg/L	0.63	0.66	-	-
Total Organic Carbon	C	4.03	3.89	4.50	5.06
Dissolved Metals (mg/L)					
Aluminum	Al	0.066	0.075	0.138	0.141
Arsenic	As	<0.0001	<0.0001	<0.0001	<0.0001
Cadmium	Cd	<0.0002	<0.0002	<0.002	<0.0002
Calcium	Ca	2.62	2.54	2.32	2.32
Copper	Cu	0.003	0.002	0.002	0.002
Iron	Fe	0.039	0.047	0.130	0.309
Lead	Pb	<0.001	<0.001	<0.001	<0.001
Magnesium	Mg	0.762	0.731	0.698	0.681
Manganese	Mn	<0.005	<0.005	0.014	0.072
Mercury	Hg	<0.00005	<0.00005	<0.00005	<0.00005
Nickel	Ni	<0.001	<0.001	<0.001	<0.001
Potassium	K	0.03	0.03	0.04	0.04
Silver	Ag	<0.0001	<0.0001	<0.0001	<0.001
Sodium	Na	1.15	1.13	1.09	1.10
Zinc	Zn	<0.005	<0.005	<0.005	<0.005

< = less than
Results expressed as milligrams per litre except for pH, Conductivity (µmhos/cm), Turbidity (NTU) and Chlorophyll (µg/L)
*** Sample Depths: A = 0.5 m, B = 5 - 11 m, C = 20 m, D = 1 meter above bottom.**

Particle Size Analysis

PROJECT NO 8921296 DRAWN .... REVIEWED .... DATE OCT-10-90

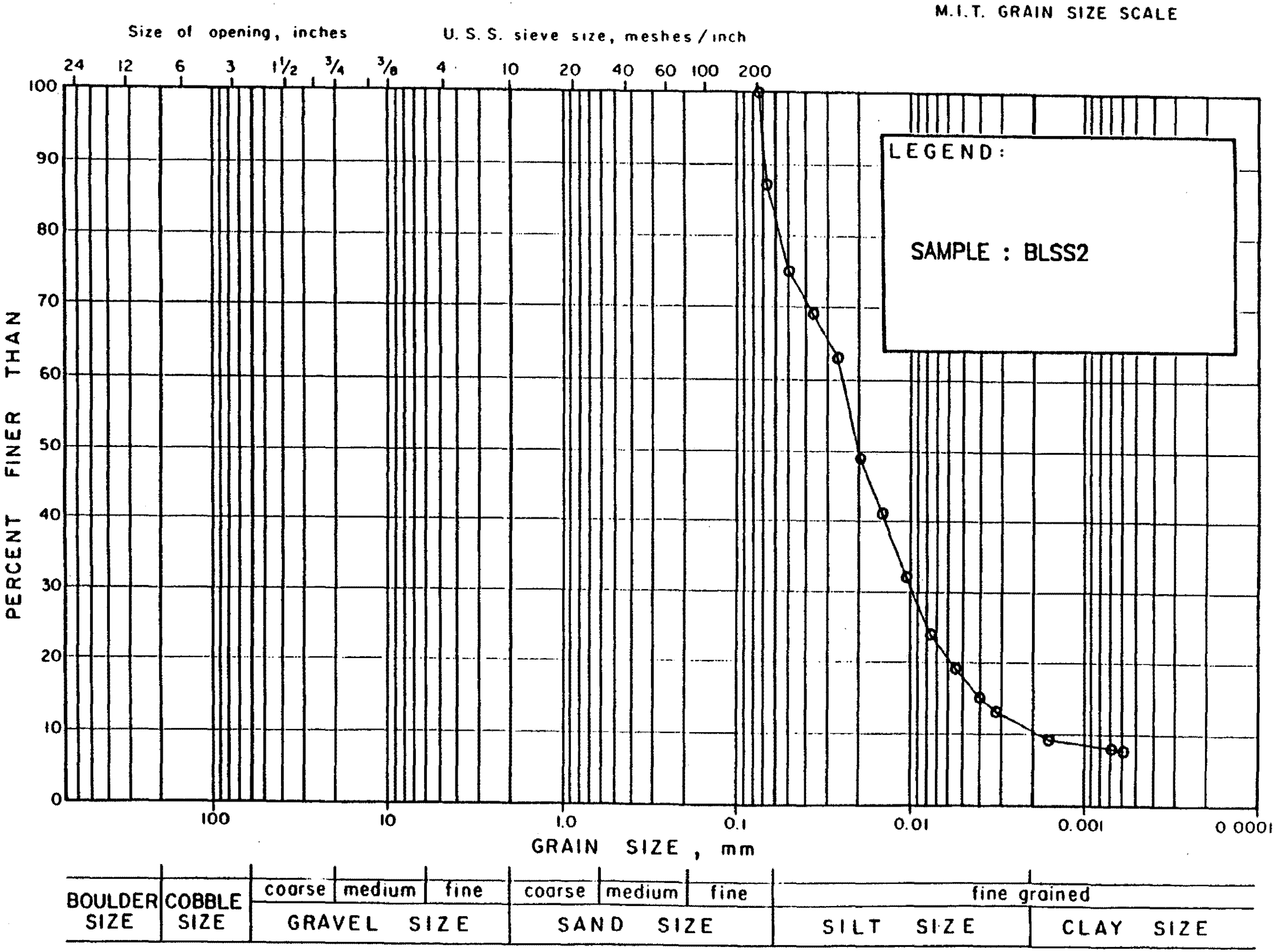


GRAIN SIZE DISTRIBUTION

Figure C-1

Golder Associates

PROJECT NO. 8921296 DRAWN .... REVIEWED .... DATE OCT-10-90

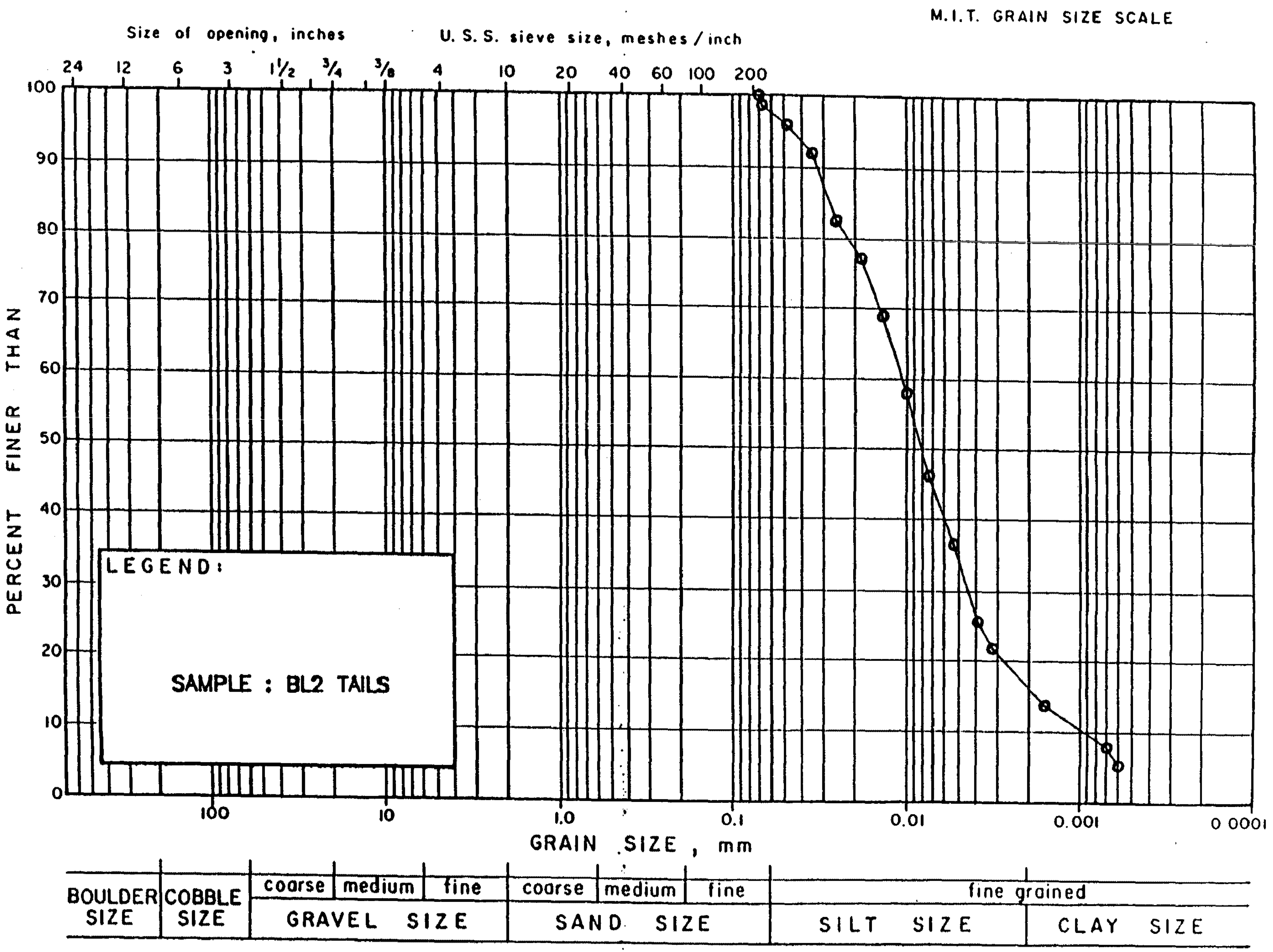


GRAIN SIZE DISTRIBUTION

Figure C-2

Golder Associates

PROJECT NO. 8921298 DRAWN .... REVIEWED .... DATE OCT-10-90

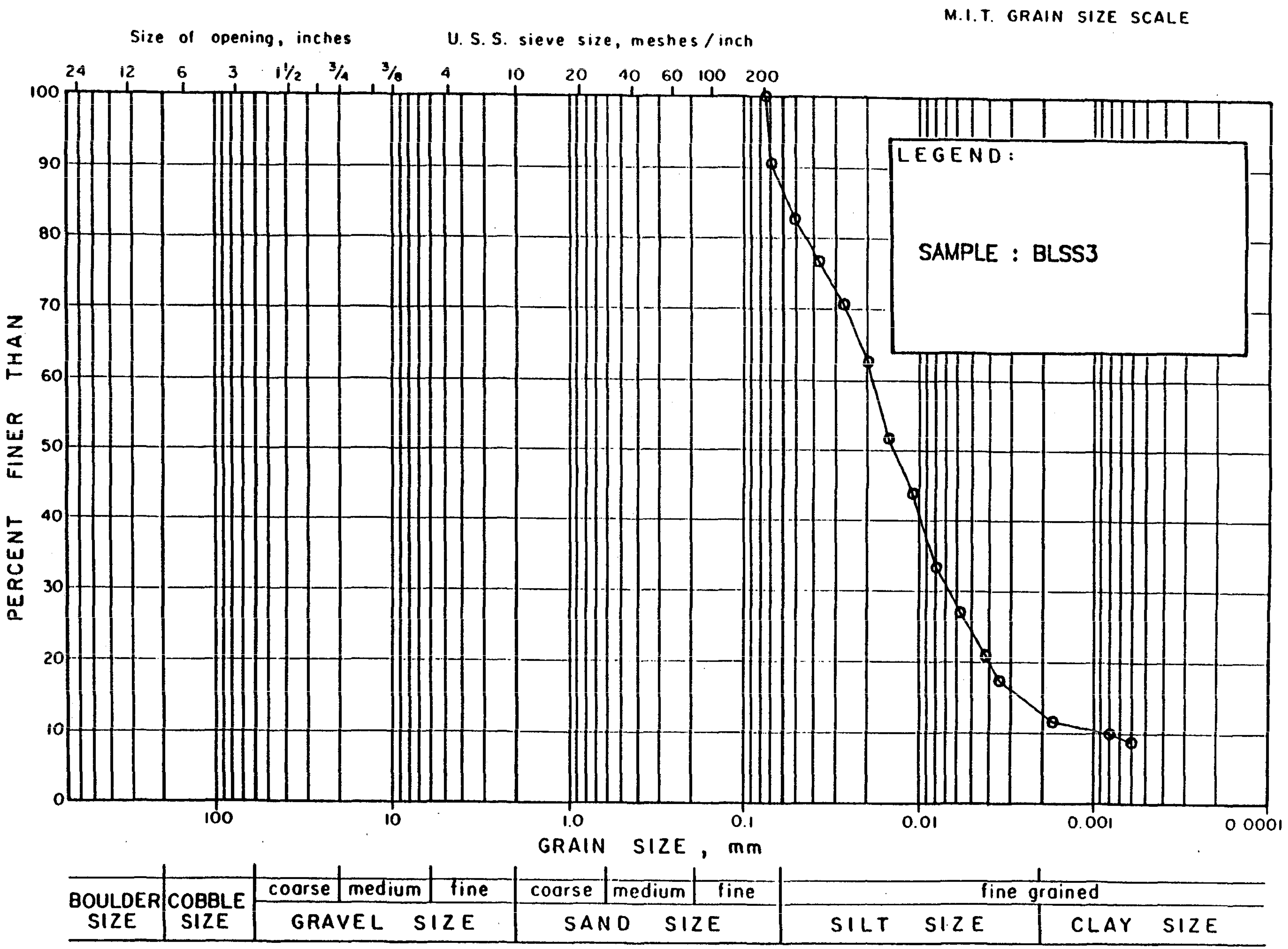


GRAIN SIZE DISTRIBUTION

Figure C-3

Golder Associates

PROJECT NO 8921296 DRAWN .... REVIEWED .... DATE OCT-10-90

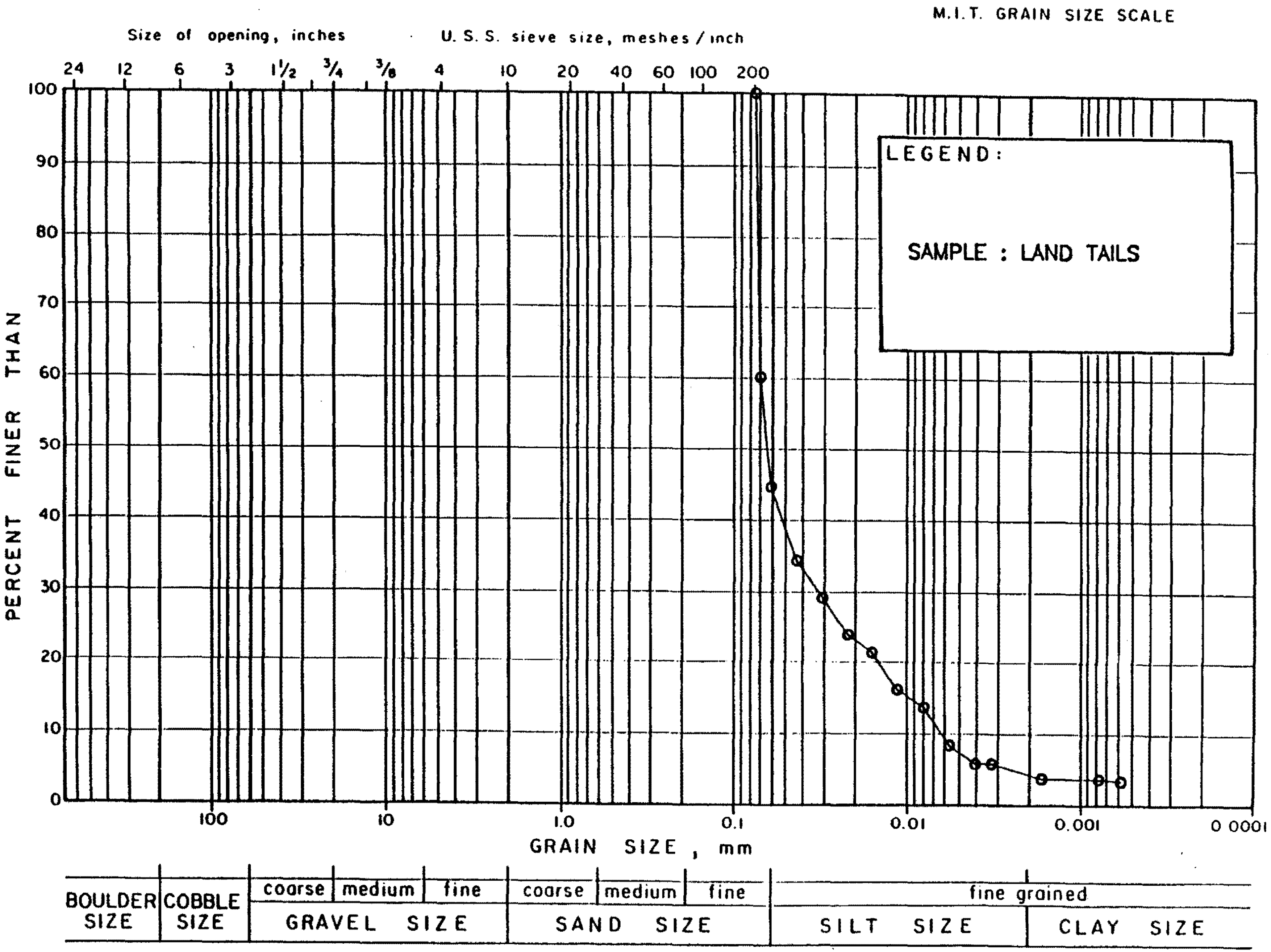


GRAIN SIZE DISTRIBUTION

Figure C-4

Golder Associates

PROJECT NO 8921296 DRAWN .... REVIEWED .... DATE OCT-10-90

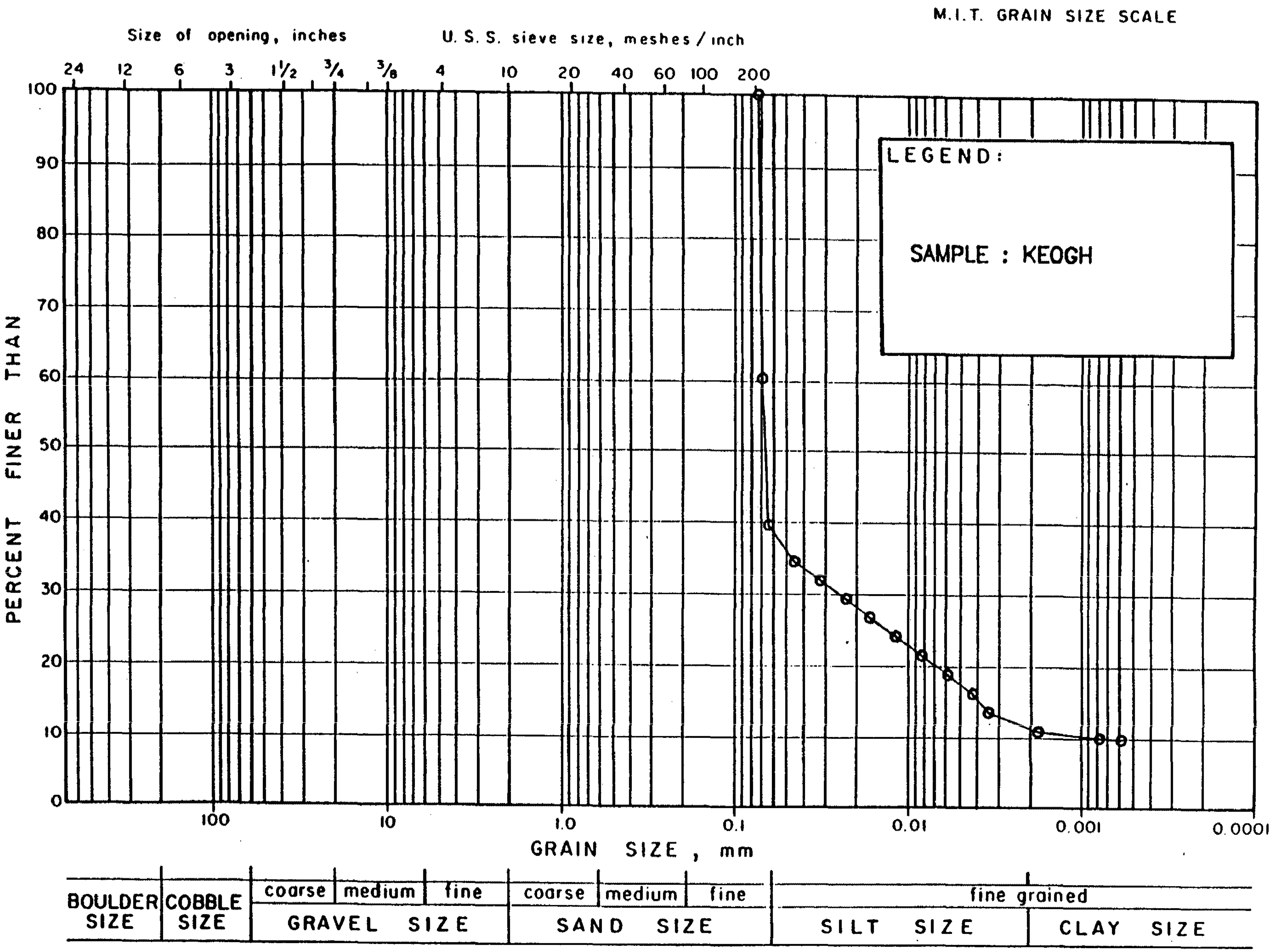


GRAIN SIZE DISTRIBUTION

Figure C-5

Golder Associates

PROJECT NO 8921298 DRAWN .... REVIEWED .... DATE OCT-10-90



GRAIN SIZE DISTRIBUTION

Figure C-6

Golder Associates

Detailed Petrographic Analysis

Sample: **BL SS 1**

Brown amorphous material	22
Feldspars	45
Amphibole	12
Epidote	4
Quartz	2
Sericite} Chlorite}	8
Carbonate	1.5
Magnetite	3.0
Hematite	0.2
Pyrite	0.2
Pyrrhotite	0.1
Chalcopyrite	trace

This material contained a high proportion of coarse organic debris, which was screened out (as was the ultra-fine portion) in order to facilitate mounting. As a result, this sample appears notably well-sized compared with others of the suite. It is mostly within the particle size range of 40 - 120 μm.

The brown, translucent/opaque-flecked phase, considered to represent organic and Fe hydroxide-rich sediment, is notably less prominent in this sample than others - almost certainly because of the screening pretreatment. The other samples of the suite were mounted "as is". To a minor degree this brown material occurs as partial rims or coatings on mineral grains, or as diffuse impregnations of porous aggregate grains (such as compact chlorite or sericite). For the most part, however, it is well segregated, and the abundant mineral component consists of clean, discrete, monomineralic grains.

The predominant constituent is feldspar (probably mainly plagioclase). This occurs as particles ranging from fresh, well-twinned, to strongly turbid, sericitized and saussuritized. A component of minutely felsitic material is also present.

Amphibole ranges from well-crystallized prismatic grains to minutely felted/fibrous aggregates of secondary aspect.

Compared with most of the other samples, garnet is relatively minor, and carbonate relatively more abundant.

Opaques, in total, are more abundant in this sample than in the other lake sediments. They consist mainly of magnetite, as free, irregular-shaped grains, 30 - 100 μm in size. Sulphides are mainly pyrite and lesser pyrrhotite. Chalcopyrite is rare.

The sulphides typically occur as individual liberated grains. Rare cases of compositing with silicates or encapsulation by organics are seen. The Fe sulphides are mainly fresh, but a minor proportion show rims of oxidation to limonite. The chalcopyrite is unaffected.

Sample: BL SS 2

Brown amorphous material	38
Feldspar	34
Amphibole	11
Chlorite	5
Quartz	5
Garnet	3
Epidote	1
Carbonate	1
Magnetite	1.5
Hematite} Limonite}	0.2
Pyrite} Pyrrhotite}	0.1
Chalcopyrite	trace

This material has a predominant particle size range of 5 - 150 μm. A few larger fragments of the amorphous organic-rich phase are also present.

The latter material (brown, translucent, isotropic, with dark opaque, possibly ferruginous speckles), makes up a somewhat higher percentage in this sample than in others of the suite.

The mineral grain component making up the remainder of the sample consists principally of feldspar (plagioclase), showing varying degrees of saussuritic alteration. A minor component of quartz and some compact chloritic material are also present.

Garnet and epidote are notably less abundant in this sample than in many others of the suite.

Sulphides, also, are notably minor. They consist of rare, tiny liberated grains, 5 - 30 μm (rarely to 50 μm) in size, of pyrite, pyrrhotite and chalcopyrite. The Fe sulphides in this sample occasionally show partial marginal oxidation to limonite. The chalcopyrite is always fresh.

Sample: **BL 2 Tailings**

Brown amorphous material	28
Quartz	4
Feldspar	19
Amphibole	32
Garnet	8
Epidote	6
Carbonate	0.5
Magnetite	2
pyrrhotite	0.3
Pyrite	0.1
Chalcopyrite	0.1

This material is bimodal in particle size. A considerable proportion is notably fine (in the range 2 - 50 μm), but there are also more or less abundant, much coarser particles, 100 - 200 μm in size (rarely to 500 μm).

Many of the coarsest particles are apparently aggregates of organic fluff, sometimes with intermixed silt. They range from amorphous brown with opaque speckles, to greyish, sub-opaque in appearance.

The fine fraction consists mainly of liberated mineral grains in proportions as estimated above. Scattered, coarser grains of the same minerals, to 200 μm in size, are also seen.

Opaques are of low abundance. They consist principally of magnetite, as liberated anhedral grains 20 - 200 μm in size.

The most common sulphide is pyrrhotite. Very minor pyrite and chalcopyrite are also seen. The sulphides occur mainly as liberated grains in the 5 - 50 μm size (occasionally larger). Occasional composites of sulphides with garnet and other silicates are seen.

The sulphides are totally fresh.

Sample: **BL SS 3**

Brown amorphous material	30
Quartz	5
Plagioclase	36
Amphibole	12
Garnet	8
Epidote	6
Carbonate	trace
Sphene	trace
Magnetite	2.5
Hematite	0.2
Pyrite	0.1
Pyrrhotite	0.1
Chalcopyrite	0.1

This material has a particle size range of 5 - 150 μm, plus rare, coarser grains to 250 μm.

Like the other samples, it consists predominantly of the translucent, brown, amorphous material which is thought to represent organic-rich sediment. This includes diffuse opaque spots (Fe, hydroxides?, carbon?), and sometimes incorporates a little silt-sized mineral material. Occasional biogenic skeletal forms are also seen.

The remainder of the sample consists of liberated mineral grains which, in this case, appear to be principally feldspar (plagioclase). This is mostly fresh, but is sometimes flecked with saussuritic alteration, or has intimately intergrown fibrous amphibole.

Garnet forms prominent, generally rather coarse free grains. Amphibole appears less prominent than in some of the other samples; it is partly well-crystallized, prismatic, and partly as minutely felted, compact aggregates.

Opaques are minor. They consist predominantly of magnetite, occasionally with associated hematite or limenite. Sulphides - particularly Fe sulphides - are notably sparse. They occur as scattered, tiny flecks and rare, larger individuals, to 50 μm, always liberated, and always fresh.

Sample: **Benson Land Tailings**

Garnet	10
Epidote	10
Diopside	6
Amphibole	20
Feldspar	2
Quartz	15
Limonite	5
Magnetite	20
Chalcopyrite	12

This material has a particle size range of 2 - 150 μm.

It consists almost entirely of liberated mineral grains - principally calc silicates of skarnic type (garnet, epidote, actinolite, diopside, and possible olivine).

The strong orange-brown colour of the original sample suggested extensive oxidation of sulphides and a high content of limonite. The thin section shows some fairly large grains of "fluffy", earthy limonite but, for the most part, the limonite is found to be in a highly dispersed form, as staining and surface coatings on silicate grains, and some intimate impregnation of fibrous minerals. The overall content of limonite does not appear high.

This material has a high content of chalcopyrite, and it seems likely that it represents pulverized mill feed - or even selected high grade - rather than tailings.

The chalcopyrite occurs as liberated angular particles, 5 - 100 μm in size. It is totally fresh, and shows no sign of oxidation (to limonite) or secondary enrichment (development to Fe-free Cu sulphides).

The abundance of magnetite (again, as fresh free grains), and the total absence of pyrite or pyrrhotite, is a notable feature, inconsistent with the sulphide component seen in the lake tailings and sediment samples. The dominance of quartz over plagioclase is another distinctive feature.

No partially oxidized remnants of original Fe sulphides were seen, suggesting that the diffuse limonite in this sample is of transported (hydrochemically redistributed and precipitated) origin - perhaps derived from adjacent dumps or percolation of mine drainage.