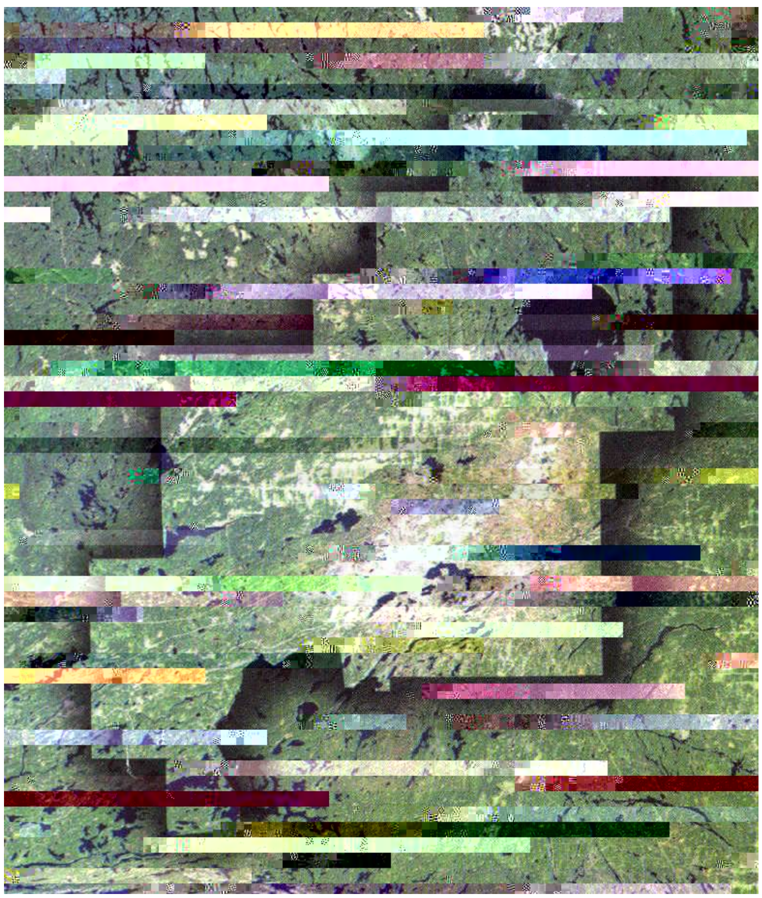
Recovery of Acid and Metal - Damaged Lakes Near Sudbury Ontario: Trends and Status



Lakes in and around the City of Greater Sudbury

Cooperative Freshwater Ecology Unit

2004

Summary

Lakes in a large area around Sudbury, Ontario, Canada, have been affected by the atmospheric deposition of pollutants from over

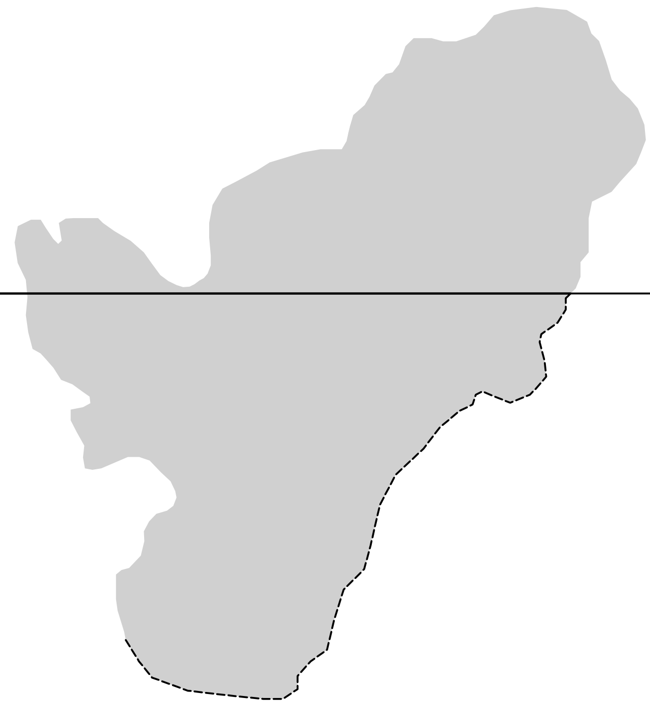
Introduction

Metal mining and smelting began in the Sudbury, Ontario, Canada, area before the turn of the 20th century. The Sudbury area subsequently grew into one of the largest metal-producing complexes in the world. Smelter emissions peaked during the 1960's, when the Sudbury area smelters constituted one of the world's largest point sources of SO_2 emissions. Thousands of tons of metal particulates have also been emitted from the Sudbury smelters over the years (Potvin & Negusanti, 1995).

Lakes in a large area of northeastern Ontario have been severely affected by the atmospheric deposition of contaminants originating from the Sudbury smelter emissions. Over 7000 lakes within a 17,000 km^2 area (Figure 1) have been acidified to pH 6.0, the point at which significant biological damage is expected (Neary et al., 1990). The lakes most severely damaged were those located within about 20 to 30 km of the smelters, where acid conditions were combined with very high concentrations of potentially toxic trace metals, especially copper and nickel. Elevated concentrations of metals in combination with high acidity have had profound effects on biological communities (Yan & Welbourn, 1990). Some lakes near the smelters have been reported as among the most atmospherically-contaminated lakes in the world. For example, Hannah Lake, 4 km from the Copper Cliff Smelter, had pH 4.3 and copper and nickel concentrations of over 1000 µg/L, in 1974 (Yan et al. 1996a). Highly elevated metal concentrations have also been documented in non-acidified Sudbury lakes and have had severe effects on lake ecosystems. Some Sudbury area lakes were also subjected to severe watershed disturbances (logging, fires, SO_2 fumigations and vegetation damage, soil erosion) that in extreme cases resulted in virtually barren watersheds (Gunn, 1996).

However, much has changed in the aquatic ecosystems around Sudbury. As emissions of SO_2 and metals were dramatically reduced during the 1970's (Figure 2), large improvements in lake water quality were observed in the surrounding area (Keller & Pitblado, 1986; Keller et al., 1992a) and biological improvements have followed (Gunn & Keller, 1990; Keller et al., 1992b; Havas et al., 1995). Unexpectedly, some of the most dramatic decreases in acidity have occurred in the most highly affected lakes close to the Sudbury smelters. Large additional decreases in SO_2 emissions were achieved by 1994 (Figure 2) as part of Ontario's Countdown Acid Rain Program. Further decreases in metal emissions accompanied these SO_2 emission reductions. Overall, reductions in SO_2 and metal emissions of about 90% have been achieved in recent decades (Potvin & Negusanti, 1995).

This report examines recent trends in the chemistry of Sudbury lakes for evidence of continuing chemical recovery, and summarizes the current status of these lakes with respect to acidity and metal contamination. The biological characteristics of recovering Sudbury lakes and their possible relationships to physical, chemical and biological factors that may influence the lake recovery process are also examined. In this report our focus is on the lakes close (< 30 km) to the smelters that historically were the most severely affected, but information is included on some lakes out to about 100 km from Sudbury.



SudburyLake Wanapitei

Chemical Recovery and Status

Table 1. Time trend analyses (1990 to 2002) of the 44 SES Extensive Lakes using the Mann Kendall Test. Trends are significant at $p < 0.05$.

Parameter	Positive Trend	Negative Trend	No Trend
pH	29 (66%)	0	15 (34%)
Sulphate	0	43 (98%)	1 (2%)
Calcium	0	42 (95%)	2 (5%)
Magnesium	0	39 (89%)	5 (11%)
Sodium	2 (4.5%)	2 (4.5%)	40 (91%)
Potassium	0	31 (70.5%)	13 (29.5%)
Chloride	1 (2%)	2 (5%)	41 (93%)
Copper	0	17 (39%)	27 (61%)
Nickel	0	29 (66%)	15 (24%)
Zinc	0	38 (86%)	6 (14%)
Aluminum	0	33 (75%)	11 (25%)
Manganese	1 (2%)	32 (73%)	11 (25%)
Iron	0	17 (39%)	27 (61%)

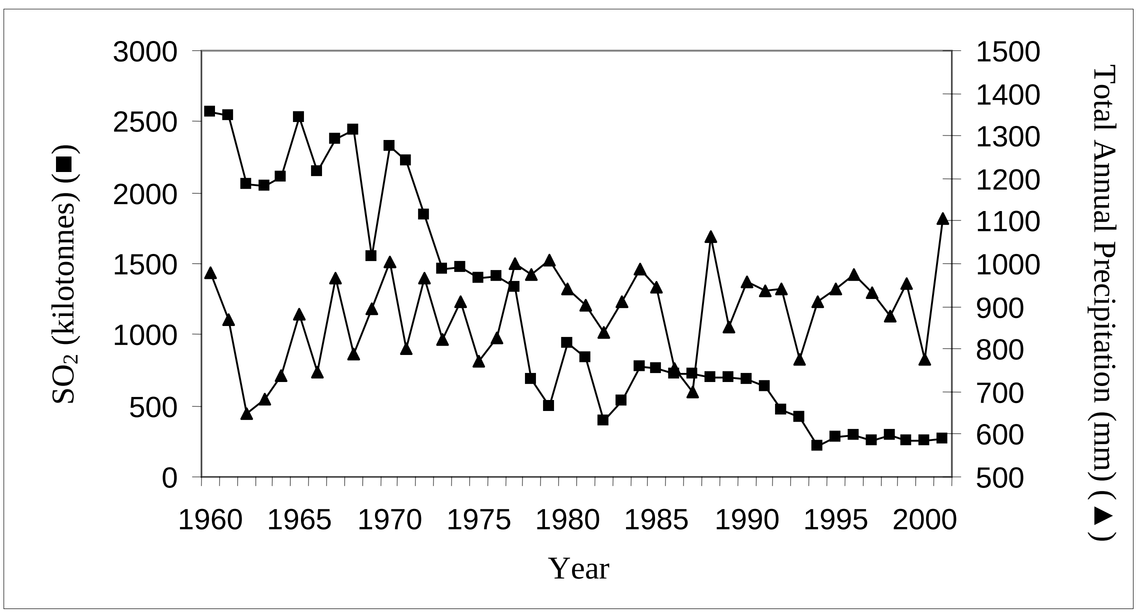
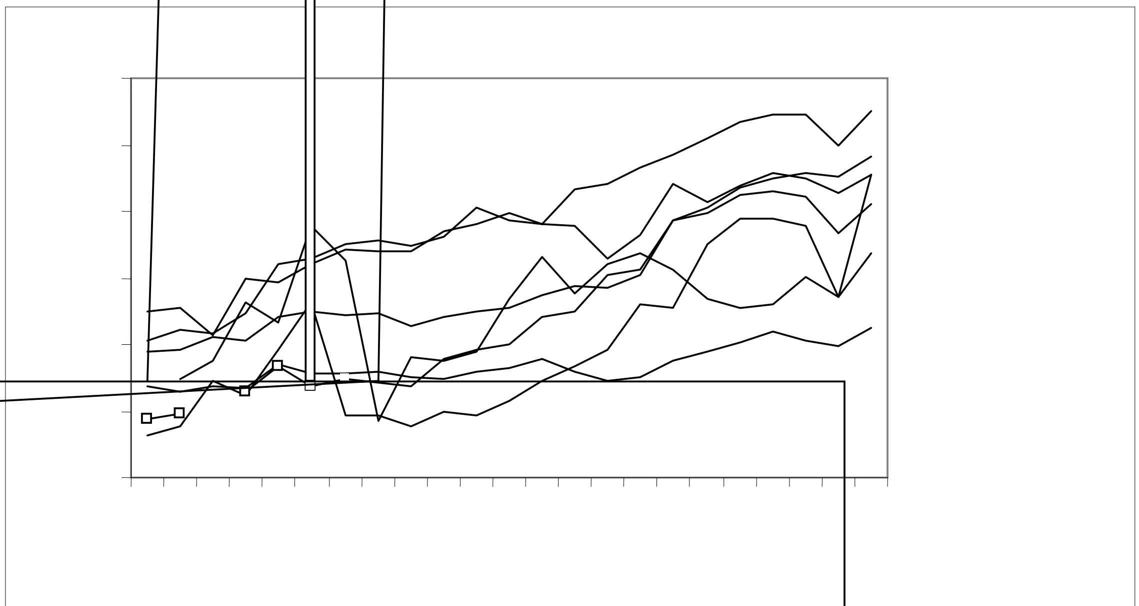


Figure 2. Sulphur dioxide emissions (combined for the Sudbury area smelters) and total annual precipitation.



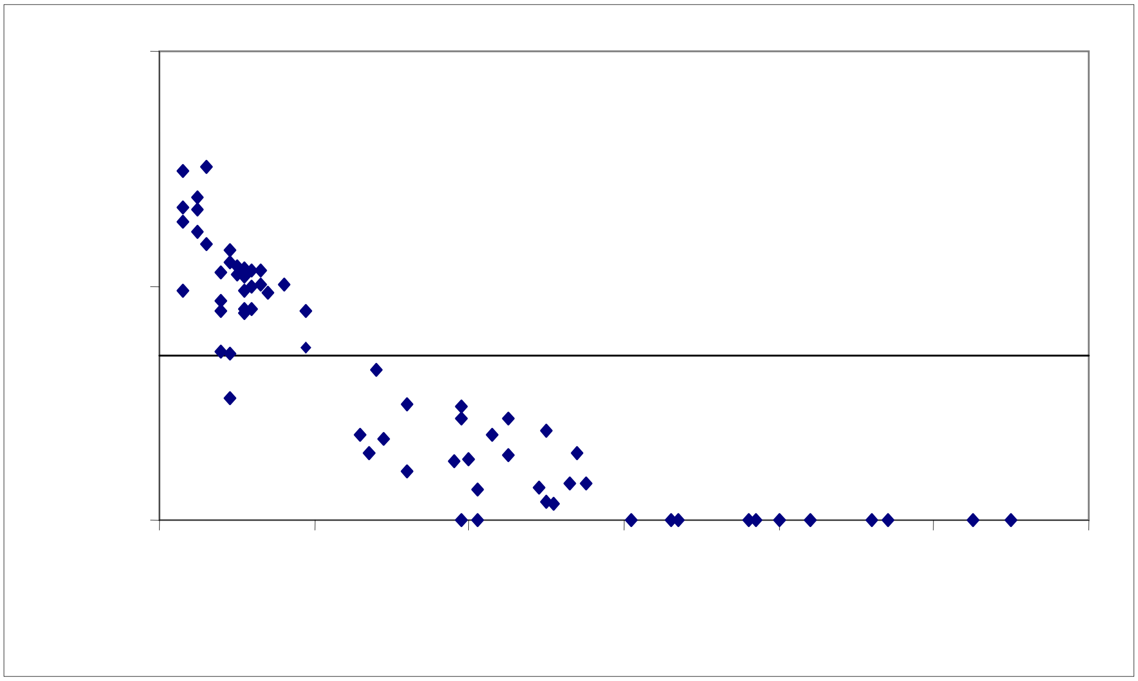
d

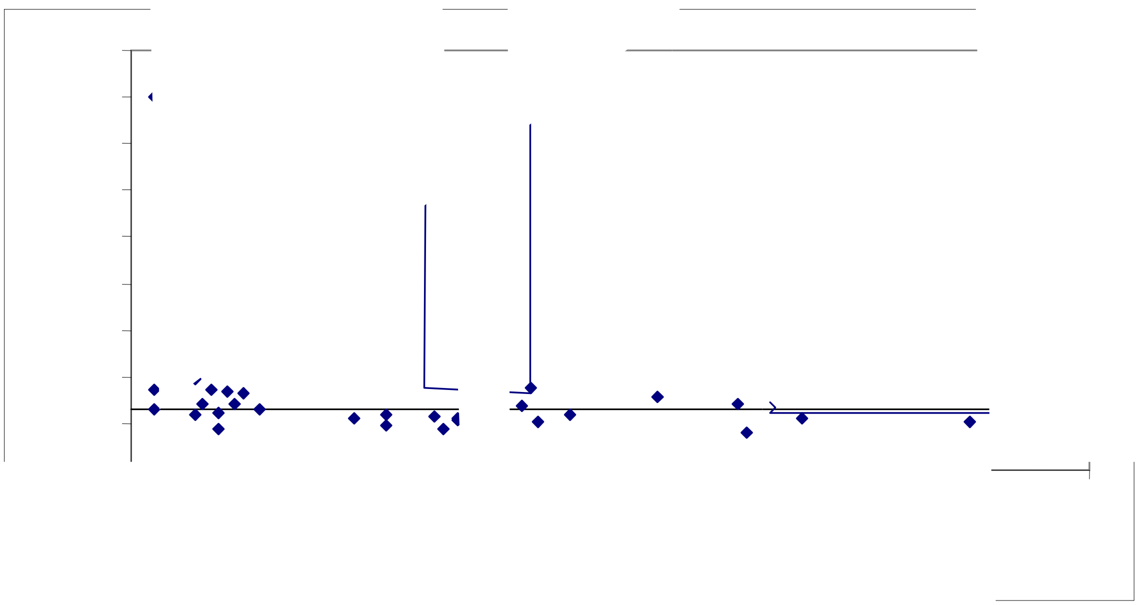
s

Metals

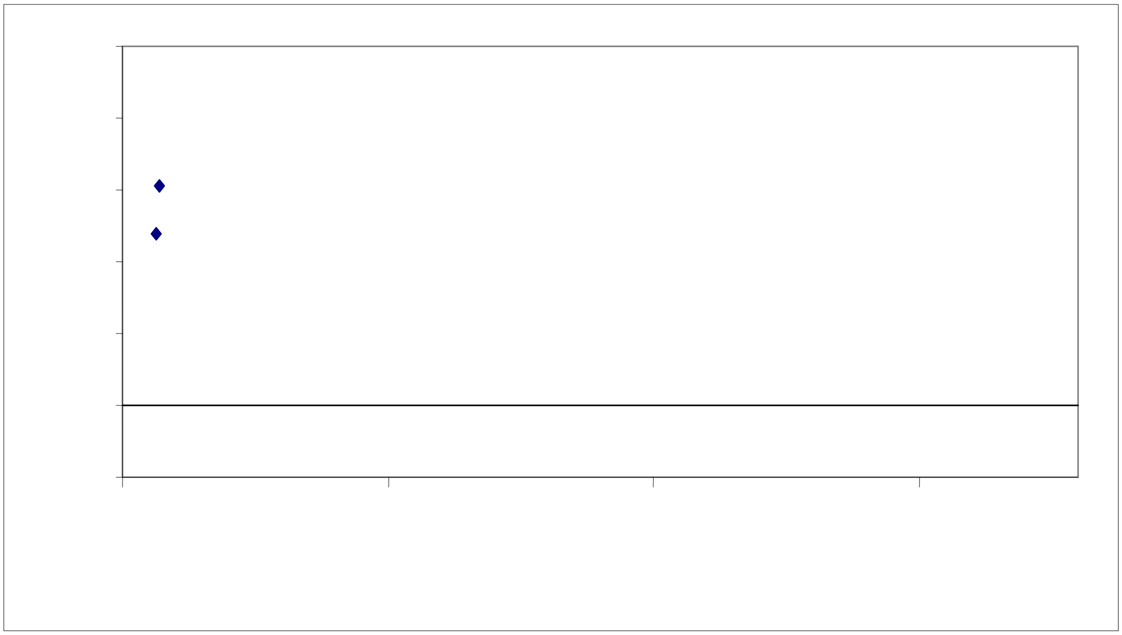
During surveys in the 1970's, elevated concentrations of total copper and nickel were detected in lakewaters extending out to >50 km from Sudbury (Conroy et al., 1978). Reductions in smelter metal emissions have resulted in substantial decreases in lakewater metal concentrations. Reduced concentrations of copper and nickel were first observed in Sudbury area lakes after the emission reductions that were implemented in the late 1970's (Keller & Pitblado, 1986). Some lakes showed evidence of continuing decreases during the 1980's but others showed no clear patterns or even showed metal increases (Figure 5). Evaluation of patterns during the 1980's is, however, complicated by the effects of two years (1982, 1983) of markedly reduced smelter emissions because of production cuts, and a two year (1986-87) drought (Figure 2) that had dramatic effects on lake chemistry, as discussed later.

During the 1990's, reductions in metal concentrations in lakes close to Sudbury were again observed, accompanying the emission reductions resulting from the implementation of the Countdown Acid Rain Program (Figure 5; Table 1). Copper and nickel concentrations exceeding Ontario's Provincial Water Quality Objectives (MOEE, 1994) for the prot





Sediment surveys during the 1970's documented elevated concentrations of copper and nickel extending to >50 km from Sudbury (Semkin & Kramer, 1976; Conroy et al., 1978). Metal contaminated sediments in Sudbury area lakes are still a concern. Comparatively recent (1990's) sediment data (Appendix 2) showed continuing relationships between concentrations of metals including copper, nickel, cobalt and lead in surface sediments and distance from Sudbury. Surface sediments were contaminated with copper and nickel out to ~ 50 km from Sudbury, and sediment copper and nickel concentrations of well over 1000 µg/g occurred in the lakes closest to the smelters (Figure 8). Such values are much higher than the Ontario sediment quality guidelines which consider severe biological effects to potentially occur above 110 µg/g for copper and 75 µg/g for nickel (MOEE, 1993). Concentrations of lead were elevated in some lakes in the Sudbury area, but the relationship to distance from Sudbury was not clearly defined, probably reflecting a general effect of urbanization, not simply an effect of smelter emissions (Figure 9). Lead concentrations in lake sediments often approached, and in one case exceeded, severe effect levels (MOEE, 1993). Cobalt concentrations exceeding open water disposal guidelines (MOEE, 1993) occurred in lakes within about 20 km of Sudbury (Figure 9). Snetsinger (1993) reported concentrations of arsenic exceeding the severe effect guideline (33 µg/g; MOEE, 1993) in some lakes within 20 km. It is important to note, however, that sediment quality guideline levels can be naturally exceeded in northern Ontario lakes for some metals because of geological effects (Painter, 1992; Hunt, 2003).



Factors Affecting Chemical Recovery

Dramatic changes in lake chemistry have accompanied the recent emission reductions at the Sudbury smelters, however, the observed water quality changes can not simply be attributed to the direct effects of pollution controls. Weather patterns can have a profound effect on long term patterns in lake chemistry (Schindler et al., 1990, 1996), as has been observed previously in the Sudbury area (Keller et al., 1992a). Drought results in oxidation of reduced sulphur stored in lake catchments from years of elevated atmospheric deposition. Wetlands are particularly important sites for sulphur storage within lake catchments (Dillon & LaZerte, 1992; Dillon et al., 1997). Remobilization of stored acidity when wet conditions resume can lead to lake re-acidification and many related physical and chemical changes including metal mobilization, changes in thermal structure, and increased UV-B penetration (Yan et al., 1996b). Such effects, which can have major impacts on lake biota (Arnott et al., 2001), were observed in Sudbury area lakes following the two-year drought of 1986-87 (Keller et al., 1992a; Yan et al., 1996b). Some of the recent changes in lake chemistry (Figures 3, 4 & 5) may still reflect recovery from this drought-induced acidification event. Recent changes may also, in part, still be a continuation of the general long-term recovery of lakes and watersheds that began decades ago in the Sudbury area.

The general relationship between lakewater sulphate concentrations and distance from Sudbury that has been observed during previous surveys spanning several decades (Keller & Carbone, 1997) is still evident (Figure 10), although sulphate concentrations have declined greatly over the years. This indicates a continuing smelter effect. However, much of this effect may be historical and not due to current smelter emissions. Based on studies in 1978-80, the Sudbury emissions appeared to be a relatively minor contributor to sulphur deposition in the Sudbury area, contributing about 25% (Chan et al., 1984). W

in watersheds are undoubtedly a very important factor in the recovery of severely damaged Sudbury lakes. Lakes and their watersheds are intimately linked (Dillon & Evans, 1995). Thus, in situations of landscape-scale disturbance like some areas around Sudbury, the recovery of terrestrial communities may play an important role in the recovery of aquatic systems. For example, land liming and tree planting programs have had noticeable effects on the water quality of some lakes (Yan et al., 1996a). The respective roles of the above factors on the recent lake recovery trends are not known. However, it is clear that water quality improvements are continuing in response to a combination of these factors.

With time, reduced inputs of metals originating from smelter emissions are also expected to lead to improved sediment quality in Sudbury lakes, although interpretation of any changes in metal profiles is quite complicated (Belzile & Morris, 1995). There is some evidence of improvements in sediment quality (Nriagu & Rao, 1987), but studies are limited. Relatively recent (1996) examination of core profiles in four lakes within 15 km of Sudbury showed apparent declines in copper and nickel concentrations in the uppermost (1 cm) sediments in two of the lakes (Borgmann et al., 1998). The burial of contaminated sediments by cleaner sediments will, however, be a slow process.

Biological Recovery and Status

Much evidence of biological recovery is emerging from lakes in the large zone affected by the Sudbury smelter emissions (Keller & Gunn, 1995; Keller & Yan, 1998; Keller et al., 1999b; Keller et al., 2002; Findlay, 2003; Holt & Yan, 2003; Snucins, 2003). Comparatively few investigations have focused on the severely affected city lakes closest to the smelters. However, there are some encouraging signs of biological recovery even in these lakes.

Fish

The City of Greater Sudbury has over 330 lakes, the vast majority of which support fish communities. Viable sportfish populations, some of them re-introduced in recent decades to lakes from which they had disappeared (Gunn & Keller, 1995), are very positive evidence of improvements. Fortunately, fish in Sudbury lakes also appear to have quite low concentrations of mercury in their flesh, probably because of an antagonistic effect between selenium from smelter emissions and mercury assimilation (Chen et al., 2001). The total number of fish species that occur within the city is approximately 30, consisting mainly of indigenous species, typical of lakes in this region of the Precambrian Shield (Appendix 3). Rainbow smelt (*Osmerus mordax*) an exotic species of marine origin, and largemouth bass (*Micropterus salmoides*) a southern warm water species, are probably the only two current species that were not present when the area was settled at the turn of the last century. However, there have been dramatic changes in species composition within individual lakes in recent decades. Three main changes include:

1) Widespread legal and illegal introduction of several sport fish species (walleye (*Sander vitreus*), lake trout (*Salvelinus namaycush*), brook trout (*Salvelinus fontinalis*), and smallmouth bass (*Micropterus dolomieu*)), and other species introductions including rock bass (*Ambloplites rupestris),* -d0Ppkinsed [()]TJ/TT2 1 Tf0.0403 Tc 0.11847Tw 6.203 0 Td(MLe

Walleye is probably the most sought after sport fish in the Sudbury area, and walleye populations exist in about 30 of the city lakes. Many of the current populations were established

The phytoplankton community of Clearwater Lake, one of the most highly affected Sudbury lakes in the 1970's, has now become similar to communities of near-neutral, more pristine lakes on the Precambrian Shield (Winter et al., 2004). The crustacean zooplankton community of Clearwater Lake has also shown recovery but is not yet similar to communities in non-acidic reference lakes (Yan et al., 2004a). Changes in fish communities may be having significant effects on invertebrate communities in Clearwater Lake and other area lakes as fish populations become established. Clearwater Lake was fishless for over 50 years. Bait species such as fathead minnows (*Pimpephales promelas*), northern redbelly dace (*Phoxinus eos*) and brook sticklebacks (

responsible for sediment toxicity to the amphipod *Hyalella* in Sudbury lakes (Borgmann, 2003). Elevated waterborne metal concentrations are a likely explanation for the lack of recovery of cladoceran zooplankton in Middle Lake, in Sudbury (Yan et al., 2004b).

It is generally felt that while acidification can greatly alter the composition of aquatic communities, the important functional processes of aquatic ecosystems such as productivity and nutrient cycling remain essentially intact (Schindler, 1987). Evidence from some Sudbury lakes indicates that this may not always be the case in lakes subjected to extreme stress. Low species richness appears to still be a general characteristic of many lakes close to Sudbury, which have been subjected to a variety of anthropogenic stresses in addition to high atmospheric contaminant inputs. Many of these lakes still have crustacean zooplankton communities that have fewer species than expected in more pristine, near-neutral lakes (Figure 12; Appendix 5).

The zooplankton species composition of lakes within the core area of the City of Greater Sudbury is also still quite different from communities expected to occur in more natural lakes (Figure 13a). In agreement with the observations of Yan et al. 2004b, copepod assemblages in Sudbury lakes (Figure 13c) appear to be somewhat more typical and show more recovery than cladoceran assemblages (Figure 13 b). This may be attributable to the generally greater sensitivity of cladocerans to metals, in comparison to copepods (Yan et al. 2004b).

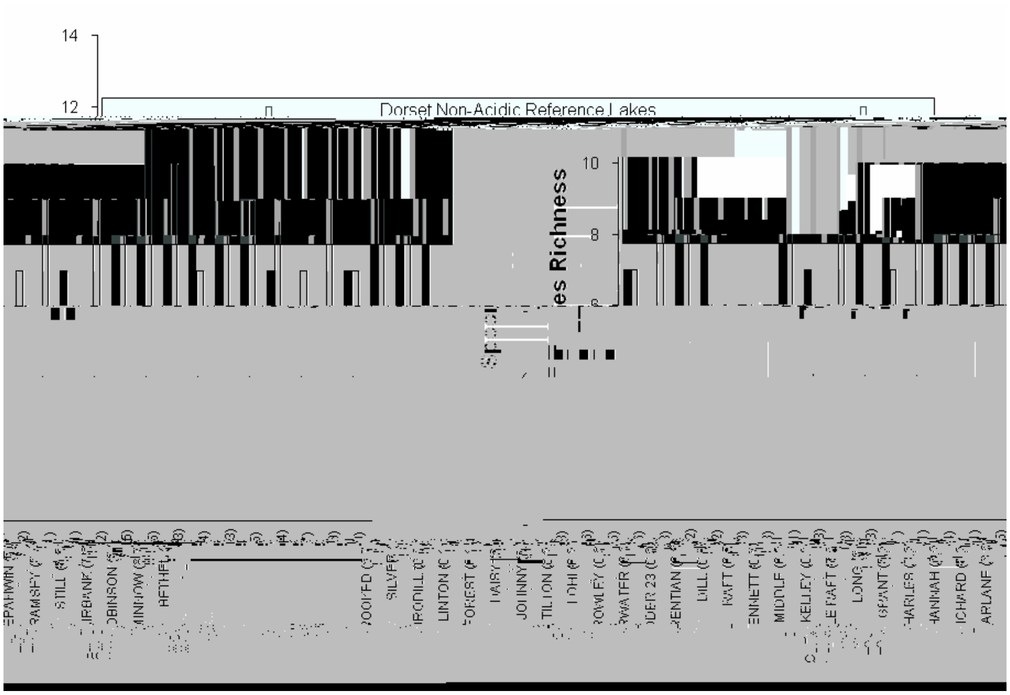
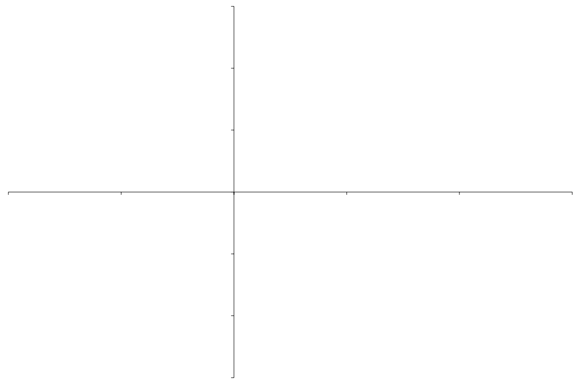
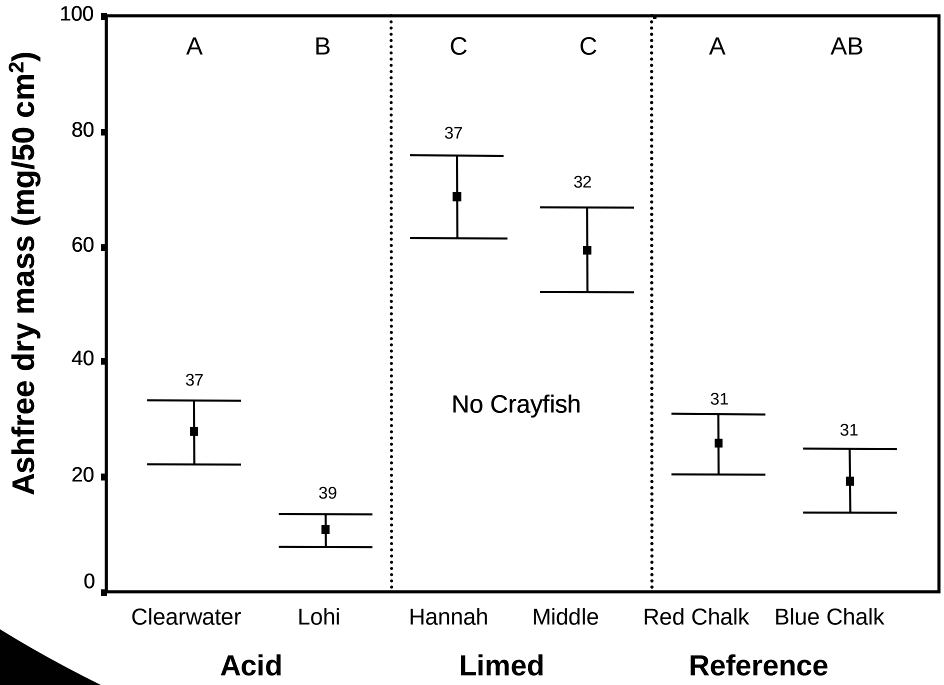


Figure 12. Number of species of crustacean zooplankton collected from Sudbury lakes in 1990 (solid bars) and 2003 (open bars). Lakes were sampled once during summer, at a single deep basin, with a net haul from one m above bottom to surface. Lakes are arranged in order of increasing current pH (indicated in brackets). Species richness (± 2 SD) for 22 near-neutral reference lakes around Dorset, Ontario, about 200 km southwest of Sudbury, is provided for comparison.

Even at near-neutral pH, some Sudbury lakes still exhibit other very unusual biological characteristics, including the absence or extreme scarcity of molluscs, amphipods, mayflies and crayfish, ubiquitous organisms that would be expected to be common in such lakes (Gunn & Keller, 1995; Heneberry, 1997; Reasbeck, 1997; Borgmann et al., 1998). Grazers such as these play an important role in energy transfer and their absence or scarcity may have important implications for nutrient cycling in Sudbury lakes. For example, Middle and Hannah lakes, which were experimentally neutralized in the 1970's and have since maintained near-neutral pH (Yan et al., 1996c), have unusual, extensive benthic growths of filamentous algae (Heneberry, 1997) which



appear to be related to the absence of large grazers, particularly crayfish (Figure 14). In turn, impaired energy transfer through lower trophic levels may be a factor causing low fish biomass in these lakes (Wright, 1995). As well, a scarcity of large invertebrate prey may greatly directly affect the growth of fish such as yellow perch in Sudbury lakes, resulting in populations comprised mainly of stunted individuals (Iles, 2003).The relative roles on fish growth of physiological stress from elevated body burdens of some metals and the indirect effects of metals on food availability are, however, not yet completely understood (Sherwood et al., 2000; Audet & Couture, 2002; Sherwood et al., 2002; Rajotte & Couture 2003).



Conclusions

Smelter emission reductions in the Sudbury area have resulted in substantial improvements in the water quality of area lakes. Evaluation of the di

Acknowledgements

This report is a contribution from the Aquatic Restoration Group of the Cooperative Freshwater Ecology Unit, a partnership between Laurentian University, the Ontario Ministry of the Environment, the Ontario Ministry of Natural Resources, Inco Limited, Falconbridge Limited, and Environment Canada.

References

Appelberg, M., H.M. Berger, T. Hesthagen, E. Kleiven, M. Kurkilahti, J. Raitaniemi & M. Rask, 1995. Development and intercalibration of methods in Nordic freshwater fish monitoring. Water Air Soil Pollut. 85 : 401-406.

Arnott, S.E., N. Yan, W. Keller & K. Nicholls, 2001. The influence of drought-induced acidification on the recovery of plankton in Swan Lake (Canada). Ecol. Applicat. 11: 747-763.

Audet, D. & P. Couture, 2003. Seasonal variations in tissue metabolic capacities of yellow perch (*Perca flavescens*) from clean and metal-contaminated environments. Can. J. Fish. Aquat. Sci. 60:269-278.

Belzile, N. & J.R. Morris, 1995. Lake sediments: sources or sinks of industrially mobilized elements. In: J.M. Gunn (ed.), Restoration and Recovery of an Industrial Region. Springer Verlag, New York: 183-193.

Bodo, B.A. & P.J. Dillon, 1994. De-acidification trends in Clearwater Lake near Sudbury, Ontario, 1973-1992. In K. W. Hippel et al. (eds.): Proc. Stochastic and Statistical Methods in Hydrology and Environmental Engineering. Kluwer Academic, Dordrecht, the Netherlands: 285-298.

Dillon, P.J. & H.E. Evans, 1995. Catchment management in the industrial landscape. In: J. M. Gunn (ed.), Restoration and Recovery of an Industrial Region. Springer Verlag, New York: 313-323.

Dillon, P.J., L. A. Molot & M. Futter, 1997. The effect of El Nino related drought on the recovery of acidified lakes. Environ. Monitor. Assess. 46: 105-111.

Findlay, D.L., 2003. Response of phytoplankton communities to acidification and recovery in Killarney Park and the Experimental Lakes Area, Ontario. Ambio 32: 190-195.

Girard, R., N.D. Yan, J. Heneberry & W. Keller, 2003. Physical and chemical data series from Clearwater, Lohi, Middle and Hannah lakes near Sudbury Ontario: long term responses to liming and natural recovery from historical acidification and metal contamination. Unpublished Data Report.

Gunn, J.M. & W. Keller, 1990. Biological recovery of an acid lake following reductions in industrial emissions of sulphur. Nature 345: 431-433.

Gunn, J.M. & W. Keller, 1995. Urban lakes: integrators of environmental damage and recovery. In: J. M. Gunn (ed.), Restoration and Recovery of an Industrial Region. Springer Verlag, New York: 257-269.

Gunn, J.M., 1996. Restoring the smelter-damaged landscape near Sudbury, Canada. Restorat. Manage. Notes 14.2: 129-136.

Gunn, J.M. & K.H. Mills, 1998. The potential for restoration of acid-damaged lake trout lakes. Restoration Ecology 6: 390-397.

Hamed, K.H. & A.R. Rao, 1998. A modified Mann-Kendall test for autocorrelated data. J. Hydrol.

204: 182-196.

Havas, M., D.G. Woodfine, P. Lutz, K. Yung, H.J. MacIsaac & T.C. Hutchinson, 1995. Biological recovery of two previously acidified, metal-contaminated lakes near Sudbury, Ontario, Canada. Water Air Soil Pollut. 85: 791-796.

Heneberry, J.H., 1997.

Keller, W., S.S. Dixit & and J. Heneberry. 2001a. Calcium declines in northeastern Ontario lakes. Can. J. Fish. Aquat. Sci. 58: 2011-2020.

Keller, W., P. J. Dillon, J. Heneberry, M. Malette & J. Gunn. 2001b. Sulphate in Sudbury, Ontario, Canada lakes: recent trends and status. Water Air Soil Pollut. 130: 793-798.

Keller, W., J. Heneberry, M. Malette, J. Binks & J. Gunn, 2001c. Data report: extensive monitoring of acidified lakes in the Sudbury area, 1981-2000. Cooperative Freshwater Ecology Unit Report. Sudbury, Ontario, 152 p.

Keller, W., N. D. Yan, K. M. Somers & J. H. Heneberry, 2002. Crustacean zooplankton communities in lakes recovering from acidification. Can. J. Fish. Aquat. Sci. 59: 726-735.

Keller, W., J.H. Heneberry & S.S. Dixit, 2003. Decreased acid deposition and the chemical recovery of Killarney, Ontario, lakes. Ambio 32: 183-189.

Matuszek, J. E., J. Goodier & D. L. Wales, 1990. The occurrence of cyprinidae and other small fish species in relation to pH in Ontario lakes. Trans. Amer. Fish. Soc. 119: 850-861.

MOEE (Ministry of Environment and Energy), 1993. Guidelines for the protection and management of aquatic sediment quality in Ontario. Tech. Rep. Ontario Ministry of Environment and Energy, Toronto, Ontario, Canada, 24 pp.

MOEE (Ministry of Environment and Energy), 1994. Water management policies, guidelines, provincial water quality objectives. Tech. Rep. Ontario Ministry of Environment and Energy, Toronto, Ontario, Canada, 31 pp.

Neary, B. P., P. J. Dillon, J. R. Munro & B. J. Clark, 1990. The acidification of Ontario lakes: an assessment of their sensitivity and current status with respect to biological damage. Tech.

Rep. Ontario Ministry of Environment, Dorset, Ontario, Canada, 171 pp.

NIVA (Norwegian Institute for Water Research), 1997.

(*Perca flavescens*). Can. J. Fish. Aquat. Sci. 59:1296-1304.

Reasbeck, J.A., 1997. Changes in benthic macroinvertebrate community structure in acid and metal contaminated lakes following water quality improvements. M. Sc. Thesis, Laurentian University, Sudbury, Ontario, Canada.

Schindler, D.W., 1987. Detecting ecosystem responses to anthropogenic stress. Can. J. Fish. Aquat. Sci. 44 (Suppl.1):6-25.

Schindler, D.W., K.G. Beatty, E.J. Fee, D.R. Cruikshank, E.R. DeBruyn, D.L. Findlay, G.A. Lindsey, J.A. Shearer, M.P. Stainton & M.A. Turner, 1990. Effects of climatic warming on lakes of the central boreal forest. Science 250: 967-970.

Schindler, D.W., P.J. Curtis, B.R. Parker & M.P. Stainton, 1996. Consequences of climate warming and lake acidification for UV-B penetration in North American boreal lakes. Nature 379: 705-708.

Semkin, R. & J.R. Kramer, 1976. Sediment geochemistry of Sudbury area lakes. Can. Mineralogist 14: 73-90.

Sherwood, G.D., J.B. Rasmussen, D.J.

Snetsinger, R., 1993. Historic metal contamination of Sudbury area lake sediments. M. Sc. Thesis, Queens University, Kingston, ON.

Snucins, E., 2003. Recolonization of acid damaged lakes by the benthic invertebrates *Stenacron interpunctatum, Stenonema femoratum,* and *Hyalella azteca.* Ambio 32: 225-229.

Snucins, E. and J.M. Gunn, 2003. Use of rehabilitation experiments to understand the recovery dynamics of acid-stressed fish populations. Ambio 32: 240-243.

Watson, G., 1992. Factors affecting the distribution of the freshwater amphipod (*Hyalella azteca*) in Sudbury area lakes. B. Sc. Thesis, Laurentian University, Sudbury, Ontario, Canada.

Watson, G., C. Hunt & W. Keller, 1999. Natural and enhanced aquatic ecosystem development at Inco's former Garson 10.2 open pit mine. p. 419-428, In D. Goldsack, N. Belzile, P. Yearwood, and G. Hall(eds.) Proc. Mining and the Environment II, Sudbury, Ontario.

Winter, J.G., W. Keller, A.M. Paterson, K.M. Somers & N.D. Yan, 2004. Monitoring biological recovery of Clearwater Lake from acid and metal contamination using phytoplankton community composition (Brief submitted for inclusion in the 2004 National Acid Rain Assessment Report).

Wright, E.M., 1995. Assessment of temporal changes in yellow perch (*Perca flavescens* (Mitchill)) biomass as evidence of recovery of acid and metal stressed lakes near Sudbury, Ontario. M. Sc. Thesis, Laurentian University, Sudbury, Ontario, Canada.

Yan, N.D. & P.M. Welbourn, 1990. The impoverishment of aquatic communities by smelter activities near Sudbury, Canada. In: G. M. Woodwell (ed.), The Earth In Transition - Patterns and Processes of Biotic Impoverishment. Cambridge University Press, New York :

477-494.

Yan, N.D., W. Keller, K.M. Somers, T.W. Pawson & R.G. Girard, 1996a. Recovery of crustacean zooplankton communities from acid and metal contamination: comparing manipulated and reference lakes. Can. J. Fish. Aquat. Sci. 53: 1301- 1327.

Yan, N.D., W. Keller, N.M. Scully, D.R.S. Lean & P.J. Dillon, 1996b. Increased UV-B penetration in a lake owing to drought-induced acidification. Nature 382: 141-143.

Yan, N.D., P.G. Welsh, H. Lin, D.J. Taylor & J.M. Filion, 1996c. Demographic and genetic evidence of the long-term recovery of *Daphnia galeata mendotae* (Crustacea: Daphnidae) in Sudbury lakes following additions of base: the role of metal toxicity, Can. J. Fish. Aquat. Sci. 53: 1328-1344.

Yan, N.D. & W. Keller, 2004a. Promising progress in recovery of the zooplankton in Clearwater Lake (Brief submitted for inclusion in the 2004 National Acid Rain Assessment Report).

Yan, N.D., R. Girard, J. Heneberry, W. Keller, J. Gunn, & P.J. Dillon, 2004b. Recovery of copepod, but not cladoceran, zooplankton from severe and chronic effects of multiple stressors. Ecology Letters 7: 452-460.

Appendices

The following appendix tables contain various chemical and biological data for a number of Sudbury area lakes. The name

Appendix 1- Water Chemistry

Water chemistry data for 31 lakes in the core area of the City of Greater Sudbury in 1990 and 2003. Non-volume-weighted, tygon tube composite

Appendix 1 - Water Chemistry

	Bennett		Bethel		Broder #23		Brodill		Clearwater		Crooked		Crowley		Daisy		Dill	
	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003
pH	6.88	6.74	7.77	9.00	6.04	6.38	5.42	6.05	4.88	6.33	4.43	5.78	5.88	6.31	4.82	6.20	6.57	6.61
Conductivity (µS/cm)	32.6	27.2	401.5	255.0	42.3	29.2	38.9	27.2	80.5	61.0	84.0	54.2	35.2	27.6	55.0	35.4	47.6	37.4
Alkalinity (mg/L)	6.39	6.06	48.40	50.42	2.72	2.45	0.14	0.94	-0.85	1.19	-2.40	1.33	1.69	2.10	-0.88	2.02	3.74	4.46
Ca (mg/L)	3.39	2.44	17.90	13.50	3.24	2.34	2.88	1.94	6.10	4.30	5.20	2.50	3.30	3.28		2.58	3.52	2.84
Mg (mg/L)	1.10	0.85	7.32	5.45	1.16	0.84	1.05	0.75	1.36	1.09	1.60	1.05	0.98	0.76		1.23	1.64	1.29
Na (mg/L)	1.08	0.96	50.90	27.20	0.96	0.94	1.02	0.93	3.14	4.00	1.96	1.94	1.02	0.95		1.09	1.45	1.70
K (mg/L)	0.640	0.395	2.320	1.840	0.600	0.445	0.560	0.420	0.640	0.575	0.770	0.685	0.540	0.435		0.420	0.710	0.545
Cl (mg/L)	<0.8	0.67	92.30	39.23	<0.60	0.36	<0.40	0.43	9.10	8.00	3.30	2.48	<0.60	0.35	<0.70	0.73	1.70	2.59
SO_4 (mg/L)	11.52	3.71	9.28	7.32	11.09	8.10	12.20	8.17	16.74	10.70	23.35	9.55	11.94	7.85	19.08	10.43	10.22	6.54
SiO_3 (mg/L)																		

Appendix 1 - Water Chemistry

	Richard		Robinson		Silver		St. Charles		Still		Tilton	
	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003
pH	7.31	7.25	7.55	7.70	4.32	6.00	7.11	7.22	7.83	7.55	5.78	6.28
Conductivity (µS/cm)	187.0	195.0	362.0	389.0	377.0	355.0	210.0	243.0	600.0	605.0	57.0	58.8
Alkalinity (mg/L)	17.61	21.85	29.85	34.36	-2.90	0.87	7.66	14.70	31.83	38.43	0.84	2.63
Ca (mg/L)		8.46	17.40	15.80	9.00	7.34	10.60	9.24	20.50	18.00	4.83	3.50
Mg (mg/L)		2.81	5.66	5.22	3.22	2.74	3.94	3.38	6.11	5.84	1.22	0.97
Na (mg/L)		24.50	42.10	78.80	42.60	54.60	19.50	29.10	92.20	28.00	1.77	2.01
K (mg/L)		0.890	1.970	1.840	1.290	1.750	1.800	1.550	2.060	2.180	0.520	0.460
Cl (mg/L)	31.90	9.70	70.40	88.77	75.10	93.50	34.60	50.08	143.00	158.72	3.60	3.77
SO_4 (mg/L)	15.73	2.50	25.43	17.74	38.07	17.20	29.15	18.13	22.65	15.42	14.06	9.00
SiO_3 (mg/L)		0.24	1.22	0.04	2.18	0.12	0.86	0.32	1.44	0.56	0.74	0.74
Al (µg/L)	<20	6	<30	46	860	14	<60	16	<50	181	<40	17
As (µg/L)		<=0.5		<2.0		<=0.5		<=0.5		<1.5		<=0.5
Ba (µg/L)		17.2		18.6		22.4		19.2		40.7		14.6
Be (µg/L)		<=0.03		<=0.03		<=0.02		<=0.03		<=0.03		<=0.02
Cd (µg/L)		<=0.6		<=1.0		<=1.3		<=1.0		<=1.0		<=0.8
Cr (µg/L)		<=1.0		<=1.0		<=1.0		<=1.0		<=1.0		<=1.0
Co (µg/L)		<=1.5		<=1.5		4.9		<=1.5		<=1.5		<=1.5
Cu (µg/L)	10	8	9	10	320	17	27	21	14	15	14	9
Fe (µg/L)	<=20	53	320	227	<80	90	120	76	130	424	190	75
Mn (µg/L)	42	168	38	39	160	88	50	18	64	100	90	45
Mo (µg/L)		<=0.8		<=1.6		<=1.5		<=1.6		<=1.6		<=1.5
Ni (µg/L)	88	57	60	36	590	105	190	95	72	58	83	50
Pb (µg/L)	<=5	<=11	<=5	<=11	<20	<=11	<=5	<=11	<=5	<=11	<=5	<=11
Se (µg/L)		<=0.5		<=0.5		<=0.5		<=0.5		<=0.5		<=0.5
Sr (µg/L)		31.5		55.6		40.6		42.1		75.0		20.3
Ti (µg/L)		0.96		1.74		0.40		1.48		6.33		<=0.30
V (µg/L)		<=0.9		<=1.5		<=1.0		<=1.5		<=1.5		<=1.0
Zn (µg/L)	<=0.5	3	7	1	79	18	15	6	4	8	11	12
P (µg/L)	2	12	24	35	<3	7	11	8	19	45	<8	7
NH_3+NH_4 (µg/L)	<=2		34	144	30	44	12	44	64	222	22	32
NO_2 (µg/L)	<=1		<3		<3		5		<2		<4	
NO_3+NO_2 (µg/L)	<5		<=5	22	205	<6	25	10	<10	36	<=5	<=2
TKN (µg/L)		250	440	459	130	238	450	296	680	790	220	203
DOC (mg/L)		2.8	4.1	4.7	<0.3	3.4	4.8	4.8	10.8	10.2	2.5	2.6

Appendix 2 - Sediment Chemistry

	CLEARWATER			DAISY			FAIRBANK			GENEVA		
	A	B	C	A	B	C	A	B	C	A	B	C
pH	4.10	4.00	4.00	4.30	4.50	4.50	5.00	4.90	5.30	3.80	3.90	3.80
Loss on ign. (mg/g dry)	198.00	200.00	208.00	134.00	147.00	126.00	107.00	108.00	99.00	211.00	214.00	208.00
Carbon, Total Organic (mg/g dry)	96.00	97.00	100.00	60.00	67.00	61.00	41.00	45.00	41.00	110.00	110.00	110.00
Aluminum (µg/g dry)	18000.00	18000.00	18000.00	25000.00	25000.00	24000.00	13000.00	13000.00	15000.00	12000.00	12000.00	12000.00
Barium (µg/g dry)	78.00	75.00	80.00	110.00	85.00	85.00	740.00	560.00	590.00	61.00	63.00	63.00
Beryllium (µg/g dry)	<0.71	<0.84	<0.68	<0.81	<0.61	<0.7	<0.62	<0.66	<0.69	<0.8	<0.82	<0.8
Cadmium (µg/g dry)	7.70	7.20	4.70	1.70	1.10	1.10	5.80	5.80	5.20	3.00	2.70	2.90
Chromium (µg/g dry)	53.00	51.00	52.00	69.00	66.00	64.00	33.00	35.00	40.00	30.00	30.00	29.00
Cobalt (µg/g dry)	80.00	88.00	61.00	45.00	45.00	43.00	23.00	22.00	22.00	18.00	21.00	19.00
Copper (µg/g dry)	1900.00	1800.00	1600.00	670.00	730.00	760.00	280.00	260.00	250.00	79.00	89.00	79.00
Iron (µg/g dry)	21000.00	26000.00	23000.00	29000.00	31000.00	39000.00	46000.01	69000.02	45000.01	24000.00	26000.00	25000.00
Lead (µg/g dry)	150.00	150.00	150.00	57.00	64.00	73.00	150.00	140.00	150.00	99.00	110.00	110.00
Manganese (µg/g dry)	130.00	140.00	150.00	230.00	180.00	190.00	69000.00	38000.00	34000.00	440.00	460.00	450.00
Molybdenum (µg/g dry)	<2.5	<2.4	<2.2	<=0.5	<0.85	<0.74	34.00	25.00	20.00	<1.1	<1.4	<0.85
Nickel (µg/g dry)	2100.00	2300.00	1700.00	1200.00	1300.00	1100.00	350.00	320.00	310.00	95.00	110.00	96.00
Strontium (µg/g dry)	20.00	20.00	21.00	27.00	23.00	23.00	43.00	36.00	39.00	25.00	24.00	23.00
Titanium (µg/g dry)	440.00	450.00	430.00	670.00	640.00	610.00	390.00	390.00	510.00	660.00	610.00	600.00
Vanadium (µg/g dry)	39.00	40.00	40.00	45.00	46.00	44.00	41.00	46.00	49.00	41.00	41.00	42.00
Zinc (µg/g dry)	330.00	350.00	200.00	120.00	85.00	89.00	270.00	260.00	260.00	140.00	150.00	160.00

Appendix 2 - Sediment Chemistry

pH

Appendix 2 - Sediment Chemistry

	RAMSEY			TYSON			WHITSON		
	A	B	C	A	B	C	A	B	C
pH	4.40	4.40	4.50	4.40	4.40	4.10	4.70	4.70	4.80
Loss on ign. (mg/g dry)	82.00	86.10	88.30	195.00	207.00	196.00	210.00	133.00	140.00
Carbon, Total Organic (mg/g dry)	48.00	48.00	45.00	95.00	95.00	90.00	97.00	60.00	63.00
Aluminum (µg/g dry)	19000.00	20000.00	21000.00	23000.00	23000.00	24000.00	17000.00	15000.00	15000.00
Barium (µg/g dry)	69.00	51.00	140.00	150.00	110.00	140.00	84.00	66.00	66.00
Beryllium (µg/g dry)	<0.75	<0.79	<0.81	<1.4	<1.4	<1.5	<0.63	<0.52	<0.52
Cadmium (µg/g dry)	7.30	8.50	6.40	4.10	3.70	4.00	2.80	2.20	2.30
Chromium (µg/g dry)	62.00	70.00	76.00	45.00	44.00	47.00	49.00	46.00	44.00
Cobalt (µg/g dry)	160.00	190.00	160.00	33.00	45.00	33.00	48.00	53.00	57.00
Copper (µg/g dry)	2900.00	3200.00	2700.00	200.00	180.00	220.00	1100.00	760.00	780.00
Iron (µg/g dry)	43000.01	47000.01	44000.01	64000.01	73000.02	59000.01	52000.01	43000.01	46000.01
Lead (µg/g dry)	240.00	270.00	220.00	150.00	140.00	150.00	160.00	120.00	130.00
Manganese (µg/g dry)	430.00	420.00	420.00	1600.00	2200.00	840.00	250.00	410.00	500.00
Molybdenum (µg/g dry)	<1.5	<1.2	<1	<1.5	<2	<1.6	<0.93	<0.75	<0.72
Nickel (µg/g dry)	4100.00	4900.00	3900.00	280.00	270.00	300.00	1400.00	1100.00	1100.00
Strontium (µg/g dry)	32.00	33.00	38.00	29.00	29.00	29.00	32.00	26.00	26.00
Titanium (µg/g dry)	710.00	750.00	840.00	560.00	540.00	590.00	440.00	530.00	500.00
Vanadium (µg/g dry)	52.00	54.00	57.00	65.00	65.00	64.00	47.00	42.00	42.00
Zinc (µg/g dry)	400.00	460.00	360.00	230.00	200.00	230.00	130.00	110.00	110.00

Appendix 3 - Fish Species

	Ashigami	Bear	Caswell	Clearwater	Fairbank	Fraleck	Hannah	Kukagami	Lac St. Jean (Massey)	Little Panache	Long	Matagamasi	McFarlane	Nelson	Ramsey	Vermilion	Whitson
Surface Area (ha)	482	683	35	77	703	174	378	1900	77	131	861	1393	141	316	874	1079	437
Survey Year	2003	2003	2002	2003	2003	2003	2003	2003	2003	2003	2003	2000	2003	2000	2003	2003	2003
Number of Species	8	21	0	4	16	6	4	10	5	12	12	10	12	8	8	13	6
Blacknose dace - *Rhinichthys atratulus*		x															
Bluegill - *Lepomis macrochirus*		x															
Bluntnose minnow - *Pimephales notatus*		x			x					x							
Brown bullhead - *Ameiurus nebulosus*	x	x					x	x	x	x	x	x	x		x	x	x
Burbot - *Lota lota*		x						x						x			
Cisco (lake herring) - *Coregonus artedi*		x			x					x	x		x			x	
Common shiner - *Luxilus cornutus*	x	x									x		x	x		x	
Fathead minnow - *Pimephales promelas*				x													
Golden shiner - *Notemigonus crysoleucas*												x		x			
Iowa darter - *Etheostoma exile*					x		x										
Lake chub - *Couesius plumbeus*														x			
Lake trout - *Salvelinus namaycush*		x			x	x		x			x	x		x			
Lake whitefish - *Coregonus clupeaformis*		x			x			x									
Largemouth bass - *Micropterus salmoides*													x				
Logperch - *Percina caprodes*	x	x			x						x		x			x	
Mottled sculpin - *Cottus bairdi*		x															
Ninespine stickleback - *Pungitius pungitius*					x												
Northern pike - *Esox lucius*		x			x				x	x	x	x	x		x	x	x
Pearl dace - *Margariscus margarita*								x									
Pumpkinseed - *Lepomis gibbosus*		x		x	x	x				x	x		x		x	x	x
Rainbow smelt - *Osmerus mordax*		x								x							
Rock bass - *Ambloplites rupestris*	x	x			x			x		x		x			x	x	
Slimy sculpin - *Cottus cognatus*		x								x							
Smallmouth bass - *Micropterus dolomieu*	x	x		x	x	x		x		x	x	x	x	x	x	x	
Spoonhead sculpin - *Cottus ricei*					x												
Spottail shiner - *x*																	

Appendix 4 - Walleye Harvest Statistics

Lake	Fis

Appendix 5 - Zooplankton Species

Species Names	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003
Acanthocyclops vernalis									*		x																							
Alona sp.		x																										*						
Bosmina sp.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	*	x	x	x	x
Ceriodaphnia sp.			*															*					x		x							x		
Chydorus sphaericus			*	x					*	*			*			x									x			x						
Cyclops scutifer																								x										
Daphnia ambigua			x										x															*						
Daphnia pulex													*												*			x	x	x	*			
Daphnia retrocurva			x				x	x			*						x	x	*	x			*		*						*			
Daphnia mendotae			x		*				*		x		x						x	x			x	x	x	x	*						*	
Daphnia sp.																	x																	
Diacyclops bicuspidatus thomasi						x	x	x	*											x				x					x	x				
Diaphanosoma birgei	x	x		x	*	x	*	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	*	x	x	x			x	*	*	x
Epischura lacustris																			*					x										
Eubosmina longispina																																		

Appendix 5 - Zooplankton Species

Species Names	LITTLE RAFT		LOHI		LONG		MCFARLANE		MIDD6-0.0031 Tc 9009 TD[LO]10(H)1																					
	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003	1990	2003
Acanthocyclops vernalis																			*				*							
Alona sp.												x																		
Bosmina sp.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x		x	x	x	x	x	x	x	x
Ceriodaphnia sp.		x									x	x								x	x	x				x		x		
Chydorus sphaericus		*		x		*						x							x		x	x	x		x	x		x		
Cyclops scutifer						x									x	x												*		
Daphnia ambigua														x														x		
Daphnia pulex																											*			
Daphnia retrocurva		x			x	x					x		*						*		x	x		*	x	*				
Daphnia mendotae	*				x	x	x	x	x	x	x	*	x	x	x	x	x	x	*	x	x	*		*	x			x	x	
Daphnia sp.																														
Diacyclops bicuspidatus thomasi					x	x	x	x	x	x		*	x	x	x	x	*	x	x			x		x	x					
Diaphanosoma birgei	x	x	x	x	x	x	x	x		x	x	x		*	x	x			x	x	x	x	x	x	x	x	x	x	x	x
Epischura lacustris							*						x	x	*	x	x	x							x					
Eubosmina longispina																													*	
Eucyclops agilis																						x								
Eurycercus lamellatus								*																						
Holopedium glacialis	x	x		x											x	x													x	x
Leptodiatomus minutus	x	x	x	x	x	x	x	x	x	x	*		x	x	x	x	x	x	x	x	x	x			x	x			x	x
Leptodora kindtii																						*								
Macrocyclops albidus																														
Mesocyclops edax		x			x		x	x		*				*		x		x	x	x		x					x	x		
Orthocyclops modestus				x				x																						
Polyphemus pediculus																			*											
Sida crystallina																								x		*				
Skistodiaptomus oregonensis					x		x	x		x	x	*	x				x	x		x	x	x	*		x	x	x	x		
Tropocyclops extensus		x		x			x			x				*					x	x		x		x		x				x
Calanoid copepodid	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x	x	x	x	x	x
Calanoid nauplius	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Cyclopoid copepodid	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Cyclopoid nauplius	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

x = Species present
* = Only one individual detected