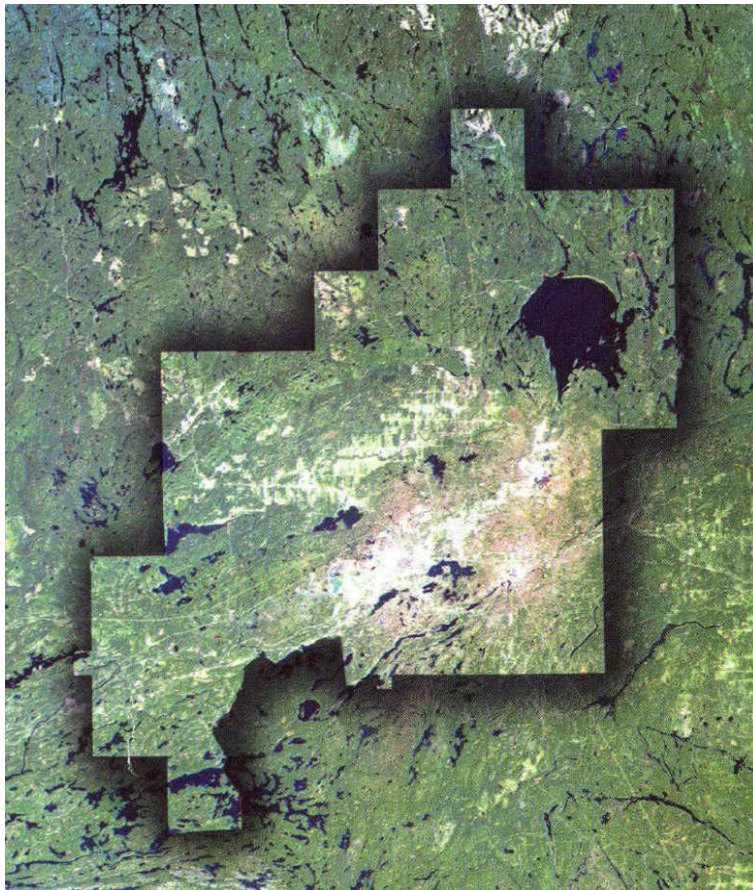


# **Recovery of Acid and Metal - Damaged Lakes Near Sudbury Ontario: Trends and Status**



*Lakes in and around the City of Greater Sudbury*

**Cooperative Freshwater Ecology Unit**

**2004**

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

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**2004**

Prepared for the SARA Group, 64 Baker Street, Guelph, Ontario, N1H 4G1, Supporting Report for the Ecological Risk Assessment, Sudbury Soils Study

## Summary

Lakes in a large area around Sudbury, Ontario, Canada, have been affected by the atmospheric deposition of pollutants from over a century of operations at the Sudbury area metal smelters. The lakes closest to the smelters, which historically received very high deposition of both acid and metal particulates, were the most severely affected. Smelter emissions were greatly reduced in the 1970's, lake water quality began to improve, and some recovery of biological communities was observed. Further reductions in smelter emissions during the 1990's have been accompanied by continuing improvements in aquatic habitat quality, but the evaluation of lake responses to emission controls is complicated by the interaction of lake acidity and metal concentrations with other factors. Weather-related variations in storage and release of sulphur from lake catchments appear to greatly influence patterns of chemical recovery. Despite the dramatic water quality improvements observed to date, some lakes are still acidic and elevated levels of copper, nickel, and other metals persist in the water and sediments of many lakes. Very positive evidence of biological recovery is emerging for many groups of aquatic biota including zooplankton, phytoplankton, benthic invertebrates and fish. However, severely damaged biological communities have often been slow to recover, in part reflecting continuing habitat quality limitations. Future recovery of lakes close to Sudbury from the effects of acidification and metal contamination will also be influenced by the effects of other local (eg. urbanization), regional (eg. arrival of invasive species) and global (eg. climate change) factors. Continuing studies of recovery within a multiple stressor framework are needed.

## **Introduction**

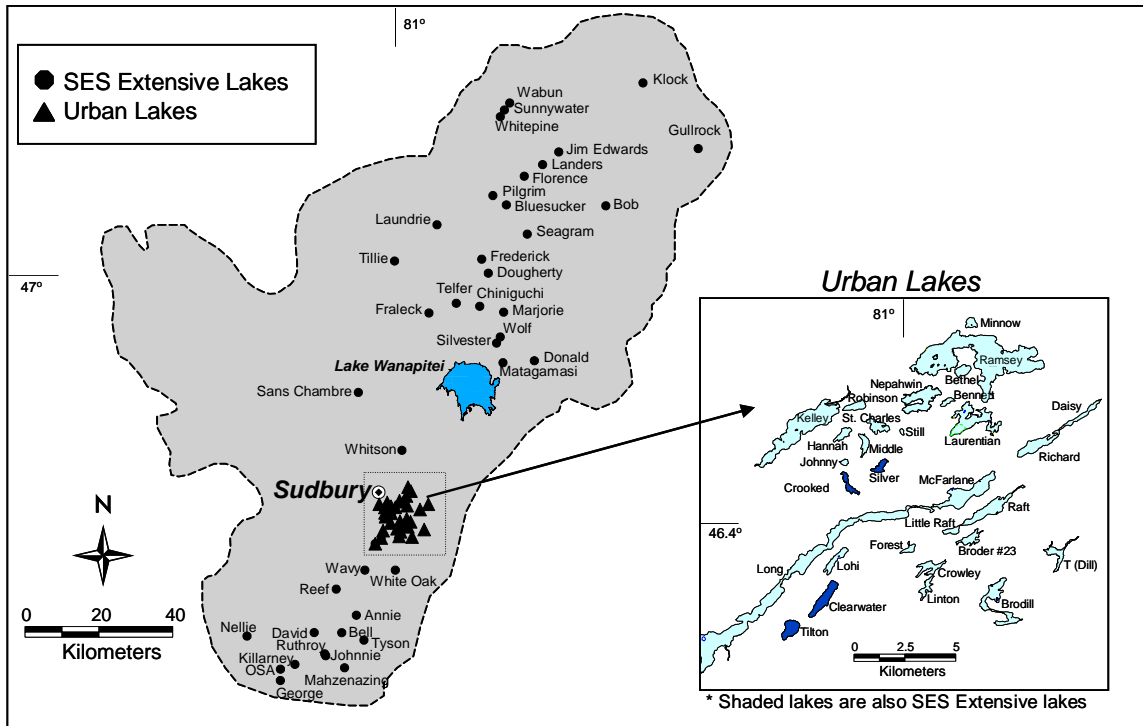
Metal mining and smelting began in the Sudbury, Ontario, Canada, area before the turn of the 20<sup>th</sup> century. The Sudbury area subsequently grew into one of the largest metal-producing complexes in the world. Smelter emissions peaked during the 1960's, when the Sudbury area smelters constituted one of the world's largest point sources of SO<sub>2</sub> 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<sup>2</sup> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions were achieved by 1994 (Figure 2) as part of Ontario's Countdown Acid Rain Program. Further decreases in metal emissions accompanied these SO<sub>2</sub> emission reductions. Overall, reductions in SO<sub>2</sub> 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.



**Figure 1.** The zone of lakes affected by the Sudbury smelters (Neary et al., 1990). This 17,000 km<sup>2</sup> zone contains over 7,000 lakes estimated to have been acidified to pH <6.0, the apparent threshold for significant biological damage. The locations of lakes sampled under two of the main monitoring programs providing the data used in this report, the SES Extensive Monitoring Program (1981-present), and the Sudbury Urban Lakes Study (1990, 2003), are indicated.

## **Chemical Recovery and Status**

### **Acidity, Sulphate, Base Cations**

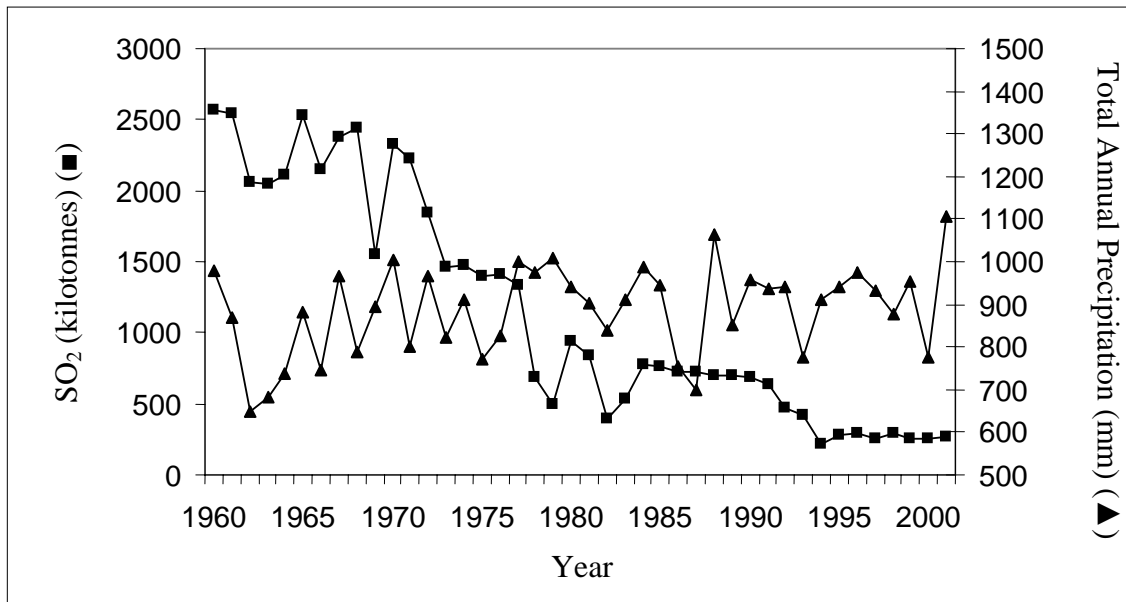
Large changes in water quality followed the reductions of sulphur emissions that occurred during the 1970's. Chemistry changes included increased pH and alkalinity and decreased concentrations of sulphate and base cations (Keller & Pitblado, 1986; Gunn & Keller, 1990; Keller et al., 1992a; Keller et al., 1999a; Keller et al., 2001a; Keller et al., 2001b; Keller et al., 2003).

Changes continued during the 1990's, which spanned the implementation of the recent Countdown Acid Rain Program. Annual monitoring has been conducted since 1981 on 44 lakes within about 100 km of Sudbury (Keller et al., 2001c). Time trend analyses of this data set were conducted with the Mann Kendall test (Hamed & Rao, 1998), a conservative procedure, for the period 1990 to 2002. Dominant trends (Table 1) included increased pH (66% of the lakes), and decreased concentrations of sulphate, calcium and magnesium (98, 95, and 89% of the lakes, respectively).

There was much between-lake variability in temporal chemistry patterns, as shown for seven study lakes within 30 km of Sudbury in Figures 3 & 4. However, these lakes showed evidence of continuing declines in acidity, decreased sulphate, and decreased base cations between 1990 and 2003. The overall water quality changes in some of these lakes have been quite remarkable. For example, Clearwater Lake, which was highly acidic (pH ~ 4) in the 1970's (Dillon et al., 1986), is now over pH 6 (Figure 3).

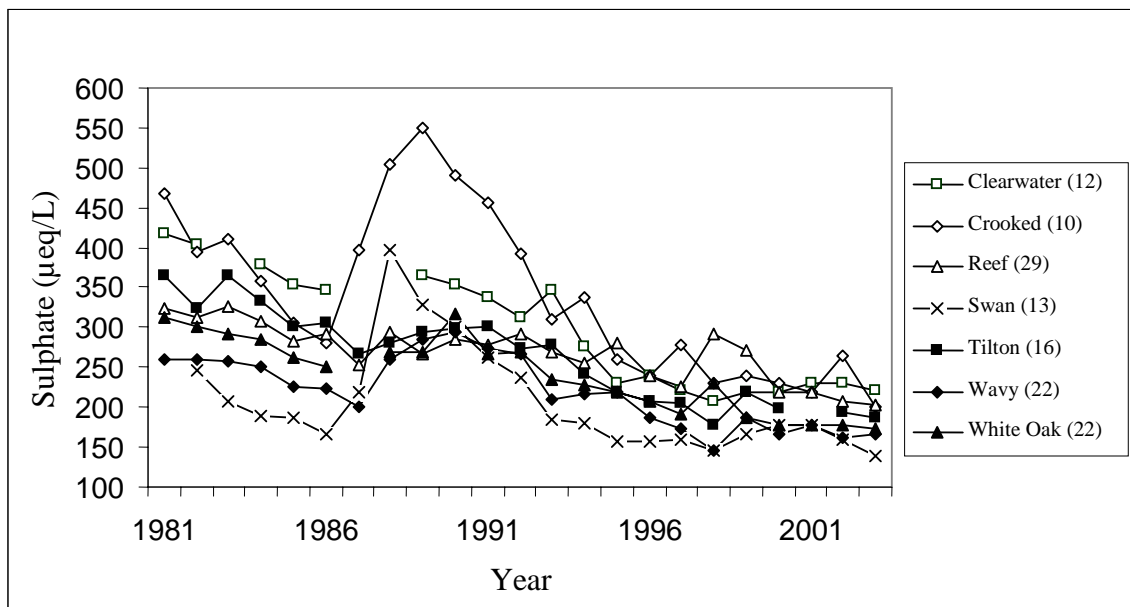
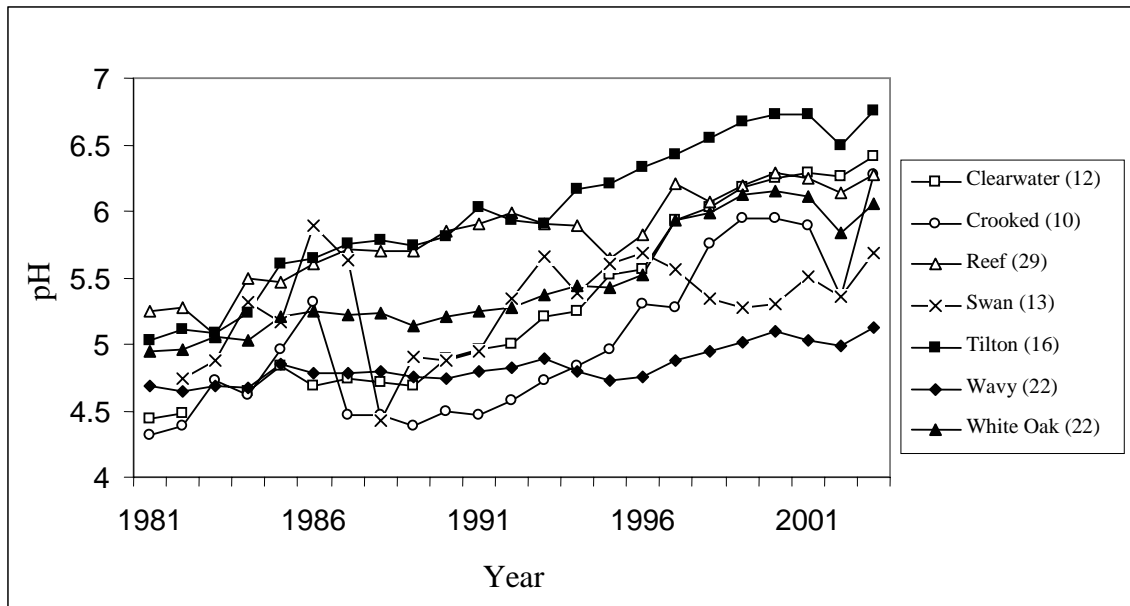
**Table 1.** Time trend analyses (1990 to 2002) of the 44 SES Extensive Lakes using the Mann Kendall Test. Trends are significant at  $p < 0.05$ .

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%)

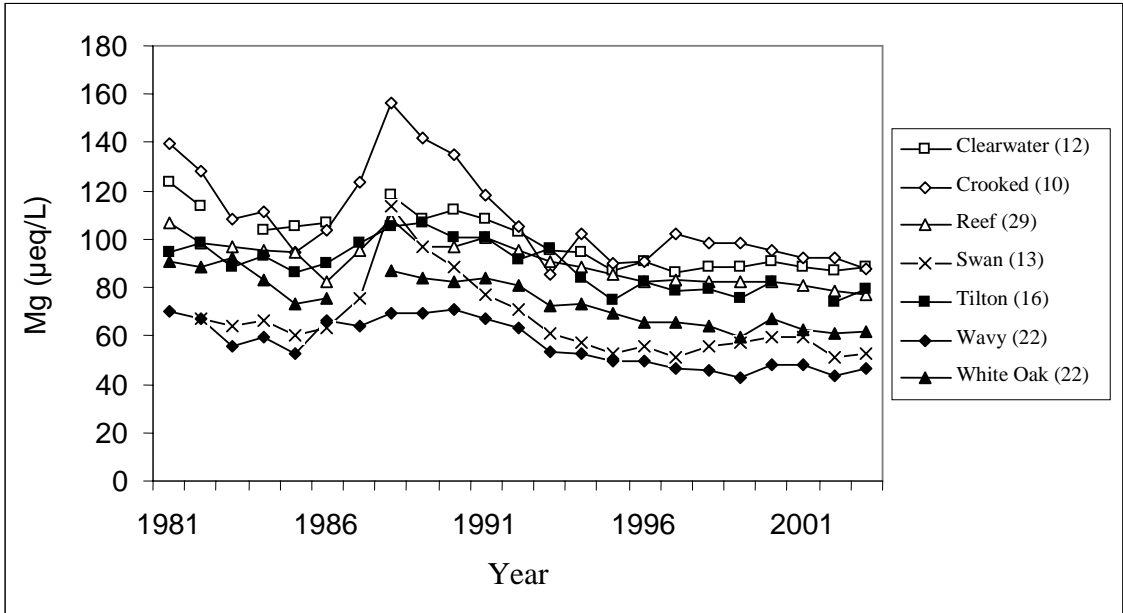
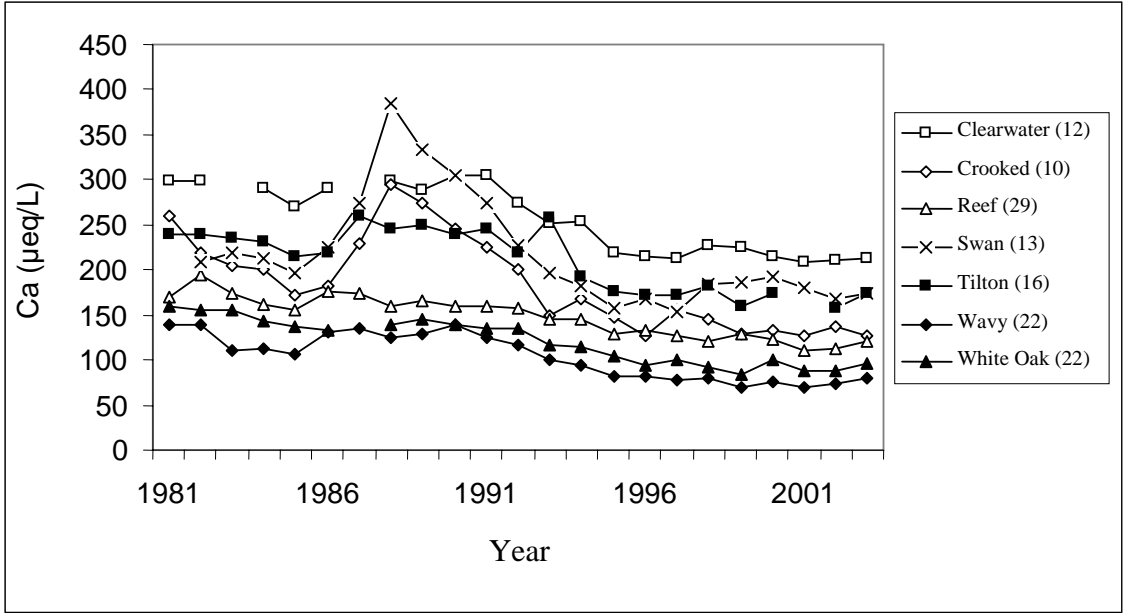


**Figure 2.** Sulphur dioxide emissions (combined for the Sudbury area smelters) and total annual precipitation.





**Figure 3.** Patterns of pH and sulphate concentrations in seven lakes within 30 km of Sudbury during the period 1981-2003. Numbers in brackets beside the lake names indicate the distance (km) from Sudbury.

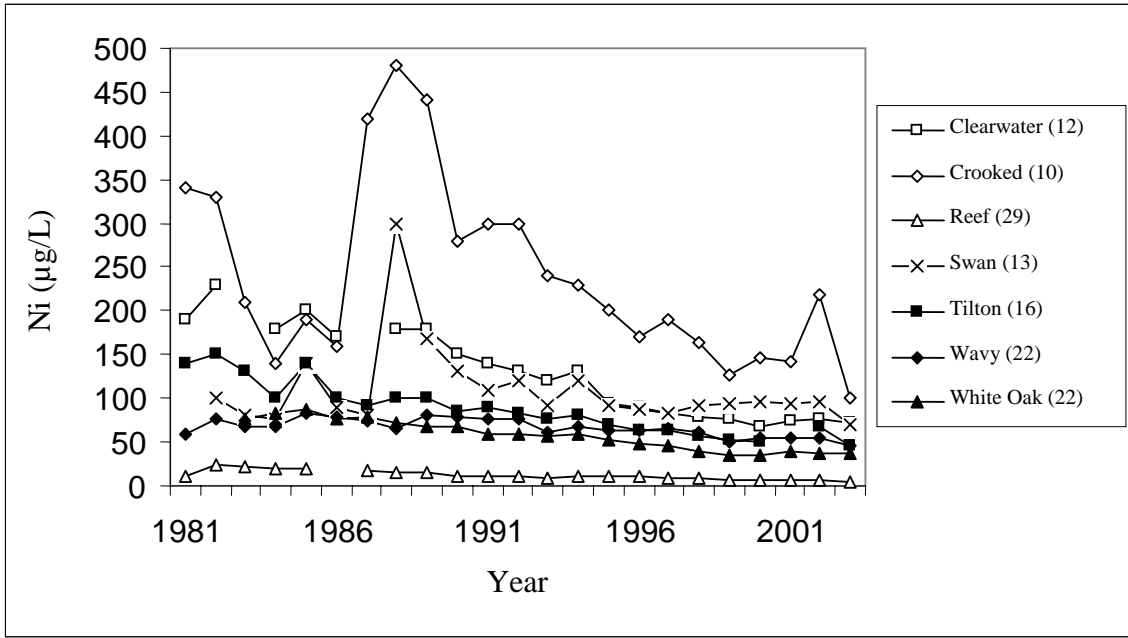
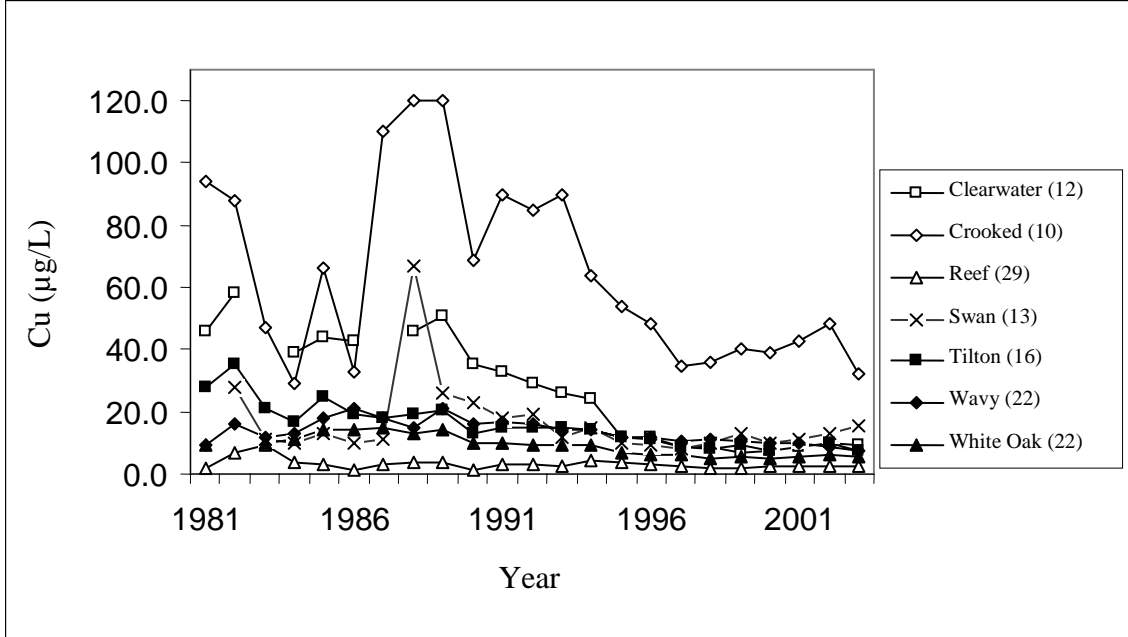


**Figure 4.** Patterns of calcium and magnesium concentrations in seven lakes within 30 km of Sudbury during the period 1981-2003. Numbers in brackets beside the lake names indicate the distance (km) from Sudbury.

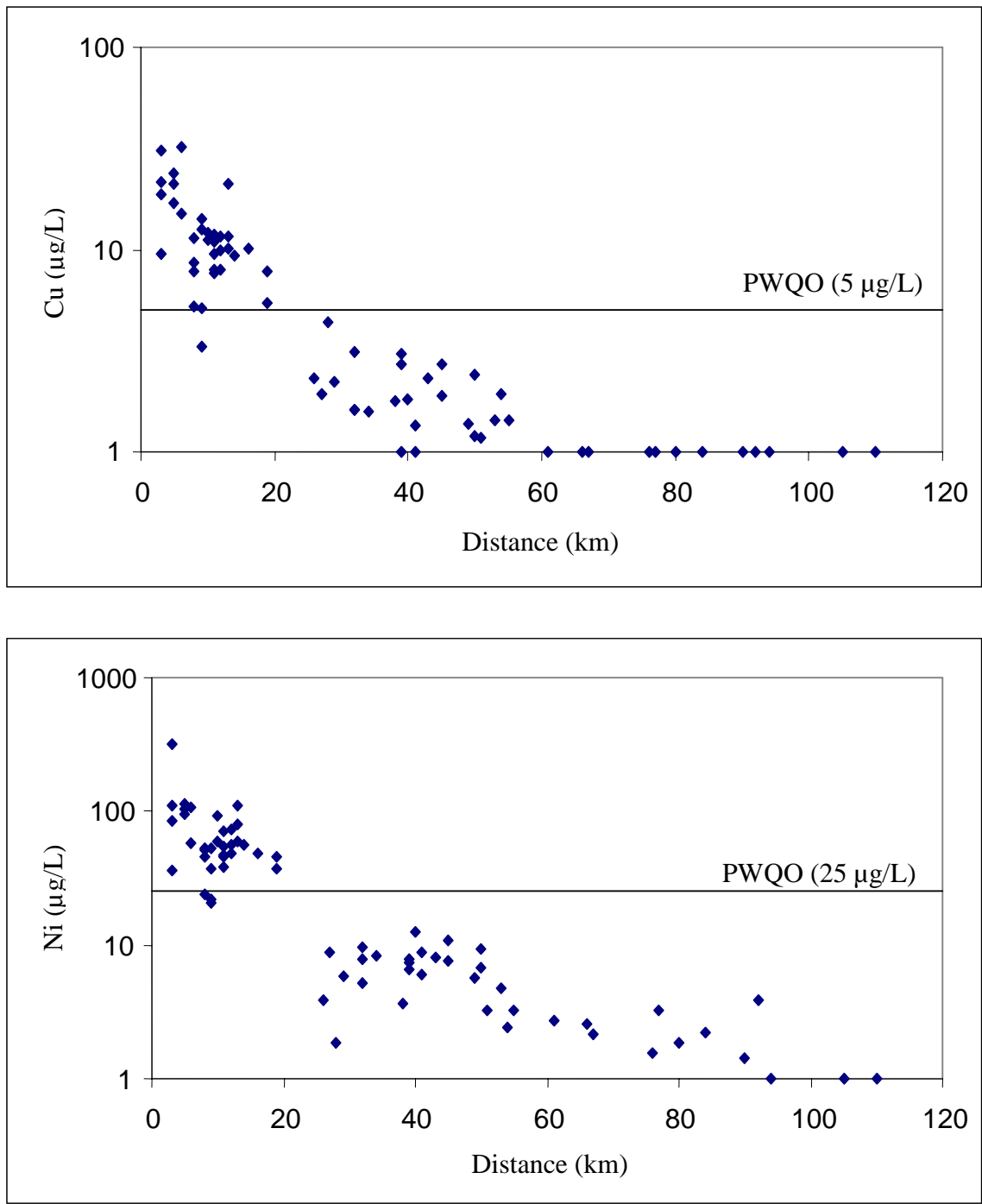
## Metals

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.

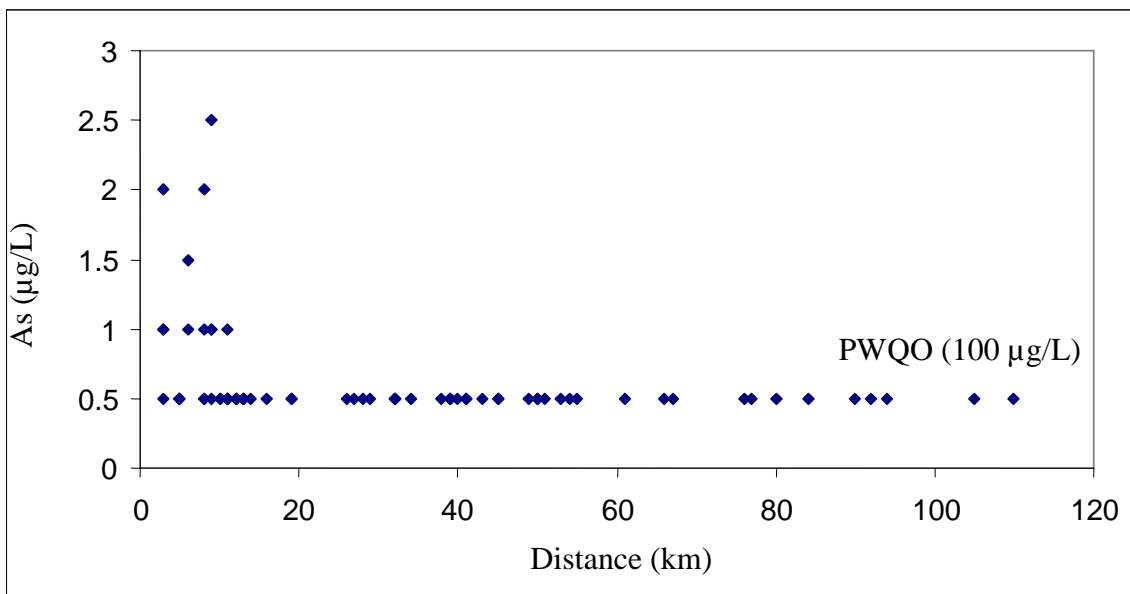
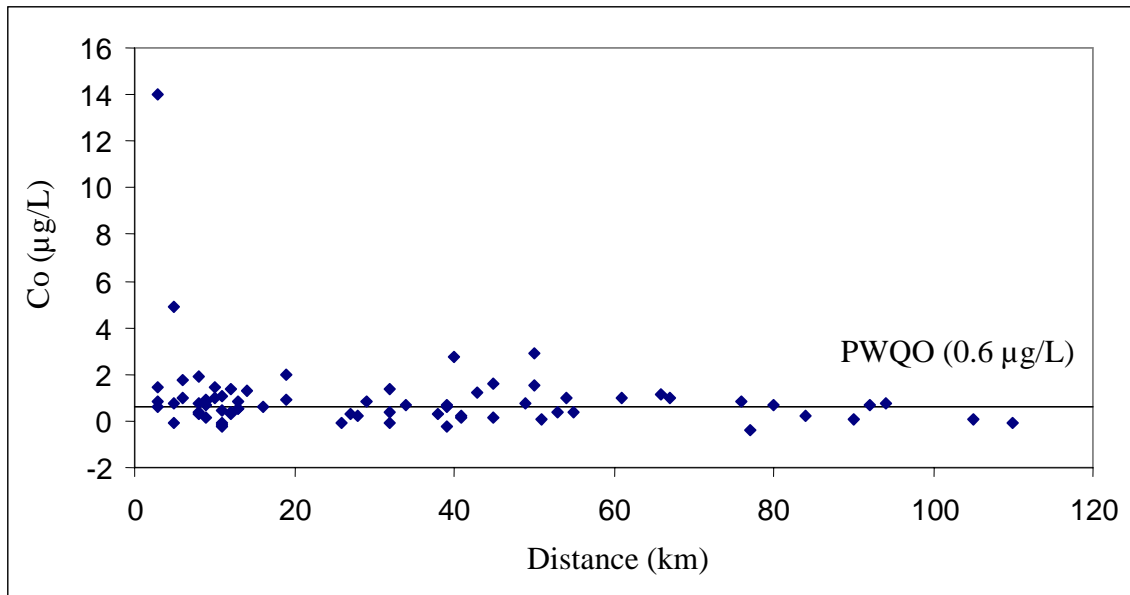
During the 1990's, reductions in metal concentrations in lakes close to Sudbury were again observed, accompanying the emission reductions resulting from the implementation of the Countdown Acid Rain Program (Figure 5; Table 1). Copper and nickel concentrations exceeding Ontario's Provincial Water Quality Objectives (MOEE, 1994) for the protection of aquatic communities in surface waters are now restricted to lakes within about 20 km of Sudbury, and in some cases PWQO's are approached or met in these lakes (Figure 6). Concentrations of other metals (Appendix 1) including cobalt and arsenic (Figure 7) are detectably elevated in some lakes close to Sudbury.



**Figure 5.** Patterns of total copper and nickel concentrations in seven lakes within 30 km of Sudbury during the period 1981-2003. Numbers in brackets beside the lake names indicate the distance (km) from Sudbury.

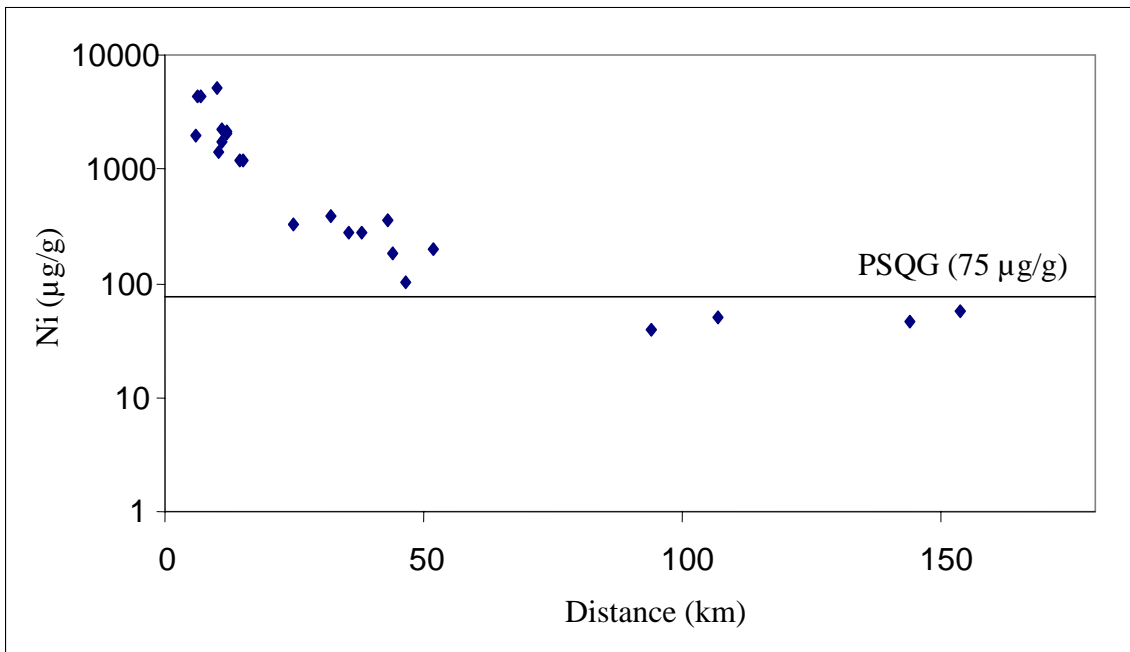
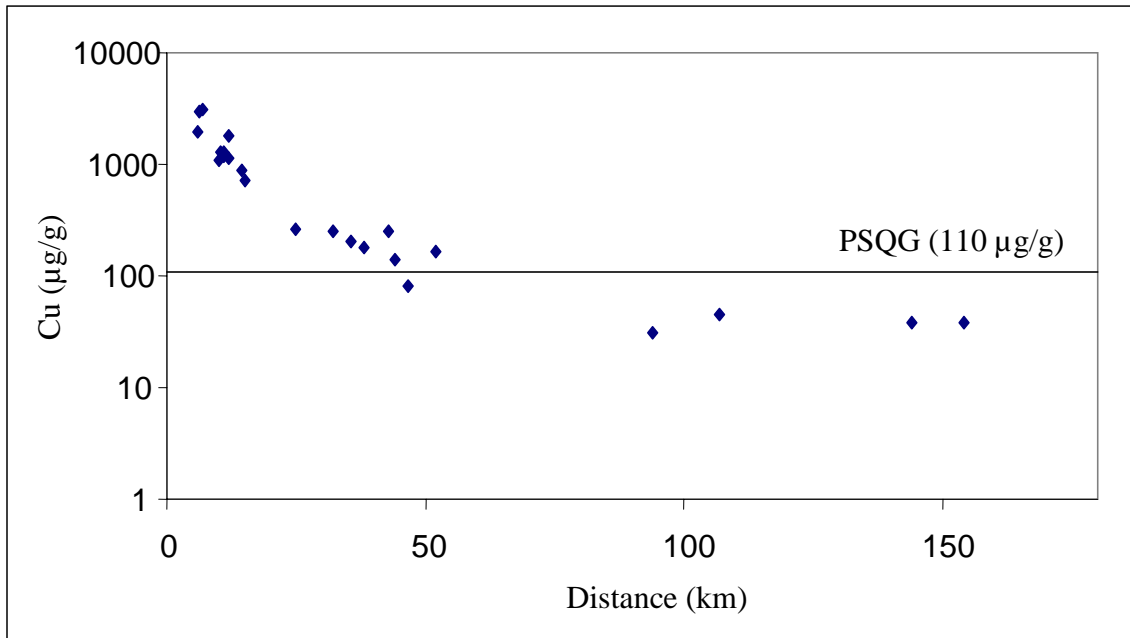


**Figure 6.** Concentrations of total copper and nickel (note the log scale) in Sudbury area lakewaters as a function of distance from Sudbury, based on surveys conducted in 2003. Provincial water quality objectives (MOEE, 1994) for the protection of aquatic life are indicated.



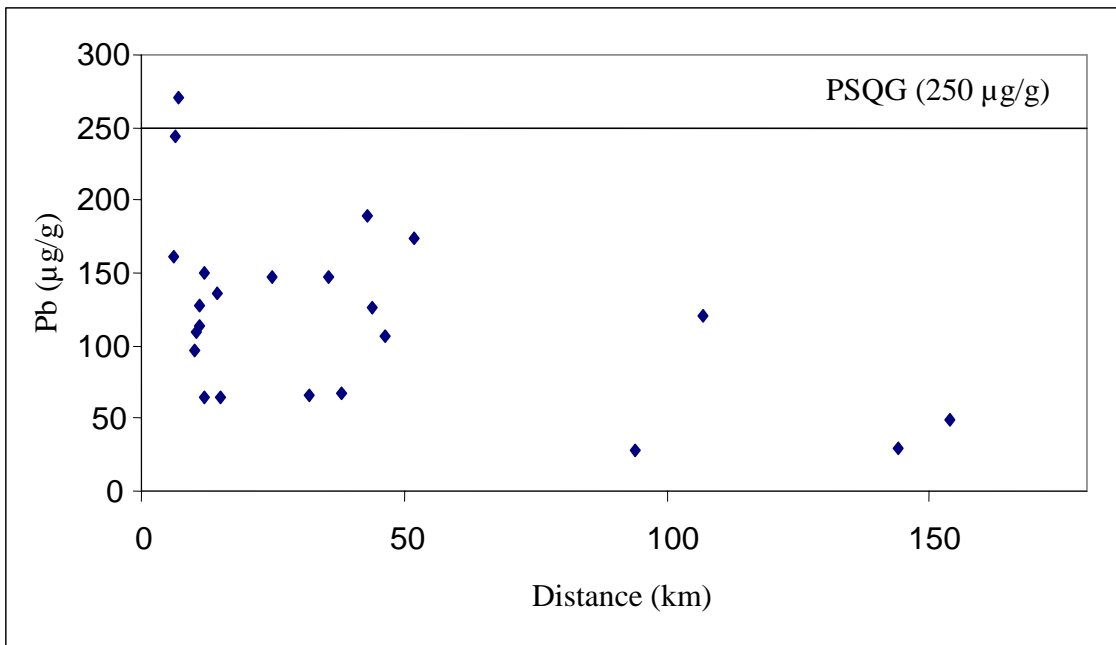
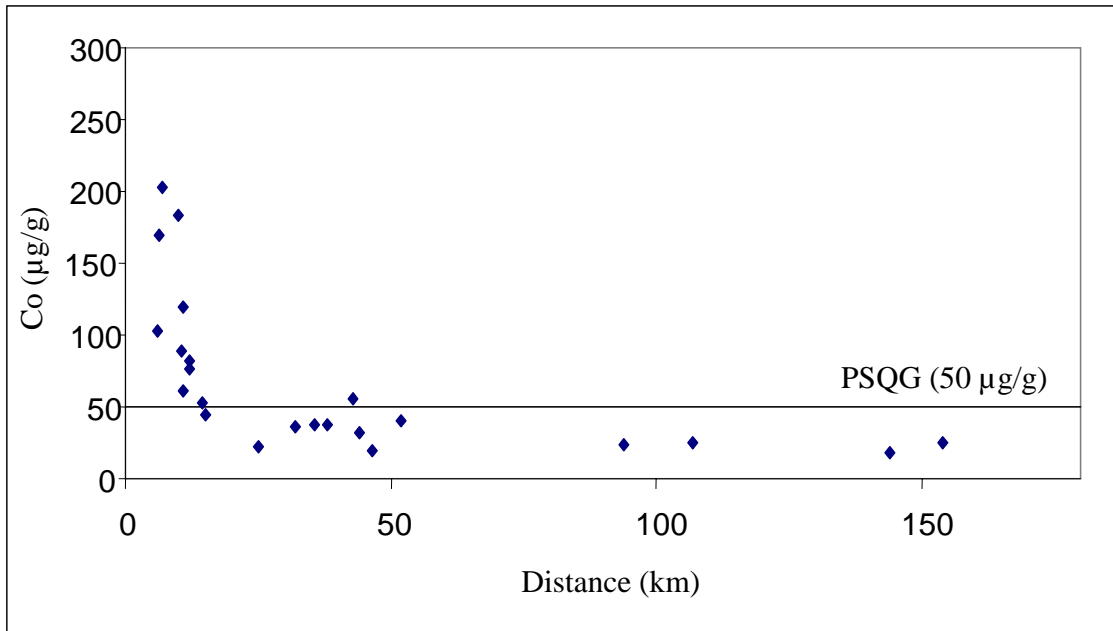
**Figure 7.** Concentrations of total cobalt and arsenic in Sudbury area lakewaters as a function of distance from Sudbury, based on surveys conducted in 2003. Provincial water quality objectives (MOEE, 1994) for the protection of aquatic life are indicated.

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).



**Figure 8.** Concentrations of copper and nickel (note the log scale) in surface sediments of Sudbury area lakes as a function of distance from Sudbury, based on surveys conducted in 1993-1996 (Data sources: Gunn & Keller 1995; Borgmann et al. 1998; W. Keller, unpublished data). Provincial sediment quality guidelines (MOEE, 1993) are indicated.





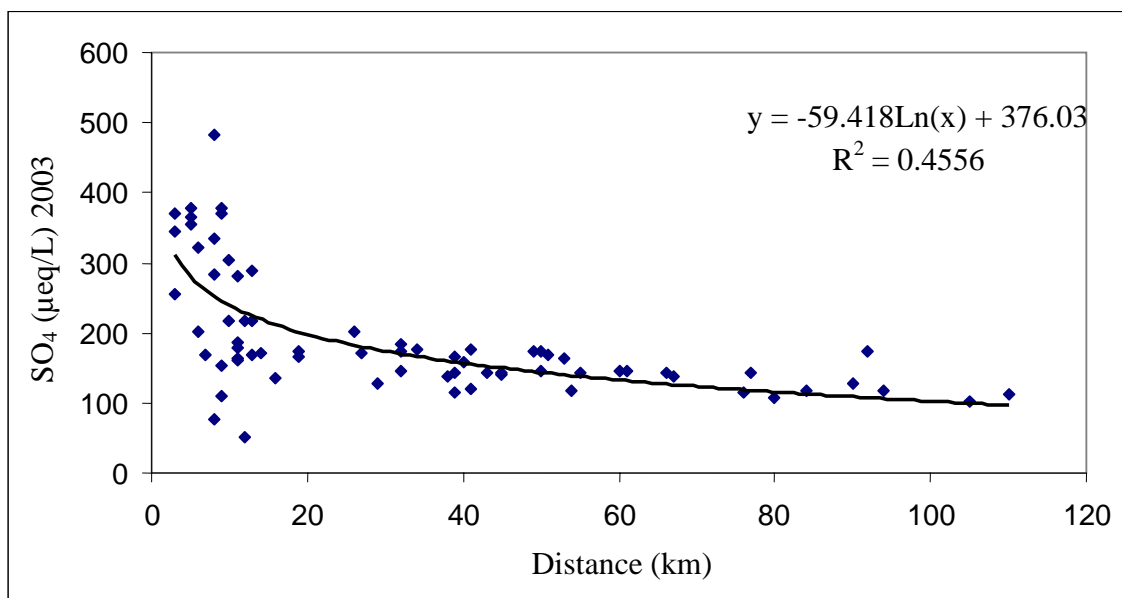
**Figure 9.** Concentrations of cobalt and lead in surface sediments of Sudbury area lakes as a function of distance from Sudbury, based on surveys conducted in 1993-1996 (Data sources: Gunn & Keller 1995; Borgmann et al. 1998; W. Keller, unpublished data). Provincial sediment quality guidelines (MOEE, 1993) are indicated.

## **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). With the additional emission reductions implemented since then, the current Sudbury contribution to local sulphur deposition is expected to be even lower. This suggests, that in agreement with previous assessments (Bodo & Dillon, 1994), the current atmospheric deposition of sulphur to catchments around Sudbury is dominated by the influence of long-range transport. The “Sudbury effect” still evident in lakewaters appears to be largely due to historical deposition and lag time in the responses of lakes and watersheds. Variation in these factors probably accounts for the substantial variability in current sulphate concentrations along the distance gradient (Figure 10).



**Figure 10.** Lakewater sulphate concentrations as a function of distance from Sudbury in 2003.

The reasons for the remarkable declines in acidity seen in some Sudbury lakes are not clear. Comparable acidity decreases have not been seen in other regions of the world where acid deposition has been reduced (Jeffries, 1997; NIVA, 1997). The magnitude of emission reductions has, however, been much greater in the Sudbury area than in other regions. It has been previously suggested that the natural buffering capacity of many acidified Sudbury lakes was probably relatively high, but was simply overwhelmed by the magnitude of the historical acid load (Keller & Gunn, 1995). In fact, it is interesting to note that because of naturally high buffering capacity many lakes close to Sudbury were never acidified. For example, a survey of the 32 largest lakes within the City of Sudbury in 1990 revealed only 9 lakes with  $\text{pH} < 6$  (Gunn & Keller, 1995), although some of these lakes were affected by liming in their watersheds (Yan et al., 1996a). If lake and/or watershed buffering capacity was indeed overwhelmed rather than exhausted in non-limed cases, a rapid rebound might be expected under greatly reduced acid loads. Paleolimnological data support this hypothesis, indicating that before industrialization, acidified Sudbury lakes did tend to have higher natural buffering capacity than lakes in other acid-damaged regions (Smol et al., 1998).

Why, in particular, some lakes closest to the smelters, within the City of Sudbury, have shown such dramatic recovery is not known. A possible factor that merits further investigation is the stimulation of internal alkalinity-generating processes by abundant nutrients. Nutrient inputs may have resulted from shoreline development, from the re-establishment of vegetation in formerly denuded lake watersheds, or from erosion of soils in barren watersheds. Such effects would be expected to be very lake specific, depending on the particular history of a lake and its watershed. Effects of changes

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:

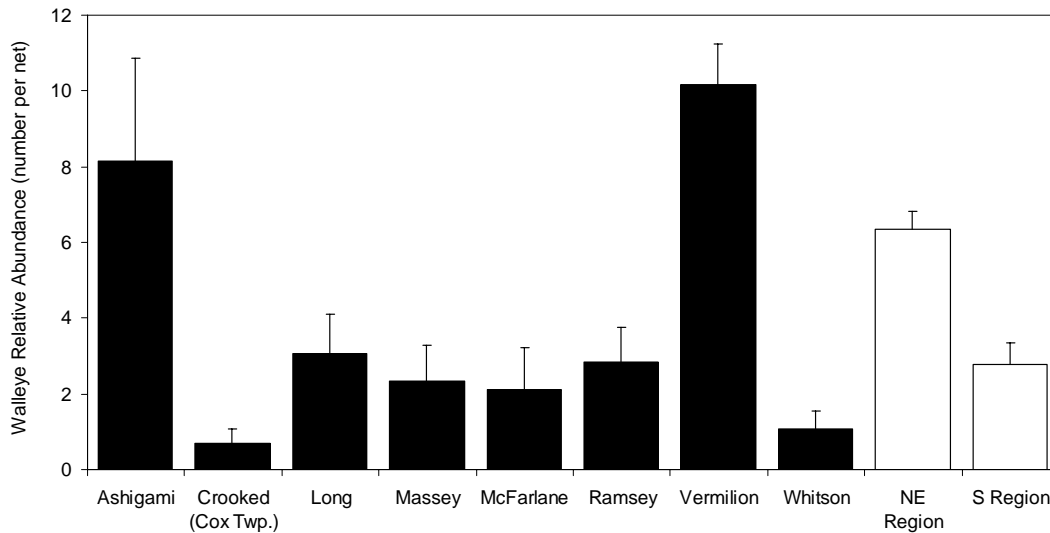
- 1) Widespread legal and illegal introduction of several sport fish species (walleye (*Sander vitreus*), lake trout (*Salvelinus namaycush*), brook trout (*Salvelinus fontinalis*), and smallmouth bass (*Micropterus dolomieu*)), and other species introductions including rock bass (*Ambloplites rupestris*), pumpkinseed (*Lepomis gibbosus*), and smelt through emptying of bait buckets (E. Snucins, unpublished data).
- 2) Improvements in water quality (reduced acidity and metals), and other factors such as eutrophication, that have allowed for hatchery stocking or natural colonization of many lakes (Gunn & Mills, 1998).
- 3) Changing weather conditions that have expanded opportunities for warm water species (e.g. smallmouth bass, largemouth bass, rock bass) to invade recovering lakes within the Sudbury area (Snucins & Gunn, 2003).

Until recently, we lacked an efficient method to study whole-community fish species composition or depth distribution within lakes. The developing Nordic depth-stratified multi-mesh netting method (Appelberg et al., 1995) appears to provide the solution to this problem. The Nordic methodology (recent Nordic netting data for 17 Sudbury lakes are provided in Appendix 3) should provide quality data to help researchers 1) understand the effects of the environmental changes on the fish themselves, and 2) assess how the changing fish communities may affect other components of the ecosystems (e.g. zooplankton, benthic invertebrates, phytoplankton).

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 through hatchery stocking programs, primarily the Community Fisheries Involvement Program (CFIP). Popular fishing lakes such as Ramsey, McFarlane, Long and Whitson are among the lakes stocked by CFIP groups.

Studies are underway on eight walleye lakes (Figure 11) to assess the effects of altered fish prey communities on walleye growth and work is planned to extend this work to the effects of loss of benthic invertebrates on food web functions. The relative abundance of walleye in these eight study lakes is indicated in Figure 11, and abundances are compared to the average condition in northeastern and southern Ontario walleye lakes. Individual lakes vary widely in their abundance of walleye, but in Sudbury the average walleye lake is probably more typical of an exploited southern Ontario lake than less-used northeastern Ontario lakes. Walleye populations in urban areas of Sudbury are stressed by a variety of factors including water quality and habitat damage, but high angling exploitation undoubtedly has a major effect on the abundance and size of the fish. For example, during the 6-week winter angling period in Ramsey Lake (March 1 – April 15, 2003), an estimated 9016 angler-hours (10.3 hrs/ha) harvested 1738 walleye (G. Morgan, unpublished data). This is a very high exploitation rate, but given its location in the center of a city of 150,000 people, it represents a remarkable success story that such a recreational resource has been re-established there (see Appendix 4 for harvest statistics of other walleye lakes).





**Figure 11.** Relative abundance of walleye (number per net) sampled using the Fall Walleye Index Netting (FWIN) method in 2003. The average catches  $\pm$  1SE are indicated for the 8 named Sudbury lakes and are compared to the whole lake average catch in a large number (>100) of northeastern and southern Ontario lakes.

## Invertebrates

Populations of a number of acid and/or metal sensitive invertebrate species have been observed to recolonize some lakes, including the important crustacean zooplankton *Holopedium* (Keller & Yan, 1991) and *Daphnia mendotae* (Yan et al., 1996a, c). These changes seem to be largely a response to reduced metal concentrations. In 1999, littoral zone mayflies of the genus *Stenonema* were found in Ramsey Lake in the center of the city of Sudbury. *Stenonema* had not been found in surveys of Ramsey Lake in 1995 and 1996 (W. Keller, unpublished data). In 2003, loons successfully reproduced in Daisy Lake for the first time in over 20 years (M. and D. Schoenefeld, personal observations). This probably reflects the re-establish of fish populations after the pH recovered (J. Gunn, personal observations).

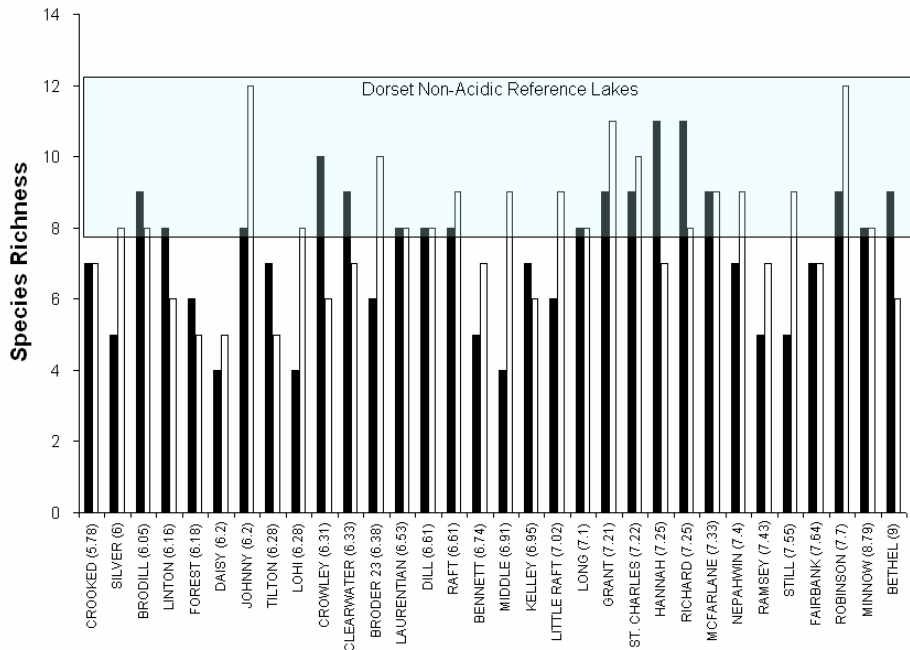
The phytoplankton community of Clearwater Lake, one of the most highly affected Sudbury lakes in the 1970's, has now become similar to communities of near-neutral, more pristine lakes on the Precambrian Shield (Winter et al., 2004). The crustacean zooplankton community of Clearwater Lake has also shown 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 (*Pimephales promelas*), northern redbelly dace (*Phoxinus eos*) and brook sticklebacks (*Culaea inconstans*) were first observed in the late 1990s. In 2001, an abundant perch (*Perca flavescens*) population was present. By 2003 the first smallmouth bass was captured.

The substantial biological recovery observed in Clearwater Lake, a lake that was extremely damaged, is very promising, supporting a very positive outlook for the future recovery of other highly affected systems after stresses are removed. However, there is little detailed recent survey work from which to assess the current biological status of all but a few Sudbury lakes. The rate and extent of biological recovery appear to be related to both the initial severity of damage and continuing habitat limitations (Yan et al., 1996b). The existing evidence of invertebrate community recovery in severely affected Sudbury lakes, even lakes that have maintained near-neutral conditions for many years, while very encouraging, is still limited. Elevated lakewater concentrations of metals, and metal-contaminated sediments, undoubtedly still affect aquatic communities in some lakes close to the Sudbury smelters. Nickel, in particular, has been implicated as the contaminant most

responsible for sediment toxicity to the amphipod *Hyaletella* 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).

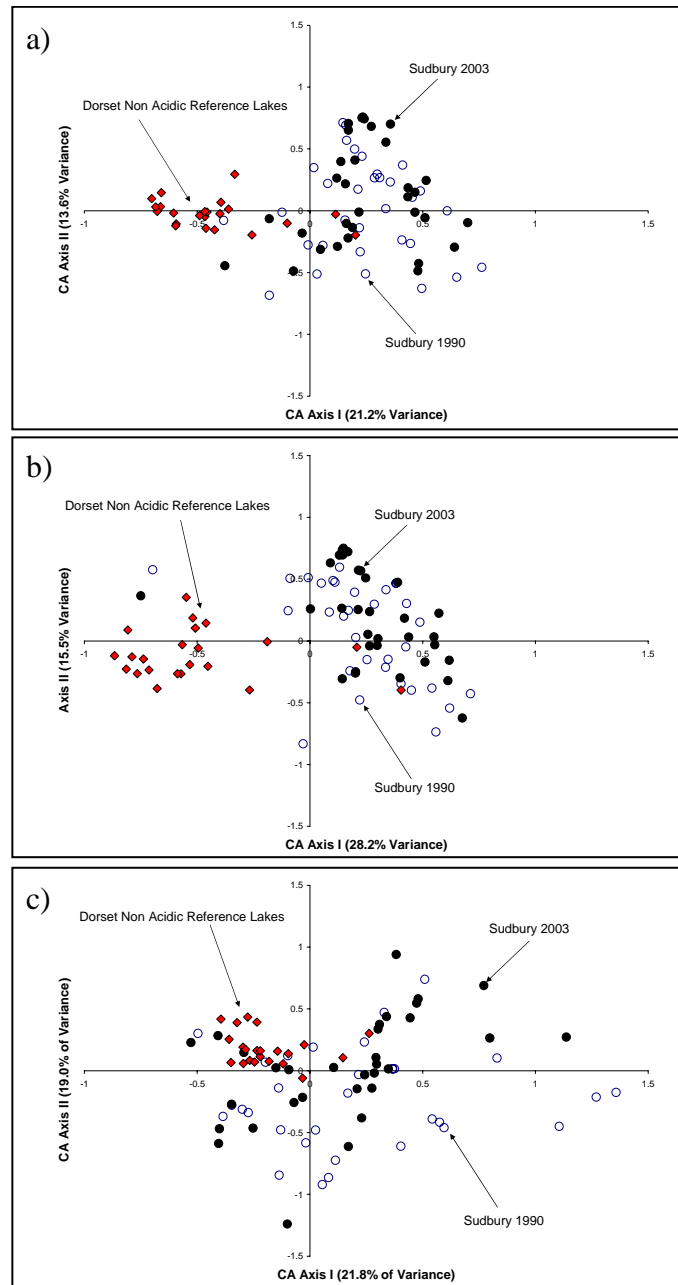
It is generally felt that while acidification can greatly alter the composition of aquatic communities, the important functional processes of aquatic ecosystems such as productivity and nutrient cycling remain essentially intact (Schindler, 1987). Evidence from some Sudbury lakes indicates that this 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).



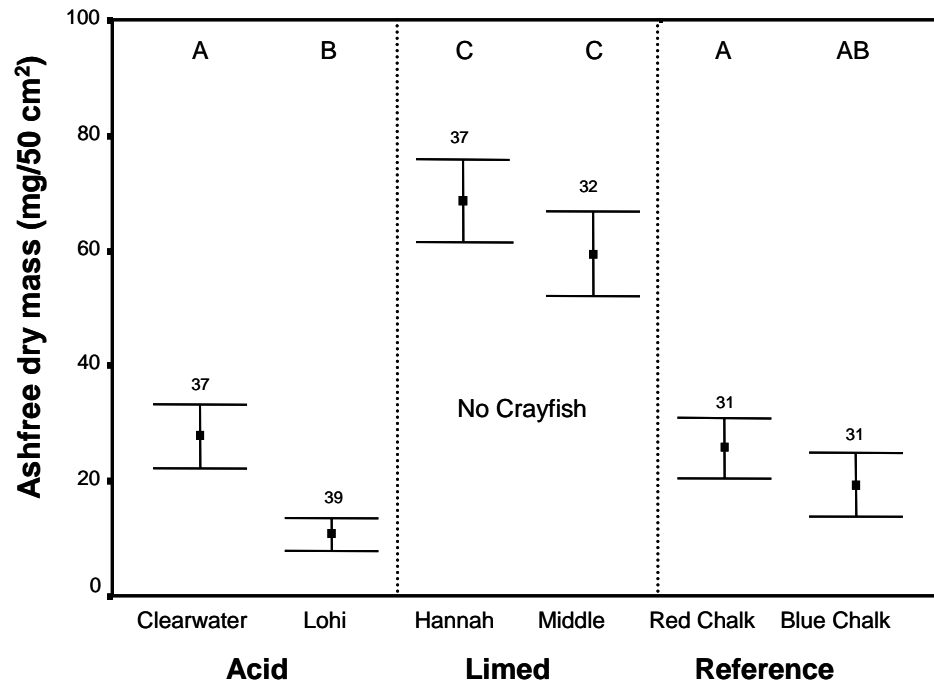
**Figure 12.** Number of species of crustacean zooplankton collected from Sudbury lakes in 1990 (solid bars) and 2003 (open bars). Lakes were sampled once during summer, at a single deep basin, with a net haul from one m above bottom to surface. Lakes are arranged in order of increasing current pH (indicated in brackets). Species richness ( $\pm 2$  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



**Figure 13.** Composition of crustacean zooplankton communities in Sudbury lakes in 1990 and 2003: a) all Crustacea, b) cladocerans only, c) copepods only, as defined by Correspondence Analyses axes. Immature copepods were not included in the analysis. Similar communities fall in similar locations in ordination space. For reference, data for relatively unaffected lakes near Dorset, Ontario were included in the analysis.

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).



**Figure 14.** Ash-free dry mass (mg/50 cm<sup>2</sup>) of periphyton collected from rocks in study lakes during June-August 1996. Clearwater, Lohi, Middle and Hannah lakes are located in Sudbury. Middle and Hannah were limed in the early 1970's and have maintained near-neutral pH, while Clearwater and Lohi are acidic lakes being monitored for natural recovery. Blue Chalk and Red Chalk are non-acidic reference lakes located near Dorset, Ontario. Means, 95% confidence intervals and sample size are indicated. Groups with non-corresponding letters are significantly different at p<0.05.

Two general factors may be causing the continuing absence of key aquatic organisms from some Sudbury lakes: a failure to reach these systems to permit colonization; or unsuccessful colonization because of continuing inhospitable habitat conditions (Gunn & Keller, 1995). In Sudbury lakes both these factors are likely operating to some degree. Based on field exposures and distributional observations it appears that organisms such as crayfish and amphipods can survive in some lakes where populations do not currently exist (Heneberry et al., 1992; Watson, 1992) suggesting dispersal difficulties. But, dispersal for many species will depend simply on time, with enough time many species can reasonably be expected to naturally colonize recovering Sudbury lakes. This expectation is supported by a growing number of examples of effective dispersal by a number of zooplankton, phytoplankton and benthic invertebrate species to lakes in the Sudbury area without residual populations (Watson et al., 1999; Pollard et al., 2003). On the other hand, in some cases new species only appeared sporadically, but did not become successfully established (N. Yan, W. Keller, unpublished data), and attempts at experimental reintroductions of a number of invertebrate species including zooplankton, mayflies, amphipods and crayfish have generally been unsuccessful (W. Keller, J. Gunn, J. Heneberry, unpublished data). This suggests that habitats have not sufficiently recovered. Aquatic ecosystems in urban environments can also be subjected to a wide range of anthropogenic stressors (Gunn & Keller, 1995; Pearson et al., 2003). Recovery from acid and metal contamination, our focus in this report, will occur against a background of other local and global stressors which may also greatly influence the recovery process in urban settings. Recovery will also be linked to the sometimes dramatic physical changes such as altered transparency and thermal regimes that accompany chemical recovery (Arnott et al., 2001; Girard et al., 2003).

## Conclusions

Smelter emission reductions in the Sudbury area have resulted in substantial improvements in the water quality of area lakes. Evaluation of the direct effects of the most recent emission reductions is, however, complicated by the continuing effects of previous emission reductions and the effects of weather induced variations in lake chemistry. Continued monitoring will be essential to determine the ultimate effect of emission reductions and develop a more complete understanding of the recovery process. Our understanding of aquatic recovery is only beginning, and some lakes in the Sudbury area are still affected by acidification and metal contamination.

In the large area of northeastern Ontario historically affected by the Sudbury emissions there is considerable evidence of both chemical and biological recovery, in aquatic ecosystems. In the most severely affected lakes closest to the smelters, however, chemical recovery has not always been associated with substantial biological recovery. In some cases the absence of key species appears to have substantial effects on ecosystem dynamics. Increasing documentation of the recovery of a number of groups of organisms including fish, zooplankton, phytoplankton, benthic invertebrates, and even loons is, however, emerging. While this evidence is very encouraging, detailed surveys permitting the assessment of trends in biological status in these lakes are limited, restricting our ability to evaluate the overall extent of biological recovery.



## 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.

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## Appendices

The following appendix tables contain various chemical and biological data for a number of Sudbury area lakes. The names and locations of lakes included in the appendices are listed below.

Lake Name	Township	Lake Area (ha)	Decimal Latitude	Decimal Longitude
Ashigami	Scadding	434.7	46.6523	80.5802
Bear	Roosevelt	691.9	46.1901	81.4545
Bennett	McKim	13.6	46.4576	80.9715
Bethel	McKim	31.2	46.4713	80.9617
Broder 23	Broder	36.9	46.3977	80.9582
Brodill	Broder	112.1	46.3690	80.9488
Caswell	Aylmer	39.8	46.8627	80.7070
Clearwater	Broder	76.0	46.3702	81.0511
Crooked	Broder	26.3	46.4215	81.0358
Crooked (Cox)	Cox	113.4	46.1456	80.7397
Crowley	Broder	43.5	46.3837	80.9856
Daisy	Dill	36.6	46.4518	80.8843
Fairbank	Denison	705.1	46.4690	81.4253
Forest	Broder	15.8	46.3925	80.9972
Fraleck	Fraleck	166.3	46.9125	80.8832
Geneva	Hess	356.4	46.7644	81.5461
Grant	Broder	8.5	46.4167	80.9833
Hannah	Broder	27.7	46.4431	81.0389
Johnnie	Carlyle/Goschen	342.3	46.0833	81.2333
Johnny	Broder	8.1	46.4286	81.0381
Kelley	Broder	340.8	46.4437	81.0679
Kukagami	Kelly	1864.8	46.7352	80.5540
Lac St. Jean	Capreol	78.5	46.6722	80.8536
Laurentian	Broder	157.0	46.4502	80.9536
Linton	Broder	27.7	46.3751	80.9851
Little Panache	Louise	102.9	46.2811	81.3646
Little Raft	Broder	19.7	46.4010	80.9693
Lohi	Broder	41.6	46.3870	81.0432
Long	Broder, Eden, Waters	861.3	46.3651	81.0922
Matagamasi	Rathbun	1317.1	46.7925	80.6192
McFarlane	Broder	166.1	46.4185	80.9615
Middle	Broder	28.1	46.4382	81.0254
Minnow	McKim	20.9	46.4928	80.9563
Nelson	Bowell	308.8	46.7280	81.0949
Nepahwin	McKim	127.0	46.4586	80.9960
Raft	Broder, Dill	109.6	46.4118	80.9430
Ramsey	McKim	792.2	46.4734	80.9528
Richard	Dill	83.6	46.4392	80.9135
Robinson	Dieppe	33.6	46.4548	81.5524
Silver	Broder	21.8	46.4293	81.0152
St. Charles	Broder	41.3	46.4469	81.0161
Still	Broder	3.1	46.4422	81.0014
T (Dill)	Dill	44.4	46.3900	80.8991
Tilton	Broder	51.7	46.3564	81.0720
Tyson	Sale	1142.2	46.1169	81.1164
Vermilion	Fairbank	1126.6	46.5131	81.4232
Whitson	Blezard	473.4	46.5826	80.9798

## **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 samples through the epilimnion and metalimnion were taken during midsummer at a single deep basin in each lake. Analyses were conducted by the Ontario Ministry of the Environment.

## **Appendix 2 – Sediment Chemistry**

Results of analyses of sediment samples from 11 Sudbury area lakes sampled in the mid-1990's (W. Keller, Ontario Ministry of the Environment). Samples represent the top 2 cm of sediment collected with an Ekman dredge. Three replicate samples were taken in a single deep basin in each lake. Analyses were conducted by the Ontario Ministry of the Environment.

## **Appendix 3 – Fish Species**

Fish species present in 17 recently surveyed (2000-2003) lakes within the City of Greater Sudbury. Sampling conducted using the Nordic multimesh gillnets.

## **Appendix 4 – Walleye Harvest Statistics**

Sudbury area late winter creel survey summary statistics for 4 walleye lakes. Creel survey conducted from March 1 to April 15, 2003.

## **Appendix 5 – Zooplankton Species**

Crustacean zooplankton species collected in 32 lakes in the City of Greater Sudbury in 1990 and 2003. Samples were single vertical net hauls with an 80 u mesh, 30 cm-mouth-diameter, non-metered net. Single samples were taken during midsummer at a single deep basin in each lake.

Appendix 1 - Water Chemistry

	Bennett	Bethel	Broder #23	Brodrill	Clearwater	Crooked	Crowley	Daisy	Dill									
pH	6.88 0.61	6.74 1.99	7.77 2.00	9.00 2.00	6.04 0.61	6.38 2.00	5.42 6.05	6.05 2.00	4.88 0.61	6.33 2.00	4.43 0.61	5.78 2.00	5.88 0.61	6.31 2.00	4.82 0.61	6.20 2.00	6.57 0.61	6.61 2.00
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	3.30	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	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	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	<0.70	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 <sub>4</sub> (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 <sub>2</sub> (mg/L)	<0.22	1.10	1.12	0.68	0.98	0.96	1.70	1.26	0.76	1.10	2.26	0.98	1.34	0.92	1.40	<0.10	0.60	0.60
Al (µg/L)	<30	14	<40	30	<30	23	<100	47	130	16	230	87	<50	26	360	30	<60	48
As (µg/L)	<2.0	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Ba (µg/L)	11.3	26.8	15.6	15.8	17.6	0.03	17.8	14.5	14.5	16.0	16.0	14.5	<0.03	<0.03	<0.03	<0.03	<0.03	11.4
Be (µg/L)	<=0.03	<=0.03	<=0.03	0.03	<=0.03	<=0.03	<=0.03	0.03	<=0.03	<=0.03	<=0.03	0.03	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03
Cd (µg/L)	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0
Cr (µg/L)	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0
Co (µg/L)	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5
Cu (µg/L)	18	9	5	3	11	10	19	9	35	10	78	35	14	11	76	12	16	10
Fe (µg/L)	370	319	120	99	170	36	<80	60	<60	15	350	781	110	49	<80	36	370	331
Mn (µg/L)	9	15	270	127	48	28	89	44	250	26	160	58	71	32	150	24	17	32
Mo (µg/L)	<=1.6	<=1.6	<=1.6	<=1.6	<=1.6	<=1.6	<=1.6	<=1.6	<=1.6	<=1.6	<=1.6	<=1.6	<=1.6	<=1.6	<=1.6	<=1.6	<=1.6	<=1.6
Ni (µg/L)	44	24	26	21	63	49	100	56	160	70	310	108	89	55	290	80	66	49
Pb (µg/L)	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11
Se (µg/L)	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5
Sr (µg/L)	12.0	15.4	45.9	1.53	13.8	1.64	14.7	14.4	14.7	21.7	14.2	13.4	1.39	12.9	12.9	1.06	16.0	16.0
Ti (µg/L)	1.54	1.54	1.53	1.53	1.64	1.44	1.44	1.44	<=0.30	<=0.30	0.70	0.70	1.39	1.39	1.06	1.67	1.67	1.67
V (µg/L)	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5
Zn (µg/L)	6	3	<1	1	7	5	12	14	23	11	29	11	9	6	17	6	7	5
P (µg/L)	21	32	156	56	<2	6	<6	6	<=2	5	<7	19	<7	9	2	9	17	19
NH <sub>3</sub> +NH <sub>4</sub> (µg/L)	54	168	234	468	122	60	30	36	26	86	52	36	36	36	<=2	34	34	76
NO <sub>2</sub> (µg/L)	<=1	6	6	9	9	7	7	<3	<2	<2	<2	<2	<2	<2	<=1	9	9	9
NO <sub>3</sub> +NO <sub>2</sub> (µg/L)	<=5	8	<=5	50	<5	20	65	36	<5	<5	<5	14	<10	6	<10	<5	8	8
TKN (µg/L)	540	459	1620	3320	340	200	200	200	140	233	230	364	250	218	430	388	388	388
DOC (mg/L)	5.0	8.0	7.3	7.7	2.8	3.0	2.2	3.2	0.5	2.9	<0.2	5.3	2.9	3.3	2.0	5.9	6.4	6.4

Appendix 1 - Water Chemistry

	Forest	Grant	Hannah	Johnny	Kelley	Laurentian	Linton	Little Pat								
pH	6.01 1990	6.18 2003	7.21 1990	7.21 2003	7.06 1990	7.25 2003	6.80 1990	6.76 2003	7.30 1990	6.95 2003	6.41 1990	6.53 2003	5.41 1990	6.16 2003	7.08 1990	7.02 2003
Conductivity (µS/cm)	41.0	36.4	310.0	355.0	359.0	190.0	310.0	297.0	1720.0	1690.0	33.5	129.0	40.2	24.0	51.0	39.4
Alkalinity (mg/L)	0.95	1.48	34.71	39.18	12.10	16.93	6.25	13.22	64.77	41.49	3.43	3.23	0.56	1.10	8.17	6.31
Ca (mg/L)	3.94	2.94	17.70	15.70	13.40	10.60	13.10	9.22	204.00	274.00	2.28	3.44	3.20	2.08	4.39	3.30
Mg (mg/L)	1.02	1.00	5.24	4.82	4.56	3.57	4.14	2.96	22.00	43.50	1.08	1.35	0.94	0.71	1.48	1.13
Na (mg/L)	1.22	1.52	35.10	49.90	44.60	62.80	38.10	42.70	122.00	112.00	1.26	1.720	1.02	0.98	1.34	1.55
K (mg/L)	0.580	0.515	1.570	2.540	1.980	1.660	1.160	0.940	18.400	20.100	0.720	0.710	0.520	0.375	0.730	0.535
Cl (mg/L)	1.50	1.79	58.50	79.77	76.30	91.90	30.70	78.86	114.00	107.00	<0.90	33.01	<0.50	0.30	<0.50	1.45
SO <sub>4</sub> (mg/L)	12.13	14.55	17.87	13.65	28.98	16.60	26.18	12.30	621.31	6.60	5.25	12.97	8.11	9.44	7.78	7.78
SiO <sub>2</sub> (mg/L)	0.68	1.06	0.74	0.60	0.38	0.26	0.46	1.26	3.22	1.98	0.42	0.34	0.88	0.66	2.02	0.86
Al (µg/L)	<30	27	<=10	7	200	13	<=10	31	150	32	<90	38	<80	34	10	9
As (µg/L)	<=0.5	<=0.5	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<=0.5	<=0.5	<=0.5	<=0.5	<1.0	<1.0
Ba (µg/L)	22.0	29.0	21.9	29.3	37.9	11.0	11.0	11.0	0.04	0.04	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03
Be (µg/L)	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03	<=0.03
Cd (µg/L)	<=0.6	<=0.6	<=0.6	<=0.6	<=0.6	<=0.6	<=0.6	<=0.6	<=0.6	<=0.6	<=0.6	<=0.6	<=0.6	<=0.6	<=0.6	<=0.6
Cr (µg/L)	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0	<=1.0
Co (µg/L)	<=1.5	<=1.5	1.9	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	14.0	14.0	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5
Cu (µg/L)	16	12	6	5	64	22	17	19	53	31	34	14	19	10	27	8
Fe (µg/L)	<70	50	<=20	161	290	114	270	656	950	249	650	585	<90	50	350	82
Mn (µg/L)	77	39	720	1020	38	70	28	168	190	102	19	30	61	25	24	27
Mo (µg/L)	<=0.8	<=0.8	<=0.8	<=0.8	<=1.2	<=1.2	<=1.6	<=1.6	<=0.8	<=0.8	<=0.8	<=0.8	<=0.8	<=0.8	<=0.8	<=1.6
Ni (µg/L)	100	91	46	53	180	111	150	85	510	317	56	37	100	59	43	38
Pb (µg/L)	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11
Se (µg/L)	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5	<=0.5
Sr (µg/L)	17.2	17.2	53.5	57.3	57.3	57.3	50.1	50.1	425.0	425.0	17.7	17.7	12.6	12.6	18.1	18.1
Ti (µg/L)	1.23	1.23	1.12	<=0.30	<=0.30	<=1.5	<=1.5	2.17	<=0.30	<=0.30	2.19	2.19	1.66	1.66	1.56	1.56
V (µg/L)	<=0.9	<=0.9	<=0.9	<=1.5	<=1.5	<=1.5	<=1.5	<=1.5	<=0.9	<=0.9	<=0.9	<=0.9	<=0.9	1.0	<=1.5	<=1.5
Zn (µg/L)	11	10	<1	5	11	3	6	3	15	14	7	2	11	7	6	2
P (µg/L)	<=2	6	<=20	36	21	8	<9	14	88	39	39	33	<6	8	35	15
NH <sub>3</sub> +NH <sub>4</sub> (µg/L)	18	24	<6	122	20	66	42	262	742	742	70	116	48	34	36	86
NO <sub>2</sub> (µg/L)	<=1	<=1	<=1	<=1	<=1	<=1	<=1	<=1	139	126	12	<3	<3	<3	5	<=5
NO <sub>3</sub> +NO <sub>2</sub> (µg/L)	<20	6	<=5	22	<=5	<6	<5	12	1490	126	<10	30	<15	8	<=5	8
TKN (µg/L)	<150	211	325	400	430	418	780	503	5200	5420	740	533	260	207	575	331
DOC (mg/L)	3.2	3.1	4.1	4.8	3.8	3.6	5.1	5.3	4.5	4.3	6.9	6.1	2.9	3.0	2.5	3.5

Appendix 1 - Water Chemistry

	Lohi		Long		McFarlane		Middle		Minnow		Nepahwin		Raft		Ramsey	
	96	2003	99	2003	99	2003	96	2003	99	2003	99	2003	96	2003	96	2003
pH	4.92	6.28	6.90	7.10	7.10	7.33	6.57	6.91	8.91	8.79	7.71	7.40	6.81	6.61	7.48	7.43
Conductivity (µS/cm)	90.8	71.6	161.0	184.0	314.0	380.0	258.0	286.0	2000.0	575.0	500.0	418.0	50.4	37.8	300.0	357.0
Alkalinity (mg/L)	-0.69	2.57	13.79	16.83	31.68	33.72	5.78	11.71	40.74	45.22	30.91	37.93	3.75	3.72	23.74	30.26
Ca (mg/L)	6.18	4.34	10.20	8.46	16.40	15.70	10.30	11.00	24.80	19.40	20.50	19.10	4.08	3.18	15.40	15.20
Mg (mg/L)	1.75	1.31	3.10	2.79	5.08	4.75	3.53	3.21	6.02	4.65	6.57	6.23	1.46	1.11	4.82	4.33
Na (mg/L)	3.89	5.71	14.20	22.40	33.50	52.50	29.70	40.30	82.50	79.50	70.70	82.30	1.05	1.17	31.80	47.80
K (mg/L)	0.850	0.720	1.120	1.430	1.610	1.810	0.730	0.730	1.930	1.280	2.540	2.910	0.640	0.505	1.610	1.470
Cl (mg/L)	10.30	10.78	24.80	36.44	58.10	86.35	50.30	66.29	134.00	153.23	115.00	134.00	<0.90	0.69	56.30	80.13
SO <sub>4</sub> (mg/L)	19.57	10.39	18.13	13.46	20.66	16.04	25.37	17.53	36.00	17.80	30.26	23.20	14.89	10.37	24.75	18.21
SiO <sub>2</sub> (mg/L)	0.56	1.12	1.28	1.02	1.00	0.58	1.20	0.80	0.60	0.64	<0.20	<0.02	<0.18	0.30	1.52	0.32
Al (µg/L)	130	22	<20	14	<50	8	<30	13	<40	25	<20	10	<=10	10	<20	4
As (µg/L)																
Ba (µg/L)																
Be (µg/L)																
Cd (µg/L)																
Cr (µg/L)																
Co (µg/L)																
Cu (µg/L)	50	12	15	12	8	8	28	24	6	5	13	11	4	12	19	12
Fe (µg/L)	130	106	30	27	<40	22	<80	26	180	155	<80	19	<=20	24	<=20	11
Mn (µg/L)	230	41	16	9	170	59	110	20	110	29	9	36	14	31	5	12
Mo (µg/L)																
Ni (µg/L)	200	59	80	47	63	51	230	114	25	22	76	45	85	74	95	55
Pb (µg/L)	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11	<=5	<=11
Se (µg/L)																
Si (µg/L)																
Ti (µg/L)																
V (µg/L)																
Zn (µg/L)	29	10	7	7	2	9	16	11	3	1	4	4	9	7	3	2
P (µg/L)	<=2	9	<5	8	10	18	<6	7	24	33	<=2	18	<=2	9	<6	9
NH <sub>3</sub> +NH <sub>4</sub> (µg/L)	44		<14		<8		20		28	124	36	74	10	34	20	
NO <sub>2</sub> (µg/L)	<1		<2		<2		<1		<2		<3		<1		<4	
NO <sub>3</sub> +NO <sub>2</sub> (µg/L)	45		90		40		<20		<=5	14	<=5	12	<5	10	50	
TKN (µg/L)	<=170	300	160	242	180	383	270	312	470	408	340	352	<=200	257	260	300
DOC (mg/L)	1.1	3.4	3.4	4.1	3.8	4.6	3.3	3.6	4.6	4.5	3.5	4.0	2.3	2.5	2.8	3.5

Appendix 1 - Water Chemistry

	Richard	Robinson	Silver	St. Charles	Sill	Tilton						
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 <sub>4</sub> (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 <sub>2</sub> (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	18.6	22.4	19.2		19.2		40.7		14.6
Be (µg/L)		<=0.03	<=0.03	<=0.03	<=0.02	<=0.03		<=0.03		<=0.03		<=0.02
Cd (µg/L)		<=0.6	<=1.0	<=1.0	<=1.3	<=1.0		<=1.0		<=1.0		<=0.8
Cr (µg/L)		<=1.0	<=1.0	<=1.0	<=1.0	<=1.0		<=1.0		<=1.0		<=1.0
Co (µg/L)		<=1.5	<=1.5	<=1.5	4.9	<=1.5		<=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	<=1.6	<=1.5	<=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		<=0.5
Sr (µg/L)		31.5	55.6	55.6	40.6	42.1		42.1		75.0		20.3
Ti (µg/L)		0.96	1.74	1.74	0.40	1.48		1.48		6.33		<=0.30
V (µg/L)		<=0.9	<=1.5	<=1.5	<=1.0	<=1.5		<=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 <sub>3</sub> +NH <sub>4</sub> (µg/L)	<=2		34	144	30	44	12	44	64	222	22	32
NO <sub>2</sub> (µg/L)	<=1		<3		<3		5		<2		<4	
NO <sub>3</sub> +NO <sub>2</sub> (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

	JOHNNIE			LONG			MCFARLANE			NEPAHWIN		
	A	B	C	A	B	C	A	B	C	A	B	C
pH	4.10	4.20	4.20	4.80	4.70	4.70	4.70	4.50	4.50	4.70	4.40	4.60
Loss on ign. (mg/g dry)	280.00	261.00	283.00	89.20	84.10	85.30	102.00	107.00	110.00	115.00	114.00	103.00
Carbon, Total Organic (mg/g dry)	140.00	130.00	140.00	46.00	42.00	41.00	49.00	51.00	52.00	58.00	55.00	57.00
Aluminum (µg/g dry)	29000.00	28000.00	27000.00	20000.00	19000.00	19000.00	16000.00	17000.00	17000.00	22000.00	22000.00	22000.00
Barium (µg/g dry)	52.00	62.00	63.00	120.00	120.00	110.00	37.00	26.00	33.00	20.00	22.00	19.00
Beryllium (µg/g dry)	<1.8	<1.6	<1.7	<1.1	<1.1	<1.1	<0.66	<0.7	<0.68	<0.88	<0.87	<0.88
Cadmium (µg/g dry)	5.10	4.20	5.00	4.60	4.80	4.40	6.40	7.10	6.90	9.80	10.00	10.00
Chromium (µg/g dry)	47.00	45.00	45.00	57.00	55.00	55.00	50.00	58.00	51.00	72.00	72.00	74.00
Cobalt (µg/g dry)	41.00	27.00	27.00	90.00	90.00	88.00	110.00	130.00	120.00	200.00	200.00	210.00
Copper (µg/g dry)	140.00	100.00	180.00	1300.00	1300.00	1200.00	1200.00	1200.00	1200.00	3200.00	2900.00	3200.00
Iron (µg/g dry)	42000.01	41000.00	28000.00	31000.00	30000.00	30000.00	32000.00	34000.00	33000.00	47000.01	44000.01	46000.01
Lead (µg/g dry)	130.00	97.00	150.00	110.00	110.00	110.00	110.00	120.00	110.00	270.00	260.00	280.00
Manganese (µg/g dry)	560.00	680.00	320.00	510.00	470.00	460.00	910.00	1100.00	970.00	1700.00	1700.00	1700.00
Molybdenum (µg/g dry)	<2	<1.3	<1.8	<=0.5	<=0.5	<=0.5	<0.74	<=0.5	<=0.5	2.60	2.80	2.90
Nickel (µg/g dry)	210.00	130.00	210.00	1400.00	1400.00	1400.00	2200.00	2400.00	2200.00	4400.00	4200.00	4600.00
Strontium (µg/g dry)	25.00	25.00	24.00	32.00	30.00	30.00	30.00	32.00	31.00	34.00	35.00	33.00
Titanium (µg/g dry)	530.00	430.00	480.00	720.00	750.00	780.00	720.00	750.00	740.00	760.00	770.00	730.00
Vanadium (µg/g dry)	62.00	59.00	56.00	45.00	43.00	44.00	40.00	41.00	41.00	53.00	53.00	53.00
Zinc (µg/g dry)	320.00	220.00	300.00	290.00	290.00	290.00	420.00	460.00	450.00	650.00	670.00	680.00

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

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 - <i>Rhinichthys atratulus</i>		X															
Bluegill - <i>Lepomis macrochirus</i>		X								X							
Bluntnose minnow - <i>Pimephales notatus</i>		X			X					X							
Brown bullhead - <i>Ameiurus nebulosus</i>		X					X	X		X		X	X			X	X
Burbot - <i>Lota lota</i>		X						X									
Cisco (lake herring) - <i>Coregonus artedii</i>		X								X	X		X	X		X	
Common shiner - <i>Luxilus cornutus</i>											X		X	X			
Fathead minnow - <i>Pimephales promelas</i>				X													
Golden shiner - <i>Notemigonus crysoleucas</i>					X							X		X			
Iowa darter - <i>Etheostoma exile</i>					X		X										
Lake chub - <i>Colestus plumbeus</i>														X			
Lake trout - <i>Salvelinus namaycush</i>		X			X	X		X		X	X	X		X			
Lake whitefish - <i>Coregonus clupeaformis</i>		X			X			X									
Largemouth bass - <i>Micropterus salmoides</i>		X	X		X						X		X				X
Logperch - <i>Percina caprodes</i>		X	X														
Mottled sculpin - <i>Cottus bairdi</i>		X															
Ninespine stickleback - <i>Pungitius pungitius</i>					X												
Northern pike - <i>Esox lucius</i>		X			X				X	X	X	X	X			X	X
Pearl dace - <i>Margariscus margarita</i>								X									
Pumpkinseed - <i>Lepomis gibbosus</i>		X		X	X	X				X			X			X	X
Rainbow smelt - <i>Osmerus mordax</i>		X	X					X		X						X	
Rock bass - <i>Ambloplites rupestris</i>		X	X							X						X	
Slimy sculpin - <i>Cottus cognatus</i>		X	X							X							
Smallmouth bass - <i>Micropterus dolomieu</i>		X	X	X	X	X		X		X	X	X	X	X	X	X	
Spoonhead sculpin - <i>Cottus ricei</i>					X												
Spottail shiner - <i>Notropis hudsonius</i>					X						X					X	
Trout-perch - <i>Percopsis omiscomaycus</i>		X			X											X	
Walleye (yellow pickerel) - <i>Sander vitreus</i>		X	X		X	X	X	X	X	X	X	X	X	X	X	X	X
White sucker - <i>Catostomus commersoni</i>		X	X		X	X	X	X	X	X	X	X	X	X	X	X	X
Yellow perch - <i>Perca flavescens</i>		X	X		X	X	X	X	X	X	X	X	X	X	X	X	X

## Appendix 4 - Walleye Harvest Statistics

Lake	Fishing Effort	Walleye Angler Success Rate	Number Harvested	Average Size of Walleye	Walleye Yield
McFarlane	784 angler-hours (5.6 hours·ha <sup>-1</sup> )	None caught	0 walleye		
Ramsey	9016 angler-hours (10.3 hours·ha <sup>-1</sup> )	0.403 walleye·hour <sup>-1</sup> (1 fish for 2 hours)	1738 walleye	283mm 181g	314kg (0.36kg·ha <sup>-1</sup> )
Vermilion	3491 angler-hours (3.2 hours·ha <sup>-1</sup> )	0.089 walleye·hour <sup>-1</sup> (1 fish for 11 hours)	59 walleye	291mm 225g	13kg (0.01kg·ha <sup>-1</sup> )
Whitson	1285 angler-hours (2.9 hours·ha <sup>-1</sup> )	None caught	0 walleye		



Appendix 5 - Zooplankton Species

Species Names	LITTLE RAFT		LOHI		LONG		MCFARLANE		MIDDLE		MINNOW		NEPAHWIN		RAFT		RAMSEY		RICHARD		ROBINSON		SILVER		ST. CHARLES		STILL		TILTON	
	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		
<i>Acanthocyclops vernalis</i>																														
<i>Alona</i> sp.																														
<i>Bosmina</i> 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	
<i>Ceriodaphnia</i> sp.		X																												
<i>Chydorus sphaericus</i>		*		X		*						X																		
<i>Cyclops scutifer</i>																														
<i>Daphnia ambigua</i>																														
<i>Daphnia pulex</i>																														
<i>Daphnia retrocurva</i>		X																												
<i>Daphnia mendotae</i>	*																													
<i>Daphnia</i> sp.																														
<i>Diacyclops bicuspidatus thomasi</i>																														
<i>Diaphanosoma birgei</i>	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	
<i>Epischura lacustris</i>													*																	
<i>Eubosmina longispina</i>																														
<i>Eucyclops agilis</i>																														
<i>Eurycerus lamellatus</i>													*																	
<i>Holopedium glacialis</i>	X	X			X																									
<i>Leptodiatomus minutus</i>	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	
<i>Leptodora kindtii</i>																														
<i>Macrocyclus albidus</i>																														
<i>Mesocyclops edax</i>		X											X	X																
<i>Orthocyclops modestus</i>														X																
<i>Polypheumus pediculus</i>																														
<i>Sida crystallina</i>																														
<i>Skistodiaptomus oregonensis</i>													X	X																
<i>Tropocyclops extensus</i>		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	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	
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	
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 = Species present  
 \* = Only one individual detected