Selected Headings for Chapter 9, The Past, Present and Future of Sudbury's Lakes

Chapter 9
The Past, Present and Future of Sudbury's Lakes

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Abstract

The City of Greater Sudbury contains a greater number and diversity of lakes than any other city in Canada. Approximately 12% of the 3637 km^2 area of the City of Greater Sudbury is occupied by 330 lakes, each over 10 ha. Most owe their location to the action of Pleistocene ice sheets that carried away the soil and scoured basins in the bedrock as they advanced, and then, as the ice melted, left behind dams of rock debris. Other lakes are variously controlled by other features: 2 possible meteorite impact craters; numerous faults and folds; a meandering, oxbow-forming river; man-made dams and water-filled abandoned pits.

Sudbury's lakes not only provide essential services such as drinking water and effluent disposal, but also create an impressive recreational and aesthetic asset that shapes the culture of the community. Unfortunately, a long history of industrial pollution, inadequate sewage disposal systems, urban runoff and a lack of public understanding about the impact of lakeshore development have seriously degraded many lakes. Most industrial contamination has been caused by widespread atmospheric deposition of acid-forming compounds and metallic particles from Sudbury's smelter stacks. Additional local effects have arisen from acidic and metal-rich runoff from tailings and waste rock. Fortunately, containment and treatment of mine-site wastewater has greatly improved and, more importantly, smelter stack emissions have been reduced by nearly 90% since 1970. Several modern sewage treatment plants have also been built. As a result of all these beneficial changes, many damaged lakes and their ecosystems are slowly recovering. However, other problems created by storm water discharges, nutrient enrichment, shoreline and watershed alteration, waste disposal, littering, and the introduction and invasion of exotic animal and plant species are serious in some lakes. Furthermore, impending global climate warming will complicate the recovery from acid precipitation and metal contamination, perhaps even reversing the trend toward biological improvements. Public and political awareness of the need to be active in protecting lakewater quality in Sudbury is growing and a water quality protection and improvement program, involving widespread monitoring and lake stewardship groups, is underway.

INTRODUCTION

Lakes lie scattered on the Sudbury landscape like raindrops on a window pane. There are 330 lakes, each measuring 10 ha or more (of which only 227 have official names) within the City of Greater Sudbury; there are also several hundred smaller lakes and ponds. All of Sudbury's named lakes are included and indexed on Map 3 (back pocket). Water covers 12.1% of the city; wetlands, such as swamps and marshes, cover another 4.2%. Seen from space (Photo 9.1), the most visible emblem of the area is Wanapitei Lake, which alone makes up almost a third of the total lake area. Sudbury, with its abundant lakes, is a microcosm of the Canadian Shield. The Shield is host to most of Canada's 1.5 to 2 million lakes (Schindler 1998).

Many visitors to Sudbury are surprised to find a "city of lakes", where swimming (Photo 9.2) and fishing (Photo 9.3) are part of everyday life, and where drinking water comes from a lake just a stone's throw from the downtown core (Photo 9.4). Within 12 km of downtown there are many lakes that have little or no shoreline development.

Despite their attractive appearance, Sudbury's lakes have been severely disturbed by pollution from industry, especially mining and smelting and, in some cases, by the effects of urban and shoreline development.

Ironically, just as industrial stress is abating and public interest in dealing with urban and residential development problems seems to be rising, the threat from global climate warming is looming. Until recently, scientific study of Sudbury's lakes was focussed on tracking their recovery from the stresses of the past. Now the challenge is to predict the future as global environmental stress interacts with the recovery process.

GEOLOGICAL CONTROL OF SUDBURY'S LAKES

Lakes on the Canadian Shield usually lie in a pattern that reflects the structure of the underlying bedrock, etched by hundreds of millions of years of weathering and recently scoured by successive sheets of slowly moving glacial ice.

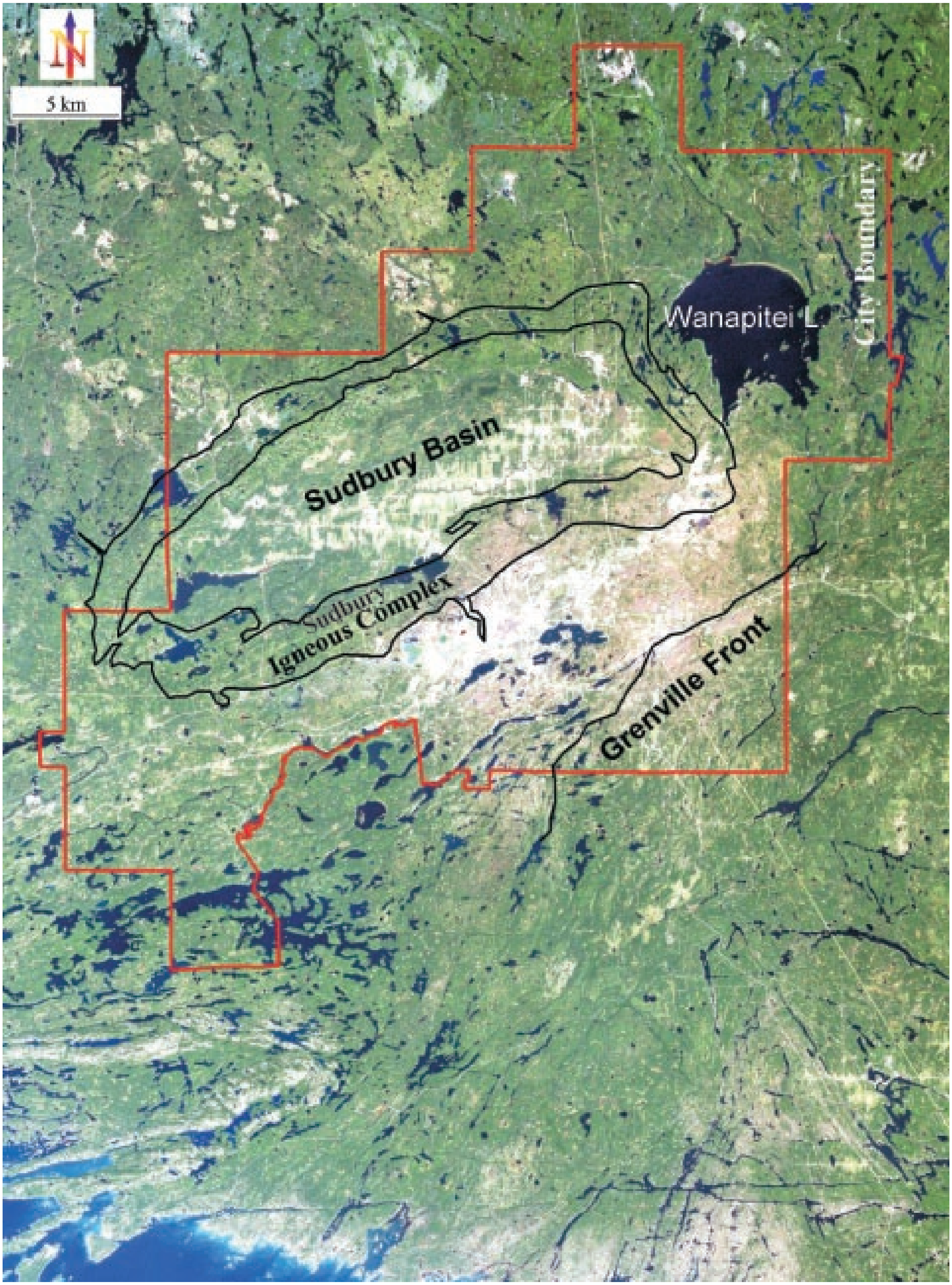

Photo 9.1. Landsat 7 satellite photo (August 27, 2000; United States Geological Survey) of the Sudbury area, showing the boundary of the City of Greater Sudbury and some major geological features.

Sudbury's lakes have been given their pattern by a more varied and dramatic geological history than any other city in Canada, and perhaps in the world. Two craters (the Sudbury Basin and Lake Wanapitei), both considered to be the result of meteorite impact; the eroded roots of a former, transcontinental mountain belt (the Grenville Orogen); and the flat bed of a 600 km^2 glacial lake make this part of the Canadian Shield a unique underlay for the city's lakes.

Photo 9.2. Sunbathers on the university beach, Lake Nepahwin.

Photo 9.3. Fishing in front of the Sudbury Yacht Club on Ramsey Lake.

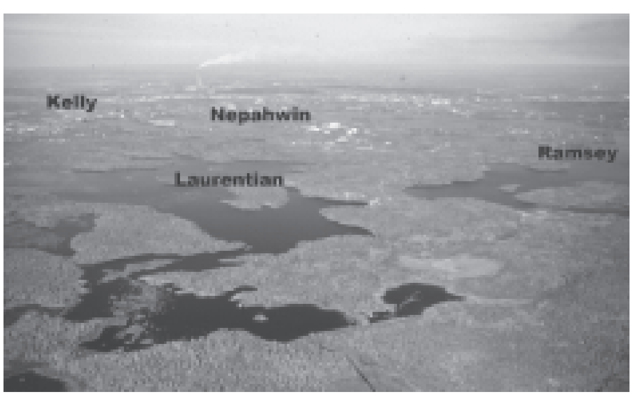

Photo 9.4. Lakes to the south of downtown Sudbury and the Copper Cliff smelter, looking west-northwest. The smelter stack is 10 km away.

Wanapitei Lake, the area's largest (13 257 ha) and most striking lake (its Ojibway name means "hollow molar tooth"; D.H. Rousell, personal communication, 2001), is framed by the northeast boundary of the city and fills a 37 million-year-old meteorite crater (Dence and Popelar 1972; Rampino 1999). As a result, no doubt, of its explosive rather than simply erosional origin, it is also the deepest lake in the Sudbury area (142 m).

One crater in the city would be remarkable enough, but prevailing geological opinion holds that the Sudbury Basin itself is also a meteorite crater (Dietz 1964), although much older (1850 Ma) than Lake Wanapitei and, therefore, considerably more eroded. The morphology of the Sudbury Basin and its surrounding rim of hills that form the North, East and South ranges (*see* Barnett and Bajc, this volume) exerts a strong influence on the distribution and shape of the lakes (*see* Map 3). The distinctive patterns of lakes in areas of different geological history outside the Sudbury Basin are largely influenced by faults and folds as well as differences in weathering between rock types and varying susceptibility to glacial scouring (*see* Photo 9.1).

The hilly, oval band of igneous rock that rims the Sudbury Basin supports some of Sudbury's most popular recreational lakes like Whitson, Whitewater, Fairbank and Windy (*see* Map 3). They and many smaller lakes, such as Nelson and Joe, and including the highest (but unnamed) in the city at 420 m, lie in scoured rock basins that are sometimes controlled by faults. For example, in the East Range near Capreol, a series of faults (Dressler 1984a) controls the orientation of a prominent, curved band of lakes, including Selwyn, Waddell and Ella on the west shore of Wanapitei Lake (*see* Photo 9.1). Dence and Popelar (1972) suggested that the concentric drainage pattern surrounding Lake Wanapitei might reflect the fracturing expected around a meteorite crater.

The most important controlling geological feature in the northeastern part of the Sudbury Basin rim is the 15 km long, south-trending fault that allows the Vermilion River to break through the North Range near Capreol. The Vermilion River then meanders to the west, along the base of the hills forming the North Range, before being joined by the Onaping River, turning south, spreading into Vermilion Lake and then cutting through the southwest rim of the basin.

Vermilion Lake is a small remnant of a 600 km^2 glacial lake that filled the Sudbury Basin 10 500 years ago when the last continental ice sheet was melting (*see* Bajc and Barnett, this volume). Fine sediment brought by the meltwater rivers that emptied into that unnamed lake filled any glacially scoured bedrock depressions in the lake floor and led to the flat, agricultural land of "the Valley". The Sudbury Basin lake drained into glacial Lake Algonquin through the gap in the South Range now followed by the Vermilion River. Small but spectacular oxbow ponds, formed by meanders in the loose sand and silt of the old lake bed, are characteristic of the Vermilion River flood plain (Photo 9.5).

The lakes most affected by the growth of Sudbury's urban core, such as Ramsey, Nepahwin and Kelly, are south of the Sudbury Basin. They lie in a belt of quartzite and gabbro hills between the South Range and a geologically well-known zone of intense faulting and folding (the Grenville Front Tectonic Zone) that includes the Grenville Front thrust fault. This continentally significant zone of mountain-building deformation stretches 1700 km to Labrador. Where the Grenville Front Tectonic Zone crosses the southeast corner of Sudbury it controls a prominent sequence of elongate lakes (Long, MacFarlane, Richard, Daisy and Baby; *see* Photo 9.1) South of the Grenville Front Tectonic Zone the lakes, for example Red Deer Lake, and rivers tend to follow the faults and folds in the eroded roots of the former mountains that now make up the Grenville geological province.

The city's southernmost lakes, dominated by Lake Panache (8958 ha) with its intricate shoreline and many islands, are just 25 km from the shore of Georgian Bay. They lie in scoured depressions in sedimentary strata near the foot of the La Cloche Mountains that dominate the skyline of nearby Killarney Provincial Park.

Glaciation not only scoured out rock basins but in some areas melting ice also left thick deposits of glacial sand and gravel (*see* Barnett and Bajc, Chapter 3, this volume). Near the Sudbury airport a group of so-called kettle lakes fill pit-like depressions in the gravel that mark the resting place of huge blocks of ice that were buried in the gravel as the ice front receded (Photo 9.6). Barnett and Bajc (Chapter 3, this volume) suggest that the ice blocks were part of the roof of a melt water tunnel in the ice sheet. When the thinning roof of the tunnel collapsed, huge blocks of ice were buried. Lakes were created as the stranded blocks of ice slowly melted.

Not all lakes in the Sudbury area are the result of geological forces. For example, water has filled several abandoned openpit mines (Photo 9.7), one of which, the Moose Mountain iron mine north of Capreol, has been used for fish farming. Lake Laurentian, a 157 ha lake that drains into Ramsey Lake, was formed by damming a creek to create waterfowl habitat within the Nickel District Conservation Authority property (*see* Photo 9.4).

WATERSHEDS AND WATERSHED UNITS

Watersheds in the City

Although lakes can be recognized as individual components of the landscape, they are also parts of linked systems or watersheds that include their surrounding drainage areas (*see* Map 3 and Photo 9.1). The Sudbury area is divided between 2 secondary watersheds of the Great Lakes and St. Lawrence System. To the east is the French River watershed, and to the west is the Spanish River watershed (Ministry of Natural Resources 1974). Two river systems, one in each watershed, are responsible for draining almost all of the area within the boundary of the city.

In the central and western part of the Sudbury area, the Vermilion River and its tributaries flow to the southwest as part of the Spanish River watershed. The confluence of the Vermilion and Spanish rivers is just west of the city boundary. The Spanish River then enters the North Channel of Lake Huron at the Spanish River Harbour, where high

Photo 9.5. Oxbow lakes on the Vermilion River north of Chelmsford, looking southeast across the boundary of Morgan and Balfour townships. It is approximately 5 km, as the crow flies, where the Vermilion River crosses the photograph.

Photo 9.6. Kettle lakes south of Sudbury airport, looking northwest. The field of view is 1 km; the right hand lake is approximately 250 m across.

Photo 9.7. The flooded Murray open pit with the Clarabelle Mill in the background, looking southeast. The Copper Cliff smelter is 6 km away.

concentrations of nickel and copper in the sediment are evidence of the Sudbury connection (Dixit et al. 1998).

Most of the water in the eastern part of the Sudbury area flows into the Wanapitei River that then joins the French River and drains into Georgian Bay. Although this system is much less contaminated by industrial runoff from Sudbury than the Spanish River to the west, it does receive water from the creeks that drain the area of the former Coniston smelter, closed in 1972. Sediment and water in the Wanapitei River show elevated nickel and copper concentrations until the confluence with the French River. At the confluence, dilution of the Wanapitei River by the French River lowers metal concentrations to regional background levels (Fitchko 1978).

A small area just inside the city boundary, immediately east of Lake Wanapitei, including Ashigami Lake, drains into the Sturgeon River, reaching Lake Nipissing at North Bay. Water leaves Lake Nipissing in the French River, flows south where it meets the Wanapitei River, thereby circuitously reuniting with water from the Lake Wanapitei area that had flowed directly south.

Watershed Units

The Vermilion River and Wanapitei River secondary watersheds can be divided into a large number of smaller areas depending on the purpose. For example, Jeffries et al. (1984), and Gunn et al. (2001) used individual stream catchments of just a few hectares in examining the water budgets and stream chemistry in the individual drainage basins of several acidified Sudbury lakes. Groups of connected lakes and their catchments make up informal watershed units. The 25 watershed units presented here (*see* Map 3) average about 150 km^2 and provide a framework for tracking the movement of contaminants in drainage basins. For example, as emissions of sulphur dioxide and metallic smelter dust have diminished in the last 30 years (Potvin and Negusanti 1995), the atmospherically deposited metal load to some watershed units, especially those more distant from the smelter stacks, may now be exceeded by the loss of metals carried downstream in dissolved and mobile phases. By the same token, other watershed units may now be impacted more by the arrival of waterborne metals from upstream rather than by previously dominant atmospherically deposited particles.

Emerging patterns of metal distribution can be anticipated as different components of the historical metal load are separated by weathering, soil complexation processes, and surface runoff. Such patterns have already been noticed on a small, single-stream catchment scale around Daisy Lake (Gunn et al. 2001). On a larger scale, the pattern will include depositional storage areas such as the deep basins of lakes (Pearson et al., Chapter 8, this volume), terrestrial rock basins and wetlands, in contrast to eroding slopes. Consideration of watershed units will provide a suitable framework for understanding and modelling the evolving physical, chemical and biological interactions in the terrestrial and aquatic environments around Sudbury. These same watershed units can also be useful for management purposes (Dillon and Evans 1995) and for encouraging public awareness of how one person's actions in a watershed can affect their neighbours.

ENVIRONMENTAL HISTORY AND PROGNOSIS

Glacial rebound during the last 10 000 years has progressively raised Sudbury by about 180 m relative to the southern tip of Ontario (Andrews 1989), thereby reversing the direction of once northerly flowing major rivers, like the French River, and draining the flooded postglacial landscape. Today the scattered, remnant lakes are in balance with the topography; however, like lakes everywhere they are dependent on rainfall and evaporation, both of which are predicted to change as global warming alters precipitation patterns and raises average air temperatures. Observation and computer modelling show that these changes are already occurring much faster than they did when the last ice sheet melted (Intergovernmental Panel on Climate Change 1990). It is perhaps ironic that as Sudbury's lakes are recovering from the local industrial stresses of the twentieth century, they are about to share in the effects of the global stresses of the twenty-first. Our lakes are entering a new chapter in their environmental history.

Pre-Settlement

Although scientific records of Sudbury's lakes only date back to the late 1950s (Gordon and Gorham 1960), pre-settlement environmental conditions have been studied using the siliceous remains of diatom and chrysophyte algal species preserved in lake sediment. Study of the diatom and chrysophyte communities in 72 Sudbury area lakes of varying acidity, nutrient and metal concentrations (Dixit et al. 1989, 1992) has provided a tool for inferring past lakewater characteristics from assemblages of species preserved in sediment cores dated for ^{210}Pb. Interpretation of algal assemblages in cores that represent about 150 years of sedimentary and biological history from a dozen lakes in the city has shown that in the pre-industrial period they were slightly acidic to neutral, with low levels of nutrients and trace metals (Dixit et al. 1991; Smol et al. 1998). In other words lakes in the area were typical of those elsewhere on the Canadian Shield.

The Impact of Industrial Environmental Stresses

The chemical composition of lakewater provides a revealing indicator of the impact of various environmental stressors. A survey of 37 Sudbury lakes in 1990 illustrated the range of chemical values and concentrations found within about 20 km of the downtown core (Table 9.1). This chemical snapshot of lakes that had just over a decade to respond to significant emission reductions (Keller et al. 1992), provides a useful baseline against which to measure subsequent change. A new water quality monitoring program is being initiated at the time of writing and future data will be available to the public on a website.

The most important industrial stresses on the chemistry and biology of lakes in the Sudbury area have been erosion, acid deposition and metal contamination as a result of the logging and the mining industries. Smaller industries such as sawmills and a creosoting plant added to the problem. These stresses did not operate alone; rather they interacted with each other in their effect on water quality and aquatic ecosystems. Acidity of surface water, for example, increases the solubility of metals, and a lack of organic matter in soil reduces the capacity of the soil to bind metals such as copper.

EROSION

Intense logging, forest fires and strongly acidic fumes from open roasting of ore combined to destroy the vegetation over a large part of the Sudbury area beginning in about 1875 and accelerating as mining and smelting expanded (Winterhalder 1995, Chapter 7, this volume). Loss of plant cover left the soil exposed and at its peak, erosion may have increased by two orders of magnitude over the normal rate in this part of the continent. During spring runoff in the early 1970s as much as 1000 $m^3/km^2/yr$ of sediment was eroded from denuded slopes (Pearce 1976). The hills north of Kelly Lake show the severity of the erosion (Photo 9.8).

Large volumes of sediment suddenly being washed into lakes resulted in siltation and severe damage to shoreline habitat as well as a rapid increase in sedimentation rate and loss of habitat for bottom-dwelling organisms. Some small shallow lakes may well have been sufficiently overwhelmed by sediment that they were converted into wetlands. By the same token, some wetlands were likely to have been choked, resulting in loss of habitat and water storage ability. In one of the most affected lakes, Kelly Lake, massive delta growth occurred (*see* Photo 9.8). The hydrology of the inflowing creek was radically altered by increased peak flow volumes because of rapid runoff during spring melt and after rain-

Table 9.1 Water quality data from a 1990 survey of 37 lakes within 20 km of the Copper Cliff smelter (Co-operative Freshwater Ecology Unit data).

Lake	pH	Cond.	Alk. mg/L	SO_4^{2-} mg/L	Cu µg/L	Ni µg/L	Zn µg/L	Fe µg/L	Mn µg/L	Al µg/L	Ca mg/L	Mg mg/L	Na mg/L	Cl mg/L	D.O.C. mg/L
Bennett	6.67	51.0	10.16	8.93	26.0	100.0	6.5	1200.0	90.0	32.0	4.5	1.4	1.3	1.1	4.8
Bethel	7.38	472.0	58.99	13.02	18.0	62.0	4.9	250.0	380.0	29.0	21.2	8.6	56.4	96.2	6.9
Bibby	6.10	39.9	3.94	9.04	14.0	58.0	10.0	860.0	220.0	60.0	3.1	1.3	1.1	0.5	4.4
Broder 23	6.40	42.0	2.13	12.43	11.0	77.0	7.3	20.0	37.0	10.0	3.6	1.2	1.1	0.5	2.8
Brodill	6.02	44.0	1.01	13.62	20.0	110.0	12.0	98.0	87.0	110.0	3.4	1.2	1.1	0.6	1.7
Camp	6.41	42.0	1.84	13.39	12.0	100.0	9.3	24.0	23.0	21.0	3.9	1.2	1.1	0.5	1.9
Chief	4.80	39.9	-1.50	12.16	31.0	120.0	17.0	40.0	130.0	180.0	2.3	0.8	1.0	0.5	0.7
Clearwater	4.71	84.0	-0.83	17.56	47.0	180.0	25.0	46.0	290.0	140.0	6.5	1.4	3.2	10.0	0.5
Crooked	4.41	98.0	-1.54	28.33	120.0	460.0	41.0	120.0	220.0	370.0	6.7	2.1	2.2	4.4	0.3
Crowley	6.32	42.0	1.80	13.14	14.0	100.0	9.1	28.0	67.0	24.0	3.9	1.2	1.1	1.8	2.3
Daisy	4.67	60.0	-0.98	21.05	87.0	370.0	22.0	25.0	200.0	330.0	4.0	1.4	1.4	0.9	0.8
Forest	5.84	49.0	0.83	14.22	17.0	130.0	13.0	30.0	57.0	38.0	3.8	1.2	1.4	1.6	2.4
Grant	7.21	320.0	36.21	21.85	8.1	89.0	4.7	20.0	180.0	10.0	18.4	5.6	33.6	59.0	3.5
Hannah	7.12	338.0	13.86	34.22	20.0	200.0	59.0	20.0	83.0	10.0	15.7	5.3	47.0	82.5	3.6
Johnny	6.57	348.0	5.47	34.41	22.0	230.0	11.0	120.0	51.0	15.0	14.6	4.9	38.9	73.4	3.7
Kelly	7.42	1780.0	50.18	732.05	39.0	400.0	14.0	42.0	130.0	86.0	222.0	21.9	127.0	0.0	2.4
Lady Macdonald	4.39	715.0	-3.20	309.80	300.0	9100.0	210.0	420.0	470.0	790.0	77.8	28.6	19.8	29.7	2.4
Laurentian	6.25	47.0	5.63	11.03	61.0	95.0	8.5	300.0	61.0	53.0	3.6	1.4	1.8	1.7	7.1
Linton	5.79	44.0	0.54	14.27	19.0	130.0	13.0	58.0	57.0	63.0	3.7	1.1	1.1	0.4	2.4
Little Raft	6.85	65.0	10.13	14.98	12.0	110.0	8.9	190.0	150.0	19.0	6.1	1.9	1.6	1.3	1.7
Lohi	4.64	92.0	-0.84	20.60	90.0	250.0	36.0	39.0	260.0	170.0	6.8	1.8	3.6	9.9	0.5
Long	7.33	168.0	17.00	20.64	15.0	88.0	9.0	45.0	17.0	23.0	11.1	3.4	13.6	24.8	3.0
McFarlane	7.54	327.0	35.59	21.99	8.4	72.0	2.8	20.0	5.7	10.0	18.2	5.4	35.0	59.9	3.6
Middle	6.81	261.0	7.18	27.62	21.0	250.0	15.0	20.0	16.0	10.0	11.1	3.8	28.6	53.1	3.2
Minnow	7.48	969.0	71.81	46.69	9.5	120.0	19.0	92.0	340.0	31.0	37.6	8.9	139.0	232.0	4.5
Nepahwin	7.46	531.0	32.20	30.22	17.0	86.0	9.5	25.0	5.1	25.0	21.4	6.8	70.1	115.0	3.4
Perch	6.51	56.0	4.73	15.10	18.0	86.0	6.5	240.0	62.0	38.0	4.2	1.9	1.6	7.0	5.0
Pine	4.56	46.0	-1.65	14.25	47.0	140.0	13.0	160.0	120.0	250.0	2.1	0.7	0.9	0.5	0.4
Raft	6.77	52.0	4.24	15.30	11.0	95.0	8.1	20.0	5.1	10.0	4.8	1.5	1.2	0.7	1.9
Ramsey	7.45	321.0	26.81	26.38	28.0	110.0	6.1	22.0	5.0	26.0	17.5	5.4	36.1	60.4	3.0
Richard	7.12	181.0	18.19	19.16	14.0	120.0	5.3	20.0	26.0	28.0	11.9	3.6	17.9	31.2	2.1
Robinson	7.06	772.0	45.60	36.21	35.0	210.0	19.0	250.0	230.0	78.0	24.9	8.0	83.9	147.0	4.5
Silver	4.17	384.0	-2.70	41.39	410.0	770.0	94.0	55.0	190.0	1100.0	9.9	3.7	47.5	81.4	0.4
St. Charles	6.99	249.0	11.28	34.35	27.0	220.0	18.0	66.0	98.0	20.0	13.2	5.2	21.0	37.4	4.1
Still	7.08	833.0	36.81	37.09	20.0	220.0	39.0	220.0	310.0	80.0	28.0	0.9	117.0	212.0	8.6
T / Dill	6.17	68.0	3.89	18.49	21.0	130.0	16.0	480.0	76.0	110.0	5.3	2.3	1.7	2.1	5.3
Tilton	5.80	60.0	0.82	16.18	16.0	110.0	14.0	45.0	82.0	72.0	5.2	1.4	1.8	3.8	1.9

Abbreviations: Cond., conductivity; Alk., alkalinity (milligrams per litre of $CaCO_3$); D.O.C., dissolved organic carbon.

storms (*see* Pearson et al., Chapter 8, this volume). On the other hand, low flow volumes were no doubt diminished during dry periods because of the absence of water that would normally have been released slowly from the soil cover.

Erosion also alters lake water chemistry through such factors as a lower contribution of dissolved organic carbon from forest soil, and increased dissolved elements such as phosphorus from eroded mineral soil. An added disturbance related to erosion is the warming of runoff water because of the high thermal capacity of rock surfaces compared with vegetation. However, the implications of warm in-flowing water for the physical and biological features of lakes are still poorly understood.

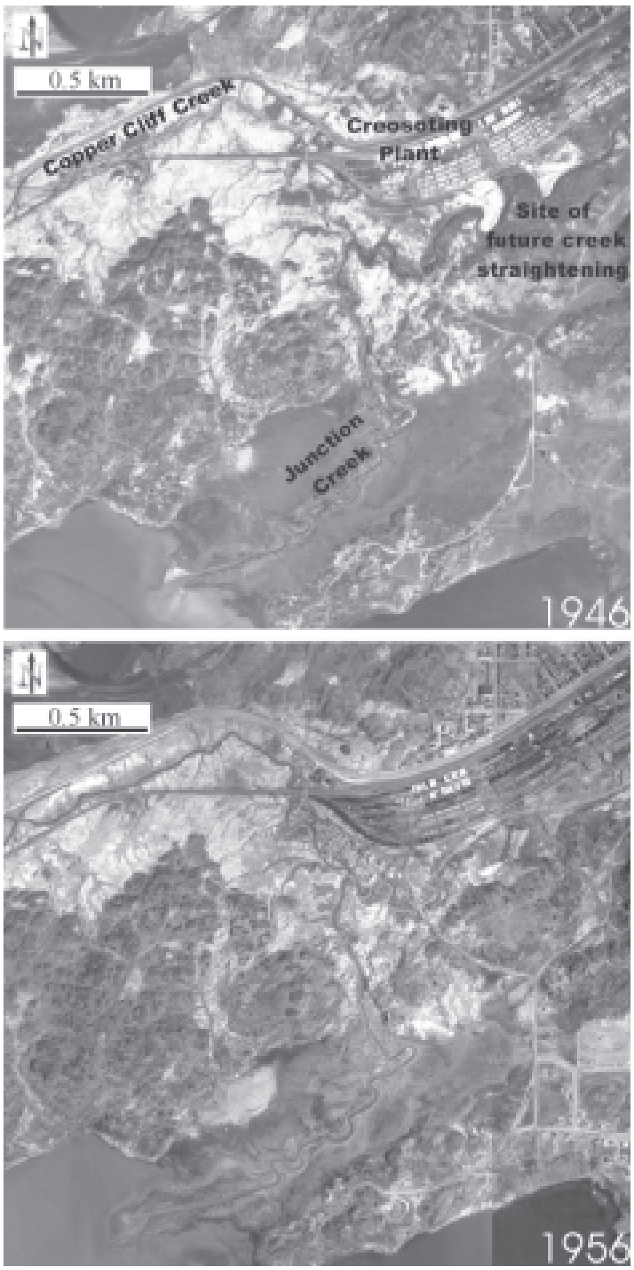

Photo 9.8. The Junction Creek delta entering Kelly Lake; note the creosoting plant, and the location of straightened meanders in Junction Creek.

ACID DEPOSITION

Interpretation of diatom and chrysophyte assemblages indicates that many lakes over a wide area in the Sudbury region have been moderately to severely acidified for some period of their recent history (Dixit et al. 1992; Smol et al. 1998). An estimated 7000 of the lakes within a 17 000 km^2 area almost completely encompassing the City of Greater Sudbury, were acidified to pH 6.0 or below in the 1980s (Neary et al. 1990; Figure 9.1). This is the level at which damage to sensitive aquatic organisms can be expected. An excess of sulphate ions in these lakes and the location of the most intensive acidification close to the smelter stacks, indicated that sulphurous emissions from the Sudbury smelters were largely responsible. It was not a surprising conclusion considering that Sudbury was then one of the largest point sources of sulphur dioxide on the planet (Potvin and Negusanti 1995). The extent of the acidification, however, was not just the downwind expression of emission plumes but also reflected the natural buffering capacity of the lakes receiving acidic deposition. This is especially evident to the east of Sudbury (*see* Figure 9.1).

A detailed examination of the algal record in 22 lakes (Dixit et al.1995) showed that acidification began around 1930, when the tall stacks were built in Copper Cliff. Acidification intensified until the 1970s when recovery began after dramatic reductions in sulphur dioxide emissions from the Sudbury smelters (Figure 9.2). Some of the most acidic lakes, such as Silver Lake with a pH in 1990 of 4.0, are less than 10 km from the Copper Cliff smelters, but distance alone is clearly not the controlling factor (Figure 9.3). Indeed, most lakes near the smelters were never acidified, even though they received a heavy dose of sulphur dioxide through both acid precipitation and direct, dry fumigation of their watersheds (Keller and Gunn 1995). In 1990 only 11 of 37 lakes close to the Copper Cliff smelter in the urbanized and residential area of the city were found to have a pH < 6.0 (*see* Table 9.1, Figure 9.3; Keller and Gunn 1995; Keller et al. 1999). It appears that larger lakes, with a longer flushing time, were more resistant to acidification. Some lakes even became more alkaline (Smol et al. 1998). For example, from the diatom record in its sediment, the inferred pre-industrial pH for Ramsey Lake is 6.6. While other lakes acidified, Ramsey's pH rose to 7.7 in the 1980s (Dixit et al. 1996).

Although the causes remain to be determined, the variation in pH in Sudbury lakes illustrates that the alkalinity budget of a lake does not depend only on the composition of the precipitation but also on the complex interaction of watershed weathering and in-lake chemistry (Keller et al. 1999), especially at the sediment water interface. Schindler (1986) noted that the conversion of sulphate to sulphide in the presence of degradable organic matter in lake sediment generates alkalinity. Dixit et al. (1996), in their study of long term water quality changes in Ramsey Lake, listed chemical sulphate reduction as a potential explanation of the pH history of that lake. They emphasized that Ramsey Lake is known to have seen algal growths attributable to poorly

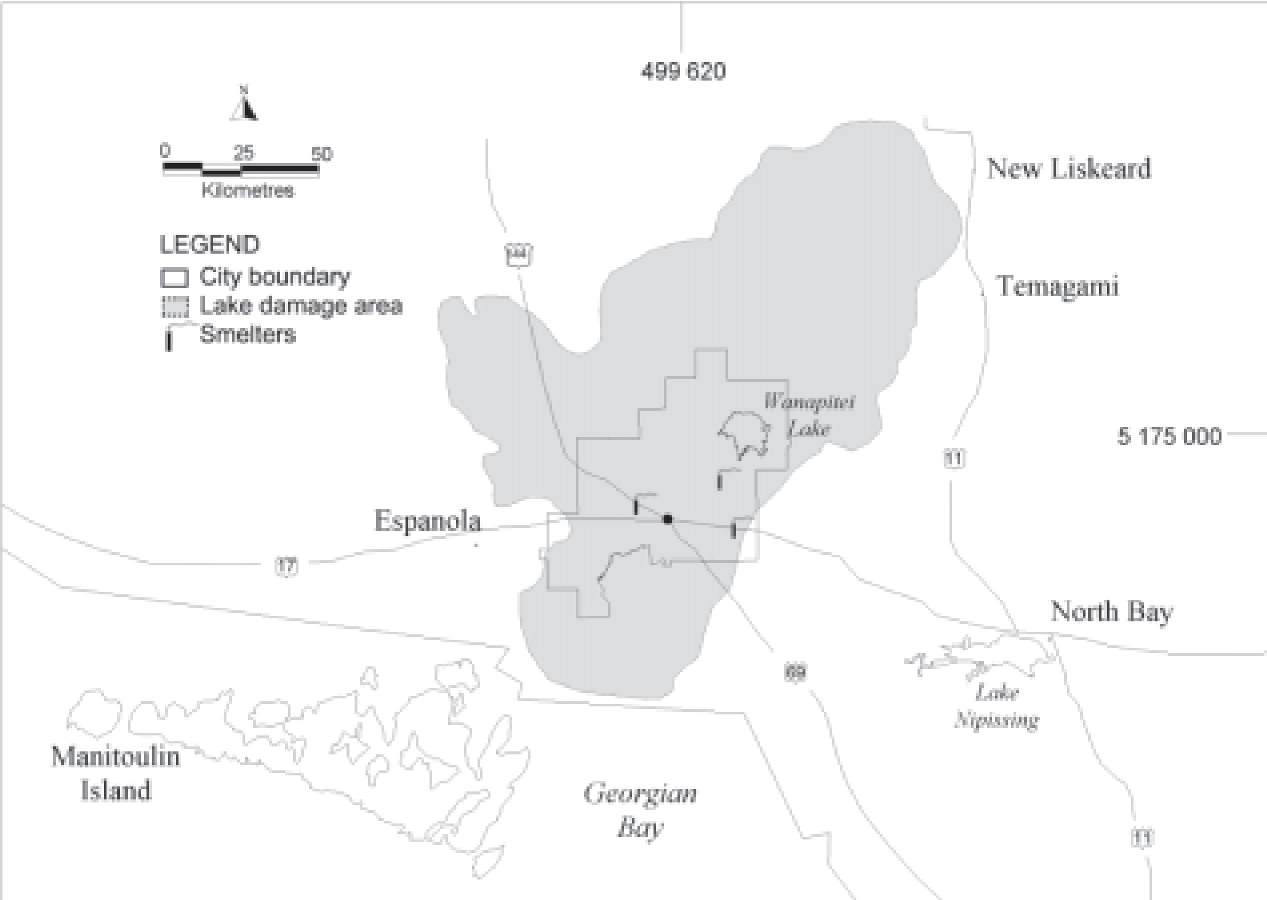

Figure 9.1. Extent of acidified lakes with a pH < 6.0 in the 1980s (*after* Neary et al. 1990).

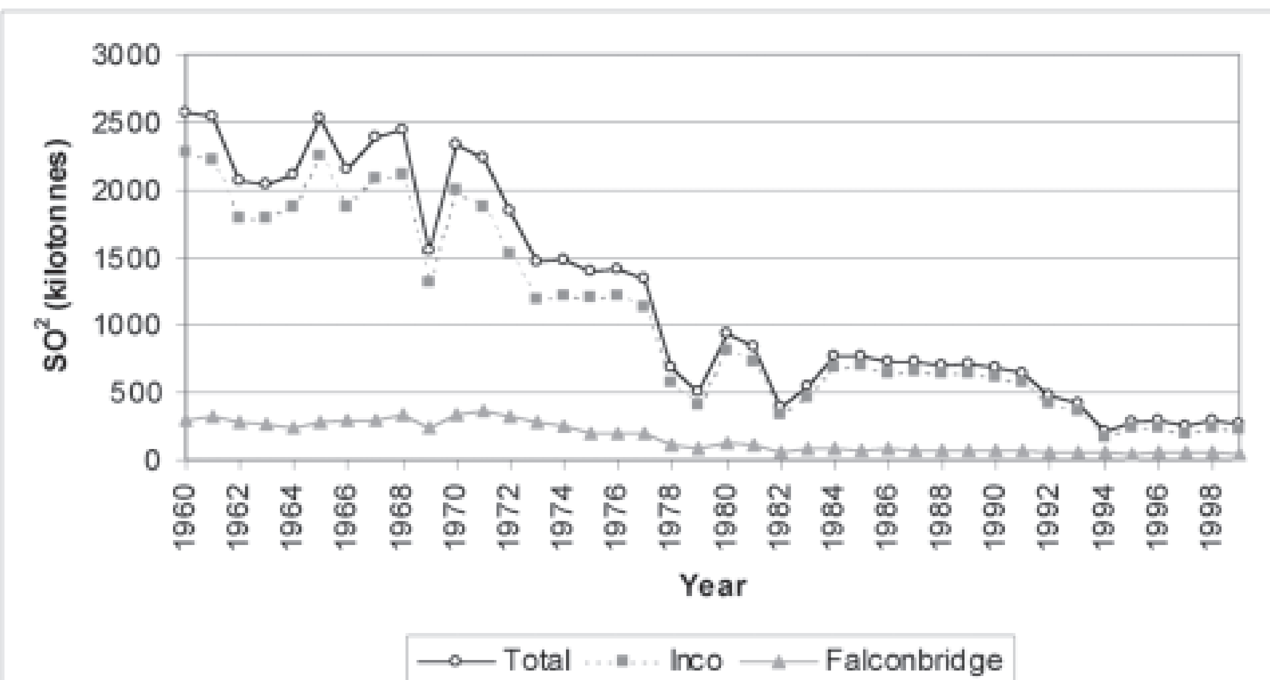

Figure 9.2. Sulphur dioxide emissions from Sudbury smelters 1960–1999 (company data as provided to the Ministry of the Environment).

functioning septic systems (Dolson and Niemi 1989) and that this could have supplied the organic matter required for sulphate reduction.

The Ramsey Lake watershed includes extensive exposures of gabbro, which are rich in the easily weathered, calcium-containing minerals plagioclase and pyroxene (Card 1978). It is not difficult to find outcrops where evidence of up to 0.5 cm of industrially induced weathering is visible. With the gabbro typically containing 10% CaO by weight (Card 1978), weathering at that rate would have released about 100 g of dissolved calcium/ha/yr during 80 years of acidified precipitation, with a clear impact on the base cation and alkalinity budget of the lake. The increase in the naturally high carbonate content in Ramsey Lake sediment from 15 to nearly 40%, beginning in 1920 (Dixit et al. 1996), is most reasonably interpreted as a reflection of accelerated calcium weathering, a process that is, itself, acid consuming. However, not all Sudbury lakes with gabbro exposed in their catchment areas have followed the path shown by Ramsey Lake (Jeffries et al. 1984). The net result of several interacting factors is obviously lake specific and the dominant effect of the smelters was to cause a decline in lake water alkalinity and pH throughout the Sudbury area.

A 1996 survey of acidity in 123 lakes in Sudbury identified 24 with a pH still < 6.0 (Co-operative Freshwater Ecology Unit, unpublished data, 1996). Results in subsequent years (Figure 9.4) from Clearwater, Crooked, Silver and Tilton lakes show that the number of low pH lakes is decreasing. Some small, isolated, severely acidified lakes, such as Silver Lake, are recovering only very slowly and the extent of persistent acidification remains to be determined. Now that local emissions of sulphur dioxide have been

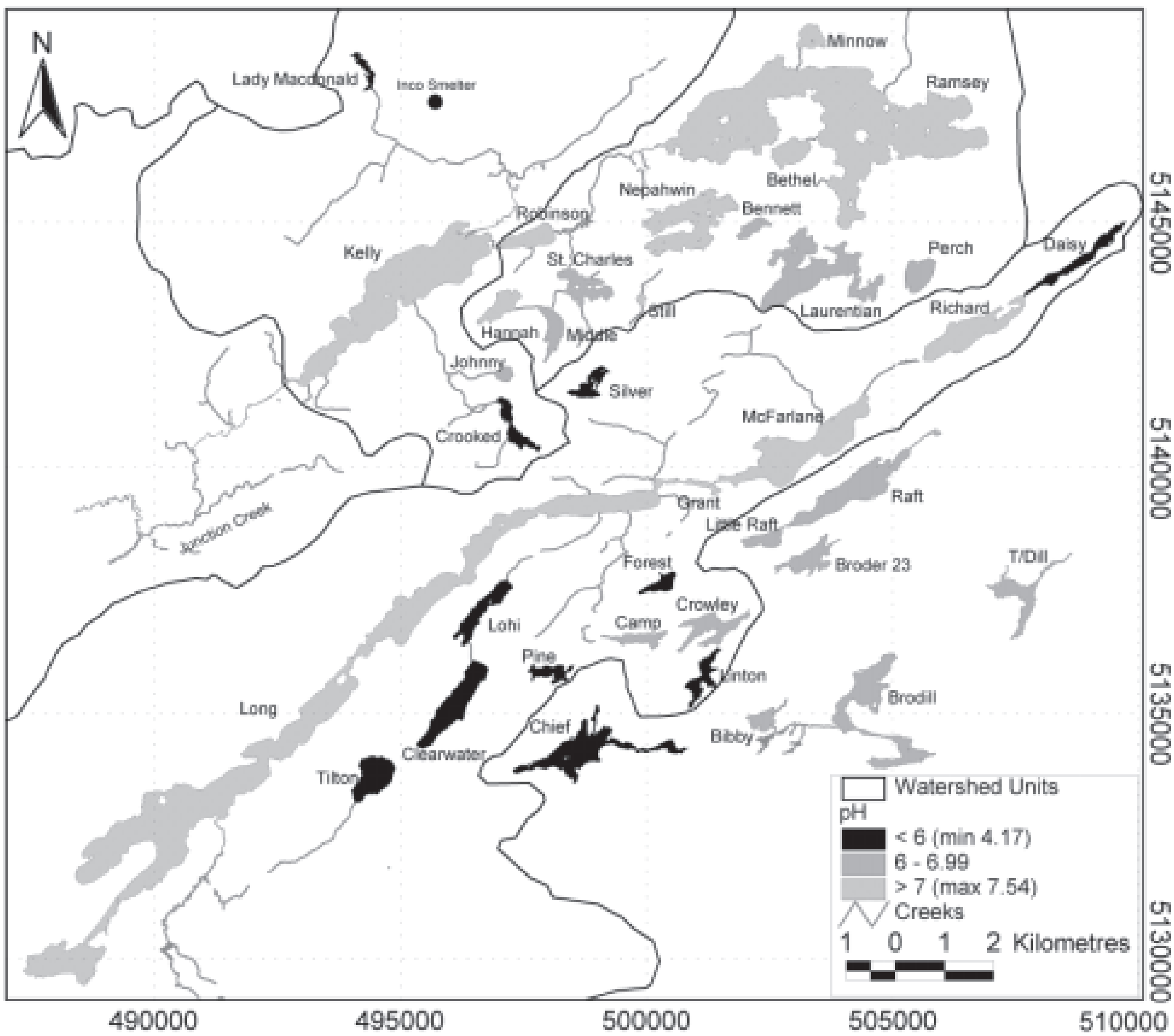

Figure 9.3. Levels of pH in 37 lakes within 20 km of the Copper Cliff smelter (1990).

greatly reduced (Bouillon 1995), the relative contribution of long range transport from the northeastern United States has become more significant (Keller et al. 2001).

METAL CONTAMINATION

Metal concentrations in both the sediment and the water of most Sudbury area lakes have been raised above the natural background by airborne metallic dust carried up the stacks of smelters and refineries by hot gasses. Metals in the water draining from waste rock piles and tailings have also contaminated some lakes, such as those in the Junction Creek system. Lakes near the centre of the city all show the effect of atmospheric deposition of metallic dust. In 1990 concentrations of copper and nickel in water approached or exceeded Provincial Water Quality Objectives of 5 µg/L for copper and 25µg/L for nickel (Ministry of the Environment 1984; Keller et al. 1999) in all lakes within 20 km of the Copper Cliff smelter (Figures 9.5, 9.6). The sediments of most of these lakes also have concentrations of metals that far exceed Ontario government biological effects guidelines (Semkin and Kramer 1976; Ministry of Environment and Energy 1993; Keller et al. 1999).

Metal concentrations in the water of some deeper lakes that stratify in the summer and have plentiful organic matter in their sediment, are strongly influenced by sediment-water interactions. Metals can be either stored or released into the water depending on several microbiological and chemical factors, especially the dissolved oxygen content of the bottom water (Belzile and Morris 1995). For example, manganese is known to be released from sediment under these conditions (DiToro 2001) and manganese concentrations in the deep water at the eastern end of Ramsey Lake rise as dissolved oxygen decreases in the winter (Pearson, unpublished data, 2000). This probably explains the manganese-related discolouration of the drinking water from the David Street Water Treatment Plant, which until recently drew its water from the deepest part of Ramsey Lake. It is significant that the problem was ameliorated when the water in-take was raised (Paul Graham, personal communication, 2001).

One especially contaminated lake, Kelly Lake, receives treated wastewater from the Copper Cliff smelter site. It also receives metals from several other tributaries via Junction Creek as well as through the atmosphere and from the Sudbury Sewage Treatment Plant. Sediment in Kelly Lake has high concentrations of rare metals such as palladium, iridium and platinum (Crocket and Teruta 1976) as well as being heavily contaminated with copper and nickel. However, concentrations of copper and nickel have declined since peaking in the 1960s and 1970s (*see* Pearson et al., Chapter 8, this volume).

The high concentration of metals in the water column and sediments in Sudbury's most contaminated lakes has probably created toxic conditions for many aquatic species (Campbell and Stokes 1985; Spry and Weiner 1991; Wren and Stephenson 1991). This may be the reason why certain sensitive bottom-dwelling invertebrates, such as the amphipod *Hyalella azteca,* are absent from many relatively high pH lakes where they might otherwise be expected (Gunn and Keller 1995; Borgmann et al. 2001). The common, sediment-burrowing mayfly *Hexagenia* is absent from Ramsey, Nepahwin, McFarlane, and Long lakes, the only Sudbury urban lakes surveyed for this species to date (W. Keller, unpublished data, 1995). Although the most toxic sediment may slowly be buried under layers of less contami-

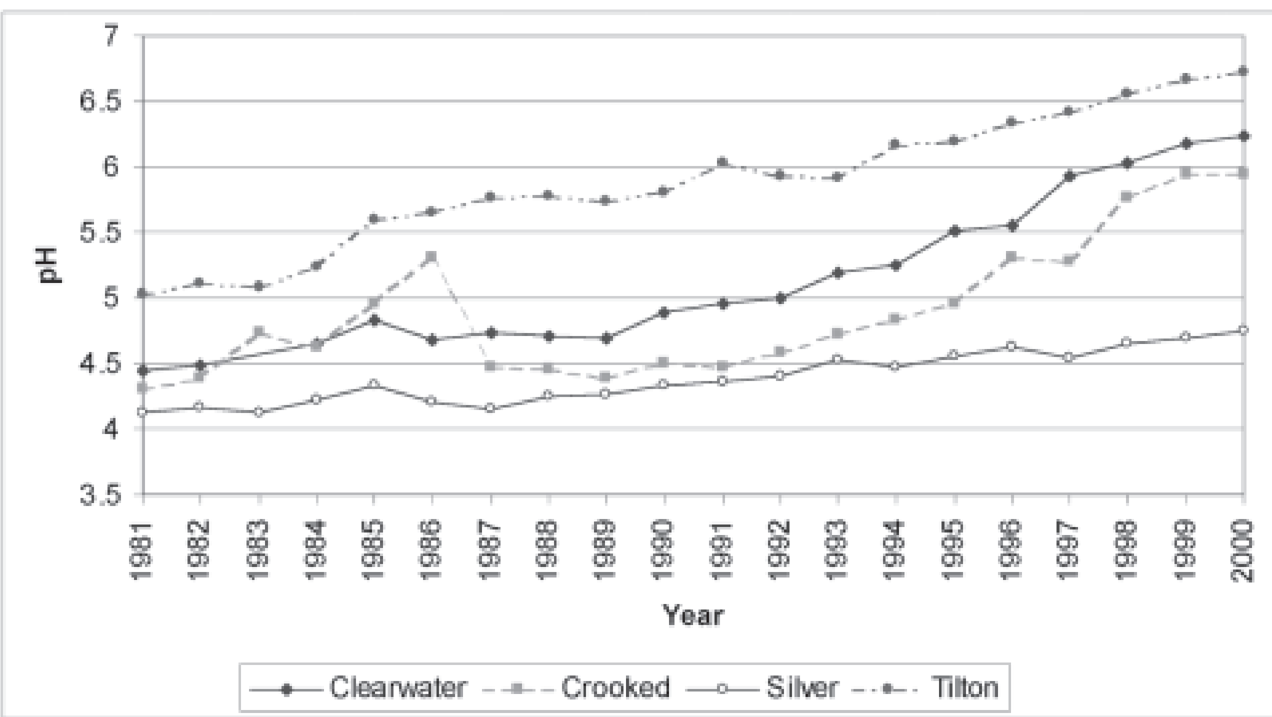

Figure 9.4. pH records from 1981–2000 for 4 acidified Sudbury lakes.

nated material, sediments may long continue to be biologically impoverished habitats in Sudbury's lakes.

SAWMILL WASTE

The demand for lumber from the railway and construction industries led to the building of sawmills on several Sudbury lakes and streams including Minnow Lake, Ramsey Lake and Junction Creek (Wallace 1993). The mill on Minnow Lake operated for 23 years and during that period sawdust and wood waste were dumped in the southwest bay of the lake (Photo 9.9). Approximately 1 to 2 m is still slowly decaying on the bottom of the lake, contributing to the excessive consumption of dissolved oxygen and hence poor water quality (Regional Municipality of Sudbury and the City of Sudbury 1991).

CREOSOTE SPILLS

Between 1921 and 1960 one of the largest creosoting plants in eastern Canada operated on the western edge of downtown Sudbury, approximately 800 m north of Junction Creek and 3 km upstream from Kelly Lake (*see* Photo 9.8). Creosote that leaked from the site evidently reached Junction Creek through a small storm water course (Stantec Consulting Ltd., unpublished report prepared for the City of Sudbury, 2000). Creosote is now found in lake sediment near the mouth of Junction Creek and in the silt of the vegetated delta top (*see* Pearson et al., Chapter 8, this volume; Bova 2001). Being denser than water, the creosote obviously travelled downstream along the bed of the creek to Kelly Lake where it was incorporated by wave action into shoreline sediment.

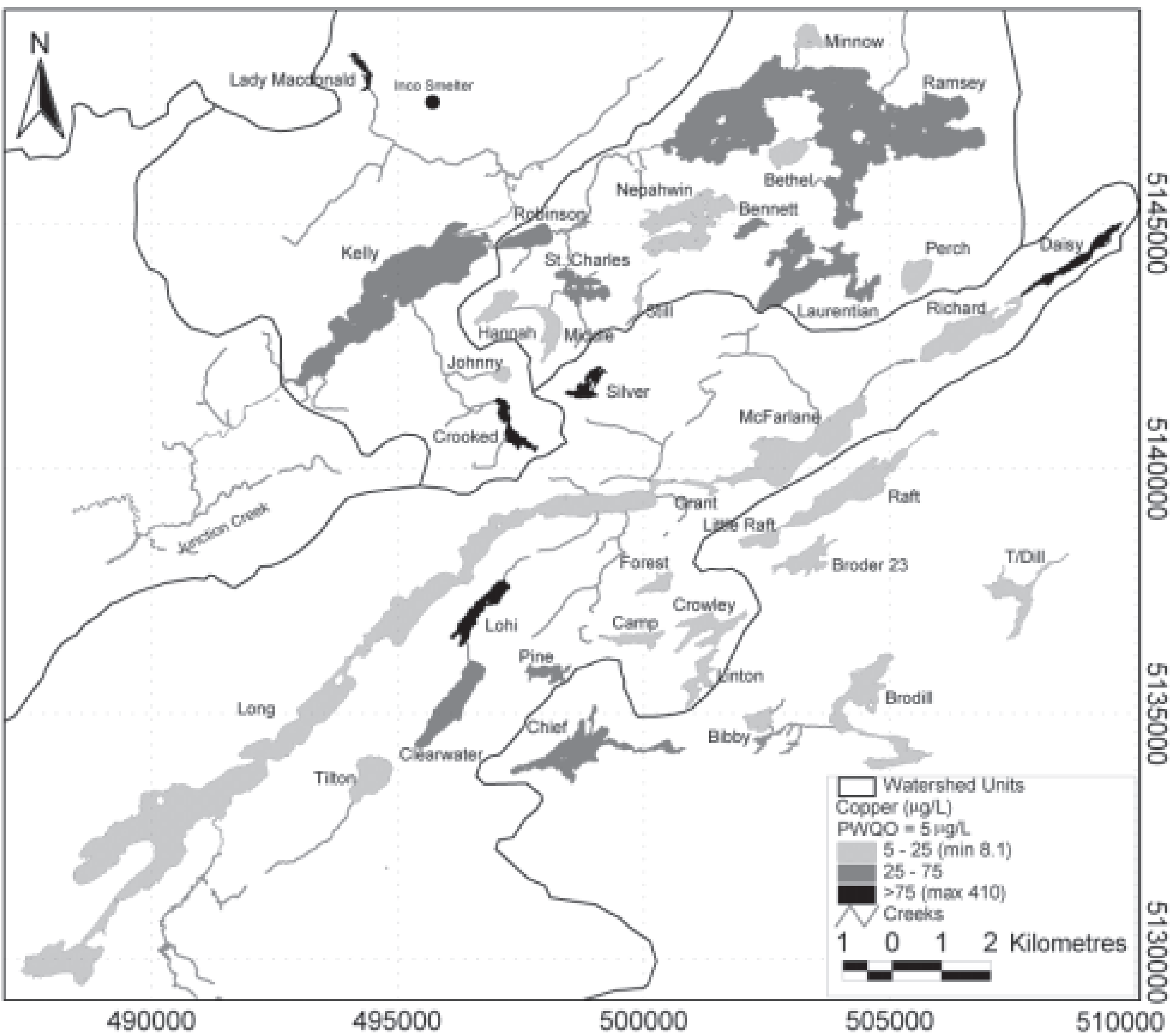

Figure 9.5. Copper concentrations in 37 lakes within 20 km of the Copper Cliff smelter (1990). Abbreviation: PWQO, Provincial Water Quality Objectives.

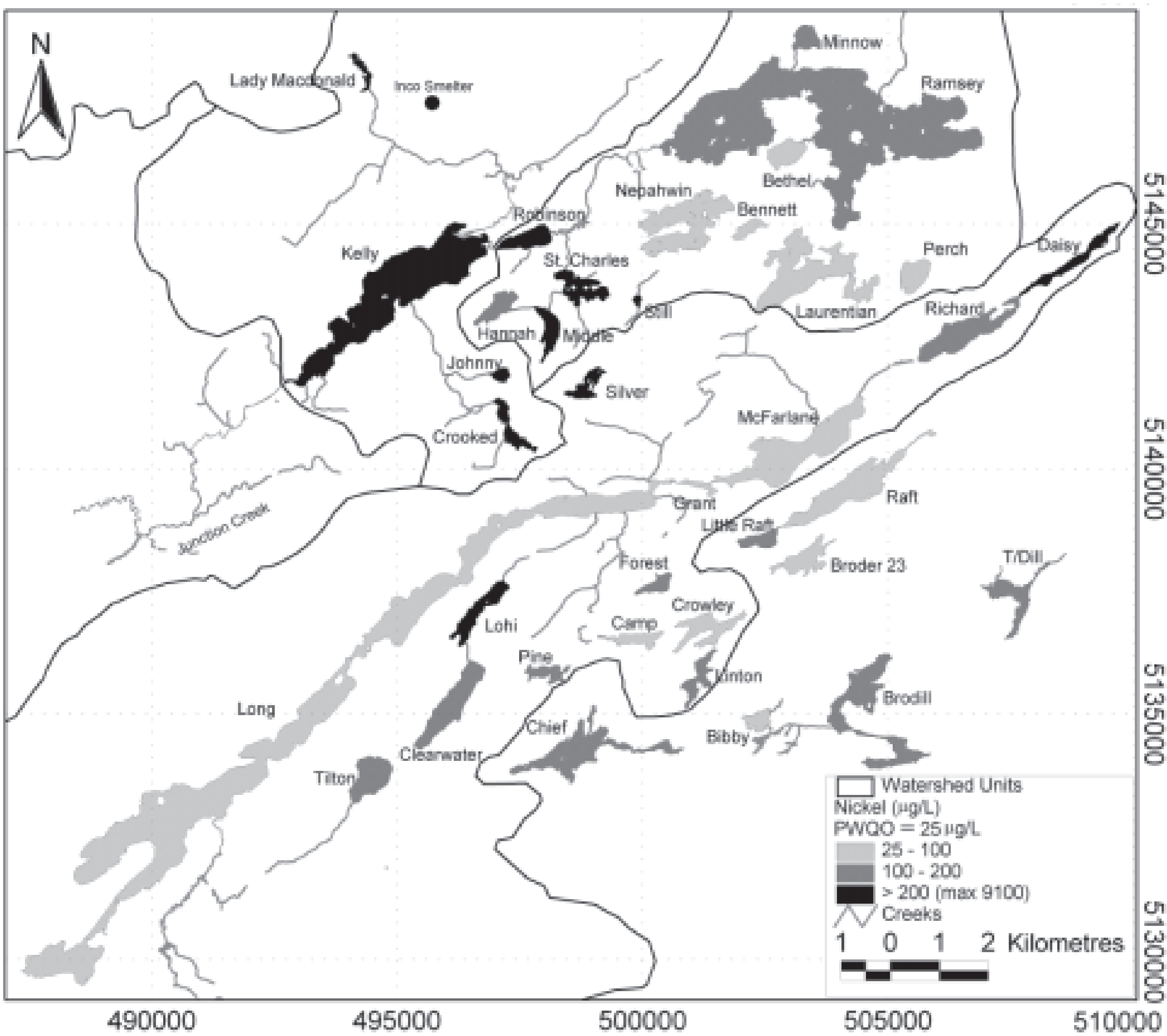

Figure 9.6. Nickel concentrations in 37 lakes within 20 km of the Copper Cliff smelter (1990). Abbreviation: PWQO, Provincial Water Quality Objectives.

Urban Environmental Stresses

Environmental stresses resulting from industrial activity can almost always be related to specific point sources such as smelter stacks. Most of the lake-related environmental consequences of urban and residential development, with the exception of sewage treatment plant effluent, are the result of diffuse and multiple sources of contamination as well as widespread public attitudes and behaviour. They are often more difficult to measure but as regulations and technology have reduced the impact of industry on Sudbury's lakes, urban and lakeshore development stresses are becoming more significant. The most important of them are oversupply of nutrients from municipal sewage effluent and private septic systems; storm water contamination; shoreline alteration; altered hydrology, especially in relation to flow volumes and timing; and the introduction and invasion of exotic species.

NUTRIENT ENRICHMENT

Eutrophication is a process whereby lakes store and internally recycle nutrients received from their drainage basins.

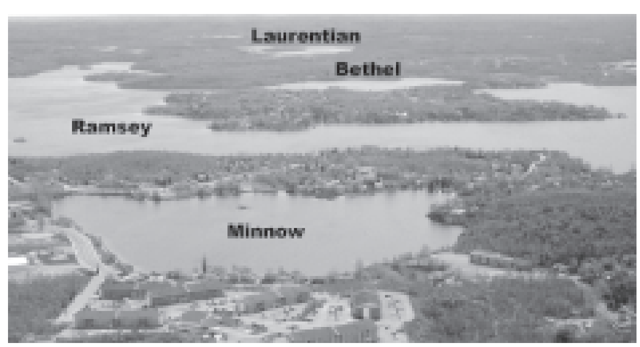

Photo 9.9. Minnow, Ramsey and neighbouring lakes west of downtown Sudbury. Looking south. Lake Laurentian is 6 km away.

They become more nutrient-rich, more biologically productive, and fill with organic matter as they age. Although eutrophication occurs naturally on a time scale of thousands of years, human activities can prematurely enrich a lake, especially through the addition of phosphorus from sewage and septic systems. Phosphorus is a plant fertilizer and is the nutrient that usually controls plant growth in lakes, both algae and aquatic weeds. This phenomenon is called "cultural eutrophication".

Bethel Lake and Kelly Lake are examples of lakes that show the classical symptoms of advanced cultural eutrophication (Vollenweider 1968; Vallentyne 1974). Those symptoms include high levels of phosphorus and/or nitrogen, prolific growth or blooms of algae (Photo 9.10), and low dissolved oxygen levels with occasional associated fish kills when the algae decay.

Kelly Lake was downtown Sudbury's sewage lagoon from the day the community began to grow. Junction Creek was little more than an open sewer and carried essentially untreated sewage directly to Kelly Lake until a treatment plant was built near the mouth of the creek in 1972. Phosphorus removal technology was added at the plant in 1987, considerably reducing phosphorus concentrations in the effluent and in the lake. Unfortunately, organic matter stored in the lake sediment continues to release phosphorus into the lake and has slowed the improvement of downstream water quality (*see* Pearson et al., Chapter 8, this volume).

Bethel Lake was also used as a sewage lagoon, not by the municipality but by the nearby Algoma Hospital. This practice was stopped in 1986. Although phosphorus concentrations have declined greatly, Bethel Lake is still very nutrient-rich and large mats of unsightly and ecologically disruptive algae still develop each summer.

Contributions of nutrients from a variety of diffuse sources, for example, field beds and poorly maintained septic systems, lawn and garden fertilizers, and eroding soil, can also cause eutrophication. Most city lakes with houses and cottages within their drainage basins show some degree of nutrient enrichment; however, this problem is not as severe in the nutrient-poor landscape of Sudbury as it is, for example, in many agricultural areas.

STORM WATER DISCHARGE

In the United States, road sediment from streets, driveways and parking lots (Photo 9.11), is considered the most significant nonpoint source contributor of contaminants, including metals, to surface water (Sutherland and Tolosa 2000). In Sault Ste. Marie, Ontario, in 1991 concentrations of cadmium, lead, copper, zinc, manganese and chromium in the easily soluble fraction of metals in street sediment were sufficiently elevated to suggest that they could damage the quality of receiving water when mobilized by spring runoff and snow melt. However, the largest part of the total metal load was associated with the larger grain sizes (0.25 to 2.0 mm) that are most easily captured in detention systems (Stone and Marsalek 1996).

Material in road sediment is derived from several sources such as the aggregate and asphalt of roadways; vehicle wear and corrosion, including particles from brake linings, tires, mufflers, catalytic converters, and paint, various greases, oil and fluids; exhaust emissions; loose particles of dust and soil washed off rocky and vegetated slopes; and biological matter together with dry and wet atmospheric deposition (Sutherland and Tolosa 2000). Traces of herbicides and pesticides are also a component in communities where they are used for roadside treatment. De-icing chemicals, like sodium chloride, and dust suppressants are prominent if they are spread on roads.

In Sudbury, surface runoff has been measured as five times richer in nickel and twenty times richer in copper than in other northern Ontario communities (NAR Environmental Consultants 1995). Part of this enrichment is certainly due to present day metallic smelter dust being washed off surfaces where it has settled, especially when contaminated snow melts in the spring. Another part can be attributed to historically deposited particles being washed onto roadways

Photo 9.10. Algal mat on Simon Lake, August 1995, looking southwest. The far shore is 700 m away.

Photo 9.11. Road sediment and litter by a storm drain on a residential Sudbury street; the grate is 50 cm wide.

from rocky outcrops or being carried along as a component of eroding soil. It is therefore very likely, although not yet determined, that the metal load delivered to Sudbury's inner city lakes by storm drains has not diminished to the same extent that smelter stack emissions have been reduced.

Perhaps because pollution in Sudbury has been so dominated by easily visible point sources, little attention has been given to the effects of surface runoff, even though storm water is discharged directly into Ramsey Lake, the main drinking water supply for residents in the urban core. One of the consequences with possible implications for human health is the elevated concentration of sodium, derived from road salt, in Ramsey Lake (Figure 9.7). Normal background concentrations of sodium in lakewater range between 1 and 2 mg/L, but in Ramsey Lake in 1990 the concentration was just over 36 mg/L (*see* Table 9.1). Drinking water taken from the lake and treated at the David Street Pumping Station in 1999 showed sodium levels between 40 and 46 mg/L (Regional Municipality of Sudbury 2000). The highest concentration occurred in March 1999, probably reflecting the beginning of spring melting on the roads. Regulation 459/00 of the Ontario Water Resources Act (Government of Ontario 2000) requires that the local Medical Officer of Health be notified if concentrations of sodium in drinking water exceed 20 mg/L.

SHORELINE AND WATERSHED ALTERATIONS

Sudbury's lakes vary widely in the extent and type of residential, commercial and industrial development along

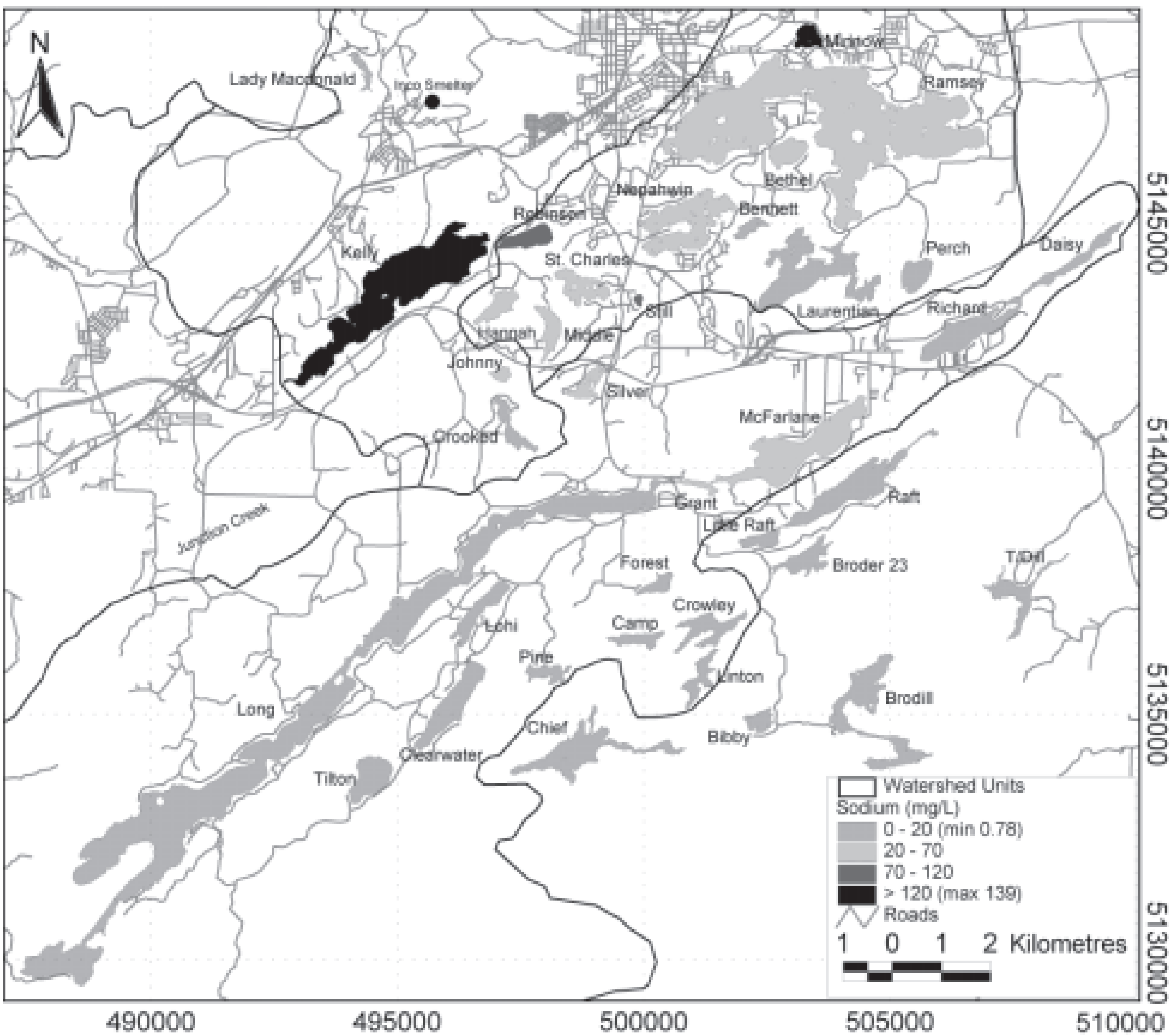

Figure 9.7. Sodium concentrations in 37 lakes within 20 km of the Copper Cliff smelter (1990).

their shorelines, from nearly complete circling of lakes by houses in the centre of the city, to lakes with only a few seasonal cottages, and lakes without any development in their catchment areas. Development has usually occurred in the low-lying areas along a web of stream valleys and shorelines at the base of the rocky hills and knobs that characterize the Sudbury landscape. Although small, older houses often fit into the shoreline landscape, many newer homes totally dominate and alter the shoreline.

Modifications to shorelines such as the building of breakwater walls, docks and boat houses on solid foundations; removal of submerged logs; clearing and dredging for beaches; and replacement of natural vegetation by lawns or patios are a common feature of residential development. What is convenient and apparently pleasing to the eye of homeowners often leads to the loss of shoreline habitat diversity and, in turn, may diminish the richness of the ecosystem and food chain in urban lakes. Erosion of soil, surface runoff that carries excess or, indeed, unnecessary fertilizer, pesticides and herbicides and removal of natural shoreline vegetation compound the damage to habitat and water quality. It is ironic that the very aesthetic and wildlife values that draw people to lakes in the first place are unwittingly damaged by some of the attitudes many bring with them. Litter (Photo 9.12) causes aesthetic pollution in some urban lakes as well and even affects many remote lakes.

WATER FLOW ALTERATIONS

A natural hydrological system in Northern Ontario includes plentiful storage of rainwater in soil and wetlands. Slow release of temporarily stored water from these natural sponges helps moderate extreme changes in habitat for terrestrial plants and animals, as well as limiting fluctuations in river and lake levels which affect aquatic organisms, especially those in shoreline habitats. Urban development encourages the rapid discharge of precipitation and melt water by eliminating wetlands and constructing channels. It also reduces infiltration of water into the soil by increasing the area of impermeable surfaces such as pavement, roofs, shopping mall parking lots, and hard-packed fill. This can dramatically affect the flow path of water and the extent and timing of water release and storage in drainage basins. In Sudbury, the loss of vegetation cover and erosion of soil from hillsides has compounded the problem by increasing surface runoff (*see* Pearson et al., Chapter 8, this volume) and reducing evapotranspiration. Flooding in the spring and after summer storms, a deeper groundwater table and falling lake levels in the summer are the well known consequences of urban development, especially if no attempt is made to design with, rather than against, the natural hydrological cycle.

In downtown Sudbury, Junction Creek has been the object of extensive flood control engineering (Photo 9.13 and *see* Photo 9.8), especially since the Nickel District Conservation Authority was created in 1957 with a mandate to control flooding (Hallsworth and Hallsworth 1993). Much of the flat ground close to Junction Creek that was so attractive to builders is actually part of the creek's flood plain. Parts of other communities, especially in the flat land of the Sudbury Basin, are built on the flood plains of the Whitson and Vermilion rivers and suffer from the same problem. As a result, the level of several of the city's urban lakes, for example Ramsey and Robinson, is controlled by dams for at least part of the year. The Maley and Nickeldale dams, were specifically built to hold back flood water from reaching downtown Sudbury.

Water flow in several rivers has been altered by hydroelectric dams such as the one on the Wanapitei River near Coniston**.** Logging companies built dams to assist in the movement of logs early in the century, for example, 2 dams were used to raise the level of Lake Onaping so as to allow water to be sent to either the Onaping River or Spanish River in 2 different watersheds. Although this takes place north of the city boundary (*see* Map 3), it can affect the volume of water in the Onaping River, one of the city's important rivers. Such construction always has ecological drawbacks even though they may be judged to be acceptable. Dams affect fish and other animal movement as well as the supply of water to downstream lakes.

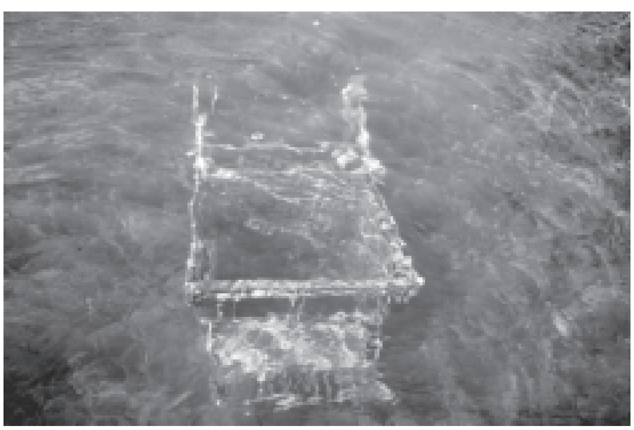

Photo 9.12. Shopping cart in Lake Nepahwin; the cart is 60 cm wide.

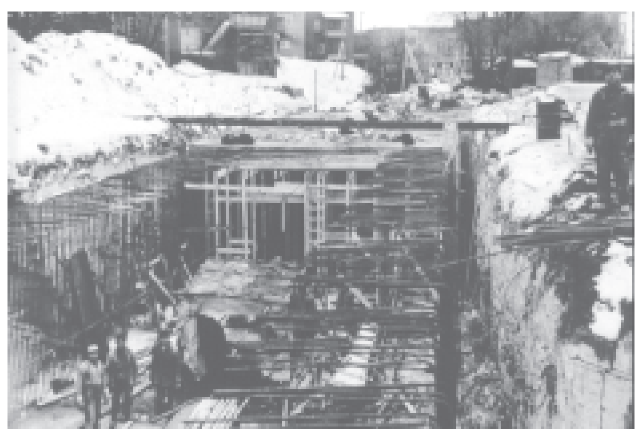

Photo 9.13. Culvert construction for Junction Creek under Memorial Park in downtown Sudbury, 1953 (Sudbury Public Library).

INVADING SPECIES

When non-native species are introduced into an ecosystem the effects can sometimes be dramatic and unpredictable, especially in the early stages. We are surrounded by many terrestrial examples of introduced species, such as the starling (*Sturnus vulgaris*) and house sparrow (*Passer domesticus*) and many non-native plants. Most such species are now taken for granted and their disruptive influence has been forgotten. Sudbury's lakes are being affected by several exotic species, intentionally or unintentionally introduced by humans. Eurasian water milfoil (*Myriophyllum spicatum*), an aggressive aquatic plant, has proliferated in Minnow Lake after first being noticed in McFarlane Lake and Long Lake. In the summer of 2000 it underwent explosive growth in Kelly Lake (Photo 9.14). A marine fish from the Atlantic coast, the highly competitive rainbow smelt (*Osmerus mordax*), has become established in Nepahwin Lake, presumably after being brought from Lake Huron.

Once they are present in an area, invading species can easily spread. For example, fragments of milfoil float downstream and travel from one watershed to another on boat trailers or on the legs of water birds, ready to take root in a suitable new habitat. Fish are carried by humans and released from bait buckets. The potential arrival of additional invading species is of concern for Sudbury lakes, especially because of their proximity to the Great Lakes. The lower Great Lakes have become a major route for invading exotic species because of the eggs, spores, larvae and resting stages of organisms that can still be alive in the freshwater ballast brought by some transoceanic vessels travelling from freshwater ports. Any ballast water illegally discharged before a ship takes on cargo has the potential to compromise aquatic ecosystems over a very wide area. The spiny waterflea (*Bythotrephes cederstroemi*) invaded the Great Lakes in 1982 and now inhabits more than 25 lakes in Ontario (MacIsaac 2001) including Lake Panache. The well known zebra mussel (*Dreissena polymorpha*) that arrived in the Great Lakes in the mid 1980s (MacIsaac 1996), has not yet been found in Sudbury lakes but it may only be a matter of time before it is.

THE RECOVERY PROCESS

Improvements in Water Chemistry and the Effects of Biological Time Lag

Water chemistry and aquatic ecosystems in Sudbury's lakes have continued to recover in recent years Keller et al. (1999, 2001). Long-term monitoring studies have clearly shown that improvement can be correlated with reductions in industrial emissions (Keller and Gunn 1995; Smol et al. 1998). In fact, studies documenting the ongoing recovery of lakes around Sudbury have provided some of the best evidence in the world supporting the implementation of pollution control programs (Gunn and Keller 1990; Keller et al. 1999). Clearwater Lake has been studied for more than 30 years and, is one of the longest-studied acidified lakes in the world; together with Crooked, Silver and Tilton, it provides a striking illustration of the decreased acidity and decreased metal concentrations that have followed smelter emission controls (Figure 9.8 and *see* Figure 9.4).

Even the most severely affected Sudbury lakes contain a variety of aquatic organisms. Highly stressed lakes, however, generally have simplified aquatic communities, mainly represented by rather tolerant species (Stokes et al.1973; Baker et al. 1990). There may be some unique problems in the most affected Sudbury lakes, but it is probably safe to conclude that basic functional processes such as respiration rates, primary productivity and nutrient cycling are generally intact. The recovery of biological communities may be substantially delayed even after water quality has improved, because of the limited dispersal ability of some organisms. Nevertheless, although biological recovery is still at an early stage, there are very encouraging signs of aquatic community improvement in some lakes, especially those farthest from the smelters. Reproducing populations of sport fish have been re-established through stocking programs in some lakes and the unaided return of some pollution-sensitive invertebrate species such as the mayfly (*Stenacron interpunctatum*) has been observed (Keller and Gunn 1995; Carbone et al.1998).

Liming of Lakes and Watersheds

Acidified lakes in many areas of the world, especially in Sweden, are treated with powdered limestone as a way of neutralizing the acidity and attempting to directly improve both water quality and biological diversity. In some cases the watershed around a lake is also treated so as to diminish the likelihood of re-acidification by acid runoff (Henriksen and Brodin 1995). Three strongly acidic Sudbury lakes, Middle, Hannah and Lohi, together with a fourth, moderately acidified Nelson Lake, were limed between 1973 and 1976 (Yan and Dillon 1984). In addition, the land surrounding Middle and Hannah lakes was limed in the early 1980s as part of the

Photo 9.14. Eurasian milfoil in the west end of Kelly Lake, September 2000. Looking northeast, the horizon is 1.5 km away and the lake is 500 m wide at the widest point in the photograph.

city's land reclamation program. In each case the acidity of the lakewater was ameliorated, alkalinity increased and metal concentrations decreased; however, the duration of the improvement varied dramatically: Lohi Lake quickly re-acidified to a pH level of less than 5 while the others retained a pH level of greater than 6 (*see* Table 9.1). An important factor in the longevity of the improvement in Middle and Hannah has undoubtedly been the liming of their catchments and the consequent improvement in stream and runoff water quality (Yan et al. 1995).

The effectiveness of landscape liming as an indirect means of improving lake water quality in Sudbury has recently been demonstrated by detailed comparative study of 2 stream catchments draining into Daisy Lake. One catchment, including its wetlands, was limed while the other was left untreated. A steady improvement in water chemistry, including a pH level greater than 6 and lower metal concentrations, has persisted since 1995 in the stream draining the treated catchment (Gunn et al. 2001).

It appears that the greatest promise for continuing to revitalize the severely damaged ecosystems around Sudbury will come from combined improving soil conditions and introducing a plant cover with specialized applications of limestone to wetlands and other important hydrological sites (Gunn et al. 2001).

SUDBURY'S LAKES IN A WARMER WORLD

Just as Sudbury's lakes are recovering from the industrial stresses of the past, they are facing a new challenge: climate warming. Current Canadian climate model studies predict that by 2050 average annual temperatures in Sudbury will be 2 to 4°C warmer than today, with most of the warming occurring in the spring (Hengeveld 2000).

The consequences of a warmer world for northern Ontario are not yet well understood but there will certainly be important changes in both water quality and quantity. Although total precipitation may not change much, there is concern that intense rainstorms and localized flooding will occur more frequently (Hengeveld 2000). However, increased evaporation from the surface of lakes and rivers is of even greater concern since evaporation increases rapidly as the air temperature rises. In the Experimental Lakes Area of northwestern Ontario, a rise in average air temperature of 1.6° over 20 years, accompanied by lower humidity and increased wind velocity, caused an increase in evaporation of 30%. This exacerbated a drop in precipitation and as a result, once permanent streams became ephemeral and were dry for as long as 150 days a year (Schindler et al. 1996).

Lower stream flow can result in lakes receiving less dissolved organic carbon from the breakdown of organic matter in soil and wetlands. Dissolved organic carbon is not only important for the aquatic food chain but also gives lake water a deep amber colour and, therefore, helps in limiting the penetration of visible and ultraviolet radiation into the dark, cold, lower water habitat of lakes (Schindler 1971). However, the implications of this sequence of events for lakes in Sudbury remain to be determined.

Lower water levels and drying streams in the Sudbury area will have important effects on the release of sulphur

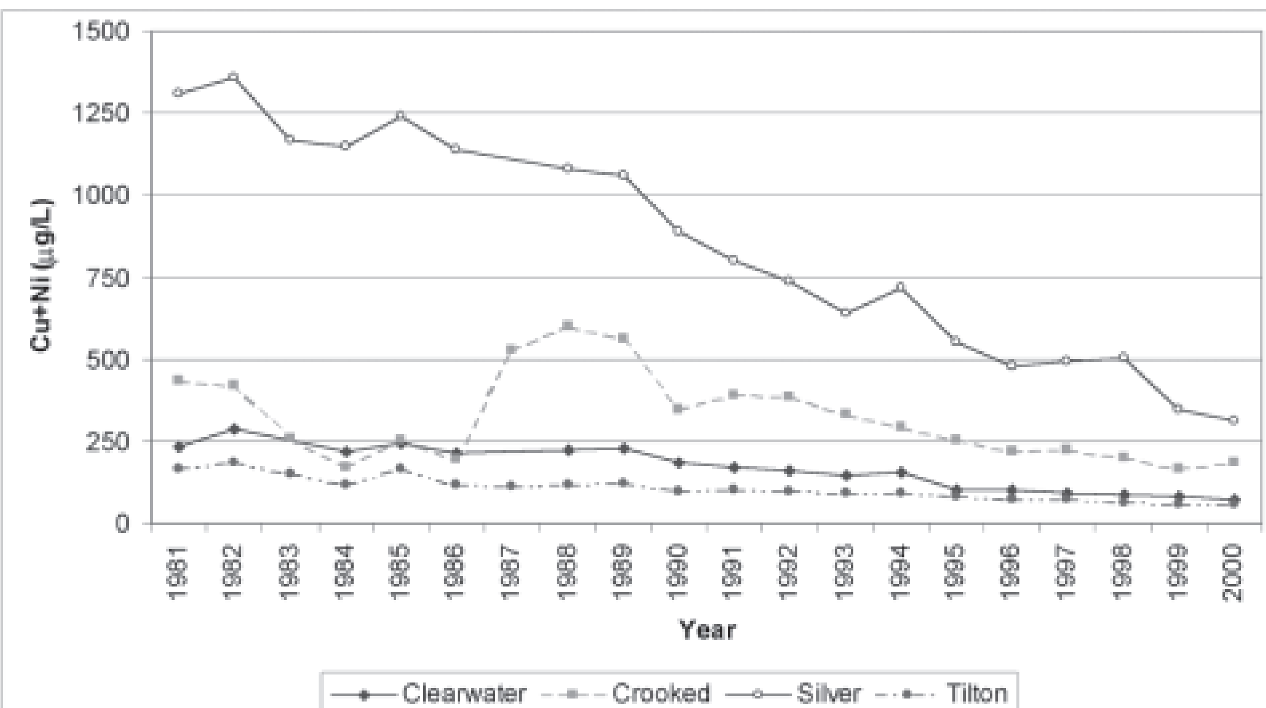

Figure 9.8. Combined annual copper and nickel concentrations from 1981–2000 for 4 acidified Sudbury lakes.

stored in watersheds. Vast amounts of sulphur have been bound as sulphides in wetlands and shoreline sediments. If water level falls, these sulphides become oxidized by contact with air and are released as sulphuric acid when rain or snow returns, acidifying the receiving stream or lake (Yan et al. 1996). This effect was observed in several Sudbury lakes following the drought of 1986 and 1987 (*see* Figure 9.4; Keller et al. 1992). Release of stored acidity is also likely to trigger other damaging changes, including mobilization of acid-soluble metals, and may exacerbate increased transparency by precipitating dissolved organic carbon (Effler et al.1985; Yan et al. 1996).

LAKES IN SUDBURY'S PLANNING POLICIES

The former City of Sudbury, now the residential core of the new City of Greater Sudbury, included many desirable policies, objectives and specific targets in the "Waterbodies" chapter of its official City of Sudbury Secondary Plan (1987). That document forms a very good starting point for protecting aquatic ecosystems and improving water quality in the dramatically larger number of lakes in the new city.

Specifically important are the general policies that state (p.3–7):

> It shall be the policy of Regional and City Council to:
>
> a. Maintain water quality of waterbodies at their current or higher levels;
>
> b. Protect and enhance fish and wildlife habitat in or around waterbodies;
>
> c. Reduce erosion within the watersheds of waterbodies;
>
> d. Reduce the pollution potential of urban run-off and storm drainage into waterbodies;
>
> e. Protect the wetlands associated with waterbodies.

Specific trophic-level targets based on total phosphorus concentrations (level I = 0 to 9.9 μg/L; level II = 10 to 18.4 μg/L; level III = 18.5 to 30 μg/L) are set for individual lakes. Eight lakes are identified for water quality improvement and rehabilitation sufficient to make them candidates for the management of sport fish. A similar lake-specific and desired use or values-oriented approach, which distinguishes the water quality and ecosystem requirements for drinking water, swimming, boating, fishing and wildlife observation, all in a watershed context, should be developed for the larger city.

Public Awareness and Involvement

Local citizens cannot alone change the impact of global environmental stress on the lakes where they live, but their awareness of how a lake works and the effect of deliberate and inadvertent human actions can make a vital difference in protecting water quality. A new program initiated by the city in 2001 recognizes the importance of an aware, educated and involved public. This initiative will involve the following:

a) a water chemistry and spring phosphorus assessment of up to 50 lakes;

b) monthly summer monitoring and sampling of up to 20 selected lakes;

c) a comprehensive physical and chemical assessment of a small number of high priority lakes, including sediment and benthic invertebrate sampling;

d) establishing stewardship or "Friends of the Lake" volunteer groups of stakeholders who will be trained to conduct water and benthic invertebrate sampling as part of a long-term monitoring program.

Monitoring data and historical records will be available on a Web site, organized on a lake by lake basis in each of the city's watershed units, and displayed on geographic screens derived from the map included with this publication (*see* Map 3).

DISCUSSION

The 1970s saw major reductions in the emissions from the Sudbury smelters. The Coniston smelter was closed and technological and process changes were made in the Copper Cliff and Falconbridge smelters. As a result, the release of sulphur dioxide from Sudbury smelters was reduced from over 2.5 million tonnes per year at the beginning of the decade to less than 1 million tonnes per year at the end (*see* Figure 9.2). At the same time particulate emissions fell to approximately 15 000 tonnes per year, including about 3200 tonnes of metal, from about double that quantity (Potvin and Negusanti 1995).

Containment of mine waste and tailings drainage also became much more effective in the 1970s and several water treatment plants were built to deal with metal concentrations and acidity before water was released to streams and lakes (Heale 1995). A major sewage treatment plant was built in 1972 to handle urban Sudbury's municipal effluent and several other smaller plants in outlying centres followed. In 1974 Sudbury launched one of the world's most ambitious and successful revegetation programs (Lautenbach et al. 1995).

So far as the environment in the Sudbury area was concerned, 1970–1980 was a turn-around decade when accelerating environmental degradation was replaced by the beginning of slow recovery. At the same time, however, the cumulative effect of small scale urban stresses on lakes began to become more significant as seasonal camps, or cottages, were converted to year-round homes, and new lakeshore homes were built for those seeking a waterfront lifestyle close to downtown.

Future management efforts for Sudbury lakes must be based on sound information. Wise management and protection of these irreplaceable assets will depend on knowing their condition and on understanding their reaction to a variety of interacting environmental stresses.

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