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Urban Lakes: Integrators of Environmental Damage and Recovery

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Most of the world's human populations now live in rapidly expanding urban areas (Richardson 1991). These cities and towns vary widely in size and appearance, but they share a common feature: They are near water. Urban waters, in the form of lakes, streams, groundwater aquifers, and the nearshore areas of oceans, satisfy a wide variety of human needs (drinking water, transportation, industrial use, agricultural use, etc.). However, with few exceptions, urban waters have been and are being badly degraded by human activities (NRC 1992). To many, it may therefore be surprising that urban waters, particularly lakes, have received very little study by ecologists in North America (Gilbert 1989; McDonnell and Pickett 1990).

Like other aspects of the "massive, unplanned experiment" (McDonnell and Pickett 1990) that urbanization represents, the study of the ecology of urban waters is complicated by the wide variety of factors affecting urban aquatic ecosystems. These confounding variables make it difficult for ecologists to construct quantitative models of the functioning of urban systems or even to establish clearly the cause of specific problems, such as fish kills, algal blooms, or the accumulation of contaminants. These problems degrade the value of these important aquatic resources and deserve greater attention.

One potentially useful way of viewing urban lakes is to consider them as measures of the conditions within the associated catchment areas (see Chapter 24). Water, the "universal solvent," samples the available nutrients, soluble contaminants, and suspendible particles from the terrestrial system as it flows to the lake. Additional inputs of solutes, gases, and particles come through the atmosphere or are added directly by human activities. The resulting chemical solution, and the life that it supports, forms a rather large integrated sample, useful for assessing the "health" of the associated urban area.

Recent studies of the urban lakes within the city of Sudbury (Fig. 20.1) provide examples of the damaging effects of industrial and urban activities. They also illustrate the resilience of natural systems and the benefits to be achieved by pollution abatement programs.

Sudbury Urban Lakes

Within the city of Sudbury, there are 33 lakes of more than 10 ha in size, as well as a wide variety of smaller lakes and ponds. The larger lakes vary in surface area from 14 to 1331 ha and in maximum depth from 3 to 36 m. They make up more than 10% of the surface area of this glacially scoured landscape, giving Sudbury one of the highest concentrations of urban lakes of any city in Canada (Fig. 20.2). The lakes are clustered into two main watersheds that drain to the French or Spanish rivers, tributaries of Lake

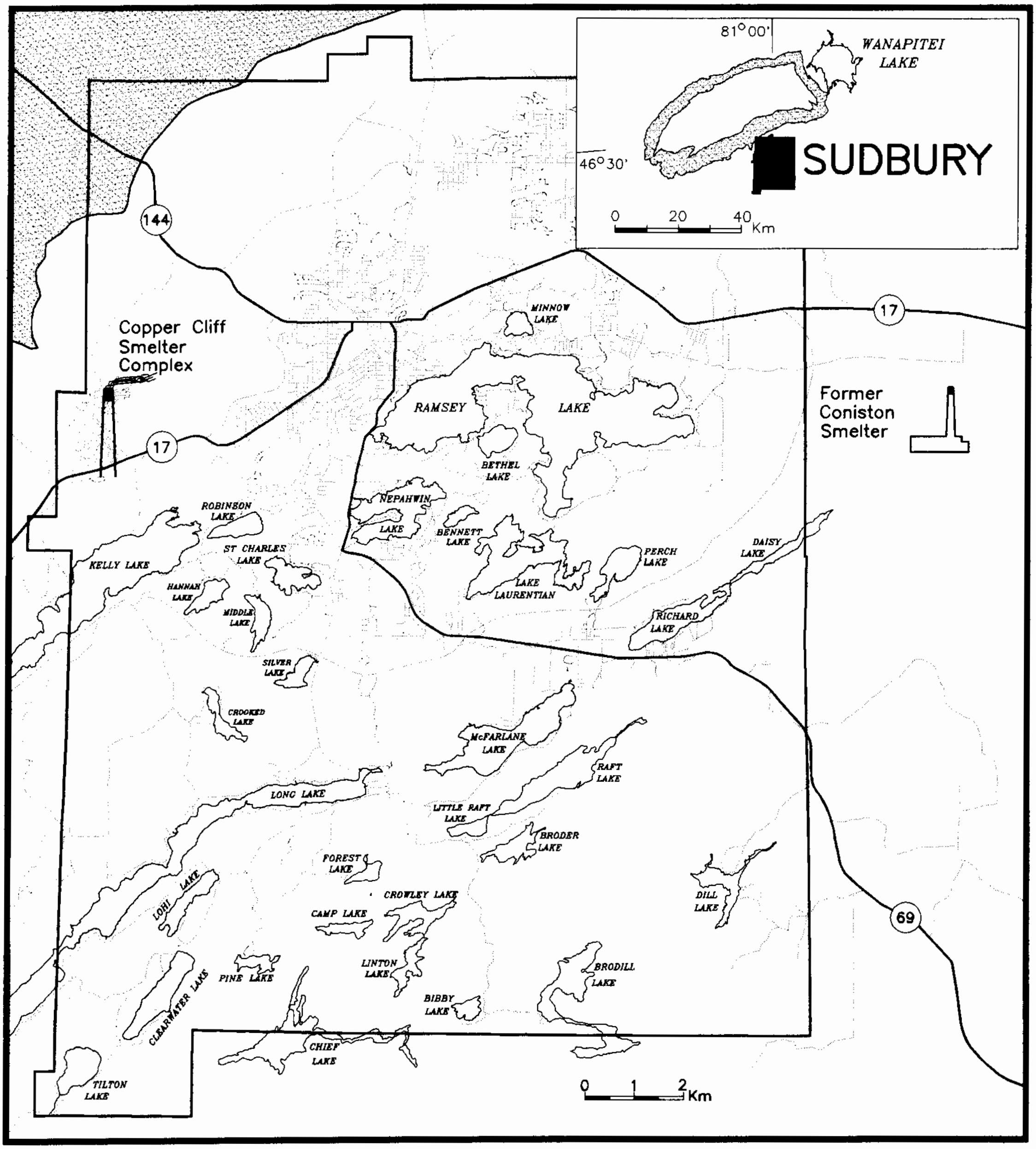

FIGURE 20.1. Municipal boundaries of Sudbury, showing urban lakes and the locations of nearby metal smelters.

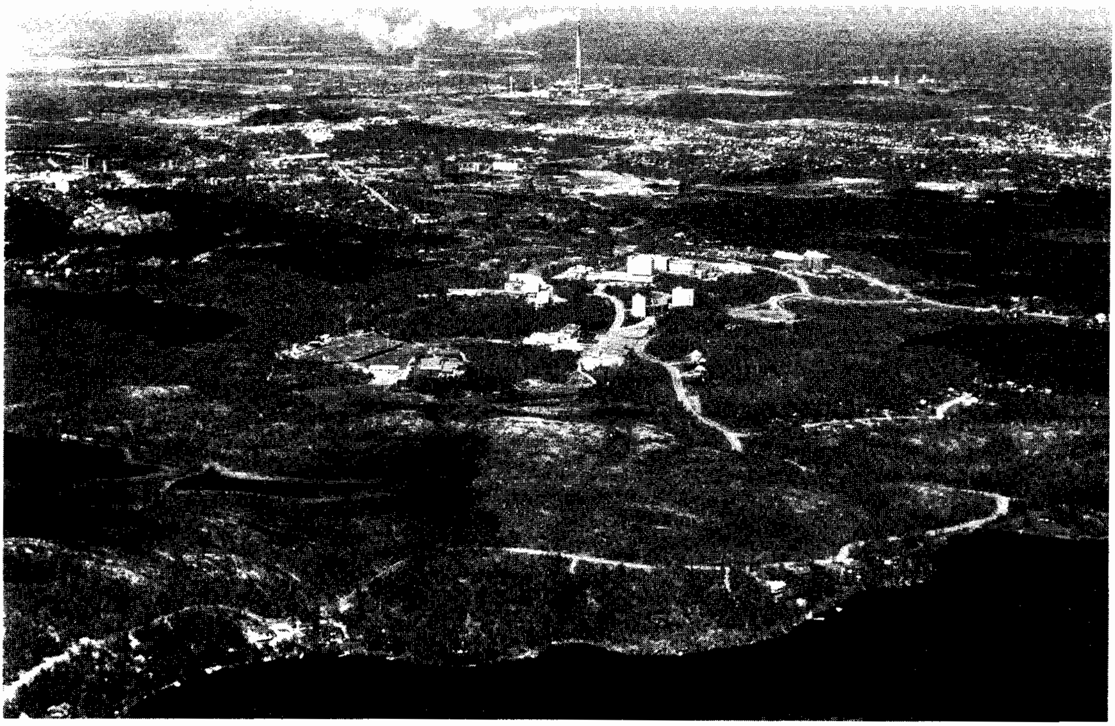

FIGURE 20.2. Sudbury—the city of lakes. Copper Cliff smelter is in the background. (Photo by E. Snucins.)

Huron. A string of lakes, called the Long Lake chain, cuts diagonally across the city, following an earthquake fault line (Fig. 20.1), and drains to the Whitefish River.

Stress Factors

Six main stresses affect the chemistry and biology of urban lakes within this industrial city: (1) acidification, (2) metal contamination, (3) eutrophication, (4) shoreline or other watershed alterations, (5) introductions and invasions of exotic species, and (6) altered hydrology.

Acidification

The pH of the lakes ranges widely, from 4.3 to 8.9. Because of elevated sulfur deposition, due to the local smelting industry, 11 of the lakes are acidified to the point (pH <6.0) that damage to sensitive aquatic organisms is expected (see Chapter 5). Although there is some evidence of an association between acidic lakes and proximity to smelters (Fig. 20.3), a more surprising observation is that not all lakes are acidic even though they are close to such enormous sources of sulfur dioxide. This variability demonstrates the key role that the geochemistry of the bedrock and surficial soils within lake catchments plays in determining lake water quality (Jeffries et al. 1984). Catchments buffer the effects of incoming acid precipitation. In fact, the alkalinity of a few Sudbury lakes has actually increased under the enhanced weathering rates produced by acidic precipitation (Dixit et al. 1992). However, the overwhelming effect of the smelters has been a decline in lake water alkalinity and pH throughout the greater Sudbury area (see Chapter 5).

Metal Contamination

All the lakes in the city show the effects of industrial emissions of metals to the atmosphere (Fig. 20.3). Copper (4–320 µg/L) and

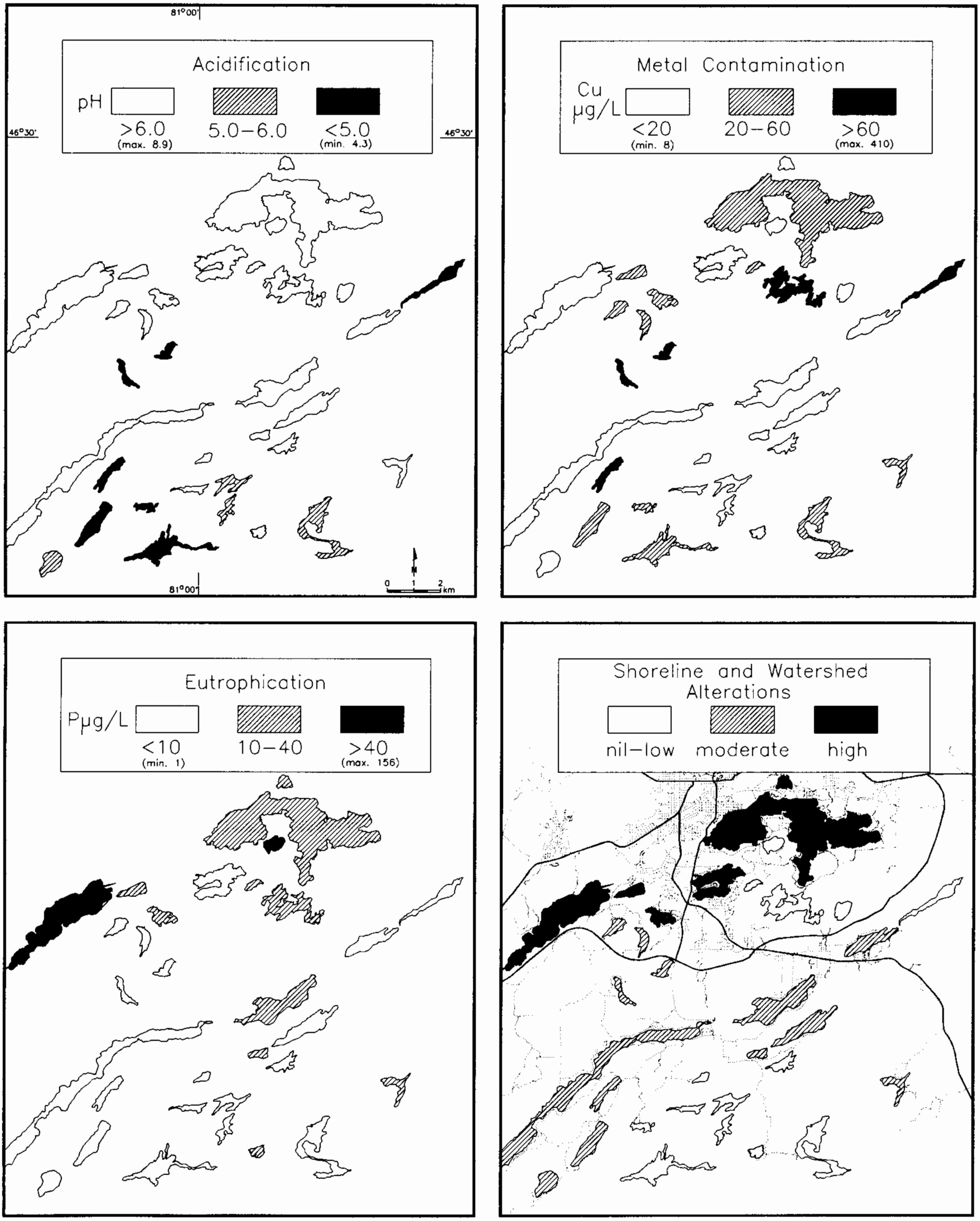

FIGURE 20.3. Effect of various environmental stresses on Sudbury urban lakes.

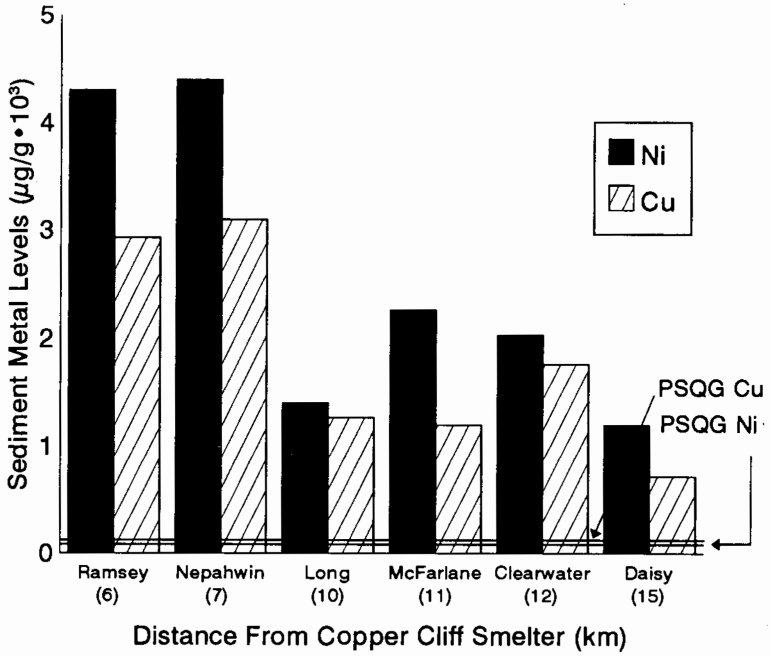

Figure 20.4. Concentrations of copper and nickel in the surface (2 cm) sediments of several Sudbury urban lakes in 1993. While concentrations are clearly highest in lakes nearest the Copper Cliff smelter, all lakes have very high concentrations, well above Ontario provincial government sediment quality guidelines (PSQG: copper 110 µg/g, nickel 75 µg/g; MOEE 1993).

nickel (25–590 µg/L) concentrations approach or exceed Ontario government water quality protection objectives (copper 5 µg/L, nickel 25 µg/L; MOE 1984) in all lakes. Silver Lake, a highly oligotrophic lake located about 6 km from the Copper Cliff smelter, is probably one of the world's most heavily contaminated lakes, considering lakes affected only by atmospheric deposition. During water quality surveys since 1981, concentrations of copper, nickel, zinc, and aluminum in Silver Lake of up to 460, 900, 120, and 1400 µg/L, respectively, have been recorded.

Most urban lakes in close proximity to the smelter have high accumulation of toxic metals in bottom sediments (Fig. 20.4). One particularly contaminated lake, Kelly Lake, receives treated liquid effluent from the Copper Cliff smelter site. The lake also receives inputs of metals from several other tributaries, as well as through atmospheric inputs and from a municipal sewage treatment plant. Sediments in Kelly Lake are not only heavily contaminated with copper and nickel but also have high concentrations of rare metals such as palladium, iridium, and platinum (Crocket and Teruta 1976).

Cultural Eutrophication

Two lakes (Bethel, Kelly) show the classical symptoms of advanced cultural eutrophication (Vollenweider 1968; Vallentyne 1974; Schindler 1977), as a result of nutrient inputs from private and municipal sewage plants (see Fig. 20.3). These symptoms include high levels of phosphorus and nitrogen, high standing crops of algae, particularly nuisance blue-green algae, and low dissolved oxygen levels with associated fish kills. The sewage treatment plant inputs to Bethel Lake were stopped in 1986, and although lake phosphorus concentrations declined from more than 200 µg/L in the late 1970s and early 1980s to less than 100 µg/L by the early 1990s, the lake is still highly eutrophic. Similarly, despite construction of a municipal sewage treatment plant in 1972 and implementation of phosphorus removal at the plant in 1987, Kelly Lake is still eutrophic.

Eutrophication also occurs by inputs of nutrients from a variety of diffuse sources (lawn and garden fertilizer, septic fields, eroding soil, etc.). This problem is not as severe in the nutrient-poor landscape of Sudbury as it is in

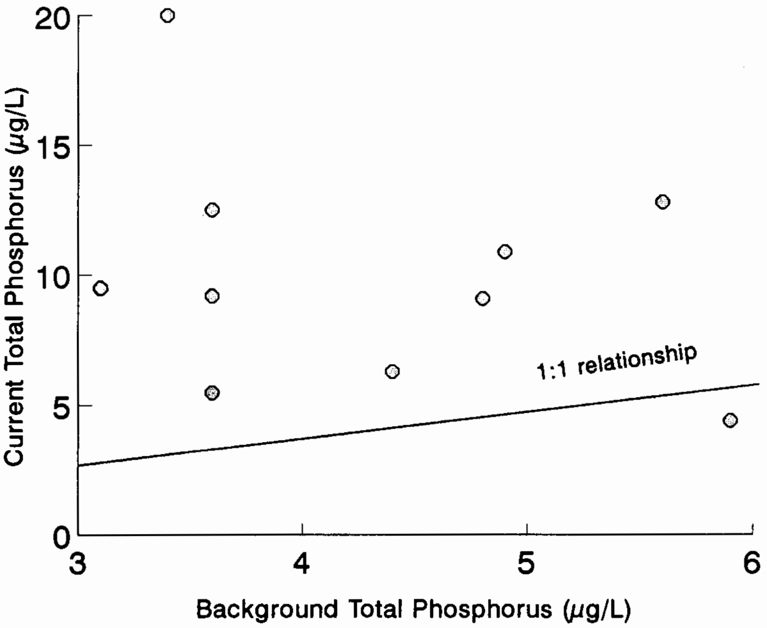

FIGURE 20.5. Comparison between recent measured concentrations of total phosphorus in several Sudbury urban lakes (Ministry of Environment and Energy, *unpublished data*) and pristine (predevelopment) concentrations estimated from a watershed-based total phosphorus model (Dillon et al. 1986).

many agricultural areas, but most lakes with houses and cottages within their catchments show nutrient enrichment (Fig. 20.5).

Shoreline and Watershed Alterations

Sudbury's city lakes vary widely in the extent and type of residential and industrial development around their shorelines—from nearly complete circling of the lakes by houses in the center of the city, to lakes with only a few seasonal cottages, to parkland lakes with no current development in the lake catchment areas (see Fig. 20.3). Typically, housing development has occurred in the low-lying areas along a web of stream valleys and lake shorelines at the base of the rocky hills and knobs that characterize Sudbury. Loss of wetlands has been a common feature of much of the development.

In a few cases, lakes have been eliminated through infilling by industrial waste (Fig. 20.6). However, most shoreline alterations are of a less-extreme type (construction of beaches, docks, breakwalls, etc.). These incremental changes also eventually lead to dramatic deleterious effects, particularly on the biology of urban lakes, through the loss of reproductive or other critical habitats for fish (Bryan and Scarnecchia 1992).

Exotic Species

Like the more familiar terrestrial examples, such as the House Sparrow (*Passer domesticus*) and the many introduced plants, urban lakes are affected by exotic species, intentionally or unintentionally introduced by humans. The introduction of the eurasian water milfoil (*Myriophyllum spicatum*), a nuisance aquatic plant that has proliferated in lakes within the Long Lake chain, and the establishment of a marine fish species, the highly competitive rainbow smelt (*Osmerus mordax*) in Nepahwin Lake, are two examples of exotic species in Sudbury urban lakes. In neither case is the source of the colonizers known.

Altered Hydrology

Urbanization creates dramatic effects on the flow path of water and the extent and timing of release and storage of water in the catchment. Usually, urban development encourages the rapid discharge of precipitation and meltwater

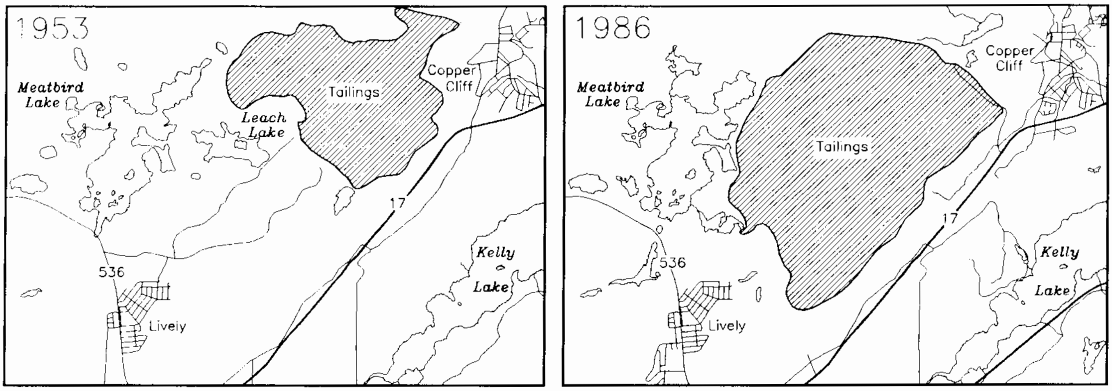

FIGURE 20.6. Infilling of lakes near the Copper Cliff smelter by expanding tailings and slag piles, 1953–1986.

through channelization, elimination of wetlands, and reduced infiltration of water by increasing the amount of impermeable surfaces (pavement, roofs, hard-packed fill). In Sudbury, the historical loss of soil and vegetation cover from the hillsides further decreases water retention and reduces evapotranspiration.

Flooding in the spring and lowered groundwater or lake levels in the summer are the well-known consequences of the alterations described above. Sudbury urban lakes have all these usual problems, necessitating engineered flood control structures and water-level control dams on many of the lakes. However, these solutions are far from perfect. Dams affect fish and other animal movement and the supply of water for downstream lakes. Storm water drainage (Fig. 20.7) brings high levels of road salt, metals, and other contaminants to the lakes (Pye et al. 1983). For example, chloride concentrations increased from about 40 to 50 and 75 to 100 mg/L in lakes Ramsey and Nepahwin, respectively, between the late 1970s and the late 1980s (Ministry of Environment and Energy, *unpublished data*). It is estimated that the background concentration of chloride in lakes before urbanization is usually under 2 mg/L (Neary et al. 1990).

FIGURE 20.7. Stormwater drainage. (Photo by J.M. Gunn.)

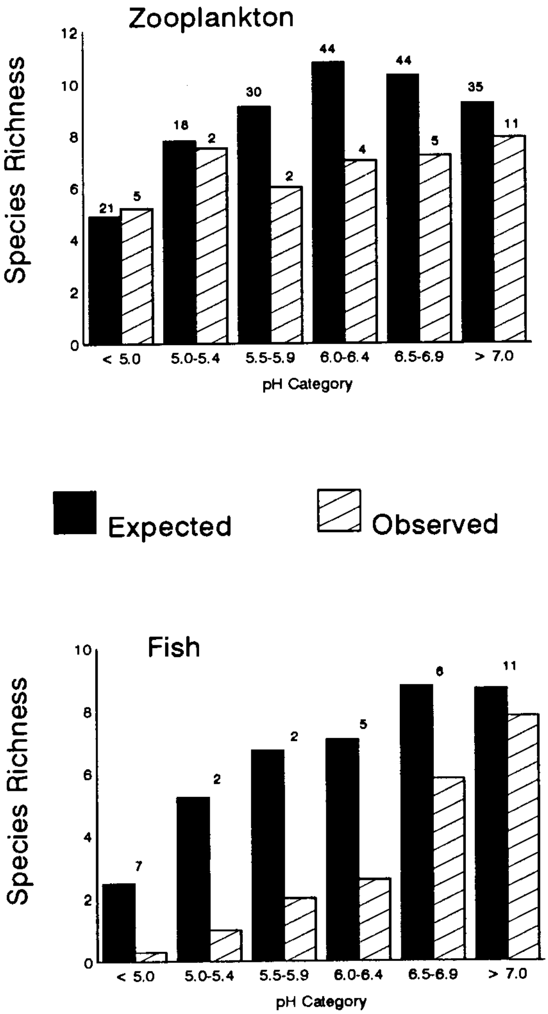

FIGURE 20.8. The observed and expected average number of species of crustacean zooplankton and fish in Sudbury urban lakes. For zooplankton, the expected number of species by pH interval is that observed in more remote lakes of a similar size range in Ontario (Keller and Pitblado 1984). For fish, the expected number is calculated from established relationships between species richness, pH, and lake area (Matuszek et al. 1990). Numbers above the bars indicate the number of lakes in the interval.

Integrators of Ecosystem Function and Health

Distinguishing the magnitude or relative importance of the multiple stresses on urban lakes is obviously difficult. However, many management questions deal with the overall condition of lakes rather than the details of specific causes (e.g., are the lakes improving? deteriorating? What recreational opportunities do they provide?). For these types of questions, biological monitoring provides the most direct measure of the effects of stresses operating in urban ecosystems. Some of the advantages of biological monitoring over inferring, or modeling, ecosystem responses from chemical or physical variables include (Schindler 1987; Fausch et al. 1990; Brinkhurst 1993; Johnson et al. 1993)

1. biological communities integrate the effects of temporal and spatial habitat degradation
2. monitoring of carefully chosen sensitive "indicator species" can be useful for identifying the type of stress(es) operating
3. biological attributes (e.g., presence of fish species) often have high societal values, aiding in the interpretation of the findings to the public
4. biological monitoring by experts can be more cost-effective than reliance on intensive sampling of organic and inorganic contaminants

In contrast with the limited information available on the effects of urbanization, there has been a great deal of work on the effects of acidification on the biology of freshwater lakes in north temperate areas (Baker et al. 1990) (see Chapter 5). This literature provides a basis for beginning to examine the effects of multiple stresses on Sudbury lakes by first attempting to separate the effects of low pH from other stresses. For example, an assessment of the species richness (the number of species present) of fish and crustacean zooplankton suggests that there are far fewer species present in Sudbury urban lakes than would be predicted from the measured acidity of these waters (Fig. 20.8). This result is surprising, because human activities often introduce new species (e.g., through release of bait fish). In this case, two different hypotheses can be proposed for the observed scarcity of species:

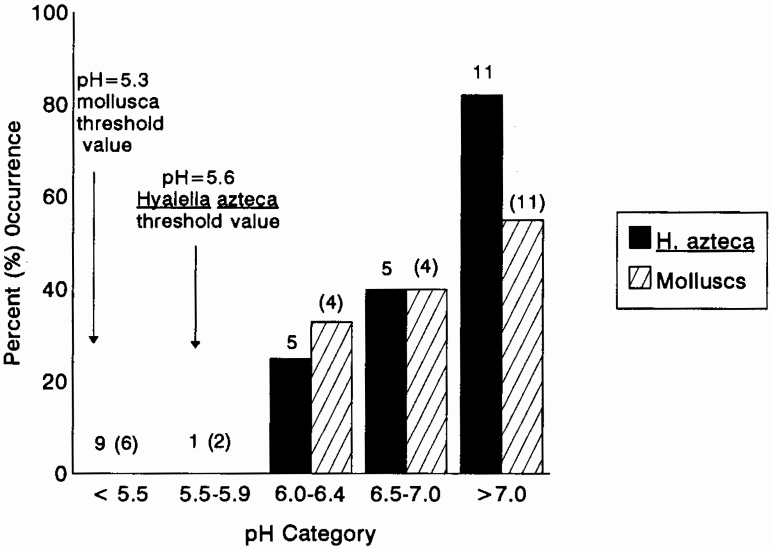

FIGURE 20.9. The distribution of amphipods (*Hyalella azteca*) and molluscs from the 1990–1993 biological survey of the Sudbury urban lakes. Occurrence was determined from a standard sampling effort on each lake. The *vertical lines* are the lower limit of pH tolerance of *Hyalella azteca* (Stephenson and Mackie 1986) and the minimum pH of occurrence for most common mollusc species (Eilers et al. 1984). Numbers above bars indicate the number of lakes sampled in the pH intervals for *Hyalella azteca* and common mollusc species (*in brackets*).

1. species are missing because of the presence of additional stresses (e.g., metals, habitat loss)
2. chemical changes have occurred, but biological responses lag behind

There is some support for both of these hypotheses.

Additional Stress Factors

The high concentrations of metals in the water column and sediments (see Fig. 20.4) in Sudbury urban lakes probably create toxic conditions for many aquatic species (Campbell and Stokes 1985; Spry and Weiner 1991; Wren and Stephenson 1991). This may be the reason that certain sensitive benthic macroinvertebrates, such as molluscs and the amphipod *Hyalella azteca*, are absent from many relatively high pH lakes (Fig. 20.9). The common sediment burrowing mayfly (*Hexagenia* sp.) is absent from Ramsey, Nepahwin, McFarlane, and Long lakes, the only Sudbury urban lakes surveyed for this species to date (W. Keller, *unpublished data*). Although metal contamination may be particularly severe in an industrial city, elevated metal concentrations are a common problem in many urban areas (Purves and MacKenzie 1969; Culbard et al. 1988).

Loss of habitat diversity through input of eroded soils from hillsides, or construction of human structures such as beaches and breakwalls, may also contribute to the low species richness in urban lakes.

Improvements in Lake Chemistry and the Effects of Biological Lag Time

There is very encouraging evidence from long-term monitoring studies on Clearwater Lake (Fig. 20.10) that water quality has begun to improve with reductions in industrial emissions (see Chapter 5). Although such intensive monitoring data do not exist for many of the urban lakes, it can be shown through paleolimnological reconstructions, using diatom and chrysophycean fossils preserved in lake sediments (Dixit et al. 1989) (see Chapters 3 and 5) that water quality has recently improved in several Sudbury lakes. Because of the limited dispersal ability of some organisms (see Chapter 15), biological communities may be delayed in recovering in urban lakes where water quality has improved. The discrepancy between observed and expected community and population status in Figures 20.8 and 20.9 may therefore partially reflect the lag time needed for the biological components

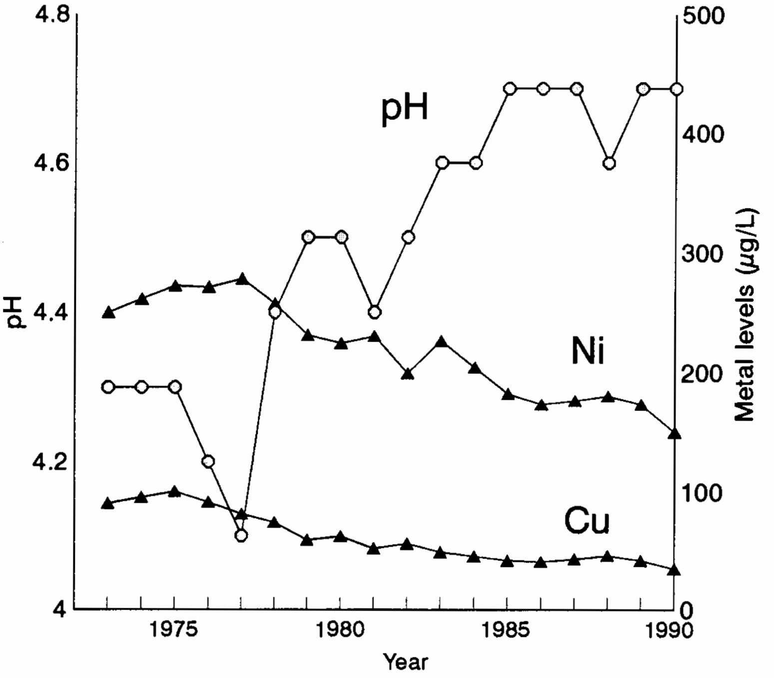

FIGURE 20.10. Changes in lake water pH and dissolved metals in Clearwater Lake, 1973–1990 (from Bodo and Dillon, in press).

of the system to catch up with the chemical changes.

The sediment accumulation of metals remains a potential encumbrance to recolonization by sensitive benthic invertebrates. But, as shown in Chapter 14, sediments can become an effective sink for contaminants, where over a very long time metals become buried under layers of less-contaminated sediments. However, with the abundance of metal particulates in most urban environments (Purves and MacKenzie 1969), lake sediments may always remain as biologically impoverished habitats.

Summary

Given the stresses that urban lakes are subjected to, it may be surprising to some readers that there is no such thing as a "dead lake". Even the most severely stressed lakes contain a variety of aquatic life forms. Generally, highly stressed lakes have simplified aquatic communities, represented mainly by rather tolerant species (Stokes et al. 1973; Baker et al. 1990); but the overall productivity of the urban lakes in industrial cities may be very similar to more pristine systems with the same levels of nutrients (Dillon et al. 1979). There may be some unique problems in Sudbury lakes because of extreme metal contamination of sediments, but it is probably safe to conclude that general functional characteristics of the lakes, such as respiration rates, primary productivity, and nutrient cycling, are not markedly affected. Such characteristics are therefore not particularly useful early indicators of ecosystem damage (Schindler 1987) or recovery.

The structure and composition of biological populations and communities that inhabit urban lakes can provide more sensitive and more useful indicators of ecosystem health than the functional characteristics descibed above (Karr 1991). The presences of naturally reproducing sensitive species (Marshall et al. 1987; Baker et al. 1990), without skin or spinal abnormalities (Hinton and Lauren 1990) and without elevated burdens of toxic contaminants (Campbell and Stokes 1985; Wren and Stephenson 1991), are some of the encouraging signs that human activities are not adversely affecting urban lakes. These are some of the types of measures that should be

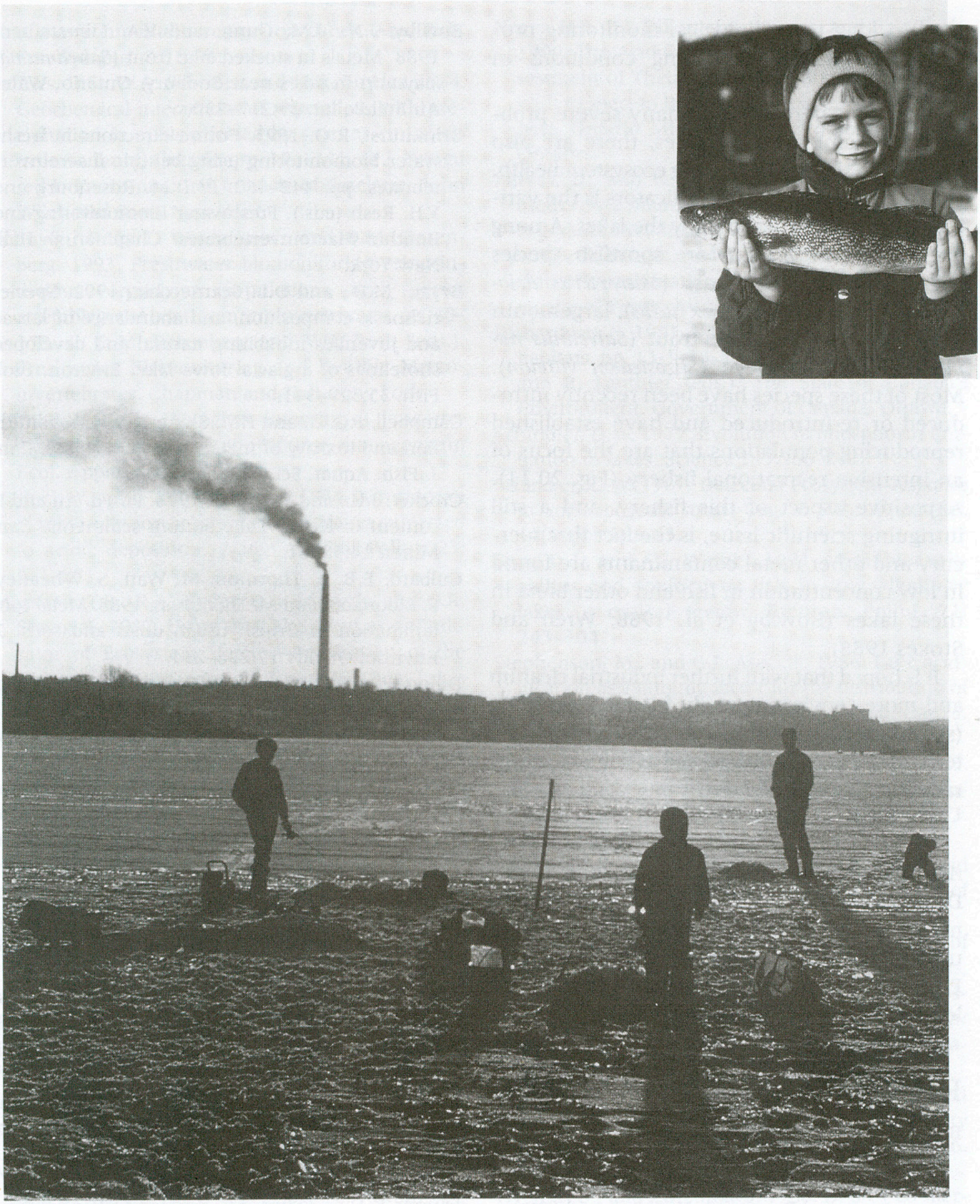

FIGURE 20.11. Winter angling on Ramsey Lake in downtown Sudbury. (Photo by W. Keller.)

used in long-term biological monitoring programs to examine changing conditions in urban lakes.

Although there are still many severe problems in Sudbury urban lakes, there are also convincing signs of improving ecosystem health. One of the most tangible indicators is the variety of fish species that occupy the lakes. Among the 30 species present are sportfish species such as smallmouth bass (*Micropterus dolomieui*), northern pike (*Esox lucius*), largemouth bass (*M. salmoides*), lake trout (*Salvelinus namaycush*), and walleye (*Stizostedion vitreum*). Most of these species have been recently introduced or re-introduced and have established reproducing populations that are the focus of an intensive recreational fishery (Fig. 20.11). A positive aspect of this fishery, and a still intriguing scientific issue, is the fact that mercury and other metal contaminants are found in low concentration in fish and other biota in these lakes (Bowlby et al. 1988; Wren and Stokes 1988).

It is hoped that with further industrial cleanup and more "environmentally friendly" planning (see Chapter 24), the many still-degraded systems can some day be restored as valuable natural assets in this urban environment.

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