24

Catchment Management in the Industrial Landscape

Peter J. Dillon and Hayla E. Evans

A catchment can be defined as the area that encompasses a particular aquatic environment (e.g., a lake or a stream) including the land that drains into it. In Sudbury, a catchment can vary from a few hectares of area drained by a small temporary stream to the thousands of square kilometres drained by major rivers in the area.

Catchments can be considered as individual ecosystems with their own sets of biological, physical, and chemical inter-relationships; however, it must be recognized that catchments are linked to each other through processes including material transport that occur in the atmosphere and by hydrologic transport from one catchment to another. Catchments are therefore very important ecological units, but the concept of the catchment is also a very tangible and appealing one from the human perspective. For example, municipal planners have made increasing use of the catchment (or watershed) as the appropriate level for environmental planning (RCFTW 1992). The sense that the drainage water leaving a catchment integrates the inputs to the area, as well as the human activities within the area, creates a real sense of "place" for many people and thus a recognition of the need for responsible management planning. Some suggestions and challenges for providing effective management of catchment are the focus of this chapter.

Integrated Approach to Catchment Management

Managing catchments as ecosystems requires that the effort be integrated at various levels or through various processes. First, the efforts of government, industry, academia, and non-government organizations must be integrated effectively. This includes establishing agreed-on goals for the management of the ecosystem and requires the integration of responsibilities and expertise from a wide cross section of organizations and, in many cases, from within an organization (Fig. 24.1). For example, within government, integration must occur at all jurisdiction levels. That is, it is essential that the municipal, the provincial (or state), and the federal government be aware of what every other level is doing and not be working at cross purposes or duplicating efforts.

In the Sudbury region, an excellent example of a successful multidisciplinary group is the Vegetation Enhancement Technical Advisory Committee. This committee, established in 1974, consists of members from the local mining industries, various government agencies, elected politicians, the academic community, public interest groups, and individual citizens. It has successfully developed, initiated, and carried out many projects aimed at improving highly visible barren land in and

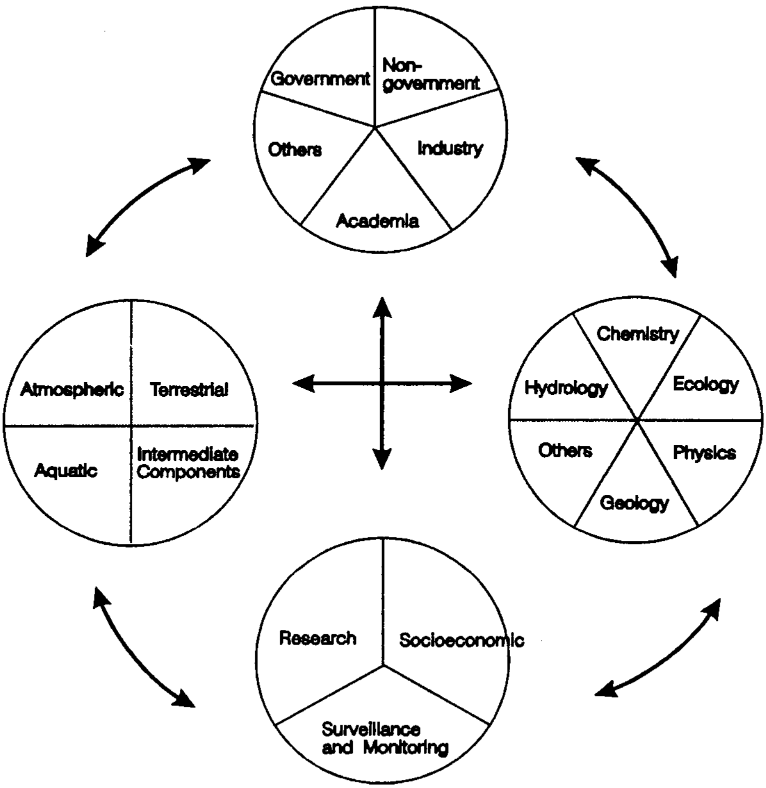

FIGURE 24.1. Levels of integration required for catchment management.

around the environs of Sudbury (see Chapter 8).

In a similar manner, scientists and managers must integrate the disciplines needed to examine the various components of the ecosystem (Fig. 24.1). Chemists, biologists, ecologists, hydrologists, atmospheric scientists, and others must work together. This means, too, that methodologies must be consistent among the various scientists and disciplines. Most important, the main subcomponents of the catchment ecosystem, the aquatic, terrestrial, and atmospheric components, must all be considered. Furthermore, it is necessary to study not only the terrestrial, the atmospheric, and the aquatic portions individually but also any interactions among them. For example, although sulfate is deposited from the atmosphere onto both the terrestrial and the aquatic portions of catchments, sulfate falling on forests or soils or wetland areas may be stored there for an extended period and ultimately enter a lake or stream (i.e., as groundwater or run-off) as a consequence of changes in other environmental factors. The questions then become how, when, and in what form.

It is also important when integrating the measurements on the physical and biological components of the catchment not to overlook areas of the ecosystem. In the Sudbury region, for example, very little work has been done on streams. Wetlands and the littoral zone of lakes are other areas that are sometimes under-represented in sampling and management strategies, but they are important because they link the aquatic and terrestrial environments. This lack of attention implies that these areas are less important as sources or sinks of pollutants or as refuges or dispersal routes for organisms. However, quite the contrary is true (Dillon and LaZerte 1992; Devito and Dillon 1993).

Surveillance and monitoring (i.e., assessment of the status of the ecosystem) and the research efforts of scientists also must be integrated, not only with respect to each other but also with respect to socioeconomic considerations. The establishment of surveillance and monitoring programs is critical to establish "baseline" conditions and to determine natural variation in the ecosystem. Only then can anthropogenic disturbances be readily detected. Although one does not always need these scientific data to demonstrate that an environment is degraded (i.e., it may be intuitive, as is the case in the Sudbury region), survey and monitoring data are necessary to identify less severely damaged areas at a stage at which abatement programs may be more effective. For example, it was only by routine monitoring of precipitation in the Muskoka/Haliburton area of Ontario (250 km south of Sudbury) in the mid-1970s, that the effects of long-range transport of sulfur dioxide on remote ecosystems became apparent (Dillon et al. 1978).

The data from monitoring studies also provide the foundation on which scientific research, including the important core component—predictive models, are built. These research activities allow scientists to predict the effects on the ecosystem of a reduction or an increase in the level of the stressor. The accuracy of these predictions can be tested only if monitoring studies are continued, even after the stress is entirely eliminated. Thus, the integration of monitoring and surveillance programs with scientific research is not only logical but essential. Unfortunately, monitoring is an activity that governments and academia are reluctant to undertake because of the amount of time and money involved. Furthermore, for many scientists, simply "describing the extent of the damage" (or lack thereof) is considered to be boring (Haukioja 1993). In other words, there is little interest in characterizing pristine ecosystems or in monitoring what is often a very gradual response to long-term changes in stressor levels. Thus, monitoring and surveillance programs often may not be initiated early enough to establish the initial conditions of the ecosystem(s).

The integration of scientific endeavors (monitoring, surveillance, and research) with socio-economic considerations is perhaps the most important area of integration in terms of overall catchment management. This marriage of science and society is essential to produce sound management policies a priori and/or, in situations in which the stress has already occurred (such as in Sudbury), sound rehabilitation or remediation practices. The return of highly damaged areas to conditions that even closely resemble "historical" conditions (i.e., restoration) is often not possible (Moore and Luoma 1990). Thus, it is important for society to be able to assess the benefits (e.g., economic, health, environmental) to be achieved through reducing the magnitude of the stressor before deciding how much stress they are willing to let an ecosystem tolerate.

Environmental Protection Model for Managing Catchments

Recently, Somers et al. (1994) developed a conceptual model of the environmental protection process (Fig. 24.2) that shows the inter-relationship between monitoring/surveillance activities (collectively termed *assessment* in their model), scientific research, policy development, and reporting. This model is directly applicable to management of industrial areas such as the Sudbury region and emphasizes the need for integration at many different levels. Step 1 involves reporting on the state of the ecosystem. This requires sound and extensive data that have been collected through monitoring activities (temporal patterns) and surveys (spatial patterns). The response of the public, non-government agencies, governments, industry, etc., (step 2) can then be used to set or revise the ecosystem goals or objectives (step 3) (i.e., what society views as acceptable conditions). These are then used to judge if the current state of the ecosystem is acceptable or unacceptable (step 4). If the ecosystem is acceptable, then the "assessment" or monitoring/surveillance loop is followed. Ongoing characterization of the ecosystem through monitoring programs allows for the establishment of baseline conditions (step 5). However, because it is impossible to monitor all components of the ecosystem, chemical, physical, and/or biological indicators of ecosystem health are selected (step 6). This usually requires some sort

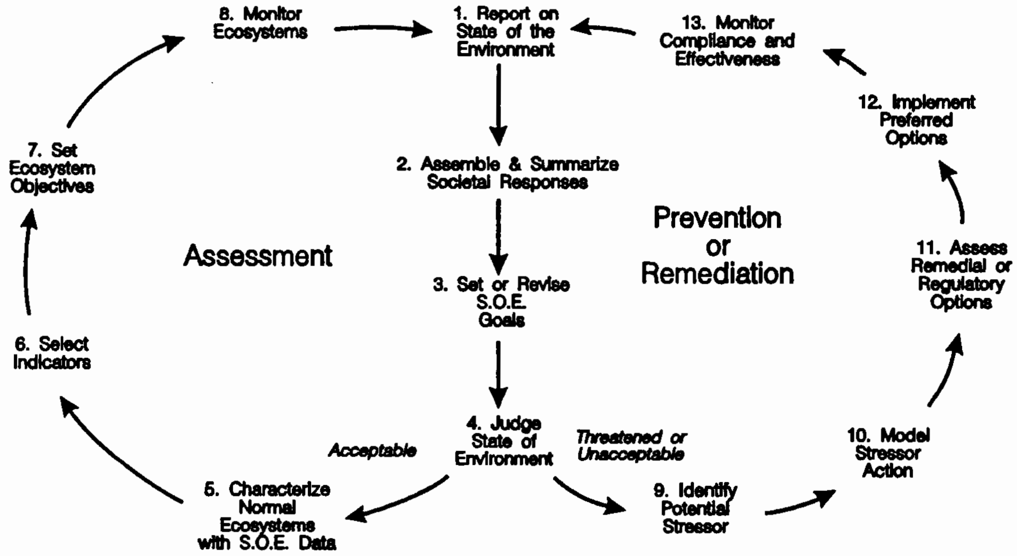

FIGURE 24.2. Essential activities inherent in the environmental protection process (from Somers et al. 1994).

of scientific research. Then, by using these indicators together with an idea of what the normal ecosystem should look like, scientifically based objectives that satisfy the goals established in step 3 can be developed (step 7). However, as mentioned earlier, continued monitoring and surveillance is required (step 8) to ensure that the ecosystem goals and objectives are met.

However, if in step 4 the state of the environment is deemed to be unacceptable, then the prevention/remediation loop is followed. First, the stressor must be identified (step 9), usually through scientific research efforts. Once the stressor is identified, its origin, fate, and mode of action must be evaluated and modeled (step 10) so that the effect of the stressor on the ecosystem indicators can be predicted. This allows for the assessment of remedial or regulatory actions (step 11), followed by implementation of the preferred options (step 12), which usually includes a reduction in the levels of the stressors, although in the worst scenario, it may include only ecosystem manipulation designed to counter the effects of the stressor without reducing the magnitude of the stressor. Then, as in the assessment loop, monitoring programs must be pursued to assess the compliance and effectiveness of the prevention/rehabilitation strategy. The prevention loop is identical to the rehabilitation loop except for the fact that prevention is initiated before the ecosystem damage.

In summary, the integration of monitoring and research data with socioeconomic factors means that although scientists can collect data, test hypotheses, and make recommendations, it is the responsibility of many people, often, most important, the public, to determine the direction that management policies will take. An excellent example is provided by the city of Sudbury, which recently used an "ecosystem approach" to lake management to develop an award-winning community improvement plan for Ramsey Lake (see Chapter 25).

Specific Management Issues in the Sudbury Region

As shown in previous chapters in this book, management of the Sudbury region as a whole generally provides a test of the integrated approach to catchment management

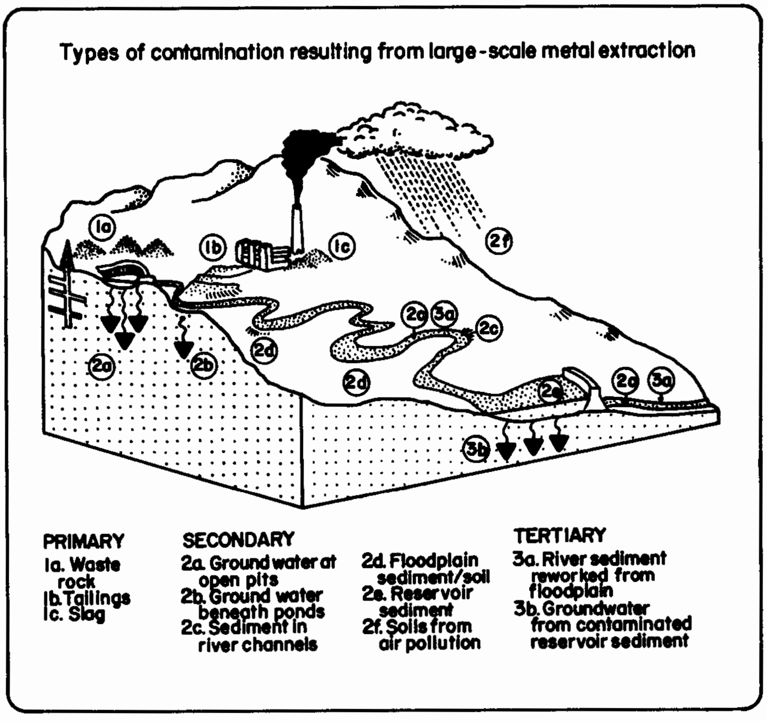

FIGURE 24.3. Contamination pathways resulting from large-scale metal extraction (from Moore and Luoma 1990).

(see Fig. 24.1). First, the ability to manage and the responsibility for management of the area has rested with and continues to rest with many organizations including government, industry, academia, and non-government organizations, but an informed public is increasingly becoming the force that ensures that these agencies honor these responsibilities. Second, a very significant body of scientific data, representing most compartments of the ecosystem, has been collected by hundreds of scientists over the past 30 years, beginning with the first published studies by Gorham and Gordon (1960). Finally, these data have provided the foundation for sound management practices and for the development of restoration techniques relevant to the regional problems.

Difficulties in Applying the Integrated Approach

Despite this potential for an integrated approach to catchment management, serious challenges have and still are faced by those attempting to set policies for the Sudbury region. The reasons for the difficulties stem from the fact that pollution often has no political, geographical, social, or temporal boundaries.

Secondary and Tertiary Pollution

First, as illustrated in Figure 24.3, there is the problem of secondary and tertiary pollution. This means that one cannot only look at one ecosystem (catchment) in isolation but also must study those downstream and downwind of that catchment. Most lakes in regions that have been glaciated have an outflow. Consequently, the presence, for example, of elevated metals in a lake means that potentially all the lakes downstream of it may become contaminated with metals (Dillon et al. 1982). This is illustrated by the fact that large areas of metal-contaminated sediments have been documented at the mouths of rivers that drain the Sudbury area (Fitchko 1978; Spanish Harbour Rap Team 1993), as is the case in other metal smelting areas of the world (Baumann 1984; Moore and Luoma 1990). Similarly, although the completion of the 341-m Superstack in 1972 alleviated the unacceptable air quality conditions in Sudbury, it increased the area

FIGURE 24.4. La Cloche Mountain lakes located approximately 40–60 km south of Sudbury were the first lakes in Canada where the damaging effects of acidification were identified (Ontario Ministry of Natural Resources photograph).

affected by high sulfate and metal (copper and nickel, primarily) deposition. It has been estimated that as much as 97% of the sulfur emitted from the Superstack is carried farther than 60 km from Copper Cliff and, thus, contributes to more widespread problems of acid deposition (Hutchinson 1982). Thus, what was perceived to be an acceptable solution to the local problem may have far-ranging consequences (Fig. 24.4).

Time Scale

Another consideration in managing areas such as Sudbury is one of time scale. From a management perspective, this is an issue because both short-term and long-term remediation efforts must be considered and the relative effort to be placed on each must be assessed. Thus, efforts spent on rehabilitation techniques such as lake liming (see Chapter 15) (Dillon et al. 1979; Molot et al. 1986, 1990) or fertilization (Yan and LaFrance 1984), fish stocking, and watershed liming and fertilization, which are only short-term solutions to the long-term problem (Havas et al. 1984), are not a substitute for reducing the levels of the stressors. These must be weighed against the efforts invested in establishing the acceptable sulfur and metal emission and deposition rates.

From a scientific perspective, time presents a problem with respect to determining long-term or sublethal effects of the stress on the ecosystem. Although the extirpation of fish species such as the aurora trout (see Chapter 11), the loss of entire fish populations (Beamish and Harvey 1972; Beamish 1974), and the denudation of the landscape (see Chapter 2) are obvious and direct lethal effects of high acid and metal deposition, long-term or chronic effects on biota are not so readily discernible. For example, the copper concentrations in many of the Sudbury area lakes typically exceed 2 μg/L (Keller et al. 1992) (i.e., are greater than the provincial water quality objective). Although the copper levels in the worst cases are high enough to be acutely toxic to some biota, in many cases the effects may be chronic and therefore less readily observable.

Time presents a complication when managing systems for another reason. It is known that the capacity for the terrestrial and wetlands portion of catchments to "store" strong acid (in the form of reduced sulfur compounds) and trace metals is high (Urban et al. 1989; Dillon and LaZerte 1992). However, evidence has shown (Bayley et al. 1987; RMCC 1990) that terrestrial areas may release these compounds for periods of years to decades. For example, in Plastic Lake, Ontario, the pH and acid neutralizing capacity (ANC) of the water decreased gradually from 1979 to 1985, despite the fact that atmospheric deposition of sulfate and strong acid decreased sharply during that same period (Dillon et al. 1987). The reason for this is that the wetlands in the catchment continued to supply sulfate to the water despite the reductions in the sulfate deposition. A similar situation has been documented in the Sudbury area (Keller et al. 1992). Thus, detrimental effects on biota may be observed and measured long after the stress (i.e., sulfate deposition) has been reduced or even eliminated. This presents a challenge to scientists who must try to predict the effect of the stress (see step 10 in Fig. 24.2) without knowing its future level in the ecosystem.

Interactions between Stresses

The interaction between stresses is another problem that became apparent during the integrated studies carried out in Sudbury. One example is forest denudation (resulting from both logging activities and acid metal deposition), which led to increased soil erosion, higher surface reflective temperatures, and enhanced frost action (see Chapter 18). A second example is the interaction between sulfate (and H^+ ion) deposition and trace metals. Because of smelting activities, copper and nickel concentrations in soil, water, and biota are elevated in the immediate vicinity of Sudbury. Thus, biota there must contend not only with high metal levels but also with low pH. It has been well documented that pH can have a synergistic (i.e., enhancing) effect on metal toxicity (e.g., Campbell and Stokes 1985; Cusimano et al. 1986; Hutchinson and Sprague 1986; Hickie et al. 1993). For example, Welsh et al. (1993) found that the toxicity (expressed as the 96-hour LC_{50}) of copper to fathead minnows (*Pimephales promelas*) increased fourfold as pH decreased from 7.2 to 5.6.

Acidic precipitation also can cause leaching and mobilization of other metal ions such as calcium, magnesium, aluminum, manganese, iron, and zinc from soils and bedrock (Mayer and Ulrich 1980; Jeffries et al. 1984). As a result, biota that are in ecosystems remote from industries that emit metals into the atmosphere may have to contend with the combination of high levels of both acid and metals. A discussion of the complexities of metal–H^+ or metal–metal interactions is beyond the scope of this chapter. However, depending on the organism in question as well as the mitigating circumstances in the lake/soil, the toxicity of chemical "mixtures" can be either (1) synergistic (i.e., the presence of one enhances the toxicity of the other), (2) additive (i.e., the presence of one adds to but does not have an effect on the toxicity of the other), or (3) antagonistic (i.e., the presence of one decreases the toxicity of the other, e.g., selenium/mercury, calcium/aluminum). When making policy decisions for a catchment, one must be aware of these potential interactions and, as discussed previously, conduct "integrated" scientific research.

External Factors

Although scientists can study, model, and predict to a certain extent the effects of these multiple stresses on the ecosystem, factors external to the principal stressors often can impinge on the situation and complicate the issue. A few examples follow.

Climate/Weather Change

As discussed above, wetlands, soils, and even the littoral zone of lakes are able to store strong acid in the form of reduced sulfur compounds. Catchment mass balances have shown that the storage of sulfate and/or the oxidation of stored reduced sulfur usually occurs during dry seasons (Dillon and LaZerte 1992) or in dry years when the water table becomes lowered. At the beginning of the next wet season, or in a wet year, the stored sulfate is then released back into the outflowing waters. Given that you cannot predict the weather, it is difficult to imagine managing a catchment if you are unable to predict when these pulses of acid might occur. However, long-term monitoring studies might provide insight into climatic trends and thus allow for modeling efforts.

Decrease in Atmospheric Ozone

The recent attention given by the scientific and non-scientific communities to the decrease in the ozone layer also has consequences with respect to biota in the Sudbury region. It is well documented that ultraviolet (UV) radiation can have detrimental effects on biota and that UV levels that lakes and other ecosystems are experiencing are increasing as a result of a decrease in ozone levels in the upper atmosphere. It is the dissolved organic matter (usually measured as dissolved organic carbon [DOC]) in lakes that absorbs strongly in the UV range. Unfortunately, acidification results in the reduction of DOC levels in streams and lake water (Dillon et al. 1987), and the soft water, low alkalinity, acidic lakes typical of the Sudbury region generally have low DOC concentrations. Thus, they are particularly vulnerable to a decrease in the ozone layer.

Nitrate Release from Catchments

After sulfate, deposition of nitrogen compounds is the next most important class of anthropogenic acids entering aquatic systems in Canada (RMCC 1990). However, emission of NO_x and deposition of related compounds should not be directly influenced significantly by mining/smelting activities but perhaps indirectly because most mining industries make massive uses of energy, which is often derived from the combustion of fossil fuels. Thus, although emissions of sulfur dioxide and declines in the atmospheric deposition of SO_4 may have occurred in Ontario since the mid-1970s, NO_x emissions and NO_3 deposition have not decreased (Dillon et al. 1988). In the past, this has not been thought to be a problem because terrestrial ecosystems are often limited by nitrogen, and thus, they have been a sink for nitrogen inputs (Driscoll and van Dreason 1993). However, declining vegetational demands coupled with increased deposition of nitrogen from the atmosphere may result in saturation of the terrestrial ecosystem.

Consequently, in Europe and in parts of the northeastern United States, there has been evidence of surface water acidification resulting from elevated NO_3 (Henriksen and Brakke 1988; Driscoll and van Dreason 1993). This means that even if large-scale reductions in sulfur dioxide emissions were implemented, recovery of lakes from acidic deposition may be delayed due to offsetting increases in NO_3 concentration.

Other Stresses

Kelly Lake in Sudbury, like several other lakes in the region that have calcareous deposits in their catchments, at present is not adversely affected by acidification, even though it lies at the center of the high sulfate deposition zone. However, it is the recipient of sewage from the city of Sudbury and, thus, suffers from all the problems typical of municipal lakes—it is eutrophic, bacterial counts often exceed guidelines established for human health protection, and macrophytes proliferate along its shoreline. It is important for those who are involved in management decisions for communities, such as Sudbury, that are affected by mining activities, not to overlook lakes such as Kelly in their eagerness to remediate only those lakes that have problems due to smelting activities. However, there may be indirect links between acid rain and eutrophication. Caraco et al. (1993) suggested that anthropogenically induced increases in sulfate concentrations in lakes can cause an increase in the magnitude of phosphorus released from the sediments, as well as an increase in the availability of that phosphorus to biota. Thus, two seemingly independent stressors may, in fact, behave in an inter-active way, again demonstrating it is apparent that the need for integrated research and management policies is essential to overall catchment management.

Summary

The management of catchments that have been damaged by anthropogenic activities or that may be potentially stressed in the future is a complex problem requiring (1) an informed public, (2) the cooperation of many individuals, government agencies, and non-government organizations, (3) the coordination of all scientific endeavors, and (4) the consideration of both scientific and socioeconomic factors. Consequently, in this chapter, we have described and emphasized the need for an integrated whole-ecosystem approach to catchment management (see Fig. 24.1).

Although the management in the Sudbury area generally has set an example of how the integrated approach to catchment management should work, serious challenges have been faced by those attempting to set policies for the region. The reasons for these difficulties arise from the fact that pollution transcends political, geographic, social, and temporal boundaries. Secondary and tertiary pollution (see Fig. 24.3) and multiple stresses such as interactions between sulfate and trace metals and forest denudation leading to increased soil erosion, higher surface reflective temperatures, and enhanced frost action have complicated scientific findings. Sulfur storage in the terrestrial and wetland portions of catchments and its potential release long after sulfate deposition has been reduced also presents a challenge to scientists who must try to predict the effect of the sulfate without knowing its future concentration in the ecosystem. Also, the element of time confuses the issue, not only for the scientist, who must determine both long-term (chronic) and short-term (acute) effects of the stress on the ecosystem but also for the manager, who must weigh the advantages/disadvantages of short-term versus long-term remedial actions.

Other factors, external to the principal stressors (high sulfate and metal deposition) can affect the Sudbury region and complicate matters even further. These include climate or weather changes, decreasing ozone levels in the atmosphere, nitrate release from the terrestrial portion of the catchment, and phosphorus inputs from sewage.

In conclusion, we emphasize that only when scientific research activities are integrated with responsive and responsible management policies can overall catchment management be successful.

References

Baumann, A. 1984. Extreme heavy metal concentrations in sediments of the Oker—a river draining an old mining and smelting area in the Harz Mountains, Germany, pp. 579–591. *In* J. Nriagu (ed.). Environmental Impact of Smelters. Advances in Environmental Science Series. John Wiley and Sons, New York.

Bayley, S.E., D.H. Vitt, R.W. Newbury, K.G. Beaty, R. Behr, and C. Miller. 1987. Experimental acidification of a *Sphagnum*-dominated peatland: first year results. Can. J. Fish. Aquat. Sci. 44:194–204.

Beamish, R.J. 1974. Loss of fish populations from unexploited remote lakes in Ontario, Canada as a consequence of atmospheric fallout of acid. Water Res. 8:85–95.

Beamish, R.J., and H.H. Harvey. 1972. Acidification of the La Cloche Mountain lakes, Ontario and resulting fish mortalities. J. Fish. Res. Board Can. 29:1131–1143.

Campbell, P.C.G., and P.M. Stokes. 1985. Acidification and toxicity of metals to aquatic biota. Can. J. Fish. Aquat. Sci. 42:2034–2049.

Caraco, N.F., J.J. Cole, and G.E. Likens. 1993. Sulfate control of phosphorus availability in lakes: a test and re-evaluation of Hasler and Einsele's model. Hydrobiology 253:275–280.

Cusimano, R.F., D.F. Brakke, and G.A. Chapman. 1986. Effects of pH on the toxicities of cadmium, copper and zinc to steelhead trout (*Salmo gairdneri*). Can. J. Fish. Aquat. Sci. 43:1497–1503.

Devito, K.J., and P.J. Dillon. 1993. The influence of hydrologic conditions and peat oxidation on the phosphorus and nitrogen dynamics of a conifer swamp. Water Resource Res. 29:2675–2685.

Dillon, P.J., D.S. Jeffries, and W.A. Scheider. 1982. The use of calibrated lakes and watersheds for estimating atmospheric deposition near a large point source. Water Air Soil Pollut. 18:241–258.

Dillon, P.J., D.S. Jeffries, W. Snyder, R. Reid, N.D. Yan, D. Evans, J. Moss, and W.A. Scheider. 1978. Acidic precipitation in south-central Ontario: recent observations. J. Fish. Res. Board Can. 35: 809–815.

Dillon, P.J., and B.D. LaZerte. 1992. Response of Plastic Lake catchment, Ontario, to reduced sulphur deposition. Environ. Pollut. 77:211–217.

Dillon, P.J., M. Lusis, R.A. Reid, and D. Yap. 1988. Ten-year trends in sulphate, nitrate and hydrogen deposition in central Ontario. Atmos. Environ. 22:901–905.

Dillon, P.J., R.A. Reid, and E. de Grosbois. 1987. The rate of acidification of aquatic ecosystems in Ontario, Canada. Nature 329:45–48.

Dillon, P.J., N.D. Yan, W.A. Scheider, and N. Conroy. 1979. Acidic lakes in Ontario, Canada: characterization, extent and responses to base and nutrient additions. Arch. Hydrobiol. Beih. 13: 317–336.

Driscoll, C.T., and R. van Dreason. 1993. Seasonal and long–term temporal patterns in the chemistry of Adirondack lakes. Water Air Soil Pollut. 67:319–344.

Fitchko, Y. 1978. The distribution, mobility and accumulation of nickel, copper and zinc in a river system draining the eastern part of the metal–polluted Sudbury smelting area. Ph.D. thesis, University of Toronto, Toronto, Ontario.

Gorham, E., and A.G. Gordon. 1960. The influence of smelter fumes upon the chemical composition of lake waters near Sudbury, Ontario and upon the surrounding vegetation. Can. J. Bot. 30:477–487.

Haukioja, E. 1993. Research on ecological effects of aerial pollution: a Finnish perspective, pp. 67–69. *In* M.V. Kozlov, E. Haukioja, and V. Yarmishko (eds.). Aerial Pollution in Kola Peninsula. Proceedings of International Workshop, April 14–16, 1992, St. Petersburg, Russia. Kola Scientific Center, Apatity, Russia.

Havas, M., T.C. Hutchinson, and G.E. Likens. 1984. Red herrings in acid rain research. Environ. Sci. Technol. 18:176–186.

Henriksen, A., and D.F. Brakke. 1988. Sulfate deposition to surface waters. Environ. Sci. Technol. 22:8–18.

Hickie, B.E., N.J. Hutchinson, D.G. Dixon, and P.V. Hodson. 1993. Toxicity of trace metal mixtures to alevin rainbow trout (*Oncorhynchus mykiss*) and larval fathead minnow (*Pimephales promolas*) in soft, acidic water. Can. J. Fish. Aquat. Sci. 50: 1348–1355.

Hutchinson, N.J., and J.B. Sprague. 1986. Toxicity of trace metal mixtures to American flagfish (*Jordanella floridae*) in soft, acidic water and implications for cultural acidification. Can. J. Fish. Aquat. Sci. 43:647–655.

Hutchinson, T.C. 1982. The ecological consequences of acid discharges from industrial smelters, pp. 105–122. *In* F.M. D'Itri (ed.). Acid Precipitation: Effects on Ecological Systems. Ann Arbor Science.

Jeffries, D.S., W.A. Scheider, and W.R. Snyder. 1984. Geochemical interactions of watersheds with precipitation in areas affected by smelter emissions near Sudbury, Ontario, pp. 195–241. *In* J. Nriagu (ed.). Environmental Impacts of Smelters. Advances in Environmental Science Series. John Wiley and Sons, New York.

Keller, W., J.R. Pitblado, and J. Carbone. 1992. Chemical responses of acidic lakes in the Sudbury, Ontario area to reduced smelter emissions, 1981–89. J. Fish. Res. Board Can. 49:25–32.

Mayer, R., and B. Ulrich. 1980. Input to soil, especially the influence of vegetation in intercepting and modifying inputs—a review, pp. 173–182. *In* T.C. Hutchinson and M. Havas (eds.). Effects of Acid Precipitation on Terrestrial Ecosystems. Plenum Press, New York.

Molot, L.A., P.J. Dillon, and G.M. Booth. 1990. Whole–lake and nearshore chemistry in Bowland Lake, before and after treatment with $CaCO_3$. Can. J. Fish. Aquat. Sci. 47:412–421.

Molot, L.A., J.G. Hamilton, and G.M. Booth. 1986. Neutralization of acidic lakes: short–term dissolution of dry and slurried calcite. Water Res. 20: 757–761.

Moore, J.N., and S.M. Luoma. 1990. Hazardous wastes from large–scale metal extraction. Environ. Sci. Technol. 24:1278–1285.

Research and Monitoring Coordinating Committee (RMCC). 1990. The 1990 Canadian Long-Range Transport of Air Pollutants and Acid Deposition Assessment Report. Part 4. Aquatic Effects Studies, Toronto, Ontario.

Royal Commission on the Future of the Toronto Waterfront (RCFTW). 1992. Regeneration: Toronto's Waterfront and the Sustainable City (Final Report). Toronto, Canada.

Somers, K., G. Mierle, and N.D. Yan. 1994. An Environmental Protection Model for the Management of Ontario's Water Resources. Technical report. Ontario Ministry of Environment and Energy, Ontario.

Spanish Harbour Rap Team. 1993. The Spanish Harbour Area of Concern, Environmental Conditions and Problem Definition, Remedial Action Plan, Stage 1 Report. Intergovernmental report. Ontario Ministry of Environment and Energy, Sudbury, Ontario.

Urban, N.R., S.E. Bayley, and S.J. Eisenreich. 1989. Export of dissolved organic carbon and acidity from peatlands. Water Resource Res. 25:1619–1629.

Welsh, P.G., J.F. Skidmore, D.J. Spry, D.G. Dixon, P.V. Hodson, N.J. Hutchinson, and B.E. Hickie. 1993. Effect of pH and dissolved organic carbon on the toxicity of copper to larval fathead minnow (*Pimephales promelas*) in natural lake waters of low alkalinity. Can. J. Fish. Aquat. Sci. 50: 1356–1362.

Yan, N.D., and R. LaFrance. 1984. Responses of acidic neutralized lakes near Sudbury, Ontario to nutrient enrichment, pp. 243–282. *In* J. Nriagu (ed.). Environmental Impacts of Smelters. Advances in Environmental Science Series. John Wiley and Sons, New York.