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Integrated Management and Progressive Rehabilitation of Industrial Lands

Ellen L. Heale

Member companies of the Mining Association of Canada and the Ontario Mining Association are committed to the concept of sustainable development. "Sustainable development requires balancing good project stewardship in the protection of human health and the natural environment with the need for economic growth" (Mining Association of Canada 1990; Ontario Mining Association 1993).

To meet the challenge of sustainable development and improve the level of environmental protection, it is necessary for companies to adopt several operating principles throughout exploration, mining, processing, and decommissioning activities. These basic principles include compliance with applicable legislation; applying cost-effective best management practices to minimize environmental risks; maintaining self-monitoring programs; supporting research to improve treatment technologies; expanding scientific knowledge of mining industry's impact on the environment; and assisting in the development of equitable, cost-effective, and realistic laws for environmental protection.

An integrated approach to decision making and management is essential to implement environmentally sustainable economic development (Lecuyer and Aitken 1987). Environmental decision making involves

1. the wise use of air, water, land, and energy
2. mitigating adverse environmental impacts arising from mining-related activities
3. safeguarding the health of people and the natural environment
4. recycling and reducing wastes
5. disposing of non-recyclable wastes in an environmentally sound manner
6. rehabilitating disturbed land to a safe, stable, and productive condition

In previous chapters, authors describe programs for the rehabilitation of tailings areas (see Chapters 9 and 10) and technological developments for the reduction of atmospheric emissions (see Chapter 21). In this chapter, integrated planning approaches, progress in achieving environmental improvements in air and water quality, and site remediations are presented. Most of the examples are drawn from work at Inco Limited's Sudbury area operations.

Improvements in Air and Water Quality

In compliance with provincial government regulations, Sudbury companies have significantly reduced sulfur dioxide emissions. Inco's sulfur dioxide abatement program (Inco Limited 1992) and Falconbridge Limited's smelter environmental improvement project (Falconbridge Limited 1992) represent the largest environmental projects ever undertaken by any mining companies. Since 1970, Falconbridge has reduced their sulfur dioxide output by more than 85% (Falconbridge Limited 1992). Inco's emissions reduction program will achieve an 87% reduction in sulfur dioxide emissions from 1972 to 1994. Of the sulfur in the ore, 90% will be contained and not emitted into the atmosphere (Inco Limited 1991).

As described in the previous chapter, the air pollution prevention approaches adopted in Sudbury have both environmental and economic benefits. Immediate improvements in air quality are some of the obvious environmental benefits (Dobrin and Potvin 1992), but as shown in other chapters in this book, the reduced emissions have also allowed for vegetation establishment (Allum and Dreisinger 1986), restoration of land (see Chapter 8), and biological recovery of lakes (Keller et al. 1992).

Water Management and Treatment

In addition to air quality improvements, both Inco and Falconbridge have developed extensive water management and treatment programs aimed at reducing the downstream impact of mining effluents, as well as reducing costs. Water conservation and recycling initiatives reduce the amount of fresh water that must be used for processing and, ultimately, the amount of process waste water requiring treatment before discharge. To reduce the amount of surface drainage that must be treated, considerable amounts of stormwater are diverted away from areas of potential contamination. Research is ongoing to determine the impact of revegetation on run-off water quantity and quality within industrially disturbed watersheds. With favorable research results, substantial long-term environmental and economic benefits are possible.

Inco's ore processing facilities at Copper Cliff operate entirely on recycled water decanted from the tailings area (Van Cruyningen and Puro 1987). Water levels in storage ponds and lakes, upstream of Inco's waste water treatment plants, are controlled to ensure that sufficient water is available for processing, yet capacity is available in the system to retain water that enters during storm events and spring freshet. This prevents process interruptions and avoids spills to the environment. Since 1992, the retention capacity upstream of the Copper Cliff waste water treatment plant has been increased to 5.26 billion liters.

Not all water can be retained on site, primarily due to the large influx of precipitation, which far exceeds the evaporation rate. Large volumes must be treated to satisfy government regulations before being released to the environment. Inco operates two waste water treatment plants in the Copper Cliff area, having a combined treatment capacity of 216,000 m^3/day. Reactor-clarifier technology is used, with hydrated lime and polymer as the reagents. According to an Ontario Ministry of the Environment and Energy report, this method has been identified as among the best available treatment technologies for base metal mine effluents. At smaller more-remote sites, batch lime addition is used, with clarification occurring in large retention ponds. Although much simpler, this method is equally effective.

Lime treatment is relatively inexpensive compared with other treatment methods. Lime ($Ca(OH)_2$) or calcium oxide (CaO) is added, at a controlled rate, to raise the pH of waste water for the purpose of precipitating dissolved metals. Precipitation of dissolved iron occurs at pH 7, whereas other metals such as zinc and nickel require pHs between 9 and 10.6. Sludges generated by this process tend to be voluminous and are not stable when exposed to rain and oxygen. Generally, recovery of metals from these sludges is currently not feasible, and disposal is expensive. At Copper Cliff, sludges are continually pumped from the waste water treatment plant to the tailings area. Remote batch lime facilities are periodically dredged and the sludge transported by truck to the Copper Cliff tailings area.

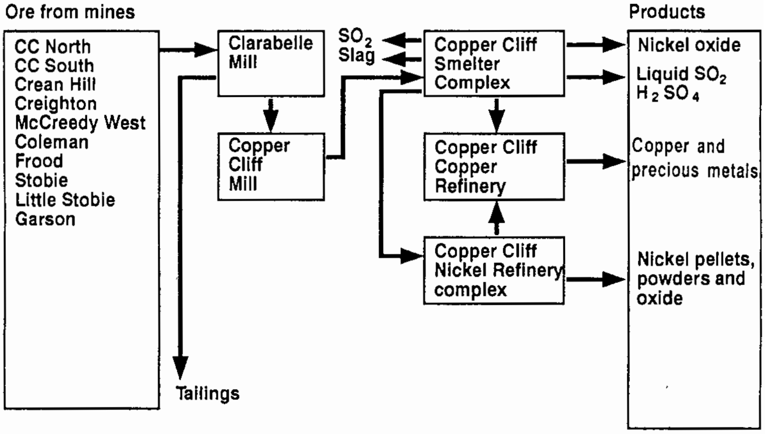

FIGURE 22.1. Inco Limited, Sudbury District operations flowsheet.

Many companies are required to reduce the alkalinity of their effluent after lime treatment and before discharge to the natural environment. Recently, carbon dioxide, rather than strong acids, has been used because it is less hazardous to handle and does not add chemicals to the treated water. There is less risk of overdosing with carbon dioxide, and a minimum pH of 5.6 is achievable. Falconbridge's Moose Lake facility incorporates carbon dioxide into the treatment process for neutralization of the final effluent to pH 7 (M. Wiseman, *personal communication*).

Although the requirement for pH adjustment is intended to reduce the toxicity of effluents, the desired effect is not always achieved. In tests performed on effluents of member companies, the Ontario Mining Association found that in some cases, toxicity actually increased after adjustment to pH 7.

Industrial Lands

Mining, milling, smelting, and refining operations are very large and visible operations in the Sudbury region. Privately owned industrial lands include tailings disposal areas, mine and plant sites, adjacent barren rocky outcrops, waste rock and slag piles, and sand pits. Integrated management of these lands is required due to the history, size, and scope of the impacted areas and because of the diversity of processes (Fig. 22.1), the variety of land uses, and the many interactions between environmental stresses.

Inco, a leading producer of nickel, copper, precious metals, and cobalt, has been operating since 1902. Falconbridge, a major producer of nickel, copper, and cobalt, has been in operation in Sudbury since 1928. Industrial operations are often complex, large, or spread out over a variety of terrains (Fig. 22.2). Other sites may be remote, with limited access or abandoned. Sites do not represent single confined processes or problems (Moore and Luoma 1990), and therefore management of these sites must reflect a wide variety of factors.

In addition to the plants and mines, byproducts of these operations are stored on industrial lands. For every 100 tonnes of ore that Inco currently mines, 90 tonnes is rejected as tailings waste. Inco produces 7.7–8 million tonnes of tailings each year. Approximately 25% of this material is used to fill mined-out areas underground. Falconbridge produces 1 million tonnes of tailings annually, and two-thirds of the tailings is pumped back underground. The balance of the tailings is disposed of in large tailings disposal areas (Fig. 22.3). Inco's Copper Cliff tailings area has a total storage capacity of 700 million tonnes and covers an area of 2225 h (Van Cruyningen and Puro 1987). Falconbridge stores 45 million tonnes of tailings in the Sudbury area.

Smelting produces 9 tonnes of slag (see Plate 13 following page 182) for every 100 tonnes of ore that is mined. Slag is a glasslike residue, primarily an iron silicate material. Falconbridge stores approximately 10 million tonnes of slag. More than

FIGURE 22.2. Inco Limited's Copper Cliff smelter complex. (Photo by Bob Chambers.)

FIGURE 22.3. Aerial view of tailings disposal area at Falconbridge. Treated waste water from the site has developed into a productive marsh area supporting various fish and wildlife species. (Photo by Ed Snucins.)

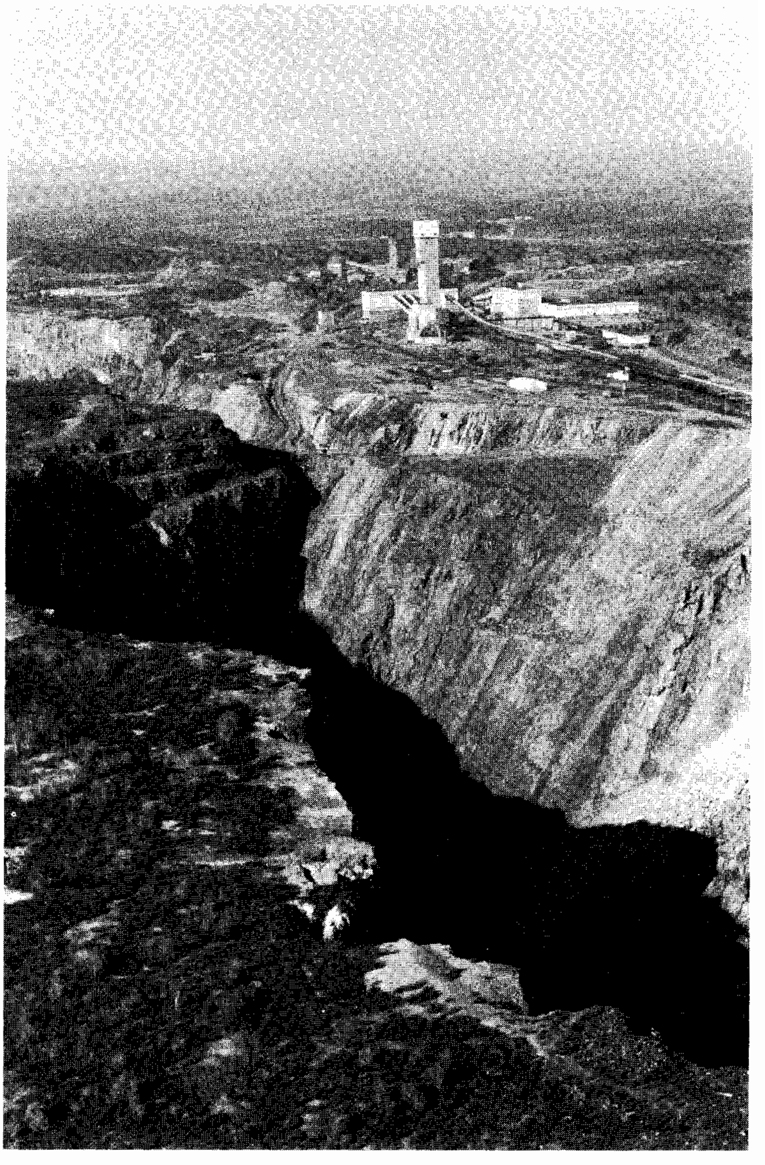

FIGURE 22.4. Framed by Inco's Frood-Stobie Mine complex, the 33.4 million-m^3 open pit was mined from 1938 to 1961. This is one of several pits that could be used for the disposal of acid-generating waste rock and tailings. (Photo by Bob Chambers.)

119 million tonnes of slag are stored on Inco property. The largest of four stockpiles is located at Copper Cliff, where more than 100 million tonnes of slag are stored in an area that covers 240 ha (see lower part of Fig. 22.2). Slag is slow-cooled on dumps and crushed or granulated. Some Inco slag is sold for road and rail ballast and domestic fill. Inco's 1993 rate of slag production was approximately 1.3 million tonnes/year.

Industrial sites also include areas for the storage of waste rock. Large quantities of waste rock are generated with the development of open pits, sinking of shafts, and mining of drifts (Fig. 22.4). It is estimated that Inco has 31 million tonnes of waste rock located in more than 65 piles. The largest storage pile contains 11 million tonnes of waste rock, spread to a maximum depth of 21 m. Falconbridge's total waste rock storage is in the order of 20 million tonnes.

Acid Rock Drainage

The large amounts of sulfur in Sudbury ores present unique environmental challenges, because for every 1 part of nickel, there are 8 parts of sulfur. Tailings and waste rock contain these sulfide minerals, and as the sulfides oxidize, in the presence of water and oxygen, acidic drainage is generated (Steffen Robertson and Kirsten 1989a,b). Traditional revegetation of tailings or waste rock piles will reduce the infiltration of precipitation or surface water. However, vegetation will not stop the acid generation process.

$$MS + 3O_2 + 2H_2O \rightleftarrows 2H_2SO_4 + M^+$$

metal sulfide + oxygen + water → *sulfuric acid + dissolved metals*

Acidic drainage or seepage waters are characterized by low pH, elevated levels of dissolved solids, total acidity, trace elements, and inorganic compounds. Acidic seepage is also responsible for impacts on aquatic biota (Huckabee et al. 1975). Acid rock drainage is one of the most significant environmental and economic challenges facing the mining industry.

Both mining companies are active participants in Mine Environment Neutral Drainage, a cooperative research program sponsored by the Canadian mining industry and government agencies. Research and investigations are underway to develop reliable and affordable methods to prevent, monitor, control, and treat acid rock drainage (Skousen et al. 1987; Itzkovitch 1993) (see Chapter 10). From 1988 to 1992, contributions (from all participants) to the research program totalled $Can 8.1 million.

One solution to reducing the amount of sulfur released into the atmosphere during the smelting process is to ensure that much of the pyrrhotite in the ore (up to 30% sulfur) is rejected before the ore is smelted. However, storing pyrrhotite in the tailings area creates an additional source of acid generation.

To stop the oxidation process that leads to acid formation, pyrrhotite tailings are stored under water, or under a 30–100-cm cover of less reactive tailings slimes (Michelutti 1987), or at sites where the seepage can be collected and treated. Falconbridge is involved in research to develop oxygen barriers over tailings to control acid seepage effectively. Covers of partially decomposed domestic waste, digested sewage sludge combined with alkaline materials, or shallow water covers are being examined. Another approach that Falconbridge is investigating is the construction of a porous envelope around tailings disposal areas. An impervious cap on top can prevent ground- and surface water from entering the tailings whereas groundwater will flow around the tailings in the more porous envelope, minimizing its contact with tailings (Falconbridge Limited 1991). Treatment of acid seepage using wetlands to facilitate the development of natural alkaline-generating, sulfate-reducing microbial processes is being tested at Inco and Falconbridge (see Chapter 10).

To demonstrate more economically feasible methods for detecting acid rock drainage and identify areas requiring remediation, major projects were conducted in and around Inco property in 1993. It was determined that non-intrusive ground conductivity survey methods, using standard exploration equipment, were a useful tool in the environmental assessment of groundwater to detect acid rock drainage. Another project used an underwater probe, dragged by a boat, to detect sources of acid rock drainage discharging into surface waters. An investigation in the Copper Cliff tailings area involved piezocone technology. Measurements from an electronic piezocone, typically used to characterize soil stratigraphy and geotechnical parameters, will be correlated with chemical constituents from corresponding drilled samples to determine if a relationship exists (Itzkovitch 1993).

The production of a low-sulfur tailings is also currently being investigated by Inco. A new process in the milling circuit will produce a low-sulfur (0.4%) tailings to encapsulate and reduce the oxidation potential of the high-sulfur (15–20% sulfur) and pyrrhotite tailings stored in the center of Inco's current tailings disposal area. Low-sulfur tailings are a non-acid-generating waste.

Waste rock, containing sulfide minerals, is also a source of acidic drainage. As is practical, waste rock remains underground. It is used as backfill and for road bed construction. On surface, acid-generating waste rock is placed underwater in pits to stop the oxidation process. Inco has 23 pits, with a total volume capacity of 145 million tonnes. These pits are potential sites for the disposal of acid-generating waste rock (Fig. 22.4). When these alternatives are not feasible, seepage from waste rock piles is collected for treatment before to its release to the environment. Waste rock piles are currently being inventoried and assessed to determine acid-generating potential.

Progressive Rehabilitation

Mining companies in Ontario face additional environmental and economic challenges. Recent amendments to the Mining Act of Ontario have introduced legislation to set standards for the closure of mines and the rehabilitation of lands used for mining activities (Ontario Ministry of Northern Development and Mines 1992). Progressive rehabilitation and the development of closure plans are legislated to protect public health and safety, alleviate or eliminate environmental damage, and allow productive use of land in its original condition or an acceptable alternative.

Engineering and environmental studies required for the preparation of closure plans are underway by both companies. Inco is monitoring groundwater, conducting site inventories at active and abandoned mines, properties, and quarries, and sampling soil and vegetation. Closure plans and the estimated costs to implement the plans will be submitted to the Ontario Ministry of Northern Development and Mines for acceptance. Once approved, financial assurance will be negotiated to ensure economic resources for future work. Annual reports updating progressive rehabilitation and progress on studies will be required.

Progressive rehabilitation is essential to reduce the company's financial liability. Filling pits with acid-generating waste rock for underwater disposal, demolition of abandoned buildings, revegetation and restoration are current progressive rehabilitation activities. Perpetual monitoring and treatment of acidic seepage, for example, are not economically feasible or desirable. Companies may need to modify current operating practices. Also, industries cannot afford to wait until a facility closes to initiate rehabilitation activities.

The challenges for restoration of industrial lands include identifying and assessing environmental impacts (Bridges 1991), treatment, and rehabilitation costs. These factors must not be considered in isolation. Areas of impact, such as watersheds and neighboring lands, must be managed as an ecosystem unit.

At locations where mining operations are in close proximity to one another, an integrated approach to rehabilitation and closure is required. Inco's Levack Complex and Falconbridge's Onaping Complex, northwest of Sudbury, are within the same watershed management area. Joint technical planning groups have been established to implement a joint closure plan for this area. Integration of planning efforts within a company is also required. For example, Inco is currently developing an integrated watershed management plan for nine sites in the Copper Cliff area. For a detailed discussion of watershed or catchment planning, see Chapter 24.

Aerial Treatment Program

Surface run-off from the Nolin Creek watershed (850 ha), northeast of Copper Cliff, is currently being treated at one of Inco's waste water treatment plants. However, as shown in other parts of this book, the barren rocky outcrops in this area can be treated with surface applications of ground limestone to detoxify soil and allow plant growth (Winterhalder 1988) (see Chapter 8). Such treatments offer considerable promise for reducing containment export from metal-contaminated sites.

In 1980, Inco began a labor-intensive program on company-owned property to manually apply agricultural limestone, fertilizer, and grass seed to treat a few hectares of land in

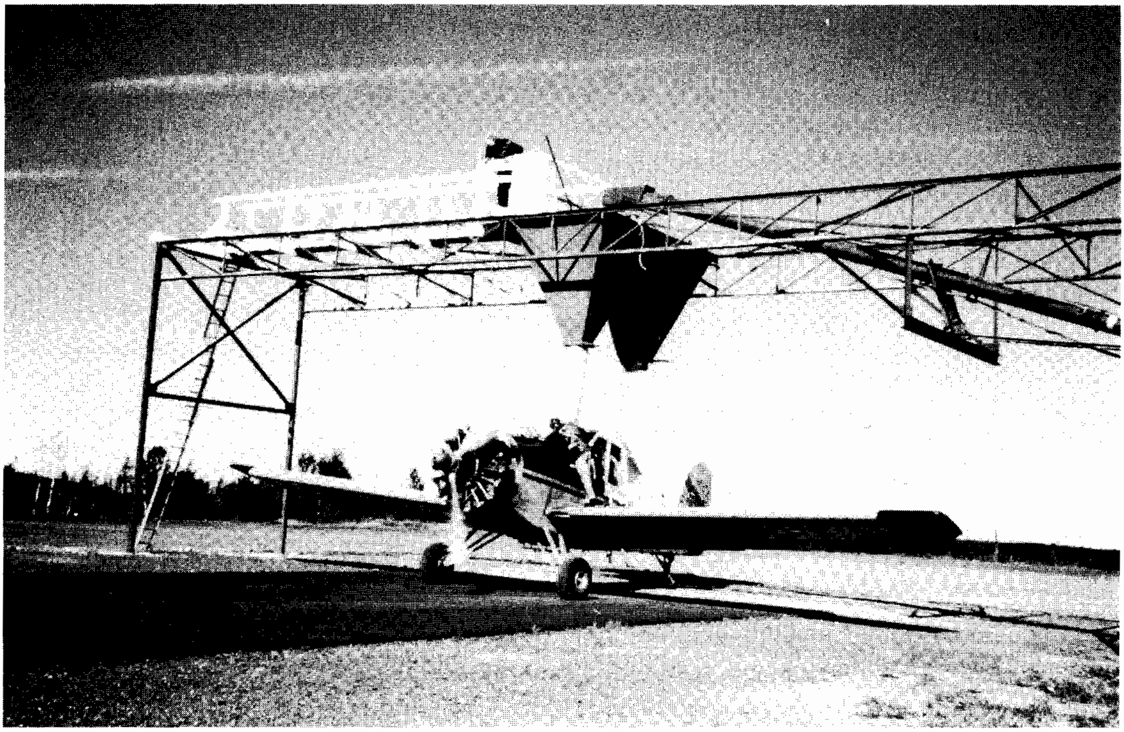

FIGURE 22.5. Airplane being loaded with agricultural limestone. Between 1990 and 1994, Inco treated more than 650 ha of barren rocky outcrops with its innovative aerial treatment program. (Photo by Ellen Heale.)

Copper Cliff. These areas were virtually treeless, with sparse vegetation or shallow pockets or crevices of bare soil. By the mid-1980s, four-wheel-drive all-terrain vehicles, specially fitted with spreaders, treated 8–12 ha/year. In 1990, an innovative program to reclaim barren rocky outcrops began. Suitably equipped aircraft (Fig. 22.5), capable of carrying 1.5 tonnes of material, dropped agricultural limestone, followed by applications of a fertilizer and grass seed mix, over the stressed lands.

In 1990, an initial 50-ha site in the Nolin watershed was treated. With the establishment of successful vegetation covers (Fig. 22.6), the aerial treatment program was expanded. From 1990 to 1994, 650 ha of rocky outcrops have been treated. Productivity was increased in 1992 with the construction of a bulk lime-loading system for the aircraft (see Fig. 22.5). This aerial technique allows the company to treat relatively inaccessible areas in a safe, efficient, and cost-effective manner.

It is expected that revegetation will have a significant impact on the quantity and quality of surface run-off water and thus reduce the amount requiring treatment. With the application of agricultural limestone, a critical factor in the success of the revegetation program, natural colonizing species quickly become established. The grassed sites are subsequently planted with coniferous forestry seedlings.

Self-Sustaining Ecosystem Development

Restoration of mining land is necessary for many reasons, including responsible corporate business practice, surface stabilization, improving run-off water quality, aesthetic en-

FIGURE 22.6. Seven months after an aerial application of limestone, fertilizer, and grass seed, a vegetation cover has been established over rocky outcrops on Inco Limited property. Volunteer native tree seedlings were 15 cm high 3 months later. (Photo by Ellen Heale.)

hancement of the area, and compliance with legislation. These successful rehabilitation efforts lead to diversification of vegetation species, promotion of wildlife habitats, and overall ecosystem development (Australian Mining Industry Council 1987; Green and Slater 1987). This, in turn, leads to a reduction in further soil erosion and surface water run-off and the need for mitigation of the effects of metal contaminants in run-off waters. A variety of land use options is available (Powell 1992). Both Inco and Falconbridge have focused their efforts on the development of self-sustaining ecosystems with the promotion of wildlife habitats.

Inco's Copper Cliff tailings area has been designated as a wildlife management area (see Chapter 9). Efforts continue to diversify the number and types of vegetation species to supply suitable habitats and food sources for a wide variety of birds and wildlife. More than 86 different native and introduced species of vegetation have been identified on the tailings, including trees, shrubs, grasses, wetland species, legumes, field weeds, and mosses (Heale 1991). Over an 8-year period, 92 species of native and migratory birds have been identified on tailings (Peters 1984).

In less than 10 years, a 160-ha lifeless bog, adjacent to the Falconbridge smelter, was successfully converted into a productive wetland with a transient population of hundreds of birds, small fish, and mammals (Fig. 22.3). Treated alkaline waste water was directed into the bog to neutralize the existing acidity and reduce metal toxicity (Michelutti 1987). Cattails (*Typha latifolia*) and reedgrass (*Phragmites australis*) cover 90% of the area. Falconbridge has turned this productive marsh site into a wildlife sanctuary and conservation area. Fish and waterfowl thrive in a natural wildlife area in the settling pond of the Falconbridge tailings area. Red Pine Lake, 1 km from the smelter complex, provides a stopover point for migratory waterfowl and is a popular fishing spot. The lake also supports thousands of speckled trout (*Salvelinus fontinalis*). Falconbridge was a partner in the release of 45 Peregrine falcons in the Sudbury area from 1990 to 1993 (see Chapter 12).

Inco has initiated studies to identify potential sites for the development of aquatic ecosystems. Three abandoned sand pits, at various stages of rehabilitation, are being investigated for water chemistry, physical features, aquatic invertebrate species, and vegetation diversity. Work is ongoing, in conjunction with the Sudbury Game and Fish Protection Association, to develop walleye (*Stizostedion vitreum vitreum*) fingerling rearing ponds on company property. Habitat development is also being assisted with the construction and placement of artificial nesting islands for loons (*Gavia immer*) in area lakes and the installation of osprey (*Pandion haliaetus*) nesting platforms.

FIGURE 22.7. Environmental sampling is being conducted to characterize seepage from Inco's slag piles. (Photo by Inco Limited.)

Future Challenges

There have been significant improvements in water quality in and around mining operations (Ontario Mining Association 1993). However, water quality remains a focus for concern. The impacts of mining activities on water quality continue to be assessed. Methods to minimize risk, mitigate those impacts, or economically treat water must also be examined. The environmental impacts and economic realities of preventing, controlling, or treating acid rock drainage are only one set of challenges (see Chapter 10).

Sampling to assess the environmental impacts of slag is ongoing (Fig. 22.7). This includes identification and characterization of seepage from slag piles and leachate tests on different types of slag. A joint study between Laurentian University and Inco is examining the microbial leaching of slag.

Studies to assess the impacts of reclamation on surface run-off water quantity and quality are underway. Inco is in the first year (1993) of an intensive long-term study to establish a baseline by which to gauge future conditions in revegetated watersheds, compared with unreclaimed sites. Integrated management of watersheds involves multidisciplinary expertise (see Chapter 24). Work will include mapping watershed boundaries, water sampling, acute toxicity testing, and soil and vegetation identification, mapping, sampling, and analyses.

Research is also needed to develop a cost-effective method of removing ammonia from effluent streams. Groundwater investigations will continue to examine the hydrogeology and geochemistry of Inco's tailings area. This involves the installation of boreholes and monitoring wells and surface electromagnetic and borehole conductivity mapping. Additional research, technology development, and monitoring needs for the integrated management and progressive rehabilitation of industrial lands are outlined (Box 22.1).

The cooperative efforts of government, industry, academic institutions, and private citizens have resulted in significant progress and success in the restoration of the Sudbury region. Future environmental improvements depend on continuing cooperation, innovative technology and techniques, and multidisciplinary research (Moore and Luoma 1990). Inco and Falconbridge have formalized their commitment to sustainable development and decommissioning within corporate environmental policies.

To meet future challenges, environmental and economic decision making and integrated management will ensure continued progressive rehabilitation of industrial lands and ecosystem development in the Sudbury region.

Acknowledgments. I thank Mark Wiseman of Falconbridge Limited and Dr. Tom Peters, re-

Box 22.1.

Research, technology development, and monitoring programs are key requirements for environmental protection and the ongoing rehabilitation of industrial lands and watersheds in the Sudbury area. Although not prioritized, the following list represents some of the environmental challenges and research needs facing the mining industry, not only in Sudbury but elsewhere in Canada.

To ensure sustainable development of the mining industry, proposed solutions must be reliable, practical, and affordable.

1. methods to prevent and control acid rock drainage
2. characterization of large waste rock piles
3. rehabilitation techniques for waste materials, including tailings disposal areas, waste rock, and slag piles
4. water use, re-use, treatment, and conservation management, including the impact of naturally occurring wetlands on industrial effluent
5. impact of industrial activities on groundwater movement, quality, and quantity and methods for mitigation
6. decommissioning of abandoned sites
7. impact and fate of trace metals in the environment
8. potential for biotechnology and genetic adaptation to enhance rehabilitation and restoration techniques
9. further initiatives for emission reductions and metals recovery
10. recycling and waste reduction
11. potential for ecosystem recovery with no direct treatment
12. maintenance and monitoring of perpetual treatment systems

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