Removal of Nickel from Mine Water by a Natural Wetland in Northern Manitoba

By:

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REMOVAL OF NICKEL FROM MINE WATER BY A NATURAL WETLAND IN NORTHERN MANITOBA

BY

ALLAN G. HAMBLEY

A Thesis/Practicum submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

MASTER OF NATURAL RESOURCES MANAGEMENT

ABSTRACT

Wetlands are well known for their ability to remove many contaminants including metals from wastewater streams. This dissertation studied the processes of wetlands that act to retain metals and allow wetlands to be effective passive treatment systems for mine wastewater.

The research effort focused on the Birchtree fen that has received neutral mine drainage containing elevated concentrations of nickel for almost 30 years. The objectives of the study were to determine the extent of nickel contamination in the Birchtree fen in terms of area and depth. In addition, an important aspect of this study included determination of the form of nickel to provide insight into the future fate of the metal. The above study provided the site analysis component for a detailed reclamation strategy for the Birchtree fen. The reclamation strategy is expected to be incorporated into the Decommissioning plan for Birchtree Mine.

The following conclusions and recommendations were reached:

1) The data collected from soil and water sampling supports the conclusion that the Birchtree fen is an effective filter for the removal of nickel from Birchtree mine water.

2) Over the two summer field seasons 96.4% of the nickel entering the Birchtree fen was retained in the fen. Approximately 140 kg of nickel was deposited via mine water discharge. Approximately 150 kg of nickel was deposited over the entire fen by means of atmospheric deposition over 15 months.

2.1. Smelter emissions contributed less than 5 kg of nickel to the area of study in the Birchtree fen. However, when considering the entire area of the fen (approximately 95 ha) stack emissions contribute as much or more nickel to the fen.

3) The majority of nickel deposited from mine water discharge is confined to an area of approximately 1.8 ha adjacent to the fen inlet and is contained within the top 30 cm of the peat soil.

4) Nickel can be expected to flush through the fen during periods of peak runoff due to increased flow and a reduced retention period. Consequently, increased levels of nickel in the fen effluent are expected in the spring and after heavy rains. This event was observed in the two field seasons, however, even during the heavy rains experienced in August 1995, the peak concentration of nickel was only 0.2 ppm.

5) Based on the sequential extraction performed on Birchtree fen soils, it was determined that 97 percent of the nickel captured in the Birchtree fen substrate is bound by various bonding processes and is unlikely to become remobilized in the future.

6) Based on the rudimentary survey of Birchtree fen vegetation, it is unclear as to the impact of the mine water on fen vegetation. Presumably, certain species unable to tolerate metal-contaminated sites have not become established, while species such as cattails and redtop grass, which dominate Birchtree fen, are known for their tolerance to elevated nickel in soils. Additionally, conditions such as "die-back" and symptoms of nickel toxicity are not noticeable. The fen appears to be a vigorous and healthy wetland.

The following recommendations are derived from these conclusions:

1) A passive reclamation strategy is recommended for the Birchtree fen. The strategy is to allow the fen to recover naturally.

2) An intensive monitoring and evaluation program is critical to the success of the reclamation effort. The following parameters are recommended as part of the monitoring and evaluation process:

   - Maintain monitoring water quality of the fen outflow, including metals and pH, and periodic flow measurements. This is a relatively easy means of monitoring the performance of the Birchtree wetland.

   - Soil sampling should be carried out annually. Important parameters to be monitored include chemistry of the soil and pore water, and forms of nickel in the substrate.

   - Evaluation of percent cover and species occurrence of fen vegetation.

   Trends toward decreasing pH, increasing soluble nickel in the outflow, and degrading vegetation in the study area should signal that the fen is degrading and the strategy is not working. A revisit to the reclamation options is required.

3) Initiate Reclamation Strategy in 1996. The reclamation strategy should be carried on for five years.

4) Information gathered should be published and available in the public domain. The Birchtree fen represents a unique opportunity to study the natural recovery of a wetland used for long-term wastewater treatment.

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1. INTRODUCTION

1.1 General

Inco Limited has been operating nickel mines in Northern Manitoba since 1960. The Birchtree Mine, near Thompson, Manitoba, was in operation from 1966 to 1977 when it was closed and maintained on a standby basis. The Mine was reopened in 1988 and production began in May 1989.

A condition placed upon reactivating the Birchtree Mine was that Inco submit an Environmental Impact Assessment to the Manitoba Department of Environment to address all sources of pollutants received at, generated at, and released from the mine site, as well as long-term reclamation plans (Inco 1993). A major area of concern to the Government was the use of a natural wetland as a treatment system for mine wastewater. Since 1966 Inco Limited has been utilizing a natural wetland to treat Birchtree mine water containing elevated nickel concentrations. After passing through the wetland concentrations of nickel are reduced to levels well below water quality limits required under their operating licence.

Wetlands are known for their ability to treat heavy metal contaminated mine water (Eger et al 1994), industrial and municipal wastewater (Kadlec and Kadlec 1979, and Hantzche 1985), and sewage sludge (Giblin 1985). They are also becoming a treatment option for the amelioration of acid mine drainage (AMD) and acid rock drainage (ARD) by increasing pH and removing heavy metals such as nickel and arsenic (Fyson et al 1994). The waterlogged organic soil, vegetation, and microorganisms all contribute to the removal of heavy metals, nutrients, and suspended solids from the water. There is also a large literature base on constructing wetlands for water quality improvement taking advantage of a wetlands ability to treat various water pollution situations, in a low cost, low maintenance and efficient way (Moshiri 1993; Hammer 1992; and Wildeman et al 1993).

The intent of this study is to determine the extent of nickel contamination in terms of depth and area and identify forms of nickel present in the Birchtree wetland. This information is required to produce a reclamation plan for the site as part of the Decommissioning strategy for Birchtree mine. This study examines the processes of a wetland which make it an effective wastewater treatment system for nickel. Nickel is the primary contaminant of concern in Birchtree mine water because it occurs in large concentrations compared to the other contaminants.

1.2 Current Operations

Inco Limited's Birchtree Mine is located 6.5 kilometres south of Thompson, Manitoba (55°48'N, 97°52'W). The location of the mine site and the wetland is shown in figure 1.2. The mine currently discharges water from mining operations such as drilling, the cement flush process and natural ground water directly into a natural wetland. The wetland acts to filter heavy metal contaminants and improve effluent quality at its outflow.

The quality of Birchtree Mine water and outflow from the wetland is monitored routinely and analyzed for metals, pH, and suspended solids in accordance with the <u>Fisheries Act Metal Mining Liquid Effluent Regulations (MMLER)</u>. Historically, all metals except nickel are well below MMLER guidelines in Birchtree Mine water effluent. However, all contaminants are well below effluent guidelines after passing through the wetland. Concentrations of nickel in Birchtree mine effluent are reduced from an average of 5.12 mg/l to an average of 0.08 mg/l after passing through the wetland.

1.3 Site Conditions

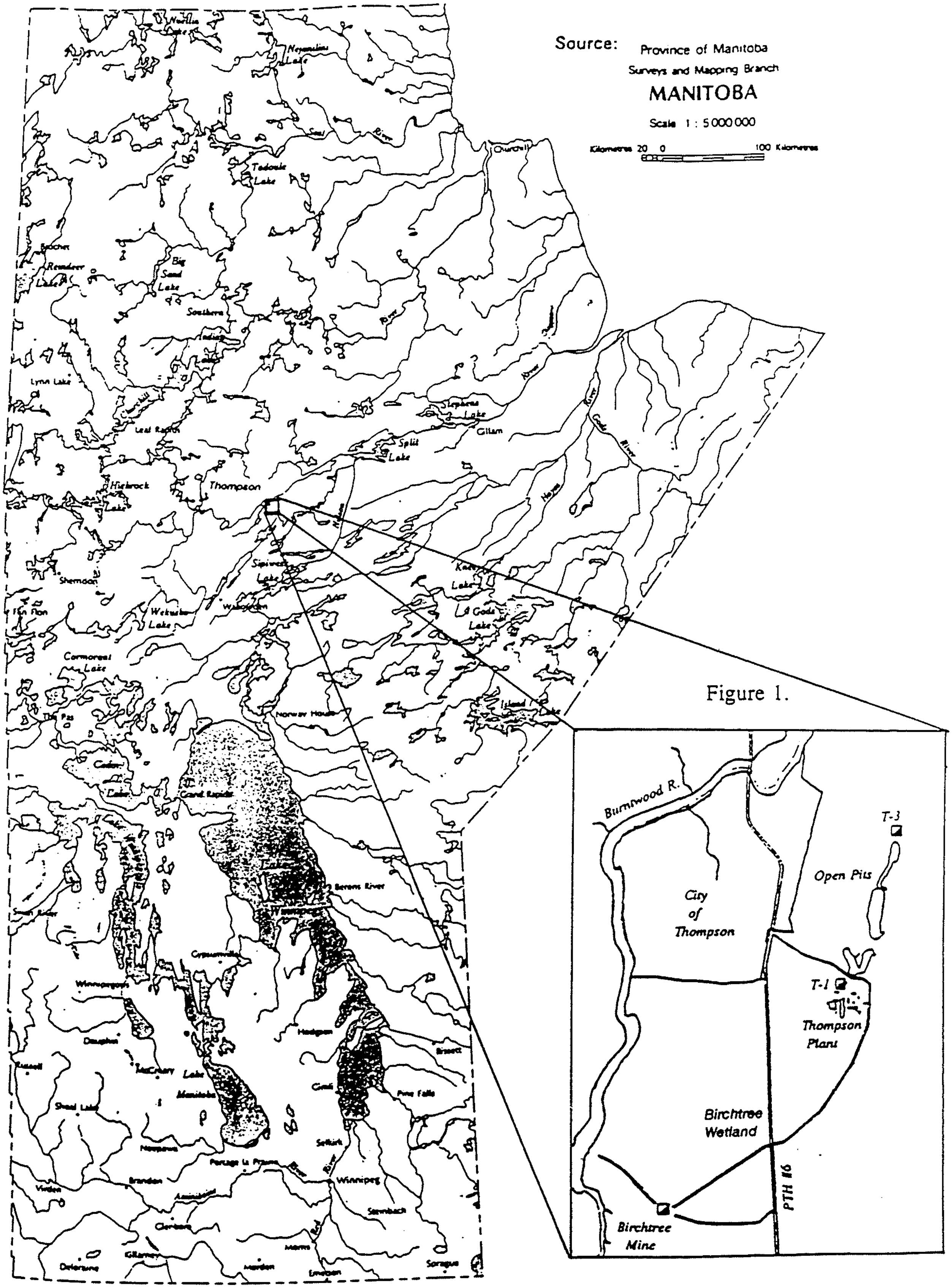
1.3.1 General

The Thompson area is situated in the Kazan Upland Division of the Canadian Shield (Phillips and Slaney 1980). The topography varies from nearly level to rolling, with undulating and hummocky terrain being most common (Phillips and Slaney 1980). The topography is mainly controlled by bedrock, but a thick mantle of clay subdues the bedrock relief to a great extent. Organic landforms (bogs and fens) develop in depressions and on gentle slopes. The dominant surficial deposits in the region are mainly varved clay (alternate layers of clay and silt) of glacio-lacustrine origin and moderately to very strongly calcareous (Klohn Leonoff 1992). Thickness of the lacustrine deposits varies from deep (over 20 metres) in valleys to very shallow (less than one metre) on ridges (Phillips and Slaney 1980).

Thompson has a continental climate typical of the Central Canada Region, characterized by long, cold winters and short warm summers (Inco, 1993). The mean annual range of temperature is large. The average January mean daily temperature is -25° C, and the average July mean daily temperature is 15.7° C. The length of the frost free season is generally 85 to 95 days.

Precipitation is considered to be moderate to light with summer being the season of greatest precipitation since the extreme cold of winter results in little available moisture (Phillips and Slaney 1980).

Organic deposits occur extensively in the area. Bogs and muskeg occupy 50 to 80 percent of the eastern section, which includes Thompson (Phillips and Slaney 1980). They result from the accumulation of vegetative debris in poorly drained areas which are usually wet to saturated for most of the year. The thickness of the deposits ranges from 40 cm to over 160 cm deep.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Hodgson
Gimli
Pine Falls
Selkirk
Neepawa
Portage la Prairie
Brandon
Virden
Steinbach
Morris
Boissevain
Emerson
Sprague
Burntwood R.
T-3
Open Pits
City of Thompson
T-1
Thompson Plant
Birchtree Wetland
PTH #6
Birchtree Mine

Figure 1.

Permafrost occurs in both mineral and organic soils, but is more prevalent in organic materials (Phillips and Slaney 1980).

Vegetation in the Thompson region belongs to the Boreal Forest Region and, more specifically, the Nelson River Section (Phillips and Slaney 1980). The diagnostic cover type is closed-crown coniferous forest on upland sites. The climax forest type is closed stands of black spruce (*Picea mariana*) or balsam fir (*Abies balsamea*). White spruce (*Picea glauca*) and poplar (*Populus tremuloides*) occurs along river banks and lake shores. Jack pine (*Pinus banksianna*) is a common seral stage after fire (Phillips and Slaney 1980).

1.3.2 The Birchtree Wetland

1.3.2.1 Classification

The term "wetland" is used generically to describe a variety of wetland types including marshes, swamps, bogs and fens. Wetlands are classified into types based on specific conditions such as hydrology, water chemistry, soils and vegetation.

The Birchtree wetland is classified as a *fen* because it possesses all the characteristics of a fen under the Canadian Classification of Wetlands (Zoltai and Pollet 1979). A fen is characterized by having a high water table, and low gradient slopes; organic soil consisting of poorly to moderately decomposed peat at the surface and well decomposed peat at the base; vegetation cover dominated by sedges and grasses and sparse medium shrubs and trees; water chemistry - termed minerotrophic- is influenced by nutrient rich minerals from clay in the soil; pH is less acidic than bogs and sometimes alkaline. Birchtree fen characteristics are now described in detail. Appendix A.1 shows pictures of the Birchtree fen.

1.3.2.2 Hydrology

The Birchtree mine water flows via ditch for approximately 154 metres before entering the fen. Once the water enters the fen it disperses and flows in a northeast direction following gradual contours. Pools of standing water are common throughout the fen. The water migrates northward from entry to the fen until eventually, at the fen outflow, the flow becomes defined and contained within a channel.

The mine water inputs an average of 460,000 litres per day into the fen during the 1994/95 study period. Estimated volumetric flow rate of water leaving the basin as measured at the fen outflow averaged 1.8 million litres per day over the study period. Annual losses due to evapotranspiration are approximately 300 mm according to the Canadian Hydrology Atlas (Inco, 1993). Evapotranspiration exceeds precipitation during the growing season and is effectively nil in the late fall and winter, when most of the precipitation occurs as snow. Flows from the basin fluctuate with maximum flows during the spring freshet in May and early June, and lowest flows in mid-August.

1.3.2.3 Soil

Organic soils in the Birchtree fen consist of fibrous fen peat. Fen peat is a result of the accumulation of humified herbaceous debris, like sedges and grasses (Phillips and Slaney 1980). Soil sampling determined that the depth of the peat layer is quite variable throughout the fen ranging from 30 cm to 120 cm. Lacustrine clay underlies the fen peat in two distinct horizons: an upper brown clay and a lower grey clay.

1.3.2.4 Vegetation

Species occurrence in the Birchtree wetland was recorded for four strata including trees, medium shrubs, dwarf shrubs and herbs and bryophytes (mosses). Cattails(*Typha latifolia*) dominated the vegetation in areas of high water and where periodic flow occurs, such as at the fen inlet. Grasses (*Agrostis* spp.) and sedges (*Carex* spp.) dominate the expansive depressions and areas of standing water. Areas above the water table such as islands and hummocks show the greatest diversity of vegetation with labrador tea (*Ledum groenlandicum*), willow (*Salix* spp), twin flower (*Linneae borealis*), and scrub birch (*Betula glandulosa*) being common.

1.4 Behaviour of Nickel in a Wetland

A variety of processes are responsible for metal removal in wetlands. These processes include a mixture of chemical, biological, and microbiological reactions that occur in the aerobic and anaerobic zones of wetlands (Eger et al. 1994). Nickel is relatively amenable to adsorption onto iron and manganese hydroxides, clay particles, and organic surfaces (Fyson et al. 1994; Swatzbaugh et al. 1992). Because of these properties, nickel removal can be anticipated in wetland environments.

1.5 Other Sources of Nickel to the Fen

The Birchtree fen also receives nickel from atmospheric deposition, the source being Inco smelter emissions. In order to determine the impacts of atmospheric deposition and establish background conditions of nickel two control wetland sites were established. Control fen #1 is in close proximity to the experimental fen while control fen #2 is 50 km south of Thompson on PTH 6. Samples of surface water and soil were collected at both sites to determine background conditions in a fen receiving smelter emissions versus true background conditions in a fen not impacted by smelter emissions nor mine water. Phillips and Slaney (1980) showed that at distances greater than 18 km, the amount of nickel from flue dust was negligible.

1.6 Reclamation of the Birchtree Wetland

As of April 1, 1996, Inco is required to treat all effluent from Birchtree mine to meet water quality standards before being discharged to the environment (Inco 1993). Consequently, mine water discharge to the wetland must be halted, and plans for wetland reclamation prepared. Thus, a second aspect of this study is to propose a reclamation strategy for the wetland receiving Birchtree Mine water to be incorporated into the Birchtree Mine Decommission Plan. Aspects of the plan will include site analysis, specific goals and objectives of a reclamation strategy, wetland design and its critical parameters, implementation of the plan, monitoring of objectives, and evaluating the success of the reclamation effort.

1.7 Problem Statement

Wetlands are recognized for their wastewater filtering and heavy metal removal capabilities. Birchtree mine has been using a fen as a treatment system for mine water for almost 30 years. Preliminary investigation of the Birchtree fen influent and effluent shows it is effective in filtering nickel from the mine water. There are a number of processes responsible for the removal of nickel in a wetland. It is important to identify these processes to determine the future fate of the nickel and the probability or risk of the nickel becoming mobile. Given this situation two main problems need to be addressed:

1. To Determine the extent of nickel contamination in the fen in terms of depth and area as well as form of nickel in wetland sediment.

2. Secondly, based on the above information, to establish a detailed reclamation plan in compliance with the agreement to reactivate Birchtree Mine.

1.8 Objectives

The following objectives are proposed:

1. To assess the literature and case studies of industrial use of wetlands for wastewater management, focusing on the behaviour of nickel in a wetland environment;

2. To assess literature to determine the expected impact nickel-contaminated wastewater has on a wetland ecosystem.

3. To determine the extent of nickel contamination in the Birchtree fen through collection of empirical data;

4. To determine the form of nickel in the wetland sediment which will allow predictions of the future availability of nickel in the wetland;

5. To recommend a reclamation plan for the site.

1.9 Clients and Importance of Study

Inco Limited, Manitoba Division, is the main client for this study. Inco is committed to the concept of sustainable development in all aspects of its operation as outlined in the Company's Environmental Policy (Inco 1989). The principles of sustainable development include "Enhancement of the long-term productive capability, quality, and capacity of our natural ecosystems" and "Rehabilitation and reclamation to restore damaged or degraded environments to beneficial uses" (Manitoba Round Table, 1991).

Sustainable development in the mining and minerals industry takes on a slightly different connotation compared to other natural resource industries. By definition ore bodies are a finite resource. Eventually, it will become no longer economical to extract ore and the mine will close. In this sense, such a development is not sustainable. The emphasis then, is to minimize impacts on the environment and implement decommissioning and reclamation plans to return the site to natural conditions. Reclamation and enhancement of the Birchtree wetland abides by the principles of sustainable development and is consistent with Inco's Environmental Policy.

1.10 Report Organization

This report is organized into six chapters. The first chapter provides a general overview of the Birchtree wetland site conditions, nature of the study, problem statement and specific objectives to be met.

Chapter two is an extensive review of the related literature with particular focus on the role of wetlands in the mining industry and the use of wetlands for treating mine water streams.

Chapter three details the methods employed in this study which include literature review, field trips, soliciting expert opinion, and collection and interpretation of empirical data.

Chapter four and five is the analysis of the data compiled in a Results and Discussion section.

Chapter six is the reclamation plan for the Birchtree fen. Using the information gathered in the field, expert advice, and literature examination a detailed reclamation plan is provided. It is intended that this section become incorporated into the Birchtree mine progressive decommissioning and closure strategy.

The final chapter is the conclusions reached as a result of the study and recommendations that follow the conclusions.

2. LITERATURE REVIEW

2.0 Organization of the Literature Review

A review of related literature focuses on five main topics: (1) Wetland classification; (2) the effectiveness of wetlands/peatlands in filtering industrial wastewater; (3) the chemistry of nickel in an aquatic environment; (4) ecological effects of nickel in a wetland; and (5) reclamation and rehabilitation of wetlands.

2.1 Introduction

Wetlands are a combination of water, soil, and vegetation. They act to modify water quality in many ways. They cycle elements, store organic materials, adsorb metals and other ions, and often improve the quality of the water which flows through them (Carter, et al., 1978). A formal definition of Canadian wetlands was written by the National Wetlands Working Group (1988):

> "Wetland is defined as land having the water table at, near, or above the land surface or which is saturated for a long enough period to promote wetland or aquatic processes as indicated by hydric soils, hydrophytic vegetation, and various kinds of biological activity which are adapted to the wet environment."

Fens and bogs belong to a major class of wetlands called peatlands that occur as freshwater wetlands throughout much of the boreal zone of the world (Mitsch and Gosselink, 1986). Fens are peat-filled wetlands with a water table at or near the surface and support hydrophillic vegetation such as sedges, grasses, reeds and cattails (Zoltai et al 1979). Vegetation is affected by the quality of water and therefore serves as an indicator of water chemistry and ecosystem health.

2.1.1 Wetland Classification

Wetland managers have found it necessary to both define the different types of wetlands that exist and to determine their extent and distribution. Over the last century reasons to classify and inventory wetlands have ranged from finding wetlands that could be drained for human use to later classifications and inventories comparing different types of wetlands in a given region, to most recently, the protection of multiple ecological values of wetlands (Mitsch and Gosselink 1986).

Classification, inventory, and monitoring the wetland resource is critical to establish a data base on which long-term planning and land management decisions can be made. A primary goal of wetland classifications, according to Cowardin et al. (1979) "is to impose boundaries on natural ecosystems for the purposes of inventory, evaluation, and management". There are four major objectives of the classification system:

1. to describe ecological units that have certain homogeneous natural attributes;
2. to arrange these units in a system that will aid decisions about resource management;
3. to furnish units for inventory and mapping; and
4. to provide uniformity in concepts and terminology throughout the United States.

Wetland classifications enable the wetland manager to deal with wetland regulation and protection in a consistent manner from region to region and to pay selectively more attention to those types of wetlands that are functionally the most valuable to a given region (Cowardin et al. 1979). In addition, classifications provide consistency for inventories, mapping, concepts, and terminology. Consistency allows comparison between different regions so that there is a common understanding of wetland types among wetland scientists, wetland managers, and wetland owners.

A classification system of wetlands is important in restoration and reclamation of mined out areas. Successful efforts to restore degraded wetlands or create new wetlands depend on identification and duplication of important wetland function and values (Dennison and Berry 1993), detailed by a classification system. However, this creates some implications. In the U.S., for example, there is a policy of "no net loss" of wetlands. The mandate under this policy is the mitigation of wetland losses in area and function (Dennison and Berry 1993). The implication here is that restoration or creation of a wetland in area and functional value is difficult and costly and success is not guaranteed (Brooks 1993). Kusler (1986) notes that most naturally occurring wetlands represent thousands of years of geologic and hydrologic processes with resulting build-up of soil profiles and particular ecologic niches of plant and animal species. Therefore, an objective requiring a replication of the original condition is unreasonable and not likely to be met.

2.1.2 Peat and Peatlands

Peat is a term commonly used to refer to wetland organic soils. On the basis of organic content, two general groups of soils are commonly recognized - mineral and organic (Brady, 1984). Organic soils have minimum organic content of 20 % of clay content is low, and a minimum organic content of 30 percent if clay content is high (Brady 1984). They are classified in the order *Histosols* in the soil classification system. These soils have developed in a water saturated environment such as marshes, bogs and fens, and swamps which have provided conditions suitable for the accumulation of organic deposits (Brady 1984).

Peat consists of the partially decomposed remains of plant material produced by the present vegetation or by vegetation that occupied the site during earlier stages of fen development. Brady (1984) states that peat can be classified into three categories according to its parent materials including sedimentary peat, fibrous peat, and woody peat. Under this classification, the peat in the Birchtree fen is *fibrous peat*, consisting of cattails, sedges, grasses, reeds and mosses.

The nature of the peat depends primarily on the type of plant material and the degree of decomposition or ultimately on the hydrology and water chemistry of the site. The well decomposed state of organic material is referred to as humus (Eilers, et. al, n.d.). In fens, vascular plant materials such as cattails, grasses and sedges is added to the peat as leaf litter and as dead roots, branches and stems. In a bog, by contrast, a moss carpet, such as that of Sphagnum, grows at the surface and dies at the base. In many peatlands, these moss carpets determine the structure of the surface peat.

Peat possesses several qualities that make it an effective medium for the removal of pollutants (Viraraghavan, Mathavan, and Rana, 1987). Ruel, et al. (1977) identified peat as having great potential as a filtering and adsorption agent for heavy metals. Brooks (1987) indicates that sphagnum peat may be used as an economical method of wastewater treatment providing a high quality effluent. Northern peatlands have a demonstrated capability for the advanced treatment of secondary municipal wastewater. Kadlec (1987) found nutrients and heavy metals are rapidly removed from the surface water and held within the stationary ecosystem confined to a region surrounding the irrigation point. Peat is such an effective filter that there is technology now available that takes advantage of the properties of the metal binding capacities of biological materials to remove toxic metal contaminants from wastewater streams (Jeffers et al 1994). This technology uses "bio-beads" as a medium for removal of nickel in mine drainage and surface drainage (Inco 1995). The beads consist of organic material bound in a polymer case.

2.1.3 Peatland Hydrology

All natural wetland functions are a result of, or are closely related to wetland hydrology (Carter et al., 1978). An understanding of the presence and movement of water through individual wetlands, wetland complexes, and drainage basins containing wetlands is basic to an in-depth understanding of wetland function and the values that can be attributed to the functions. The hydrologic functions of wetlands provide a measure of the hydrologic value of wetlands, and give the foundation necessary for determination of all other related wetland functions and processes (Carter et al. 1978).

Most of the water that enters a peatland leaves as a vapour. Water that does not leave a peatland by evapotranspiration either goes to stream flow, recharges ground water, or is stored in the peatland (Verry and Boelter, 1978). Water is critical for the development and maintenance of all wetlands. Peatlands can be divided on the basis of the source of the water into wetlands receiving only rain water and snow (ombrotrophic) such as bogs, and those influenced also by water that has been in contact with the mineral soil (minerotrophic) peatlands, which are fens (Damman and French, 1987). The hydrologic characteristics and chemical composition of water influence both nutrient cycling and plant community development within peatlands.

Kadlec (1987) says the hydrology of a peatland is a controlling factor in system. The water sheet does not move uniformly in 'plug flow'. Instead, the water may move laterally above ground, or as vertical flow through the stem zone, litter zone, and through the peat. Damman and French (1987) identify two major peat horizons: the acrotelm and catotelm. The acrotelm is the surface peat above the low-water table, and the catotelm is the permanently anaerobic peat below this level. The acrotelm tends to regulate the flow and maintain average flow levels. The rate of lateral movement within the acrotelm depends on the permeability of the peat. Live peat is very porous and water percolates easily through the live undecomposed sphagnum but moves very slowly through well decomposed peat.

The catotelm is constantly saturated with water and changes in water storage occur only if the bog is drained (Damman and French, 1987).

2.1.4 Physical Properties of Peat

Physical properties of peat such as water-holding capacity, bulk density, porosity, and hydraulic conductivity determine, to a very large extent, the hydrology of peatlands. The physical properties of peat change with time. Decay breaks down the structure of the organic matter and increases the density of the peat. The weight of the overlying material compresses the peat and also increases its density. As density increases the porosity of the peat decreases. Low porosity contributes to a high water-holding capacity and slow permeability. As a result, peat becomes denser and more humified with age. The rate of decay varies among peatlands, depending especially on aeration and fertility of the peat horizons (Damman and French 1987).

Peat has a very high water-holding capacity on a weight basis. An undecayed or only slightly decomposed moss or sedge peat, in contrast to mineral soils, can hold water to the extent of 12 to 20 times its dry weight (Brady, 1984). Organic soils are also very light weight when dry. The bulk density of peat is low, 0.20 - 0.30 Mg/m^3 compared to mineral soils, which are typically 1.25 - 1.45 Mg/m^3.

Hydraulic conductivity is the rate at which water flows through a soil in response to a potential gradient. Decay and compaction of peat also decrease its hydraulic conductivity. Hydraulic Conductivity is greatest near the water table. Compaction increases with depth therefore hydraulic conductivity decreases with increasing depth through the soil profile.

2.1.5 Peatland Chemistry

Soil water chemistry is one of the most important factors in the development and structure of the fen ecosystem. Factors such as pH, available nutrients, and cation exchange capacity influence the vegetation types and productivity (Mitsch and Gosselink, 1986).

PH

In general, the capacity of soil for most trace elements is increased with increasing pH, with the maximum under neutral and slightly alkaline conditions. Exceptions include arsenic (Adriano 1986). The relative mobility of some trace elements in soils as influenced by soil pH is summarized: In acidic soils (pH 4.2 to 6.6) Ni, Cd and Zn are relatively mobile; Cu and Pb are less mobile; In neutral to alkaline soils (pH 6.7 to 7.8), Ni, Cu and Pb are slowly mobile, while As becomes relatively mobile (Adriano 1986).

Cation Exchange Capacity

Most soil colloids including clays and humic acids, have an electro-negative charge. They attract cations, a measure of which is known as the cation exchange capacity (CEC)(Eilers, et. al, n.d.). The cation exchange capacity of soil is largely dependent on the amount and type of clay, organic matter, and iron, manganese, and aluminum oxides. These soil components have different cation exchange properties. In general, the higher the CEC of soil, the greater the amount of a metal a soil can accept without potential hazards. Organic soils have a high cation exchange capacity.

Organic Matter

Some trace elements, including Ni, exhibit rather high affinities for soil organic matter. Peat has been shown to bind trace elements in soils. However, organic matter has both high cation exchange capacity property and the chelating ability. Chelate is applied to compounds in which certain metallic cations, such as Ni^{2+}, are complexed or bound to an organic molecule (Brady 1984). The metal bound to chelates is protected from reacting with inorganic constituents and thus remains soluble and available to plants. Therefore, organic matter is sometimes viewed as a source of soluble complexing agents for trace elements.

Oxides of Iron, Manganese, and Aluminum

These oxides are important in sorbing and occluding various trace elements. They provide the principal control on the fixation of trace elements in soils and freshwater sediments.

Redox Potential

The water content of soils influences their capacity for trace elements through biological or chemical oxidation-reduction reactions. Whether soil conditions are oxidizing (aerobic) or reducing (anaerobic) will strongly affect the types of microbiological activity and contaminant transformation and degradation processes that may occur (Boulding 1994). The mobility of many heavy metals varies with oxidation state. In oxidized soils, oxidation-reduction (redox) potential may range from about +400 to +700 mV. In sediments and flooded soils, redox potential may range from -400 (strongly reduced) to +700 (strongly oxidized). Under reducing conditions, sulfides of elements such as Cd, Zn, Ni, Cu, Pb, can form. The sulfides of these elements are quite insoluble, so that their mobility and phytoavailabilty are considerably less than would be expected under oxidizing conditions (Adriano 1986).

2.2 The Effectiveness of Peatlands/Wetlands in Filtering Industrial Wastewater.

Extensive studies have shown wetlands to be effective in filtering industrial wastewater. Wetlands are used for wastewater discharge sometimes by design and sometimes arbitrarily, for a variety of reasons including a belief that wetlands have high filtration and storage capacities for nutrients, heavy metals, and water (Richardson and Nicholls, 1985). Hantzsche (1985) discusses four basic functions of wetlands that make them potentially attractive for wastewater treatment one of which is the physical entrapment of pollutants through sorption in the surface soils and organic litter. Kadlec and Kadlec (1979) found the heavy metal content of waters entering a wetland appears to be reduced upon passage through that ecosystem. Wetland ecosystems may function naturally to remove nutrients, suspended solids, and heavy metals from sewage sludge (Giblin, 1985). Hedin and Nairn (1993) suggest that in wetlands contaminant concentrations are reduced because of two distinct processes: chemical and biological mechanisms; and dilution by inputs of uncontaminated water.

2.2.1 Mine Drainage

Eger et al (1994) found pilot and full-scale overland flow wetlands have removed 90% of the nickel in neutral mine drainage, and 50 to 90% of other metals in test work done in northeastern Minnesota.

Fyson et al (1994) tested the capacity of sediments from muskeg ponds to treat waste rock seepages with mean concentrations of Arsenic and Nickel. It was found that more than 90% of the As and Ni present at the beginning of the experiment was removed within two months of start-up.

Eger et al, (1993) found wetlands are an effective passive treatment system to treat waste rock seepage water containing elevated concentrations of nickel. In all cells studied, concentrations of nickel were reduced to meet water quality standards. In addition, it was found that lower water levels and thus greater contact with the peat substrate produced longer residence times and consequently greater nickel removal.

Eger et al (1993) also found that treatment capacity of wetlands can be extended by reducing flow and increasing residence time. This can be accomplished by lowering water levels and/or adding barriers to produce serpentine overland flow. Adding peat or other organic material to the wetland can extend the treatment life by providing new adsorption sites or by increasing the rate of sulphate reduction. The material that has been added can be periodically removed, and new material added to increase the life of the system. With this type of a program, the wetland can be used indefinitely, and then the original wetland could be re-established when the treatment has been completed or when the input metal load has been reduced to a point that any residual metal can be handled by the re-established wetland (Eger et al, 1993).

2.2.2 Acid Mine Drainage

Wetlands have also been found to ameliorate the impacts of acid mine drainage (AMD). Witthar (1993) found wetlands decrease acidity, metals, pathogens, trace organics, and, to a lesser extent, nitrogen and phosphorus concentrations in wastewater, mine drainage, and other waters. Before construction of two wetlands, drainage leaving both sites typically had pH of 3. The pH of the water leaving the wetlands now is above 6. Over the same time period, iron content of the drainage from each of these sites has decreased from over 10 mg/L to less than 1 mg/L.

The use of a peat/wetland treatment system has shown excellent results for heavy metal removal (Frostman 1993). The use of a passive peat/wetland treatment system requires little operational maintenance. The results of the demonstration project have illustrated that the dynamics of a peat/wetland treatment system are such that AMD can be successfully treated for pH adjustment and heavy metal removal.

2.2.3 Created Wetlands

There is a growing literature base on creating wetlands rather than using natural wetlands for water quality improvement. *Wetland creation* refers to the construction of wetlands where they did not exist before and can involve much more engineering of hydrology and soils. Created wetlands are also called constructed wetlands or artificial wetlands (Mitsch and Gosselink 1993).

2.2.3.1 Natural vs Created Wetlands

Johnston (1993), suggests that wetlands in general can be very effective in the short term at reducing suspended solids and nutrient concentration in wastewater; but that over the long term, some of those functions can break down and the wetland can become a source of contaminants as it releases stored materials.

Bastian and Hammer (1993) describe some technical and practical problems encountered by users of constructed wetlands for wastewater treatment. The lack of long-term operational data creates uncertainty when establishing project design and operation guidance. Seasonal variability in treatment performance and concerns over the potential impact on wildlife may create serious operational constraints and difficult permitting conditions. It is clear, however, that moderately loaded systems designed to duplicate natural marshes will provide low-cost, low-maintenance, efficient wastewater treatment to meet stringent discharge limits (Bastian and Hammer 1993).

Brix (1993) compares natural systems to constructed wetland systems. Both natural and constructed wetlands have been used as wastewater treatment systems; it is generally found that both systems may act as efficient water purification systems and nutrient sinks. Long retention times and an extensive amount of sediment surface area in contact with the flowing water provide for effective removal of particulate matter. The sediment surfaces are also where most of the microbial activity affecting water quality occur, including oxidation of organic matter and transformation of nutrients.

Brix (1993) points out that there are difficulties in making such comparisons. Natural wetlands are characterized by extreme variability in functional components, making it virtually impossible to predict responses to wastewater application and to translate results form one geographical area to another. Although significant improvement in the quality of the wastewater is generally observed as a result of flow through natural wetlands, the extent of their treatment capability is largely unknown. The performance may change over time as a consequence of changes in species composition and accumulation of pollutants in the wetland. Therefore the treatment capacity of natural wetlands is unpredictable, and design criteria for constructed wetlands cannot be extracted form results obtained in natural wetlands (Brix 1993).

Hedin and Nairn (1993) studied 11 wetlands constructed to treat coal mine drainage and found that in these wetlands removal of contaminants occurs in a manner consistent with well-known chemical and biological processes. To recognize the effects of chemical and biological processes and make comparissions between sites it was necessary to (a) remove the effects of dilution; (b) evaluate removal from a rate perspective; and (c) avoid sites with low contaminant loading rates. Using this method, distinctive patterns of contaminant removal emerge.

Constructed wetlands offer several advantages compared to natural wetland, including site selection, flexibility in sizing, and most importantly, control over the hydraulic pathways and retention time. In addition, Wildeman et al (1993) suggests that a natural system will accommodate all the removal processes but will probably not operate to maximize a certain process. A constructed wetland can however, be designed to maximize a certain process suitable for the removal of certain contaminants from water.

The pollutants are removed through a combination of physical, chemical, and biological processes including sedimentation, precipitation, adsorption to soil particles, assimilation by the plant tissue, and microbial transformation, as in natural wetlands.

Natural and constructed wetlands for wastewater treatment may in some locations have several advantages compared to conventional secondary and advanced wastewater treatment systems. Some of these advantages are: low cost of construction and maintenance; low energy requirements; systems are flexible and less susceptible to variations in loading rate than conventional treatment systems. The major disadvantages of constructed wetland treatment systems are the increased land area required, compared to conventional systems, and the possible decreased performance during winter in temperate regions. However, Sobolewski et al (1995) found that copper removal exceeded 98% in two experimental wetlands in central B.C. even during the winter months.

2.2.5 The Capacity of Wetlands to Filter Mine Wastewater

Giblin (1985) suggests areas of further study to increase the accuracy of metal budget estimations. Accurate information is needed on hydrology of wetlands, pore water chemistry, flux of metals through wetlands, and interactive effects of nutrients and metals. Long term studies are needed as the capacity of wetlands to retain heavy metals may change over time.

Estimations of metal uptake and losses from wetlands have been difficult. Giblin (1985) suggests one approach by Windom (1975) is measurement of metal burial by accretion in the sediments. When metal inputs are known or can be estimated, the accumulation of metals by the sediment can be used to calculate the retention of metals by the ecosystem.

Metal-budget data for wetland ecosystems show that the percentage of metal removed by passage through the ecosystem varies widely among metals and among wetlands. Although in a geochemical sense, wetlands are "sinks" for some metals, studies indicate that they may not function as efficient "traps" for all metals (Giblin, 1985).

2.3 Metal Removal Processes in Wetlands

2.3.1 Introduction

In wetland treatment systems, pollutants are removed by a complex variety of physical, chemical, and biological processes. Wildeman et al (1993), Jacobson (1995), Fyson et al (1994), Brix (1993), and others outline the various removal processes that can operate in a wetland. These include: exchange of metals by an organic-rich substrate, usually peat; sulphate reduction with precipitation of iron and other sulfides; precipitation of ferric and manganese hydroxides; adsorption of metals by ferric hydroxides; metal uptake by plants; filtering suspended and colloidal material from water; and adsorption or exchange of metals onto algal materials.

2.3.2 Sedimentation

When water-borne suspended solids enter a wetland, the decrease in water velocity causes them to settle out onto the soil surface, thereby benefiting downstream water quality.

2.3.3 Plant Uptake

Aquatic macrophytes such as cattails, sedges and grasses, remove pollutants by directly assimilating them into their tissue, and by providing surfaces and a suitable environment for microorganisms to transform pollutants and reduce their concentrations (Brix 1993). Plant uptake and microbial transformations may also be of importance (Brix 1993). However, Jacobson (1995) and Eger et al. (1994) suggests that plant uptake of metals as a removal mechanism is not significant. The main contribution of vegetation in wetlands is flow dispersal, substrate stabilization, addition of organic material, and improved aesthetics.

2.3.4 Microbial Action

Sediments are environments in which bacterial thrive, which are able to increase pH and thereby reduce acidity as well as metal concentrations in overlaying water (Kalin, n.d.). Fyson et al (1994) demonstrated the removal of arsenic and nickel from acid mine drainage using muskeg sediment in the lab as well as in the field. The metal removal is associated with reducing conditions and is accelerated by the addition of readily degradable organic amendments which feed microbial processes. The microbial community was active, as suggested by the decline in sulphate, the H_2S odour indicating sulphate reduction, the increases in dissolved iron, the dramatic decline in nitrate (dentrification) and the rise in pH. The decline in nickel can be attributed to precipitation of $NiCO_3$ and/or NiS following the rise in pH generated by anaerobic microbial processes.

2.3.5 Adsorption

Trace metals have a high affinity for adsorption and complexation with organic material and will be accumulated in the wetland sediment. Alloway (1990) suggests the most important chemical processes affecting the behaviour and bioavailability of metals in soils are those concerned with the adsorption of metals from the liquid phase on to the solid phase. These processes control the concentrations of metal ions and complexes in the soil solution and thus exert a major influence on their uptake by plant roots. Several different mechanisms can be involved in the adsorption of metal ions, including cation exchange, specific adsorption, organic complexation and co-precipitation

Cation Exchange

Most heavy metals exist mainly as cations in the soil solution, and their adsorption therefore depends on the density of negative changes on the surfaces of the soil colloids. In order to maintain electro-neutrality, the surface negative charge is balanced by an equal quantity of oppositely charged counter-ions. Ion exchange refers to the exchange between the counter-ions balancing the surface charge on the colloids and the ions in the soil solution (Alloway 1990).

Specific Adsorption

Specific adsorption involves the exchange of heavy metal cations and most anions with surface ligands to form partly covalent bonds with lattice ions. It results in metal ions being adsorbed to a far greater extent than would be expected from the CEC of a soil. Specific adsorption is strongly pH dependent and is related to the hydrolysis of the heavy metal ions (Alloway 1990).

Co-Precipitation

Co-precipitation is defined as the simultaneous precipitation of a chemical agent in conjunction with other elements by any mechanism and at any rate.

Organic Complexation

Humic acids also adsorb metals by forming chelate complexes. Low-molecular-weight organic ligands can form soluble complexes with metals and prevent them from being adsorbed or precipitated.

Crowder et al. (1987) observed that where oxidized and reduced iron occur in wetland substrates, iron hydroxide plaques, and occasionally FeS plaques are deposited on the roots of monocots, dicots and non-flowering plants. The plaque adsorbs and co-precipitates nutrients and metals. Under oxidizing conditions iron hydroxides and oxides act as a major sink for trace metals in aqueous systems.

2.3.5 Sulphate Reduction

Giblin (1985) says that in most wetlands, due to the presence of saturated soil conditions and large amounts of organic matter, the biochemical oxygen demand exceeds the rate of oxygen diffusion. Without oxygen, the sediments become highly reduced as microbial respiration proceeds. Where sulphate reduction is predominant, wetland sediments will retain metals since most metal sulfides are extremely insoluble. Sediments that are high in organic matter have been shown to absorb more heavy metals from water than those that are high in mineral matter (Vestergaard, 1979, in Giblin 1985).

While plant uptake of nickel may be important Eger et al. (1994) found that ninety-nine percent of the metal removed by a wetland was associated with the peat; only 1% associated with the vegetation (cattails, sedges, grasses).

Jacobson (1995) also suggests that plant uptake of metals is insignificant compared to metal removal in wetland sediment. Eger et al (1994) also found effective removal occurs in the top 20 to 30 cm of the peat. Up to 60 % of the nickel was associated with the organic fraction of the peat to a depth of 20 cm; the next largest fraction was associated with sulphide precipitation. In the deeper peat (20 to 30 cm) there was little increase in nickel concentration and most of the nickel was in the precipitated form (Eger et al 1994).

2.3.6 Sequential Extraction

The most common technique of partitioning solid phase metals into chemically similar forms is by using sequential extraction with selective chemical reagents. Forms identified include the residual form (sulfides), exchangeable form, organically bound, adsorbed, and carbonate form. The residual form is considered the most stable form on Ni because it requires the most drastic extracting agent for its removal. Using sequential extraction, Eger et al (1994) found the majority of Nickel in peat samples was contained in the top 30 cm of the peat horizon. In the top layer (<10 cm) nickel was organically bound, while at depth (15-31 cm) most of the nickel was in the residual form.

It is important to characterize the various forms of nickel in fen sediment. Data provided from sequential extraction experiments to determine nickel forms in the sediment will allow estimations of wetland performance as a polishing system as well as better prediction of the future availability of the removed nickel. If the removal is primarily due to removal by organics, then the system lifetime is limited by the total amount of removal sites that are available in the top portion of the wetland. If the primary removal mechanism is sulphate reduction, the process would continue as long as there was an organic food source and an input of sulphate (Eger et al. 1994).

2.4 Factors Affecting Mobility and Availability of Nickel

Nickel is very mobile in acidic, high Eh water, while in high pH, low Eh (reducing) conditions, stable nickel sulphides can form. In addition, nickel is relatively amenable to adsorption onto iron and manganese hydroxides, clay particles, and organic surfaces (Fyson et al. 1994; Swatzbaugh et al. 1992). Because of these properties, nickel removal can be anticipated in wetland environments.

2.4.1 PH

The solubility and plant availability of most heavy metals in soils are known to be inversely related to pH. The effects of pH on Ni chemistry in soils have been demonstrated in soil retention studies, sewage sludge application on land, reclamation of serpentine soils, plant uptake studies, and others. In soil sorption studies, the amount of Ni retained was dependent upon the pH of the soil, with retention increasing with increasing pH.

The reaction of nickel in organic soils is definitely affected by the pH, organic matter content, and the oxidation-reduction potential of the soil (Brady, 1984). At pH values 6.5 and above nickel tends to be slowly available to plants, and most soils will tie up relatively large quantities of these elements if the soil pH is high and the drainage good. In aquatic plants the rate of nickel uptake increases with exposure concentration (Moore and Ramamoorthy, 1984). As with other metals, the presence of chelators in water reduces nickel sorption. Although actual uptake mechanisms are not known, it is likely that ion exchange processes occur in most species. These involve the release of calcium and other cations from the cell, coincident with replacement by $Ni(+2)$. The rate of exchange depends on culture pH, and decreases with time as the number of binding sites falls (Moore and Ramamoorthy, 1984).

Kabata-Pendias and Pendias (1992) and McGrath and Smith (1990) say that generally, the solubility of soil Ni is inversely related to the soil pH. Ni sorption on Fe and Mn oxides is especially pH-dependent, probably because $NiOH^+$ is preferentially sorbed and also because the surface charge on sorbents is affected by pH.

2.4.2 Complexation

Nickel is known to complex readily with a variety of inorganic and organic ligands. Nickel-halides are generally soluble in water, while nickel carbonate is fairly insoluble (Adriano 1986). Complexing ligands such as SO_4^- and organic acids reduce the sorption of Ni. The remobilization of Ni from solid phases appears to be possible in the presence of humic and fulvic acids. Thus, Ni may be quite mobile in soils with high complexation ability (e.g., organic-rich and polluted soils).

2.4.3 Organic Matter

In organic soils, Ni tends to accumulate in the surface organic layer. Adriano (1986) suggests there is a declining trend in Ni concentration with depth. However, considerable leaching in the soil profile could occur in instances where the soil has been severely acidified.

Nickel in the solid phase of soils occurs in several chemical forms. These include occurrence in the usual exchange sites, specific adsorption sites, adsorbed or occluded into sesquioxides, fixed within the clay mineral lattice, or fixed in organic residues and microorganisms. In the aqueous phase, Ni may occur in the ionic form and in forms complexed with either organic or inorganic ligands (Adriano 1986).

Organic matter, depending on its nature, can either immobilize or mobilize metals. Organic matter has been shown to fix Ni, thereby rendering it less available to plants. By increasing the organic matter of soil by adding organic amendments, the adsorption capacity of the soil for metals is increased (Fyson et al 1994).

In contrast, metals can be complexed by dissolved organic matter and therefore rendered more mobile. Organic acids produced from microbial activity can act as chelating agents to form mobile complexes with nickel (Adriano 1986).

2.5 Ecological Effects of Nickel in an Aquatic Ecosystem

2.5.1 Toxicity of Nickel

Under most test conditions, nickel is less toxic to aquatic plants than mercury, copper, cadmium, silver, and thallium, but more toxic than lead and zinc (Moore and Ramamoorthy, 1984). Significant reductions in growth and photosynthesis generally occur at 0.1 to 0.5 mg Ni L^{-1}. Susceptibility to nickel poisoning is also species dependent and some algal species can adapt to high nickel levels (Moore and Ramamoorthy, 1984). Combinations of nickel and other heavy metal contaminants may act synergistically or antagonistically. As with other metals, high water hardness and the presence of chelators also reduce toxicity (Moore and Ramamoorthy, 1984; McGrath and Smith, 1990).

The mechanism of Ni toxicity to plants is not well understood, although the restricted growth of plants and injuries caused by an excess of this metal have been observed for quite a long time (Kabata-Pendias and Pendias 1992). The toxicity symptoms produced by Ni are similar to those produced by several heavy metals and consist of (1) chlorosis caused by Fe-induced deficiency, and (2) specific effects of the metal itself. A typical toxic symptom produced by Ni is the chlorosis or yellowing of leaves followed by necrosis. Other symptoms include stunted growth of root and shoot, deformed plant parts, unusual spotting, and in severe cases, death of the whole plant. With plants under Ni stress, the absorption of nutrients, root development, and metabolism are strongly retarded. Before the acute Ni toxicity symptoms are evident, elevated concentrations of this metal in plant tissues are known to inhibit photosynthesis and transpiration (Kabata-Pendias and Pendias 1992; Adriano 1986).

Iron induced chlorosis is a common symptom of nickel phytotoxicity (Adriano 1986). Interaction between Ni and other trace metals, Fe in particular, is believed to be a common mechanism involved in Ni toxicity. The excess of Ni is believed to cause an actual Fe deficiency by inhibiting the translocation of Fe from roots to tops. Studies have shown that Ni/Fe ratio, rather than the Ni and Fe concentrations in plants, has shown better relationships with the toxic effects of Ni.

Generally the range of excessive or toxic amounts of Ni in most plant species varies from 10 to 100 ppm (DW). Several species are known for their great tolerance of nickel. Endemic species of serpentine soils or the so-called Ni accumulators which may contain several thousands ppm of Ni (Adriano 1986). The pronounced ability of some plant species to accumulate Ni when grown in soil over Ni ore bodies may make them useful biogeochemical indicators (Kabata-Pendias and Pendias 1992; Adriano 1986).

McGrath and Smith (1990) noted that elevated concentrations of Ni occur in a variety of plants growing in the highly contaminated soils in the vicinity of the large Ni-Cu smelting complex at Sudbury, Ontario. Foliar concentrations of over 900 mg/kg have been found in *Deschampsia flexuosa* and *Vaccinium angustifolium* a few kilometres from the source. In fact, the grass *Deschampsia cespitosa* has evolved multiple metal tolerance on soils contaminated by Cu, Ni and Co in the Sudbury mining and smelting area. Other nickel tolerant genotypes include *Agrostis gigantea* and *Phragmites communis*.

Phillips and Slaney (1981) examined the impacts of sulphur dioxide and heavy metals in smelter emissions on the natural environment of the Thompson area. While the method of nickel deposition in the Birchtree fen is via effluent discharge rather than atmospheric deposition, this information is useful to determine plant species which are tolerant of nickel and the effects of nickel on the environment.

Phillips (1981) collected species composition and abundance data for the black spruce bog study site near Thompson. By examining species occurrence at the black spruce bog subsite Phillips (1981) determined relative resistances of species to sulphur dioxide and heavy metal emissions. It was concluded that species differ widely in their ability to incorporate nickel in their foliage. <u>Evernia mesomorpha</u> and moss species have a high affinity for metals. <u>Linnaea borealis</u> has the potential to accumulate large quantities of heavy metals; <u>Cornus canadensis</u> accumulates nickel and copper in greater amounts than most angiosperms; all shrub species and aspen trees have high foliar content of heavy metals and sulphur at close-in sites, demonstrating metal uptake via the roots or from emissions directly from the atmosphere; Jack pine (*Pinus banksiana*) takes up heavy metals in response to available concentrations in the environment; Black spruce (*Picea mariana*), on the other hand, shows only a slight response to the elevated levels heavy metals.

Gignac and Beckett (1985) found elevated concentrations of nickel in the peat, water, soil, and vegetation of the peatlands in the Sudbury area. Nickel from smelter emissions was deposited in the peatland and incorporated into the plants via root uptake. Gignac and Beckett (1985) showed that with increasing distance and decreasing concentrations of Cu and Ni, conditions gradually permit growth of the oligotrophic Sphagnum species. Beyond 30 km, Sphagnum dominates all portions of the peatlands.

2.5.2 Bioaccumulation

Moore and Ramamoorthy (1984) suggest nickel does not accumulate through the food chain. Residues of nickel in aquatic plants, invertebrates and fish from the Sudbury (Canada) area were 3-690 mg kg^{-1}, 4-39 mg kg^{-1}, and 10-14 mg kg^{-1} respectively. Studies looking at bioaccumulation and biomagnification of heavy metals found similar results. For example, Mance (1987) describes a study where four groups of commercial species were collected in UK coastal waters. Mollusc filter feeders, mollusc predators, crustacean predators, and fish were analyzed for mercury, cadmium, lead, chromium, nickel, zinc, and copper. All trophic levels showed metal accumulation, but biomagnification was not observed.

Nickel is one of the least toxic priority heavy metals in invertebrates. Exposure to chronic levels of nickel generally results in a reduction in growth, reduced fecundity, reproduction, and respiration in several species (Moore and Ramamoorthy, 1984).

Phillips (1981) analyzed tissue samples from small mammals to determine the concentration of elements known to be present in Thompson smelter emissions. It was concluded that heavy metal depositions at close-in areas surrounding the smelter are not accumulating through the trophic levels.

2.6 Wetlands Reclamation

Several terms are frequently used in connection with the ecological engineering and reclamation of wetlands. *Wetland restoration* usually refers to the rehabilitation of wetlands that may be degraded or hydrologically altered and often involves reestablishing the vegetation. *Wetland creation* refers to the construction of wetlands where they did not exist before and can involve much more engineering of hydrology and soils. Created wetlands are also called constructed wetlands or artificial wetlands (Mitsch and Gosselink 1993).

2.6.1 Reasons for Creating and Restoring Wetlands

There are many reasons to create or restore wetlands. Two reasons which Inco is most interested in are: *Mitigation wetlands* for habitat restoration or replacement, where the intent is the replacement of wetland function in areas of degraded or destroyed wetlands; and, *Wastewater wetlands* for water quality enhancement. Most activity involving the use of wetlands for wastewater treatment now centres on constructing new wetlands rather than using natural wetlands. In addition, Brix (1993) lists several reasons why constructed wetlands are a better alternative than natural wetlands.

Acid mine drainage (AMD) is a major water pollution problem in many mining regions of the world. In the 1980's more than 140 wetlands were constructed in the eastern United States alone to control mine drainage. The use of wetlands to control this type of water pollution is viewed as a low-cost alternative to costly chemical treatment or to downstream water pollution where no other alternative is feasible (Mitsch and Gosselink 1993). However, while the potential use of wetlands to treat wastewater is promising, long-term affects are not yet known (Fyson et al. 1994) . In fact, Kalin et al. (1991) found that heavy metal concentrations and extreme pHs can kill wetlands (bogs) as easily as other systems.

2.6.2 Wetland Rehabilitation Principles and Goals

Mitsch and Gosselink (1993), Kent (1994), Zentner (1994), and Hammer (1992) describe the following principles and techniques necessary for successful wetlands rehabilitation/reclamation. Formulation of a reclamation plan is paramount in any reclamation strategy. A detailed reclamation plan must include the following: Site Analysis, Goals and Objectives, Wetland Design parameters, Implementation, Monitoring, and Evaluation.

2.7 Summary of Literature Review

Important findings from the literature review that are relevant to this study are summarized below.

Classification of wetlands provides for a common understanding of wetland types among wetland scientists, wetland managers, and wetland owners. Classification of wetland types provides for consistency of inventories, concepts, and terminology.

Wetlands are passive treatment systems that are proven to be effective to treat wastewater streams and improve water quality to meet regulatory standards. Wetlands have advantages over traditional chemical treatment in that they provide treatment at low-cost, low-maintenance and have the ability to be self-maintaining. Wetlands have been used in the mining industry and shown to be effective for neutral mine drainage, and acid mine drainage.

A low inflow velocity and in particular a low flow-through velocity is necessary to allow time for effective wastewater treatment. This results in increased retention time for contaminants and increased treatment effectiveness. Treatment effectiveness can be further enhanced by adding soil amendments to increase adsorptive sites and water levels can be maintained to increase the rates of sulphate reduction.

Metal attenuation in wetlands occurs because of (a) dilution; and (b) chemical and biological mechanisms. Chemical and biological processes include adsorption onto the organic substrate, exchange of metals, sulphate reduction in the anaerobic zone, precipitation and co-precipitation, sedimentation, and plant uptake.

Susceptibility to nickel poisoning is species dependent. Several species are known for their great tolerance to nickel and are considered "hyper-accumulators". Certain species may evolve a tolerance to nickel after long-term exposure to the metal. Nickel has not been shown to be bioaccumulating, that is it does not accumulate through the food chain.

There is a lack of a long-term data base. The potential use of wetlands to treat mine drainage is promising but as Kalin et al (1991) found heavy metal concentrations and extreme pH's kill bogs as easily as other systems. The capacity of wetlands to remove metals from wastewater streams has not been clearly demonstrated in the long-term. This illustrates a need for long-term evaluation of wetland treatment systems.

In terms of wetland reclamation, any restoration effort, reclamation plan, or rehabilitation program must begin with a detailed plan. Specific goals and objectives must be described and an extensive monitoring and evaluation program implemented to ensure the objectives are being met and the reclamation effort is successful.

3. METHODS

3.0 Introduction

In order to achieve the stated objectives a number of methods were drawn on throughout this research including an extensive literature review, field trips, soliciting experts and empirical field data collection. All analytical procedures were performed by the Inco production lab.

3.1 Literature Review

The literature in the following areas was consulted: Wetlands and wetland use in industry, with particular emphasis on mining; environmental toxicology of nickel in wetland environments; natural and constructed wetland processes for the treatment of metal contaminants particularly nickel; and the use of wetlands for reclamation.

3.2 Field Trips

Field trips to Inco Ontario Division's Sudbury/Copper Cliff operations to view how various wetland processes are used to treat acid rock drainage including the use of floating cattail rafts in acidic drainage to attenuate acidity and remove metals from solution. Cattails are tolerant to high concentrations of metal ions and a wide range of pH. Cattails produce a large biomass which supports microbial activity which removes excess nitrogen and generates alkalinity. These plants are also a source of organic carbon so the process is self-maintaining.

A field trip to Elliot Lake, Ontario to view the various decommissioning and reclamation projects of abandoned Rio Algom Ltd uranium mine sites. Of particular interest was the Panel Wetland site and the Quirke mine site. The Panel wetland shows natural recovery of a wetland covered by uranium tailings after a containment dyke failed. The Quirke mine is attempting to establish wetland vegetation on its flooded tailings areas to promote tailings stabilization.

3.4 Empirical Data

3.4.1 Water Quality

Water samples from the Birchtree mine water discharge were collected normally twice per week throughout the field season and once per week during the fall and winter months. Water samples of the fen outflow were collected twice per week up until freeze up and then again on first thaw. Water samples are analyzed at Inco's production lab for nickel, copper, iron, lead, zinc, arsenic, and cadmium, pH, sulphates, and nitrates. Analytical methods are described in detail in the manual on Analytical Methods prepared by Inco, Thompson.

Water samples from the control fens were collected once per month over the course of the two field seasons and analyzed for the same parameters as described above.

3.4.2 Birchtree Mine Water

Mine water from drilling, the cement flush process and natural ground water is collected in a regional sump and pumped or drained via a series of pipelines, drainage ditches and drain holes to the main drainage system at the shaft. The water is drained to the settling sump at 2300 level. The solids are settled off and disposed within the mining voids underground. Two Mather and Platt pumps pump water at a rate of 800 US gallons per minute. Only one pump pumps at any one time. The average pumping rate over a one month period is 125 U.S. gallons per minute (Inco 1993).

The pumping system is automated and set to operate once the liquid levels reach a specified height in the sumps. Pumping activity is carried out daily. It is estimated that pumping takes place for 15 minutes every four hours. Total monthly flow is obtained from Birchtree mine operations each month.

3.4.3 Fen outflow

The stream flow rate is needed to calculate the quantity of nickel leaving the wetland. Flow rate is determined by multiplying the Average Velocity in a stream profile by the Area of the stream profile.

Stream Area

The area of the stream was calculated using the Simpsons Rule (Langs Handbook of Chemistry (1980)).

$$A_s = \tfrac{1}{3}h[(y_0 + y_n) + 4(y_1 + y_3 + \ldots + y_{n-1}) + 2(y_2 + y_4 \ldots + y_{n-2})]$$

Where:

A is the area in inches squared (Simpson's rule);

h is the distance between parallel chords;

y is the length (depth in inches) of a series of parallel chords; and,

n is the number of chords. The greater the value of n, the greater the accuracy of approximation.

(note: n must be even)

Figure 3.1 shows how to use the Simpson's Rule in the field.

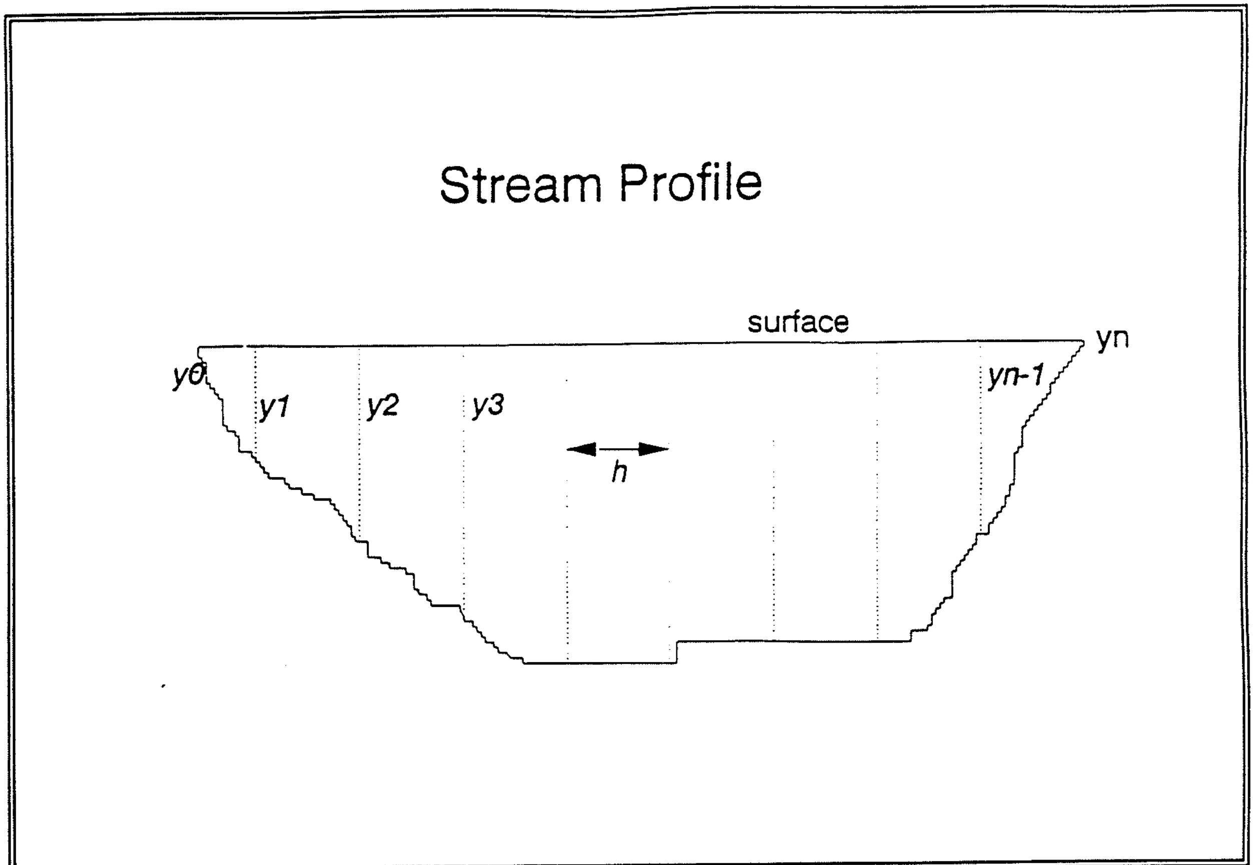


Figure 3.1 Area of a stream using Simpsons Rule, where: A is the area in inches squared (Simpson's rule); h is the distance between parallel chords; y is the length (depth in inches) of a series of parallel chords; and, n is the number of chords. The greater the value of n, the greater the accuracy of approximation.

Stream Velocity

Stream velocity measurements (feet per second) of the wetland outflow are taken twice a week using a Teledyne Gurley No. 625 Pygmy Current meter. A minimum of twelve to fourteen measurements were taken along the stream profile to obtain average stream velocity. Velocity measurements were taken as soon as possible after first thaw in order to capture the peak spring runoff period and immediately after heavy rains during the field seasons in order to capture peak precipitation runoff.

Stream Flow Rate

The flow rate is determined by multiplying the stream area by stream velocity.

The calculations to determine flow rate and ultimately the mass of nickel entering and leaving the fen are as follows:

$$V_{avg}(in/s) \times A(in^2) = \text{Flow Rate } (in^3/s) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where, Vavg is average velocity as determined by the current meter; and A is area of stream as determined by Simpson's Rule;

Flow Rate:

$$In^3/s \times 16.387 = cm^3/s \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$cm^3/s \times 75.768 = \text{imperial gallons per minute (IGPM)} \quad \ldots\ldots (3)$$

$$\text{IGPM} \times 60(\text{min.}) \times 24(\text{hr.}) = \text{imperial gallons per day} \quad \ldots\ldots (4)$$

Mass of Metal:

$$\text{IGPD} \times [\text{Ni(ppm)}] \times 0.00001 = \text{Nickel pounds per day} \quad \ldots\ldots (5)$$

3.5 Soil

Soil sampling is designed to provide information on the extent of nickel contamination including area, depth, and form of nickel in the Birchtree fen. The soil sampling was also used to construct a map of showing isolines of nickel concentrations throughout the study area. This plot (presented in chapter 4) shows the extent of nickel contamination as a result of receiving mine effluent, and areas of highest concentrations of nickel.

3.5.1 Sampling

In 1994 five transects were established in the Birchtree fen. The transects radiate out from a single point for approximately 120 metres. A sixth transect line was established 400 metres from the inlet running perpendicular to the wetland drainage. Soil samples for chemical analysis were collected at 30 metre intervals along each transect. Samples were collected using an AMS stainless steel soil auger. PH, Eh, and conductivity were done immediately on each sample then the sample was placed in an airtight plastic bag, labelled, and placed in a freezer to await further analysis.

In 1995, transect lines one and two were extended to include sites D and E, and six additional sample sites were established between transects for further determination and clarification of levels of nickel in Birchtree fen soil. Samples were handled and stored as above.

3.5.2 Depth of removal

Samples were sectioned to determine depth of nickel removal. Soil samples were sectioned at 0-30cm, 30-60cm, and 60+ cm. The literature suggests that nickel is captured in the top 20 to 30 cm of peaty soil in wetlands.

By confirming these results, it gives us a better understanding of the capacity of the wetland to filter mine wastewater. On occasion, it was unnecessary to sample at depths greater than 60 cm because of the clay material encountered.

3.5.3 Control Fens

Soil samples collected from the control fens are analyzed to determine background levels of contaminants in fen soils. Samples collected from Control #1 will show elevated levels of nickel due atmospheric deposition from the close proximity to the Thompson smelter stack. Samples collected from Control fen #2 will show background levels of nickel in soils not impacted by smelter emissions.

Soil samples were collected from the two control fens in 1995. Duplicate samples from three locations in Control fen #1 were sampled using the AMS stainless steel soil auger. Duplicate samples from four locations were collected at Control fen #2. Samples were sectioned at 30 cm and 60 cm intervals. All samples were handled and stored as above.

3.5.4 Analysis

All soil samples were analysed at Inco's production lab for the following parameters: Nickel, copper, iron, lead, zinc, arsenic, and cadmium, moisture content, and percent sulphur.

3.5.5 Sequential extraction

A sequential extraction procedure adopted from Eger et al 1994 was used to differentiate the forms of nickel in the peat substrate. Various reagents are used at seperate stages on samples of peat. At each stage a particular fraction of nickel is removed and the form of metal is determined based on the removal stage. Figure 3.2 shows a schematic diagram of the sequential extraction process.

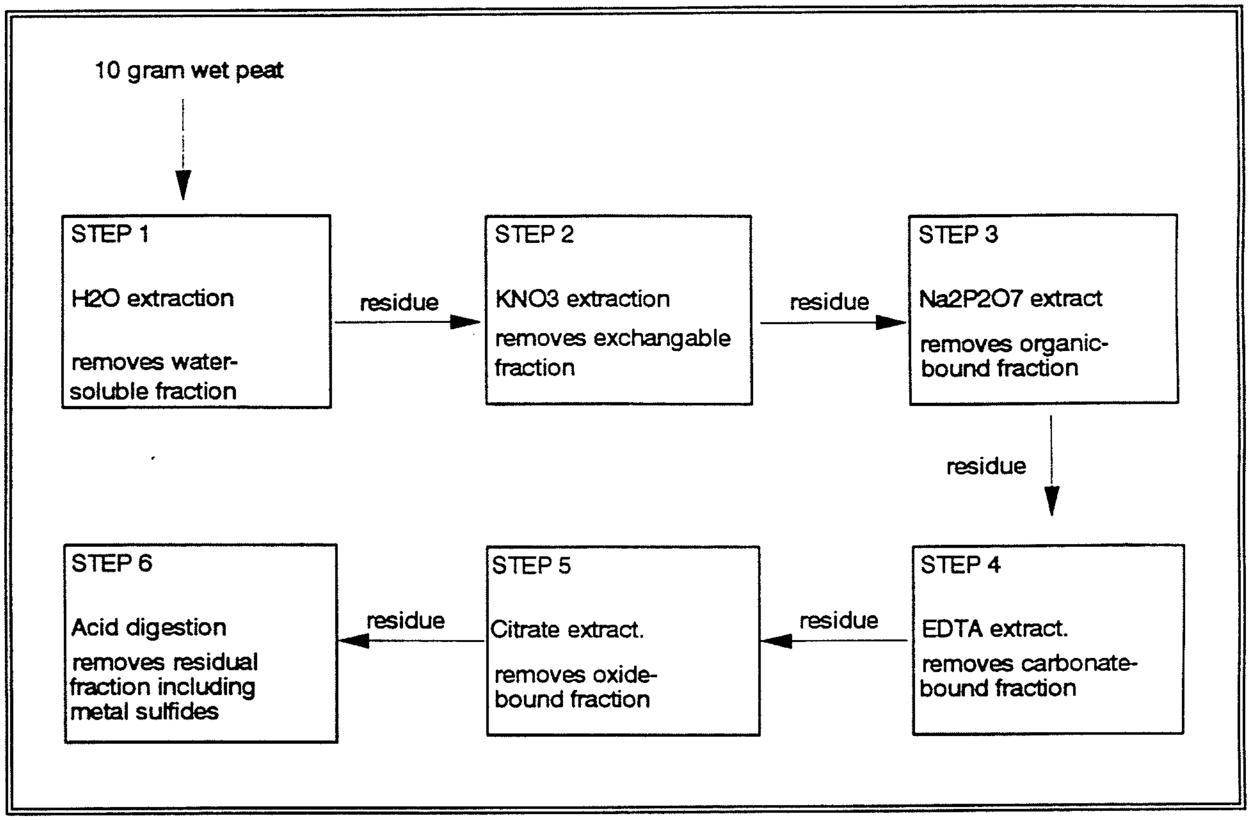


Figure 3.2 Sequential Extraction Procedure. The procedure used to determine various forms of nickel in Birchtree fen peat. In general, each extraction step becomes more difficult to remove the Ni ion. Step 1 removes the water soluble fraction and thus is easily removed. Step 6 requires acid to remove the residual nickel thus this fraction is strongly bound. Source: Eger et al (1994).

Triplicate samples were collected from two sites within the Birchtree fen. The sites were selected within 80 metres of the fen inlet.

3.6 Vegetation

This section describes the methods used to collect data on species occurrence in the Birchtree fen study area. Species occurrence in the Birchtree wetland was recorded for four strata including trees, tall shrub, dwarf shrubs and herbs and bryophytes (mosses). This method is adapted from Slaney and Company (1977). There was no chemical analysis done on the foliage because it is beyond the scope of this study. Vegetation analysis was to determine species occurrence only.

3.6.1 Trees

A five metre wide belt transect was set up through the long axis of the site. Identification of the tree species was recorded.

3.6.2 Tall Shrubs

Tall shrubs are woody plants taller than 50 cm with an indefinite number of stems arising from a single root stalk (Slaney and Company 1977). Data on the kinds of shrubs were collected to provide descriptions of species occurrence in the tall shrub stratum.

The five metre wide belt transect described in the previous section formed the sampling unit for the data collection. Each tall shrub within the transect was identified. These data were collected concurrently with the data on tree species.

3.6.3 Low Shrubs and Herbs

Low shrubs are woody plants less than 50 cm high with an indefinite number of stems arising from a single root stock (Slaney and Company 1977). Herbs are non-woody higher plant species. Data on the kinds of low shrubs and herbs were collected on the Birchtree site to provide identification of species occurrence in this stratum.

The sampling was done by placing quadrats running parallel to soil sampling transects. Twenty-four (25 cm X 25 cm) quadrats were placed systematically along each of the six transects. The interval between quadrat placements was determined by dividing the total transect length by 25, and rounding this distance to the next lowest number. They were place at 3 m intervals along the transect, the first being located at the three metre distance.

A 100 m tape was laid along a transect and the first transect was placed one interval distance from the end. In 1995, 24 quadrats per transect were placed in the Birchtree fen and species of low shrub and herb were identified.

3.6.4 Mosses

The sampling strategy described in the previous section formed the sampling unit for the data collection. Mosses within the quadrats was collected. These data were collected concurrently with the data on low shrub and herb species. Field identification of the mosses was difficult, so specimens were numbered wrapped in moist paper towel and placed in a plastic sample bag and refrigerated. Identification was done by Dr. J.M. Stewart at the University of Manitoba.

3.7 Atmospheric Emissions

The Inco smelter stack is a source of nickel, sulphur, and other contaminants through atmospheric deposition. The information gathered through analysis of dustfall and sulphation will provide insight into the impact of smelter emissions on the Birchtree fen. Dust fall canisters and sulphation plates were installed at Control fen #1 and Control fen #2. Control fen #1 is in close proximity to the Birchtree fen and thus should receive similar atmospheric deposition. The Birchtree wetland and Control fen #1 are approximately 4.5 kilometres from the Inco smelter.

3.7.1 Dust Fall

Canisters are located in a clear area. Samples were collected once per month from June 1994 to August 1995. Samples of dust are chemically analysed to assess the level of all those elements present in the stack emissions.

3.7.2 Sulphation Rates

Two sulphation plates are placed at each location in a clear area near the dustfall containers. The plates are collected every month and analyzed for exposure to sulphur in the atmosphere. The results provide average monthly exposure values to sulphur dioxide at specific locations within the study area. All analysis was done at Inco's main production lab.

4. RESULTS

4.1 Introduction

Results from field investigation are organized in the following manner: water quality, soil, and vegetation analysis.

4.2 Water Quality

Data on water quality was collected from the mine water entering the Birchtree fen and water quality at the fen outflow to determine the effectiveness of the wetland to filter mine wastewater. Data was also collected from two control sites to (a) determine the impacts of smelter emission fallout; and (b) determine background conditions.

The distance the mine water travels from the discharge point to the fen outflow is approximately 4 kilometres. The change in elevation over the 4 kilometres is approximately 8 metres and the entire area of Birchtree fen is approximately 95 hectares (Inco 1993). The area of the fen most intensively studied is approximately 10.5 hectares.

4.2.1 Birchtree Mine Water Chemistry

Birchtree mine water can be characterized as neutral to alkaline drainage with elevated concentrations of nickel. Average nickel concentrations over the course of the study were 5.12 mg/l but ranged as high as 19.87 mg/l. This water also contains very high concentrations of sulphates and nitrates.

Table 4.1 summarizes the chemistry of Birchtree Mine water entering the fen in 1994 and 1995. This table compares water quality of Birchtree mine water with water quality of the fen outflow over the course of two field seasons. All parameters analyzed in the mine water effluent, with the exception of nickel, are well below Metal Mining Liquid Effluent Regulation (MMLER) guidelines outlined in the Birchtree Mine Environment Act Licence (Manitoba Environment 1994). All other contaminants in the mine water effluent are at or near background levels as determined by the samples collected at the control sites. At the fen outflow, levels of nickel are reduced and all contaminants are well below acceptable limits. (Refer to Appendix 1.1 for complete water quality data of Birchtree fen inflow and outflow).

The source of nickel in the mine water is from Birchtree ore which consists of mineralized peridotite and a sulfide matrix (Inco 1993). The source of high pH in this water is from cement used in underground rock-cement fill system. A cement slurry plant mixes 20 ton batches of water, cement and cement retardant. The batch is sent to a holding tank and is followed by a water flush to clean out the boreholes and lines. The flush water drains into a sump and ultimately discharged as part of the Birchtree mine water. This has two effects, one is to raise the pH of the water; and two, the alkaline nature of the hydroxide present will precipitate the soluble nickel as nickel hydroxide (Inco 1993). The source of nitrogen is from ammonium nitrate residue used in blasting material. Elevated levels of sulphate is the result of oxidizing of the highly sulfide content of the ore (Inco 1993).

4.1.2 Control Sites

Table 4.1 also shows a summary of water quality from the two control sites (refer to Appendix 1.2 for complete water quality data of control sites). Control Fen #1 shows elevated levels of nickel in surface water. The source of the nickel is fallout from atmospheric emissions from the main smelter stack,

Table 4.1 Water quality of Birchtree mine water entering the fen, fen outflow, and water quality from control fens during the 1994 and 1995 field season (± 1 Standard Deviation). Control Fen #2 represents background conditions.

Parameter	Birchtree Mine Effluent	Fen Outflow	Control Fen #1	Control Fen #2
pH	8.4 ± 0.86	7.4 ± 0.47	7.5 ± 0.39	6.9 ± 0.32
Conductivity mS/cm	5.67 ± 1.03	1.58 ± 0.38	0.68 ± 0.22	0.18 ± 0.04
Nickel (Ni) mg/l	5.12 ± 4.87	0.08 ± 0.03	0.41 ± 0.23	0.02 ± 0.01
Copper (Cu) mg/l	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01
Lead (Pb) mg/l	0.05 ± 0.06	0.02 ± 0.01	0.02 ± 0.01	0.03 ± 0.02
Iron (Fe) mg/l	0.23 ± 0.49	0.33 ± 0.28	0.41 ± 0.18	0.30 ± 0.16
Arsenic (As) mg/l	0.10 ± 0.11	0.06 ± 0.04	0.03 ± 0.02	0.04 ± 0.02
Zinc (Zn) mg/l	0.02 ± 0.03	0.02 ± 0.01	0.01 ± 0.01	0.01 ± 0.01
Cadmium (Cd) mg/l	0.04 ± 0.10	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01
Sulphates (SO4-) mg/l	1046 ± 290	---	245 ± 119	2.31 ± 0.30
Nitrates (NO3) mg/l	68.4 ± 90.1	---	0.41 ± 0.09	0.89 ± 0.13

dust produced from haulage trucks hauling ore from Birchtree mine to the main plant site, and road dust. All other contaminants are at or near background conditions.

Control fen #2 is 50 km south of Thompson on PTH #6 and does not receive significant amounts of fallout from atmospheric emissions thus nickel levels are representative of background levels. The contribution of nickel from atmospheric deposition is discussed in section 4.3.2.

4.3 Metal Removal

To determine the quantity (mass) of nickel retained in the Birchtree fen it was necessary to collect data on the volume of mine water entering and leaving the fen as well as concentrations of nickel in the two streams.

4.3.1 Flow Rates

Flow rates of mine water to the fen averaged 460,000 litres per day over the two summer field seasons. Flow rate of the fen outflow was measured a minimum twice per week over the course of two field seasons. In the 1994 field season flow rates leaving the basin averaged 1,325,000 litres per day; in 1995, flow rates averaged 2,360,000 litres per day. Figure 4.1 shows mine water volumes to the fen and outflow volumes from the fen over two field seasons. In May and early June high water volumes at the outflow are the result of runoff. Summer peaks in outflow volumes particularly in August, 1995, are periods of heavy rains. Volumes of the fen outflow were not determined over the winter months. The mine water inflow volume remains relatively constant.

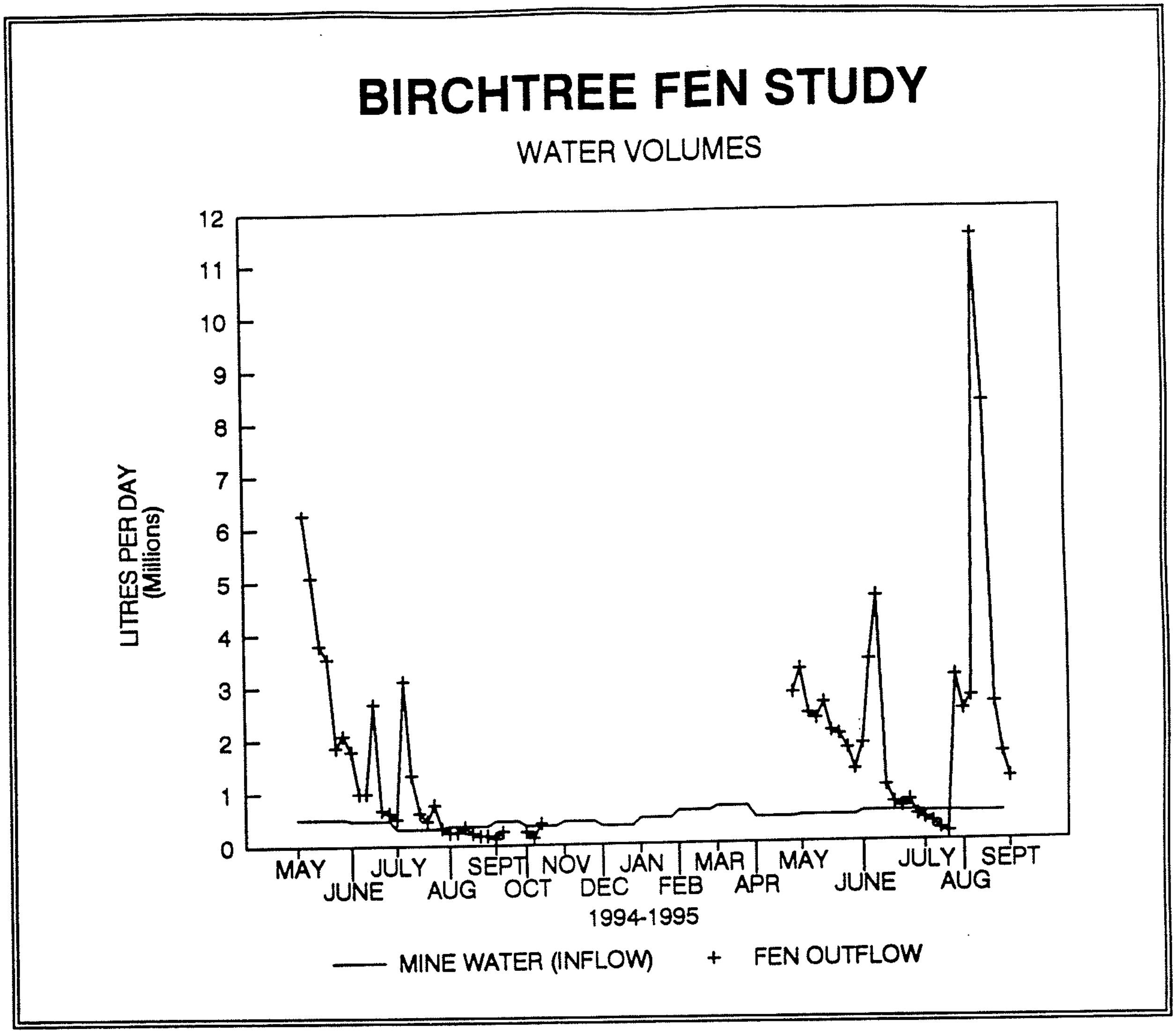


Figure 4.1 Volume of mine water entering the Birchtree fen versus Volume of fen Outflow measured over the course of the 1994-95 field seasons. No volumes were measured at the fen outflow over the winter months.

4.3.2 Nickel from Atmospheric Deposition

Dustfall containers were placed at the two control sites to provide information on the significance of nickel deposited on the Birchtree fen from stack emissions. Table 4.2 shows the amount of nickel deposited from smelter emissions on the Birchtree fen over the two field seasons. Control site #1 is approximately the same distance from the Inco smelter stack as the Birchtree fen and should recieve a similar quantity of dust. As indicated in Table 4.2, smelter emissions contributed approximately 2.6 kilograms/hectare of nickel to the Birchtree fen from June 1994 to August 1995. Control fen #2 received approximately 0.34 kg/ha over the same time period.

Control fen #1 also receives nickel from road dust created by haulage trucks carrying Birchtree ore to the main Inco plant site, however this dust component was not quantified. Dust collected in containers is a combination of road dust and flue dust.

Table 4.2 Nickel deposited on Control fens from smelter emissions in 1994 and 1995.

	Control Fen #1 Nickel (kg/ha/month)	Control Fen #2 Nickel (kg/ha/month)
JUNE 1994	0.24	0.07
JULY	0.14	0.02
AUGUST	0.21	0.01
SEPTEMBER	0.29	0.01
OCTOBER	0.15	0.02
NOVEMBER	0.05	0.02
DECEMBER	0.07	0.01
JANUARY 1995	0.12	0.02
FEBRUARY	0.05	0.02
MARCH	0.14	0.02
APRIL	0.13	0.02
MAY	0.42	0.04
JUNE	0.24	0.02
JULY	0.19	0.02
AUGUST	0.15	0.02
TOTAL	**2.59**	**0.34**

4.3.3 Nickel Retained in Fen

Nickel mass input and output for the Birchtree fen was determined by multiplying the total daily flow by the measured nickel concentration in the mine water and in the fen outflow. In addition, the quantity of nickel deposited via smelter emissions was calculated from monthly dustfall data (Table 4.2) and added to the nickel balance calculation. Table 4.3 shows the quantity of nickel in mine water entering the fen plus the nickel from atmospheric deposition and the quantity of nickel in the fen outflow on a monthly basis. The difference is the percent quantity of nickel retained in the fen. Mass balance calculations based on the difference between the inflow and outflow mass indicates that approximately 280 kg of nickel was retained in the wetland over the 2 summer field seasons.

Table 4.3 Monthly quantities of nickel entering the Birchtree wetland versus the amount of nickel leaving the wetland for the two summer field seasons. The nickel in dustfall is calculated in kilograms per hectare and then multiplied by the area of the fen (95 ha). Percent nickel retained is determined by Kg Ni OUT/kg Ni IN X 100 = %Ni OUT. Subtract 100 = %Ni retained.

1994	Birchtree Mine Effluent (kg Ni)	Nickel in Dustfall (kg Ni)	Fen Outflow (kg Ni)	Nickel Retained (%)
May	7.50	---	0.77	89.7*
June	19.16	22.8	0.40	99.1
July	16.68	13.3	0.52	98.3
August	7.00	20.0	0.09	99.7
Total	50.34	56.1	1.78	98.3

1995	Birchtree Mine Effluent (kg Ni)	Nickel in Dustfall (kg Ni)	Fen Outflow (kg Ni)	Nickel Retained (%)
May	40.50	39.9	2.86	96.4
June	7.90	22.8	1.63	94.7
July	29.46	18.1	0.41	99.1
August	11.71	14.3	3.50	86.5
Total	89.57	95.1	8.37	95.5

* Does not include nickel input from stack emissions.

In 1994, mass removal of nickel averaged 98.3 %. In 1995, mass removal averaged 95.5 %. Over the 2 field seasons, nickel removal in the Birchtree fen was 96.4%. The relatively low nickel retention in August 1995 is due to the increased volume of water flowing through the fen which corresponds to lower residence time and less nickel retention. Figure 4.1 shows the increased water volume measured at the fen outflow as a result of heavy rains in August.

4.3.4 Other Sources of Nickel to the Wetland

It is important to characterize other potential sources of nickel to the fen for a complete nickel balance and to determine if other sources may be significant.

4.3.4.1 Birchtree Lagoon

Birchtree sewage lagoon (figure 4.2) is discharged to the wetland periodically as per the regulations for operation of sewage lagoons. Analysis of the discharge water (Table 4.4) shows background levels of nickel and heavy metals, suggesting the sewage lagoon water is not a source of heavy metals to the wetland.

Table 4.4 Levels of metals in Birchtree Lagoon discharge water. Results for metals in ppm; conductivity is measured in mS/cm.

Tot. Ni	Sol. Ni	pH	Cond.	Cu	Fe	Pb	As	Zn
0.03 ± <.01	0.02 ± <.01	8.4 ± 0.3	0.21 ± 0.11	0.01 ± ---	0.63 ±	0.01 ± ---	0.02 ± 0.01	0.01 ± 0.01

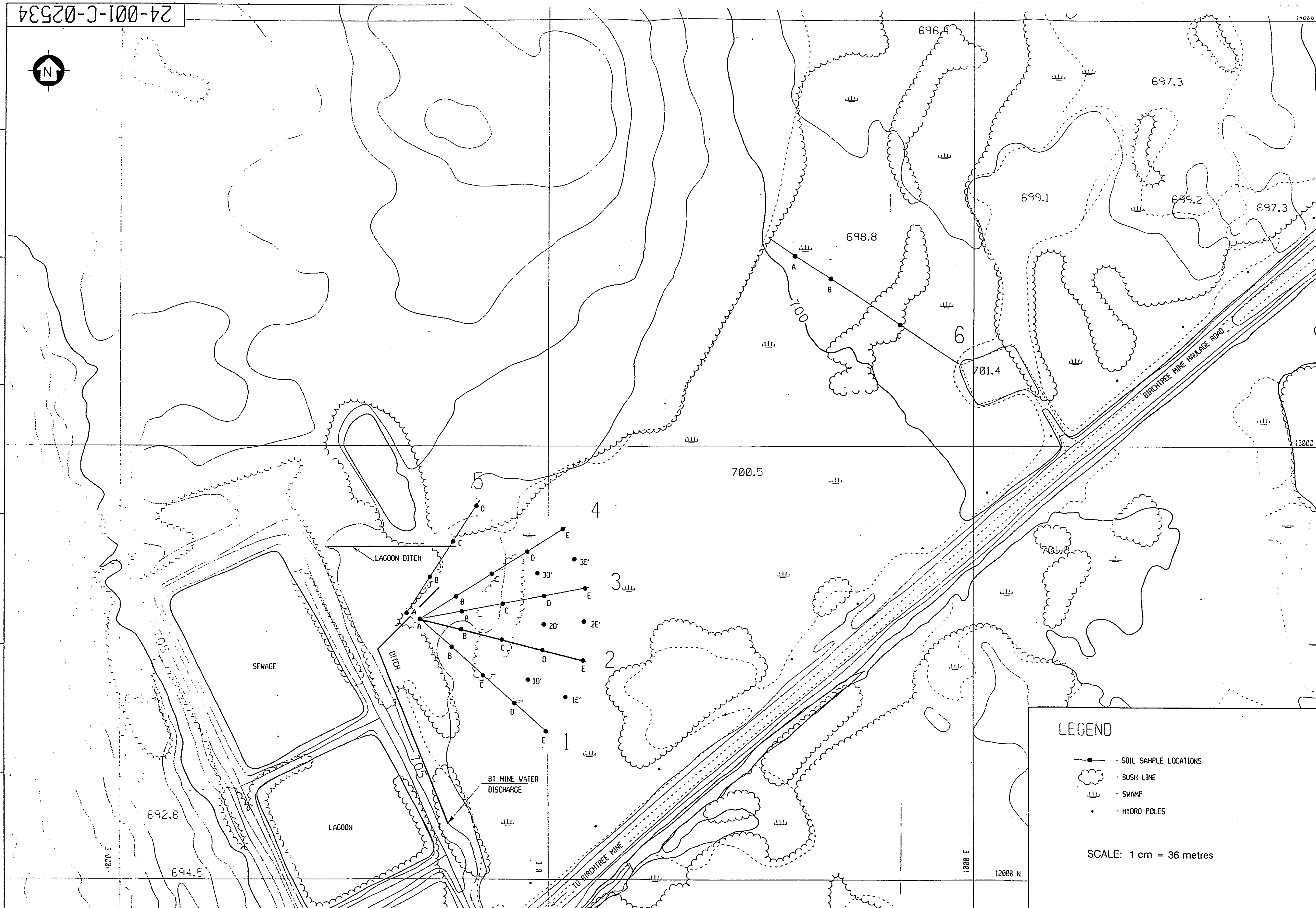
4.3.4.2 Nickel in Dustfall

Table 4.2 shows that approximately 2.6 kg/ha was deposited on the Birchtree fen over the 15 months dustfall data was collected. This amounts to approximately 5 kg nickel in a 1.8 ha area immediately adjacent to the mine water inflow (figure 4.3).

4.4 Soil

4.4.1 Soil Chemistry

Figure 4.2 shows soil sampling locations in the Birchtree fen. This area most intensively studied is approximately 1.8 ha. Table 4.5 shows the mean results of chemical parameters from samples collected at 0-30 cm at these locations and compares this to soil chemistry in the control fens. The complete results of the soil sampling campaign are given in Appendix 2.



NUMBER	REFERENCE DRAWINGS	NO.	REVISION	DATE
24-001-C-02546	NI CONCENTRATION ISOLINE PLAN			
		1		01-18-96

INCO LIMITED

MANITOBA DIVISION

	NAME	DATE
DRAWN	H. O'HANDLEY	09-29-95
CHECKED	A. HAMBLEY	01-18-96
DESIGNED	N/A	
CHECKED		
REVIEWED	H. TSOI	01-18-96

THOMPSON PLANT — BIRCHTREE MINE

WETLAND STUDY SITE — SITE PLAN

SOIL SAMPLE LOCATION PLAN

24-001-C-02534

PROJ. REF. E6214

REVISION 1

Table 4.5 Mean and standard deviation (± 1 S.D.) of chemical parameters measured in soil samples collected in the Birchtree fen and control fens.

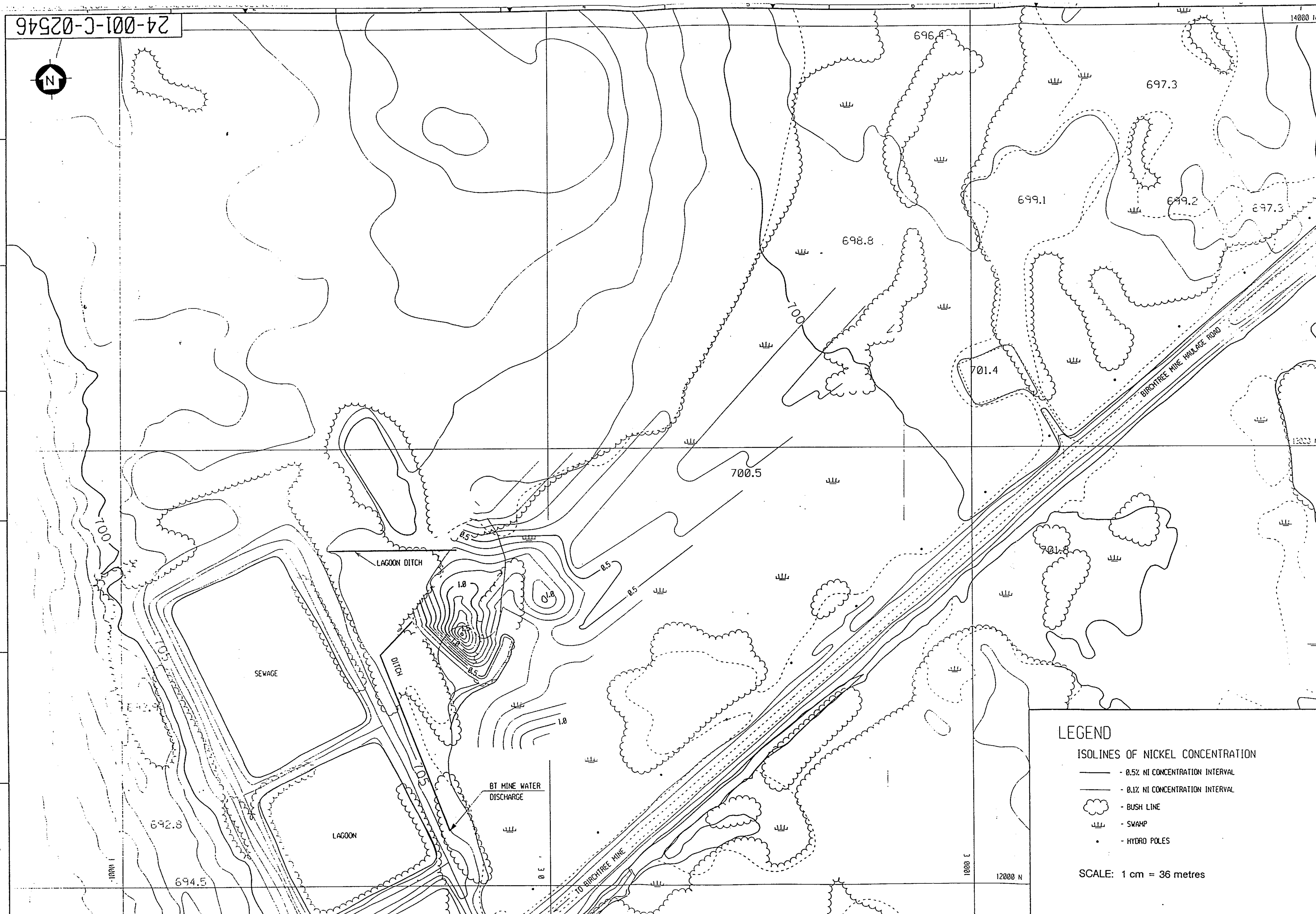
Site	Depth (cm)	pH	Eh	Cond (mS/cm)	Ni %	Cu %	Fe %	Pb %	Zn %	As %
BT Fen	0-30	6.8 ± 0.52	123 ± 76	1.14 ± 1.14	0.59 ±0.34	0.02 ±0.02	4.01 ±1.91	0.02 ±0.02	0.01	0.01 ±0.01
Ctl 1	0-30	6.0 ±0.26			0.02± <.01	0.01	4.49 ±1.05	0.05 ±0.06	0.01	0.01
Ctl 2	0-30	6.5 ±0.15			0.01± <.01	0.01	4.08 ±0.25	0.06 (.04	0.01	0.01

Results of soil sampling indicate that the Birchtree fen has elevated concentrations of nickel. All other contaminants are at or near background levels as determined by control sites.

4.4.2 Area of Nickel Removal

The data obtained from soil sampling is used to construct a map showing isolines of nickel concentrations in the Birchtree fen. Figure 4.3 shows the majority of the nickel is contained within 125 metres of the fen inlet. Concentrations of nickel reach a peak of 1.54 % 35 metres from the inlet and gradually diminish to 0.20% as the mine water follows gradual contours in a northeast direction.

This map shows that the nickel deposited in the Birchtree fen via mine water is largely contained in an area approximately 1.8 hectares in extent.



NUMBER	REFERENCE DRAWINGS	NO.	REVISION	DATE	BY	CHD	CORD	PROJ
24-001-C-02534	SOIL SAMPLE LOCATION PLAN							
		1	ISSUED FOR INFORMATION	01-18-96	HOH	HT		

INCO LIMITED

MANITOBA DIVISION

	NAME	DATE
DRAWN	H. O'HANDLEY	09-29-95
CHECKED	A. HAMBLEY	01-18-96
DESIGNED	N/A	
CHECKED		
REVIEWED	H. TSOI	01-18-96

THOMPSON PLANT — BIRCHTREE MINE

WETLAND STUDY SITE — SITE PLAN

NI CONCENTRATION ISOLINE PLAN

24-001-C-02546

PROJ. REF. E6214

REVISION 1

4.4.3 Depth of Nickel Removal

Table 4.3.1 (Appendix 2) also shows that the majority of the nickel is contained within the top 30 centimetres of the peat layer. The average nickel concentration contained in this layer is 0.59 %. In depths greater than 30 cm, average concentrations of nickel drop to 0.15 %. There are some exceptions however. At sample site BT1E, concentrations of nickel were 0.92% at a depth greater than 30 cm. Sites BT2D, BT3D, BT4C, and BT4D, concentrations exceeded 0.35%.

4.4.4 Forms of Nickel

A sequential extraction procedure was performed on peat collected from two sites within the fen, shown on figure 4.2. Triplicate samples were collected from each site. Sample depth was 0-30 cm as it was determined that the majority of nickel is contained in this region. Figure 4.4. shows that 45% of the nickel is associated with the organic fraction of the peat; 24 % of the nickel forms precipitates with carbonates; 22% co-precipitates with iron and manganese-oxides; 5 % of the nickel is strongly held as sulphide precipitates; 2% is adsorbed in the exchangeable fraction; and less than 1 % is water soluble.

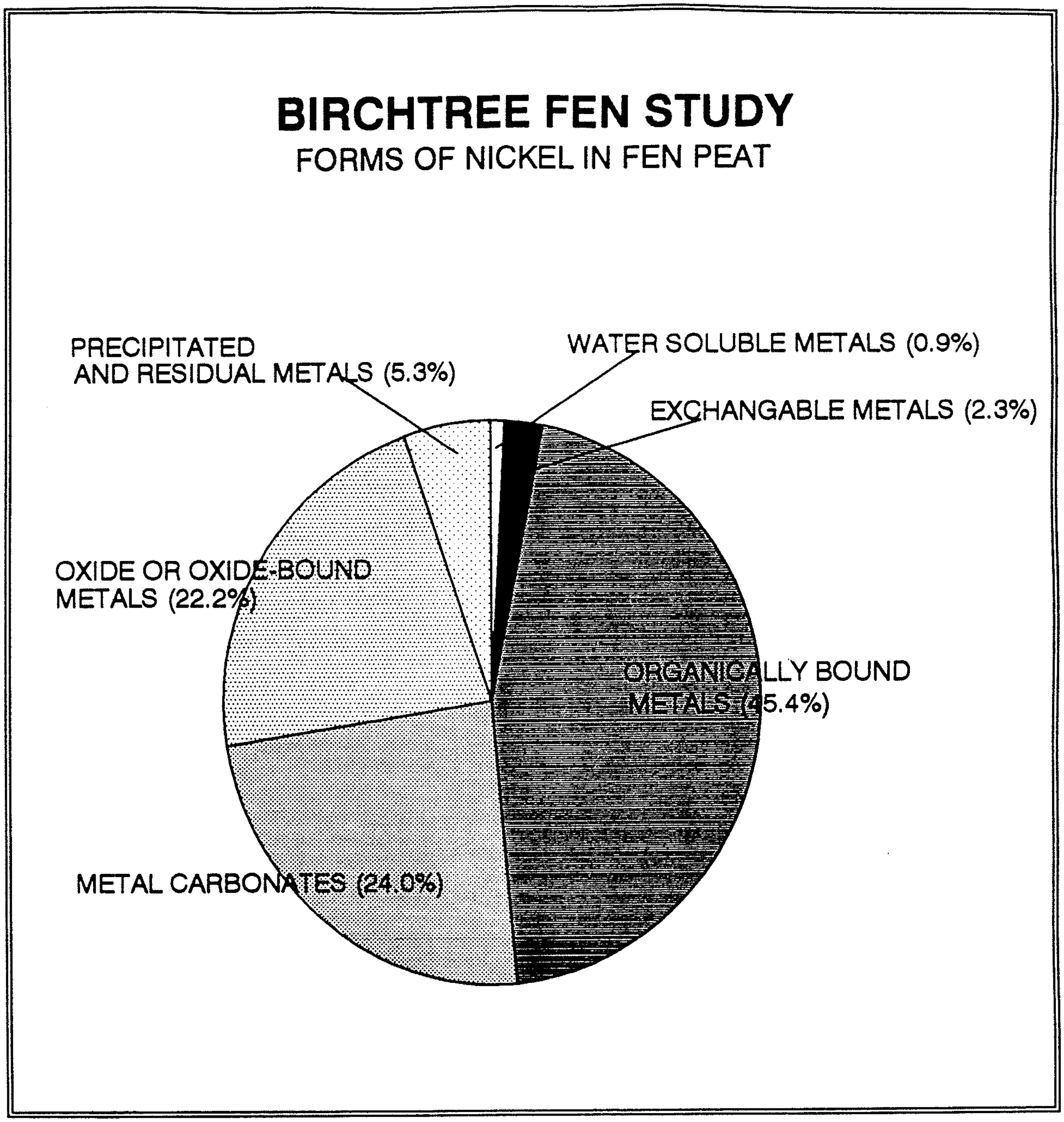


Figure 4.4. Forms of Nickel in Birchtree Fen Peat as determined by sequential extraction. Forty-five percent of the nickel is associated with the organic fraction of the peat; 24 % of the nickel forms precipitates with carbonates; 22% co-precipitates with iron and manganese-oxides; 5 % of the nickel is strongly held as sulphide precipitates; 2% is adsorbed in the exchangeable fraction; and less than 1 % is water soluble.

4.5 Vegetation

The objective of vegetation sampling was to firstly identify and determine the various species in the Birchtree fen to compare to species occurrence lists of vegetation found in typical fen environments. Secondly, it was hoped this list would provide a basis for more intensive future studies in the Birchtree fen as part of the monitoring program developed in the reclamation plan. Thirdly, this list was prepared to identify plant species which are possibly tolerant to conditions of high concentrations of nickel.

Species occurrence data was collected for four vegetative strata in the Birchtree fen: Trees, medium shrubs, dwarf shrubs and herbs, and bryophytes. The list is given in Appendix 3. This list is compared to a species occurrence list taken from Phillips and Slaney (1980). Their list is more extensive perhaps indicating increased species occurrence in locations of lower nickel contamination, or simply the fact that their survey was more intensive and complete.

5. DISCUSSION

5.1 Introduction

An assessment of the literature has shown wetlands are capable of assimilating heavy metals including nickel in wastewater streams and improving water quality at the outflow. The discussion section is organized in the following manner: water quality and nickel retention in the Birchtree fen; soil analysis including area and depth of nickel removal and forms of nickel; and vegetation analysis.

5.2 Water Quality

Nickel is the main element of concern in the Birchtree mine water as it occurs in large quantities compared to other contaminants. The fen is an effective filter as concentrations of nickel are reduced from an average of 5.12 mg/l in mine water to 0.08 mg/l after passing through the fen.

Control fen #1 is not impacted by Birchtree mine water. Thus, elevated levels of nickel found here are probably the result of two factors. The first is proximity to the Inco smelter stack and the deposition of nickel from atmospheric fall-out. Dust collected from one dustfall container located near Control fen #1 shows that approximately 2.6 kg/ha nickel was deposited in the vicinity of the Birchtree fen and Control fen #1 over the course of 15 months. The second source of nickel may be dust generated from hauling Birchtree ore to the main Thompson mine site.

5.2.1 Nickel Retention

Table 4.3 shows the effectiveness of the wetland in retaining nickel. Overall, 96.4 % of nickel entering the Birchtree fen, from both mine water influent and atmospheric deposition, is effectively retained. Over the 1994 and 1995 field seasons approximately 280 kg of nickel was retained in the Birchtree fen.

The reduced retention of nickel in 1995 may be partly explained by the different hydrologic conditions between years. A summary of the Thompson Airport Climatological Data, 1967 to 1990, is given in Appendix 5 along with total precipitation recieved from 1990 to 1995. The 1994 field season was dry with monthly total precipitation well below normals. Less water flowing through the fen results in increased retention or increased "residence" time and more effective removal of nickel. Nickel retention in the 1994 field season was 98.3%.

Nickel retention in the 1995 field season was 95.5%. The 1995 field season was initially dry with below normal precipitation in May and June but July and August were wet with above normal precipitation as a result of heavy rains and thunder storms. The increased volume of water flowing through the fen in August may explain the relatively lower nickel retention as a result of reduced residence time.

Figure 5.1 graphically displays the relationship between water volume and quantity of nickel in the outflow. The quantity of nickel in the fen outflow is directly related to the volume of the outflow. During spring thaw, less nickel is retained because: a)increased volume of water; and b) the ground remains frozen and the water is unable to penetrate the substrate. Both factors result in reduced retention time and increased nickel levels at the outflow. Thus, during spring thaw and during periods of above normal precipitation in the summer, nickel levels can be expected to increase at the fen outflow.

The relationship between nickel in mine water and nickel in the fen outflow is less clear. Peak levels of nickel in the fen outflow do not necessarily correspond to peak concentrations of nickel in mine water. This is expected as there is a lag period from the time nickel enters the fen to the time the nickel appears at the outflow. However, a general trend is seen in figure 5.2, whereby increased concentrations of nickel in the mine water result in increased concentrations in the fen outflow.

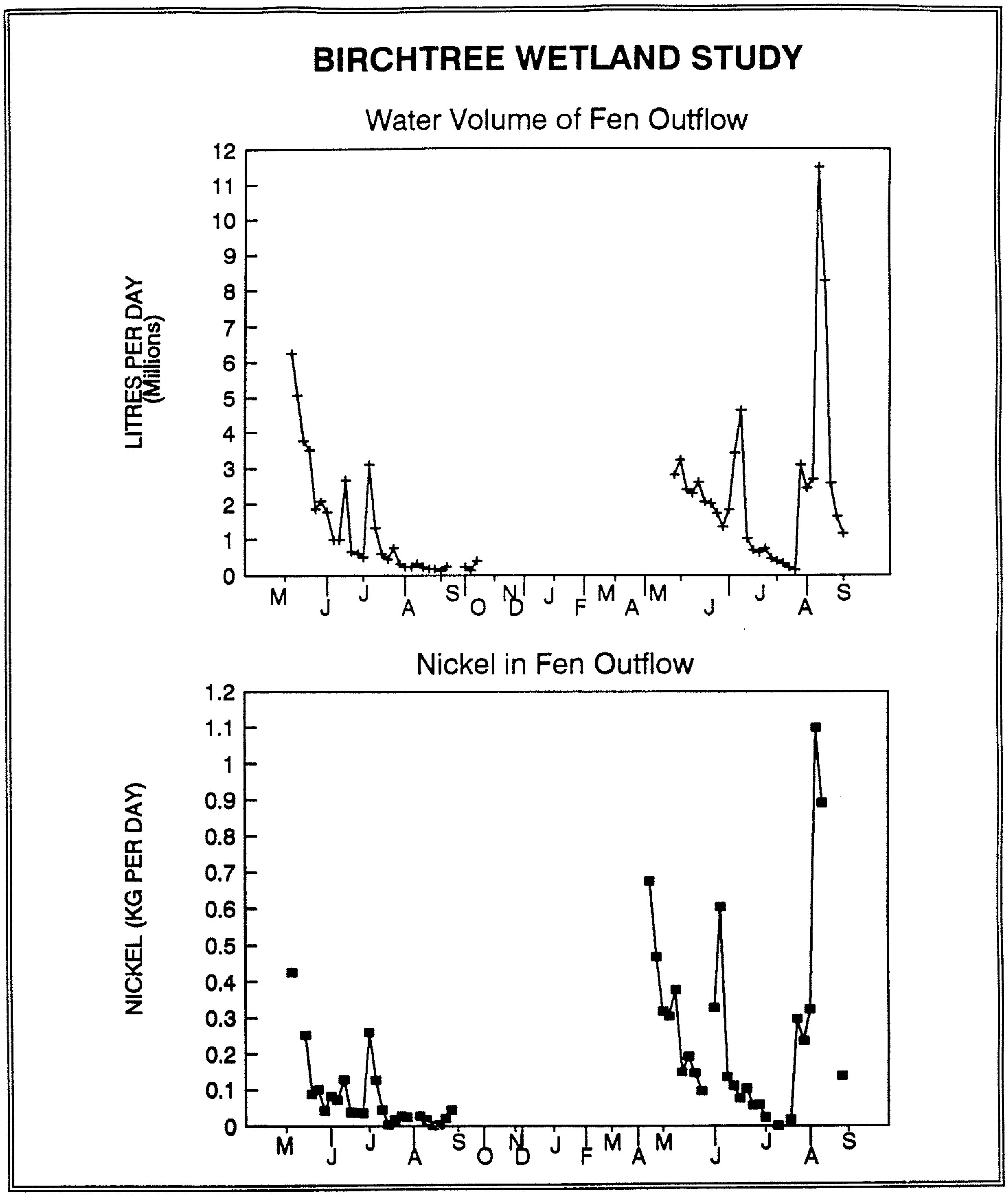


Figure 5.1 Volume of water in the fen outflow versus quantity of nickel in the outflow for the 1994-1995 field seasons. The quantity of nickel in the outflow is directly related to volume of the outflow.

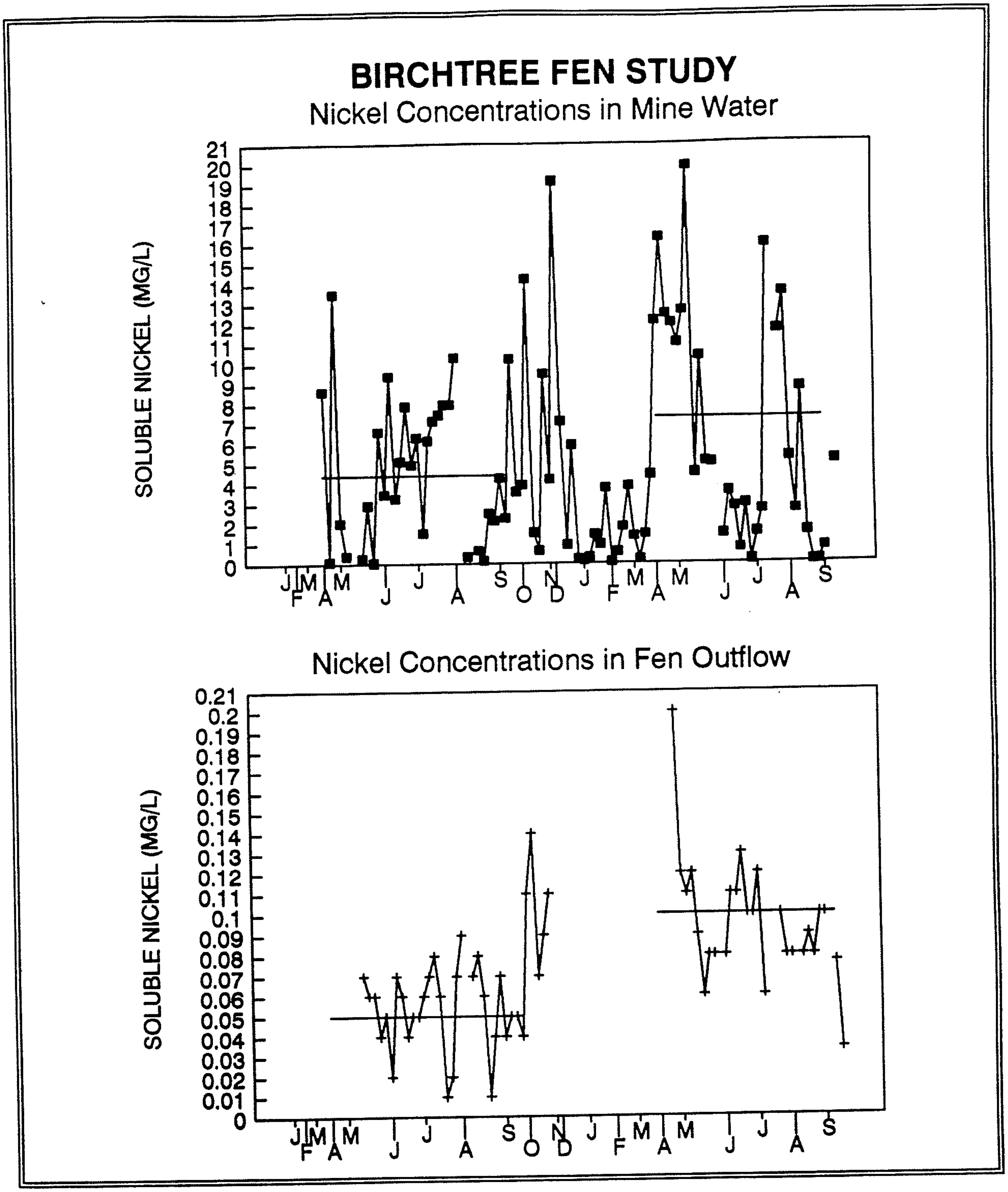


Figure 5.2 Relationship between concentrations of nickel in Birchtree mine water entering the fen and concentrations of nickel in the fen outflow. Mean concentrations of nickel are depicted by lines. In general, increased concentrations of nickel in mine water result in increased concentrations in the outflow.

5.3 Soil

Results from soil sampling in the Birchtree fen and control sites show that concentrations of nickel in the Birchtree fen are 28 to 75 times greater than background levels as a result of receiving mine water. All other contaminants measured in the fen soil are at or near background levels determined from soil samples collected from control sites 1 and 2 (refer to Table 4.5). It was thought that soil samples collected at control fen #1 would have elevated concentrations of nickel in the soil due atmospheric fallout from the smelter stack. This was not the case however, as nickel in soil from control fen #1 was 0.02% or near background levels. Therefore it appears that nickel deposited from atmospheric fallout is not bound in the substrate similar to nickel in mine water. This nickel may be characterised by examining the pore water content of the soil. Most of the nickel from the stack is in soluble sulphate form (Orr, pers. comm.)

5.3.1 Area of Removal

Figure 4.3 is a map showing isolines of nickel concentration as a result of mine water deposition. The majority of nickel is retained within 125 metres of the fen inlet, covering an area of approximately 1.8 hectares. The highest concentrations of nickel (isoline 1.5% Ni) are found approximately 35 metres from the fen inlet. An area of particular interest is the apparent increase in nickel moving south toward the haulage road. This may signal possible seepage from the mine water ditch, or an external source of nickel of unknown origin. It would not appear to be the influence of road dust because of the low concentrations of nickel in soils from control fen #1 which a similar distance from the haulage road.

Nickel deposited from the atmosphere was determined to be in the order of 2.6 kg/ha. Over 1.8 hectares, stack emission fallout constitutes less than 5 kg of nickel to the area over the course of 15 months of this study. This is a relatively insignificant source of nickel in this local area compared to the mine water. However, when considering nickel deposition from the atmosphere over the entire 95 hectares of the fen, smelter emissions become an greater contributer of nickel to the outflow than the mine water.

5.3.2 Depth of nickel in soil

Appendix 4.3.1 and 4.3.2 shows the majority of nickel is contained within the top 30 cm of the fen soil. This is consistent with Eger et al (1994) who says effective metal removal occurs in the top 20 to 30 cm of the peat. This occurs as a result of a minimal vertical hydraulic gradient and a decrease in hydraulic conductivity with depth (Eger et al 1994). In some cases high concentrations of nickel were measured at depths greater than 30 cm, but this was not common. Phillips and Slaney (1981) found all the nickel contained within 100 cm.

Determining the depth of nickel in the fen is important when developing a reclamation strategy. For example, if the decision is to remove the contaminated material from the wetland, effective removal depth would be 50 cm, leaving the remaining natural soil in place and minimizing disturbance to the fen.

5.3.3 Forms of Nickel

It is important to characterize the various forms of nickel in the fen substrate. This provides valuable information regarding the capacity and capability of the fen in removing nickel. Most importantly insight is gained into the potential risk of the nickel re-mobilizing. Nickel forms were determined by sequential extraction procedure. The procedure was performed by Inco's

Environmental Lab.

Figure 4.4 shows the breakdown of the results of the sequential extraction procedure. Less than 1% of the nickel is water soluble and will detach readily from the substrate and diffuse out into solution (Orr 1996, pers. comm.). Approximately 2.3% of the nickel is loosely bound in the exchangeable form and may easily become re-solubilized. As expected, the largest portion of nickel is bound to organic matter. Forty-five percent of the nickel is retained by the organic fraction and is not likely to re-solubilize as long as organic binding sites are available (Orr 1996, pers.comm.). Forty-six percent of the nickel is precipitated as carbonates and co-precipitated with iron or manganese oxides (steps 4 and 5 respectively). It is unlikely that these forms of nickel will re-solubilize back into solution (Orr 1996, pers.comm.). Finally, 5.3% of the nickel is bound in the residual fraction, probably precipitated as a sulphide. Because this extraction step is the most drastic using nitric acid, the bonds are presumed to be strongly held. However, Orr (1996, pers.comm.) suggests that the nickel may become soluble if the sulphides are allowed to oxidize.

5.4 Vegetation

5.4.1 Nickel Toxicity

Under most test conditions, nickel is less toxic to aquatic plants than mercury, copper, cadmium, silver, and thallium, but more toxic than lead and zinc (Moore and Ramamoorthy, 1984). Significant reductions in growth and photosynthesis generally occur at 0.1 to 0.5 mg Ni L^{-1}. However, there is considerable variation. Susceptibility to nickel poisoning is also species dependent (Moore and Ramamoorthy, 1984). Endemic species of serpentine soils for example may contain several thousand ppm of Ni (Adriano 1986).

The toxicity symptoms produced by Ni are similar to those produced by several heavy metals and consist of (1) chlorosis caused by Fe-induced deficiency, and (2) specific effects of the metal itself. A typical toxic symptom produced by Ni is the chlorosis or yellowing of leaves followed by necrosis. Other symptoms include stunted growth of root and shoot, deformed plant parts, unusual spotting, and in severe cases, death of the whole plant. With plants under Ni stress, the absorption of nutrients, root development, and metabolism are strongly retarded (Adriano 1986).

Examination of uptake of nickel by vegetation was not in the scope of this study, thus levels of nickel in Birchtree fen vegetation were not determined. However, effects of nickel toxicity were not observed in the Birchtree fen. There is no visual evidence in terms of "die-back" or acute nickel toxicity to indicate that fen vegetation is adversely affected by elevated levels of nickel in the substrate. However, a meticulous survey of the vegetation in the fen may reveal a trend to increased species diversity as one proceeds from the inlet to the outlet which indicates that elevated nickel may prevent certain vegetative species from becoming established. A more detailed and extensive investigation of Birchtree fen vegetation is recommended, especially in areas of lower concentration to see if species occurrence increases.

5.4.2 Species Occurence

A rudimentary survey of species occurrence in the Birchtree fen was performed in 1995. Several species known to be tolerant of metal-contaminated sites were identified. The compiled list (Appendix 4) is noticeably shorter than one compiled by Phillips and Slaney (1981) of a fen subsite. This may indicate that certain plant species usually common in fens could not tolerate the high concentrations of nickel in the vicinity of the fen inlet. On the other hand, conditions are such that tolerant species can thrive.

Certain plant species found in the Birchtree fen are known to be tolerant to metal contaminated soil with high concentrations of nickel (Winterhalder 1995; Fyson et al 1994). Winterhalder (1995) in his studies on natural recovery of the areas surrounding metal smelters in the Sudbury region, found the rush (*Juncus brevicaudatus*) and bog birch (*Betula glandulosa*) to be efficient colonizers of metal-contaminated sites. Both species were identified in the Birchtree fen. Other species tolerant of metal-contaminated sites found in the Birchtree fen include Redtop grass (*Agrostis stolinifera*) which dominates the fen; willow species; Labrador Tea (*Ledum groenlandicum*); and the moss *Pohila nutans*. Cattails (*Typha latifolia)* thrive in the Birchtree fen in areas where water periodically flows and surrounding standing water pools. Cattails are frequently used to improve pollution control performance in wetlands with regard to heavy metals because of their tolerance to metal contaminated conditions (Shutes et al 1993; Kalin 1985).

6. RECLAMATION STRATEGY FOR BIRCHTREE FEN

6.1 Introduction

As stated previously, Inco is committed to the concepts of sustainable development and progressive decommissioning. Progressive decommissioning is defined as rehabilitation done continually and sequentially within a reasonable time, during the entire period that the project (mining operations at Birchtree) continues (SENES Consultants Ltd. 1991).

This chapter provides Inco with a guideline for the reclamation of the Birchtree fen which must be considered given Inco's commitment to the above concepts. The following draws on the literature and correspondence with experts.

6.2 Wetland Reclamation

Several terms are frequently used in connection with the ecological engineering and reclamation of wetlands. *Wetland restoration* usually refers to the rehabilitation of wetlands that may be degraded or hydrologically altered and often involves reestablishing the vegetation. *Wetland creation* refers to the construction of wetlands where they did not exist before and can involve much more engineering of hydrology and soils. Created wetlands are also called constructed wetlands or artificial wetlands (Mitsch and Gosselink 1993). The term wetland restoration applies to the Birchtree wetland as the fen has been altered hydrologically and chemically by the input of mine water. The following principles and goals are designed to aid in the reclamation of the Birchtree fen to as natural a state as possible.

6.3 Birchtree Wetland Reclamation Principles and Goals

Formulation of a reclamation plan is paramount in any reclamation strategy. Mitsch and Gosselink (1993), Kent (1994), Zentner (1994), and Hammer (1992) describe principles and techniques necessary for successful wetlands reclamation. A detailed reclamation plan must include the following:

1. Site Analysis
2. Goals and Objectives
3. Wetland Design, which includes parameters:
    - hydrology;
    - substrate/soil;
    - vegetation;
4. Implementation
5. Monitoring
6. Evaluation

Using the above principles as a guide, a reclamation plan for the Birchtree fen will be described.

6.3.1 Site Analysis

The Birchtree fen site characteristics are described in detail in preceding sections. In summary, figure 4.3 shows that the majority of the nickel is confined to an area of approximately 1.8 hectares close to the mine water source. Thus, the reclamation plan will concentrate on that area of the fen most contaminated.

Analysis of Birchtree fen influent and effluent data show that the fen was effective in capturing 96.4 percent of the nickel over two field seasons. Extensive soil sampling shows the majority of nickel is bound by various processes in the top 30 cm of the fen substrate. Soil samples submitted for sequential extraction analysis show that 97 percent of the nickel is bound in the fen substrate primarily by adsorption to organic material, precipitation as nickel carbonates and co-precipitates with oxides of iron and manganese. It is hypothesized that there is a low risk of the nickel becoming soluble and mobile in this environment (Orr 1996, pers. comm.).

Vegetative species such as Redtop grass, cattails, and bog birch thrive in the fen and are known to be tolerant of metal contaminated sites. In addition, there is no visual evidence in terms of "die-back" or acute nickel toxicity to indicate that fen vegetation is adversely affected by elevated levels of nickel in the substrate.

6.3.2 Goals and Objectives

The setting of specific goals and objectives is critical to wetland rehabilitation projects. Goals define monitoring elements and protocols, and establish standards for judging success of the reclamation effort (Zentner 1994). Project goals should specifically include a substantive element that is also a measurable parameter.

The major objective in the Birchtree fen reclamation strategy is the recovery of the fen to as natural a state as possible. This can be achieved in several ways including: (1) physical removal of the contaminants and active site reclamation; (2) enhanced natural recovery; and (3) allow the fen to recover naturally.

While the physical removal of the soil in the area of the Birchtree fen most contaminated (determined to be approximately 1.8 ha) would effectively negate the liability to Inco of this material becoming a problem in the future, there are several reasons why such a strategy is not recommended at this time.

1) Nickel is bound in the substrate and there is low risk of the metal becoming resoluble in this environment;

2) disturbance of a thriving fen ecosystem;

3) High cost involved with physical removal and site revegetation, and low probability of successfully reclaiming the area;

4) removed material will have to be disposed of somewhere else and release of nickel will have to be treated;

5) it would be premature to implement a plan to restore the fen by means of an extensive reclamation strategy such as removing the contaminated material and revegetating the site, when the ability of the wetland to recover naturally has not been quantitatively measured;

6) Most importantly, one would have to prove that the source of nickel in the outflow is from that area of the fen receiving mine water. Given that stack emissions are a source of nickel in the outflow, physical removal of the material may not improve the problem.

The second reclamation option is enhancement of the natural recovery of the Birchtree fen. This is done through maintenance of the water table and adding soil amendments. As Eger et al. (1993) point out adding peat or other organic material to the contaminated area can extend the treatment life by providing new adsorption sites or by increasing the rate of sulphate reduction. This option is not recommended at this time because of the increased cost involved compared to option three. In addition, there is reason to believe the fen will recover naturally without the addition of amendments.

Therefore the recommendation outlined in this plan is:

- **to allow the wetland to recover naturally from the stress of metal contaminated mine water influent and monitor the progress of recovery by annual vegetation, soil, and water quality surveys.**

An aggressive monitoring and evaluation campaign is crucial in the recommended reclamation strategy. The proposed monitoring program is described in section 6.3.5. The monitoring program provides data for the evaluation of the reclamation objectives.

There are three principle reasons for this strategy. First, there is a strong possibility that the Birchtree fen will recover naturally. The Panel Wetland in Elliot Lake, Ontario, for example, is a thriving wetland that recovered naturally after a containment dam failed causing the discharge of uranium tailings (Dave' 1993). The wetland was covered by approximately 400 tons of tailings material. It was found that wetland vegetation quickly returned and over several years the wetland reestablished itself. The water quality of the wetland outflow continues to be monitored and remains below effluent limits for total dissolved metals including Fe, Ni, Cu, Zn, U, sulphate ($SO4^{2-}$) and Ra-226.

A second reason that natural recovery is the recommended reclamation option is research potential. There is a need for long-term data and research (Eger 1996, pers. comm.). Wetlands are being developed/constructed to be used as passive treatment alternatives to chemical treatment systems. Questions that remain include how long can a wetland act as a treatment system before its treatment capacity is exceeded. The Birchtree fen was effective in removing nickel in mine water over the 15 months of this study. It also appears to have effectively treated mine water for close to 30 years as the majority of the nickel is contained in an area relatively close to the mine water source. What remains to be seen is will the nickel stay bound and confined in this area. This type of data may be critical in support of or in opposition to using wetlands as an abandonment strategy to treat waste water.

Additionally, research on industrially-stressed lands in the Sudbury region identified many plant species tolerant of various levels of pollution (Heale 1991; Winterhalder, 1995). The Birchtree wetland site may have provided conditions for the evolution of metal tolerant plant species. This is valuable information as these plants may be introduced in reclamation projects in areas of similar climate and conditions.

The third reason for recommending natural recovery is cost effectiveness. Wetlands constructed for wastewater treatment or as natural treatment systems have been shown to be an effective, low-cost, low-maintenance treatment option for various wastewater streams including mine water. There is virtually no cost involved with leaving the system to recover naturally. Mitsch and Gosselink (1993) point out that, in general, a design that can use natural processes to achieve the objectives will yield a less expensive and more satisfactory solution in the long-run.

6.3.2.1 Contingency

If the monitoring program shows the fen is not recovering, a new strategy may be implemented. A contingency plan would begin by adding soil amendments to increase adsorption sites for nickel and maintenance of the water table to maintain hydrological conditions. A last resort would be the physical removal of the contaminated material if the above methods are ineffective. The contingency plan would be triggered if the monitoring program showed degrading water quality, trend to lower pH in water and soil, increased nickel at the fen outflow, or noticeable vegetation degradation.

6.3.3 Wetland Design

Because the Birchtree fen is a natural wetland, design is not discussed in detail here. However, certain aspects of wetland design are appropriate and worth noting including hydrology, vegetation, and soil.

Hydrology is the most important variable in wetland design. If the proper hydrologic conditions are developed, the chemical and biological conditions will respond accordingly (Mitsch and Gosselink 1993). Improper hydrology leads to the failure of many created wetlands and failure of reclamation strategies. Ultimately, the hydrologic conditions determine the wetland function.

Figure 4.1 shows a simple water balance for the Birchtree fen. Based on this information, the termination of mine water to the fen results in a decrease of 20 to 35% of water to the wetland. As a result of a reduction in water influent certain changes are expected. Over time the water table will drop and a general drying of the area will occur. Initially, reduced water levels may result in increased vegetative diversity as there are more dry land species than emergent species (Stewart 1996, pers. comm.). There will be a trend to ombrotrophic (bog) conditions as the only source of moisture to the wetland becomes precipitation and runoff from the surrounding water shed. In addition, invader species may move in to the site taking advantage of a new situation. However, in the long-term a trend towards ombrotrophic conditions implies reduced plant diversity and replacement of fen species (minerotrophic) by species adapted to bog conditions (Zoltai and Pollet 1979; Mitsch and Gosselink 1993).

Since removal of soil and vegetation is not recommended at this time active revegetation is not necessary. The surrounding wetland vegetation will act as a seed source to naturally revegetate the area (Hammer 1992). To develop a wetland that will ultimately be a low-maintenance one, natural successional processes need to be allowed to proceed. Often this means some initial period of invasion by undesirable species, but if proper hydrologic conditions are imposed, those invasions may be temporary (Mitsch and Gosselink 1993). If the affected area appears to be revegetating slower than what would be expected, some seeding may be needed.

Removal and replacement of contaminated soil in the Birchtree wetland is not recommended in this reclamation strategy. Over time, the change in hydrology may result in natural succession to ombrotrophic bog conditions and accumulations of *Sphagnum* peat as the dominant component of the organic layer. If soil amendments are required it should be of similar quality (organic content) and sufficient depth. Improper depth over the clay substrate may limit root and rhizome penetration and may be impermeable to water for plant roots (Mitsch and Gosselink 1993).

6.3.4 Implementation

A system to treat Birchtree Mine effluent is to be in operation by April 1, 1996, as per the operating licence for the Birchtree Mine development under The Environment Act. The reclamation plan should be initiated at this time to be consistent with Inco's policy of progressive decommissioning of sites impacted by mining activities.

6.3.5 Monitoring

An intensive monitoring program is recommended for the Birchtree fen reclamation plan. It is critical to monitor the performance of the fen over time to determine the success of the reclamation effort. Monitoring should begin in the spring of 1996. This monitoring program should include annual surveys of vegetation cover, soil chemistry, and surface water quality. In addition, weekly sampling of the fen outflow is required. This monitoring program follows the evaluation criteria outlined in the next section.

Weekly monitoring of the fen outflow for chemical parameters such as nickel and other metals, pH and conductivity is an easy method of monitoring fen performance as a polishing system (Eger 1996, pers. comm.). For example, increases in nickel content and/or decreases in pH signal that the fen is degrading as a polishing system and more active reclamation may be required.

Water quality surveys should include collection and analysis of pore water. This is water contained within the pores of the fen soil and could contain a significant quantity of soluble nickel. The amount of nickel contained in the Birchtree fen pore water was not determined in the above study. It is important to determine the fraction of nickel in the pore water because it is a soluble species and can be flushed through the system.

Measures of the properties of soils are useful in describing wetland structure, and provide clues to wetland function (Kent 1994). Monitoring chemical parameters such as pH, will provide a data base that will show trends in soil chemistry over time which is also an indication of wetland performance. Annual collection of soil samples for sequential extraction to determine species of nickel will show changes in how the nickel is bound in the soil. This will show if nickel previously bound to the substrate re-solubilizes. It must be noted that there may be tremendous variability in the results obtained from the soil samples and one should be careful to obtain enough samples for statistical analysis so that trends will be revealed (Eger 1996, pers. comm.).

The performance of the vegetation is an index of the suitability of the substrate for plant growth. The simplest measure of an individual plant is survival, i.e. whether the plant is dead or alive. Other measures include plant height, cover, including ground cover and canopy cover, reproduction, and productivity, all can be used as indicators of plant growth rate (Kent 1994).

6.3.6 Evaluation

Progress toward achieving reclamation goals should be periodically assessed on the basis of measurable criteria (Kent, 1994). Evaluation will provide the necessary information to make in-program adjustments to operational reclamation procedures. If monitoring over a period of time shows little significant progress to the stated objectives, steps to improve the situation can be implemented (soil amendments, active revegetation, etc.). Criteria selected for ecological evaluations of reclamation should be those that will provide the most information on system performance at the least cost (Boyum et al. n.d.).

The following evaluation method is adopted from Hunsburger and Michaud (1994) who developed a **Reclamation Success Evaluation System (RSES)**. The RSES is a tool for evaluating the success of Abandoned Mine Lands sites that facilitates the comparison of reclamation efforts at different sites because it can be applied to a wide variety of sites, can be conducted by one person, and the results are easily interpreted.

In the Birchtree fen reclamation strategy, three criteria are selected to measure success of a reclamation effort: (1) Surface Water Quality, (2) Soil Chemistry, and (3) Success of the Vegetative Cover.

6.3.6.1 Evaluation of Surface Water Quality

Water quality within the fen will be compared to water quality at the fen outflow. A trend towards increased nickel levels in the outflow may indicate the release of metals from the fen. There is a good data base of fen water quality during the period of mine water discharge and this will be compared to monitoring post-mine water discharge.

PH is an important parameter to monitor because it is a good indicator of the performance of the fen. A trend towards lower pH suggests more nickel will become soluble and contribute to increased nickel at the fen outflow. This suggests a decrease in the ability of the fen to remove nickel and should signal a revisit to the reclamation options.

6.3.6.2 Evaluation of Soil Chemistry

Soil samples will be collected at locations within the Birchtree fen and analyzed for the various chemical parameters outlined in the Methods section. Samples will also be collected for analysis of nickel forms in the substrate as described in the Methods section.

6.3.6.3 Evaluation of Vegetative Cover

Good vegetative cover leads to the formation of an organic layer and is visually correlated with successful reclamation (Hunsburger and Michaud 1994). Common parameters used to measure vegetation success include percent cover, density, and frequency of cover. The percentage of vegetation cover (determined by Notched Boot Method) was used for the RSES (Hunsburger and Michaud 1994). This method was chosen because it fit the overall objectives of the RSES guidelines of 1) performed easily by one person, 2) produced reliable results that were easily interpreted, and 3) did not an require extensive amount of time.

Hunsburger and Michaud (1994) and Boyum et al. (n.d.) also suggest other possible criteria to evaluate the success of a reclamation program including soil microbial population, vegetative species, vertebrate and invertebrate communities. These criterion may be incorporated at some point, however they require more extensive time, cost and/or resources for their implementation, measurement and evaluation (Hunsburger and Michaud 1994). The idea of using the above parameters is that it is easy, can be conducted by one person, and provides reliable information. It is effective as an indicator of potential problems and where required a more detailed evaluation can be carried out.

6.4 Summary

A wetland reclamation strategy was presented for the Birchtree fen. As of April 1, 1996, the mine will no longer use the wetland as a discharge sink. As a result, Inco is required to develop decommissioning plans in compliance with the decommissioning strategy for the Birchtree Mine operation (Inco 1993).

The main objective of the reclamation strategy is the recovery of the Birchtree fen to as natural a state as possible. To achieve this objective a passive reclamation approach is recommended, whereby the fen is allowed to recover naturally after the mine water effluent is prevented from entering the wetland.

The following points are critical to this reclamation strategy:

It is imperative that monitoring and evaluation programs are established. This is to ensure that the objectives are being met, and if necessary, to implement changes to the strategy in the event the strategy is not working. The monitoring program should include:

- water quality surveys to monitor trends in pH and nickel;
- soil chemistry surveys including parameters pH and metals;
- annual vegetation surveys to monitor changes in percent cover.

Monitoring the above parameters should be carried on for a period of five years. If this reclamation strategy is not successful a contingency plan would be implemented which may include the option to remove the soil in the contaminated area.

Kusler (1986) suggests that long-term success of most wetland restoration efforts or wetland enhancement projects in meeting specific goals is simply not known. Very specific goals have rarely been articulated prior to reclamation efforts. There has been very little post-project monitoring of vegetation, hydrology, fauna or other characteristics for public or private projects. Most of the monitoring to date has been short-term which provides only modest indication of long-term success. Monitoring and evaluation will determine the success of the Birchtree wetland reclamation strategy and this will add to resource base of wetland restoration efforts. In addition, the Birchtree wetland may be used as a demonstration project testing particular restoration and creation approaches.

7. CONCLUSIONS AND RECOMMENDATIONS

This dissertation studied the processes of wetlands that act to retain metals and allow wetlands to be effective passive treatment systems for mine wastewater.

The research effort focused on the Birchtree fen that has received neutral mine drainage containing elevated concentrations of nickel for almost 30 years. The objectives of the study were to determine the extent of nickel contamination in the Birchtree fen in terms of area and depth. An important aspect of this study included determination of the form of nickel to provide insight into the future fate of the metal. The above study provided a detailed site analysis which is incorporated into a reclamation strategy for the Birchtree fen. A detailed reclamation plan was also presented.

The following conclusions and recommendations were reached:

1) The data collected from soil and water sampling supports the conclusion that the Birchtree fen is an effective filter for the removal of nickel from Birchtree mine water.

2) Over the two summer field seasons 96.4% of the nickel entering the Birchtree fen was retained in the fen. Approximately 140 kg of nickel was deposited via mine water discharge. Approximately 150 kg of nickel was deposited over the entire fen by means of atmospheric deposition over 15 months.

2.1. Smelter emissions contributed less than 5 kg of nickel to the area of study in the Birchtree fen. However, when considering the entire area of the fen (approximately 95 ha) stack emissions contribute as much or more nickel to the fen.

3) The majority of nickel deposited from mine water discharge is confined to an area of approximately 1.8 ha adjacent to the fen inlet and is contained within the top 30 cm of the peat soil.

4) Nickel can be expected to flush through the fen during periods of peak runoff due to increased flow and reduced retention period. Consequently, increased levels of nickel in the fen outflow are expected in the spring and after heavy rains. This phenomenon was observed in the two field seasons, however, even during the heavy rains experienced in August 1995, the peak concentration of nickel was only 0.2 ppm.

5) Based on the sequential extraction performed on Birchtree fen soils, it was determined that 97 percent of the nickel captured in the Birchtree fen substrate is bound by various bonding processes and is unlikely to become remobilized in the future. However, nickel contained in the pore water of the fen soil was not determined and this could represent a significant source of soluble nickel. It is recommended that future surveys determine nickel in fen pore water.

6) Analysis of surface water from the two control fens show elevated levels of nickel in water collected in Control Fen #1 and background levels of nickel in Control Fen #2. The source of nickel in Control Fen #1 is atmospheric deposition. The two control sites show similar levels of nickel in the substrate. This would indicate that soil deposited from atmospheric emissions does not become bound in soil as does nickel from mine water. This suggests that nickel from stack emissions is in a more soluble form than nickel in mine water. Analysis of pore water is recommended to define the amount of nickel in pore water as this is a

soluble fraction.

7) Based on the rudimentary survey of Birchtree fen vegetation, it is unclear as to the impact of the mine water on fen vegetation. Presumably, certain species unable to tolerate metal-contaminated sites have not become established. However, conditions such as "die-back" and symptoms of nickel toxicity are not noticeable. The fen appears to be a vigorous and healthy wetland.

The following recommendations are derived from these conclusions:

1) A passive reclamation strategy is recommended for the Birchtree fen. The strategy is to allow the fen to recover naturally.

2) An intensive monitoring and evaluation program is critical to the success of the reclamation effort. The following parameters are recommended as part of the monitoring and evaluation process:

- Maintain monitoring water quality of the fen outflow, including parameter pH, and periodic flow measurements. This is a relatively easy means of monitoring the performance of the Birchtree wetland.

- Soil sampling should be carried out annually. Important parameters to be monitored include chemistry of the soil and pore water, and forms of nickel in the substrate.

- Evaluation of percent cover of vegetation.

Trends toward decreasing pH, increasing soluble nickel in the outflow, and degrading vegetation in the study area should signal that the fen is degrading and the strategy is not working. A revisit to the reclamation options is required.

3) Initiate Reclamation Strategy in 1996. The reclamation strategy should be carried on for five years.

4) Information gathered should be published and available in the public domain. The Birchtree fen represents a unique opportunity to study the natural recovery of a wetland used for long-term wastewater treatment.

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APPENDIX 1.1

Analysis of Water Quality in the Birchtree Fen

BIRCHTREE WETLAND STUDY
WATER QUALITY OF MINE EFFLUENT (FEN INFLOW)

DATE 1994		MINE WATER SOL.NI (PPM)	pH	Cu	Fe	Pb	Zn	As	Cd	SO4-	NITRATES
J											
F											
M											
A	6	8.64	7.2								
	13	0.13	10.2								
	25	13.52	7.6								
M	3	2.05	8.4								
	12	0.41	10.1								
	16										
	18										
	20	0.27	10							867	93.5
	24	2.94	8.3	0.01	0.01	0.01	0.01	0.01	0.01	1012	82.5
	26	0.06	10.3	0.01	0.38	0.01		0.01	0.01	296	27.5
	31	6.59	8.1	0.01	0.01	0.05	0.01	0.01	0.01	1141	99
J	3	3.48	8.5	0.01	0.07			0.01		1012	
	7	9.4	7.7							1017	99
	14	3.27	8.1								
	20	5.11	8.3	0.01	0.4	0.07		0.01			
	27	7.89	8	0.01	0.19	0.03		0.1		1038	
	30	4.95	8.7								
J	1	6.3	7.7	0.02	0.02	0.01	0.02	0.14	0.01		
	6	1.53	7.7							848	86
	11	6.16	8.2								
	15	7.15	8	0.01	0.02	0.02	0.01	0.13	0.01		
	18	7.46	8							943.2	65.6
	21	7.96	8								
	27	7.98	8.3								
A	2	10.32	8.2	0.02	0.02	0.01	0.01	0.03		1140	77.4
	8										
	10	0.36	9.9	0.01	0.01	0.01	0.01	0.05	0.01		
	12										
	17	0.65	9.7								
	22	0.16	9.7	0.01	0.02	0.02	0.01	0.05			
	26	2.51	7.7								
	30	2.16	7.6	0.01	0.01	0.05	0.01	0.06	0.01		
S	1	4.28	7.5	0.01	0.01	0.05	0.01	0.07	0.01	1292	65.2
	12	2.28	8.5	0.02	0.01	0.04	0.01	0.1	0.01	1365	69.1
	19	10.24	8	0.01	0.64	0.02	0.01	0.05	0.01	1057	89.8
	26	3.59	8.4	0.01	0.11	0.02	0.01	0.08	0.01	837	65.6
O	3	3.92	8	0.01	0.05	0.04	0.01	0.07	0.01	996.6	45.8
	11	14.25	7.8	0.05	0.41	0.07	0.05	0.11	0.05	1092	66.4
	17	1.54	7.8	0.05	2.51	0.05	0.05	0.05	0.05	922.8	66.9
	24	0.64	9.5	0.01	0.01	0.02	0.01	0.06	0.01	1012	63.8

	31	9.5	7.8	0.01	0.06	0.07	0.01	0.09	0.02	1140	112.2
N	21	4.21	7.8	0.01	0.16	0.01	0.01	0.05	0.01	1088	65.6
D	1	19.16	8.7	0.01	0.72	0.23	0.01	0.24	0.5	1621	48.8
	6	7.09	8.1	0.01	0.27	0.46	0.01	0.66	0.59	1231	53.5
	13	0.91	9.2	0.01		0.1	0.01	0.06	0.02	976	19.4
	19	5.89	8.7	0.01	0.01	0.04	0.01	0.01	0.01	1174	15.8
	28	0.22	9.7	0.01	0.36	0.02	0.01	0.05	0.01	1275	18.9
J	5	0.17	9.5	0.01	0.4	0.01	0.01	0.05	0.01	1041	10.56
	10	0.3	10.5	0.01	0.06	0.01	0.01	0.05	0.01	1971	13.2
	19	1.44	8.4	0.01	0.13	0.01	0.01	0.07	0.01	1446	19.9
	25	0.94	8.3	0.01	0.06	0.01	0.01	0.1	0.01	608	19.8
	31	3.76	8.3	0.05	0.07	0.06	0.05	0.2	0.05	989	15.4
F	8	0.08	10.7	0.05	0.05	0.05	0.05	0.05	0.05	704	14.1
	13	0.56	8.8	0.01	0.03	0.05	0.01	0.15	0.01	681	11.9
	20	1.82	8.5	0.01	0.01	0.05	0.01	0.26	0.05	1206	15.4
	27	3.84	7.8	0.01	0.83	0.05	0.05	0.44	0.05	521	59.8
M	7	1.36	8.6	0.01	0.03	0.05	0.05	0.15	0.05	754	10.56
	14	0.21	9.8	0.01	0.02	0.01	0.05	0.02	0.05	860	14.52
	22	1.45	8.5	0.01	0.01	0.05	0.05	0.05	0.05	775	66.4
	27	4.41	8.1	0.01	0.05	0.05	0.03	0.08	0.01	1073	55.4
A	4	12.12	7.5	0.01	0.01	0.05	0.03	0.1	0.02	957	96.8
	10	16.29	7.6	0.01	0.01	0.06	0.04	0.12	0.01	1043	92.8
	17	12.44	7.5	0.01	0.01	0.03	0.02	0.24	0.01	809	62.3
	24	11.99	7.7	0.01	0.01	0.05	0.04	0.37	0.01	959	46.6
M	3	11.03	7.6	0.01	0.06	0.02	0.01	0.07	0.01	1220	87.1
	5	12.62	7.3								
	8	19.87	8.1	0.01	0.05	0.06	0.02	0.09	0.02	1354	93.5
	11	4.51	8.7								
	15	10.34	8.3	0.01	0.05	0.04	0.01	0.16	0.01	1142	65.6
	18	5.08	7.8	0.01	0.04	0.08	0.04	0.13	0.02		
	23	5.02	8.5	0.01	0.03	0.01	0.02	0.14	0.01	1088	67.88
	26										
J	6	1.46	8.8	0.01	0.03	0.05	0.01	0.06	0.01	686	34.8
	8	3.59	8.3								
	12	2.83	8.2	0.01	0.21	0.03	0.01	0.06	0.01	1020	105.6
	17	0.75	9.8								
	20	2.98	8.3	0.01	0.04	0.03	0.02	0.07	0.01	1044	89.3
	27	0.17	9.6	0.02	0.06	0.1	0.01	0.21	0.02	955	37.4
J	3	1.54	8.3	0.03	0.07	0.06	0.02	0.09	0.01	853	32.6
	10	2.68	7.6	0.01	0.09	0.06	0.01	0.1	0.01	997	83.6
	17	15.94	7.8	0.01	0.09	0.03	0.01	0.09	0.02	1226	80.5
	23										
	26	11.66	7.8	0.01	1.78	0.05	0.01	0.11	0.01	1110	26
	31	13.52	7.9	0.02	0.86	0.04		0.09	0.01	1245	53
A	8	5.28	7.9	0.01	0.16	0.03	0.19	0.02	0.01	2153	116
	11	2.68	7.6								
	15	8.76	8.1	0.01	0.01	0.02	0.03	0.03	0.01	953	708
	17	1.56	8.7								
	22	0.1	10.8	0.04	2.3	0.05	0.01	0.06	0.01	811	92
	28	0.13	10.1	0.02	0.05	0.03	0.01	0.09	0.01	1038	12.8
S	2	0.81	8.6	0.02	0.07	0.03	0.01	0.08	0.01	1071	55.9
	Mean	5.12	8.38	0.01	0.23	0.05	0.02	0.10	0.04	1049	67.91
	Std	4.87	1.25	0.01	0.49	0.06	0.03	0.11	0.10	292	90.84
	Max.	19.87	11	0.05	2.51	0.46	0.19	0.66	0.59	2153	708.00
	Min.	0.06	7.20	0.01	0.01	0.01	0.01	0.01	0.01	296	10.56
	No.	85	85	63	62	62	58	63	58	60	58

BIRCHTREE WETLAND STUDY
WATER QUALITY OF FEN OUTFLOW 1994-95 FIELD

			FEN OUTFLOW					
DATE	SOL.NI	pH	Cu	Fe	Pb	Zn	As	Cd
JAN 1994								
FEB								
MAR								
APRIL								
MAY								
	0.07	10.1	0.01	0.26	0.01	0.01		0.01
	0.06	7.1						
	0.06	7.1	0.01	0.01	0.01	0.01	0.01	0.01
	0.04	7.2	0.01	0.13	0.01		0.01	0.01
	0.05	7.2						
JUNE	0.02	7	0.01	0.26			0.01	
	0.07	6.8						
	0.06	7.3						
	0.04	7.1	0.01	0.19	0.02		0.06	
	0.05	7.2	0.01	0.89	0.05		0.07	
	0.05	7.3						
JULY	0.06	7						
	0.07	7.3						
	0.08	7.4						
	0.06	7.3	0.01	0.57	0.05	0.01	0.1	0.02
	0.01	7.5						
	0.02	7.4						
	0.07	7.7						
AUG	0.09	7.6	0.01	0.84	0.01	0.01	0.03	
	0.07	9.4	0.01	0.36	0.02	0.01	0.07	0.01
	0.08	7.4	0.01	0.37	0.03	0.01	0.09	0.01
	0.06	7.4						
	0.01	7.5	0.01	0.71	0.01	0.01	0.14	
	0.04	7.5						
	0.07	7.4	0.01	0.42	0.05	0.01	0.01	
SEPT	0.04	7.5	0.01	0.01	0.05	0.01	0.06	0.01
	0.05	7.4	0.01	0.13	0.04	0.01	0.08	0.01
	0.05	7.4	0.01	0.11	0.04	0.07	0.01	0.01
	0.04	7.6	0.01	0.08	0.03	0.01	0.08	0.01
OCT	0.11	7.6	0.05	0.05	0.01	0.01	0.05	0.01
	0.14	7.6	0.05	0.05	0.05	0.05	0.06	0.05
	0.07	7.7	0.05	0.06	0.05	0.05	0.06	0.05
	0.09	7.6	0.01	0.11	0.02	0.01	0.03	0.01

NOV				FROZEN					
DEC									
1995									
FEB									
MAR									
APR									
	24	0.2	7	0.01	0.11	0.03	0.01	0.26	0.01
MAY	3	0.12	7.2	0.01	0.29	0.01	0.01	0.01	0.01
	5	0.11	7						
	8	0.12	6.9	0.01	0.26	0.04	0.02	0.01	0.01
	11	0.09	7.1						
	15	0.06	7.2	0.01	0.15	0.03	0.01	0.08	0.04
	18	0.08	7.6						
	23	0.08	7.2	0.01	0.18	0.01	0.01	0.06	0.01
	26								
JUNE	6	0.08	7.4	0.01	0.42	0.02	0.01	0.03	0.01
	8	0.11	7.3						
	12	0.11	7.3	0.04	0.19	0.02	0.01	0.01	0.01
	17	0.13	7						
	20	0.1	7.4	0.01	0.75	0.03	0.02	0.14	0.02
	27	0.1	7.4	0.01	0.73	0.07	0.01	0.23	0.01
JULY	3	0.12	7.4	0.02	0.56	0.06	0.01	0.03	0.01
	10	0.06	7.4	0.01	0.47	0.01	0.01	0.01	0.01
	17								
	23								
	26	0.1	7.5	0.01	0.4	0.01	0.01	0.01	0.01
	31	0.08	7.2	0.01	0.98	0.01		0.01	0.01
AUG	8	0.08	7.2	0.01	0.46	0.01	0.01	0.01	0.01
	11								
	15	0.08	7.1	0.01	0.23	0.01	0.02	0.01	0.01
	17	0.09	7.1						
	22	0.08	7.1	0.01	0.38	0.02	0.01	0.01	0.01
	28	0.1	7.3	0.01	0.47	0.03	0.01	0.03	0.01
	2	0.1	7.3	0.02	0.53	0.03	0.01	0.05	0.01
Mean		**0.0765**	**7.39**	**0.01**	**0.33**	**0.02**	**0.01**	**0.05**	**0.01**
S.D.		**0.0334**	**0.49**	**0.01**	**0.26**	**0.01**	**0.01**	**0.05**	**0.01**
Max.		**0.2**	**10.1**	**0.05**	**0.98**	**0.07**	**0.07**	**0.26**	**0.05**
Min.		**0.01**	**0.49**	**0**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
No.		**60**	**60**	**42**	**41**	**40**	**36**	**40**	**35**

APPENDIX 1.2

Analysis of Water Quality in the Control Fens

BIRCHTREE WETLAND IMPACT STUDY
CONTROL SITES

WATER QUALITY

CONTROL FEN #1

	DATE	SOL.NI	pH	Cu	Fe	Pb	Zn	As	Cd	SO4-	NITRATES
1994	1994										
	FEB										
	MAR										
	APR										
	MAY	0.11	7.4	0.01	0.3	0.01	0.01	0.04	0.01		
	JUNE	0.02	7.6	0.01	0.26	0.01	0.01	0.07	0.01		
	JULY	0.45	7.4	0.01	0.3	0.01	0.01	0.03	0.01		
	AUG	0.56	7.4	0.01	0.62	0.01	0.01	0.03	0.01		
	SEPT	0.2	7.5	0.01	0.55	0.02	0.01	0.01	0.01		
1995	1995										
	FEB										
	MAR										
	APR										
	MAY	0.48	7.1	0.02	0.34	0.01	0.01	0.03	0.01	300	0.29
	JUN	0.63	7.2	0.01	0.69	0.01	0.01	0.04	0.01		
	JUL	0.79	8.6	0.02	0.11	0.02	0.01	0.02	0.01	355	0.44
	AUG	0.51	7.6	0.01	0.61	0.02	0.01	0.01	0.01		
	SEPT	0.3	7.4	0.01	0.3	0.01	0.01	0.01	0.01	80	0.5
	avg	0.405	7.52	0.012	0.408	0.013	0.01	0.029	0.01	245	0.41
	max	0.79	8.6	0.02	0.69	0.02	0.01	0.07	0.01	355	0.5
	min	0.02	7.1	0.01	0.11	0.01	0.01	0.01	0.01	80	0.29
	std	0.23	0.39	0.00	0.18	0.00	0.00	0.02	0.00	118.81	0.09

WATER QUALITY

CONTROL FEN #2

	SOL.NI	pH	Cu	Fe	Pb	Zn	As	Cd	SO4-	NITRAT
1994										
FEB										
MAR										
APR										
MAY	0.01	6.4	0.01	0.06	0.01	0.01	0.01	0.01	2.6	0.9
JUNE	0.01	6.1	0.01	0.04	0.03	0.01	0.05	0.01	2.28	1.1
JULY	0.01	7.2	0.02	0.37	0.04	0.02	0.04	0.01	1.95	0.88
AUG	0.02	7	0.01	0.45	0.04	0.01	0.08	0.01	1.89	1.1
SEPT	0.02	7	0.02	0.31	0.03	0.01	0.02	0.01	2.2	0.91
1995										
FEB										
MAR										
APR										
MAY	0.02	6.8	0.01	0.3	0.02	0.01	0.02	0.01	2.6	0.76
JUN	0.03	6.9	0.01	0.28	0.01	0.01	0.01	0.01	2.7	0.65
JUL	0.04	7.1	0.02	0.6	0.07	0.01	0.06	0.01	2.4	0.88
AUG	0.02	7	0.02	0.34	0.04	0.01	0.05	0.01	1.91	0.8
SEPT	0.01	7	0.01	0.22	0.01	0.01	0.02	0.01	2.6	0.9
avg	0.019	6.85	0.014	0.297	0.03	0.011	0.036	0.01	2.313	0.888
max	0.04	7.2	0.02	0.6	0.07	0.02	0.08	0.01	2.7	1.1
min	0.01	6.1	0.01	0.04	0.01	0.01	0.01	0.01	1.89	0.65
std	0.009	0.323	0.004	0.158	0.017	0.003	0.022	1E-10	0.298	0.130

APPENDIX 2

Soil Sampling Results from Birchtree Fen

Table 4.3.1. Results of soil sampling in Birchtree wetland, **0 - 30 cm**, summer field season 1994 and 1995. BT1A-A refers to Birchtree wetland Transect line 1, point A, Sample A (0-20 cm).

Date	Depth (cm)	Sample No.	pH	Eh	Cond. mS/cm	Ni %	Cu %	Fe %	Pb %	Zn %	As %
94-08-16	0-10	BT1A-A	6.7	25	0.5	0.38	<.01	4.6	<.01	<.01	0.01
	0-10	BT1B-A	6.7	38	1.07	0.50	0.01	4.1	0.04	0.01	<.01
	10-30	BT1B-B	6.3	---	0.12	0.02	<.01	4.4	0.01	<.01	0.01
	0-20	BT1C-A	6.7	80	0.83	0.46	<.01	1.8	<.01	.01	<.01
95-08-01	0-30	BT1D-A	6.3	52	---	0.71	<.01	3.5	<.01	<.01	<.01
	0-30	BT1E-A	6.4	45	---	1.13	<.01	1.55	<.01	<.01	<.01
	0-20	BT2B-A	7.1	78	2.30	1.54	0.01	4.0	<.01	0.01	0.01
	20-40	BT2B-B	7.4	35	0.47	0.35	0.01	4.9	<.01	<.01	0.01
	0-20	BT2C-A	6.7	50	0.37	0.45	0.01	0.88	<.01	0.01	0.01
	20-40	BT2C-B	6.9	125	0.11	0.48	<.01	0.33	<.01	---	0.01
95-08-01	0-30	BT2D-A	6.5	56	0.32	0.66	<.01	1.08	<.01	<.01	<.01
95-09-14	0-30	BT2D'-A	6.2	36	0.55	0.61	0.01	1.44	0.08	<.01	<.01
95-08-01	0-30	BT2E-A	6.6	77	0.56	0.72	<.01	2.27	0.05	<.01	<.01
95-09-14	0-30	BT2E'-A	6.3	45	1.10	0.48	0.01	2.93	0.12	<.01	<.01
	0-20	BT3B-A	7.9	110	1.90	1.28	0.02	4.6	<.01	0.01	0.01
	0-20	BT3C-A	6.5	---	0.30	0.59	0.01	1.59	0.01	0.01	0.02
94-08-24	0-30	BT3D-A	6.9	220	0.33	1.03	0.08	6.00	0.01	---	<.01
95-09-14	0-30	BT3D'-A	6.5	73	0.60	0.72	<.03	6.23	<.01	<.01	<.01
	0-30	BT3E-A	6.9	180	1.40	0.59	0.06	6.09	0.01	---	0.01
	0-30	BT3E-B	7.2	220	0.10	0.43	0.04	5.77	<.01	---	<.01
95-09-14	0-30	BT3E'-A	6.3	150	1.09	0.34	<.01	6.64	<.01	<.01	<.01
94-08-16	0-10	BT4B[N]	9.1	245	1.24	0.13	0.01	5.58	0.01	0.01	0.01
	0-60	BT4B-A[O]	7.1	---	---	1.14	0.03	4.44	0.01	0.01	0.02
	0-30	BT4C-A	6.7	1.30	5.01	0.97	0.07	6.34	0.01	0.01	0.02
	0-20	BT4D-A	6.9	210	3.15	0.82	0.04	6.78	0.03	0.01	0.02
	20-40	BT4D-B	7.1	217	3.35	0.58	0.05	6.86	0.02	0.01	0.02
	0-20	BT4E-A	6.8	145	2.31	0.45	0.03	7.44	0.03	0.01	0.04
	20-40	BT4E-B	6.7	180	0.92	0.35	0.02	4.78	0.03	0.01	0.01
94-08-29	0-30	BT5A-A	7.1	---	---	0.17	0.01	3.88	0.01	---	<.01

	0-30	BT5B-A	7.2	180	---	0.82	0.03	4.56	0.01	---	0.01
94-08-24	0-20	BT5C-A	6.8	25	0.57	0.68	0.01	4.25	0.01	---	0.01
	20-40	BT5C-B	6.4	78	1.5	0.44	0.03	4.69	<.01	---	<.01
95-08-01	0-30	BT5D-A	6.7	41	0.86	0.02	<.01	5.08	<.01	<.01	<.01
94-08-26	0-30	BT6A-A	6.6	190	2.85	0.34	0.01	2.21	<.01	---	0.01
	0-30	BT6B-A	6.8	250	0.30	0.33	0.02	2.15	0.01	---	<.01
	0-30	BT6C-A	6.0	260	0.04	0.09	0.02	1.73	<.01	---	<.01

[N] Surface sediment [O] Sample represents depth of 0-60 cm. Unable to obtain a core.

Table 4.3.2 Results of soil sampling in Birchtree wetland at depths greater than 30 cm. Summer field seasons 1994 and 1995.

Date	Depth (cm)	Sample No.	pH	Eh	Cond. (mS/cm)	Ni %	Cu %	Fe %	Pb %	Zn %	As %
94-08-16	10-40	BT1A-B	6.5	—	—	0.02	0.01	5.1	0.03	<.01	<.01
	40-70	BT1A-C	6.5	—	—	0.04	<.01	5.5	0.01	<.01	0.01
	40-90	BT1B-C	6.9	—	—	0.02	0.01	4.7	<.01	<.01	<.01
	60-90	BT1C-C	6.8	—	—	0.02	0.01	4.6	0.01	<.01	<.01
95-08-01	30-60	BT1D-B	6.3	25	0.10	0.05	<.01	4.47	<.01	<.01	<.01
	60-90	BT1D-C	6.2	29	0.56	0.07	<.01	1.28	0.08	<.01	<.01
	30-60	BT1E-B	5.7	61	0.35	0.92	<.01	0.27	0.02	<.01	<.01
	60-80	BT1E-C	6.3	46	0.98	0.06	<.01	0.24	<.01	<.01	<.01
94-08-16	45-65	BT2B-C	7.4	—	0.45	0.05	<.01	4.7	0.01	<.01	<.01
	40-60	BT2C-C	6.7	50	0.37	0.03	0.01	5.40	0.01	<.01	<.01
95-08-01	30-60	BT2D-B	6.3	25	1.08	0.39	<.01	1.59	<.01	<.01	<.01
	35-60	BT2D'-B	6.3	45	0.42	0.03	<.01	5.14	<.01	<.01	<.01
95-08-01	30-60	BT2E-B	—	48	1.40	0.02	<.01	5.74	0.38	<.01	<.01
94-08-16	30-50	BT3B-C	6.6	75	—	0.12	0.01	4.72	0.01	0.01	0.01
	30-50	BT3C-B	6.7	60	3.3	0.13	0.01	5.70	0.01	0.01	0.01
	30-60	BT3D-B	6.8	211	0.20	0.47	0.01	2.32	<.01	—	<.01
95-09-14	35-60	BT3D'-B	6.5	18	0.68	0.11	<.01	5.50	<.01	<.01	<.01
	30-60	BT3E'-B	5.9	27	0.64	0.1	<.01	5.42	<.01	<.01	<.01
94-08-16	30-40	BT4C-B	6.7	120	3.36	0.38	0.01	4.62	0.01	0.01	0.01
	40-70	BT4C-C	6.4	210	3.15	0.06	0.01	5.07	0.01	0.01	0.01
	50-80	BT4D-C	6.6	160	0.77	0.36	0.02	4.83	0.02	0.01	0.01
	50-80	BT4E-C	6.0	260	1.93	0.08	0.01	4.06	0.03	0.01	0.01
	30-60	BT5A-B	6.5	—	—	0.14	0.01	3.88	0.01	—	<.01
94-08-29	60-80	BT5A-C	6.6	—	—	0.06	0.02	5.55	0.01	—	<.01
	30-60	BT5B-C	6.7	—	—	0.13	0.01	5.34	0.01	—	<.01
94-08-24	30-70	BT5C-C	6.7	45	—	0.08	0.01	5.75	0.01	—	<.01
94-08-26	30-70	BT6A-C	6.6	—	—	0.35	0.05	5.71	0.01	—	<.01
	30-60	BT6B-C	6.5	—	—	0.04	0.01	5.61	<.01	—	<.01
	20-40	BT6C-B	6.6	120	2.58	0.08	0.01	2.70	0.01	—	<.01
	40-70	BT6C-C	6.5	35	2.60	0.04	0.01	5.73	0.01	—	<.01

APPENDIX 3

Vegetation Species Occurence in the Birchtree Fen

SPECIES OCCURENCE AT FEN SUBSITE[1] AND BIRCHTREE FEN

STRATA	FEN SUBSITE	BT FEN
Trees	*Picea mariana* *Populus tremuloides*	*Picea mariana* *Populus*
tremuloides		
	Larix laricina	*Larix laricina*
Tall Shrubs	*Betula glandulosa*	*Betula glandulosa*
	Ledum groenlandicum	*Ledum*
groenlandicum		
	Ribes spp *Salix spp*	*Ribes lacustre* *Salix pedicellaris, S.discolor, S.*
S. lutea, alaxensis, S.		
		planifolia, S. pellita.
	Sheperdia canadensis	
Dwarf Shrubs/ Herbs	*Arctostaphylus uva-ursi* *Aster spp* *Carex spp*	*Carex spp* *Epilobium*
angustifolium		
	Equisetum spp *E. sylvaticum* *E. variegatum* *Fragaria vesca* *Galium spp* *Graminae spp*	*Equisetum fluviatile* *Agrostis stolonifera, Phragmites*
communis,		
		Calamagrostis spp. *Hordeum jubatum*
	Juncus spp	*Juncus nodosus, J. brevicaudatus*
	Linnaea borealis *Mitella nuda* *Oxycoccus microcarpus*	*Linnaea borealis* *Oxycoccus*
microcarpus		
	Parnassia multiseta	

	Petasites sagitattus	
	Picea mariana	*Picea mariana*
	Pyrola spp	
	Ranunculus spp	
		Rumex occidentalis
		Sonchus arvensis
	Spiranthes romanzofflana	
	FEN SUBSITE	BT FEN
		Typha latifolia
	Vaccinium vitis-idaea	
Bryophytes	*Aulacomnium palustre*	*Aulacomnium*
palustre		
	Blepharstoma trichophyllum	
		Bryum
pseudotriquetrum		
	Caillergon giganteum	
	C. richardsonii	
	Ceratodon purpureus	
	Drepanocladus exannulatus	
	D. revolvens	
	Hypnum pratense	
	Meesla tritaria	
	M. triquetra	
	Pleurozium schreberi	
	Pohila nutans	*Pohila nutans*
	Ptillum crista-castrensis	
	Sphagnum warnstorfil	
	Tomenthypum nitens	*Tomenthypum*
nitens		
	Tritomaria quinquedentata	

[1]Source: Phillips and Slaney, 1981

APPENDIX 4

Summary of Thompson Airport Climatological Data

Table VI-2.1 - Summary of Thompson Airport Climatological Data

Parameter	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Temperature (oC)													
Mean Daily Maximum	-19.5	-14.3	-5.6	4.6	13.2	19.3	22.6	20.7	12.6	4.2	-7.2	-17.1	2.8
Mean Daily Minimum	-30.6	-27.9	-21.0	-9.5	-0.6	5.2	8.8	6.9	1.7	-4.2	-16.5	-27.3	-9.6
Extreme Maximum													
Extreme Minimum													
Mean Daily	-25.0	-21.0	-13.3	-2.4	6.3	12.3	15.7	13.8	7.2	0.1	-11.8	-22.1	-3.4
No. of Years	23	23	23	24	24	24	24	24	24	23	24	24	
Precipitation													
Rainfall (mm)	0.1	0.2	1.3	6.0	30.7	69.0	84.3	77.5	59.3	21.3	1.7	0.3	351.7
Snowfall (cm)	22.5	15.8	21.6	23.3	15.9	2.6	0.0	0.2	3.9	27.2	35.9	32.0	200.9
Total Precipitation (mm)	20.3	13.9	21.3	28.0	45.8	71.5	84.3	77.7	63.4	47.5	33.8	28.1	535.6
Maximum Precipitation	40.6	30.7	46.1	63.7	92.3	166.1	210.4	132.0	174.4	91.4	99.9	62.2	691.6
Minimum Precipitation	6.2	2.8	8.2	7.7	1.0	22.5	25.9	10.0	15.4	17.6	13.3	9.5	383.2
Max. Daily Rainfall	0.8	1.8	20.6	22.6	34.3	46.4	52.6	54.6	62.0	31.0	13.7	1.8	62.0
Max. Daily Precipitation	14.5	11.4	21.0	24.1	34.3	46.4	52.6	54.6	62.0	45.0	28.3	15.8	62.0
No. of Years	23	22	23	24	24	24	24	23	24	23	23	24	
Lake Evaporation (mm)													
Maximum					100.7	157.6	159.6	132.2	73.4				
Minimum					100.7	95.7	120.1	73.5	46.4				
Estimated Mean Lake Evaporation					50	128	135	110	57				480
No. of Years	-	-	-	-	1	11	20	18	6	-	-	-	

(Source - AES CD-ROM database, 1967 to 1990 period of record)

Source: SEACOR Environmental Engineering Inc. (1996)

SUMMARY OF PRECIPITATION DATA IN THOMPSON 1990 - 1995

TOTAL PRECIP (mm) 1990-1995

Year	Month	Total Precip (mm)	Year	Month	Total Precip (mm)
1990	J	18	1993	J	5.3
	F	13.2		F	21.8
	M	11.3		M	19.9
	A	50.5		A	15.5
	M	2.8		M	37.5
	J	75.8		J	87.6
	J	61		J	68.8
	A	27.6		A	74.5
	S	15.4		S	37.6
	O	54.6		O	39.2
	N	99.9		N	25.2
	D	21		D	9.7
1991	J	20.8	1994	J	9.3
	F	6.4		F	17.7
	M	6.8		M	43.2
	A	78		A	1.4
	M	39.7		M	36.4
	J	93.3		J	39.2
	J	58.8		J	63
	A	59.2		A	26.4
	S	53.6		S	37.2
	O	23		O	35
	N	51.7		N	45.3
	D	36.9		D	17.4
1992	J	16.1	1995	J	33.2
	F	20.9		F	17.5
	M	21.3		M	4.6
	A	13.8		A	23
	M	45.9		M	10.2
	J	70.1		J	39.6
	J	37		J	112.4
	A	21.5		A	110.9
	S	90.5		S	21.7
	O	26		O	28.6
	N	17.2		N	26.1
	D	16.2		D	43.8