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Volume 3-Chapter 4

WATER RESOURCES

Minnesota Environmental Quality Board
Regional Copper-Nickel Study

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Minnesota Environmental Quality Board
Regional Copper-Nickel Study
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REGIONAL COPPER-NICKEL STUDY REPORT OUTLINE

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- Chapter 1 Historical Perspective
- Chapter 2 Study Goals and Objectives
- Chapter 3 Study Region and Copper-Nickel Resources
- Chapter 4 Copper-Nickel Development Alternatives
- Chapter 5 Environmental Impacts
- Chapter 6 Socio-Economics Impacts
- Chapter 7 Report Organization and Supporting Documentation

Volume 2 - Technical Assessment
- - Introduction and Summary to Volume
- Chapter 1 Exploration
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- Chapter 14 Mineral Economics
- Chapter 15 Regional Economics
- Chapter 16 Local Economics
- Chapter 17 Copper-Nickel Development Profitability

ABBREVIATIONS

ac-ft/yr - acre-feet per year
As - Arsenic
BWCA - Boundary Waters Canoe Area
Cd - Cadmium
CEU - Copper Equivalent Unit
cfs - cubic feet per second
Co - Cobalt
CSI - Calcite Saturation Index
Cu - Copper
EPA - Environmental Protection Agency
ft - foot
gal - gallon
gpm - gallons per minute
ha - hectare
Hg - mercury
kg - kilogram
km - kilometer
MDH - Minnesota Department of Health
MDNR - Minnesota Department of Natural Resources
MEQB - Minnesota Environmental Quality Board
MPCA - Minnesota Pollution Control Agency
MRRC - Mineral Resources Research Center, University of Minnesota
mg - milligram
mi - mile
min - minute
mtpy - metric tons per year
N - Nitrogen
Ni - Nickel
P - Phosphorus
Pb - lead
ppb - parts per billion
ppm - parts per million
Q - flow (see Table 7 for additional definitions)
SO_2 - Sulfur dioxide
SO_4 - Sulfate
TSI - Trophic State Index
ug/l - micrograms per liter
USGS - United States Geological Survey
yr - year
Zn - Zinc

Volume 3-Chapter 4 WATER RESOURCES

4.1 INTRODUCTION AND SUMMARY OF FINDINGS

4.1.1 Introduction

The prospect of major copper-nickel development and the accompanying growth in human settlement in northeastern Minnesota clearly raises the potential for major impacts on the region's water resources. It is the purpose of this report to characterize existing water resources and provide a preliminary assessment of these impacts, which include water use, water quality, aquatic ecosystems, and legal standards.

4.1.1.1 Basic Issues. A variety of water use issues are raised in terms of: water resource conservation; competition over limited regional sources of water for industrial, municipal, recreational, and fisheries and wildlife uses; regional water management and supply systems; need for large storage reserviors; and changes in natural drainage patterns and flow conditions. Copper-nickel development, like taconite development, is a water intensive industry and because of the large land areas affected by such development, significant watershed changes will occur. The combination of limited headwater resources, large users (both existing and potential new users), and high natural variability in watershed discharge may cause conflicts and require strategies for regional planning, coordinated watershed management, and multiple use supply systems. Management techniques that may be required include water use reduction, water storage capabilities to minimize the withdrawal of water during droughts, and the timing of discharges.

This chapter describes typical amounts of water used and managed within the development area (the mine, wastepiles, processing plant, tailing basin, smelter, refineries and undisturbed watershed between and immediately surrounding these facilities) under various climatic conditions and changes in stream flow conditions due to direct or indirect water withdrawals and discharges.

A variety of water quality concerns are raised because of: the large volume of water used during the mining, processing, smelting and refining of copper, nickel, and other valuable minerals; the large land areas disturbed by such activities; the large quantities of waste rock and tailings requiring on-land disposal; and the sulfide composition of the minerals in question. These concerns are compounded by the very high quality and sensitivity of most surface waters in the region; the ubiquitous distribution of lakes, streams, and wetlands in and near the resource area; the proximity of the resource area to water-based recreational resources (especially the Boundary Waters Canoe Area); and the increasing acidification of regional water (especially poorly buffered headwater lakes and streams) due to acid rain. In terms of copper-nickel development, potential water contaminants include copper, nickel, cobalt, zinc, processing reagents, sulfates, and hydrogen ions (acidity). Other parameters of potential concern, should they appear in greater quantities than are now indicated, include arsenic, lead, mercury, cadmium and silver. This chapter characterizes existing quality of water and estimates possible changes that may result from copper-nickel development. The implication of such water quality changes on aquatic ecosystems is discussed in Volume 4-Chapter 1.

Water pollution may arise from both active processes and passive processes. Active processes are those activities where the production (or control) of a water pollutant occurs as a result of an industrial process (e.g. mill, refinery, acid plant, water treatment plant). When the industrial process ceases, the pollutant discharge potential is eliminated. Passive processes are those activities where the production (or control) of a water pollutant is independent of technological processes. An example involves the physical and/or chemical weathering of waste materials and exposed (or stored) ore. When the active process is complete, the passive pollutant discharge potential continues, in some cases, indefinitely. Since copper-nickel development will result in the production of large quantities of waste materials, the issue of waste water management and treatment during the operating life of the copper-nickel development and for an extended period after the facility has been deactivated must be addressed. This chapter discusses the potential of water pollution following mine retirement and methods which have been demonstrated to be effective in controlling such wastes. Neither this chapter nor other report chapters address the question of long term economic costs or who should be liable for these costs.

Finally, the existence of various <u>legal standards</u> (existing and proposed) specifying limits for water discharges and maximum concentrations of various pollutants in surface waters provides a reference framework for discussion. Many of the standards are explicit as to the parameter controlled and the level of control required. Other standards state general protection or management goals and are open to broad variations in application and interpretation. Those standards stated explicitly in terms of ambient concentrations are compared to simulated discharges and resultant ambient conditions. The effectiveness of various mitigating measures emerges automatically from the various impact assessment discussions.

4.1.1.2 Basic Approach. To address the various concerns noted above, a four-step approach was adopted by the Regional Copper-Nickel Study:

1) Characterize water resource: the present nature of water resources in northeastern Minnesota is assessed. Both surface water and groundwater hydrology, and water quality are examined in detail (sections 4.2 and 4.3).

2) Simulate copper-nickel sources: a set of hypothetical water use, management, and discharge models are created to simulate the types and amounts of pollutants which may be released to the hydrosphere by copper-nickel development. The models quantify the amounts of water appropriated, consumed, recycled, and stored in the copper-nickel development water management area under various climatic conditions and management practices. A range of models are presented to reflect the application of various mitigating methods and various assumptions as to the magnitude and quality of potential discharges (section 4.4 and 4.6).

3) Assess copper-nickel impacts: the changes in downstream water quantity (flow and discharge) and quality resulting from the hypothetical copper-nickel models are assessed using a conservative mass balance technique and stream flow models. Changes are compared to: existing conditions; aquatic biological and hydrological impact guidelines developed by the Regional Copper-Nickel Study; legal standards; existing water users in the Area; and natural variations in stream flows (sections 4.5 and 4.7).

4) Examine additional mitigation measures: additional mitigation measures in the form of special water management practices and treatment systems are discussed (section 4.7).

For more detailed information in these various areas, the interested reader is referred to the technical reports prepared by and for the Study indicated at the beginning of each section.

4.1.2 Summary of Findings

The major findings are briefly outlined below. While a smelter or refinery could be located elsewhere, for the purpose of this study all facilities were assumed to be located in the Regional Copper-Nickel Study Area (Figure 1). The bulk of the impact discussion focuses on the Study Area, and more generally on the larger Water Quality Research Area (Figure 2).

Figures 1 and 2

4.1.2.1 Hydrology (Section 4.2). The Copper-Nickel Study Area contains parts or all of 14 watersheds of interest, nine north of the Laurentian Divide, and five south of the Divide. Hydrologically, this area is a headwater region, that is, surface flow originates in this area. Waters north of the Divide are a part of the Rainy River Watershed, which includes a portion of the Boundary Waters Canoe Area, and eventually drain into Hudson Bay. Waters south of the Divide are a part of the St. Louis River Watershed, which drains into Lake Superior and eventually into the Atlantic Ocean via the St. Lawrence River. The larger Water Quality Research Area (Figure 2), which includes the complete watersheds of 14 streams of interest, is used for much of the hydrological analysis.

Ninety-one percent of the surface waters of the Study Area is located north of the Divide. The Kawishiwi system is the major river north of the Divide. Nine streams are tributary to the Kawishiwi system. This area is predominantly

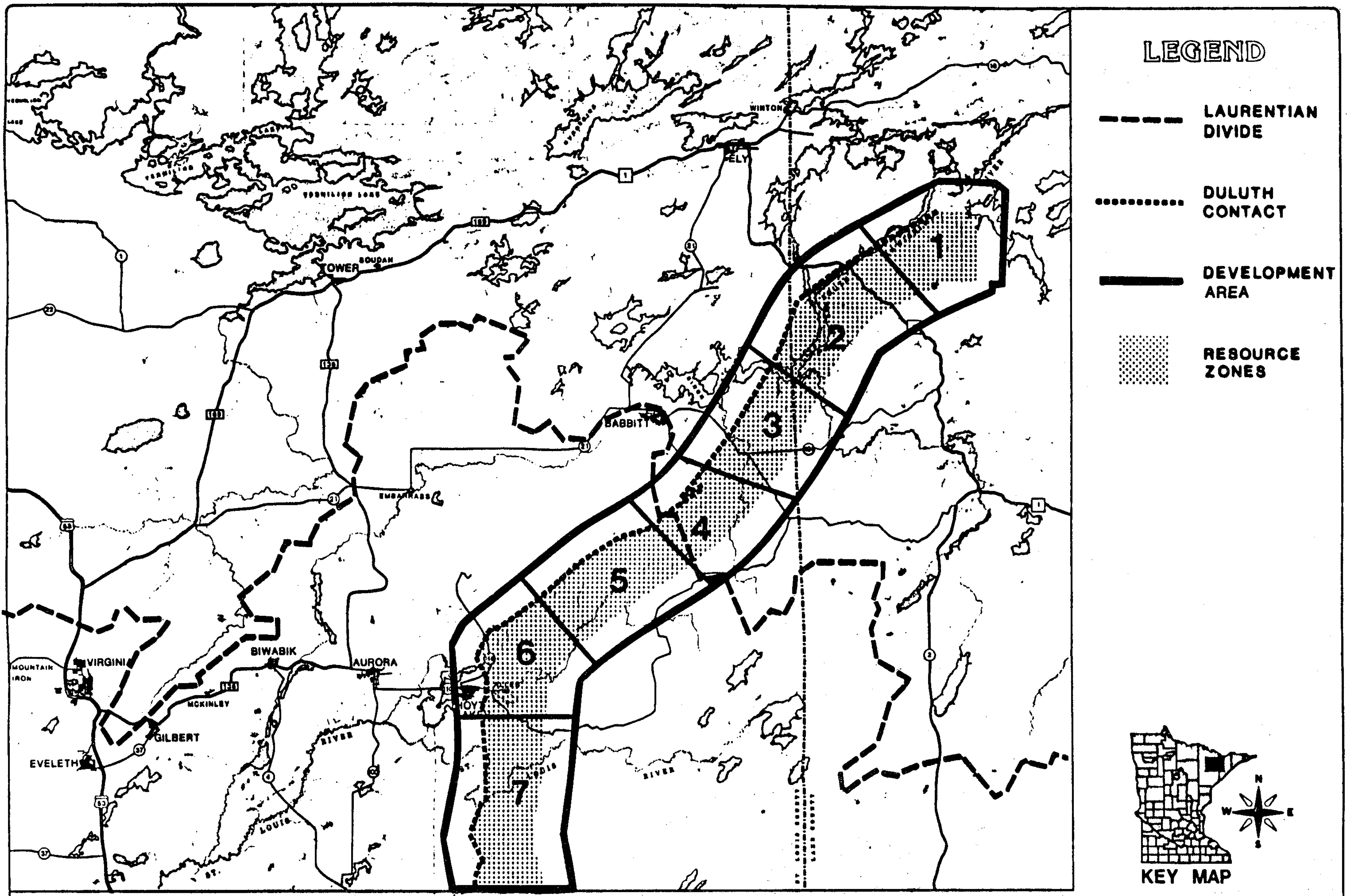


FIGURE 1

MEQB REGIONAL COPPER-NICKEL STUDY

MN CU-NI DEVELOPMENT AND RESOURCE ZONES

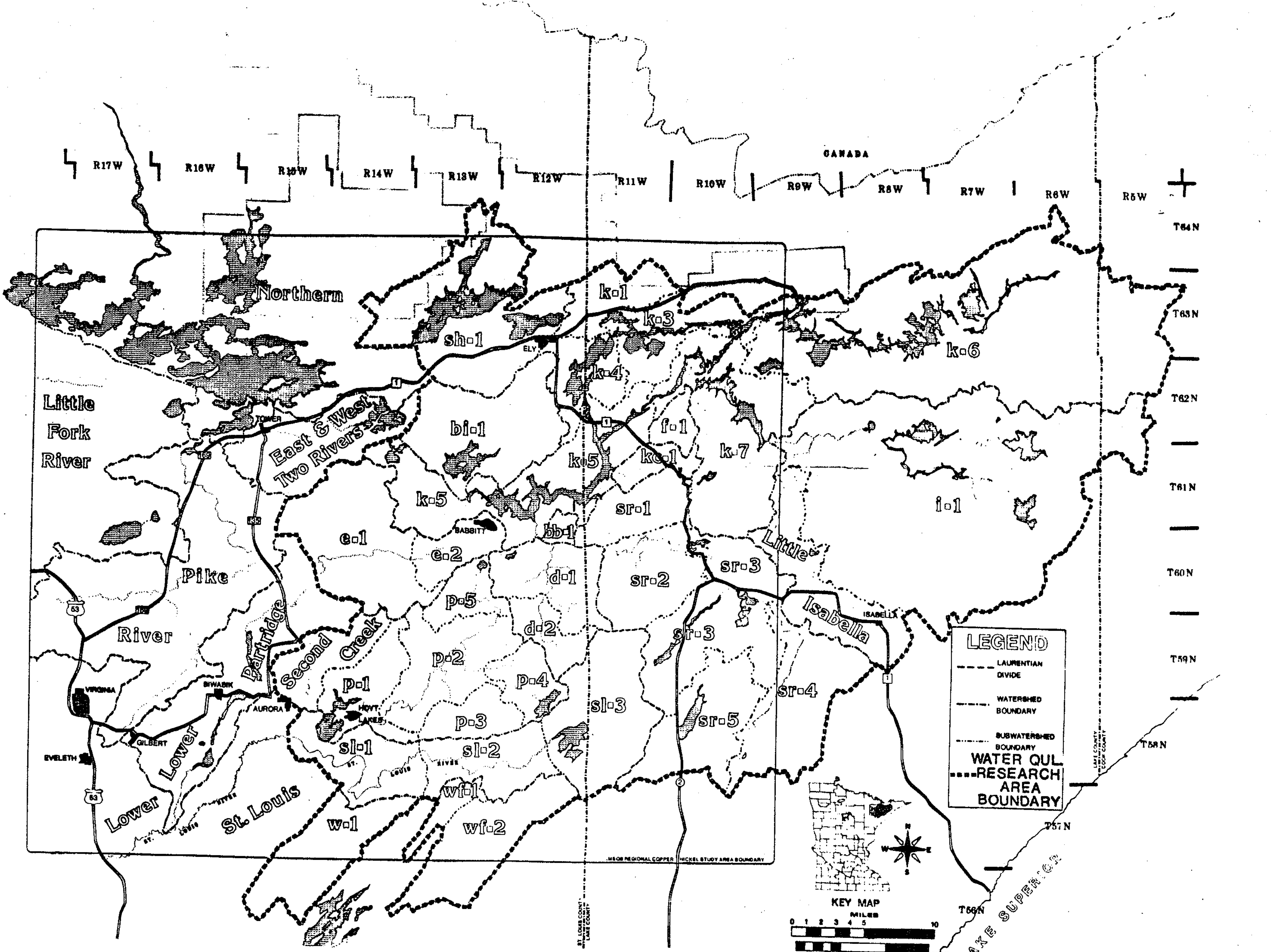


FIGURE 2 THE WATER QUALITY RESEARCH AREA

forested, with pine accounting for about 30 percent of the growth. Mining activities (taconite) occupy a small portion (0.3 percent) of the Kawishiwi drainage area. The soil thickness north of the Divide is very shallow (0-3 meters or 0-10 feet) and bedrock outcropping is common. The soils are nutrient poor, low in trace metals and acidic (Volume 3-Chapter 2).

The major river south of the Divide is the St. Louis River. Only the Partridge River joins the St. Louis within the Study Area boundaries. This area is also heavily forested, but aspen-birch predominate. Spruce, fir, and pine, in that order, are the next important species. The soil thickness is greater in this area (3-30 meters or 10-100 feet). Groundwater availability is meager, although there are two small aquifers located in this region. One-third of the area is classified as bog; and drumlins, eskers, and other glacial features dominate the landscape.

Surface water is abundant in the Research Area, partly because precipitation exceeds evaporation from lake and land surfaces. Average annual runoff in the region is about 10 inches, one of the higher runoff values in Minnesota. Analysis of streamflow in relation to drainage area has shown that average annual runoff in the region is 0.79 cfs/mi^2.

Nearly 75 percent of the Research Area is north of the Laurentian Divide, but an even larger amount of the surface water is in the north. Lakes are more numerous and larger Volume of stream flow is greater partly because a larger area is being drained. Not all of the water north of the Divide is directly available for use, however, because the BWCA dips into the region.

Streamflow in the Research Area is variable, and dependent on variations in precipitation and evapotranspiration, as well as infiltration rates, soil cover, and vegetation. Precipitation stored in the winter snowpack contributes greatly to flow in the spring. Average annual flow in 12 streams of various stream orders in the area studied by the U.S. Geological Survey ranged from 23 to 1,027 cfs. The average low flow for a period of seven days in these streams is 2 to 186 cfs, the average high flow for seven days is 87 to 4763 cfs. Average high flow exceeds average low flow by a factor of 15 to 120 for each stream. Streams with numerous lakes and bogs in their watersheds exhibit less variation in discharge because flow is regulated by the stored water.

The many lakes in the Research Area are in basins scoured from bedrock by glaciers, formed from ice blocks buried in glacial drift, or formed by differential deposition of till. The lakes are affected more slowly than streams by precipitation variations, so they have more stable volumes of water.

There is a great deal of variability within the water resource system of the Study Area. As discussed in the geology chapter (Volume 3-Chapter 1), most of the Study Area consists of shallow glacial deposits which overlay igneous bedrock. The low hydraulic conductivity of these materials result in generally limited amounts of groundwater in the area. Wells in till and bedrock generally yield less than 5 gal/min. Two relatively small parts of the Study Area, the Embarrass and Dunka River sand plains have aquifers which can yield up to 1,000 gal/min. The highly impermeable nature of bedrock in the region limits significant bedrock groundwater resources to fractured and leached bedrock areas. Wells in the Biwabik Iron Formation can yield large amounts of water, more than 1,000 gal/min, in local fractured and leached zones. Throughout much of the region, groundwater supplies are inadequate for municipal or industrial uses.

Current surface water use is primarily for electric power generation. Mine-pit dewatering is the greatest groundwater use. At current levels, water use does not cause significant impacts on the region's water resources, but present use of water from some streams must be reduced during low flow periods, and shallow wells are occasionally dry during periods of little precipitation. Some of the large on-channel lakes, such as Birch Lake, could supply large water users, but use of stream water could be restricted by variable flow. The aquifer under the Embarrass River Valley is the only identified groundwater source in surficial materials that could supply large water users.

4.1.2.2 Water Quality (Section 4.3). Because little information regarding water quality of the region was available prior to this study, a comprehensive regional monitoring program was conducted for three main purposes:

--Begin the long-term process of gathering environmental data for the establishment of a pre-development environmental base line against which change resulting from development can be assessed.

--Characterize the surface and groundwater quality in the Study Area.

--Assess the susceptibility of the surface waters to potential impacts from copper-nickel mining and associated development.

The quality of the region's water resources is generally very good. Exceptions are several streams with watersheds disturbed by extensive mining activities, and groundwater from glacial till or from wells proximate to Duluth Complex sulfide mineralization. A summary of median values of various water quality parameters in relatively undisturbed streams and all lakes monitored in the Study Area is presented in Table 1. Streams draining largely undisturbed watersheds have soft water with low alkalinity, are low in nutrients, highly colored, and very low in trace metals. Streams draining disturbed watersheds (Partridge, Embarrass, upper

St. Louis and lower Dunka rivers, and Unnamed Creek--see Figure 3) have moderately hard to hard waters, and elevated concentrations of dissolved solids, nutrients, and trace metals relative to the undisturbed watersheds. Color and fecal coliform concentrations are similar in the two watershed classifications. Most water quality parameters tend to be less variable in undisturbed streams as compared to disturbed streams. The quality of lakes studied is similar to that of undisturbed streams. Streams and lakes north of the Divide tended to have lower levels of constituents than those south of the Divide.

Table 1, Figure 3

Calcite saturation indices (CSI) were calculated to measure the ability of Study lakes to resist a change in pH due to an acid input. The poorly buffered lakes in the region are with few exceptions headwater lakes. This is because buffering is mostly a function of watershed geology. The chemistry of headwater lakes often reflects that of precipitation, with watershed contributions to lake chemistry assuming secondary importance. In general, as one proceeds from headwater to downstream lakes in the Study Area, the ability of the lakes to assimilate hydrogen ions increases. CSIs were also calculated for 30 lakes located in the BWCA. Half of these BWCA lakes were found to be poorly buffered, and with few exceptions, these represented headwater lakes. This analysis indicates that the headwater areas of the region are generally not well-buffered and have limited abilities to assimilate additional and possibly present acid loadings.

Phosphorus and nitrogen are the major nutrients in aquatic systems. Concentrations of both nutrients in Study Area streams are at the low end of the range of values for streams in the United States. The greatest variability in

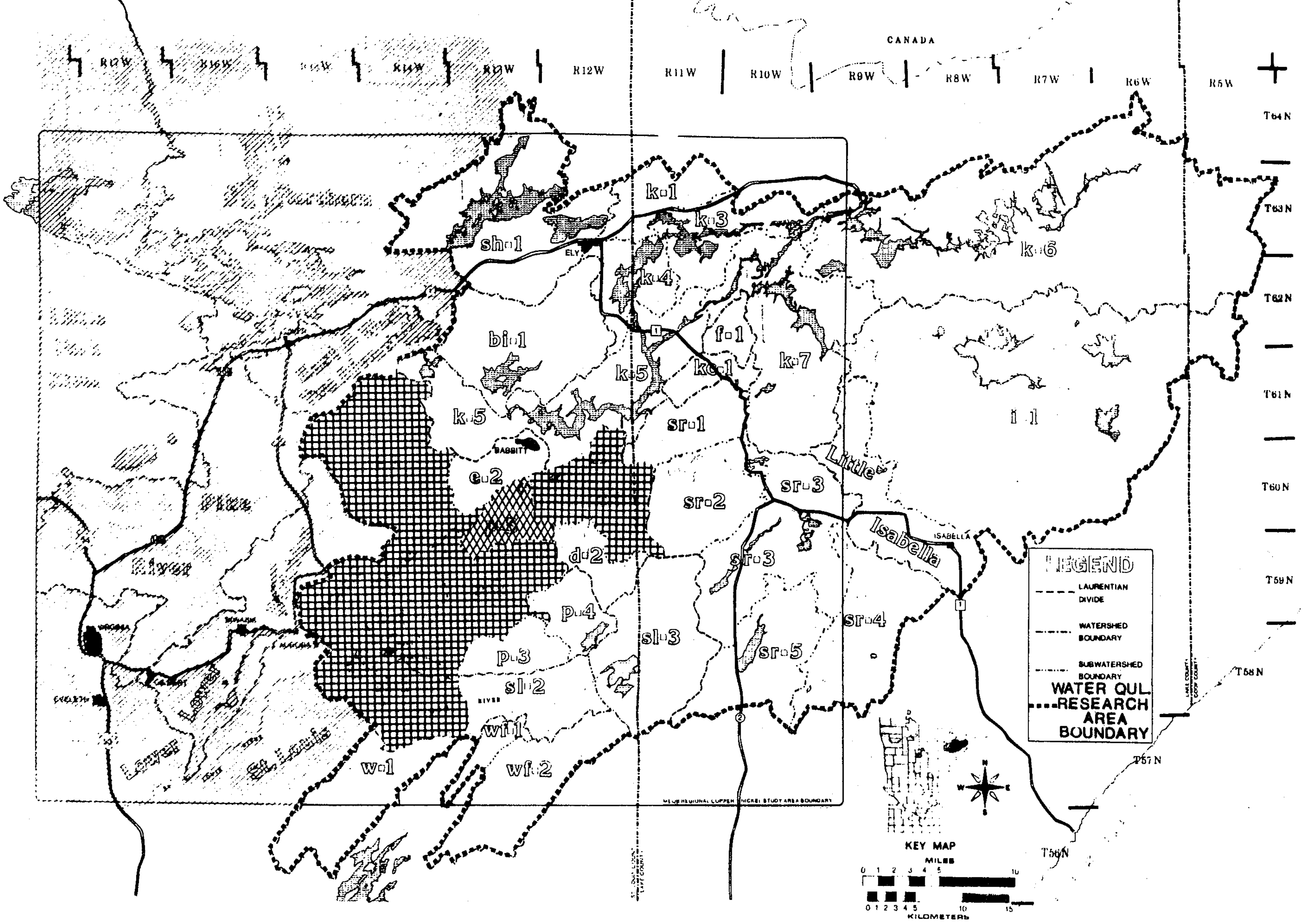
Table 1. Median values of various water quality parameters in relatively undisturbed streams and lakes in the Study Area. (November, 1975, to September, 1977).

PARAMETERS	UNDISTURBED STREAMS	LAKES
Al (ug/l)	90	77
As (ug/l)	0.8	0.6
Ca (mg/l)	6.0	7.2
Cd (ug/l)	0.03	0.03
Cl (mg/l)	1.6	1.6
Co (ug/l)	0.4	0.4
Cu (ug/l)	1.3	1.5
Fe (ug/l)	560	350
F (mg/l)	0.181	—
Hg (ug/l)	0.08	0.28
K (mg/l)	0.6	0.6
Mg (mg/l)	3	3.1
Mn (ug/l)	35	29
Na (mg/l)	1.6	1.8
Ni (ug/l)	1.0	1.0
Pb (ug/l)	0.5	0.4
Zn (ug/l)	2.0	1.8
Alkalinity (mg/l)($CaCO_3$)	19	19
TOC (mg/l)	15	14
P-total (ug/l)	20	22.9
NO_2 NO_3 (ug/l)	80	20
SO_4 (mg/l)	6.6	7.8
pH	6.9	7.1
Specific conductance (umhos/cm)($25^{\circ}C$)	55	65
Color (Pt-Co)	90.2	80
Silica (mg/l)	6.3	4.8

FIGURE 3

▦ IMPACTED WATER SHEDS BASED ON REGIONAL COPPER-NICKEL STUDY MONITORING DATA FOR THE PERIOD, NOVEMBER, 1975 TO APRIL 1977.

▨ AREA NOT STUDIED



nutrient concentrations occurred in disturbed streams. The highest concentrations of nitrogen were measured downstream from mining operations where nitrogenous blasting compounds are used. Biological activity in Study Area lakes is phosphorus-limited. For the 26 lakes monitored, 7 of 26 can be considered eutrophic. An additional 16 can be considered meso-eutrophic. The least productive lake was Tofte; the most productive was South McDougal. The most fertile lakes were all headwater lakes and for the most part were shallow and surrounded by extensive bog and marsh areas.

A limited sampling of surface waters for mineral fibers found fiber levels comparable to ambient levels reported elsewhere in the world. A sample from the Amax test shaft had elevated fiber levels, but these were several orders of magnitude below those reported in the taconite tailings at Reserve's Silver Bay plant.

At undisturbed stream and lake stations, copper, nickel, and zinc are comparable in concentration, with median concentrations in the range of 1-2 ug/liter. Other trace metals of biological importance (As, Cd, Co, Hg, and Pb) had median concentrations below 1 ug/liter.

Water quality standards and criteria for many parameters have been adopted or are proposed for adoption by the Minnesota Pollution Control Agency or the Federal Environmental Protection Agency. In the case of copper, iron, mercury, manganese, nitrogen (as NO_2 + NO_3), sulfate, pH, specific conductance, and color, the recommended levels have been exceeded in one or more streams. Recommended criteria levels for cadmium, lead, nickel, and zinc may also have been exceeded in one or more streams. In most cases, the exceedance occurred only in one stream located in a disturbed watershed (Unnamed Creek at BB-1), or in other streams located in disturbed watersheds. In other cases (e.g. color), the region's streams and lakes have naturally high concentrations.

All streams monitored appeared to exceed proposed MPCA mercury standards and EPA criteria of 0.05 ug/liter. Elevated concentrations of mercury in fish tissue have been found in the region by the Department of Natural Resources. The median concentration of mercury for all streams monitored was 0.08 ug/liter with a range in values of 0.01 to 0.6 ug/liter. The very low concentrations involved are at or close to the limit of detection of the analytical method used and could contain significant error.

The quality of surficial groundwater is primarily dependent on aquifer material. Water from the sand plain aquifers contains about one-half of the dissolved solids as till aquifers in the Study Area. Groundwater in bog areas is normally soft, highly colored, and high in dissolved organic carbon. On the other hand, water from areas with glacial till is moderately hard to very hard. Groundwater from wells proximate to the Duluth Gabbro contact have higher levels of trace metals and sulfate than do wells located at a distance from the contact. In general, concentrations of most chemical constituents are higher in groundwater than in streams and lakes of the area. Bedrock groundwaters also vary significantly with their location. Generally, the concentrations of trace metals and other constituent parameters were similar to those in surficial groundwaters except near the mineralized zone of the Duluth Contact. Highly saline groundwater has been encountered in some bedrock areas of the Study Area. The source and spatial distribution of this water is unknown.

Unique water quality conditions have been identified in the Study Area which are directly related to the presence of copper-nickel sulfide mineralization. Filson Creek, located in the northeastern part of the Study Area adjacent to the BWCA, flows across exposed mineralized gabbro. Total concentrations of copper and nickel in the year 1977 generally increased from headwater locations to Filson's point of discharge into the Kawishiwi River. Total nickel concentrations measured in Filson's headwaters were, except for one sample, less than 1 ug/liter, while the nickel concentration near the mouth of the watershed averaged 3 to 5 ug/liter. The smaller copper and nickel concentrations at Filson Creek headwater locations reflect the smaller percentage of sulfide bearing material in the till and the greater distance from the mineralized contact zone.

The elevated metal values measured at the mouth of Filson Creek may not be completely due to natural weathering of sulfide minerals in this watershed. Mineral exploration activities, including the taking of a bulk surface mineral sample, occurred prior to 1977. A small volume surface discharge from the foot of the site has elevated concentrations of trace metals (10,000 to 13,000 ug/l Ni; 360 to 1,000 ug/l Cu; and 190 to 5300 ug/l Zn). A small tributary of Filson Creek receives this discharge. Increases in copper and nickel concentrations in Filson Creek due to the tributary flowing past the bulk sample site were about 5 ug/l and 9 ug/l, respectively. This change in trace metal concentrations was not sufficient to result in measureable biological changes in the Creek.

In another case, a small watershed which drains into Birch Lake at Bob Bay contains several wastepiles containing mineralized gabbro from a nearby taconite mining operation. The large surface area of the waste rock facilitates the chemical weathering process. There are surface seeps containing high concentrations of sulfates and trace metals, especially nickel, which flow into Unnamed Creek. The magnitude of the change in this specific case is largely mitigated by natural chemical processes due to the presence of a bog in the watershed. The metal concentrations would be significantly higher if not for the effect of the bog. While the bog helps mitigate this water pollution problem, the bog is showing some signs of stress, such as vegetation damage. Clearly, extensive disturbance of the mineralized gabbro without corrective mitigation results in significant changes in water quality.

The quality of precipitation in the Study Area was monitored at several sites. Eighty-seven percent of the samples (41 of 47) had a pH less than 5.7. Half the samples had a pH of 3.6 to 4.4. The geometric mean pH of samples collected in the Area was 4.6. These values are comparable to, or even less than, values measured in areas of the world where acidic precipitation has caused ecological damage. If most of this acidity is the result of conversion of atmospheric sulfur dioxide (SO_2) to sulfuric acid or acid salts; then local sources of SO_2 are not major contributors to depressed acidity of precipitation in the region. Atmospheric dispersion modeling indicates that out-state and out-of-state sources, possibly in the St. Louis, Chicago, and the Ohio Valley areas, are the major cause of acid rain in northeastern Minnesota.

Atmospheric deposition rates for all parameters were found to be low. With the exception of iron, aluminum, lead, and chloride, the primary sources of the constituents deposited in northeastern Minnesota lie outside the region.

Studies of snowmelt water in the Filson Creek watershed in 1976 and 1977 showed that the pH of this water was 2.5 units less than in streams. Snowmelt water has little (if any) capacity to buffer the acidity deposited in snow. Concentrations of most elements are low in snow.

Soil pHs tend to be acidic (5.0-5.5) in the Study Area. Analyses of the base saturation index for the various soils show that much of the soil north of the Laurentian Divide has lost most of its capacity to buffer acidic precipitation.

4.1.2.3 Source Simulation. Water use and water discharge models for hypothetical copper-nickel operations were developed by the Regional Copper-Nickel Study in order to identify the factors within the mining development which may influence water resource management options and to allow the assessment of potential impacts of copper-nickel development on the region's water resources.

Waste rock piles, open pit mine, underground mine, lean ore piles, plant site, and undisturbed lands on the plant site are potential sources of impacts related to land (watershed) disturbance and have the greatest probability for causing potential impacts during the post-operating phase of development. Degradation of water by these sources (except undisturbed lands) is largely the result of increased physical and chemical weathering processes. Waters from these sources can usually be collected and used by the processing plant during the operating phase, but once the processing plant closes, runoff from these sources will enter nearby streams and lakes. Since the effectiveness of reclamation measures on the quality of water from waste rock piles, open pit mine, underground mine, and lean ore piles is presently unknown, the probability for potential impacts is greater during the post-operating phase than during the operating phase, unless mitigative measures during operation are not effective.

The plant site and undisturbed lands are exceptions to the above. The plant site could be a significant source of water degradation from ore stockpiles, maintenance areas, chemical spills, and other activities common to industrial sites. During the operating phase, runoff from the plant site would probably be collected and used as make up for the processing plant. Once the plant is shut down, it can be cleaned up and the site reclaimed to near original conditions.

The processing plant and the smelter/refinery complexes are classified as sources which present the greatest probability for potential impacts on water resources during the operating phase of development. Waste waters from these sources are produced only during operation. When the operation is shut down, these sources cease to exist. Associated facilities (tailing basin, slag pile, and sludge pond) are solid waste disposal facilities that are typically fully integrated with the water system of the processing plant and smelter/refinery such that water management problems associated with these facilities are primarily influenced by the operation of the processing plant and the smelter/refineries. These facilities stand alone during the post-operating phase and their impact characteristics depend on natural physical and chemical processes.

Water Budget (Section 4.4)--The ability to effectively isolate copper-nickel development activities from the surrounding undisturbed watersheds is a significant factor in the water management system and may be a determining factor of whether waste water discharges are necessary. If runoff from undisturbed watersheds is allowed to flow over disturbed areas or dilute runoff from these areas, the probability that waste water discharges will degrade the region's water resources would increase. Separation of runoff from disturbed and undisturbed watersheds in the development area is therefore a major design factor for the mitigation of water resources impacts.

Water management for a copper-nickel operation is strongly influenced by the need for and consumption of water by the various processing and extraction operations, and the direct and indirect degradation of this water. In an average year, the processing system requires fresh make-up water, even if the process water is recycled. Water lost with the concentrate, to tailing retention, from evaporation of tailing basin water, and other miscellaneous plant losses exceeds water inputs from precipitation on the tailing basin and ore moisture. Make-up water must be appropriated from a lake, stream, groundwater, or mine site runoff. Any of these methods constitutes a consumptive use of water resources.

Water from the lean ore piles, waste rock piles, open pit mine, underground mine, and plant site (in order of increasing quality) could be used as a source of processing plant make-up water. This would eliminate the need to discharge most, if not all, of the waste water produced from these sources, if runoff from undisturbed lands is segregated from the above sources and if water inputs to the tailing basin (in addition to the mill process water) can be recycled through the processing plant. If all water from these sources cannot be consumed by the processing plant, then a discharge would occur resulting in degradation of the region's water resources.

Consumptive uses of water in the smelter/refinery are small. Fresh water must be continually appropriated for both processing and cooling; but most of it is cooling water that moves through the plant and is discharged. Smelter process waste water is of poor quality and must be treated for acid neutralization and heavy metals removal before it can be reused or discharged. Cooling water requirements can be very large if once-through cooling is used, but water availability and water quality standards will probably require a closed-cycle cooling system (cooling towers). Recycling through cooling towers can reduce cooling appropriations and discharges by at least an order of magnitude (10 times).

Precipitation and evaporation can vary significantly from year to year. The combined mine/processing plant water system may experience large water deficits or excesses during such extreme years. Analysis of wet and dry periods indicates that a storage reservoir could smooth out fluctuations in demand.

The quantity of water produced from waste rock piles, lean ore piles, and the plant site depends on precipitation, evaporation, and seepage into the ground. During an average year, precipitation in the Study Area is approximately 28 inches (73 cm). Evaporation of water from stockpiles and the plant site can vary from 7 to 20 inches (18 to 51 cm). In all three cases, precipitation exceeds evaporation during an average year and the source will produce water. Depending upon the design of the source and local geology, a portion of this water will leave the source as seepage to groundwater and the balance will leave as surface runoff. If the seepage water is of poor quality compared to the groundwater in the area, it may have to be collected. Careful siting and design is necessary to control seepage.

The quantity of water produced from an open pit mine also depends on precipitation and evaporation, but water inputs from groundwater sources can also be a significant factor. The quantity of groundwater inputs can vary significantly (0 to over 800 cubic feet of water per year per foot of pit circumference) depending on local geology. For an underground mine, the only significant water input is from ground water sources. Because surficial aquifers are usually isolated from the main shafts, bedrock aquifers are the major sources of concern. Very little information on the quantity and distribution of bedrock groundwater resources exists for the copper-nickel resource area. The highly impermeable nature of bedrock in the region limits significant bedrock groundwater resources to fractured and leached bedrock areas. Based on available information, an underground mine in the resource area could produce from essentially zero to over a thousand acre-feet of water per year.

Hydrology Impacts (Section 4.5)—Copper-nickel development would change the hydrology of the Study Area by direct appropriations from surface waters, indirect appropriations by runoff control, and discharges to ground or surface waters.

Appropriation of streamflow and collection of runoff may compete with other uses of the water resource. Reductions in low flow of streams decrease the available habitat for aquatic organisms, while the reduction of flooding at spring may eliminate valuable spawning areas. Changes in streamflow or lake levels may be aesthetically undesirable and could decrease the recreational value of the resource. Less water could be available for municipal and industrial water users.

Discharges to streams could cause scouring and bank erosion or create current velocities too high for existing aquatic communities. Dissolved solids, particulates, and heat released in discharge water to lakes or streams may exceed the tolerance limits of aquatic organisms.

Factors that could affect the nature and extent of hydrology impacts during the operational phase of development include: climatic conditions; processing and cooling water requirements; storage; land area from which runoff is collected; seepage control and soil permeability; and timing of appropriation or discharge.

In the post-operational phase, hydrology impacts will be affected by: the size and nature of the area disturbed by development; timing of runoff; and distribution of runoff among surface runoff, interflow, and baseflow.

Of the development models developed by the Study, the 20 X 10^6 mtpy open pit model has the potential for the most severe hydrologic impacts. In the operational phase, water deficits or excesses can occur in very dry or very wet years, even if the operation is almost self-sufficient in an average year. A mine/mill system without storage would have an estimated deficit of 8,380 acre-feet (11.5 cfs) for the open pit model in a 100-year dry year. To meet this appropriation need, a stream would need a watershed area of 270 mi^2—the equivalent of the entire flow of the St. Louis River at SL-1 or one-fifth the flow of the Kawishiwi River at K-1. An appropriation of 8,380 acre-feet in the 100-year dry year would make the mine/mill system the second largest water consumer in the Study Area. Dewatering from existing taconite mines may be able to provide adequate flows to meet these copper-nickel mine/mill needs.

In a 100-year wet year, the open pit model without storage would discharge 14,330 acre-feet (19.9 cfs). If release is proportional to streamflow, this discharge would double flows of streams with watershed areas of 10 mi^2 and could cause significant scouring and bank erosion. For streams with watersheds greater than 150 mi^2, high flows would be increased by 10 percent at most and probably not have significant effects on stream morphology.

If a storage system is used, water from wet years could be used during dry years and largely mitigate extremes in discharges and appropriations. Consumptive needs for the mill (6,440 acre-feet/year) could be met by appropriation or collection of site runoff. If runoff from the tailing basin is collected, the appropriation would decrease to 3,180 acre-feet in an average year. If appropriation proportional to flow is used to meet this need, impacts on streams with watersheds over 100 mi^2 would be small. Constant appropriation or appropriation during spring runoff would have more severe impacts.

Use of precipitation collected by the tailing basin and all mine site runoff would result in the need for a discharge of 2,820 acre-feet for the open pit model in an average year. Need for a discharge could be minimized by reducing the size of the runoff collection area. A collection area of 10 mi^2 (compared to the mine site area of 16 mi^2) would provide sufficient water for the mill in an average year.

Containment of all runoff from the mine site (if used) should be carefully planned for several reasons: containment of runoff will reduce flow in the host watershed; discharges released into other watersheds would increase flows in the receiving watersheds; discharges released into the same watershed would partially offset flow reductions due to runoff containment; and discharges could be of poor quality.

Water use in a smelter/refinery system is largely nonconsumptive. Based on applicable thermal discharge standards, once-through cooling is not considered a viable option in Minnesota; hence a maximum recycling model, requiring 7.3 cfs, was examined. With storage, a drainage area of 10-15 mi^2 could provide sufficient water to meet the needs of a maximum recycling smelter using appropriation proportional to flow.

Smelter/refinery discharge would normally occur at approximately a constant rate. Appropriation proportional to flow and constant discharge would have the net effect of increasing base flows and decreasing peak flows--and could be detrimental to fish spawning areas in watersheds less than 100-150 mi^2. Use of holding ponds would allow for discharge proportional to flow.

In the post-operational phase, changes in surface morphology will continue to affect the hydrology of the area. Recontouring and revegetation may help to mitigate these changes.

From the standpoint of water supply, development zones 2 and 3 (Figure 1) would be best suited for copper-nickel development. Zones 4, 5, and 6 appear to be the most poorly suited to support such development. The small flow of the Dunka River in zone 4 could restrict development. In zones 5 and 6, the small flow of the upper Partridge River and competing current water users could pose limitations to development.

Water Quality Source Models (4.6)—Recent research conducted by the Regional Copper-Nickel Study, the Department of Natural Resources, and other researchers has greatly increased the level of knowledge and understanding of water quality issues associated with sulfide minerals development. However, this information is not sufficient to allow precise statements on the quality of water in possible discharges or on the effectiveness of various treatment systems and reclamation practices.

Water quality discharge models were developed for each of four mine elements: mines, stockpiles, tailing basins, and smelter/refinery. Concentrations of water quality parameters presented in these models are based on field data from analogous situations (where possible), laboratory studies, pilot plant studies, and data from the literature.

During the operational phase, discharges from the tailing basin (via direct discharge or overflow, seepage through the dam, or seepage into groundwater) are of the most concern because waters from the other three sources would be diverted to the tailing basin.

After operations cease, runoff from waste rock piles would be of greatest concern, assuming no lean ore stockpiles remain. Leaching of sulfide minerals from waste rock piles could continue for many years after mining operations cease. Open pit mines and tailing basins also present the potential for post-operation impacts on water quality.

Factors such as pile height, size, shape, grade of sulfide mineralization, particle size, mineralogy, age, water throughput, organic content and revegetation status will affect the quantity and quality of runoff from these sources. Knowing the combined effect of most if not all of these factors is necessary in order to predict accurately effluent quality and the effectiveness of mitigating methods. Such knowledge is not currently available. Unless copper-nickel development is delayed for many years and present research activities examining these factors is significantly increased, such predictive ability will not be available for pre-development design and impact assessment activities associated with the first copper-nickel mine development proposals in Minnesota. In these cases, the unavoidable uncertainties must be considered in development planning, so corrective measures can be taken if problem arise.

<u>Water Quality Impacts (4.7)</u>--Chemical parameters of concern include trace metals, total dissolved solids (specifically sulfate and chloride), pH, total suspended

solids, chemical reagents, and mineral fibers. Emphasis was placed on trace metals and sulfates.

Copper, nickel, cobalt, and zinc are of primary interest because of their relatively high concentrations in mineralized gabbro and their potential toxic effects on aquatic life. The Regional Copper-Nickel Study developed a method to examine their combined effects converting the concentrations of these four metals into a single concentration called "copper equivalent units (CEU)" (CEU = 1 * [Cu] + 0.1 * [Ni] + 1 * [Co] + 0.1 * [Zn]), which is then evaluated for aquatic biological impacts based on ranges established in Volume 4-Chapter 1. For the purposes of analysis, a CEU level of 10 ug/l (low probability of measurable impact) was chosen to indicate environmental acceptability.

The impact analyses focus on the size of watershed that would be needed to dilute a given discharge (assuming the 20 X 10^6 mtpy open pit mine model) to a given criterion level. This method was used to indicate how near or far the different model discharges are from meeting the criteria, assuming dilution was the only mitigative approach.

For the operational phase, three discharges were modeled. Using the above criteria and a number of simplifying assumptions, it was found that a larger watershed would be required for constant discharge compared with discharge proportional to flow to provide sufficient dilutional streamflows. Table 2 indicates that if control is sufficient to meet the CEU criterion, sufficient control of sulfates will also occur. For the worst case model, Discharge A, and using constant discharge, a watershed of 4,022 mi^2 is necessary to provide sufficient dilution during an average precipitation year. None of the streams or lakes in the Research Area have a watershed area this large. If discharge proportional to flow were used for discharge A, a watershed of 1,247 mi^2 would be needed. None of the watersheds south of the Laurentian Divide in the Research Area could provide sufficient dilution, while only the Kawishiwi River at station K-1 would have a sufficient watershed area. Similar analyses can be made for Discharges B and C. A large number of streams and lakes could provide sufficient dilution for the best case, Discharge C with discharge proportional to flow.

Table 2

Two discharges were modeled for the post-operational phase (Table 3)--one for lean ore piles and one for waste rock piles. The potential impacts from Discharge II (lean ore) would be similar to those from Discharge A during the operational phase. Because lean ore stockpiles are not expected to remain during the post-operational phase, the impacts from Discharge I (waste rock) should receive more attention. During the post-operational phase, discharge proportional to flow is harder to ensure, so larger watersheds would be required to guarantee sufficient dilution during low flow periods.

Table 3

Chloride concentrations in discharge waters are difficult to predict because of the unknown variability in the occurrence of saline water in the bedrock. If significant quantities of saline groundwater are not encountered by the mine, in-stream chloride concentrations due to copper-nickel development should be of the same order of magnitude as occur in disturbed watersheds (5-10 times above background) of the Study Area.

Table 2. Dilutional watershed areas required to reduce CEU and sulfate concentrations to acceptable levels—operational phase model discharges.

	MINIMUM DILUTIONAL WATERSHED AREA (mi^2)					
	Discharge A		Discharge B		Discharge C	
	constant discharge	proportional to flow	constant discharge	proportional to flow	constant discharge	proportional to flow
To achieve CEU levels less than 10 ug/l at all times	4,022	1,247	1,520	359	190	25
To achieve $SO_4^=$ levels less than 250 mg/l at all times	36	3.0	31.7	2.5	—	—

CEU = 1[Cu] + 0.1[Ni] + 1[Co] + 0.1[Zn]

Discharge A = 2,200 ug/l CEU and 380 mg/l $SO_4^=$
Discharge B = 640 ug/l CEU and 360 mg/l $SO_4^=$
Discharge C = 54 ug/l CEU

Table 3. Dilutional watershed areas required to reduce CEU and sulfate concentrations to acceptable levels—post-operational phase model discharges.

	MINIMUM DILUTIONAL WATERSHED AREA (mi^2)			
	Discharge I		Discharge II	
	constant discharge	proportional to flow	constant discharge	proportional to flow
To achieve CEU levels less than 10 ug/l at all times	266	39	3,459	1,028
To achieve $SO_4^=$ levels less than 250 mg/l at all times	54	5.0	138	6.7

CEU = 1[Cu] + 0.1[Ni] + 1[Co] + 0.1[Zn]

Discharge I (waste rock) = 320 ug/l CEU and 1,260 mg/l $SO_4^=$
Discharge II (lean ore) = 8,300 ug/l CEU and 3,620 mg/l $SO_4^=$

The major concern about pH is its effect on trace metal mobility. Generally, lower pH's increase leaching of metals. During the operational phase, any discharges are likely to have pHs on the alkaline side (above 7) because of the influence of the milling process. Acid discharges from waste rock piles are not expected because of the low content of sulfide minerals; however, field studies have detected a drop in pH in discharges from gabbro waste rock piles at Erie's Dunka Pit.

Chemical reagents used in the flotation process vary widely in toxicity and persistence in the environment, and should be considered when reagents are being chosen for the mine-mill circuit.

Mineral fiber levels in pilot plant studies were examined. The average values found in processing samples were on the order of 10^{12} fibers/liter, or approximately one-third the levels observed in the Reserve Mine tailing material at Silver Bay, and six orders of magnitude above observed background levels. Flocculant clarification of process water prior to recycling may reduce fiber levels by 4-5 orders of magnitude. Experiments conducted for the Regional Copper-Nickel Study indicate that the tailing material retains a significant fraction of the mineral fibers, regardless of the treatment used to control fiber release from recycled or discharged tailing water. If subsequent wind or water erosion of tailing material occurs, resulting emissions or discharges will contain mineral fibers. The implications to human health from these mineral fibers is uncertain, but have been considered sufficient to cause the addition of a special filtration system for the Duluth water system.

Potential impacts on BWCA water quality are dependent on proximity of the development to the BWCA and location with respect to the Laurentian Divide (Figure

4). Development south of the Divide would have a low probability of impact because the streams flow away from the BWCA. North of the Divide, the eastern part of development zone 1 has a high potential for impact because any discharge waters would flow directly into the BWCA without dilution. The remainder of zone 1, plus zones 2, 3, and part of 4, are classified as having medium impact potential because any discharges, although they would be diluted considerably before reaching the BWCA, would eventually flow through the BWCA and could cause some impacts.

Figure 4

Impacts on groundwater are possible if seepage from tailing basins or stockpiles occurs. During the operational phase, this seepage could be collected and controlled. However, seepage will continue into the post-operational phase. Special tailing basin construction techniques or the siting of mine components on impermeable materials, such as bedrock or peat would help mitigate potential for groundwater contamination.

Copper-nickel development has the potential of generating highly toxic waste waters during and after the 20 to 30 year operating life of the development. The water resources of the region where this development would occur are of the highest quality. These resources and the biological communities they support could be degraded by such wastes. Present major uses of this resource (except industrial use) include water-based recreation, fisheries, and wildlife production. Maintenance of the quality of this resource is important for these uses. Since it is unlikely that the quality of effluents can be accurately predicted prior to development and that the quality of runoff from reclaimed areas will be

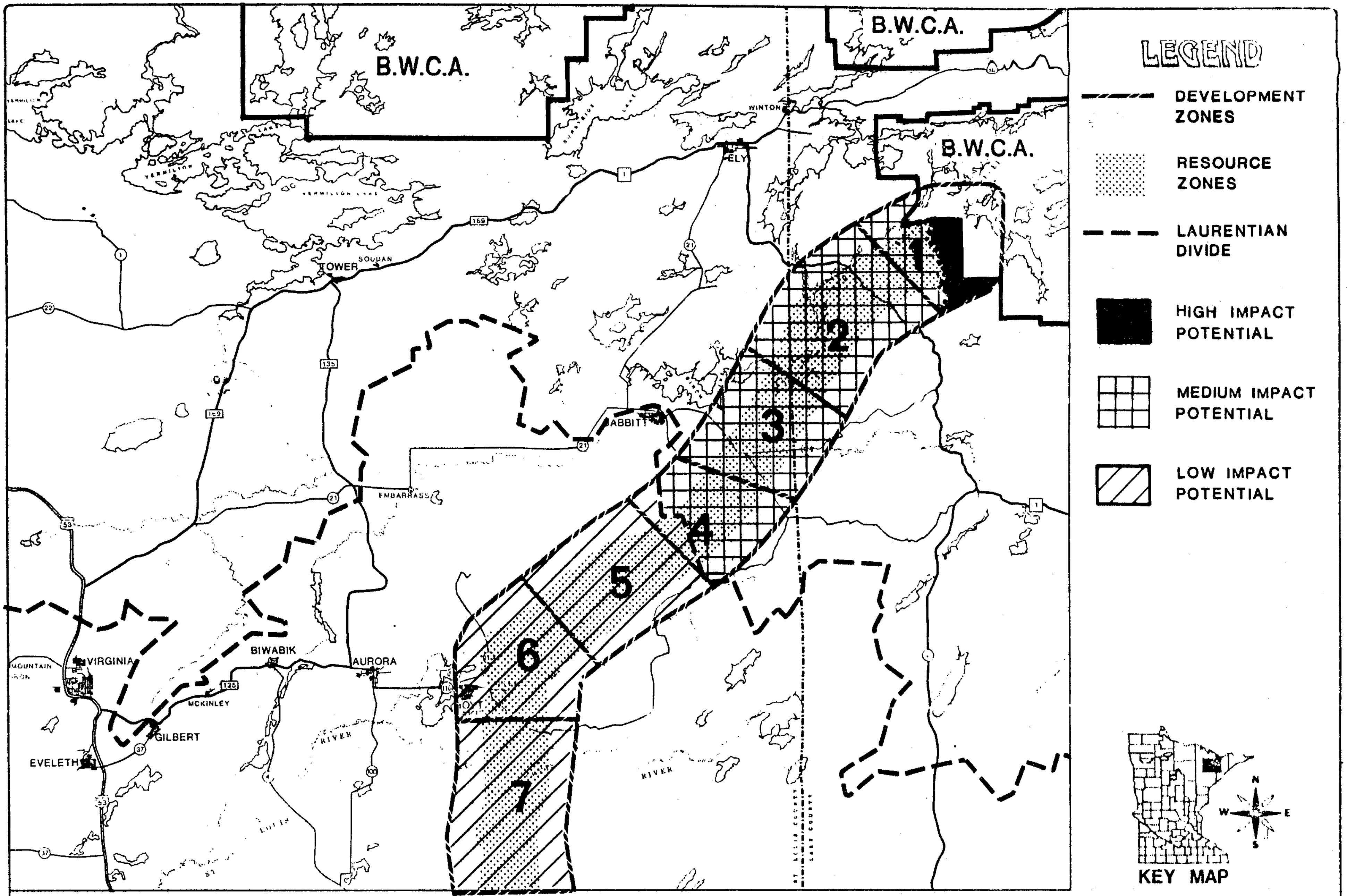


FIGURE 4

MEQB REGIONAL COPPER-NICKEL STUDY

B.W.C.A. WATER QUALITY IMPACT POTENTIAL OF DEVELOPMENT ZONES OUTSIDE THE B.W.C.A.

largely unknown for many years after development has started, the design of first copper-nickel development should have built in flexibility, should be a learning experience, should have staged development so this experience can be applied at the earliest possible date, should facilitate the timely application of corrective action, and should be designed to be able to respond to the worst assumptions, should they be realized. All risks of degrading this region's water resources cannot be identified in advance. Therefore, sources of potential water contamination should be located in areas that facilitate control and where resources are less sensitive or unique and where impact will minimal.

If certainty of outcome and very low environmental risk are state resource management goals, then the appropriate policy is no development.

4.2 HYDROLOGY CHARACTERIZATION

The occurrence, availability, and movement of surface and groundwater in and adjacent to areas of possible copper-nickel development (Figure 1) will determine, in part, the future development and water use in the area. Water is generally plentiful in the Copper-Nickel Study Area, but availability varies both by season and in response to long-term meteorological trends. This may put constraints on the magnitude of future development, especially if environmental impacts are to be minimized or prevented. Legal constraints may further limit water availability. Copper-nickel development may require appropriations or discharges of large amounts of water, and consequently change the hydrologic behavior or water quality of parts of the area. In order to assess the possible hydrologic impacts of copper-nickel development, the present hydrologic character of the region must be understood. This section presents a summary of the surface and groundwater hydrology in and adjacent to areas of possible copper-nickel development.

Hydrologically, the area monitored is a headwater region, that is, surface flow originates in this area. This region encompasses portions of two major drainage basins (the Rainy River and the St. Louis River) which are separated by the Laurentian Divide. Water north of the Divide eventually flows into Hudson Bay, while water south of the Divide flows into Lake Superior. The Boundary Waters Canoe Area cuts into the Study Area at various points, and all water leaving the area north of the Divide flows into the BWCA.

The Study Area contains parts or all of 14 watersheds, nine north of the Laurentian Divide, and five south of the Divide (Table 4). Analysis of the water quality and hydrology of the region requires information about the entire watershed of each stream. For this reason, the Water Quality Research Area (Research Area) (Figure 2), a 4,738 km^2 (1,829 mi^2) area composed of the complete watersheds of the 14 streams of interest, was created. Much of the discussion concerns the Research Area, rather than the Study Area.

Table 4

The data were obtained from a number of sources. The U.S. Geological Survey maintained streamflow stations in the Study Area. Sixteen continuous gaging stations and eight periodic measurement sites were used to collect discharge data (Figure 5). At 12 stations, 10 or more years of streamflow records were available, and these records were used to determine streamflow characteristics. Stream orders were determined by Copper-Nickel Study personnel (see Volume 4-

Table 4. Regional Copper-Nickel Study watersheds (refer to Figure 2 for locations).

NORTH OF LAURENTIAN DIVIDE (Rainy River Drainage)

WATERSHED NAME	SUBWATERSHED NAME	SUBWATERSHED AREA (km^2)	FEEDER SUBWATERSHEDS	TOTAL DRAINAGE THROUGH SUB-WATERSHED, km^2	(mi^2)
Isabella River	Little Isabella	132	none	132	(50.95)
	I-1	751	Little Isabella	883[a]	(340.84)
Filson Creek	F-1	27	none	27[a]	(10.42)
Keeley Creek	KC-1	29	none	29[a]	(11.19)
Stony River	SR-5	125	none	125	(48.25)
	SR-4	161	none	161	(62.15)
	SR-3	180	sr5+sr4	466	(179.88)
	SR-2	101	sr5+sr4+sr3	567	(218.86)
	SR-1	65	sr5+sr4+sr3+sr2	632[a]	(243.95)
Unnamed Creek	BB-1	11	none	11[a]	(4.25)
Dunka River	D-2	44	none	44	(16.98)
	D-1	84	d2	128[a]	(49.41)
Bear Island R.	BI-1	177	none	177[a]	(68.32)
Shagawa River	SH-1	256	none	256[a]	(98.82)
Kawishiwi River	K-6	655	none	655	(252.83)
	K-7	236[b]	Little Isabella+il+½k6	1447[b]	(568.96)
	K-5	262[b]	Little Isabella+il+fl+kcl+sr5+sr4+sr3+ sr2+srl+bbl+d2+dl+½k6+k7	2536[b]	(978.90)
	K-4	66[b]	Little Isabella+il+fl+kcl+sr5+sr4+sr3+ sr2+srl+bbl+d2+dl+bil+½k6+k7+k5	2779[b]	(1072.69)
	K-3	64	Little Isabella+il+fl+kcl+sr5+sr4+sr3+ sr2+srl+bbl+d2+dl+bil+k6+k7+k5+k4	3170	(1223.62)
	K-1	63	Little Isabella+il+fl+kcl+sr5+sr4+sr3+ sr2+srl+bbl+d2+dl+bil+shl+k6+k7+k5+k4+k3	3489	(1346.75)

Table 4 continued.

SOUTH OF LAURENTIAN DIVIDE (Lake Superior Drainage)

WATERSHED NAME	SUBWATERSHED NAME	SUBWATERSHED AREA (km^2)	FEEDER SUBWATERSHEDS	TOTAL DRAINAGE THROUGH SUB-WATERSHED, km^2 (mi^2)
Embarrass River	E-2	46	none	46 (17.76)
	E-1	183	e2	229[a] (88.39)
Partridge River	P-5	32	none	32 (12.35)
	P-4	48	none	48 (18.53)
	P-3	47	none	47 (18.14)
	P-2	137[c]	p5+p4+p3	264[c] (101.90)
	P-1	71	p5+p4+p3+p2	335[c] (129.31)
St. Louis River	Second Creek	69	none	69 (26.63)
	SL-3	157	none	157 (60.60)
	SL-2	86	sl3	243 (93.80)
	SL-1	107	p5+p4+p3+p2+p1+Second Creek+sl3+sl2	754[c] (291.04)
Whiteface River	WF-1	24	none	24 (9.26)
	WF-2	124	none	124 (47.86)
Water Hen Creek	W-1	118	none	118 (45.55)

SOURCE: U.S. Geological Survey, St. Paul, Minn.

[a] Drainage area of entire watershed.
[b] Drainage areas estimated because of North/South Kawishiwi River split.
[c] Includes 13 km^2 in subwatershed p2 defined by USGS as noncontributing.

Chapter 1).

Figure 5

Lake morphometric information for 26 lakes in the Study Area was collected and analyzed by Copper-Nickel Study personnel and U.S. Forest Service personnel. These are the same lakes from which water quality data were collected (Figure 5).

Groundwater information was developed by the U.S. Geological Survey from logs of wells and core holes, topographic maps, field observations, test augering, and literature pertaining to the geology and water resources of the region.

More detailed information for section 4.2 can be found in Bowers, 1977; Brooks and White, 1978; Ericson et al. 1976; Garn, 1975; Savard et al. 1978; Siegel and Ericson, 1979; and the other second level reports.

4.2.1 Hydrologic Cycle

The hydrologic cycle is a conceptual model of water movement through the earth's environment, and provides a framework for understanding the ways in which mining may affect the hydrology of the Copper-Nickel Study Area. The cycle may be divided into three principal phases: evapotranspiration, precipitation, and surface and groundwater runoff (Figure 6).

Figure 6

Moisture is evaporated to the atmosphere from the land, oceans and other water surfaces and is returned to the land or oceans as precipitation. The precipitation may: be intercepted and subsequently transpired by plants, run off over the

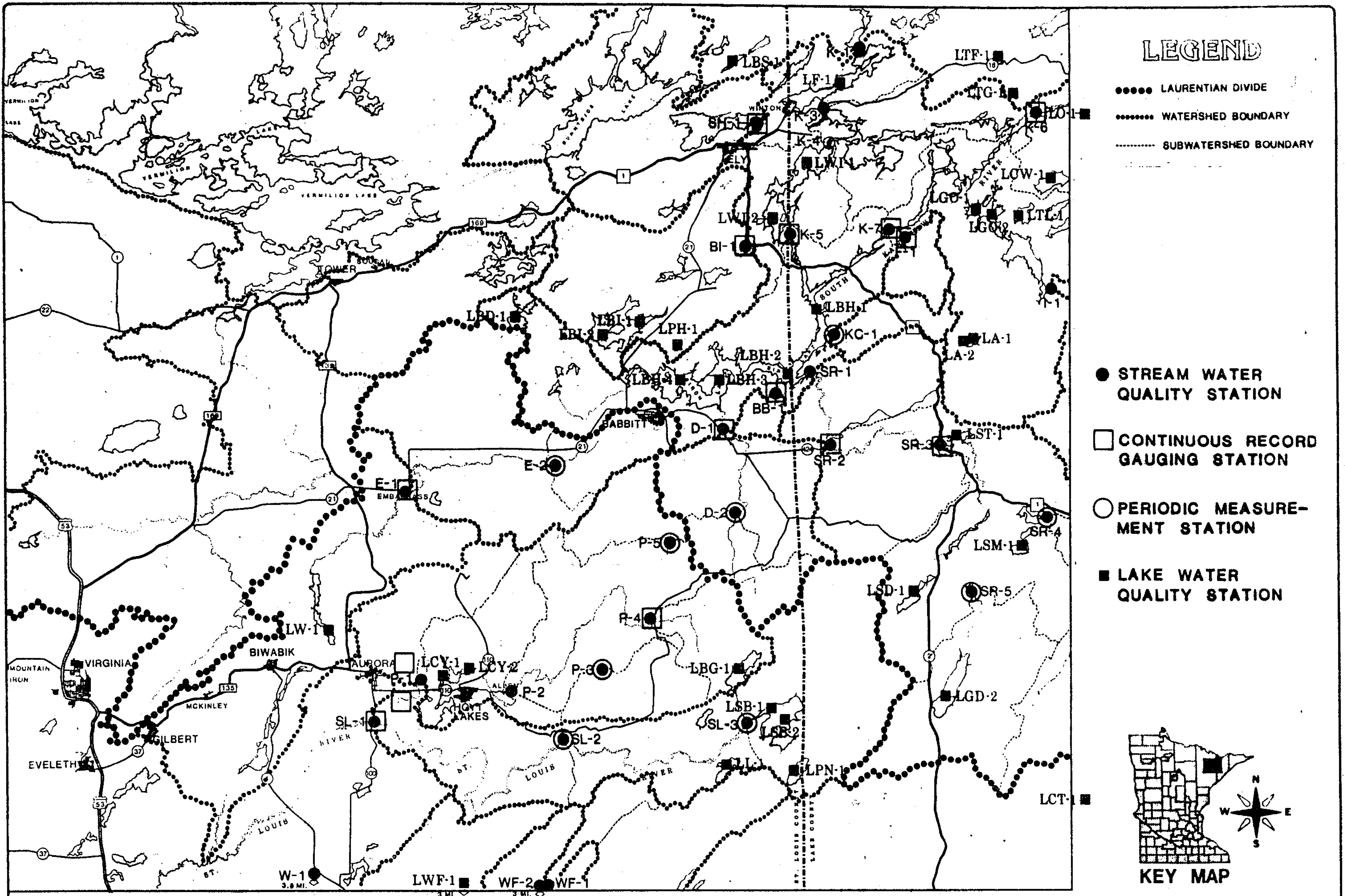


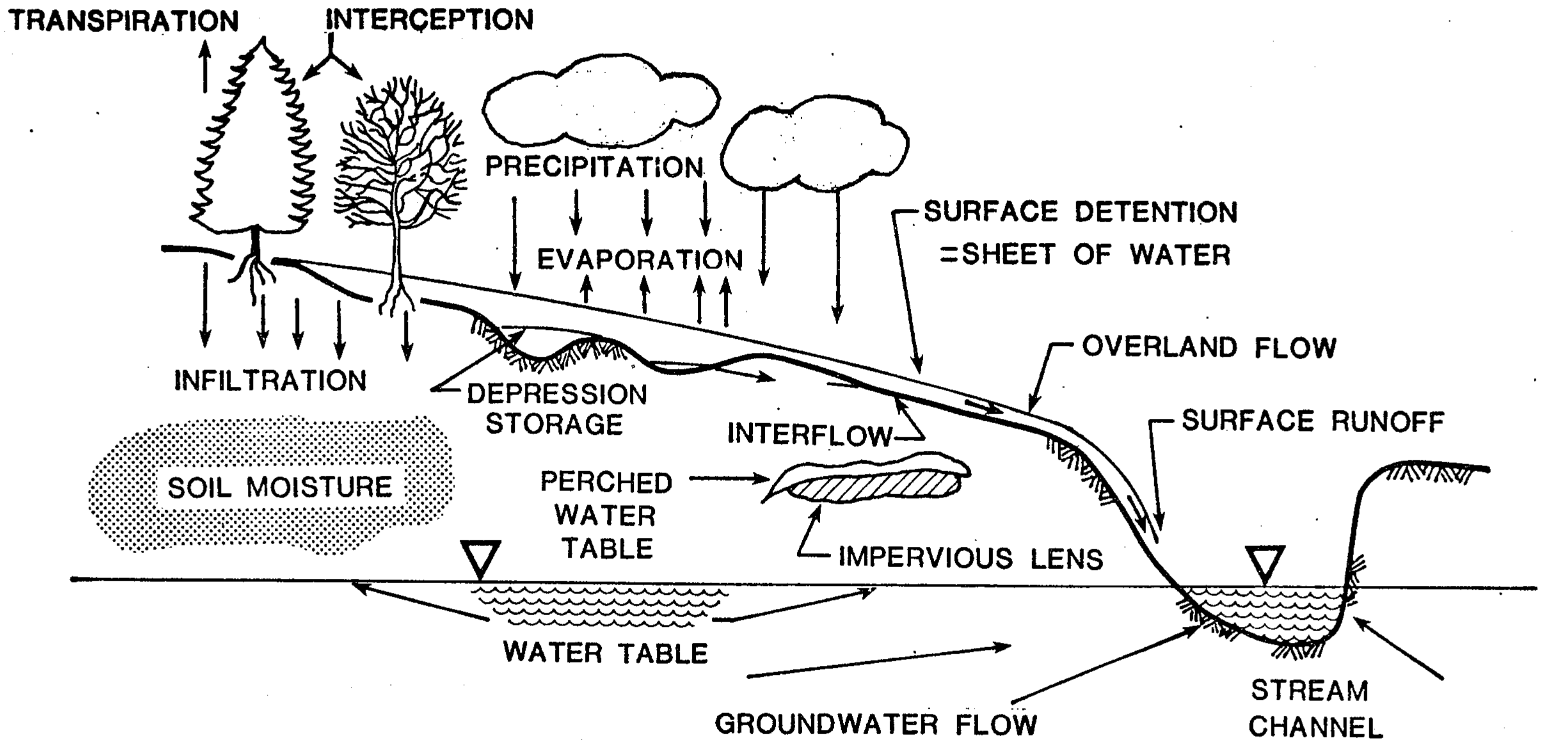
FIGURE 5

MEQB REGIONAL COPPER-NICKEL STUDY

SURFACE WATER AND SURFACE WATER QUALITY STATIONS IN THE COPPER-NICKEL STUDY AREA

FIGURE 6

THE HYDROLOGIC CYCLE



SOURCE : GREY, 1970

land surface to streams as surface runoff, or infiltrate into the ground. Much of the surface runoff is returned to the atmosphere by evaporation. The infiltrated water may be temporarily stored as soil moisture and evapotranspired, or it may percolate to deeper zones to be stored as groundwater. Groundwater sustains streams at low flow.

Removal of water at any point in the cycle will have effects on water quantity at other points. A hydrologic budget, or water budget, quantifies the parts of the hydrologic cycle in order to describe water movement in a watershed. It may be expressed as an equation (Siegel and Ericson 1979):

$$\text{Precipitation} = \text{runoff} + \text{evapotranspiration} \pm \text{changes in storage} \pm \text{underflow}$$

In the Research Area, water is stored in lakes, bogs, and groundwater aquifers. Changes in storage occur when water levels are raised or lowered. Underflow is water which flows across basin boundaries in river alluvium or through bedrock, under a gaging point, and therefore escapes detection and measurement at stream gages. Although short-term changes in storage and underflow can be significant, long-term changes are usually considered to be negligible (Lindholm et al. 1978). Over long periods of time, runoff and evapotranspiration balance precipitation in the Study Area.

4.2.2 Climatology

In the Arrowhead region of Minnesota, average annual precipitation exceeds average annual evaporation from lake and land surfaces. This allows for runoff to occur in an average year. Average annual precipitation ranges from about 700 mm in the southwestern part of the region to about 760 mm in the northeast. This exceeds average annual lake evaporation by about 200 mm per year (Watson 1978).

The average precipitation in and adjacent to areas of potential copper-nickel development has been determined by Watson (1978) from historical records. The year can be divided into a wet season, which begins about April 14, and a dry season, which begins about October 16. June and July are the wettest months in the region, and February the driest. Almost 15 percent of the annual average precipitation falls in July. The average percent of annual precipitation which occurs during each month at Babbitt is compared in Figure 7 to the percent of average annual stream discharge occurring each month in the region.

Figure 7

Variations in precipitation over the period from 1894 to 1977 at Virginia, Minnesota, are shown in Figure 8. Normal seasonal variations, as well as drought periods and wet periods, are visible. Further details of these variations are found in the air resources discussion (Volume 3, Section 3.3).

Figure 8

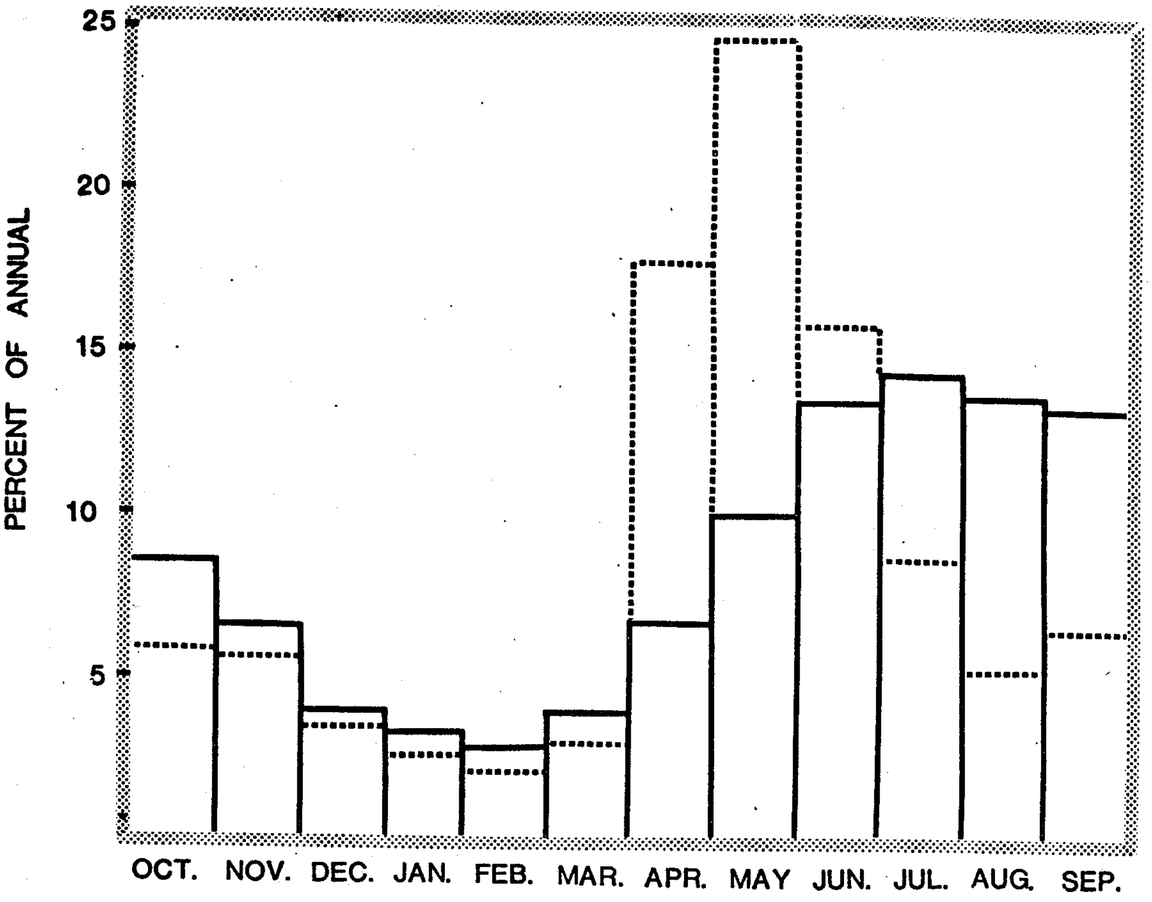
4.2.3 Stream Hydrology

Streamflow is a measure of the volume of water passing a given point per unit of time, and is generally expressed in cubic feet per second (cfs). Flow varies over time in response to precipitation and other factors, although the response may not be immediate. Garn (1975) has described the runoff pattern in the Superior National Forest, which includes most of the Copper-Nickel Study Area as follows:

> The pattern of runoff is typical of areas where snowmelt is the major

FIGURE 7

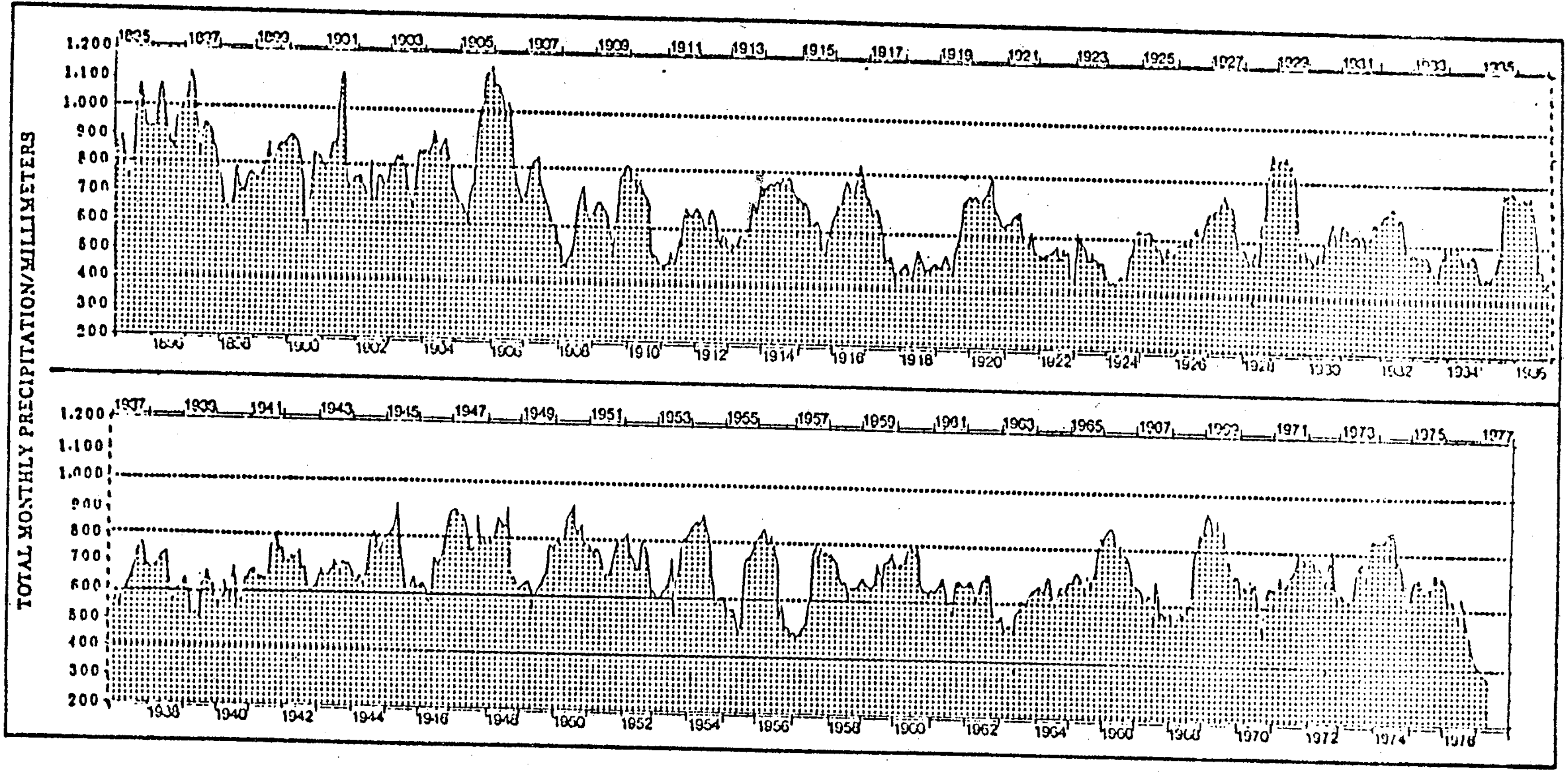
PERCENTAGE OF ANNUAL PRECIPITATION AND DISCHARGE OCCURRING EACH MONTH IN THE STUDY REGION



——— PRECIPITATION AT BABBITT (FROM WATSON 1978)

········ DISCHARGE - AVERAGE FOR 12 STATIONS IN THE REGION
(FROM SIEGEL AND ERICSON 1979)

FIGURE 8 VIRGINIA PRECIPITATION TOTALS FOR TWELVE MONTH PERIODS AT THE END OF EACH MONTH 1895-1977



[WATSON, 1978]

> source of runoff, which is augmented by spring and summer rainfall. From the spring peak flows, streamflow recedes steadily through the summer, reacting only temporarily to heavy rainfall. Streamflow stabilizes in late summer and fall, reaching a summer low in late August to September. Streams occasionally exhibit an increase in flow during October and November as evapotranspiration decreases. Streamflow recedes slowly during the late fall and winter, reaching an annual minimum during February and March. Occasionally some of the streams experience annual minimum flows during late summer or fall as a result of extended dry periods. Annual peak flows across the Forest most commonly occur in April or May as a result of rapid melting of the accumulated snowpack. However, annual peak flows may also occur during the summer and fall from excessive rain.

Figure 7 shows the average percentage of annual flow which occurs in each month for 12 stations in the Study Area. Almost 25 percent of the annual flow occurs during May, due to spring snow melt. About 57 percent of the annual flow occurs in April, May, and June. Flows during the four winter months of December, January, February, and March account for less than 11 percent of the annual flow. Late summer discharge values are low compared to precipitation values, because evaporation is high during these warm months (Siegel and Ericson 1979).

Water which falls as precipitation contributes to streamflow in these ways (Gray 1970):

1) Surface runoff - water which flows over land to the stream channel. This includes water which is temporarily stored in lakes and wetlands.

2) Interflow - water which infiltrates the soil surface and moves laterally through the upper horizons of the soil until it returns to the surface at some point downslope to flow to the stream as surface runoff, or is intercepted in its course by a stream channel.

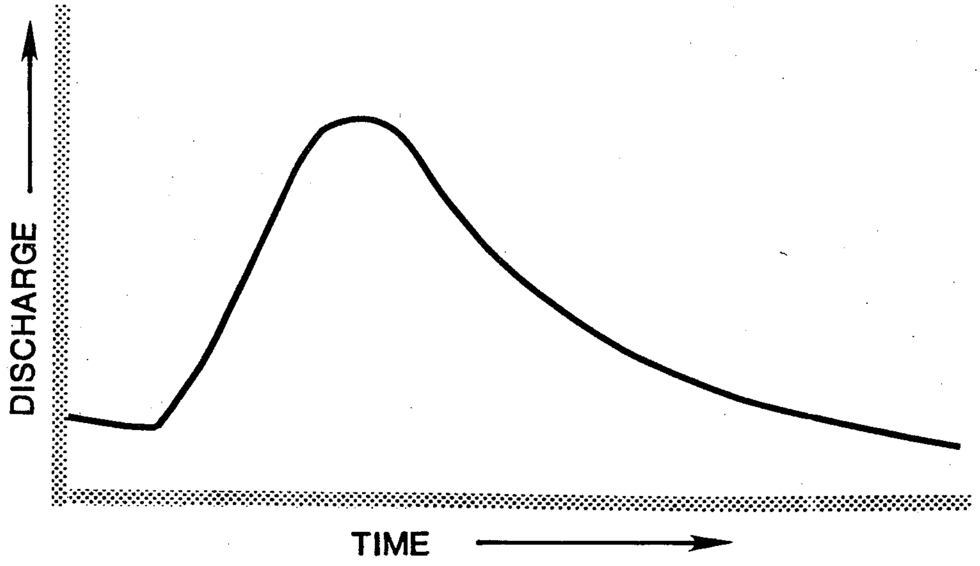
3) Groundwater flow - water which flows as groundwater and joins a stream where the channel intersects the water table.

4) Channel precipitation - water which contributes to streamflow by falling directly on lake or stream surfaces. This is usually a relatively small amount of water.

During periods of little or no precipitation, many streams continue to flow.

FIGURE 9

STREAM FLOW HYDROGRAPH



SOURCE : GRAY, 1970

Table 5. Equations relating flow to drainage area[a].

DESCRIPTION	EQUATION	CONDITIONS	SOURCE
Average annual flow	$Q^{b} = 0.79$ d.a.[c]	d.a. $50 mi^{2}$	Siegel and Ericson 1979
Average annual flow	$Q = 0.72$ d.a.		Bowers 1977
12 month low flow	$Q = 0.35$ d.a.	d.a. $1200 mi^{2}$	Bowers 1977
36 month low flow	$Q = 0.5$ d.a.	d.a. $1200 mi^{2}$	Bowers 1977
7 day, 2 year low flow	$\mathrm{Log}Q^{d} = -1.62 + 1.28 \mathrm{Log}$ d.a.		Calculated from Brooks & White 1978
7 day, 10 year low flow	$\mathrm{Log}Q = -1.9320 + 1.2479 \mathrm{Log}$ d.a.		Brooks & White 1978
7 day, 20 year low flow	$\mathrm{Log}Q = -1.9336 + 1.1951 \mathrm{Log}$ d.a.		Brooks & White 1978
30 day, 10 year low flow	$\mathrm{Log}Q = -1.77678 + 1.2204 \mathrm{Log}$ d.a.		Brooks & White 1978
30 day, 20 year low flow	$\mathrm{Log}Q = -1.8842 + 1.2091 \mathrm{Log}$ d.a.		Brooks & White 1978

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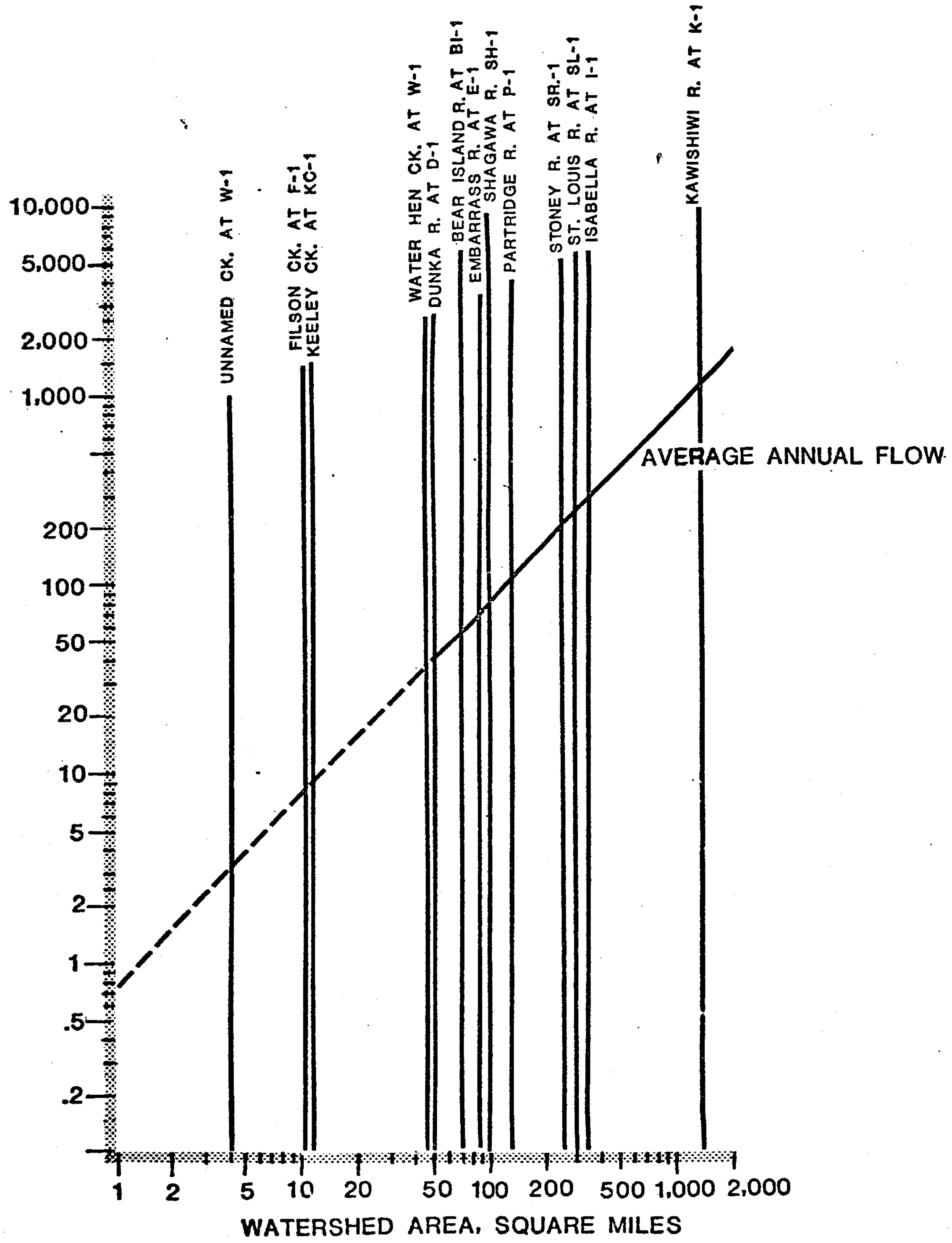
[a] Values are for the Study Area only. See Brooks and White (1978) for peak flow equations.
[b] Q=flow in cfs.
[c] d.a.=drainage area in mi^{2}.
[d] All logarithms in base 10.

FIGURE 10

AVERAGE ANNUAL FLOW AS A FUNCTION OF DRAINAGE AREA SIZE



ERICSON 1978. SEE TABLE 5

Release of water from surface storage (lakes and wetlands) and groundwater storage sustains this streamflow, called baseflow. In the Study Area, surface storage sustains baseflow to a greater extent than groundwater (Siegel and Ericson 1979).

After a precipitation event, the flow of a stream will change in response to additional runoff. This can best be illustrated by use of a graphical representation of the time distribution of streamflow, called a hydrograph (Figure 9). The shape of a hydrograph is an indication of how quickly precipitation from a storm reaches the gaging point via the pathways listed above. The timing of runoff is affected by climatic factors, and topographic and geologic features of the basin (Gray 1970). A copper-nickel operation would change the topography of the watershed in which it was located, so timing of runoff could also be expected to change. This possibility is discussed in section 4.5 (Hydrologic Impacts).

<u>Figure 9</u>

Drainage area is the most important topographic characteristic influencing streamflow (Siegel and Ericson 1979). Equations have been developed relating drainage area to peak flow, low flow and annual average flow (Table 5). Figure 10 shows an estimate of average annual flow as a function of drainage area, as calculated by the U.S. Geological Survey. This type of information will aid in understanding the effect on streamflow of containing site runoff by a mining operation, which would have the same effect as removing part of the land area of a watershed (see section 4.5).

<u>Table 5, Figure 10</u>

Lakes and bogs, which are numerous in the region, regulate streamflow because they temporarily store surface runoff and release it slowly. Streams with many lakes in their headwater channels do not exhibit flashy flows with precipitation events. During dry periods release of stored water sustains flow. Flow of some streams is also regulated by man made dams in the region (Garn 1975).

Streams become larger as they flow downstream and are joined by other streams. The concept of stream orders has been developed to describe this additive process. Stream orders also provide a convenient framework for discussing aquatic organisms (see Volume 4-Chapter 1). A headwater stream is a first order stream; a second order stream is formed when two first order streams meet; and further increases in order occur as streams of equal order join each other (Horton 1945; Strahler 1957). The major stream in a watershed may change orders along its course as it is joined by tributaries. Table 6 shows stream orders and lengths in the Copper-Nickel Study watersheds (see Figures 2 and 5 for locations). Forty-two percent of the stream miles in the Research Area are first order, or headwater, status. The Kawishiwi River, which drains the largest area and carries the largest volume of water, has the most miles of fifth order status of all the streams in the region.

Table 6

4.2.3.1 Average Flow. The average annual flow of a stream is the average of its monthly flows. Seasonal variations in flow, which may limit the availability of water in a stream and limit the stream's ability to dilute possible mine discharges, do not show up in the average annual flow. A flow parameter which takes into account the lower flows that occur part of the year is the 50th

Table 6. Stream length as a function of stream order in copper-nickel watersheds[a].

WATERSHED	STREAM ORDER 1st	2nd	3rd	4th	5th	TOTAL
	STREAM LENGTH (km)					
Kawishiwi River (Kawishiwi sub-watersheds only)	123	66	28	45	70	332
Isabella River	207	150	118	50	19	544
Filson Creek	14	.2				14
Keeley Creek	11	7				18
Stony River	105	81	53	40		279
Unnamed Creek	2.8					2.8
Dunka River	35	16	13			63
Bear Island River	33	21	23			77
Shagawa River	60	49	24	3		136
Total North of Laurentian Divide (Kawishiwi River at K-1)	590	390	259	138	89	1,466
Embarrass River	40	13	23			76
Partridge River	81	57	14	31		183
St. Louis River (St. Louis subwatersheds only)	38	14	64	6.7		123
St. Louis River at SL-1	119	71	78	38		306
Whiteface River	52	4.3	26			82
Water Hen Creek	33	17	17	3.8		71
Total South of Laurentian Divide	244	106	144	41		535
Total Cu-Ni Watersheds	834	496	403	179	89	2,001

[a] See Figures 2 and 5 for locations

percentile flow, the flow that is equalled or exceeded 50 percent of the time. Table 7 shows the average annual flow and 50th percentile annual flow for streams in the Study Area. The average flows recorded in 1976 and 1977, the Copper-Nickel Study monitoring period, are shown for comparison.

Table 7

4.2.3.2 Low Flow. Low streamflows occur in spring, summer and fall during periods of low precipitation and high evapotranspiration, and in winter when streamflow is sustained only by groundwater and lake discharge. Low flow may be reduced further by water appropriation for copper-nickel development, by controlling minesite runoff that normally would contribute to the stream, or by filling a lake or bog that previously helped to sustain baseflow from the watershed. Unintentional reduction in flow may occur if an open pit is located such that groundwater is diverted from discharging to the stream and instead seeps into the mine. Problems which may be caused by reduction of low flows include loss of aquatic habitat, decrease in current velocities, inadequate dilution of waste materials, and interference with other water users.

Statistical analysis of low flow periods is useful in planning for appropriation needs and preventing environmental damage (see sections 4.5-4.7). An example of a low flow event which may be of concern is a 7 day, 10 year low flow. This is the lowest average flow over a period of seven consecutive days which can be expected to occur on an average of once in ten years. This event has a one in ten chance of occurring in a given year, and a 96 percent chance of occurring at least once in 30 years. The 7 day, 10 year low flow is the lowest flow rate for which Minnesota water quality standards must be maintained.

Table 7. Streamflow in the Copper-Nickel Study Area.

	STATION DESIGNATION			AREA ABOVE STATION[a]	
WATERSHED	USGS Name	USGS No.	CU-NI NO.	Km^2	Mi^2
Filson Cr.	Filson Creek at mouth near Ely	05124994	F-1	16.7	10.4
Keeley Cr.	Keeley Creek at mouth near Ely	05125040	KC-1	18.0	11.2
Stony R.	Greenwood River near Isabella	05125450	SR-5	77.6	48.2
	Stony River near Murphy City	05125400	SR-4	99.8	62.0
	Stony River near Isabella	05125500	SR-3	290	180
	Stony River near Babbitt	05125550	SR-2	352	219
	Stony River at mouth near Ely	05125650	SR-1	393	244
Isabella R.	Little Isabella R. near Isabella	05124497	LI	77.7	48.3
	Isabella River near Isabella	05124500	I-1	549	341
Unnamed Creek	Tributary to Bob Bay	05125730	BB-1	5.84	3.63
Dunka River	Dunka River near Hoyt Lakes	05125950	D-2	44	17.0
	Dunka River near Babbitt	05126000	D-1	79.5	49.4
Bear Island R.	Bear Island River near Ely	05126500	BI-1	110.2	68.5
Shagawa R.	Shagawa River at Ely	05127230	SH-1	159.3	99.0
Kawishiwi R.	Kawishiwi River near Ely	05124480	K-6	407	253
	So. Kawishiwi R. near Ely	05125000	K-7	916[b]	569[b]
	So. Kawishiwi R. above White Iron Lake near Ely	05126210	K-5	1,576[b]	979[b]
	So. Kawishiwi R. at White Iron Lake outlet near Ely	05126620	K-4	1,727[b]	1,073[b]
	Kawishiwi R. near Winton	05127000	K-3	1,978	1,229
	Kawishiwi R. at Fall Lake outlet near Winton	05127250	K-1	2,176	1,352
Embarrass R.	Embarrass River near Babbitt	04016900	E-2	28.3	17.6
	Embarrass River at Embarrass	04017000	E-1	142.1	88.3
Partridge R.	Partridge R. near Babbitt	04015447	P-5	20.0	12.4
	So. Br. Partridge R. nr Babbitt	04015455	P-4	29.8	18.5
	Colvin Creek near Hoyt Lakes	04015461	P-3	29.5	18.3
	Partridge R. at Allen	04015471	P-2	155.3	96
	Partridge R. near Second Creek near Aurora	04015490	P-1	208.4	124
St. Louis R.	Second Creek near Aurora	04015500	SC-1	36.0	22.4
	St. Louis R. below Seven Beaver Lake nr Fairbanks	04015430	SL-3	97.6	60.6
	St. Louis R. near Skibo	04015438	SL-2	151.3	94.0
	St. Louis R. near Aurora	04016500	SL-1	446	277
Whiteface R.			WF-1	14.8	9.2
			WF-2	77.1	47.9
Water Hen Cr.			W-1	73.4	45.6

Table 7 continued.

		PREDICTED LOW FLOWS, in cfs (Siegel and Ericson 1979)									PREDICTED LOW FLOWS, in cfs (Brooks and White 1978)				
WATERSHED	STATION	7 day 2yr	14 day 2yr	30 day 2yr	7 day 10yr	14 day 10yr	30 day 10yr	7 day 20yr	14 day 20yr	30 day 20yr	7 day 2 yr[h]	7 day 10 yr	30 day 10 yr	7 day 20 yr	30 day 20 yr
Filson Cr.	F-1										.48	.22	.29	.19	.22
Keeley Cr.	KC-1										.53	.24	.32	.21	.24
Stony R.	SR-5										3.43	1.48	1.90	1.20	1.42
	SR-4										4.74	2.03	2.58	1.62	1.93
	SR-3										18.47	7.62	9.45	5.77	6.96
	SR-2										23.74	9.74	12.00	7.30	8.82
	SR-1										27.28	11.15	13.70	8.31	10.06
Isabella R.	LI										3.43	1.48	1.90	1.20	1.42
	I-1	52.2	53.9	57.4	31.6	32.0	33.8				41.86	16.92	20.61	12.39	15.07
Unnamed Creek	BB-1										.12	.06	.08	.05	.06
Dunka River	D-2										.90	.40	.53	.34	.40
	D-1	2.10	2.35	2.55	0.90	1.13	1.25				3.53	1.52	1.95	1.23	1.46
Bear Island R.	BI-1	3.30	3.90	5.00	0.65	0.96	1.10				5.35	2.28	2.90	1.81	2.16
Shagawa River	Sh-1	22.2	24.1	27.6	1.70	1.79	2.02	0.51	0.53	0.58	8.58	3.61	4.55	2.82	3.37
Kawishiwi R.	K-6	46.5	49.3	53.1	13.5	13.8	14.4	7.28	7.38	7.58	28.56	11.66	14.31	8.67	10.50
	K-7	96.7	100.0	105	40.5	42.6	44.5				80.66	32.08	38.52	22.86	28.00
	K-5										161.53	63.13	74.68	43.73	53.95
	K-4										181.62	70.78	83.51	48.78	60.27
	K-3	186	202	240	25.0	40.0	82.0		12.0	42.5	214.94	83.41	98.06	57.09	70.66
	K-1										243.01	94.01	110.24	64.02	79.35
Embarrass R.	E-2										.96	.43	.56	.36	.42
	E-1										7.44	3.14	3.97	2.47	2.95
Partridge R.	P-5										.60	.27	.36	.24	.27
	P-4										1.00	.45	.59	.38	.44
	P-3										.98	.43	.57	.37	.43
	P-2										8.27	3.48	4.39	2.71	3.23
	P-1										11.47	4.79	6.00	3.70	4.44
St. Louis R.	SL-1	5.30	5.63	6.11	2.18	2.29	2.49	1.68	1.77	1.92	1.28	.57	.74	.49	.56
	SL-3										4.59	1.96	2.50	1.57	1.87
	SL-2										8.02	3.38	4.27	2.65	3.17
	SL-1	25.5	27.4	29.2	9.92	10.6	11.6	6.79	6.96	7.16	32.09	1.16	16.00	9.67	11.72
Whiteface R.	Wf-1										.41	.19	.25	.17	.19
	Wf-2										3.39	1.46	1.88	1.19	1.40
Water Hen Cr.	W-1										3.19	1.37	1.77	1.12	1.32

Table 7 continued.

[a] Drainage areas do not include non-contributing areas of taconite mines. Data source: Siegel and Ericson 1979.

[b] Estimated drainage area because of Kawishiwi River channel split.

[c] Data source: USGS 1977, USGS 1978

Water year 1976 is Oct. 75-Sept. 76, Water Year 1977 is Oct. 76-Sept. 77.

$\bar{Q}$ record = average annual flow of record
$\bar{Q}$ 50 = 50th percentile flow of record
$\bar{Q}$ 76 = average flow, WY76
$\bar{Q}$ 77 = average flow, WY77
Q_{min} record = minimum instantaneous flow of record
$Q_{min}{}^{76}$ = minimum instantaneous flow, WY76
$Q_{min}{}^{77}$ = minimum instantaneous flow, WY77
Q_{max} 76 record = maximum instantaneous flow of record
Q_{max} 76 = maximum instantaneous flow, WY76
Q_{max} 77 = maximum instantaneous flow, WY77

[d] Instantaneous measurement; record through 1975 WY

[e] Data source: Siegel and Ericson 1979.

[f] Data source: Bowers 1977.

[g] Calculated from Brooks and White 1978.

Water quality violations may occur when flows fall below this rate (Minnesota Pollution Control Agency WPC 14 and 15). The 7 day, 2 year low flow can be considered to be the average 7 day low flow of a stream. A 7 day period with flows this low has a 50 percent chance of occurring in a given year.

Table 7 lists a number of low flow durations and recurrence intervals for streams in the Study Area. The low flows predicted by Siegel and Ericson (1979) are based on historical records for the individual streams. Low flows predicted by Brooks and White (1978) are the result of regional analysis of streamflow, and are calculated from drainage area using the equations in Table 5.

4.2.3.3 <u>High Flow</u>. High flows occur in response to precipitation events and to snowmelt in the spring. Over 60 percent of the annual maximum floods in the region have occurred in the spring (Siegel and Ericson 1979). Flooding is not a problem in the Study Area in most years, however, because there is little development on flood plains. High water levels, lasting for roughly a month, are necessary for spawning in the spring. If streamflow is appropriated during high flow periods, water level may be reduced, causing loss of spawning areas. Recurring high flood flows can have adverse effects on aquatic life, however, by scouring stream channels and reducing the diversity of organisms.

Like low flows, high flows can be expressed as durations and frequencies. A 15 day, 2 year high flow is the average high discharge rate lasting 15 days which can be expected to occur every other year. Fifteen and 30 day high flow durations at two and five year recurrence intervals are presented in Table 7 for streams in the Research Area. Peak flows are instantaneous measurements which gage the highest flow reached during a flood or high flow period. Spring peak flow and flood peak flow are types of peak flows often discussed. A "100 year flood" is the instantaneous discharge rate with a probability of occurring once in 100 years. The 100-year flood for some streams in the Study Area is shown in Table 7.

Copper-nickel development could affect the high flows of streams. Appropriations of streamflow during high flow periods would reduce flows. Containment of runoff in a watershed could have varying effects on peak and high flow; these could include decreasing the total volume of runoff from a given storm event, reducing peak flows, and shortening duration of high flows. Peak discharge could be increased, however, if a mine element were placed on a lake or wetland which previously had stored surface water and helped to damp runoff peaks (Hewett 1978).

High flow can increase dilution of runoff from a mining operation. However, peak discharge from the mining operation may not occur when streamflow is highest, so the mine discharge may be poorly diluted (see section 4.5).

Flow in an individual stream can vary considerably during a year, even if unusual precipitation variations do not occur. The Shagawa River at Sh-1, for example, has an average annual flow of 92 cfs (USGS 1977). The 7-day, 2-year low flow is 22 cfs, and the 7-day, 2-year high flow is 323 cfs, a 15-fold difference (Siegel and Ericson 1979). Additional flow values are found in Table 7.

4.2.3.4 Spatial Variation of Streamflow. Surface water availability will affect future use of water in the region. The area north of the Laurentian Divide accounts for 74 percent of the Water Quality Research Area, but contains 91 percent of the water surface area in the region (MLMIS 1969). A larger concentration of lakes occur in the north than in the south. Since lakes are important in sustaining baseflow and damping flood peaks, streams north of the Divide maintain higher baseflows and exhibit less extreme peak flows than streams south of the Divide. The 25-year flood runoff can be expected to range from 6.4 to 15 cfs/mi^2 in the Kawishiwi River Basin, north of the Divide, and from 8.4 to 22 cfs/mi^2 in the St. Louis River Basin, south of the Divide (Siegel and Ericson 1979). Total volume of streamflow is greater in the Kawishiwi system because a larger land area is drained.

Some differences in streamflow north and south of the Divide are caused by topography and physiography. Nine physiographic regions in the Study Area have been described in the geology and mineralogy section (Volume 3-Chapter 1), and will be referred to here (Figure 11).

Figure 11

Most of the area north of the Divide is within the Shallow Bedrock Moraine Physiographic Province, which has basins covered by thin and discontinuous glacial drift with frequent bedrock exposures and steep topography. Streams in this type of area would be expected to exhibit "flashy" and widely variable flows (Garn 1975). This is not the case in most streams north of the Divide, however, because of the large amount of surface storage which regulates streamflow.

The Kawishiwi River watershed has a high density of lakes and wetlands. Over 53 km of the river's 120 km is taken up by on-channel lakes. Records from stations K-7 and K-4 confirm that the Kawishiwi flow is well regulated by the lakes. At station K-3 near Winton, the Kawishiwi is regulated by a power plant dam. During

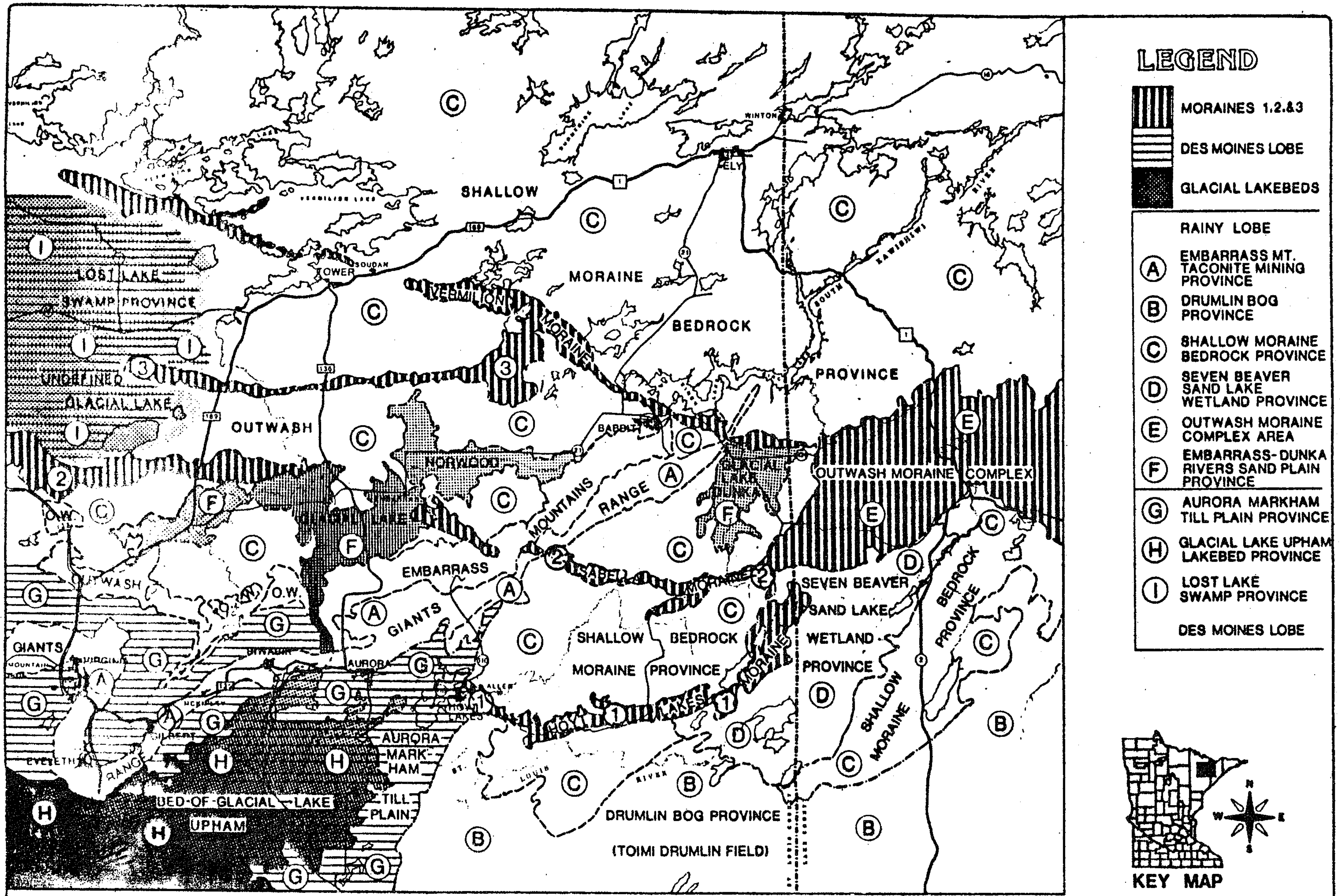


FIGURE 11

MEQB REGIONAL COPPER-NICKEL STUDY

PHYSIOGRAPHIC PROVINCES & GLACIAL FEATURES low flow periods, the river is largely regulated at the dam (Siegel and Ericson 1979).

Flood flows are reduced at stations BI-1 and Sh-1 on the Bear Island and Shagawa rivers because of large lakes in the watersheds. However, flow is not well sustained in these streams despite the presence of the lakes (Siegel and Ericson 1979). The Isabella River is regulated by lakes in its watershed (Garn 1975).

The Dunka River responds more quickly to precipitation events than do most streams in the Kawishiwi system, probably because of lack of surface water storage (Garn 1975). The largest percentage of annual flow occurs in April, instead of May, which is typical of other streams in the Study Area. Ground water discharge to the Dunka River has been reduced by diversion of flow into mine pits, although some of this water is returned to the river by mine-pit dewatering (Siegel and Ericson 1979, Benzie 1977).

South of the Laurentian Divide a larger number of physiographic provinces are represented. Although a substantial portion of the area is within the Shallow Bedrock Moraine Province, much of the area is characterized by thicker glacial deposits which provide more groundwater storage. There are fewer lakes and more bogs south of the Divide. Thirty-two percent of the area south of the Divide is bogs, compared to 14 percent in the north (MLMIS 1969). These bogs sustain baseflow and reduce flood peaks, but not to the same extent as lakes in the Kawishiwi system. Most of the mining activity in the region is south of the Divide in the Embarrass Mountain Taconite Mining Province.

The St. Louis River Watershed has a high density of wetlands, particularly in the upper end, and streamflow is quite well regulated. Partridge Reservoir in the

Partridge River Watershed supplements low flows in the St. Louis River via seepage losses (Garn 1975).

The Partridge River Watershed is 19 percent taconite mineland (MLMIS 1977). Second Creek, a tributary to the Partridge River, has the most uniform flow of the gaged streams south of the Divide because it receives mine pit water. The Partridge River flow is also stabilized by pit dewatering. Diversion of flood runoff into Partridge Reservoir occasionally reduces peak flows in the Partridge (Siegel and Ericson 1979).

A large amount of groundwater is stored in the Embarrass River Watershed, but not enough is discharged to sustain high baseflows in the river. The Embarrass River has the most variable flow of all the gaged streams south of the Divide because of its poorly sustained baseflow and lack of surface storage (Siegel and Ericson 1979).

4.2.3.5 Historical Streamflow Record. Table 3 includes data on average, minimum, and maximum annual flows of record compared to flows during the 1976 and 1977 water years for 14 stations on 11 streams in the Study Area. Lower than average flows were exhibited by most streams during both of these years, in response to low precipitation in the summer of 1976 and the winter of 1977.

In the 1976 water year (October 1975–September 1976), average flow for gaged streams in the region was normal to low. The Stony River at SR-2 was an exception, with a higher than average flow. The Dunka and Bear Island rivers and Second Creek experienced average flows, while in the Shagawa, Kawishiwi, Partridge, and St. Louis rivers, lower than average annual flows occurred.

The record minimum flow for a stream station, as given in Table 7, is the lowest instantaneous flow ever recorded at that station. In water year 1976, many streams exhibited minimum flows equal to, or just slightly above, their minimum flows of record. These streams were the Stony, Isabella, Shagawa, and Dunka rivers, Filson Creek, and the Kawishiwi River at two of three stations. The Partridge River flow at P-1 reached a new record low in 1976. The minimum flow at two stations, St. Louis at SL-1, and Kawishiwi at K-7, was much higher in 1976 than the minimum flow of record.

The record maximum flow of a stream in Table 7 is the highest instantaneous flow that has been recorded for that stream. In water year 1976, most of the peak flows were substantially less than the peak flows of record. The Stony River exceeded its previous record, however, and the Isabella River and Kawishiwi River at K-6 equalled their previous records. Filson Creek and the Kawishiwi River at K-7 experienced flows slightly lower than their record peak flows. Peak flows at the remaining stations in 1976 were much lower than record peak flows.

In the 1977 water year (October 1976-September 1977) all gaged stations experienced average annual flows that were lower than average flows of record, and lower than the average flows of water year 1976. Similarly, minimum flows in the 1977 water year were, in general, lower than the 1976 minimum flows. Five stream stations experienced new record low flows in 1977: Bear Island River at BI-1, Shagawa River at SH-1, Kawishiwi River at K-6, Partridge River at P-1, and Second Creek. Low flows at the remaining stations were equal to or slightly higher than low flows of record.

Maximum flows in water year 1977 were almost all lower than maximum flows in 1976. All peak flows in 1977 were much lower than the record peak flows.

4.2.4 Lake Hydrology

Seven percent of the surface of the Water Quality Research Area is water, and most of this is in the form of lakes (MLMIS 1969). Three hundred and sixty lakes greater than 10 acres in size are located in the Study Area (Minnesota Department of Conservation 1968). The locations of the 26 lakes monitored by the Copper-Nickel Study are shown in Figure 5. These lakes were chosen to represent a range of size and position in the watershed.

Water that recharges lakes is from precipitation, groundwater, streamflow, and overland runoff. Lake levels vary as inputs vary, but because of the ability of lakes to store water, lake levels change much less quickly than stream flows. Many lakes in the Research Area are headwater lakes, however, with small drainage basins. The level of these lakes could be lowered during periods of little precipitation or sustained large appropriations.

Lake levels fluctuate naturally during the course of a year. If the level of a lake is lowered excessively, the biologically productive shallows along the shoreline will be exposed. This may cause the amount of food available to aquatic organisms to be reduced, and fish spawning habitat to be reduced or eliminated. Lowering lake levels could also affect human water use. A number of industries depend on lake water for operation, and many different kinds of recreational activities occur on or near lakes in the Study Area.

Lake levels could fluctuate if a lake were used as a reservoir for copper-nickel milling or smelting. Appropriation from a lake would not necessarily lower the lake level, though, if the appropriation rate were less than the rates of inflow and evaporation.

Lake morphometric parameters are helpful in assessing potential impacts on lakes by copper-nickel development. Table 8 shows the values of some of these parameters for the lakes studied.

Table 8

4.2.5 Groundwater Hydrology

Groundwater is water located in the zone of saturation below the earth's surface. It occurs in aquifers, which are consolidated or unconsolidated rock materials with sufficient porosity and water-yielding ability to permit the removal of water at useful rates. Openings in which water can occur are pores between individual particles, as in sand and gravel; and crevices, joints, or fractures in hard rock (Gray 1970).

Garn (1975) has described the groundwater resources in the Superior National Forest, which includes most of the Research Area, as follows:

> Good groundwater aquifers generally do not occur over extensive areas of the Forest. Bedrock across the Forest is generally massive and yields only small supplies of water, its occurrence being limited to joints, fractures, and faults. Rocks of the Duluth Complex, Giants Range and Vermilion granite, Ely greenstone, and Soudan iron formation, and metasedimentary rocks of the Knife Lake Group—most of the major rock types of the Forest—may yield only 5-15 gallons per minute, sufficient only for rural domestic supplies. The Biwabic Iron Formation is an exception; altered parts of the formation yield up to 1,000 gallons per minute.
>
> The best groundwater supplies are obtained from stratified sand and gravel zones in glacial drift, where the saturated thickness of the drift is sufficient. Yields of up to 1,000 gallons per minute may be obtained from these deposits. The extent and permeability of the drift varies greatly across the Forest, depending on conditions of deposition, and groundwater may be difficult to locate. Thick deposits commonly occur in glacial and preglacial drainageways and in filled-in depressions of the bedrock surface.

Table 8. continued

[a] See Mustalish et al. (1978) for additional morphometric data.

[b] See Figure 5 for locations.

[c] Mean Annual discharge--Lake discharge can be assumed to be equal to inflow, if evaporation and changes in storage are ignored. The ten-year average was calculated as (Ramquist 1977, personal communication):

$$\mathrm{Log}_{10} Q = 0.9504\ \mathrm{Log}_{10}\ X - 1.9586$$

where: Q = lake discharge in m^3/sec
X = lake drainage area in km^2

The March 1, 1976, through February 28, 1977, average was calculated as:

$$\mathrm{Log}_{10} Q = 1.09\ \mathrm{Log}_{10}\ X + 5.15$$

where: Q = lake discharge in m^3/yr
X = lake drainage area in km^2

[d] Flushing Rate--The amount of time it takes for all the water in a lake to be replaced by new water, calculated by dividing mean annual discharge by volume. Toxic metals may accumulate in lakes with slow flushing rates. The residence time of water in a lake may be a number of years, which contrasts sharply with the residence time of water in a flowing stream.

[e] Stratification--Water in some lakes separates into layers characterized by different temperatures and oxygen content. Shortly after the ice melts, lakewaters are 0°C from top to bottom. Heating from the sun warms the surface waters so that some lakes become increasingly colder with depth. Lakes with cold bottom waters and warm surface waters are considered to be thermally stratified in midsummer. In the fall, or in both spring and fall, the waters mix (or undergo "turnover") and then become stratified again. Monomictic lakes exhibit one annual turnover. Dimictic lakes have two turnovers, and may be strongly dimictic with well defined thermal and oxygen profiles; or weakly dimictic, with less well-defined profiles (Ruttner 1952). Toxic materials, depending on their temperature when discharged, may become trapped and accumulate in the hypolimnion (lower layer) or float across the surface during stratification. When turnover occurs, these substances may get mixed throughout the lake. Since mixing occurs during spring and fall, which are spawning seasons, the potential for impacts on the fish population may be great.

[f] Ten year average.

[g] March 1, 1976 through February 28, 1977 average.

Table 8. Characteristics of monitored lakes in the Copper-Nickel Study Area.[a]

LAKE[b]	WATERSHED	DRAINAGE AREA (km^2)	MEAN ANNUAL DISCHARGE[c] Q×10^6 (m^{3}yr^{-1})		VOLUME V×10^6(m^3)	FLUSHING RATE[d] e (yr^{-1})		STRATIFICATION[e]
Greenwood	Stony River	105.7	29.10[f]	18.0[g]	6.43	4.53[f]	2.80[g]	Does not stratify
Sand	Stony River	41	11.82	6.72	2.98	3.97	2.56	Does not stratify
South McDougal	Stony River	37.4	10.84	6.11	.57	19.02	10.72	Does not stratify
Slate	Stony River	466	119.19	84.12	1.45	82.20	58.07	Does not stratify
Bear Island	Bear Island River	85	23.66	14.3	75.46	.31	.19	Strongly dimictic
Perch	Bear Island River	3.2	1.05	.47	1.01	1.04	.47	Weakly dimictic
Birch	Kawishiwi River	2536	596.36	490	106.18	5.62	4.61	Does not stratify
Gabbro	Kawishiwi River	1034	254.22	193	13.27	19.16	14.54	Does not stratify
White Iron	Kawishiwi River	2779	650.55	539	83.13	7.83	6.48	Weakly dimictic
August	Kawishiwi River	9.6	2.98	1.48	2.20	1.35	.67	Does not stratify
Clearwater	Kawishiwi River	9.2	2.86	1.42	19.39	.15	.07	Does not stratify
Lake One	Kawishiwi River	638	160.66	117	33.30	4.83	3.51	Strongly dimictic
Turtle	Kawishiwi River	6.4	1.95	.97	1.55	1.22	.63	Does not stratify
Fall	Kawishiwi River	3489	807.59	683	35.70	22.62	19.13	Weakly dimictic
Colby	Partridge River	332	86.31[f]	59.2[g]	7.00	12.33[f]	8.46[g]	Weakly dimictic
Big	Partridge River	9.2	2.87	1.42	4.92	.58	.29	Weakly dimictic
Seven Beaver	St. Louis River	157	42.38	27.1	8.24	5.14	3.29	Does not stratify
Pine	St. Louis River	14.8	4.50	2.33	4.14	1.09	.56	Does not stratify
Long	St. Louis River	21.6	6.43	3.45	.90	7.14	3.83	Does not stratify
Whiteface Reservoir		337	87.59	60.1	54.19	1.62	1.11	Weakly dimictic
Tofte		1.7	.56	.25	5.09	.11	.05	Monomictic
Triangle		5.5	1.75	.83	5.29	.33	.16	Strongly dimictic
Bass		13	3.97	2.03	3.77	1.4	.54	Strongly dimictic
Bearhead		13.1	4.01	2.05	12.31	.33	.17	Weakly dimictic
Wynne		374.9	96.93	67.1	12.80	7.57	5.24	Strongly dimictic
Cloquet		5.8	1.86	.88	.63	2.95	1.40	Does not stratify

Figure 12 shows both an unconfined (water table) aquifer and a confined (artesian) aquifer. The water table defines the level of water in an unconfined aquifer. The shape of the water table is a subdued replica of the topographic surface. Recharge of this type of aquifer occurs through percolation of precipitation over the major portion of the aquifer (Gray 1970). The water table fluctuates due to variations in precipitation, but response time ranges from 1½-6 months in and adjacent to areas of potential copper-nickel development. Unconfined aquifers discharge to streams, lakes, and wetlands, and help sustain baseflow in the region. Surficial deposits of till, peat, sand, and gravel, plus some bedrock formations, are unconfined water bearing materials in the region (Siegel and Ericson 1979).

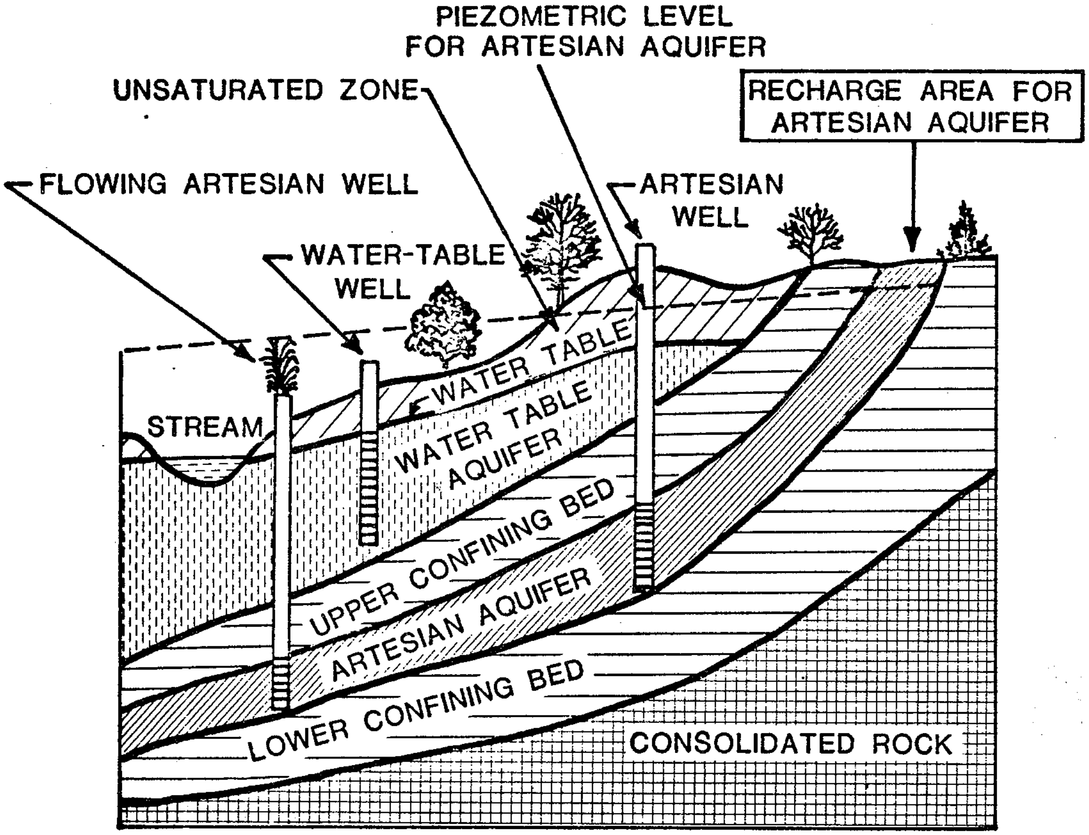
Figure 12

In a confined, or artesian aquifer, groundwater is under pressure, because it is confined between impermeable layers of rock material (see Figure 12). In the Study Area, most bedrock aquifers are confined aquifers. Water occurs in joints, fractures, and leached zones in the bedrock. Recharge is from infiltration of precipitation in outcrop areas and from leakage of overlying surficial deposits.

Because water in a confined aquifer is under pressure, it can discharge as springs or flowing wells, rising to a height called the piezometric surface (see Figure 12). Discharge will also occur where the aquifer outcrops at elevations less than the piezometric surface, such as in a mine. Taconite mines in the Study Area must be pumped continually to remove water discharged to them from surficial and bedrock aquifers. The extent of groundwater discharge from bedrock aquifers in most of the region is minimal because fractures and other openings

FIGURE 12

CONFINED AND WATER TABLE AQUIFERS



(ADAPTED FROM GRAY 1970)

are few and discontinuous. In some areas, the taconite beds are leached, providing substantial secondary porosity, and large discharges are possible (Siegel and Ericson 1979).

Groundwater moves slowly through aquifers from areas of recharge to areas of discharge. The rate of movement depends on the hydraulic conductivity of the aquifer material, and the hydraulic gradient (slope) of the water table or piezometric surface. Hydraulic conductivity (K) is determined by the particle size distribution and degree of stratification of the aquifer material. Water moves slowly through till and peat, and relatively quickly through sand and gravel. Estimated hydraulic conductivities in the Study Area are 10 to 3,500 ft/day in sand and gravel, 0.01 to 30 ft/day in till deposited by the Rainy Lobe, and 10^{-5} to 10^{-1} ft/day in till deposited by the Des Moines Lobe and peat (Siegel and Ericson 1979). Locations of geologic units are given in Volume 3-Chapter 1.

Vertical movement of groundwater can occur between aquifers. In the Copper-Nickel Study Area, recharge to surficial aquifers from underlying bedrock aquifers is generally not important, because the bedrock units are relatively impermeable. In the southern part of the region, near Aurora, however, semiconfined sand and gravel aquifers may discharge groundwater to overlying aquifers where confining beds are discontinuous (Siegel and Ericson 1979).

The volume of groundwater available for human use depends on the rate of water movement, and also on the size of the aquifer. Standard engineering practice in well-field design is to limit drawdown at a pumping well to two-thirds of the saturated thickness of the aquifer.If the saturated thickness of a formation is low, if the volume of the formation is small, or if water movement is slow, the withdrawal rate must be slow to avoid exceeding the capacity of the aquifer. Most aquifers in the Study Area can supply only small volumes of water, suitable for domestic supplies (Siegel and Ericson 1979).

Most of the current groundwater withdrawal in the region is caused by dewatering of taconite mines. This water is usually not consumed, but is discharged to surface water. Mine dewatering will likely increase if copper-nickel mining occurs. Rock material near the contact generally has a low permeability, however, so the potential for substantially lowering groundwater levels is low (Siegel and Ericson 1979).

Surface water can be unintentionally diverted into an open pit or underground mine that is located in deposits which connect to an aquifer underlying a river basin. Water from the Dunka River is presently diverted through the groundwater system to an open-pit mine (Erie Mining Co. Dunka Pit) north of the river at a rate of 300 to 500 gal/min (Siegel and Ericson 1979, Eger 1978).

Recharge to groundwater systems could be reduced if a mining operation were located on an area where infiltration previously occurred. This could reduce the baseflow of streams and lower the local water table.

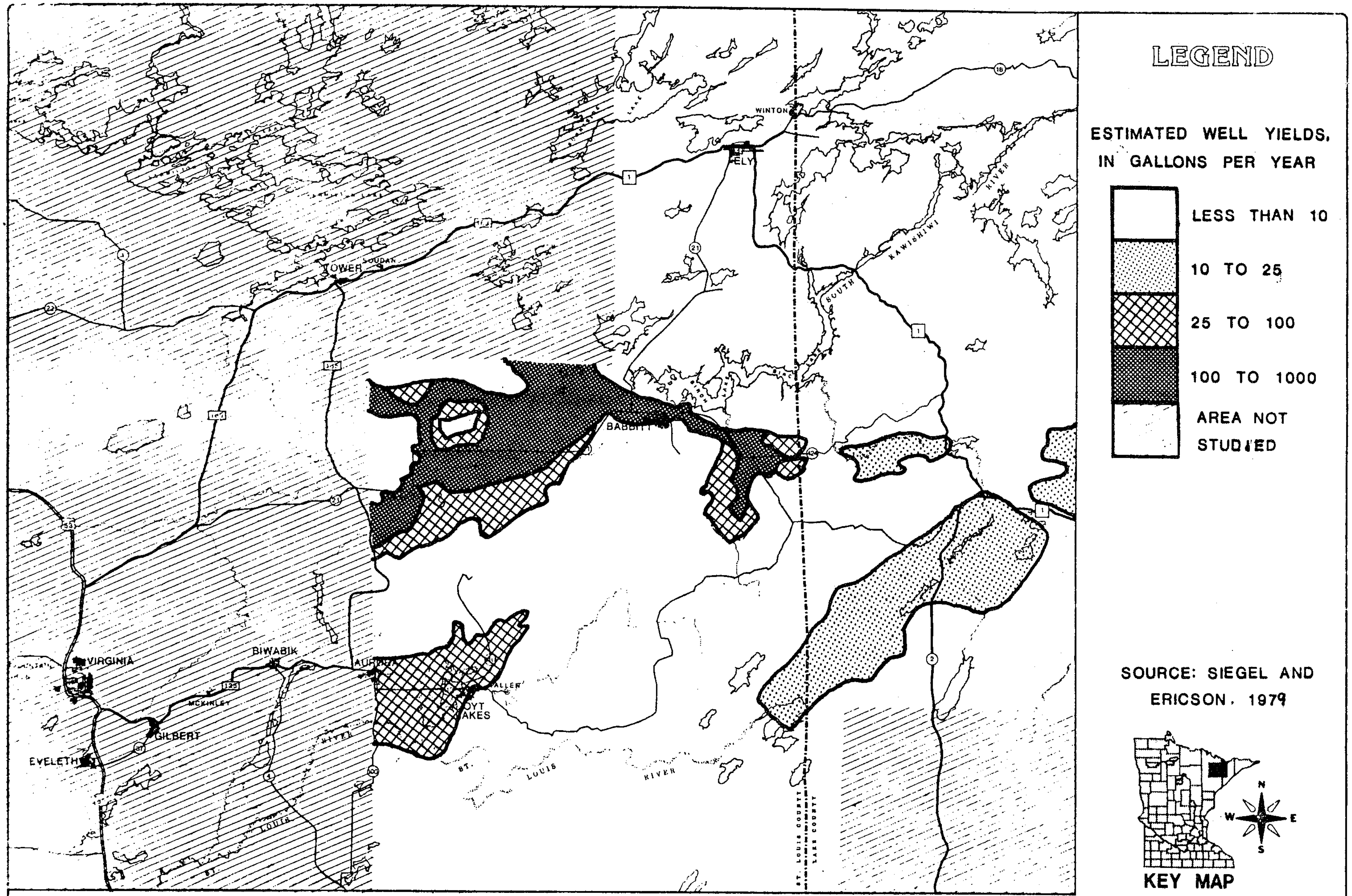
4.2.5.1 Spatial Variation of Groundwater Availability. The USGS has determined groundwater availability by physiographic area in and adjacent to areas of potential copper-nickel development (Siegel and Ericson 1979)(Table 9 and Figures 11 and 13). Physiographic areas are discussed in more detail in Volume 3-Chapter 1 and in Olcott and Siegel (1978).

Table 9, Figure 13

Table 9. Groundwater availability by physiographic area.

PHYSIOGRAPHIC AREA	WATER-BEARING UNITS	GENERAL AQUIFER THICKNESS (ft)	ESTIMATED POTENTIAL YIELD TO WELLS (gal/min)
Shallow Bedrock-Moraine Area	till upon fractured bedrock	10 ft of till; 100 ft of bedrock	5
Drumlin-Bog Area	till, discontinuous lenses of sand and gravel within till	50	5
Embarrass-Dunka Rivers Sand Plain Area	sand and gravel	50 to 200	5 to 1,000
Outwash-Moraine Complex Area	till, sand, and gravel lenses	15	5 to 25
Seven Beaver-Sand Lake Wetland Area	till, sand, and gravel lenses	15	5 to 25
Aurora-Markham Till Plain Area	sand and gravel	50 to 150	10 to 300
Embarrass Mountains Taconite Mining Area	Biwabik Iron Formation	300±	100 to 1,000

SOURCE: Siegel and Ericson, 1979.



SOURCE: SIEGEL AND ERICSON, 1979

1:422 400

MILES 0 1 2 3 4 5 10

KILOMETERS 0 1 2 3 4 5 10 16

FIGURE 13 **MEQB REGIONAL COPPER-NICKEL STUDY**

ESTIMATED AVERAGE YIELDS OF WELLS IN SURFICIAL AQUIFERS IN AND ADJACENT TO AREA OF POTENTIAL COPPER-NICKEL DEVELOPMENT

Much of the Study Area is within the Shallow Bedrock Moraine Physiographic Area. This region is characterized by thin glacial drift and numerous bedrock outcrops. Groundwater movement is slow through most of the area, and flow is disrupted by bedrock outcrops. Volume of flow is limited because saturated thickness is generally less than ten feet. Groundwater potential may be fair in localized deposits, but is poor in the region as a whole, and well yields are generally low.

The Outwash Moraine Complex Area, most of which is north of the Laurentian Divide, is characterized by knobby hills and kettle lakes resulting from slow melting of ice blocks buried in glacial drift (Olcott and Siegel 1978). Groundwater is restricted to numerous small deposits of sand and gravel, generally less than 15 feet thick. Except in a few areas, yields of wells from these deposits are estimated to be low, from 5 to 25 gal/min (Siegel and Ericson 1979).

The Embarrass-Dunka Rivers Sand Plain Area straddles the Laurentian Divide, and includes the basins of the Embarrass and Dunka rivers. Some of the thickest surficial deposits in and adjacent to the area of potential copper-nickel development are located in this region (Olcott and Siegel 1978); these deposits have the best potential for future groundwater development of any aquifer in the area. Groundwater moves quickly from recharge areas towards the Embarrass and Dunka rivers, and contributes to the flow of these rivers. Well yields as high as 1,000 gal/min are possible from coarse gravel deposits in the region (Siegel and Ericson 1979).

The Embarrass Mountains-Taconite Mining Physiographic Area consists of the Giants Range Granite flanked on the southeast by the Biwabic Iron Formation (Olcott and

Siegel 1978). Small amounts of groundwater are available from wells in the granite and overlying drift and are useful only for domestic supplies. Wells in the Biwabik Iron Formation can yield large amounts of water, more than 1,000 gal/min, in local fractured and leached zones (Siegel and Ericson 1979). Most of the Embarrass Mountains-Taconite Mining area is located south of the Laurentian Divide.

The Aurora-Markham Till Plain Area, in the southwestern part of the region, is an area of red clayey till. Underneath the till is older bouldery till, which overlies bedrock. Well yields from outwash deposits in the older till should be about 100 gal/min where the aquifer is thickest. Deep wells that tap fracture zones in the Biwabik Iron Formation may yield as much as 300 gal/min (Siegel and Ericson 1979).

A large area south of the Laurentian Divide is within the Drumlin-Bog and Seven Beaver-Sand Lake Physiographic Areas. The drumlins consist of compacted clayey till that rests on bedrock, and the interspersed bog areas are underlain by sand, peat, and bedrock. Buried sand and gravel lenses beneath the bogs could yield as much as 25 gal/min for short periods; however, sustained yields may not be possible because of limited recharge through the relatively impermeable till and peat. Wells in till and bedrock yield less than 5 gal/min (Siegel and Ericson 1979). In general, the potential for large groundwater supplies is low in the area (Garn 1975).

Throughout much of the region, ground water supplies are inadequate for municipal or industrial uses. Supplies are best in thick sand and gravel deposits (see Table 9) which are not widespread. The best potential groundwater sources are in the Embarrass-Dunka Sand Plain Physiographic Area where old bedrock valleys are now filled with sand and gravel deposits (Olcott and Siegel 1978).

4.2.6 Water Use

Water use in and adjacent to areas of potential copper-nickel development in 1975 and 1976 is summarized in Table 10. Annual water use was nearly constant at about 200 to 250 billion gallons during 1971 through 1975. During the drought in 1976, water use was only 170 billion gallons per year (Siegel and Ericson 1978). More detailed data for 1971 through 1976 can be found in Siegel and Ericson (1979).

Table 10

Surface water is currently the major source of water in the area. According to Table 10, about 96 percent of the water used in the region is drawn from surface sources. Almost 97 percent of the surface water used from 1971 to 1976 was used for electric power generation. Minnesota Power and Light Company maintains a hydroelectric power plant on the Kawishiwi River just upstream from Fall Lake and a thermoelectric power plant near Colby Lake. This water use is primarily nonconsumptive, since most of the water is returned to lakes or streams. Mining operations used about three percent of the total surface water withdrawn (consumptive use); Erie Mining Company was the largest user. Municipal supplies, campgrounds, irrigation, and other water users withdrew less than one percent of the total surface water withdrawn in the region (Siegel and Ericson 1979).

Taconite mining operations accounted for about 95 percent of the total groundwater use from 1971 to 1976. These operations are located in the Unnamed Creek,

Table 10. Water use in and adjacent to areas of potential copper-nickel development[a], 1975 and 1976[b]. (Source: Siegel and Ericson 1979).

USE CATEGORY AND USER	WATER USE IN MILLION GALLONS 1975 Surface	1975 Ground	1975 Total	1976 Surface	1976 Ground	1976 Total	CONSUMPTIVE OR NON-CONSUMPTIVE USE[c]	DISPOSAL
Municipal Supply System								
Village of Aurora		132.5	132.5		140.9	140.9	U	Treatment plant; creek to St. Louis R.
Village of Babbitt		107.2	107.2		128.1	128.1	U	Treatment plant; Embarrass River
City of Ely	409.4		409.4	409.4		409.4	U	Treatment plant; Shagawa Lake
Village of Hoyt Lakes	121.7		121.7	149.2		149.2	U	Treatment plant; Colby Lake
Village of Winton	7.4		7.4	8.8		8.8	U	Treatment plant; swamp to Fall Lake
TOTALS	538.5	239.7	778.2	567.4	269.0	836.4		
Rural supply, Self-supplied domestic, stock watering, and tourism (total)	.3	196.6	196.9	.3	195.2	195.5	U	Mainly returned to aquifer via private sewage systems
Irrigation (total)	2.3		2.3	9.9		9.9	C	Evaporation to atmosphere
Hydroelectric power-MN Power & Light Co., Winton Dam	149,082.0		149,082.0	104,163.2		104,163.2	N	Fall Lake
Thermoelectric power-MN Power & Light Co.	49,289.9		49,289.9	50,237.0		50,237.0	N	Colby Lake and Partridge River
Mine dewatering								
U.S. Steel-Stephens Mine		431.3	431.3		1,016.6	1,016.6	N	Second Creek
Pittsburg Pacific Co.- Lincoln (D Mine) and Knox Mine		1,374.5	1,374.5		1,089.7	1,089.7	N	Second Creek
Erie Mining Co.- several mines		3,907.6	3,907.6		3,396.9	3,396.9	N	Wyman Creek and First Creek to Second Creek; Unnamed Cr. to Dunka R.
Reserve Mining Co.- Peter Mitchell Mine		4,553.9	4,553.9		3,056.1	3,056.1	N	Unnamed Creek and Langley Creek to Dunka River; Partridge River
TOTALS		10,267.3	10,267.3		8,559.3	8,559.3		
Mine Processing & Operations and Potable Supply								
U.S. Steel-Stephens Mine Well		.6	.6		.3	.3	U	Second Creek
Pittsburg Pacific Co.	71.0		71.0	15.3		15.3	U	First Creek to Second Creek
Erie Mining Co.	4,637.2		4,637.2	5,856.8		5,856.8	C	Colby Lake
Reserve Mining Co.	35.4	.7	36.1	31.1		31.1	U	Langley Creek and Unnamed Creek to Dunka R.; evaporation to atmosphere
AMAX			——	2.9		2.9	U	Evaporation, infiltration
TOTALS	4,743.6	1.3	4,744.9	5,906.1	.3	5,906.4		
Other Industrial		1.9	1.9			——	U	Infiltration to aquifer
TOTAL FOR AREA	203,656.6	10,706.8	214,363.4	160,883.9	9,023.8	169,907.7		

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[a] Area shown in Figure 1.

[b] Siegel and Ericson (1979) includes additional data for 1971-1976.

[c] C=primarily consumptive use; N=primarily non-consumptive use; U=unknown.

Dunka River, and Partridge River watersheds. Mine pit dewatering accounts for most of the mining-related groundwater withdrawal; much of this water is returned to surface water. Unnamed Creek, Dunka River, and Partridge River (via Second Creek) are recipients of mine pit water. About 5 percent of the groundwater use in the region is by municipal and rural water systems, and about one-half of this use is by the villages of Aurora and Babbitt (Siegel and Ericson 1979).

Future water use in the region will depend on the adequacy of stream flow, surface storage, and groundwater supplies. Figure 14 indicates the probable source(s) of water for large users in northeastern Minnesota. The aquifer underlying the Embarrass River Valley could easily supply the projected increased population in the Babbitt area due to copper-nickel mining and expanded taconite production in the year 2000.

Figure 14

4.3 REGIONAL WATER QUALITY CHARACTERIZATION

To assess the potential impact of copper-nickel mining on water quality, the existing quality of the region's water must be understood. Because little information regarding water quality of the region was available prior to this study, a comprehensive regional monitoring program was conducted for three main purposes:

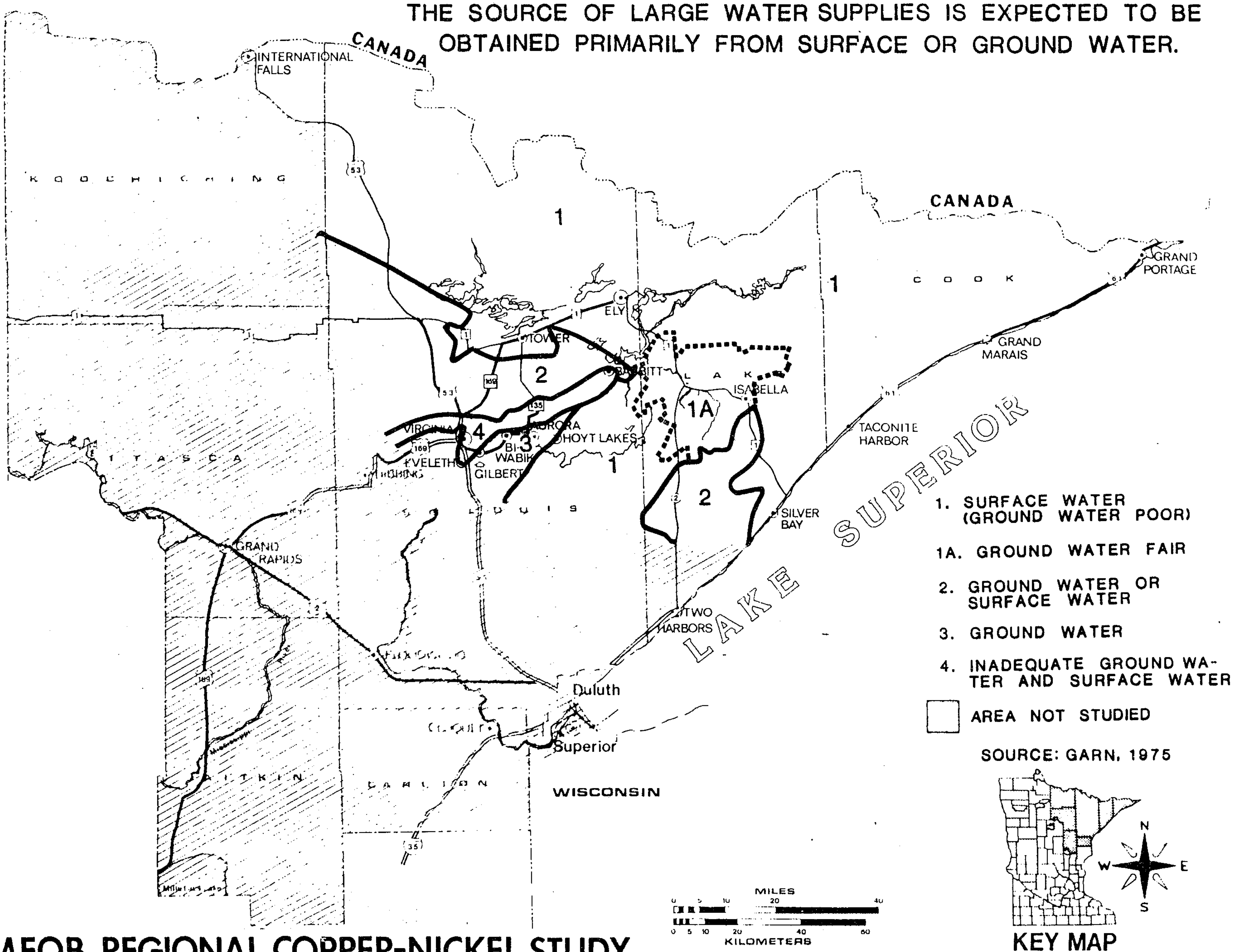
--Begin the long-term process of gathering environmental data for the establishment of a pre-development environmental baseline against which change resulting from development can be assessed.

--Characterize the surface and groundwater quality in the Study Area.

--Assess the susceptibility of the surface waters to potential impacts from copper-nickel mining and associated development.

FIGURE 14

GENERAL AREAS IN THE SUPERIOR NATIONAL FOREST WHERE THE SOURCE OF LARGE WATER SUPPLIES IS EXPECTED TO BE OBTAINED PRIMARILY FROM SURFACE OR GROUND WATER.



SOURCE: GARN, 1975

MEQB REGIONAL COPPER-NICKEL STUDY

Nine major watersheds north of the Laurentian Divide and five south of the Divide were monitored (Table 4). The total drainage area studied north of the Divide is 3,489 km^2 (1,347 mi^2) compared to 1,249 km^2 (482 mi^2) south of the Divide. Watershed boundaries are shown in Figure 2.

Surface water quality of the Study Area was sampled from March, 1976, through September, 1977. Thirty-two stream sites and 35 lake stations were established (Figure 5). The primary intent was to establish sites representing a cross-sample of terrestrial, topographic, and anthropogenic features which presumably affect water quality. During the second year of the program, samples were also collected from rainstorm events and spring melt. Groundwater quality in the Study Area was monitored by the U.S. Geological Survey (USGS).

Additional information from other sources was also used when appropriate. The U.S. Forest Service (1976) conducted a water monitoring program in the general area of Filson Creek under a cooperative agreement with INCO. Stream flow data collected by the USGS supplemented data collected by study staff. These two agencies also provided data on groundwater quality.

Water samples were collected according to acceptable methods of the Environmental Protection Agency, USGS, and the Minnesota Department of Health (MDH). Sample analysis was performed by the USGS (Denver), MDH, and University of Minnesota (see Table 11 for listing of parameters). Field measurements included water temperature, dissolved oxygen, specific conductance, secchi disk, and pH.

Table 11

Water quality data developed by this study can be used toward the establishment of a baseline. More monitoring information, especially of a site-specific

Table 11. Water quality parameter list.

General

- Residue: filterable and nonfilterable
- Turbidity
- Color
- TOC
- DOC
- Specific Conductance
- DO
- Temperature
- Secchi Disk
- pH
- Alkalinity

Metals, Nutrients, Cations, Anions

- Copper
- Nickel
- Zinc
- Cadmium
- Lead
- Iron
- Cobalt
- Aluminum
- Mercury
- Arsenic
- Selenium
- Titanium
- Phosphorus: Total & Ortho
- Nitrogen: Total, NO_2, NO_3, Kjd, NH_4
- Calcium
- Magnesium
- Manganese
- Potassium
- Sodium
- Chloride
- Sulfate
- Fluoride
- Bicarbonate

Others

- Oil & Grease
- MBAS
- Phenols
- BOD
- Fecal Coliforms
- Gross Alpha, Beta
- Chlorophyll a
- Barium

nature, is required before a statistically valid baseline can be established which addresses short- and long-term natural and existing anthropogenic variations.

More detailed information (including boxplots which illustrate the range of each sampled parameter at each stream site) for section 4.3 can be found in Thingvold et al. (1979) and Mustalish et al. (1978).

4.3.1 Quality of Surface Waters in the Regional Copper-Nickel Study Area

The various parameters have been organized into five general groupings for ease of presentation: (1) general parameters--calcium, chloride, color, magnesium, potassium, silica, sodium, specific conductance, hardness, turbidity, and total organic carbon; (2) parameters reflecting acidity and acid buffering--alkalinity, bicarbonate, pH, calcite saturation index (CSI), and sulfate; (3) nutrient parameters--total nitrogen, total phosphorus, and trophic state index (TSI); (4) mineral fibers; and (5) metals--aluminum, arsenic, cadmium, cobalt, copper, iron, lead, manganese, mercury, nickel, and zinc.

Statistical analysis of data indicated that six of the 32 stream sites had the highest levels for most chemical parameters. These six sites are divided into two groups: Group A--Bob Bay (BB-1), St. Louis-1 (SL-1), and Partridge-1 (P-1); and Group B--Partridge-2 (P-2), Embarrass-1 (E-1), and Dunka-1 (D-1) (see Figures 15 and 16). Group A and B stations are located in watersheds where significant human disturbance of the land has occurred. While human activities may be responsible for increased (or decreased) parameter values, natural geological and topographical conditions, such as weathering of outcrops of sulfide materials, cannot be overlooked. The remaining 26 sites, indicative of relatively undisturbed watersheds, were classified as Group C and can be considered indicative of background levels.

Figures 15 and 16

A comparison of the three groups of stations shows that the following parameters generally appear to be higher in Group A than Group B with both groups higher than Group C: alkalinity, bicarbonate, calcium, dissolved inorganic carbon (DIC), fecal coliform, filterable residue, fluoride, hardness, magnesium, manganese, nickel, ortho-phosphorus, pH, potassium, silica, specific conductance, sulfate, and total phosphorus. In contrast, the following parameters were higher in Group B stations than both Groups A and C: arsenic, barium, chemical oxygen demand (COD), chloride, color, complexing capacity, iron (both total and dissolved), lead, and total nitrogen. Four parameters were higher in Group C than Groups A or B: cyanide, dissolved organic carbon (DOC), hydrogen ion, and sodium. The remaining parameters showed little difference between site groups.

The lake data base was not large enough to permit a similar evaluation.

4.3.1.1 General Parameters. A summary comparison of general parameter monitoring results for the three stream classifications and lakes is presented in Table 12.

Table 12

Calcium concentrations in Study Area waters are generally low, probably due to the characteristics of the rocks and soils in the region. Streams north of the Laurentian Divide had lower levels (84 percent of the samples were at or below 10

FIGURE 15

▦ GROUP A STATIONS AND CORRESPONDING WATER SHEDS

☐ AREA NOT STUDIED

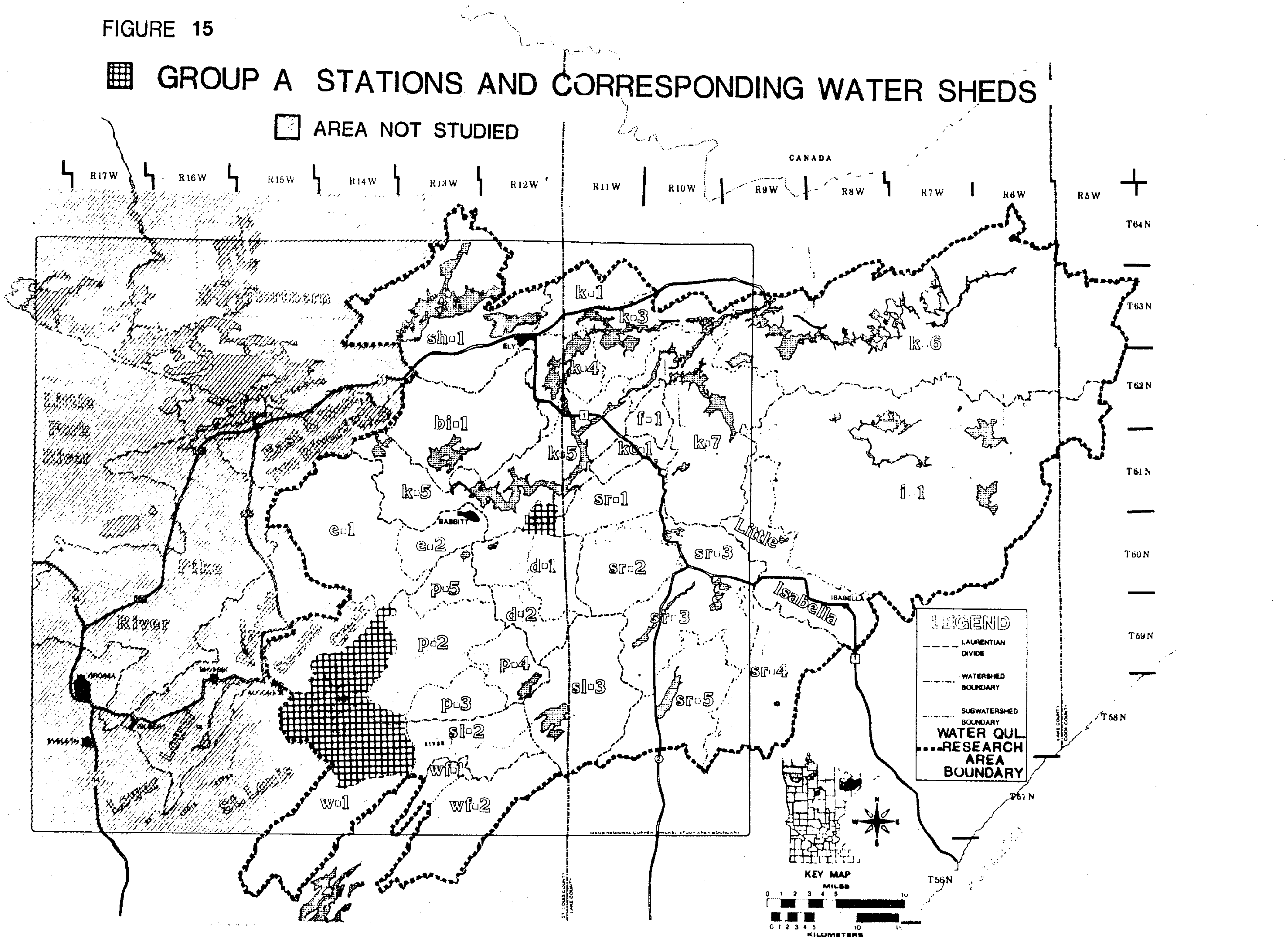


FIGURE 16

▨ GROUP B STATIONS AND CORRESPONDING WATER SHEDS

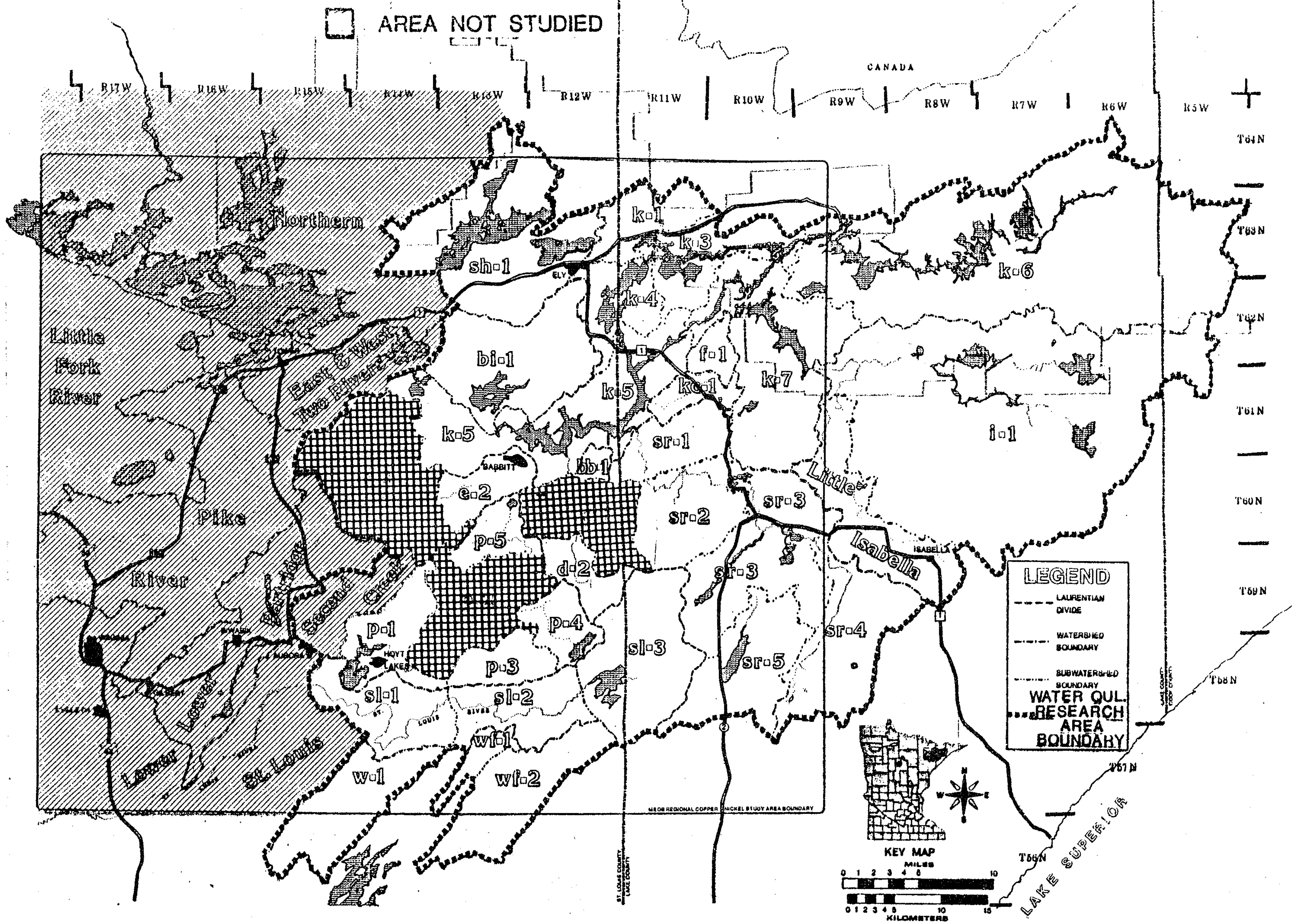


Table 12. Comparison of general water quality paramters for three groups of streams and lakes in the Regional Copper-Nickel Study Area (November, 1975, to April, 1977).

MONITORING STATIONS GROUPINGS*		A			B			C			LAKES		
Parameter	Units	Range	Median	N	Range	Median	N	Range	Median	N	Range	Median	N
Calcium (Ca)	mg/l	4.5-80	29	33	3.8-53	15	50	1.8-40	6.0	250	1.9-46	7.2	129
Chloride (Cl)	mg/l	2.8-38	9.1	55	2.9-88	17	65	0.08-41	1.6	342	0.1-9.3	1.6	94
Color	Pt-Co units	4-150	50	55	23-450	130	65	4-500	90.2	343	1-400	80	141
Magnesium (Mg)	mg/l	3-40	15	33	3-26	8	50	1-23	3	250	0.6-12.2	3.1	129
Potassium (K)	mg/l	1.0-8.4	2.3	33	0.3-5.2	1.6	36	0.2-6.2	0.6	241	0.2-2.2	0.6	84
Silica (Si)	mg/l	4.6-24	14	56	4.0-29	9.5	65	0.1-34	6.3	344	1-19	4.8	135
Sodium (Na)	mg/l	1.1-45	6.5	33	0.5-35	8.1	36	0.2-19	1.6	235	0.8-18	1.8	77
Specific conductance	micro-mhos/cm at 25°C	61-1198	323	55	12-655	181	65	24-524	55	343	24-389	65	141
Hardness	mg/l($CaCO_3$)	81-310	152	20	5.3-238	81.5	22	12-99	27.1	164	9-142	28.9	92
Turbidity	Jackson Turbidity Units	0.5-17	2.4	55	0.8-18	3.4	65	0.5-64	2.0	343	0.4-7	2.0	135
Total Carbon (TOC)	mg/l	4.7-20	10.1	6	11-22	18	5	0.4-45	15	69	4.6-38	14.0	142

*Group A stations Bob Bay-1, St. Louis R.-1, Partridge R.-1.
Group B stations Dunka R.-1, Partridge R.-2, Embarrass R.-1.
Group C stations Kawishiwi R.1-7, Bear Island R.-1, Isabella R-1, Filson Creek-1, Keeley Creek-1, Dunka R.-2, Stoney R.-5, St. Louis R-2 and 3, Partridge R.3-5, Embarrass R.-2, Whiteface R.-1 and 2, Water Hen Creek.

mg/l) than those to the south (29 percent at or below 10 mg/l). Lake calcium levels showed a similar trend when comparing those north of the Divide with those to the south.

Chloride concentrations were low and relatively constant over time throughout the region. Elevated levels were observed at Group A and B stations, and Partridge-5, and probably resulted from road salt (sodium chloride), dust suppressants (calcium chloride), or sewage effluent. Lake levels were similar to undisturbed streams.

The color of natural waters is caused by the presence of organic mateial (e.g. humus, peat, algae, weeds), organic acids, and some inorganic compounds (e.g. iron and manganese). In the Study Area, greater color was associated with two terrestrial characteristics--increasing soil depth and the presence of bogs in the watershed. These conditions are found, for the most part, in the southern portion of the Study Area between South McDougal Lake and Whiteface Reservoir. State and federal standards and criteria for color (10 Pt-Co units) were exceeded in many cases (Thingvold et al. 1979).

Magnesium is usually associated with calcium, but at lower concentrations. This was found to be true in the Study Area as magnesium was found at lower levels and showed trends similar to calcium.

Potassium levels were low and relatively constant over time. The highest levels were observed in disturbed watersheds. Lake levels were comparable to those in undisturbed streams.

Within the Study Area, spatial variations in silica (SiO_2) were closely related to the presence or absence of upstream disturbance. Stations downstream of mining (BB-1, SL-1, P-1, and P-5) exhibited the highest silica concentrations, although even these levels would have to be classified as low. The highest concentrations of silica in lakes were found in Gabbro and Wynne, with the lowest concentrations in Tofte and Clearwater. Lake levels tended to be less than those for undisturbed streams.

Sodium levels were low, with higher values observed in disturbed watersheds. Decreased sodium levels were observed in the Partridge River during periods of increased flows. Somewhat more limited dilutional effects were observed at peak of spring melt in the larger river systems, i.e. the Dunka, Stony, St. Louis, and Kawishiwi River systems.

Specific conductance is a general measure of water quality, and indicates the presence of ions, which conduct electrical current. Levels in Study Area streams and lakes were low, although disturbed streams had levels almost six times those of undisturbed streams. In at least one instance, the MPCA standard of 1,000 micromhos/cm was exceeded (Thingvold et al. 1979).

Hardness levels were low in most of the Study Area surface waters, hence these waters would be classified as "soft." Waters in disturbed watersheds (Groups A and B) had higher levels and would be classified as "moderately hard" to "hard." The Regional Study found that the toxicity of nickel to aquatic organisms decreased as hardness increased (Volume 4-Chapter 1).

Turbidity, a measure of suspended particulates in water, was found to be uniformly low in surface waters. No clear differences in stream groupings were evident.

Total organic carbon (TOC) is a measure of organic material in water. Organic compounds can bind metals, rendering some less toxic depending on a number of factors. Headwater stream stations generally showed higher TOC levels.

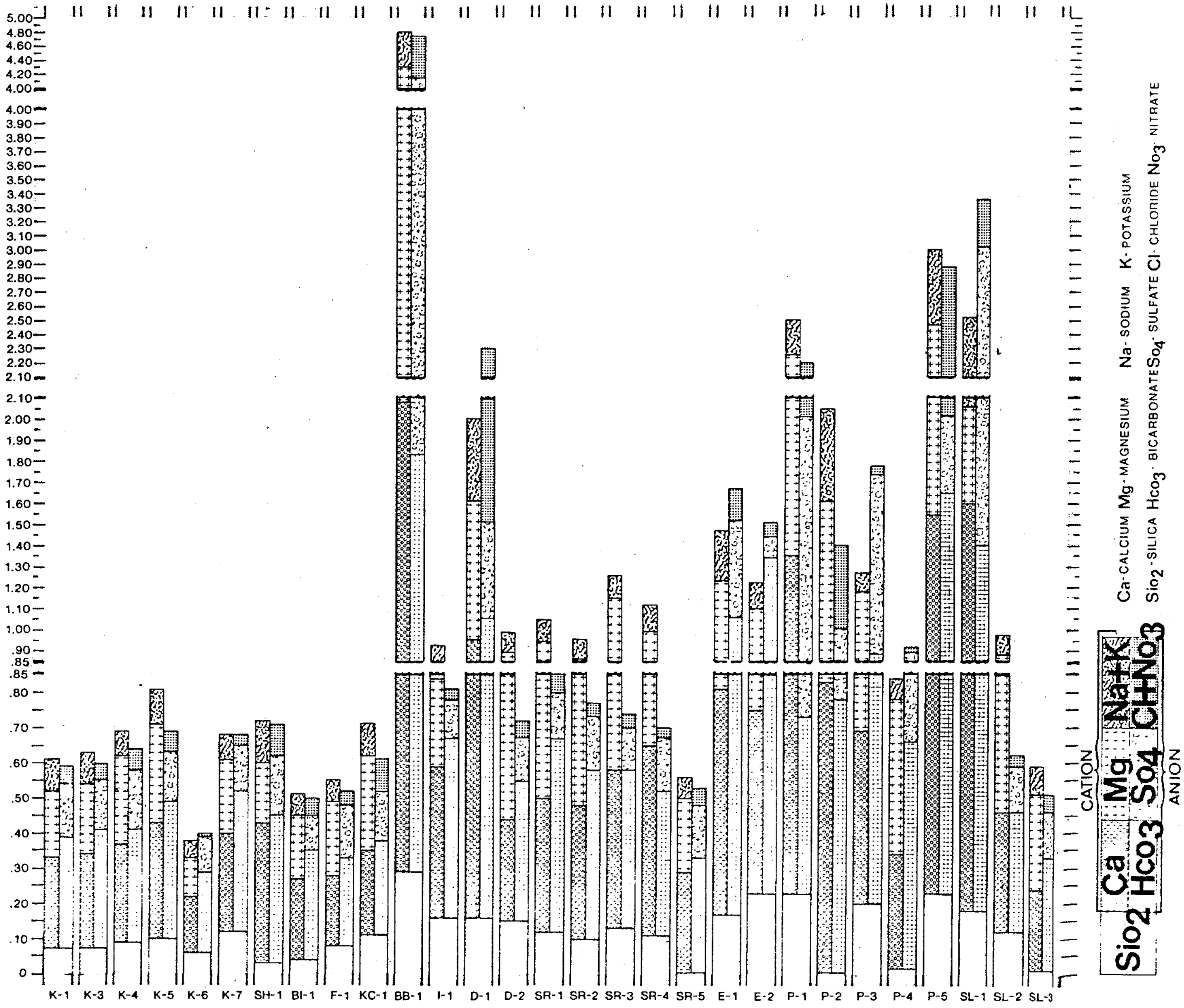
Summary Discussion--Median values for the major ions in streams of the Study Area are illustrated in Figure 17. This figure shows that Study Area waters are dominated by calcium as the major cation and carbonates as the major anion. The sum of the concentration of anions should be the same as for cations. The observed differences may be due to the analytical methods used and the possibility that ions other than those considered are important in Study Area waters. Cations exceeded anions in all waters studied except at stations K-6, D-1, E-1, E-2, and SL-1. In general, streams south of the Laurentian Divide had higher overall concentrations of major ions than those north of the Divide. Two exceptions to this, D-1 and BB-1, are downstream from mining operations.

Figure 17

Spatial variability of stream general parameters falls into a pattern of three distinct groups. Groups A and B streams are downstream of mining and had higher values for most parameters than Group C (relatively undisturbed) streams (Table 12). In most cases, levels at Group A stations were higher than those in Group A, an observation that probably indicates the relative amount of impact. While clear differences in the water quality of watersheds containing mining operations can be seen, sufficient data to prove a direct cause and effect relationship for all parameters are not available and was not the purpose of the Study's monitoring programs.

FIGURE 17

Major Ions in Streams



Throughout most of the year the concentration of most parameters is independent of flow. Two exceptions were at station P-1 (calcium and sodium) and the St. Louis River (calcium) where a distinct dilutional effect was caused by spring runoff and storm events. In two other instances (potassium at Isabella and sodium at K-5) there were slight indications that concentrations were increasing with flow.

Spatial variability of general parameters in lakes was more difficult to analyze because of limited data. In general, Tofte, Wynne, and Colby lakes showed the highest ionic concentrations. Clearwater Lake is notable for its low chloride, silica, and color levels.

Linear correlations of general parameters were examined in streams and lakes. While many correlations were expected, the most interesting relationship was the correlation of copper and nickel with calcium in lakes. The reason for this correlation (if it is real) is unknown. Correlations are discussed in more detail in Thingvold et al. (1979).

4.3.1.2 Acidity and Acid Buffering. Table 13 presents a summary comparison of parameters related to acidity and acid buffering for the three groups of streams and lakes.

Table 13

Alkalinity is a measure of a water's ability to neutralize acid. Study Area waters are generally low in alkalinity, many are below the National Technical Advisory Committee (1968) recommended minimum level of 20 mg/l. Because of the buffering effect of alkalinity and alkalinity's ability to complex some metals to

Table 13. Comparison of water quality paramters related to acidity and acid buffering for three groups of streams and lakes in the Regional Copper-Nickel Study Area (November, 1976, to April, 1977).

MONITORING STATIONS GROUPINGS*		A			B			C			LAKES		
Parameter	Units	Range	Median	N	Range	Median	N	Range	Median	N	Range	Median	N
Alkalinity	mg/l $CaCO_3$	11-140	71	56	13-160	45	65	1.0-190	19	336	1-73	19	141
Bicarbonate (HCO_3)	mg/l	14-148	54	29	16-134	65	24	6-151	22	204	9-88	20.5	38
Sulfate (SO_4)	mg/l	13-630	70	56	3.5-110	14	51	0.8-31	6.6	327	1-140	7.8	138
pH	$-\log_{10}[H^+]$	6.3-8.2	7.3	56	6.1-8.1	7.0	65	4.7-8.4	6.9	337	5.7-8.8	7.1	141

*Group A stations Bob Bay-1, St. Louis R.-1, Partridge R.-1.
Group B stations Dunka R.-1, Partridge R.-2, Embarrass R.-1.
Group C stations Kawishiwi R.1-7, Bear Island R.-1, Isabella R-1, Filson Creek-1, Keeley Creek-1, Dunka R.-2, Stoney R.-5, St. Louis R-2 and 3, Partridge R.3-5, Embarrass R.-2, Whiteface R.-1 and 2, Water Hen Creek.

reduce their toxicity, the National Academy of Sciences (1974) recommended that natural alkalinity not be reduced by more than 25 percent. For waters below 20 mg/l, alkalinity should not be further reduced (U.S. EPA 1976).

Bicarbonate (HCO_3^-) is a component of alkalinity and accounts for most of the alkalinity in Study Area surface waters. Higher bicarbonate levels were observed in Group A and B stations and P-5, possibly being related to anthropogenic disturbance of the land. Bicarbonate levels were very low in the Kawishiwi system. Tofte and Wynne lakes had the highest bicarbonate levels while Perch and Turtle had the lowest.

Sulfate ($SO_4^=$), the major form of sulfur in the aquatic environment, is derived from the oxidation of sulfide minerals and atmospheric deposition of sulfur-containing materials. Elevated levels were found in waters downstream from areas where accelerated oxidation of excavated/exposed sulfide deposits may be occurring due to mining operations, particularly at Group A stations. In at least one case, the measured level exceeded the MPCA standard of 250 mg/l for sulfate (Thingvold et al. 1979). Lake levels of sulfate were comparable to the low levels observed in undisturbed streams. Sulfate levels are of interest because the processes that generate sulfates can also generate ions, which in turn may acidify waters by overcoming the existing buffering levels.

The pH of water is an expression of the effective concentration of free hydrogen ions. Study Area surface waters generally have pH values near neutral (pH=7). Two small watersheds, Filson Creek and Keeley Creek, tended to have lower pH (more acid) values. This observation could be caused by the presence of bog material, exposed sulfide mineral zones, and/or acidic precipitation in combination with low alkalinity levels. Occasionally, pH values outside the recommended state and federal levels were observed (Thingvold et al. 1979).

Calcite saturation index (CSI) is a measure of a lake's ability to assimilate hydrogen ions (and resist pH change), and was calculated for all study lakes (Table 14). Lakes with an index less than 3.0 are considered well buffered; lakes with an index between 3.0 and 5.0 are poorly buffered with the possibility that acidification may be occurring; and an index greater than 5.0 indicates little or no buffering ability and a strong possibility that severe acidification has already occurred. The six most poorly buffered lakes studied are headwater lakes, with one exception. The chemistry of headwater lakes often reflects that of precipitation, with watershed contributions to lake chemistry assuming secondary importance. In general, in the Study Area, as one proceeds from headwater to downstream lakes, the ability of the lakes to assimilate hydrogen ions increases. The study also calculated CSIs for thirty lakes in the BWCA (Table 15). Half of these lakes were found to be poorly buffered, and with few exceptions these were headwater lakes. Because the analytical methods used to measure alkalinity levels in BWCA lakes tend to overestimate the actual alkalinity at the low levels observed, the CSIs for BWCA lakes are probably about 0.2 units higher than noted in Table 15.

Tables 14 and 15

Summary Discussion—Group A streams exhibited higher pH, alkalinity, and sulfate values than Group B streams, which in turn were higher than in relatively undisturbed streams (Group C). Alkalinity exhibited partial dilution effects in all watersheds, except those of the Kawishiwi drainage that lie downstream of

Table 14. Calcite saturation index (CSI) for Regional Copper-Nickel Study lakes studies.

LAKE	CSI[a]	LOCATION[b]
Tofte	0.3	H,N
Wynne	1.1	S
Triangle	1.4	H,N
Colby	1.4	S
Bass	1.5	N
Slate	1.5	N
Bearhead	1.6	H,N
Sand	1.8	H,N
Cloquet	2.0	H,S
Birch	2.0	N
Big	2.0	
Pine	2.1	H,S
Gabbro	2.3	N
White Face	2.3	H,S
Bear Island	2.3	H,N
Fall	2.6	N
White Iron	2.6	N
Seven Beaver	2.8	H,S
South McDougal	2.9	H,N
Clearwater	3.0	H,N
August	3.1	H,N
Turtle	3.1	H,N
One	3.2	N
Greenwood	3.3	H,N
Perch	3.4	H,N
Long	4.1	H,S

[a] 0-3 well buffered; 3-5 poorly buffered; 5+ little or no buffering

[b] H = headwater lake
N = north of Divide
S = south of Divide

Table 15. Calcite saturation index (CSI) for selected BWCA lakes.

WELL BUFFERED		POORLY BUFFERED	
LAKE	CSI	LAKE	CSI
Cypress	1.5	Silver Island	3.1
North	1.5	Vernon	3.1
South	2.2	Sawbill	3.3
Magnetic	2.2	Alice	3.3
Dunkan	2.3	Karl	3.4
Splash	2.5	Kawishiwi	3.5
Seagull	2.6	Gaskin	3.5
Kekekabic	2.6	Agnes	3.6
Crooked	2.6	Stuart	3.6
Alpine	2.7	Malberg	3.7
Saganaga	2.7	Sunday	3.7
Basswood	2.8	Grace	3.7
Gabigichigami	2.9	Cherokee	4.0
LaCroix	2.9	Carp	4.0
S. Fowl	3.0	Pauness	4.1

Note: Calculated from STORET data

large lakes. Sulfate concentrations were partially diluted during high flow in five of the streams.

The buffering parameters in lakes were quite variable due to diurnal and seasonal fluctuations which occur because of biological activity. Spatial variations in these parameters appear to be related to the location of lakes in their drainage systems, with poorly buffered lakes at headwaters and better buffered lakes downstream. Tofte and Wynne lakes tended to have the highest values for most parameters, and consequently they also had the lowest CSIs. Seven Beaver Lake had the lowest pH and Greenwood had the lowest alkalinity.

4.3.1.3 Nutrients. Table 16 presents a summary comparison of nutrient parameters for the three stream groups and lakes.

Table 16

Phosphorus, an essential nutrient for aquatic plant growth, occurs at low levels in Study Area waters and generally within guidelines of 25-100 ug/l that would control biological nuisances and eutrophication in various types of surface waters. Elevated levels generally occurred in disturbed watersheds.

Nitrate, also an essential nutrient, was found at levels far below those required for algal blooms even in disturbed watersheds where fertilizers are used in blasting compounds. The highest values were observed at Bob Bay and the Dunka River, both of which receive drainage from blasting zones. In at least one instance, nitrate levels exceeding federal standards of 10 mg/l were observed (Thingvold et al. 1979).

Table 16. Comparison of nutrient water quality parameters for three groups of streams and lakes in the Regional Copper-Nickel Study Area (November, 1975, to April, 1977).

MONITORING STATIONS GROUPINGS*		A			B			C			LAKES		
Parameter	Units	Range	Median	N	Range	Median	N	Range	Median	N	Range	Median	N
Nitrate	mg/l(NO_2+NO_3)	0.02-3.8	0.32	27	0.01-13	0.2	46	0.01-2.3	0.08	187	0.01-1.5	0.02	120
Total Nitrogen (N)	mg/l	0.17-6.3	1.05	27	0.04-14.1	1.42	46	0.01-4.0	0.79	177	0.12-9.9	0.63	78
Total (P)	ug/l	0.8-2100	19.6	27	0.8-413	32.1	46	0.8-99	20.0	187	0.8-220	22.9	140

*Group A stations Bob Bay-1, St. Louis R.-1, Partridge R.-1.
Group B stations Dunka R.-1, Partridge R.-2, Embarrass R.-1.
Group C stations Kawishiwi R.1-7, Bear Island R.-1, Isabella R-1, Filson Creek-1, Keeley Creek-1, Dunka R.-2, Stoney R.-5, St. Louis R-2 and 3, Partridge R.3-5, Embarrass R.-2, Whiteface R.-1 and 2, Water Hen Creek.

Nitrogen:Phosphorus ratios (N:P) are used to evaluate lake nutrient limitations. Lakes with N:P ratios greater than 14 may be phosphorus limited; ratios less than 14 suggest nitrogen limitation. For the 26 study lakes, N:P ratios ranged from 14-60 and half were greater than 25 (Table 17). The lakes approaching nitrogen limitation were Fall, Greenwood, One, and Long; while Colby was the most phosphorus limited.

Table 17

Trophic state indices (TSI), calculated from either phosphorus or secchi disk values, can also be used to classify lakes as follows:

Category	Index
Oligotrophic (nutrient starved)	15-25
Oligo-Mesotrophic	25-35
Mesotrophic	35-45
Meso-Eutrophic	45-55
Eutrophic (nutrient rich)	55-65

As can be seen in Table 18, 7 of the 26 lakes can be considered eutrophic and an additional 16 considered meso-eutrophic. The most fertile lakes are all headwater lakes and for the most part those are shallow and surrounded by extensive bog and marsh areas. Tofte was the least productive while South McDougal the most productive.

Table 18

The TSI values should be equal whether they are calculated using phosphorus or secchi disk. However, the secchi disk index can be biased high and low for highly colored (e.g. Seven Beaver) and highly transparent (Clearwater) lakes, respectively.

Table 17. Nitrogen:Phosphorus (N:P) ratios for Study Area lakes.

Lake and/or Site	N:P Ratio	Lake and/or Site	N:P Ratio
August		Greenwood	14
LA-1	30	Lake One	14
LA-2	27	Long	14
Bass	24	Perch	30
Bearhead	58	Pine	36
Bear Island		Sand	21
LBI-1	24	Seven Beaver	
LBI-2	25	LSB-1	34
Big	16	LSB-2	23
Birch		Slate	27
LBH-1	41	So. McDougal	--
LBH-2	34	Tofte	36
LBH-3	24	Triangle	20
LBH-4	24	Turtle	30
Clearwater	19	White Face	34
Colby		White Iron	
LCY-1	76	LWI-1	22
LCY-2	45	LWI-2	30
Cloquet	21	Wynne	52
Fall	14		
Gabbro			
LG-1	31		
LG-2	29		

Table 18. Median trophic state indices for Regional Copper-Nickel Study lakes.

LAKE	TSI (SD)	TSI (TP)	LOCATION[a]
Tofte	37	37	H,N
Bearhead	43	40	H,N
Triangle	42	46	H,N
Bass	42	47	N
Clearwater	39	50	H,N
Bear Island	46	47	H,N
August	51	42	H,N
Wynne	51	45	S
Pine	51	45	H,S
Colby	42	44	S
One	48	51	N
Big	54	55	H,S
Turtle	52	48	H,N
White Iron	53	48	N
Birch	53	49	N
Gabbro	54	48	N
Fall	52	51	N
Perch	52	51	H,N
Slate	53	54	N
Sand	56	55	H,N
White Face	58	53	H,S
Long	60	55	H,S
Cloquet	62	55	H,S
Seven Beaver	63	54	H,S
Greenwood	61	59	H,N
South McDougal	66	59	H,N

[a]H = headwater lake
N = north of Divide
S = south of Divide

SD = Secchi disk
TP = Total phosphorus

Summary Discussion--Spatial variations in nutrient parameters exhibited no clear trends between headwater and downstream stations or between small and large watersheds. Again, Group A and B stations had higher values than the undisturbed sites. Both nutrient parameters were largely independent of flow.

In lakes, overall concentrations of both nutrients were at the low end. Median values for both nutrients were higher south of the Laurentian Divide; however, phosphorus showed a greater range in variability north of the Divide.

4.3.1.4 Mineral Fibers. Mineral fibers are a potentially serious, but presently poorly understood, environmental health hazard for the occupational and non-occupational population in both Minnesota, as evidenced by the Reserve Mining controversy, and nationwide. This poor understanding can be attributed partly to confusion over and misuse of terminology and incomplete knowledge of the mechanism by which fibers affect health. These topics will be briefly discussed below. Because of the present interest and difficulties with "state of the art" analysis, this parameter is presented in more detail than other water quality parameters presented in this section. For further information, see Volume 3-Chapter 2, and Ashbrook (1978).

Asbestos is used as a collective mineralogical term encompassing the asbestiform varieties of various silicate minerals and is applied to a commercial product obtained by mining primarily asbestiform minerals. Five minerals fit this definition: chrysotile (a member of the serpentine group), and the asbestiform varieties of actinolite-tremolite, anthophyllite, cummingtonite-grunerite, and riebeckite (members of the amphibole group). Chrysotile always occurs in the asbestiform habit, amphiboles usually occur in non-asbestiform habits with the exception of riebeckite which usually occurs in the asbestiform habit as crocidolite. Asbestiform minerals occur as fibers, which resemble organic fibers in terms of circular cross section, flexibility, silky surface luster, and other characteristics. Cleavage fragments, such as those produced from crushing and processing non-asbestiform minerals, do not satisfy this definition of fibers and should be considered "fiber-like." When asbestiform and non-asbestiform minerals are subjected to crushing and processing, the resulting fragments have minor differences in morphology and physical properties that are very difficult to distinguish under a transmission electron microscope (TEM). For this reason, when the TEM is used, fibers are defined as fragments with aspect (length to width) ratio of 3:1 or greater, even though many of these fragments may not meet the mineralogic definition of a fiber. In this report, the term "mineral fiber" will be used to denote both asbestos fibers and cleavage fragments of non-asbestiform minerals because ambient levels of mineral fibers were determined by transmission electron microscopy, which did not distinguish between these two classifications. Asbestos fibers and non-asbestiform cleavage fragments have different characteristics in terms of tensile strength, flexibility, durability, and surface properties. The extent to which these differences are related to the harmful properties of asbestos is uncertain at this time.

Samples were collected throughout 1977 in conjunction with the rest of the water sampling program and consisted of 21 stream samples, a snow sample, a lake sample, an Ely tap water sample, and a sample from the AMAX shaft water. All samples were analyzed by the Minnesota Department of Health. Analysis of surface waters for mineral fibers is extremely difficult because of the large amounts of intervening materials. Little sample to sample comparison is justified. All results are shown in Table 19.

Table 19

Total fiber levels are given with and without chrysotile because the Minnesota Department of Health was uncertain whether the observed chrysotile fibers were artifacts from the filters or were actually present in the medium sampled. In 9 of the 25 samples, the amphibole blank fiber level was higher than the corresponding sample amphibole concentrations. The same was observed for chrysotile in 12 of 25 samples. These results suggest that, with the exception of the mine shaft sample, most of the fibers found in these samples come from sources other than the water sampled. Therefore, the fiber levels presented in Table 19 should be considered upper limits for the probable fiber concentrations in the Study Area.

Total fiber counts for stream samples ranged from 380,000 to 7,920,000 fibers per liter with a median of 3,310,000. Fiber levels in the Filson Creek snow sample, Ely tap water sample, and Bear Island Lake sample were similar. These levels are comparable to literature reports for other streams, as well as to levels in beer, wine, and soft drinks.

Large variations in fiber levels were observed in both disturbed and undisturbed streams. Amphibole fiber levels in the Partridge River appeared to decrease as the distance from the Reserve pit increased. Since it is not known whether Reserve was discharging during these sampling periods, the observation may be due to natural variation. The two highest fiber levels were found in undisturbed streams. Very high aspect ratios were found in the Dunka Sample and at stations

Table 19 continued.

			THOUSANDS OF FIBERS/LITER (mean aspect ratio)					
LOCATION	TYPE OF SAMPLE	DATE COLLECTED	Amphibole	Chrysotile	Non-amphibole Non-chrysotile	Ambiguous	Total Fibers	Total Without Chrysotile
Filson Creek Area	snow	11/21/77	495 (7.7)	1,130 (13.8)	2,190 (5.9)	354 (13.5)	4,170	3,040
Bear Island Lake	lake	11/21/77	212 (38.6)	636 (31.4)	1,700 (8.4)	636 (7.9)	3,180	2,550
Ely	tap water	11/21/77	244 (45.6)	610 (21.6)	1,200 (10.6)	244 (37)	2,230	1,710
AMAX-Babbitt	mine shaft	11/21/77	712,000	89,000	2,050,000	1,250,000	4,100,000	4,010,000

*Detection limit, based on one fiber observed.
**No fibers observed.

NOTE: Counting error limits are shown in Ashbrook, 1978.

K-5 and K-4, which are downstream from the Dunka. The sample from the Amax mine shaft near Babbitt contained approximately four billion fibers/liter. Half of these fibers were classified as non-amphibole/non-chrysotile, and thirty percent were ambiguous. This level is several orders of magnitude below fiber levels in taconite tailings from Reserve's Silver Bay plant.

4.3.1.5 Metals. Table 20 presents a summary comparison of metals levels in the three stream groupings and lakes.

Table 20

Levels of aluminum, arsenic, cadmium, and mercury were similar among all stream stations, and with the exception of mercury, were well below existing water quality standards. All of the surface waters monitored exceeded the mercury standard of 0.05 ug/l, which is based on the fact that some fish can concentrate mercury in their tissues by a factor of 10,000 and the Food and Drug Administration guideline of 0.5 mg/kg of mercury in edible fish. The source of mercury in Study Area waters is unknown. The low levels observed were at or near the limits of analytical techniques and could contain significant error.

Cobalt, copper, lead, nickel, and zinc levels tended to be higher at Group A and B stations than at undisturbed sites, although the differences were small and all concentrations were low. Group A stations had higher levels of these metals than Group B stations, except for zinc which was the same at both. Bob Bay, which receives runoff from mineralized gabbro stockpiles and Filson Creek, which flows directly through the Duluth Gabbro Contact, had the highest levels of cobalt, copper, and nickel.

Table 20. Comparison of metal water quality paramters for three groups of stream stations and lakes in the Regional Copper-Nickel Study Area (November, 1975, to April, 1977).

MONITORING STATION GROUPINGS*		A			B			C			LAKES		
Parameter	Units	Range	Median	N	Range	Median	N	Range	Median	N	Range	Median	N
Aluminum (Al)	ug/l	19-760	120	37	22-640	100	25	1.6-710	90	208	4-610	77	60
Arsenic (As)	ug/l	0.2-3.0	0.8	25	0.3-1.0	0.8	18	0.4-5.0	0.8	148	0.4-2.1	0.6	41
Cadmium (Cd)	ug/l	0.01-0.24	0.04	54	0.01-0.21	0.03	63	0.01-0.45	0.03	326	0.01-0.77	0.03	114
Cobalt (Co)	ug/l	0.24-3.8	0.70	54	0.16-2.0	0.5	65	0.1-11	0.4	291	0.1-2.2	0.4	72
Copper (Cu)	ug/l	0.5-8.4	3.1	56	0.16-8.4	2.2	65	0.16-12	1.3	326	0.2-10	1.5	129
Total Iron (Fe)	ug/l	60-1300	453	55	220-3800	1197	64	19.2-5500	560	338	16-2300	350	138
Dissolved Iron	ug/l	20-580	152	36	30-1500	553	41	10-3550	310	171	—	—	—
Lead (Pb)	ug/l	0.16-3.8	0.7	56	0.1-2.6	0.6	62	0.08-6.4	0.5	325	0.1-1.9	0.4	114
Manganese (Mn)	ug/l	30-1200	140	40	30-810	120	53	5-860	35	228	1-5400	29	135
Mercury (Hg)	ug/l	0.01-0.4	0.07	24	0.01-0.4	0.07	18	0.01-0.6	0.08	141	0.08-0.64	0.28	96
Nickel (Ni)	ug/l	0.6-210	2.0	54	0.8-10	2.0	65	0.08-30	1.0	328	0.4-6	1.0	129
Zinc (Zn)	ug/l	0.5-14	2.8	56	0.4-30	3.0	65	0.1-23	2.0	325	0.2-35.5	1.8	113

*Group A stations	Bob Bay-1, St. Louis R.-1, Partridge R.-1.
Group B stations	Dunka R.-1, Partridge R.-2, Embarrass R.-1.
Group C stations	Kawishiwi R.1-7, Bear Island R.-1, Isabella R-1, Filson Creek-1, Keeley Creek-1, Dunka R.-2, Stoney R.-5, St. Louis R-2 and 3, Partridge R.3-5, Embarrass R.-2, Whiteface R.-1 and 2, Water Hen Creek.

Iron and manganese (along with aluminum) are the most abundant metals in Study Area surface waters. Although some stations showed high levels of iron and manganese which could be attributed to mineralized zones or taconite mining, other stations which might be expected to show high iron levels did not—suggesting that natural mechanisms for removing iron can be significant.

Summary discussion—Iron, aluminum, and manganese dominate the total metal values measured in Study Area waters (Figure 18), but the trace metals are of primary concern on the basis of aquatic toxicity. At background stations copper, nickel, and zinc levels are comparable with median values of 1-2 ug/l. Other toxic trace metals of biological importance (arsenic, cadmium, cobalt, mercury, and lead) had median concentrations significantly below 1 ug/l (one part per billion). Watersheds impacted by mining activities or streams draining areas of sulfide mineralization, such as Filson Creek, Keeley Creek, Dunka River, Partridge River and Embarrass River, had total trace metal concentrations 2 to 33 times higher than background levels (Figure 19).

Figures 18 and 19

Filson Creek exhibited significantly higher copper concentrations than any other station, while high median values of iron, aluminum, nickel, and cobalt were also observed. Within this watershed, total concentrations of copper and nickel in the year 1977 generally increased from headwater locations to the point of discharge into the Kawishiwi River. For example, nickel levels were less than 1 ug/l in headwater locations and 3-5 ug/l at the mouth of the watershed (Siegel 1978). The elevated metal levels in Filson Creek may not be due completely to natural weathering of sulfide minerals. Considerable mineral exploration activities, including the taking of a surface bulk sample, have occurred in this watershed (see section 4.3.3.2).

The dynamics of metals in lakes are somewhat different from those in streams because the large surface area of bottom sediments with its varying oxidation-reduction potential complicates the picture. Lakes can act as sinks for metals, as is the case with iron at Colby Lake, so that the chemistry of outflowing waters is different from that of inflowing waters. Large lakes may exhibit variability in the concentration of metals within the lake itself, as is the case in Birch Lake.

Iron and lead were both elevated in South McDougal Lake while lead was elevated in Greenwood and iron was elevated in Seven Beaver. Concentrations of copper were highest in Colby and zinc in Clearwater. Triangle Lake exhibited exceptionally low levels of all four of these metals (Thingvold et al. 1979).

4.3.1.6 Other Parameters. Tables 21 and 22 present summary comparisons for the three stream groups for other parameters not discussed earlier in the text.

Tables 21 and 22

4.3.2 Quality of Groundwaters of the Regional Copper-Nickel Study Area

Identification of baseline groundwater quality conditions in the Study Area was not feasible because of the extensive variability possible and the large Study Area size. Therefore, the following information should be used only for general characterization and comparative purposes. The information adequately describes the quality of groundwater at the specific location monitored and for the time

Table 21. Comparison of miscellaneous water quality parameters for three groups of streams and all stations monitored in the Regional Copper-Nickel Study Area (November, 1975, to September, 1977).

MONITORING STATION GROUPINGS*		A			B			C			ALL STATIONS		
Parameter	Unit	Range	Median	N	Range	Median	N	Range	Median	N	Range	Median	N
Silver (Ag)	ug/l	0.02-0.1	0.036	22	0.02-0.04	0.034	16	0.008-0.04	0.032	134	0.008-0.10	0.032	172
Titanium (Ti)	ug/l	32-32	32	3	8-80	32	28	8-80	32.8	26	8-80	32.5	57
Fluoride (F)	mg/l	0.05-0.6	0.20	48	0.1-1.5	0.18	33	0.02-0.9	0.10	266	0.02-1.5	0.10	347
Chromium (Cr)	ug/l	0.3-2.1	0.52	22	0.2-2.0	0.53	16	0.08-1.7	0.40	146	0.08-2.1	0.40	184
Selenium (Se)	ug/l	0.8-3.0	0.82	17	0.8-1.6	0.84	11	0.8-2.0	0.82	117	0.8-3.0	0.82	145
Acidity (H^+)	meq/l	0.08-1.5	0.20	24	0.1-0.8	0.25	18	0.08-18	0.15	155	0.08-18.0	0.20	197
Cyanide (CN)	ug/l	0.8-9.0	0.87	10	0.8-0.8	0.80	3	0.8-10	0.85	18	0.8-10	0.85	31
Barium (Ba)	ug/l	0.8-100	18.0	11	0.8-100	65	3	0.8-100	4.4	18	0.8-100	4.7	32
Dissolved Organic Carbon (DOC)	mg/l	2.8-19.5	9.1	3	12.7-36.6	18.4	10	7.8-25.4	18.7	10	2.8-36.6	18.5	23
Dissolved Inorganic Carbon (DIC)	mg/l	12-30.1	21.2	3	5-30.2	13.1	10	0.3-20.5	5.9	10	0.3-30.2	12.0	23
Filtrable Residue	mg/l			8			30			45			83
Non-filtrable Residue	mg/l	0.4-18	3	55	0.4-28	4.4	65	0.4-27	2.0	339	0.4-28	2.0	459
Dissolved Oxygen	ppm	3.2-14	9.4	56	4.8-13.8	8.4	45	0.3-14.2	9.3	318	0.3-14.2	9.3	419
Dissolved Oxygen	%	22-100	83	55	33-100	74.3	45	2-100	84.2	316	2-100	83.8	416
Chemical Oxygen Demand (COD)	mg/l	10-69	24	24	20-110	41.5	18	4-110	38.9	155	4-110	38.9	197
Biological Oxygen Demand (BOD)	mg/l	0.8-2.0	1.4	8	1.0-1.0	1.0	3	0.8-2.0	0.89	17	0.8-2.0	0.93	28
Fecal Coliforms	No./100ml	0-256	28	9	8-78	43	3	0-125	2.0	23	0-256	5.7	35
Phenols	ug/l	0.3-12	1.9	10	1.0-2.0	1.6	3	0.8-18	1.73	17	0.8-18	1.7	30
Total Kjeldahl Nitrogen N	mg/l	0.07-2.5	0.63	27	0.01-2.9	1.1	46	0.01-2.4	0.65	185	.01-2.9	0.73	258
Ortho-phosphorus	ug/l	0.8-60	9.9	23	0.8-40	10.0	18	0.8-41	6.1	140	0.8-60	8.1	181

*Group A stations	Bob Bay-1, St. Louis R.-1, Partridge R.-1.
Group B stations	Dunka R.-1, Partridge R.-2, Embarrass R.-1.
Group C stations	Kawishiwi R.1-7, Bear Island R.-1, Isabella R-1, Filson Creek-1, Keeley Creek-1, Dunka R.-2, Stoney R.-5, St. Louis R-2 and 3, Partridge R.3-5, Embarrass R.-2, Whiteface R.-1 and 2, Water Hen Creek.

Table 22. Comparison of radioactive isotopes in surface waters of three groups of streams and all stations monitored in the Regional Copper-Nickel Study Area (November, 1975, to September, 1977).

MONITORING STATION GROUPINGS* Parameter	Units	A Range	A Median	A N	B Range	B Median	B N	C Range	C Median	C N	ALL STATIONS Range	ALL STATIONS Median	ALL STATIONS N
Alpha-D-Uranium	Pci/L	1.36-4.24	1.60	5	1.36-1.7	1.53	2	0.32-0.96	0.4	7	0.32-4.24	1.0	14
Alpha-S-Uranium	Pci/L	0.32-0.32	0.32	5	0.32-0.32	0.32	2	0.32-0.6	0.34	7	0.32-0.6	0.33	14
Beta-D-Cesium 137	Pci/L	3.3-9.5	4.3	5	3.2-3.9	3.55	2	2.7-3.4	2.9	7	2.7-9.5	3.28	14
Beta-D-Strontium 90	Pci/L	2.7-7.6	3.6	5	2.7-3.1	2.9	2	2.2-2.8	2.3	7	2.2-7.6	2.7	14
Beta-S-Cesium 137	Pci/L	0.32-0.5	0.34	5	0.32-0.5	0.41	2	0.32-0.7	0.39	7	0.32-0.7	0.37	14
Beta-S-Strontium 90	Pci/L	0.32-0.4	0.33	5	0.32-0.4	0.36	2	0.32-0.6	0.35	7	0.32-0.6	0.34	14
Dissolved Potassium 40	Pci/L	0.9-4.8	1.2	4	---	--	-	0.2-0.4	0.35	6	0.2-4.8	0.45	10
Total Gross Alpha	Pci/L	1.6-4.0	3.0	5	4.0	4.0	1	0.8-2.0	0.97	11	0.8-4.0	1.6	17
Total Gross Beta	Pci/L	3.0-10.0	5.0	5	5.0	5.0	1	1.6-6.0	2.9	11	1.6-10	3.08	17

*Group A stations Bob Bay-1, St. Louis R.-1, Partridge R.-1.
Group B stations Dunka R.-1, Partridge R.-2, Embarrass R.-1.
Group C stations Kawishiwi R.1-7, Bear Island R.-1, Isabella R-1, Filson Creek-1, Keeley Creek-1, Dunka R.-2, Stoney R.-5, St. Louis R-2 and 3, Partridge R.3-5, Embarrass R.-2, Whiteface R.-1 and 2, Water Hen Creek.

period covered, and caution is advised if any comparison is made to other monitoring locations or to areas not monitored. This information provides a perspective for regional (non-site specific) impact analysis pertaining to potential copper-nickel development.

The information in this section is based on samples collected by the USGS during 1976-1977 water year (Siegel and Ericson 1979). Samples were collected quarterly from 12 wells in glaciofluvial sand and gravel, 11 wells finished in Rainy Lobe till, and 2 wells finished in peat. An additional single sampling of U.S. Forest Service campground wells was added during a drought period in October, 1976, when ground water levels were extremely low. This sampling included 3 wells in sand and gravel, 5 in Rainy Lobe till, and 3 the Duluth Complex. Three other wells in the Duluth Complex were sampled during 1976 (see Figures 20 and 21).

Figures 20 and 21

4.3.2.1 Surficial Aquifers. Summary statistics for major dissolved constituents and other properties are presented in Tables 23 and 24. With the exception of bicarbonate, mean values of major dissolved constituents are statistically significantly higher for groundwater from Rainy Lobe till than from sand and gravel aquifers. Mean and median concentrations of the major ions, specific conductivity, and hardness in till aquifers were twice those in sand and gravel aquifers and 3 to 5 times those in undisturbed (Group C) streams.

Tables 23 and 24

Water in till can be classified as moderately hard to very hard, while sand and gravel aquifers are moderately hard to hard. The lower pH range for sand and

Table 23. Summary statistics for groundwater quality from surficial materials sampled during 1976. Concentrations in milligrams per liter except when designated otherwise.

	SAMPLES FROM TILL AQUIFERS					SAMPLES FROM SAND AND GRAVEL AQUIFERS				
CONSTITUENT OR PROPERTY	Number Samples	Max.	Min.	Mean	Median	Number Samples	Max.	Min.	Mean	Median
Specific Cond. (mmhos)	32	1250	120	368	251	40	577	5.5	193	166
pH (unitless)	25	8.0	5.7	6.81	6.70	28	7.1	5.7	6.33	6.35
Chemical Oxygen Demand	10	870	22	198	51	10	800	0	93	18.5
Hardness (Ca,Mg)	30	637	37	173	104	40	284	26	93	71
Dissolved Calcium	31	150	6.5	38.9	22.3	40	76	6.0	20	16
Dissolved Magnesium	31	64	5.1	18.0	14.0	41	31	1.1	10.2	7.3
Dissolved Sodium	31	18	2.1	7.7	6.9	41	7.3	1.4	3.1	2.9
Dissolved Potassium	31	9.3	.1	2.7	2.1	41	3.0	0.2	1.3	1.1
Bicarbonate	30	423	45	145	120	30	392	15	95	69
Dissolved Sulfide	11	12	0	1.5	.4	17	4	0	.9	.6
Sulfate	31	450	1.8	61	11	40	35	0.7	11	6
Chloride	31	35	.4	4	1.4	40	18	0.1	4	2.2
Silica	13	37	13	20.5	18.3	21	28	10	18.6	18
Solids (residue 180°)	13	938	97	293	187	14	284	55	148	130
Nitrate plus nitrite	11	12	0	1.5	0.4	37	10	.01	2.2	.62
Total Phosphorus	13	.07	0	.006	0.001	21	.04	0	---	---
Dissolved Organic Carbon	22	46	2.1	18	13	33	52	0.7	11.3	6.4

SOURCE: Siegel and Ericson (1979)

Table 24. Summary statistics for selected trace and minor metals in surficial aquifers, (concentration in micrograms per liter).

CONSTITUENT OR PROPERTY	SAMPLES FROM TILL AQUIFERS Number Samples	Max.	Min.	Mean	Median	SAMPLES FROM SAND AND GRAVEL AQUIFERS Number Samples	Max.	Min.	Mean	Median
Cadmium	29	8.4	0.00	0.8	0.3	30	1.2	0.0	0.3	0.3
Cobalt	30	28.0	0.3	3.5	1.4	30	46.0	0.1	6.3	0.7
Chromium	30	5.5	0.00	0.9	0.6	31	3.2	0.0	0.6	0.5
Copper	30	190.0	0.6	11.7	3.8	30	45.0	0.2	7.2	4.2
Lead	30	6.4	0.1	1.8	1.3	31	18.0	0.0	1.9	1.1
Nickel	27	120.0	1.0	15.2	9.0	29	40.0	0.7	7.5	5.0
Aluminum	24	200.0	0.0	20.0	20.0	30	280.0	0.0	32.0	29.0
Zinc	30	170.0	3.9	27.6	8.9	30	620.0	0.7	56.1	14.1
Iron	30	3100.0	0.0	221.0	25.0	38	67000.0	0.0	5152.0	45.0
Manganese	31	7190.0	10.0	1268.0	330.0	38	26000.0	0.0	2140.0	45.0

SOURCE: Siegel and Ericson (1979)

gravel aquifers reflects rapid recharge to the aquifer from precipitation and a shorter time available for chemical reactions. The pH of water in the two peat wells showed a range of 5.9 to 6.2.

Water in sand and gravel, and peat can be classified as a mixed calcium-magnesium bicarbonate based on predominant ions. This type of water is typical of groundwaters in contact with calcic igneous minerals, as are found in the Study Area, and which have either a short residence time or have been collected from a recharge zone. Water collected in till can be classified as either a calcium-magnesium bicarbonate or calcium-magnesium sulfate. The sulfate type comes from oxidation of sulfide minerals. Mean values of principal constituents in groundwater were not found to vary significantly between seasons.

Mean levels of nitrate, total phosphorus, total organic carbon, silica, and chemical oxygen demand were similar for sand and gravel, peat, and till.

Concentrations of copper, cobalt, and nickel generally are less than 30 ug/l, but can exceed 100 ug/l in waters contacting the mineralized Duluth Contact probably as a result of oxidation of sulfide minerals. Iron is occasionally found in anomolously high concentrations ranging up to 67 mg/l that are probably related to local conditions.

The areal distribution of copper and nickel levels in surficial aquifers reflects proximity to the mineralized Duluth Contact. Anomolous concentrations of both metals occur in zones about 5 to 10 miles wide centered on the Contact (Figures 22 and 23). Mining and exploration activities may have affected local groundwater quality. For example, copper and nickel concentrations in groundwater discharging from a bulk-ore sample site near Filson Creek are as high as

700 ug/l compared to nearby background values less than 25 ug/l. Water from an observation well finished at the base of the bulk site, had copper and nickel concentrations of 370 and 3,800 ug/l in April, 1976, as well as a cobalt concentration (440 ug/l) ten times above background levels.

Figures 22 and 23

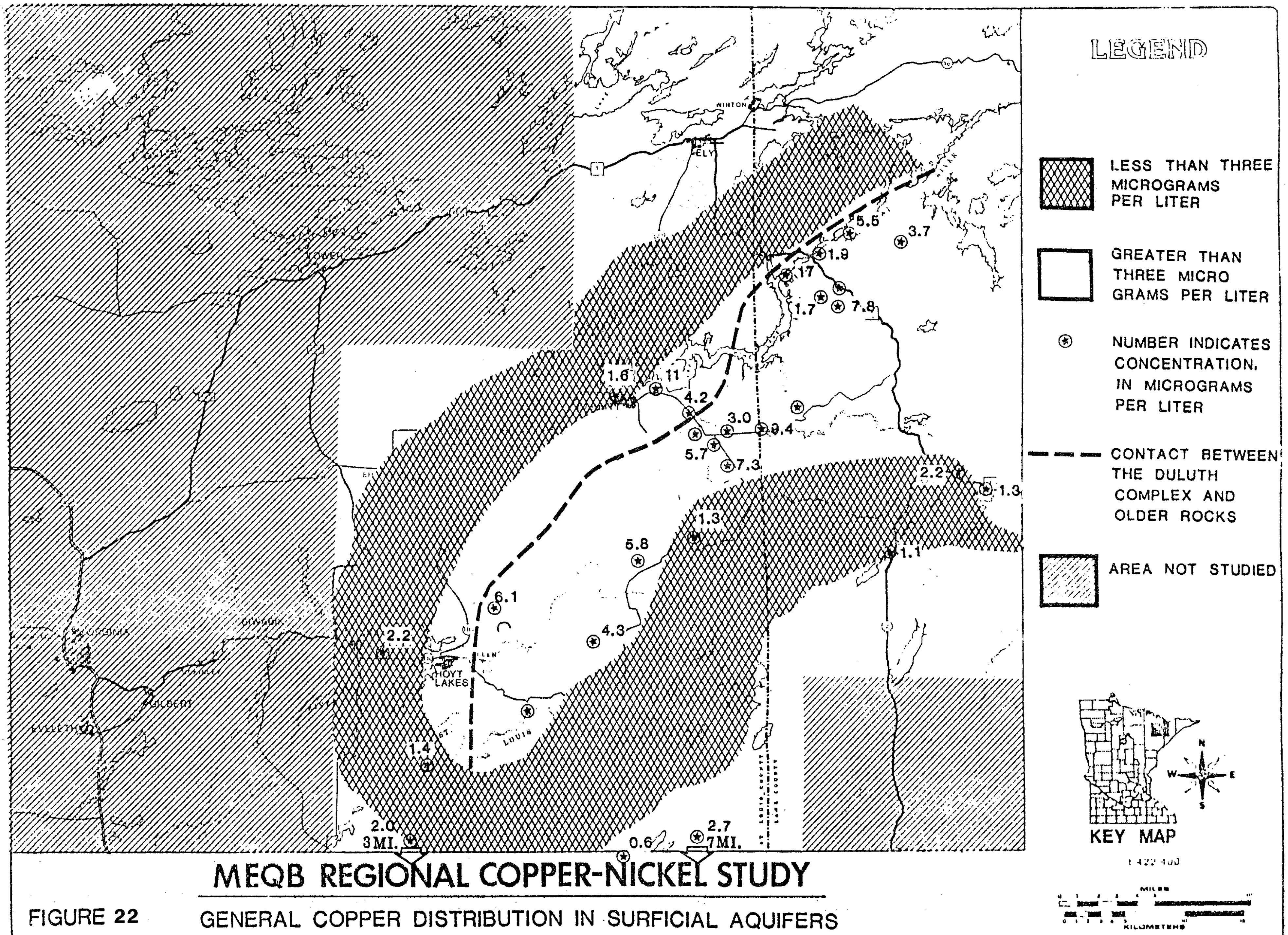
4.3.2.2 Bedrock Aquifers. Representative analyses of water samples collected bedrock wells are presented in Table 25.

Table 25

Concentrations of major constituents in water from the Duluth Complex are highly variable, ranging over as much as three orders of magnitude depending on location. Field pH in Duluth Complex water was generally one unit more basic than water from surficial lithologies in the Study Area. Duluth Complex water ranges from sodium chloride to sodium bicarbonate in type.

Waters from other bedrock aquifers are similar to those from surficial aquifers and are of a mixed calcium-magnesium bicarbonate type.

Except for iron and manganese, metal data are sparse for bedrock waters in the Study Area. Available data suggest that dissolved copper, nickel, cadmium, silver, mercury, and lead concentrations are mostly less than a few micrograms per liter. In the Duluth Complex water, iron and manganese range up to 150 and 60 ug/l, respectively. In the Biwabik Iron Formation, iron levels reach 5,000 ug/l and manganese 1,800 ug/l. Iron and manganese levels in Giants Ridge Granite can reach 500 ug/l.



MEQB REGIONAL COPPER-NICKEL STUDY

FIGURE 22 GENERAL COPPER DISTRIBUTION IN SURFICIAL AQUIFERS (DATA FROM 10-76 OR 4-76 SAMPLES)

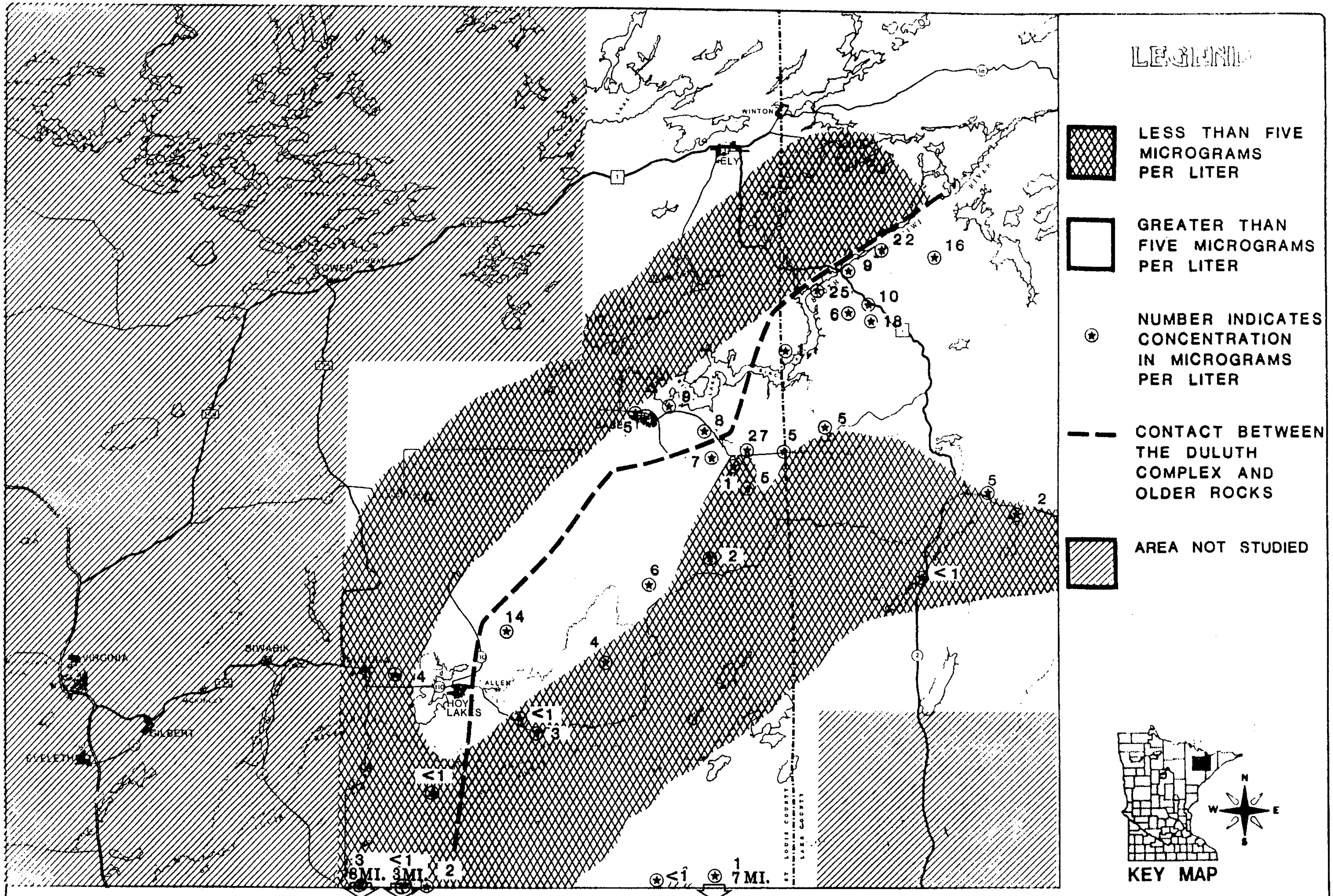


FIGURE 23

MEQB REGIONAL COPPER-NICKEL STUDY

GENERALIZED NICKEL DISTRIBUTION IN SURFICIAL AQUIFERS
(DATA FROM 10-76 OR 4-76 SAMPLES)

Table 25. Representative groundwater analyses from major bedrock units (Siegel and Ericson, USGS 1979).

PARAMETER	UNITS	1	2	3	4	5	6	7	8	9	10	11	12
Geologic Unit[a]		DCPX	DCPX	DCPX	DCPX	BBKF	BBFK	BBFK	GRNT	GRNT	GRNT	GRNT	VRGN
Total Depth of Well	feet	225	1000	125	1046	398	180	—	197	425	147	121	90
Date of sample		10/20/76	10/20/76	10/19/76	2/15/77	12/14/74	10/65	10/70	8/8/75	12/5/74	9/8/72	9/12/72	12/3/74
Specific Conductance	micro-mhos/cm	320	1300	2220	4620	380	—	—	240	143	572	237	745
pH	(units)	8.5	7.4	7.7	8.1	7.4	—	8.9	8.2	8.3	7.5	—	7.8
Hardness (Ca, Mg)	mg/l	7	150	9	1100	200	130	94	—	63	193	—	390
Dissolved Calcium (Ca)	mg/l	2.7	44	3.1	420	43	58	42	93	31	19	110	46
Dissolved Magnesium (Mg)	mg/l	0.1	9.1	0.3	2.0	22	—	—	53	9.1	6.0	10	66
Dissolved Sodium (Na)	mg/l	73	220	48	470	5	—	20	7.3	13.0	4.6	26	19
Dissolved Potassium (K)	mg/l	0.9	3.3	0.3	2.0	2.3	—	7	0.8	1.9	0.9	26	4.2
Bicarbonate (HCO_3)	mg/l	167	155	115	94	189	99	32	207	140	71	204	523
Dissolved Sulfate (SO_4)	mg/l	—	—	—	—	18	—	—	—	14	13	—	19
Dissolved Chloride (Cl)	mg/l	—	—	—	—	—	—	180	—	—	323	—	436
Dissolved Silica (SiO_2)	mg/l	3.8	45	9.6	3.6	41	47	88	17	7.3	65	13.8	22
Dissolved Solids	mg/l	5.3	310	4.3	1500	9	1.4	7.8	1.0	1.3	7.5	1.5	1.3

[a] DCPX Duluth Complex
BBKF Biwabik Iron Formation
GRNT Giantic lithologies
VRGN Virginia Formation

Summary Discussion--Fair to good correlations between specific conductivity in Study Area groundwaters and dissolved calcium, hardness, and dissolved solids exist so that the easily obtained specific conductance measurements can be used to roughly predict these constituents (Siegel and Ericson 1979).

Expected correlations between trace metals and sulfate or between dissolved organic carbon and trace metals were not found. This finding highlights the complexity of local hydrogeochemical conditions. Concentrations of trace metals are controlled by inorganic and organic mechanisms that operate non-uniformly over the region. An evaluation of local trace metal concentrations requires a site-specific understanding of the local ground water flow system and the mineral and organic constituents in the glacial drift.

Highly saline water has been encountered in some bedrock areas in the Study Area (AMAX Drill Hole 303). The source and spatial distribution of this water in the Study Area is unknown. Occurrence of saline water in significant quantities (as might occur during mining) could present significant water quality, mineral processing, and water treatment problems. Table 26 compares the analysis of a single sample of the high saline water to water from a nearby bedrock groundwater monitoring well.

Table 26

4.3.3 Existing Water Discharges and Land-Use Activities Affecting Regional Water Quality

Information presented above shows that the water quality of several watersheds more than likely is affected by man-made factors. The Study's monitoring program

Table 26. Comparison of quality of highly saline bedrock ground water to water from nearby AMAX bedrock groundwater monitoring well (B-3).

	UNITS	DRILL HOLE 303	AMAX B-3 (Jan. 1975-Sept. 1977) Range	AMAX B-3 (Jan. 1975-Sept. 1977) Mean
Acidity	mg/l as $CaCO_3$	12	2	2
Alkalinity	mg/l as $CaCO_3$	6	67-95	85.8
Barium	ug/l filtered	170	2-5	2.9
Chloride	mg/l as Cl	11,000	14-212	128.9
Cobalt	ug/l filtered	2.0	1-1	1
Copper	ug/l filtered	2.9	0.2-10	1.33
Hardness	mg/l as $CaCO_3$	12,000	1-80	34.88
Iron	mg/l filtered	4.9	0.05	0.05
Lead	ug/l filtered	3.6	No	data
Manganese	mg/l filtered	0.51	0.03	0.03
Nickel	ug/l filtered	20.0	1-6	2
pH		5.8	10.2-11.0	10.4
Sodium	mg/l as Na	1,900	70-123	101.5
Specific Conductivity		32,000	504-720	606.8
Sulfate	mg/l as SO_4	2	1-7	4
Zinc	ug/l filtered	5.0	5	5

SOURCE: AMAX Data Summaries 1975-77 and L.A. Darling 8/11/76.

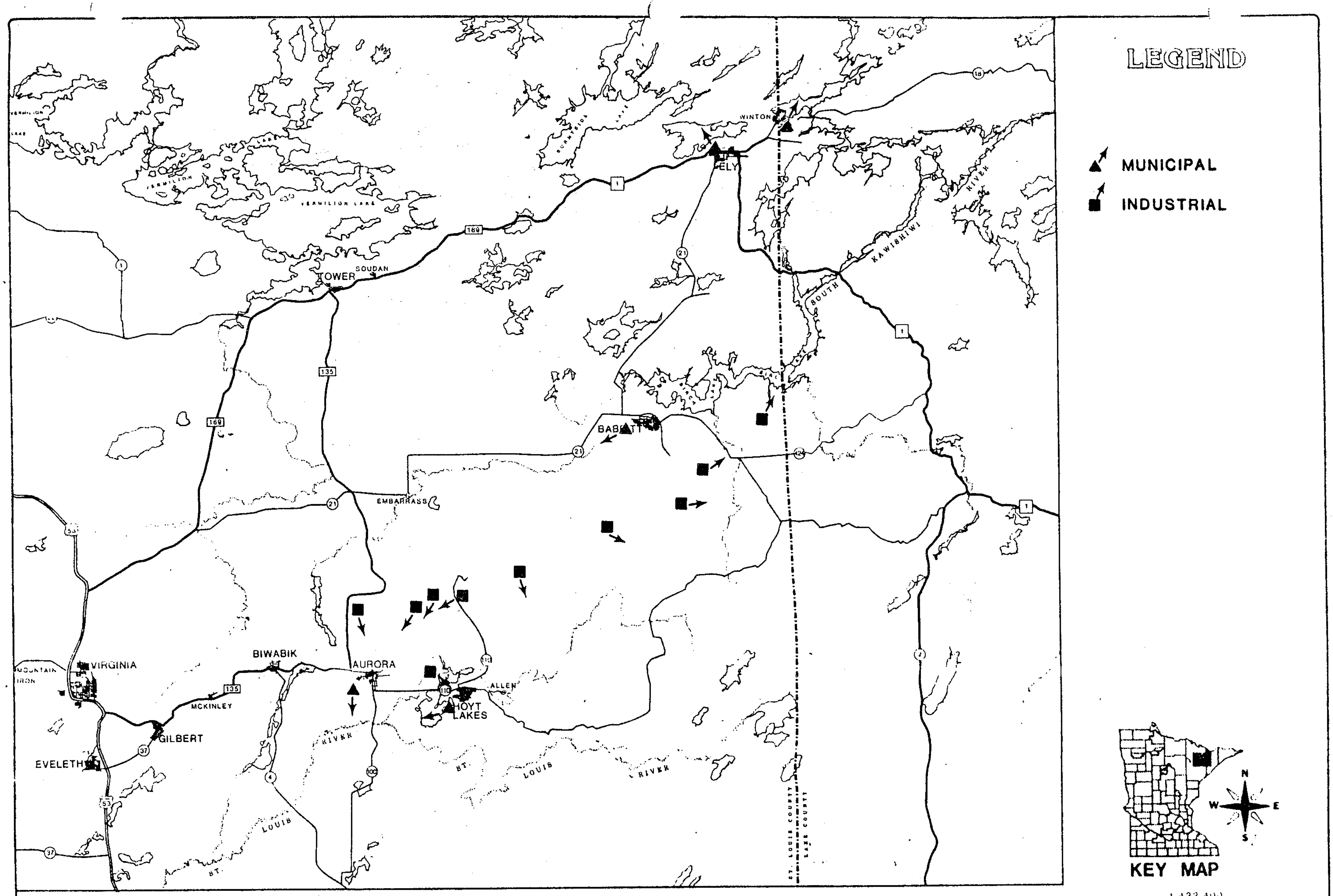
was not specifically designed to pinpoint these factors, but comparison of water quality data to regional point discharge and land use information offers a clue to those man-made factors influencing regional water quality. The reader is cautioned that no direct cause and effect between specific human activities and degradation of water quality has been shown, except in the case where Unnamed Creek (BB-1) is being affected by mining spoils.

Man-made factors affecting regional water quality can be grouped into two principal categories: point discharges and land-use activities (area sources). Atmospheric deposition has been receiving increased attention as a third source and is discussed in section 4.3.4.

4.3.3.1 Point Discharges. Major point discharges in the Study Area are either municipal discharges from sewage treatment plants or industrial discharges related to the taconite industry. These sources are identified in Figure 24.

Figure 24

There are five major sewage treatment plants in the Water Quality Research Area. Ely and Winton plants discharge into the Kawishiwi watershed, while plants servicing Babbitt, Hoyt Lakes and Aurora discharge into the Embarrass, Partridge, and St. Louis (downstream of SL-1) watersheds, respectively. In 1976, effluents from these plants on occasion exceeded the performance standard for biochemical oxygen demand (25 mg/l for 5-day BOD) set by the Minnesota Pollution Control Agency rule WPC-14 at least once with the exception of Ely which met the standards (Thingvold et al. 1979). Water quality data for the Embarrass River which receives the Babbitt sewage treatment plant effluent appears to have slightly



MEQB REGIONAL COPPER-NICKEL STUDY

FIGURE 24 MUNICIPAL AND INDUSTRIAL WATER DISCHARGES (BASED ON MASCHWITZ, 1977) elevated total phosphorus levels, but these levels have not reached concentrations which can cause plant nuisances. Total phosphorus concentrations at the outlet of Shagawa Lake (K-2) also appear higher than other sites on the Kawishiwi River. Since the existing treatment system at Ely is highly effective at removing phosphorus, the higher levels at K-2 are probably due to residual phosphorus contained in lake sediments as a result of years of inadequately treated effluents entering this watershed.

The major activity from the taconite industry resulting in discharges is mine dewatering. Table 27 compares the quality of discharges from the Reserve mine (which go into tributaries of the Dunka River) with background water quality for the Dunka. It can be seen that these discharges are highly variable in quality, but all have significantly higher levels of the various parameters. The impact of these discharges is clearly apparent in comparisons of water quality for stations D-1 (downstream) and D-2 (upstream).

Table 27

The only mine dewatering discharge for which trace metals data are available is from Erie's Dunka Pit (Table 28). Again, background water quality is significantly different from discharge quality. Copper, nickel, and sulfate levels are an order of magnitude higher in the discharge than at K-5. This discharge is probably not representative of the taconite industry because of the occurrence of mineralized gabbro in this pit. Unnamed Creek receives this discharge, but the discharge is not the principal source of trace metal and other chemical parameters in this small stream. This watershed also receives contaminated water from area sources (see 4.3.4.2).

Table 27. Comparison of mining water discharges and background surface water quality.

RESERVE MINING CO.

	DISCHARGE #001			DISCHARGE #002			DISCHARGE #004			DISCHARGE #005		
	MEAN	RANGE	#SAMPLES	MEAN	RANGE	#SAMPLES	MEAN	RANGE	#SAMPLES	MEAN	RANGE	#SAMPLES
Conductivity umhos/cm	413.3	280-800	12	394.6	210-500	12	1146.3	1090-1225	4	613.8	575-680	4
Cl mg/l	40.4	22.5-63.0	12	39.6	21.5-56.7	12	270.5	238.9-310	4	135.4	122-148	4
SO_4 mg/l	40.9	23.0-60.4	12	29.9	20.8-44.0	12	18.6	7.5-34.4	4	8.9	5.6-14.8	4
Ca mg/l	33.4	22.8-63.6	12	34.0	16.2-41.4	12	113.6	105.4-120.5	4	64.8	59-75	4
Na mg/l	15.7	9.4-36.6	12	17.4	6.8-29.3	12	39.9	30.6-48.4	4	12.4	11.3-13.5	4
K mg/l	3.2	2.1-6.8	12	4.3	2.48-5.23	12	8.4	7.1-9.5	4	3.9	2.98-4.72	4
Mg mg/l	17.3	11.6-30.9	12	16.1	8.5-19.7	12	30.1	29.3-31.8	4	19.1	18.2-20.3	4
NO_3 mg/l	4.5	1.5-8.8	12	1.2	0.1-2.1	12	0.1	0.1-0.13	4	0.1	0.1	4

DUNKA RIVER (D-2) UPSTREAM OF DISCHARGES

	MEAN	RANGE	#SAMPLES
Conductivity umhos/cm			
Cl mg/l	2.19	1.3-3.9	7
SO_4 mg/l	6.21	4.0-11.0	7
Ca mg/l	5.8	3.1-8.5	2
Na mg/l	1.8	0.9-2.7	2
K mg/l	0.65	0.5-0.8	2
Mg mg/l	5.5	3.4-7.6	2
NO_3 mg/l	no data		

Table 28

Most of the information available on point discharges is monthly average information and does not give a good picture of the variability in the quality and quantity of such discharges. Since dewatering discharges are directly controlled by mechanical pumping operation and indirectly by precipitation events, the combination of source variability, monitoring program design, and lack of adequate effluent data, makes it impossible to present a clear picture of how specific discharges are affecting the region's water quality.

4.3.3.2 Area Sources. Area source discharges arise when man's activities relating to land use cause changes in the quality and quantity of precipitation runoff. For example, paved roads and parking lots decrease infiltration of rain into the ground and increase runoff, while forest clearcutting can increase runoff and sediment levels in the runoff. Other man-made area sources include: road salt; oil, grease, and nutrients from urban areas; and agricultural fertilizers.

In the Study Area, a major source of concern is runoff which is exposed to sulfide minerals. As mentioned above, Filson Creek has high concentrations of metals compared to other stream stations. Following the taking of a bulk surface sample of sulfide minerals in this watershed, a surface discharge was discovered coming from the foot of the site with elevated metals values (10,000-13,000 ug/l Ni; 360-1,000 ug/l Cu; and 190-5,300 ug/l Zn). A small tributary of Filson Creek receives this discharge and the increased metals levels above and below the site are apparent. The average increase in nickel and copper levels in the tributary stream were 9 ug/l and 5 ug/l, respectively.

Table 28. Comparison of mine water discharge to background water quality.

Erie Pit Dewatering Discharge	Mean of monthly values (mg/l) for 9-75 through 5-76				
	Cu	Ni	SO_4	DS	pH
012	.01	.016	260	681	8.0
011	.01	.019	85	337	8.0

Background water quality for Kawishiwi River measured at K-5 for 11-75 through 3-77.

	Mean	Range	No. Samples
Cu mg/l	0.0015	0.0011-0.002	23
Ni mg/l	0.0016	0.0009-0.0032	23
SO_4 mg/l	7.79	4.4-12.0	24
pH	7.03	6.2-7.8	14

Bob Bay (of Birch Lake) also has high levels of metals. Unnamed Creek drains this watershed which contains several waste piles of mineralized gabbro from a nearby taconite operation. Surface seeps containing high levels of sulfates and trace metals, particularly nickel, are present (see section 4.6). The seeps flow into Unnamed Creek and the influence of this disturbance on the water quality of the creek is obvious. Thus far, the magnitude of pollution is largely mitigated by natural chemical processes involving absorption, chemical complexation, and chemical precipitation due to the presence of a bog. While the bog helps mitigate this problem, the bog is showing some signs of stress such as damage to vegetation.

These examples give an indication of the importance of such discharges and support the conclusion that area sources are an important factor influencing regional water quality. If future mining operations are located in watersheds affected by existing sources, then more detailed source monitoring should be performed to adequately separate potential impacts due to existing sources from impacts attributed to new sources.

4.3.4 The Influence of Atmospheric Deposition on Water Quality

The atmosphere contains particulate and gaseous matter as a result of natural and human activities. The old adage "what goes up must come down" applies since atmospheric pollutants eventually deposit on land and water surfaces. Dust storms, volcanic activity, sea spray, decaying processes, and emissions from plants and animals are examples of some of the natural processes which contribute to the atmospheric load. Human activity exacerbates the situation by burning fossil fuels, through agriculture practices, and various other domestic and commercial activity.

Chemical parameters considered important in atmospheric loading and ecological impacts include hydrogen ions, sulfur compounds, nitrates-nitrites, phosphorus, metals, and other organic and inorganic particulates. Kramer (1976) suggests that pH should be considered the master variable as it affects, directly or indirectly, trace metal migration and toxicity, secondary aquatic production, and land production.

In recent years, the problem of acid rain has been recognized. Sulfur dioxide and nitrogen oxide emissions which are converted to sulfates and nitrates, and eventually sulfuric and nitric acids, are the primary sources of acid rain. Once believed to be a local problem only, it is now recognized that sulfur dioxide can travel long distances and that acid rain is a world-wide problem.

Acid rain, especially in this region, is of concern because of its effects on aquatic and terrestrial ecosystems. Acidification of lakes and streams due to acid precipitation has eliminated or severely reduced populations of aquatic plants and animals in other parts of the world (Honetschlager 1978). Acid rain also increases the rate of element leaching from soils, which may affect vegetation growth and change the composition of runoff that reaches water bodies.

Three factors govern surface water pH: a) the rate of strong acid input; b) the location of lakes and streams relative to prevailing winds which modify (a); and c) the geochemistry of surficial sediments and bedrock which determine the buffering capacity of the surface waters and runoff waters entering the surface waters. Factor (c) is the most important (Kramer 1976).

Other air-borne pollutants such as metals and nutrients may also be important. This section of the report discusses the significance of the deposition of air-borne pollutants as measured in northeastern Minnesota.

4.3.4.1 Current Level of Acidity. Natural pH in rain is believed to be 5.7 and is caused by the reaction of carbon dioxide and water which forms carbonic acid (a weak acid), which in turn dissociates and releases a hydrogen ion. Figure 25 summarizes some of the pH values reported in the literature. Areas defined as "remote" generally have pH values above 5, whereas values near 4 are not unusual in highly impacted areas. The high pH in North Dakota precipitation may reflect the alkaline nature of the soil in this region and/or the buffering effect of fertilizer used on agricultural lands.

Figure 25

Increases in precipitation acidity have occurred simultaneously with increased emissions of sulfur dioxide and nitrogen oxides. While pH values in precipitation were once 5.7 or higher in much of the northestern United States, rain now has an average pH of 4.0-4.2 (Honetschlager 1978).

The acidity of precipitation can be neutralized by various substances in the atmosphere. Additions of even small amounts of particulates to the atmosphere may raise the pH of precipitation because their surfaces have the ability to adsorb hydrogen ions (Kramer 1976). Bases in the atmosphere which are capable of neutralizing acid rain include sea spray and ammonia.

Minnesota pH was measured on three different types of precipitation samples collected for the Regional Study: bulk; rain-event; and through-fall. Bulk samples were wet plus dry deposition; rain-event samples were collected by bottles set out when rain occurred; and through-fall samples were collected by bottles placed beneath tree canopies.

Figure 25 Selected precipitation pH values.

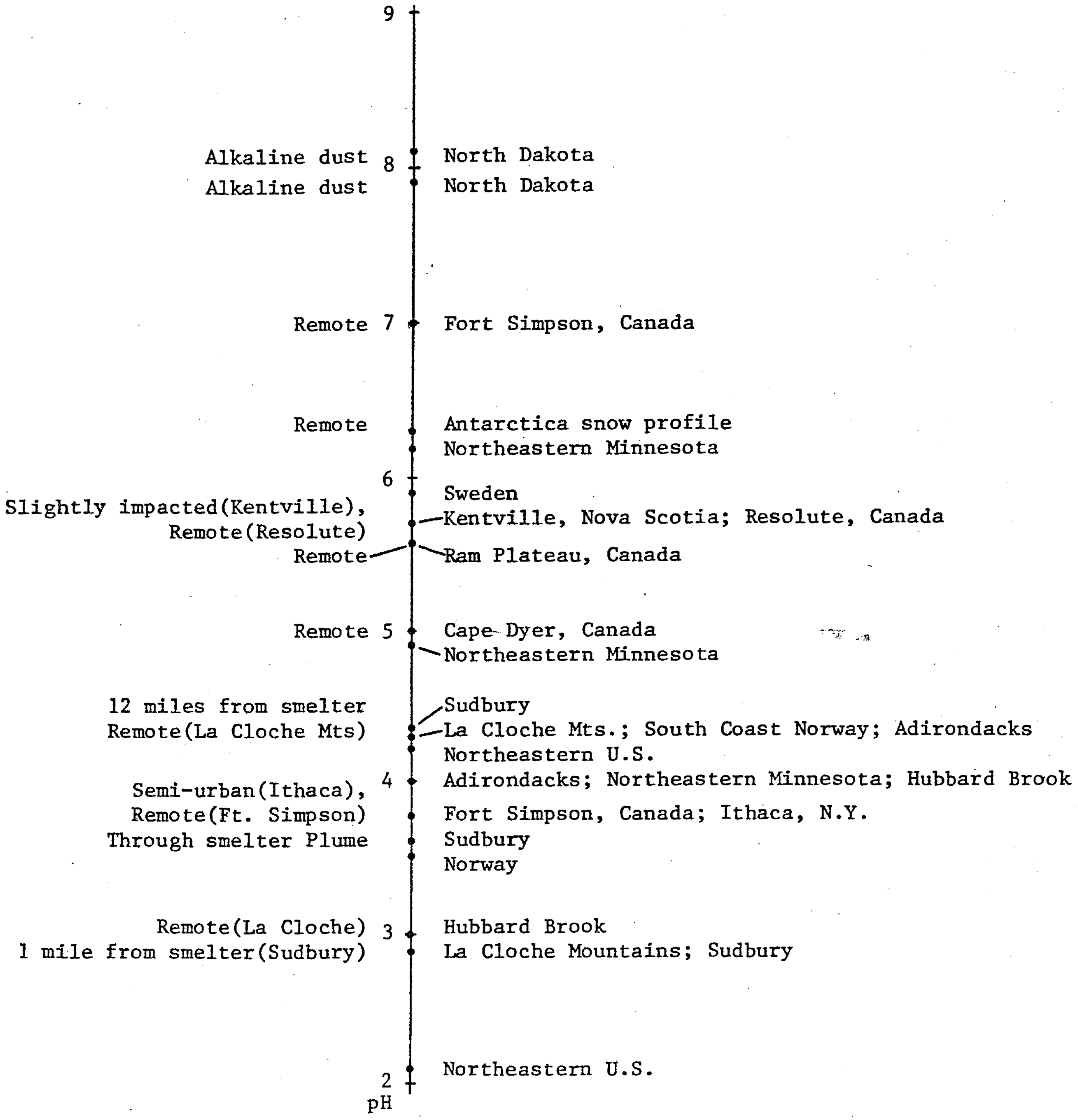


Table 29. Monthly concentration and deposition of bulk collected sulfate and hydrogen ion (March, 1977-March, 1978).

	Fernberg	Spruce Road	Dunka	Hoyt Lakes
Collection period (days)	27-35	27-35	27-37	27-37
Volume of precipitation collected (ml/collection period)	19-7000	550-8500	400-10600	300-8900
mm of precipitation during collection period	0.4-229	10.9-167.8	7.9-209.3	5.9-175.7
Total precipitation 4/77-3/78 (normal-726 mm)	818.8	653.9	722.2	732.3
pH - range	3.7-6.9	3.7-5.7	3.7-6.6	3.4-5.6
- median	4.4	4.3	4.2	4.5
(no. of samples)	(11)	(12)	(11)	(13)
Sulfate (mg/l)				
- range	(-1)-5*	(-1)-6.1	(-1)-7.1	(-1)-5.7
- median	2.1	2.3	2.8	2.3
(no. of samples)	(11)	(12)	(11)	(12)
Sulfate loading rate (kg/ha/yr)				
- range	(-5.92)-38.5	(-2.37)-34.2	(-5.92)-50.2	(-9.48)-31.5
- annual geometric mean	14.61	12.36	15.1	15.36
(no. of samples)	(11)	(12)	(11)	(11)
Hydrogen ion loading rate (ueq/ha/yr)				
- range	0.476-3310	8.04-2010	0.893-2510	6.67-1490
- median	274	320	203	235
(no. of samples)	(11)	(12)	(11)	(13)

*Minus sign indicates "less than".

For more detail see Thingvold et al. 1979.

Table 30. Monthly mean concentrations of parameters in bulk collected samples.

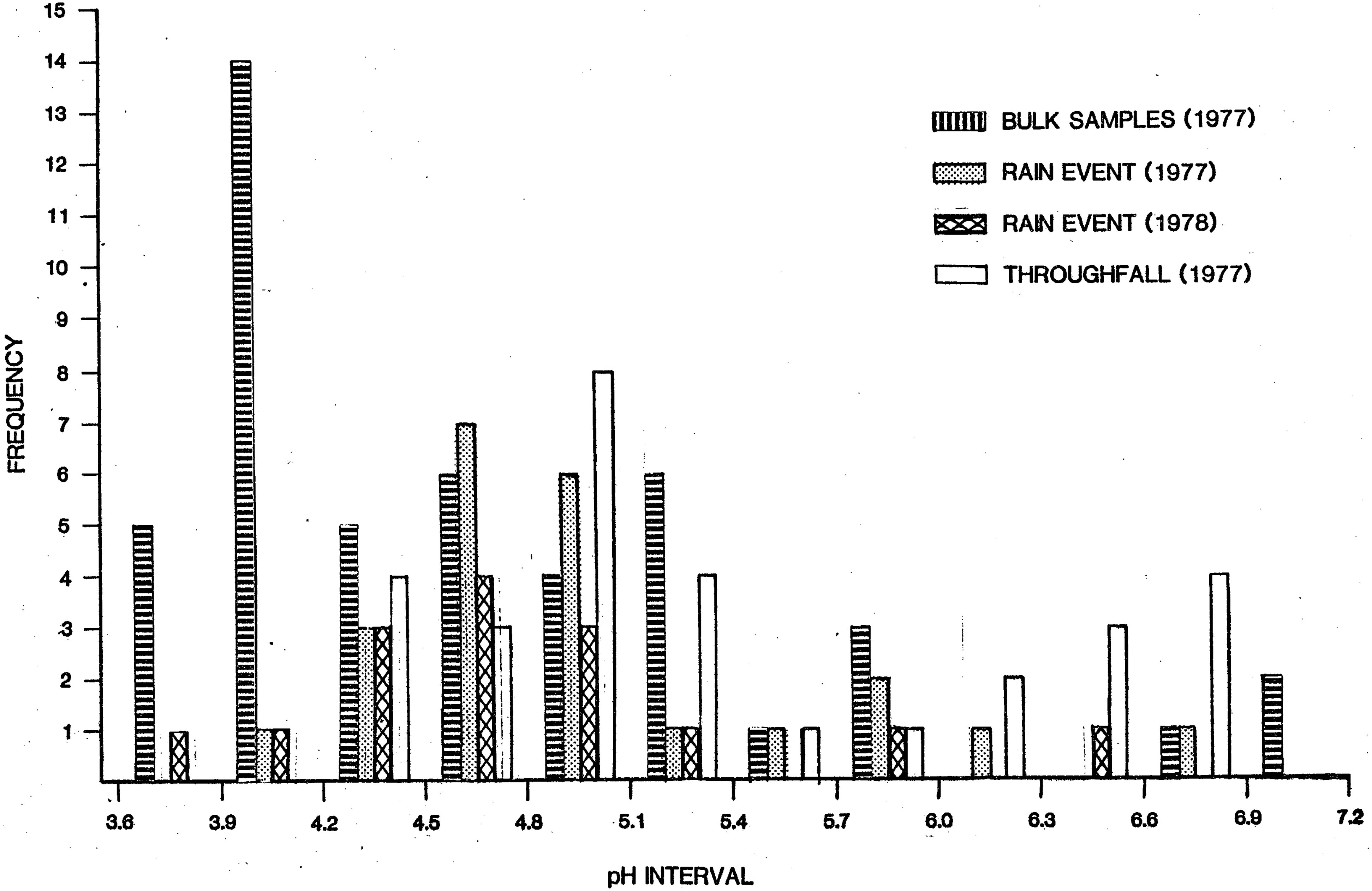
		Fernberg		Spruce Road		Dunka		Hoyt Lakes		Regional
Constituent	Units	mean	n	mean	n	mean	n	mean	n	Average
Spec. Cond.	umhos	32	11	24	12	28	11	24	13	27
SS	mg/l	8.0	11	14	12	13	11	14	11	12
TDS	mg/l	9.0	11	7.2	12	10	11	15	11	10
NO_2/NO_3	mg/l	0.26	6	0.21	3	0.32	5	0.30	6	0.27
Total P	mg/l	0.06	12	0.03	13	0.031	12	0.041	13	0.04
TOC	mg/l	3.7	12	3.1	13	5.3	12	4.3	13	4.1
Alkalinity	mg/l	-10*	11	-10	12	-10	10	-10	12	-10
Cl	mg/l	-1.4	11	-3	12	-1.4	11	-1.6	12	-1.9
Ca	mg/l	1.5	12	1.6	13	1.7	12	1.7	13	1.6
Mg	mg/l	-2.0	12	-1.4	13	1.5	12	1.4	13	-1.6
Na	mg/l	-0.5	12	-0.5	13	-0.5	12	-0.5	13	-0.5
K	mg/l	-0.5	12	-0.5	13	-0.5	12	-0.5	13	-0.5
F	mg/l	-0.1	11	-0.1	13	-0.1	11	-0.1	12	-0.1
Ni	ug/l	-1	13	-0.2	13	-2	12	-2	13	-2
Cd	ug/l	0.57	13	0.42	13	-0.33	12	0.47	13	0.45
Zn	ug/l	6.9	13	8.4	13	4.0	12	9.9	13	8.1
Pb	ug/l	12	13	10.4	13	9.1	12	12	13	10.9
Al	ug/l	51	13	80.9	13	140	12	208	13	120
Fe	ug/l	49	13	66	12	217	12	282	13	154
As	ug/l	1.1	12	0.95	13	1.1	12	3.1	13	-1.6
Cu	ug/l	1.5	13	2.1	13	1.2	12	1.3	13	1.5

*Minus sign indicates "less than".

For more detail see Thingvold et al. 1979.

FIGURE 26

HISTOGRAM OF pH VALUES IN BULK COLLECTED SAMPLES AND RAIN EVENT SAMPLES



Bulk samples were collected from March, 1977, to March, 1978, at four sites (Tables 29 and 30). Most of the low pH values occurred July through November. These months were also the wettest. As a consequence, the hydrogen ion load per unit area of land surface was one to two orders of magnitude greater during these months.

Tables 29 and 30

Rain-event pH was collected by the Study at three sites (Kawishiwi laboratory, Ely, and Bear Island) from April to September, 1977. Bottles were simply placed outdoors when the rain began and the pH measured soon after rainfall ceased. The Minnesota Department of Natural Resources (MDNR) collected rain samples from June to October, 1978, at the Amax exploration site near Babbitt. These samples were collected using a funnel to bottle arrangement such that the funnel was continually exposed to the elements and subject to dry fallout collecting on the surface that can be washed during rainfall. Therefore, it is likely that the pH values reflect some effects of buffering by dry fallout, similar to the bulk collected samples.

Figure 26 shows a histogram of northeastern Minnesota pH values. Eighty-seven percent of the bulk samples (41 of 47) had a pH less than 5.7 which means that most of the precipitation measured can be considered acidic. Half the samples had a pH less than 4.5. These values are comparable to or even less than values measured in areas of the world where ecological damage has already occurred.

Figure 26

Alkalinity is listed as less than 10 mg/l (Table 30). Since the analytical technique employed overestimates the actual values at these low levels, the actual alkalinity is probably close to zero. The likely source of this alkalinity, low as it is, is the suspended solids which average 12 mg/l. Because there is so little buffering, only small amounts of acid-forming species are needed to lower pH.

4.3.4.2 Current Level of Sulfate and Nitrogen Deposition. Natural emissions of sulfur are estimated to be twice as large as anthropogenic emissions. However, natural emissions are not considered a major factor in producing acid rain because they are assumed to be in balance with natural sources of neutralizing bases (Honetschlager 1978). Natural sources of nitrogen emissions are approximately an order of magnitude higher than anthropogenic emissions. Higher flame temperature in the combustion of fossil fuel and the increased use of nitrogen fertilizers since 1950 have contributed to increasing nitrogen emissions. Although sulfuric acid remains the largest contributor to acid precipitation, nitric acid is becoming more important in many places (Honetschlager 1978).

Sulfates are important in some parts of the world as a cause of acid precipitation. A level of 2.2 mg/l of sulfate in precipitation is indicative of excess sulfate. This value was exceeded often in northeastern Minnesota (Table 29). Based on bulk collected samples, the geometric annual mean loading rate for the region is 14.4 kg/ha/yr. The highest sulfate loadings occurred in August and September with high levels also in April and May. These months had the highest amounts of precipitation suggesting that wet scavenging of sulfate is probably more important than dry fall-out. Although these sulfate loading values are similar to those reported for "remote" areas (Honetschlager 1978), the low pH values in rain and the lack of buffering particles create a significant potential for acidification.

Dry deposition of sulfate was found to be 1.8 kg/ha/yr (Table 31) compared to the bulk (wet and dry) deposition rate of 14.4. Although there are local sources of sulfur (Ritchie 1978), it is believed that the majority of the sulfur measured as sulfate originates outside of the region. Because the dry deposition value is so low and because very little sulfur dioxide (SO_2) was measured in this region (Volume 3-Chapter 3), it is believed that most of the sulfate measured by the bulk samples originated outside of this region, perhaps several hundred miles away in areas such as Chicago, St. Louis, and the Ohio River Valley. Long-range transport of sulfate is possible when large high pressure systems are centered to the east and south of Minnesota. The clockwise vertex of winds can then move sulfur compounds to Minnesota from industrial areas to the east. Under certain conditions, Canadian cold fronts can collide with this sulfur-laden warm air mass over northeastern Minnesota causing high levels of sulfate in the precipitation. Thus, rain scavenging can be an important mechanism for sulfate deposition.

Table 31

Few measurements were made for nitrate (NO_3) and nitrite (NO_2). Because these forms of nitrogen are very reactive biotically, the values reported may not reflect the true levels in the original precipitation. The mean average nitrate/nitrite concentration at the four bulk sample sites was 0.27 mg/l, a value typical for this type of area.

4.3.4.3 Atmospheric Deposition Rates and Current Precipitation Levels of Trace Metals, Nutrients, and Other Chemical Parameteron atmospheric concentration and

Table 31. Mean dry deposition rates for nine sites in northeastern Minnesota ($ng/m^3/sec$).[a,b]

Element	Range of Values	Regional Average	
Al	1.254 - 6.310	2.820	(0.889)[c]
Cl	0.385 - 0.820	0.610	(0.192)
V	0.003 - 0.014	0.009[d]	(0.003)
Cr	0.008 - 0.060	0.026	(0.008)
Mn	0.050 - 0.150	0.087	(0.027)
Fe	7.063 - 37.090	20.680	(6.520)
Co	0.008 - 0.031	0.018	(0.006)
Zn	0.055 - 0.100	0.099	(0.003)
As	0.006 - 0.015	0.009	(0.003)
Br	0.012 - 0.128	0.034	(0.011)
Sb	0.001 - 0.003	0.002	(0.001)
Pb	0.040 - 0.408	0.109	(0.034)
Cu	0.019 - 0.061	0.033	(0.010)
S	1.400 - 2.248	1.883	(0.594)[e]
Ni	0.005 - 0.056	0.024	(0.007)
Cd	0.001 - 0.024	0.008	(0.003)

[a] Eisenreich et al. 1978.
[b] Using Chilton's dry deposition rates.
[c] kg/ha/yr.
[d] Average for 6 sites.
[e] 1.782 kg/ha/yr as $SO_4^=$

For more detail see Thingvold et al. 1979.

deposition of trace metals, nutrients, and other chemical parameters was collected from bulk samples, wet-only samples, through-fall samples, and membrane filter air samples (Tables 29, 30, and 31).

Most elements show a constancy in mean annual deposition rates over the nine sample sites except for aluminum, iron, and lead. Bearhead, Dunka, Erie, Hoyt Lakes, and Babbitt (all near taconite operations) showed elevated levels for iron. Aluminum levels were higher at Bearhead, Dunka, and Babbitt; however, there is no ready explanation why aluminum should be elevated at these sites. Lead was elevated at Erie, Hoyt Lakes, Whiteface, and Babbitt, and is probably accounted for by lead released from the use of leaded gasoline. Because most of the elements have similar levels at most sites, regardless of distance from various human activities, the origin of these elements is probably diffuse in nature, that is, local sources are believed to be insiqificant.

Total phosphorus measurements included both organic and inorganic phosphorus. Since biotic activity can change the phosphorus forms over the 30-day bulk sample period, no attempt was made to differentiate between the two forms. The annual average concentration of 0.04 mg/l is similar to values reported for northeastern Minnesota and elsewhere (Eisenreich et al. 1978).

A comparison of bulk and dry deposition rates are compared with the monitoring results from streams and lakes in Table 32. Of the ten wet/dry versus dry deposition rates that can be compared, only three elements show different rates between the two methods that can be considered significant: sulfate (discussed earlier), chloride, and iron. Iron is of particular interest because the dry deposition rate is six times the wet/dry deposition rate. The reason for this finding probably lies in the sampling methodology. The membrane samplers were about 8-15 feet farther above the ground than the bulk samplers and hence less affected by tree canopies that may screen out the iron particles. Support for this theory was found in that bulk values in the summer (when deciduous trees are foliated) were lower than in the winter. Rain scavenging can be considered much less important than dry deposition in the case of iron.

Table 32

A comparison of bulk deposition rates with those reported elsewhere is presented in Table 33. Iron is the only element that could safely be considered to occur at rates significantly higher in northeastern Minnesota than the other areas. Uncertainty in the calcium and magnesium measurements preclude close comparison so these values can be considered the same for all practical purposes.

Table 33

In summary, the deposition rates of all parameters measured except for iron are not unusual for a remote region such as northeastern Minnesota. The taconite mines influence the quality of air in this region. Based on the sameness of values across all membrane and bulk sample sites, it is believed that the origin of most of the parameters lies outside the region. Some evidence suggests that there are local sources for iron, aluminum, lead, and chloride.

4.3.4.4 Seasonal Effects of Atmospheric Deposition on Water Quality.

Periodically, extreme acid precipitation events occur and large amounts of acid are deposited in lakes and streams over short periods of time (Honetschlager

Table 32. Summary comparison between air results and surface water results.

ELEMENT	BULK DEPOSITION CONCENTRATION REGIONAL MEAN	BULK DEPOSITION RATE REGIONAL AVERAGE (kg/ha/yr)	MEAN ANNUAL DRY DEPOSITION RATE (kg/ha/yr)	MEAN STREAM CONCENTRATIONS GROUP			LAKE[b] CONCENTRATIONS
				A	B	C	
Al(ug/l)	51-208 (120)	.360-1.467(.846)	.889	174	127	112	4-610(114)[c]
As(ug/l)	–[a] 1.6	-.011	.003	.83	6.0	.82	.4-2.1(.7)
Ca(mg/l)	1.6	-11.3	—	32	19	6.8	1.9-46(9.5)
Cd(ug/l)	.45	.003	.003	.055	.061	.046	.008-.8(.05)
Cl(mg/l)	-1.9	-13.39	.192	11.7	22.7	2.4	.1-9.3(2.5)
Cu(ug/l)	1.5	.011	.010	3.0	2.7	4.2	0.2-10.(1.8)
Fe(ug/l)	49-282(154)	.345-1.99(1.08)	6.52	493	1241	723	16-2300(470)
F (mg/l)	-2	-.014	—	.233	.227	.158	.05-.5(.1)
K (mg/l)	-.5	-3.53	—	2.8	2.2	.61	.2-2.2(.7)
Mg(mg/l)	-1.6	-11.3	—	17.9	9.4	3.8	.65-12.2(3.5)
Na(mg/l)	-.5	-3.53	—	9.1	11.3	17.3	.9-18(2.5)
Ni(ug/l)	-2	-.014	.007	24.8	2.1	3.5	0.4-6.0(1.4)
Pb(ug/l)	10.9	.077	.034	1.08	2.4	.76	0.08-1.9(0.5)
Zn(ug/l)	8.1	.057	.003	3.6	3.8	3.2	0.2-35.5(3.1)
Alkalinity (mg/l)(CaCO$_3$)	-10	-70.51	—	71	58	25	1-73(23.2)
TOC(mg/l)	4.1	28.9	—	12.1	17.6	16.9	4.6-38(16)
P-total(ug/l)	40	.28	—	102	44.7	22	
NO$_2$,NO$_3$(ug/l)	290	2.04	—	764	1100	121	
TDS(mg/l)	10	70.5	—	249	146	87	
SO$_4$(mg/l)[d]	2.96	14.36	1.78	97	27	7.1	1-140(7.8)
pH	4.61			7.2	7.0	6.7	5.7-8.8(7.1)
Specific Conductance 25°C	27			355	230	65	24-389(78.5)
Suspended Solids (mg/l)	12			3.9	5.2	3.4	

[a] Indicates something less than.
[b] Surface values only.
[c] Range and (mean), totals.
[d] Geometric mean.

Table 33. Summary comaprison of atmospheric deposition of trace elements (kg/ha/yr).

ELEMENT	N.E. MINNESOTA A	LAKE SUPERIOR B	LAKE SUPERIOR A	ATIKOKAN C	LAKE MICHIGAN D
Al	.85	1.2	1.6	—	.86
Fe	1.08^2	—	1.9	.39-.55	.48
Zn	.057	—		.22-.32	.19
Cu	.011	.045	.097	.02-.03	.021
Ni	.014	0.15	.024	.015-.022	—
Mn	—	—	.079	—	.11
Pb	.077	.079	.17	.022-.033	.11
Cd	.003	.007	.006	.007-.011	.002
As	.011	—	—	—	—
Ca	11.3	4.0	4.2	3.4	14
Mg	11.3	.68	1.0	.37-.73	2.7
Na	3.5	1.8	—	.37	1.9
K	3.5	1.6	—	.37-.44	1.1
Cl	13^2	—	—	4.0-4.2	
SO_4	14.4^2	27	—	4.3-10.4	15

A-Eisenreich, et al. (1978)
B-IJC (1977)
C-Ontario Hydro (1977)
D-Eisenreich, to be published
1-Based on bulk collected samples.
2-Dry deposition rates are significantly different, see Table 31.

1978). Spring snowmelt also supplies large amounts of acid and other pollutants to lakes and streams over a short time interval. Studies have shown that concentrations of hydrogen ion, sulfate, nitrate, and heavy metals are two to three times greater in the first 30 percent of meltwater than in snow (Thingvold et al. 1979). This amounts to 40 to 80 percent of the total parameter content in the snow. Because the soils are frozen, there is no selective retention of any parameter.

Thus, the impacts of atmospheric deposition of air pollutants on surface water quality occur under two distinct sets of climatic conditions, summer and winter. During the winter months, air pollutants are deposited onto the snow-pack, stored, and later released over a very short time interval during spring melt. These pollutants are then released over a period of a few hours to several days depending on watershed size and suddenness of the spring thaw. During summer, the deposition of air pollutants is a function of the type of storm and the level and type of pollutant in question. Although sulfate and hydrogen ions are deposited most heavily during the wet months, the spring snowmelt may be the most critical in terms of short-term impacts. Over the long run, the total picture of atmospheric deposition is important.

As an example of the effects of snowmelt, the chemical composition of snow pack and runoff in the Filson Creek watershed was analyzed in 1976 and 1977. Table 34 presents the chemical analysis of the snow pack as determined by the U.S. Forest Service (1976) and compares the results with those from two other sources. In 1976, the snow pack depth was about 90 percent of normal. A snowmelt enrichment test conducted on a snow sample in this region during 1978 found that 50 to 70 percent of the 6 parameters analyzed are contained in the first 90 percent of the melt water (Glass 1978).

Table 34

Filson Creek was studied by Siegel (1978) to evaluate the relative contribution of sulfate from acid precipitation and the oxidation of sulfide minerals associated with copper and nickel deposits. During snowmelt, sulfate levels in Filson Creek increased from less than 2 mg/l to 10 mg/l. Simultaneously, the pH dropped from 6.4 to 5.8. The pH of samples from the March, 1977, snowpack was 4.7 compared with an average pH for precipitation of 5.1. The changes in sulfate concentration and pH of Filson Creek and the lower pH of snow suggest accumulation of sulfate acidity in the snowpack during winter. Snowmelt contributed more than 33 percent of the annual sulfate load discharged from Filson Creek. The groundwater contribution of sulfate was minimal compared to precipitation and surface runoff, even though sulfate levels up to 74 mg/l were observed in groundwater discharging into the creek.

A summary comparison between the Filson Creek snow pack concentration and stream concentrations at low flow, immediately prior to spring peak flow, and the highest concentrations observed is presented in Table 35. Cadmium, lead, nitrate/nitrite, and zinc had higher concentrations in the snow pack than in the streams. The pH was about 2.5 units lower in snowmelt water than in streams.

Table 35

Concentrations of most elements are low in the snow pack, so snowmelt water tends to dilute stream concentrations. However, in Filson Creek, stream levels of

Table 34. Chemical composition of snow pack, Filson Creek Watershed.

PARAMETER		EPA(1)	U.S. FOREST SERVICE, 24 March 1976 Sample 1	2	3	x	Siegel 9 March, 1977
Acidity as H^+ (Mg/l)		0.0151	.01	.01	.03	.016	
Bicarbonate (Mg/l)			0	0	0	0	
Cadmium (ug/l)	Dis		0.25	0.05	0.15	0.15	
	Tot		0.13	0.14	0.49	0.25	0.24
Calcium (Mg/l)	Dis		0.6	0.3	0.4	0.43	
	Tot		0.8	0.7	0.6	0.7	
Carbon, Tot org.(Mg/l)			2.7	4.1	4.3	3.7	1.2
Carbonate (Mg/l)			0	0	0	0	
Chloride (Mg/l)		0.2	0.7	0.3	0	0.3	
Chromium (ug/l)	Dis	5.0	1.7	0.3	0.3	0.8	
	Tot		0.5	0.5	0.7	0.6	
Cobalt (ug/l)	Dis		0.6	-0.2	-0.2	-0.3	
	Tot		0.2	-0.2	-0.2	-0.2	-0.5
Copper (ug/l)	Dis		2.6	0.8	2.2	1.9	
	Tot		6.6	0.8	7.7	5.0	1.1
Fluoride (Mg/l)	Dis	0.023	0.1	0.1	0.1	0.1	
	Sus		0	0.0	0	0	
	Tot		0.1	0.1	0.1	0.1	
Hardness (ug/l)	None		2	1	1	1.3	
	Tot		2	1	1	1.3	
Iron (ug/l)	Tot		360	350	270	327	
Lead (ug/l)	Dis		3.2	1.8	5.1	3.4	
	Tot		14.0	5.6	8.3	9.3	1.7
Magnesium (Mg/l)	Dis		0	0	0.1	0.03	
	Tot		0.2	0.2	0.3	0.2	
Nickel (ug/l)	Dis		5	1	1	2.3	
	Tot		1	1	1	1.0	-1

Table 34 continued.

PARAMETER	EPA(1)	U.S. FOREST SERVICE, 24 March 1976 Sample				Siegel 9 March, 1977
		1	2	3	x	
N - NO$_2$ as N (Mg/l)		0	0.03	0	0.01	
N - NO$_3$ as N (Mg/l)	0.29	1.1	0.70	1.5	1.1	
N - NO$_3$ as N (Mg/l)	0.099	0.15	0.14	0.13	0.14	
N - org Tot (Mg/l)		1.7	0.25	0.25	0.73	
N - KJD as N (Mg/l)		0.57	0.39	0.38	0.45	
pH (measured)		4.3	4.6	4.6	4.5	
(free acidity)	4.82	4.0	4.0	3.52	4	
p - orth as P (Mg/l)		0	0	0	0	
p - tot as P (Mg/l)		0.04	0.02	0.02	0.03	
Potassium (Mg/l) Dis		0	0	0	0	
Tot		0.1	0.1	0	0.07	
Residue - 110c (Mg/l) Sus		29	49	NA	37.5	
Silica (Mg/l) Dis		0	0	0	0	
Silver (ug/l) Dis		-0.02	-0.02	-0.02	-.02	
Sodium (Mg/l) Tot		0.1	0.2	0.2	0.17	
Specific cond 25c FLd (us		31	15	12	19.3	
Sulfate (Mg/l) Dis	1.53	1.5	1.9	2.0	1.8	-1.0
Turbidity (JTU)		3	6	5	4.7	
Zinc (ug/l) Dis		13	3.3	9.2	8.2	17
Tot		14	18	18	16.7	
Water Content (mm) (Based on 10 samples)					114.3	

- Indicates less than

1 Unpublished data 1978 (Gary Glass, EPA-ERL Duluth)

Note - runoff for wy 76 was 8.36"

Table 35. Summary comparison between snowpack concentration and stream concentrations at low-flow, spring flow and highest concentration observed.

ELEMENT	SNOW PACK CONCEN.	SPRING-PERIOD CONCENTRATION					LOW-FLOW CONCENTRATION STATIONS					HIGHEST CONCENTRATION				
		F-1	P-1	D-1	SR-2	K-6	F-1	P-1	D-1	SR-2	K-6	F-1	P-1	D-1	SR-2	K-1
Acidity, H^+ (mg/l)	.016	.20	—	—	—	.10	—	.10	.20	.10	—	0.70	1.0	1.0	1.0	7.0
pH	4.5	5.9	7.3	6.8	5.8	6.4	7.3	6.6	7.1	6.8	6.5	7.3	7.3	7.7	7.5	7.0
Bicarbonate (mg/l)	0	8.0	39	26	14	16	25	17	104	60	14	25	66	117	60	18
Alkalinity-$CaCO^3$	-	7.0	32	21	11	13	21	14	85	49	11	21	92	110	85	15
Cadmium (ug/l)	0.25	.05	.08	.05	.04	.12	.02	.43	.08	.02	.03	.18	.18	.15	.15	.13
Calcium (mg/l)	0.70	2.6	22	9.2	3.2	2.3	5.7	62	23	10	2.9	37	80	53	13	7.0
Carbon, Tot. Org. (mg/l)	3.7	21.0	—	—	—	8.8	—	4.7	11	16	—	36	28	35	30	26
Chloride (mg/l)	0.3	.9	5.6	13	1.0	.5	1.3	7.6	27.0	1.3	.2	2.7	12	88	8.8	1.8
Chromium (ug/l)	0.6	.4	.4	-	.4	.4	—	.5	.7	.3	—	1.7	1.0	.8	1.2	1.7
Cobalt (ug/l)	.2	1.5	.3	.8	.7	.4	—	3.8	1.5	.3	.2	2.0	3.8	2.0	.7	.9
Copper (ug/l)	5.0	8.7	4.0	2.3	2.8	1.6	5.5	4.0	1.7	.6	1.8	12	5.9	6.1	2.8	2.0
Fluoride (ug/l)	0.1	.10	300	300	.10	.10	—	1400	1200	600	100	700	1400	1200	600	400
Iron (ug/l) tot	327	760	820	840	750	300	2300	60	2000	930	230	3100	1300	2200	1300	400
Lead (ug/l)	9.3	1.2	.7	1.0	.9	2.4	.7	.4	.6	.4	.3	6.4	2.6	46	31	2.4

Table 35 continued.

ELEMENT	SNOW PACK CONCEN.	SPRING-PERIOD CONCENTRATION					LOW-FLOW CONCENTRATION STATIONS					HIGHEST CONCENTRATION				
		F-1	P-1	D-1	SR-2	K-6	F-1	P-1	D-1	SR-2	K-6	F-1	P-1	D-1	SR-2	K-6
Magnesium (mg/l)	.03	1.9	7.7	5.4	2.7	2.0	3.3	15	8.4	7.6	1.3	23	22	26	12	2.0
Nickel (ug/l)	2.3	8.0	6.0	2.0	2.0	4.0	6.0	7.0	2.0	2.0	2.0	8.0	7.0	10.0	3.0	4.0
NO_2, NO_3, -N(mg/l)	1.1	.15	-	-	-	.11	-	.57	34	.24	-	.99	.57	13	.29	.12
P-total (mg/l)	.03	10	-	-	-	1.0	-	10	-	.02	-	61	45	119	69	20
Potassium (mg/l)	.07	.7	1.5	1.5	.7	.5	1.6	2.0	2.6	.6	.6	3.2	2.3	5.2	.9	.6
Sodium (mg/l)	.17	1.0	1.1	1.0	.2	.3	1.9	1.5	1.8	2.4	.4	1.9	6.8	35	3.7	2.6
Specific Conductance, 25°C	19.3	29	199	104	36	28	46	433	238	93	29	55	568	655	163	42
Sulfate (mg/l)	1.8	7.9	63	9.5	6.5	4.0	5.4	190	13	5.5	3.7	15.0	260	70.0	14	7.2
Turbidity (NTU)	4.7	2.0	5.4	2.6	2.0	3.5	3.0	4.1	10	3.0	1.2	11.0	13.0	18	5.5	3.5
Zinc (ug/l)	16.7	3.20	5.0	3.1	6.5	8.70	3.8	11.0	30	2.4	.9	12.5	13.0	30.0	16.0	8.7
Color (Co-pT)	-	100	50	80	100	45	200	5	90	130	40	500	150	400	250	100
Peak flow date 1976		4/10	4/19	4/18	4/19	4/24										
Low flow prior to spring flush & date sample 1976		—	—	—	—	—	3/17	3/19	3/18	3/10	4/10					
Date of sample closest to peak flow	1976	4/06	4/07	4/06	4/15	4/21										

cadmum, copper, lead, nickel, and sulfate increased during the period when snowmelt water increased stream flows (compare spring period concentration with low flow concentration for station F-1 in Table 35). This observation is consistent with studies that have shown that many constituents in the snow pack are concentrated in the early stages of snowmelt. Still, even at a small watershed such as Filson Creek where snowmelt accounts for a major portion of stream flow, levels of these five constituents were within natural variation (i.e. they were not the highest levels observed--Table 35).

Snowmelt water had little (if any) buffering capacity as no bicarbonate was found in the snow pack. Thus, the low pH of the snow pack yields snowmelt water that is acidic in character. In small watersheds such as Filson Creek where snowmelt accounts for a major portion of stream flow, the sudden and low pH drop (1.4 units in this case) may have significant effects on aquatic communities (see Volume 4-Chapter 1).

4.3.4.5 Buffering Effects of Soils. As part of the plant pathology and terrestrial biology program, the physical, chemical, and typological characteristics of soils in the Study Area were mapped (Volume 3-Chapter 1). Five major till types and 32 named and 5 unnamed soil series distributed among 23 soil associations have been recognized in the Study Area.

During the summer months, atmospheric pollutants deposit on vegetation, soils, and surface waters directly. If the precipitation is acidic, it is usually neutralized in the watershed making runoff less acidic. Experiments have shown that acid deposition can cause increased leaching of cations from soils and vegetation; increases or decreases in plant diseases; other plant injury such as stunting plant growth; and inhibition of the nitrogen-fixing activities of legumes (Volume 4-Chapter 2). The acid effects are generally pronounced only in soils which have a pH below 5.5, especially unbuffered sandy soils and loams which have little or no base exchange capacity.

Model studies developed to simulate the long-term effects of acid rain on acid soil show that soils similar to those in northeastern Minnesota may begin to show the effects of acid rain within 5 to 10 years (EPA 1978). The model also suggested that this soil has little buffering capacity and within a short period of time, rainfall constituents such as hydrogen ions or sulfates would not sorb into the soil, but simply move through the system and eventually into the surface waters.

Distribution of the various soil types mentioned above were calculated on a watershed basis by the Minnesota Land Management Information System (MLMIS). Chemical information of the top layer of soil (0-2.5 cm or 0-6 in.) was used to obtain mean weight values for each parameter for each watershed (Table 36). For all subwatersheds in the Study Area, the pH can be considered low (5.0-5.5). It is unknown whether these values are natural or a result of acidic precipitation. These low soil pH values suggest that Study Area soils have a limited ability to buffer rainfall before it reaches surface waters.

Table 36

Another factor of concern is the base saturation index. Many of the soils north of the Laurentian Divide have base saturation values under 40 percent. When base saturation approaches 20 percent, the soil has effectively lost its buffering

Table 36. Mean weighted chemical character of top soil layer (0.6 inches) by watershed.

	C.E.C (meg/100g)	Base Saturation %	pH	SO_4	Ca	Mg	F	Mn	Cu	Fe	Zn	Ni	Cd	Co	Pb
									PPM						
North of Laurentian Divide															
Filson Creek	34	26	5.0	29	1350	450	8.0	37	1	280	2	1.0	.01	.2	1
Keeley Creek	31	4	5.0	24	1130	290	8.0	29	1	230	2	0.8	.01	.2	1
Bear Island	37	34	5.1	36	1790	650	8.0	51	1	360	4	1.3	.04	.1	2
Kawishiwi															
k-6	34	29	5.2	31	1520	540	5.8	42	1	300	3	1.1	.02	.2	1
k-7	35	30	5.2	33	1610	580	7.5	45	1	310	3	1.2	.02	.2	1
k-5	36	31	5.2	34	1660	610	7.5	47	1	320	3	2.1	.02	.2	1
k-4	36	32	5.2	35	1690	630	7.5	48	1	330	3	1.2	.02	.2	1
k-3	27	30	5.5	22	1240	300	6.3	30	.5	170	2	0.5	.01	.2	1
k-1	32	27	5.1	28	1360	420	7.4	36	1	260	3	0.9	.01	.2	1
Shagawa River	32	25	5.0	26	1210	340	7.7	32	1	240	2	0.9	.1	.18	1
Unnamed Creek	36	27	5.1	33	1500	550	7.7	42	1	310	3	1.2	.02	.2	1.2
Stoney River															
sr-5	49	46	5.4	57	2830	1350	8.2	89	2.0	570	5	2.4	.07	.06	1.9
sr-4	49	45	5.4	55	2800	1280	8.3	81	1	540	5	2.2	.08	.03	1.7
sr-3	46	43	5.4	52	2600	1200	7.8	78	1	510	4	2.1	.06	.07	1.6
sr-2	46	43	5.4	51	2600	1180	7.7	76	1	500	4	2.0	.06	.08	1.6
sr-1	44	41	5.4	49	2400	1090	7.6	72	1	470	4	1.9	.05	.09	1.5
Dunka															
d-2	43	39	5.3	46	2250	990	8.0	70	1	450	4	1.8	.05	.11	1.6
d-1	38	34	5.2	39	1900	770	7.5	56	1	370	3	1.4	.03	.14	1.4
Isabella															
Little	32	34	5.5	30	1640	540	6.8	44	1	260	3	0.9	.02	.15	1.1
i-1	33	30	5.2	29	1450	460	7.2	38	1	260	3	0.9	.01	.17	1.1

Table 36 continued.

	C.E.C	Base	pH	SO_4	Ca	Mg	F	Mn	Cu	Fe	Zn	Ni	Cd	Co	Pb
	(meq/100g)	Saturation %							PPM						
South of Laurentian Divide															
St. Louis															
sl-3	56	49	5.5	68	3260	1690	8.2	105	2	690	5	3	.08	.04	2.0
sl-2	53	49	5.5	63	3090	1550	8.3	100	2	640	5	3	.08	.05	2.0
sl-1	45	44	5.3	49	2530	1120	8.3	80	1	500	5	2	.06	.08	1.8
Partridge River															
p-5	54	39	5.2	62	2700	1440	7.8	86	2	620	3	2.5	.05	.10	.17
p-4	38	45	5.4	39	2300	870	8.6	73	1	410	5	1.7	.06	.07	.18
p-3	40	45	5.4	42	2370	950	8.4	75	1	430	5	1.8	.06	.08	1.8
p-2	41	41	5.3	44	2280	960	8.3	72	1	440	4	1.8	.05	.10	1.7
p-1	40	41	5.3	42	2200	890	8.2	69	1	420	4	1.7	.05	.10	1.7
Embarrass															
e-2	46	33	5.0	49	2150	1010	8.0	64	1.6	500	3	1.9	.05	.13	1.6
e-1	56	36	4.8	64	2640	1300	8.6	76	1.8	670	4	2.5	.09	.09	1.9
Whiteface River															
wf-2	44	46	5.3	48	2580	1100	8.6	82	1.3	500	5.3	2.0	.07	.06	1.9
wf-1	33	44	5.4	31	2020	630	8.7	64	0.9	320	5.5	1.3	.05	.08	1.7
Waterhen Creek	44	44	5.3	49	2490	1100	8.5	82	1.4	500	4.8	2.1	.06	.09	1.8
World-wide (average)								500-1000	15-40		50-100	20-30			15-25
(range)								T-10,000	T-250		T-900	T-500			T-1,200

SOURCE: Patterson and Aaseng (1978).

a - soils of the Study Area, Regional Copper-Nickel Study capacity, not only for acidic input, but also for other anions and cations. Thus, it appears (Table 35) that the surface waters of the area, particularly north of the Divide, are either losing or have lost most of their external buffering.

In summary, the physical and chemical nature of surficial material and the areal distribution of these materials have a direct bearing on the impacts of acid rain. The thicker deposits that generally contain calcareous and clayey materials which buffer acid input are generally found in the southern portion of the Study Area. In the northern part of the Study Area, the soil covering is sparse and the soil is acidic. The acidic soil in the north is caused by: a lack of calcareous material in the till; the area is underlain by granitic bedrock, a rock that is acid by nature; and the predominance of coniferous trees and their litter which contribute to acidity. In general terms, the Shallow Bedrock-Morain area (province C) and the Seven Beaver-Sand Lake Wetland area (province D) (Figure 11) are probably the most susceptible areas to acid rain. These areas also contain most of the lakes and rivers of the area.

4.4 COPPER-NICKEL DEVELOPMENT WATER BUDGET

This section presents conceptual and quantitative models of water systems associated with copper-nickel mining. The conceptual model describes the behavior of the natural and technological elements of the system and enumerates factors to be considered in developing and interpreting a water balance. Quantitative examples illustrate the use of the conceptual model and indicate the relative importance of various elements and processes. These examples are helpful in predicting the nature and extent of impacts on water resources.

Mining activities can significantly affect the water resources of an area in several ways:

1) Mining activities will change the hydrologic behavior of the site. Waste rock piles, open pits, tailing basins, and other areas developed for mining may differ from natural watersheds in total annual runoff, the proportions of surface runoff, interflow, and base flow, or the timing of outflow.

2) If runoff from disturbed areas is controlled and collected, these areas are in effect removed from the natural watershed for the life of the mining operation.

3) Make-up water may be appropriated from streams, lakes, or groundwater for use in milling, smelting, or refining.

4) Runoff which moves through the mine site will pick up such undesirable constituents as heavy metals and other dissolved solids leached from the rock, suspended sediment, and chemicals introduced during mining, such as residues from explosives and oil and grease from vehicles.

5) Excess water may be discharged to streams, lakes, or groundwater. This water may contain heavy metals, process chemicals, sanitary system effluent, excess heat, or other contaminants.

Appropriations necessary for mining can compete with other users of the water resource. Controlled or uncontrolled discharges can introduce materials to surface water or groundwater which make them unsuitable for drinking or other human uses. Fluctuations in stream flows and lake levels may be aesthetically undesireable and can interfere with recreational uses of these waters. Fluctuations also stress aquatic organisms and may cause losses of habitat or of spawning areas. Heat and chemical contaminants in runoff or in discharges may be toxic to aquatic organisms.

Development of a water balance for copper-nickel mining operations helps determine the overall water needs of the system. For example, under average conditions, will it be necessary to appropriate water from outside the system itself, or will an excess need to be discharged? How does this change in an extremely wet or dry year, or in various physiographic provinces of the Study Area? How much water must be stored to carry the operation through an extended dry period? The water balance also describes the paths water follows through the system and the approximate amounts of water following each pathway. This information can be combined with water quality data to assess quality impacts and propose management schemes. For instance, if a discharge to the environment is necessary, which element of the system provides the highest quality water? What parts of the system should receive first attention for runoff collection and treatment, revegetation, or other mitigation schemes?

Much of this section deals with the appropriation, use, and discharge of water during the production phase of mining. During this phase, the mining operation actively influences the water resources of the area. At the end of mining, the hydrologic behavior of the system becomes simpler, but remains extremely important to long-term environmental impacts.

The water balance presented here deals primarily with annual conditions. Results of the annual balance cannot be applied directly to periods shorter or longer than a year. Stream flows and processing needs fluctuate widely over the course of a year, so annual figures do not give enough information to evaluate short-term conditions. Annual figures cannot be used to assess instantaneous mass loadings of chemicals to streams, because the annual runoff coefficients do not apply to single storm events. However, if assumptions are made about the volume and timing of storm runoff from the mine site and the receiving watershed, estimates of variations in chemical concentrations can be made. Assumptions must be made as to whether water will be discharged or appropriated at a constant rate, at a rate proportional to stream flow, exclusively during high flow periods, or on an "as needed" basis (see section 4.5).

An annual budget does not provide all the information needed to analyze periods longer than a year. For instance, the annual balance indicates how much water must be stored to get through a single dry year, but it does not address the likelihood of several dry years occurring in succession.

Further details on mining water balances can be found in the second level reports on mining, milling, and smelting/refining (Volume 2-Chapters 2 through 5) and in the first level report on stockpile hydrology (Hewett 1979).

A major product of the water budget analysis is the conceptual model itself, which describes the flow paths within the copper-nickel water system and provides a way of analyzing meteorological, physiographic, and technological variations. The model allows estimates of runoff, appropriations, and discharges to be made.

4.4.1 Methodology and Description of the Water System

The overall mining, milling and smelting/refining operation has been separated into three parts in developing the water balance: Subsystems A, B, and C.

4.4.1.1 Subsystem A. Subsytem A (Figure 27) consists of the land areas which are part of the mine/mill operation, excluding the tailing basin. Movement of water through the waste rock piles, open pit, and other elements of this subsystem is controlled by natural processes. Water enters by precipitation, surface flow, or subsurface flow from adjacent catchment areas. Water may leave by evaporation, by running off over the land surface, by seepage to the groundwater system, or by being pumped out. In the upper left corner of Figure 27 is a schematic diagram of these processes. The behavior of each element of subsystem A can be described by the following water balance equation:

precipitation + inputs from catchment areas =

evaporation + surface runoff + groundwater seepage +
change in storage within the element

In notation form:

$$P + (RO_C + GW_C) = E + RO + GW + \quad S$$

Figure 27

Information required to develop the water balance for subsystem A includes:

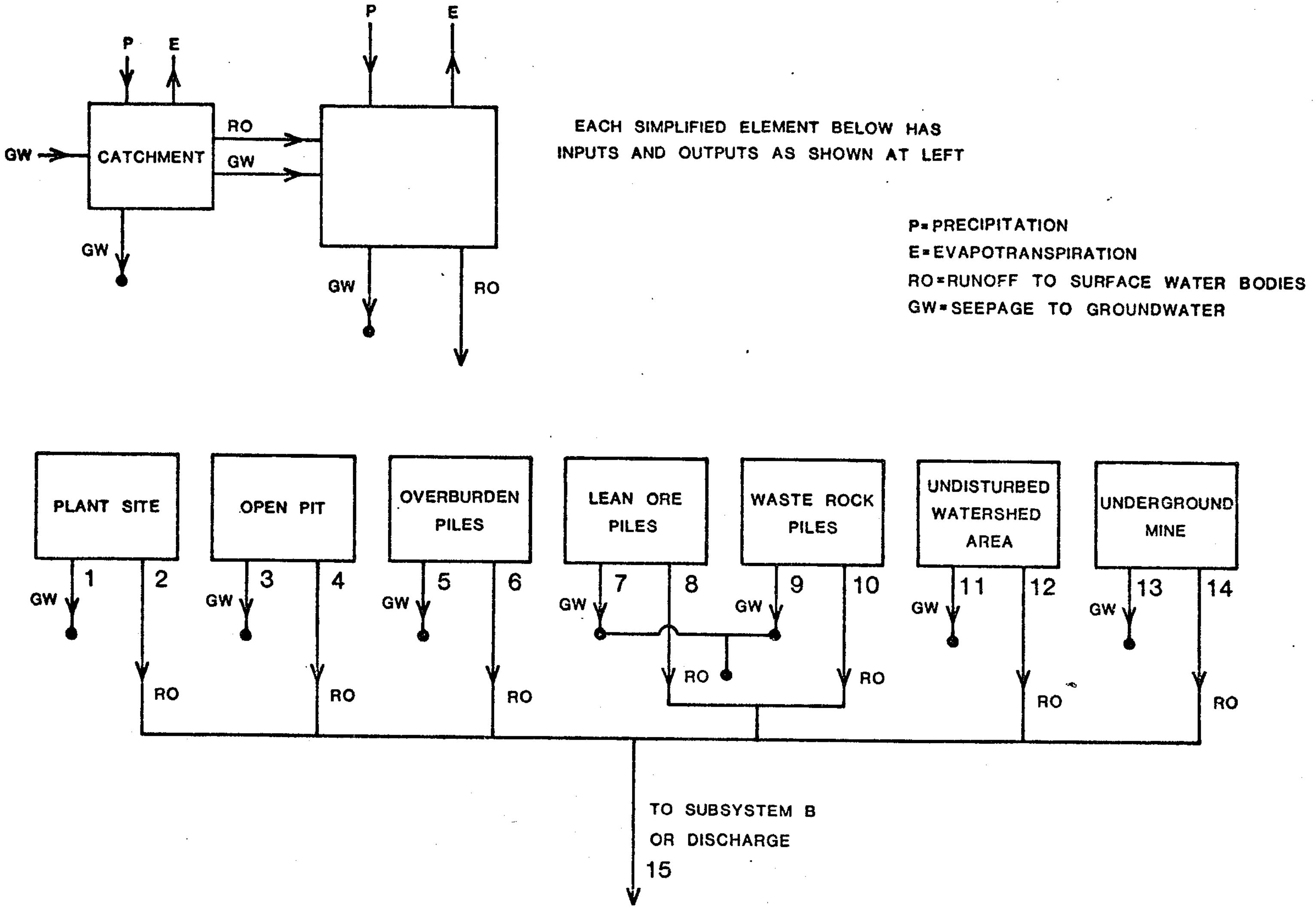
1) Area and physical nature of elements. The total volume of precipitation on or evaporation from an element depends on its area. The ratio of output (RO + GW) to input (P) and the division of output among surface runoff, interflow, and seepage to groundwater are strongly affected by the physical characteristics of the element. The areas and other characteristics of the open pit, waste rock piles, and other elements of subsystem A are presented in Volume 2-Chapters 2 and 5 and summarized in Table 37. Annual water balances were calculated using areas equal to the final size of the pit, rock piles and other elements at the end of the mining operation. In reality, the open pit, waste rock, and lean ore piles, overburden piles, and tailing basin start at zero size and grow to the indicated areas over the life of the operation.

Table 37

2) Precipitation inputs. Average, wet, and dry year conditions were based on a statistical analysis of precipitation data from Babbitt (Watson 1978). Babbitt

FIGURE 27

FLOW DIAGRAM FOR THE MINE/MILL WATER SYSTEM
SUBSYSTEM A



EACH SIMPLIFIED ELEMENT BELOW HAS INPUTS AND OUTPUTS AS SHOWN AT LEFT

P= PRECIPITATION
E= EVAPOTRANSPIRATION
RO= RUNOFF TO SURFACE WATER BODIES
GW= SEEPAGE TO GROUNDWATER

Table 37. Mine model areas (all areas in acres).*

ELEMENT	NOTES	$20X10^6$ mtpy[a] O.P.[b]	$12.35X10^6$ mtpy U.G.[c]	$11.33X10^6$ mtpy O.P.	$5.35X10^6$ mtpy U.G.
Plant site		400	260	240	120
Open pit		563	0	433	0
Overburden piles		173	0	137	0
Lean ore & waste rock piles	200 ft high	1,988	96	1,120	51
Undisturbed watershed	40% of controlled area	2,926	1,436	1,711	638
Tailing basin	70 ft deep	4,016	2,309	2,348	1,067
Smelter/refinery	100,000 mtpy	150	150	---	---
Slag piles		25	25	---	---
Total		10,241(16)[e]	5,026(7.85)[e]	5,989[d]	1,876[d]

*From Volume 2-Chapter 5. All areas given are the final size at the end of the mining operation.

[a] Metric tons per year.
[b] Open pit mine.
[c] Underground mine.
[d] No smelter/refinery.
[e] Area in square miles.

is near the center of the Study Area and has a reasonably long precipitation record which correlates well with the records from Virginia and Hoyt Lakes (Hickok 1977). Average annual precipitation is the mean rainfall over the 56 years of observation. Wet conditions refer to the 100-year wet year, which has a 1 in 100 likelihood of occurring in any one year, and a 26 percent chance of occurring in the 30 year life of the model operation. Dry conditions refer to the 100-year dry year.

3) <u>Evaporation and runoff outputs.</u> Water which evaporates or is transpired by plants is lost from the system and can neither carry out harmful materials nor contribute to stream flows. Water which is not evaporated will leave as surface runoff, interflow, or groundwater flow. The proportions of evaporation and runoff depend on climate, the physical nature of the terrain, and vegetation cover. Average year runoff coefficients for different parts of the mine site are based on published data for similar terrains or on field work done by the Copper-Nickel Study. Extreme year runoff was estimated by two different methods. Balances calculated by method I assume that the 100-year high evaporation occurs with the 100-year low rainfall, and the 100-year low evaporation with the 100-year high rainfall. This method, which provides minimum and maximum estimates of runoff, was used in most computations in this report. Additional balances combine the 100-year extreme precipitation values with the mean annual evaporation values (Method II). This second method may be more realistic, since no statistically significant correlation between annual precipitation and evaporation in the Study Area has been found (Hickok 1977). Results from the two methods do not differ sufficiently to affect the general picture of the water balance.

4) Characteristics of the site. The division of stockpile outflow among surface runoff, interflow, and seepage to groundwater depends partly on the nature of the material on which a stockpile is located. The amount of groundwater which seeps into an open pit depends on the type of material around the pit, the position of the water table, and the proximity of the pit to surface water bodies. These factors may vary greatly from one site to another, although in a given physiographic region some site conditions are more common than others. Groundwater inputs and outputs have been calculated for a range of possible conditions. Precipitation which falls on other areas can move into the mine site by surface runoff. For instance, if a waste rock pile is placed so that it blocks a natural drainageway, the runoff from the drainageway will be forced to seep through the rock pile. The amount of water which might be involved in this case is difficult to predict except on a site-specific basis.

Unit inputs and outputs for subsystem A are summarized in Table 38.

Table 38

The estimated hydrologic behavior of each of the elements is described below. Areas, runoff coefficients, and other quantities are approximate, and may vary from place to place within the Study Area, and be refined as more information becomes available.

Waste Rock and Lean Ore Stockpiles--The hydrologic behavior of stockpiles is discussed in detail because field and lab studies indicate that stockpiles will be the most significant source of poor quality runoff from the mine site (section 4.6).

Table 38. Subsystem A: model water input and output.

ANNUAL INPUT

ELEMENT	PRECIPITATION(P)			CATCHMENT CONTRIBUTION
	AVER. YR (in)	WET YR (in)	DRY YR (in)	($RO_C + GW_C$)
Plant site	28.6	39	16	
Open pit	28.6	39	16	0 to 874 ft^3/yr per ft of pit circumference
Overburden piles	28.6	39	16	0
Lean ore and waste rock piles	28.6	39	16	0
Undisturbed watershed area	28.6	39	16	0
Underground mine	0	0	0	0-1050 ac ft/yr, typically 40 ac ft/yr

ANNUAL OUTPUT

ELEMENT	EVAPORATION (E)[1]				SEEPAGE LOSSES TO GROUNDWATER (GW)			SURFACE RUNOFF (RO)		
	AVER. YR % of P	AVER. YR in.	WET YR** (in)	DRY YR*** (in)	AVER. YR (in)	WET YR (in)	DRY YR (in)	AVER. YR (in)	WET YR (in)	DRY YR (in)
Plant site	25	7.14	5.35	8.71	0	0	0	21.4	33.2	7.3
Open pit	55	15.4	12.6	18.8	0	0	0	13.2[4]	26.4[4]	-2.8[4]
Overburden piles	63	18	14.8	22.0	0	0	0	10.6	24.2	0
Lean ore and waste rock piles[5]	70[2]	20	16.4	24.4	0-1.7[3]	0-4.5[3]	0	8.6-6.9	22.6-18.1	0
Undisturbed watershed area	57	16.3	13.3	19.9	0	0	0	12.3	25.7	0
Underground mine	0	0	0	0	0	0	0	typ 40*	max 1050*	min 0*

Table 38 continued.

[1] Evaporation is calculated on the basis of method I described in the text. From statistical analysis of pan evaporation data from Hoyt Lakes, the 100 year high evaporation = 1.22 X normal. The 100 year low evaporation = 0.82 X normal. It was assumed that high evaporation occurs with low precipitation and low evaporation with high precipitation.

[2] More recent work suggests the figure may be closer to 60%.

[3] More recent work suggests maximum values could be as high as half the total outflow from the stockpiles.

[4] These figures do not include the catchment contribution, which cannot be immediately expressed in inches.

[5] Runoff coefficients and seepage to groundwater given in this table differ somewhat from values given in the text. The latter represent results of further analysis.

*Acre-feet per year (ac ft/yr).
**Wet year evaporation = average year evaporation X 0.82
***Dry year evaporation = average year evaporation X 1.22

The conceptual model presented here is based on three years of study at Erie Mining Company's Dunka Mine and at the Minnamax test site. Runoff coefficients, the distribution of output among surface runoff, interflow and baseflow, and other quantities will vary depending on the location and internal characteristics of stockpiles, as well as meteorological conditions. Stockpiles constructed in the future should be carefully monitored to determine their hydrologic behavior.

Stockpile Water Balance--The annual water yield of stockpiles is of interest because the transport of heavy metals out of the pile may be limited by the amount of water moving through it (section 4.6). Information on rainfall/runoff relationships from field studies at Erie and AMAX is summarized in Table 39 and Figure 28.

Table 39, Figure 28

The average annual runoff from 80 foot, open pit mined gabbro piles at Erie is estimated to be 30-50 percent of average annual precipitation. Current evidence suggests that runoff from stockpiles is greater than runoff from natural watersheds.

The longest period of observation covers the 1977 water year. Runoff from the stockpiles at Erie over this period was 23 percent of precipitation. An additional 5 percent of precipitation went into storage and flowed out after the budgeting period, giving a net yield of 28 percent, and evaporative losses of 72 percent. Results from the 1977 water year are probably not representative of the normal behavior of stockpiles. The winter of 1976-1977 was unusually dry, so that spring runoff from natural watersheds in the Study Area was nearly an order

Table 39. Rainfall and runoff from stockpiles and natural watersheds.

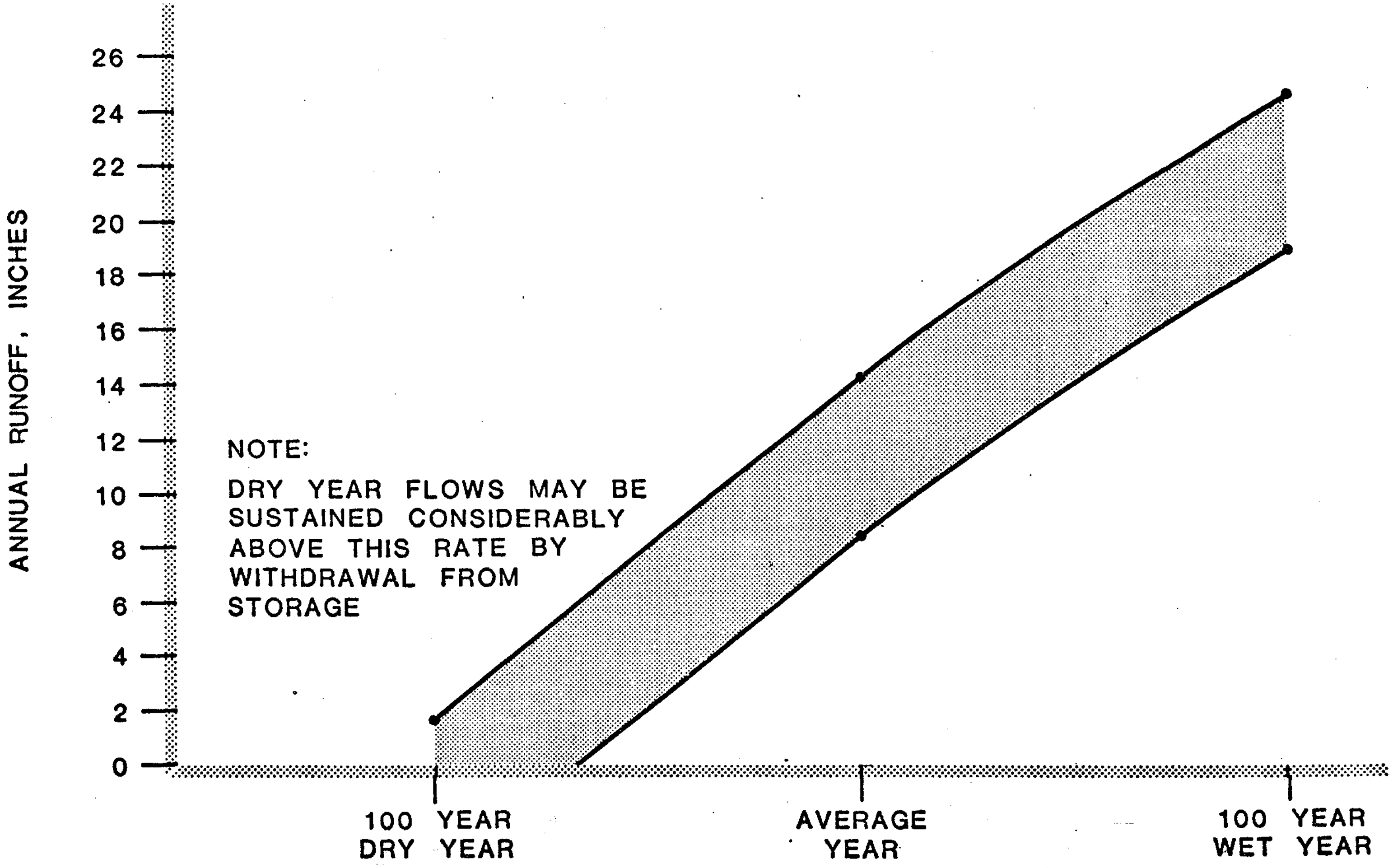
	STOCKPILE BEHAVIOR					STUDY AREA BEHAVIOR			
PERIOD	P(in)[1]	RO(in)[2]	S(in)[3]	$\frac{RO}{P}$(%)[4]	$\frac{RO+S}{P}$(%)[5]	$\frac{P_{obs}}{P_{ave}}$(%)[6]	$\frac{RO_{obs}}{RO_{ave}}$(%)[7]	$\frac{RO_{ave}}{P_{ave}}$(%)[8]	$\frac{RO_{obs}}{P_{obs}}$(%)[9]
ERIE									
10/1/76 - 9/26/77	33.38	7.76	1.52	23	28	117	58	37	18
6/27/76 - 9/25/76	4.76	1.30	-1.30	27	0	41	11	20	6
6/27/77 - 9/25/77	18.93	5.39	0.45	28	31	162	217	20	27
AMAX									
8/4/77 - 10/31/77	13.06	4.97	0	38	38	130	obs not avail.	19	obs not avail.
5/6/78 - 8/11/78	12.83	6.92	0	54	54	110	obs not avail.	41	obs not avail.

[1] Observed precip. at Erie or AMAX.
[2] Observed runoff from stockpile areas.
[3] Change in storage within stockpile areas estimated on the basis of base flow recession curves.
[4] Runoff during the period as a percent of precip. during the period.
[5] Estimate of the net percent of outflow actually resulting from the precip. during the period.
[6] Precip. observed at Erie or AMAX over the period as a percent of the average for that period at Babbitt.
[7] Runoff observed at nine gaged streams as a percent of average runoff from those streams.
[8] Average runoff of nine gaged streams as a percent of input precip. on their watersheds.
[9] Runoff observed at nine gaged streams as a percent of input precip. on their watersheds.

FIGURE **28**

ESTIMATED ANNUAL STOCKPILE RUNOFF

BASED ON 80FT HIGH OPEN PIT MINED PILES



NOTE:
DRY YEAR FLOWS MAY BE SUSTAINED CONSIDERABLY ABOVE THIS RATE BY WITHDRAWAL FROM STORAGE

of magnitude less than normal (see Figure 29). Wet conditions during the summer of 1977 brought precipitation for the water year to 117 percent of normal, but runoff from natural watersheds remained at only 58 percent of normal. It is likely that stockpile runoff for the 1977 water year was also well below normal. Table 39 shows that stockpile runoff was greater than the runoff from natural watersheds in the 1977 water year. If this is true in normal years as well, average annual stockpile runoff is greater than 37 percent, which is the average annual runoff from natural watersheds in the Study Area (Siegel and Ericson 1979).

Figure 29

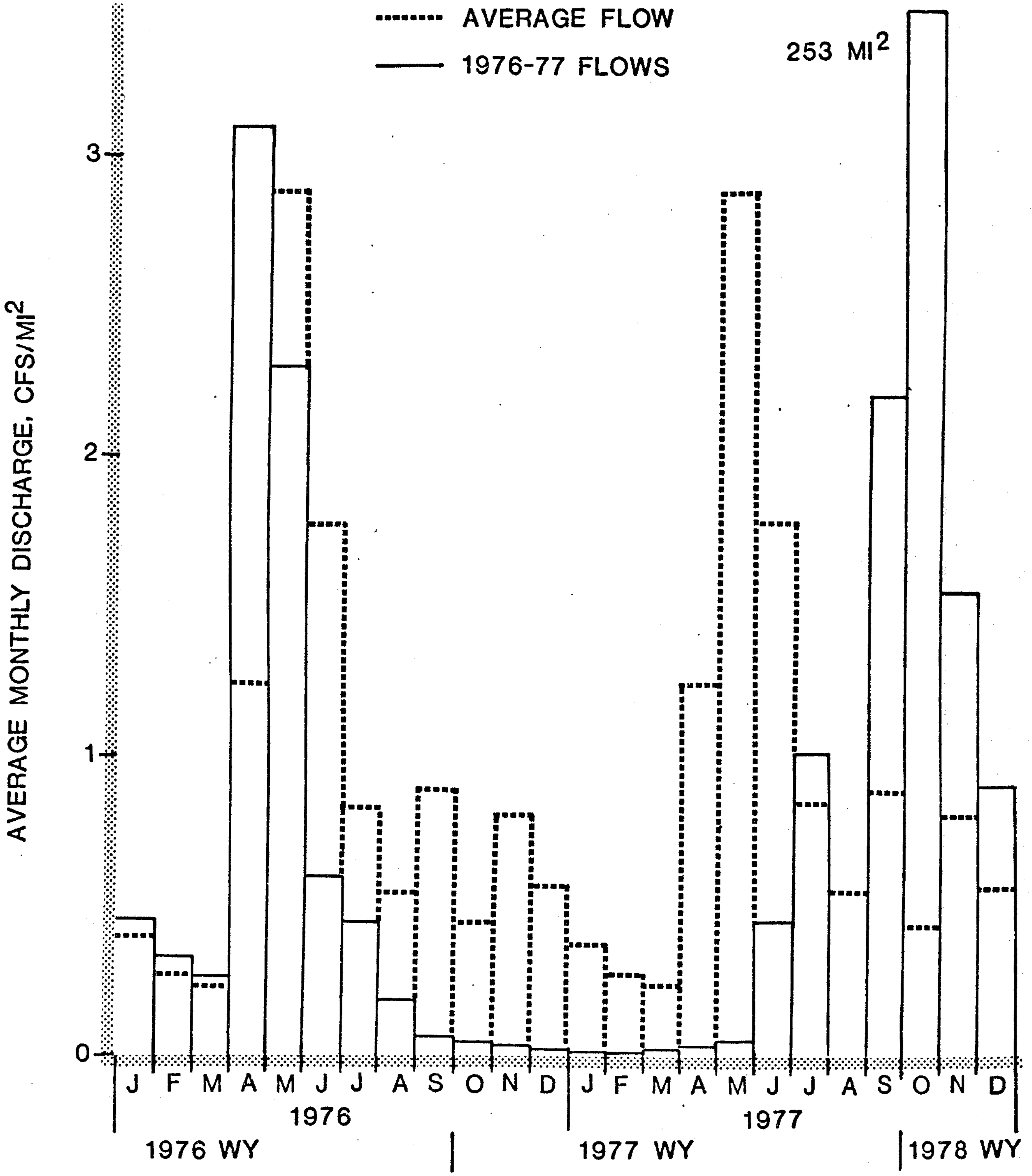
Rough approximations of the variation in stockpile runoff in wet and dry years were made by assuming that the same amount of water is lost to evaporation in a wet or dry year as in an average year. This amount was subtracted from the wet or dry year precipitation to estimate runoff, as shown in Table 40. For the stockpiles at Erie, this method predicts essentially zero runoff in a dry year, and 19 to 25 inches of runoff in a wet year. The behavior of stockpiles during dry periods is illustrated by data collected at Erie in the summer of 1976, when precipitation was less than half of normal (see Table 39). Essentially, all of the precipitation that fell during the period was evaporated, as expected, but stockpile seepages were sustained by withdrawal from storage within the piles.

Table 40

In cases where stockpiles hold more groundwater in storage than natural watersheds, the ratio of stockpile flow to watershed flow will be higher in dry

FIGURE 29

MONTHLY FLOW OF THE KAWISHIWI RIVER NEAR ELY, 1976-77



SOURCE: USGS 1977,1978; ERICSON, PERS.COMM.,1979, SIEGEL AND ERICSON,1979

Table 40. Estimate of stockpile outflow in extremely wet or dry years.

PRECIPITATION

Based on 56 years of precipitation data at Babbitt:

Average precipitation	28.57"
Driest year	16.41"
Wettest year	37.57"
100 year dry year*	16"
100 year wet year	39"

*The 100 year dry year has a probability of occurrence in any one year given by:

$$p = 1 \text{ in } 100 = 1\% = .01$$

The probability that a year this dry will occur at least once in n years is given by:

$$P = 1 - (1-p)^n$$

For instance, the probability of a year this dry in a 30-year period is:

$$P = 1 - (1-.01)^{30} = 0.26 = 26\%$$

The 100 year wet year is similarly defined.

EVAPORATION

Average year evaporation is 50 to 70% of 28.57", or 14.3 to 20". Assume it is the same in dry and wet years.

OUTFLOW

Outflow = surface runoff + seepage to groundwater

	precip(in)	evap(in)	outflow(in)	outflow(%)
Average year	28.57	14.3-20	14.3-8.57	50-30
100 yr dry yr	16	14.3-20	1.7-0	10- 0
100 yr wet yr	39	14.3-20	24.7-19	63-49

years than in average years, and adverse water quality impacts of stockpile runoff will be more severe.

No data are available to make quantitative estimates of how runoff will vary for stockpiles which differ in height, area, or particle size from the ones studied. Depletion of soil moisture by capillarity and evaporation can only extend to depths of a few feet (Brady 1974), so that increasing stockpile height may not increase evaporative losses. Decreasing the particle size of the wastes may increase the water retention capacity of the piles, allowing more water to be held at shallow depths and evaporated.

If a stockpile blocks a surface drainageway, runoff from the drainageway can seep through the pile, augmenting the flow from direct precipitation. For example, at the continuously monitored site at Erie's Dunka Mine, over half of the annual flow from the stockpile is contributed by throughflow from a blocked watershed.

Seasonal Runoff Patterns--The distribution of stockpile runoff throughout the year is of interest for assessing impacts on stream systems and planning leachate monitoring or mitigation programs. Figure 30 shows the pattern of runoff at the continuous recording station at Erie from July, 1976, to September, 1977. Flow is absent during the winter months, probably due to freezing and formation of ice dams near the margins of the stockpiles. At other times of the year, the flow never drops to zero, but is sustained between storm events by discharge of water stored within the stockpile. Spring flow (March-May) was small in the one year of record, but spring flow was also exceptionally low for natural watersheds in that year. In normal years, spring runoff from stockpiles is probably more substantial. Flows in the summer of 1976 were sustained at low rates by discharge from storage, while in the summer of 1977 a number of heavy rainstorms produced abundant runoff. A longer period of observation is needed to define the typical seasonal behavior of stockpiles.

Figure 30

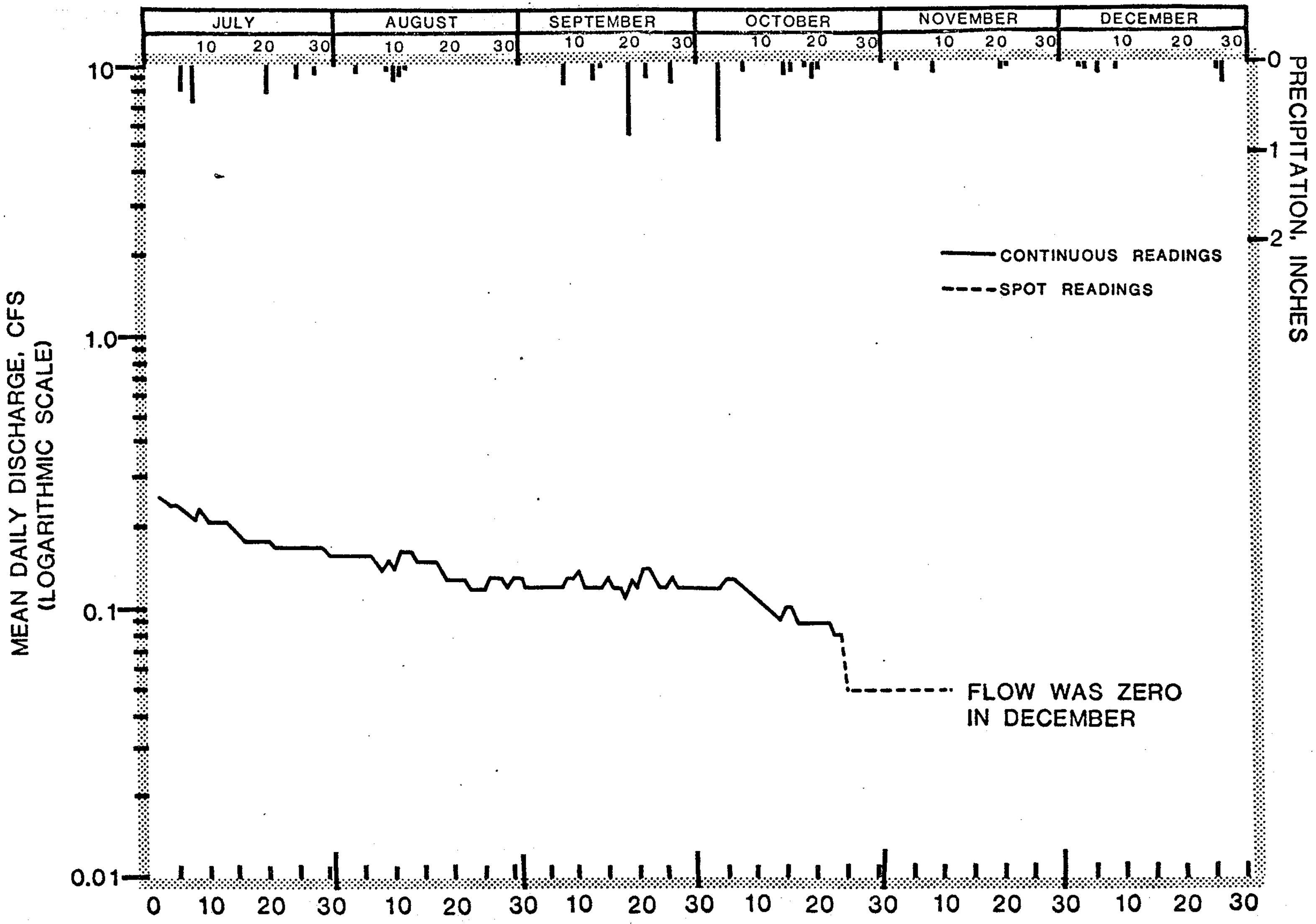
Flow Paths Within Stockpiles--The flow paths within stockpiles are shown in Figure 31. Water can enter a stockpile by direct precipitation or by runoff from surface or groundwater catchments which drain to the stockpile site. Precipitation falling on the stockpiles can either run off over the surface of the pile or infiltrate into it.

Figure 31

Surface runoff occurs when rain intensity exceeds the infiltrability of the material at the top of the pile. For an unsurfaced stockpile, the major factors affecting infiltrability are the grain size distribution of the material and the extent to which dumping, grading, and driving cause layering and compaction. For a surfaced pile, the texture and compaction of the surfacing material, and the discontinuity in conductivity at the boundary between the surfacing material and the pile will control infiltrability. No surface runoff has been observed at the Minnamax test piles. At Erie, water which runs off over the compacted surfacing material infiltrates as soon as it reaches the coarse material on the slopes of the piles.

Much of the water which infiltrates into the piles is subsequently lost to evaporation. As the rest moves down through the pile, it may encounter an impeding

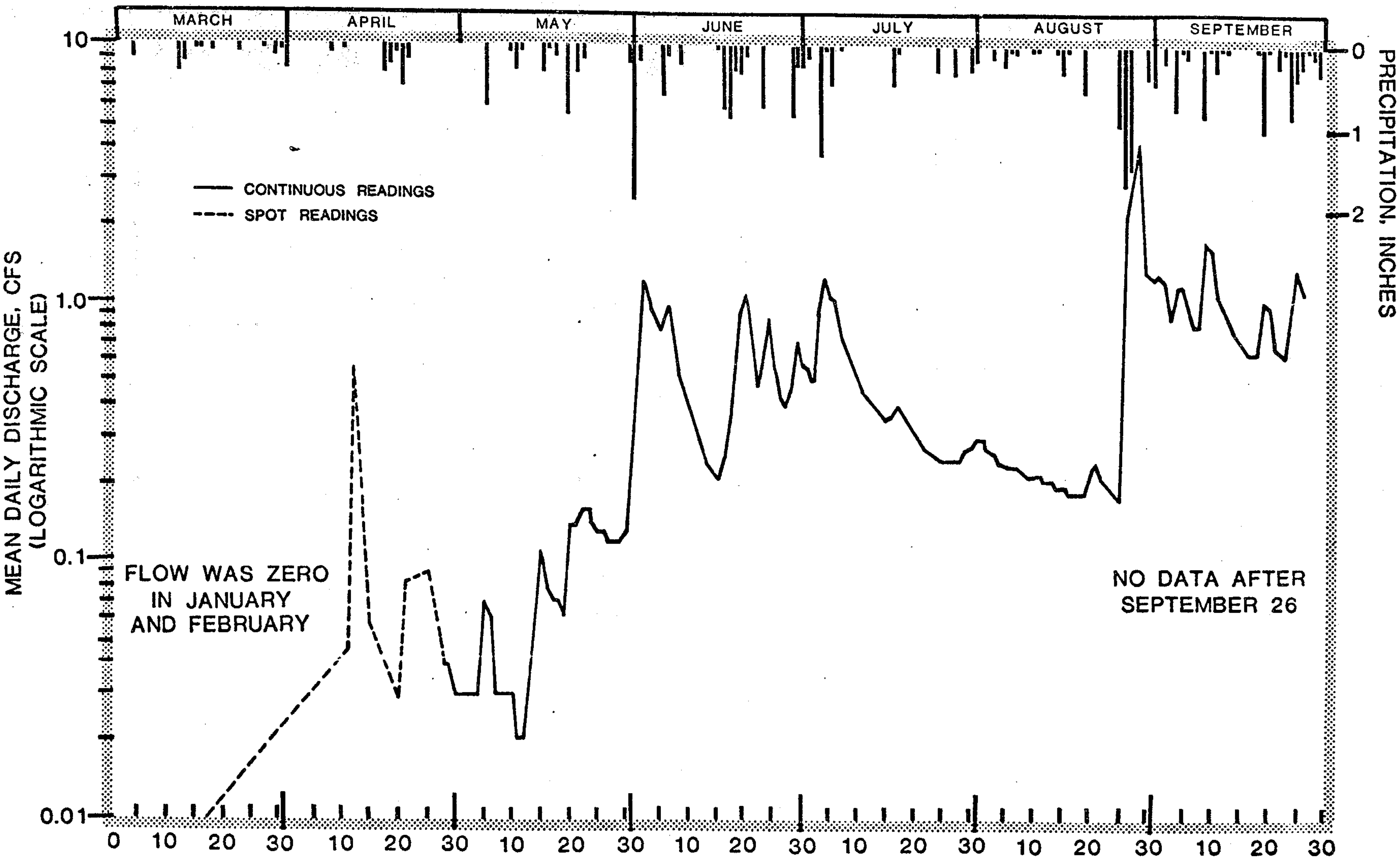
FIGURE 30 PRECIPITATION AND FLOW AT EM-8, 1976



SOURCE: HEWETT, 1979

FIGURE 30
cont.

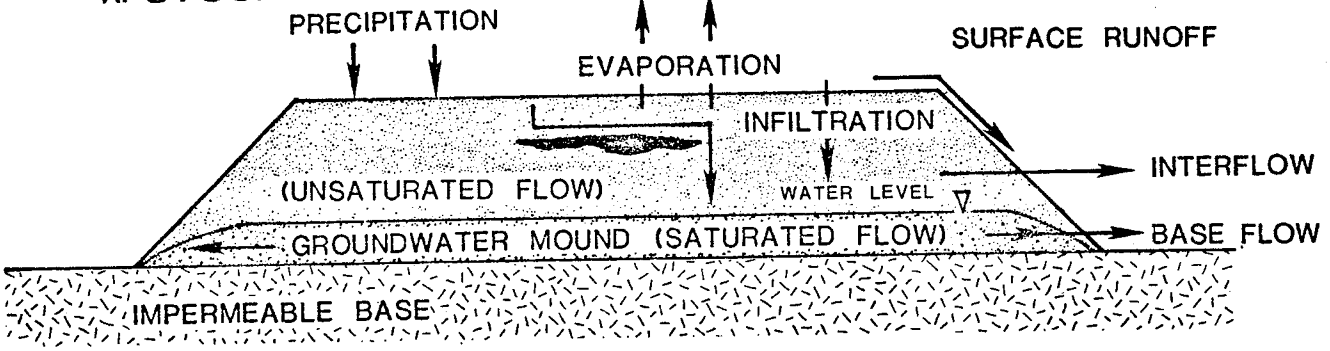
PRECIPITATION AND FLOW AT EM-8, 1977



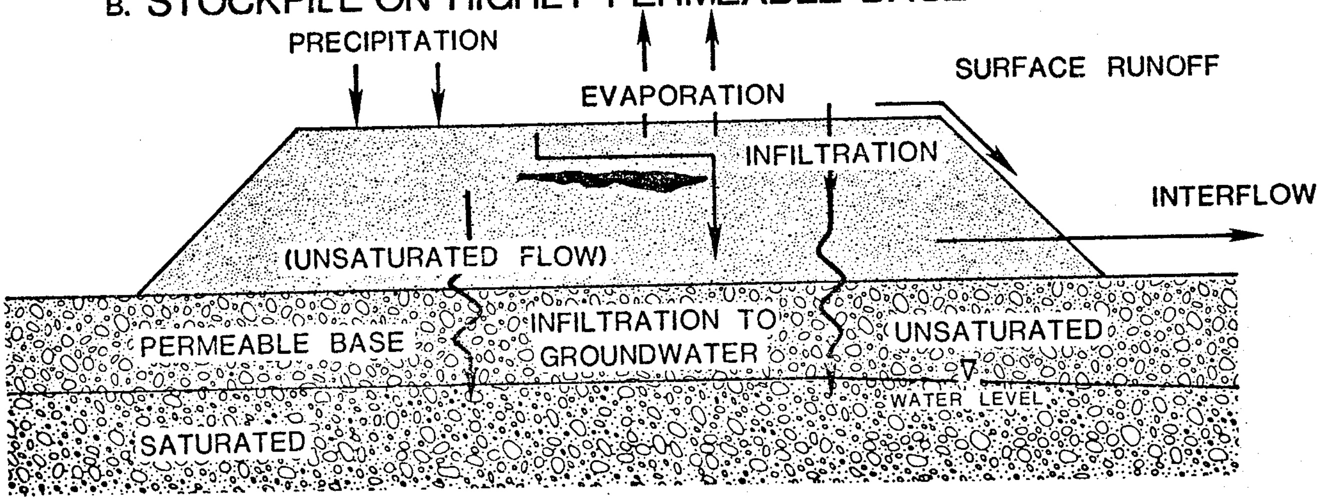
SOURCE: HEWETT, 1979

FIGURE 31 FLOW PATHS WITHIN STOCKPILES

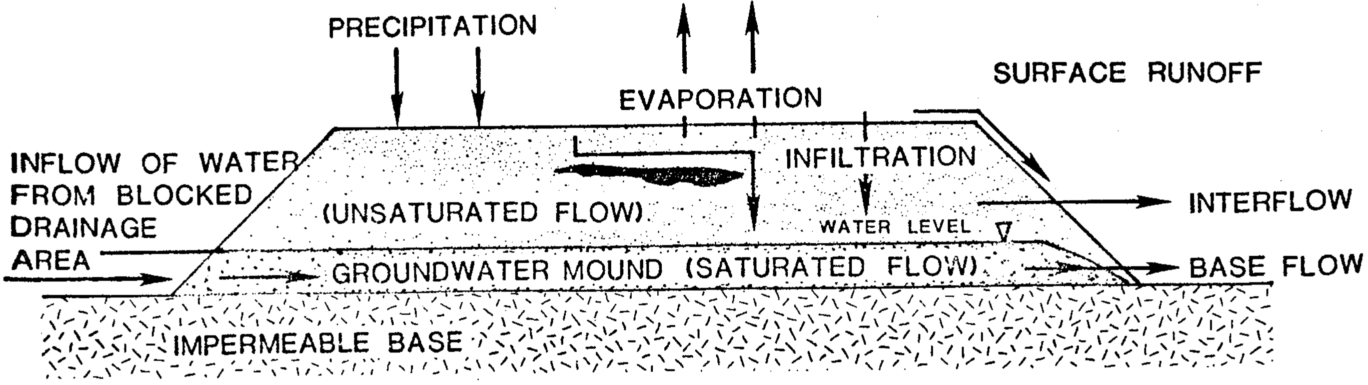
A. STOCKPILE ON IMPERMEABLE BASE



B. STOCKPILE ON HIGHLY PERMEABLE BASE



C. STOCKPILE ON IMPERMEABLE BASE, BLOCKING SURFACE DRAINAGEWAY



layer, run laterally over it, and emerge along the margin of the pile as interflow. Impeding layers could include: surfacing material spread on intermediate lifts and then compacted by haul trucks; relatively fine-grained, compacted layers of rock created by grading the top of lifts; layers created by fine-grained material which works its way to the base of the pile and fills voids between larger fragments; and, the native materials on which the pile is sited.

Interflow appears at seeps at the base of stockpiles at both Erie and Minnamax within a few days of most precipitation events.

Interflow accounts for varying proportions of the total runoff from a particular storm, increasing as the intensity and duration of storm increases. Field observations of interflow volumes at Minnamax and Erie are summarized and compared with models of streams in the Study Area in Table 41. Over the period of observation, interflow volumes have amounted to as much as 75 percent of the input precipitation from individual storms. This is comparable to the observed behavior of three natural watersheds in the Study Area over somewhat longer periods.

Table 41

The timing of high stockpile flows relative to the timing of high flows in the streams which receive stockpile runoff has an important effect on dilution. If the peak flow from the stockpile happens to arrive at the same time as the watershed peak, then dilution of stockpile runoff is maximized. In general, this will not be the case. The time of arrival of the stockpile peak is strongly dependent on the location of the pile within the watershed. In addition, the

Table 41. Storm response of stockpiles and natural watersheds.

	RO/P %	I/RO %	I/P %
AMAX*	0 to 75	100	0 to 75
Erie*	0 to 66	0 to 95	0 to 54
Streams**	0 to 90	20 to 95***	0 to 85

RO=runoff; P=precipitation; I=interflow.

*Observations over periods described in technical report on stockpile hydrology (Hewett 1979).

**From hydrologic models of Filson Creek, Stony River, and Partridge River, Fig. 7 and 9, pg 18 and 20, Savard et al. 1978.

***For streams I/RO represents the proportion of surface runoff and interflow to total runoff. For the stockpiles, there is no surface runoff.

stockpiles studied respond more slowly to precipitation than natural watersheds of the same size. The stockpile at Erie, which has an area of 0.17 mi^2, tended to reach peak discharge 24 to 30 hours after short rainstorms. Time to peak should increase with increasing stockpile area and height, but no data are available to predict the nature of the relationships.

The stockpiles at Erie store water which sustains flow from the piles between precipitation events. It is thought that the water is stored in groundwater mounds (saturated zone) at the bases of the piles (Figure 31). Such a mound can generally form only if the pile is located on material of low or zero permeability (the exception is a pile on permeable material in a groundwater discharge area). Impermeable materials in the Study Area are peat compressed by the weight of a stockpile and bedrock.

If a stockpile is on permeable material, some water will seep into the material below the pile, eventually reaching the local groundwater system. Extremely permeable materials may prevent the formation of a groundwater mound within the pile (Figure 31). In the Study Area, such materials include Rainy Lobe till, glaciofluvial deposits, and alluvium.

About 20 percent of the Study Area is covered with impermeable materials, 70 percent with permeable materials, and 10 percent with Des Moines Lobe till, which covers a wide range of permeabilities (Volume 3-Chapter 1). Since the hydraulic conductivities are variable, the actual behavior of a stockpile in any given location can only be determined by on-site investigations. The model water budget assumes a range of permeabilities for the materials underlying stockpiles.

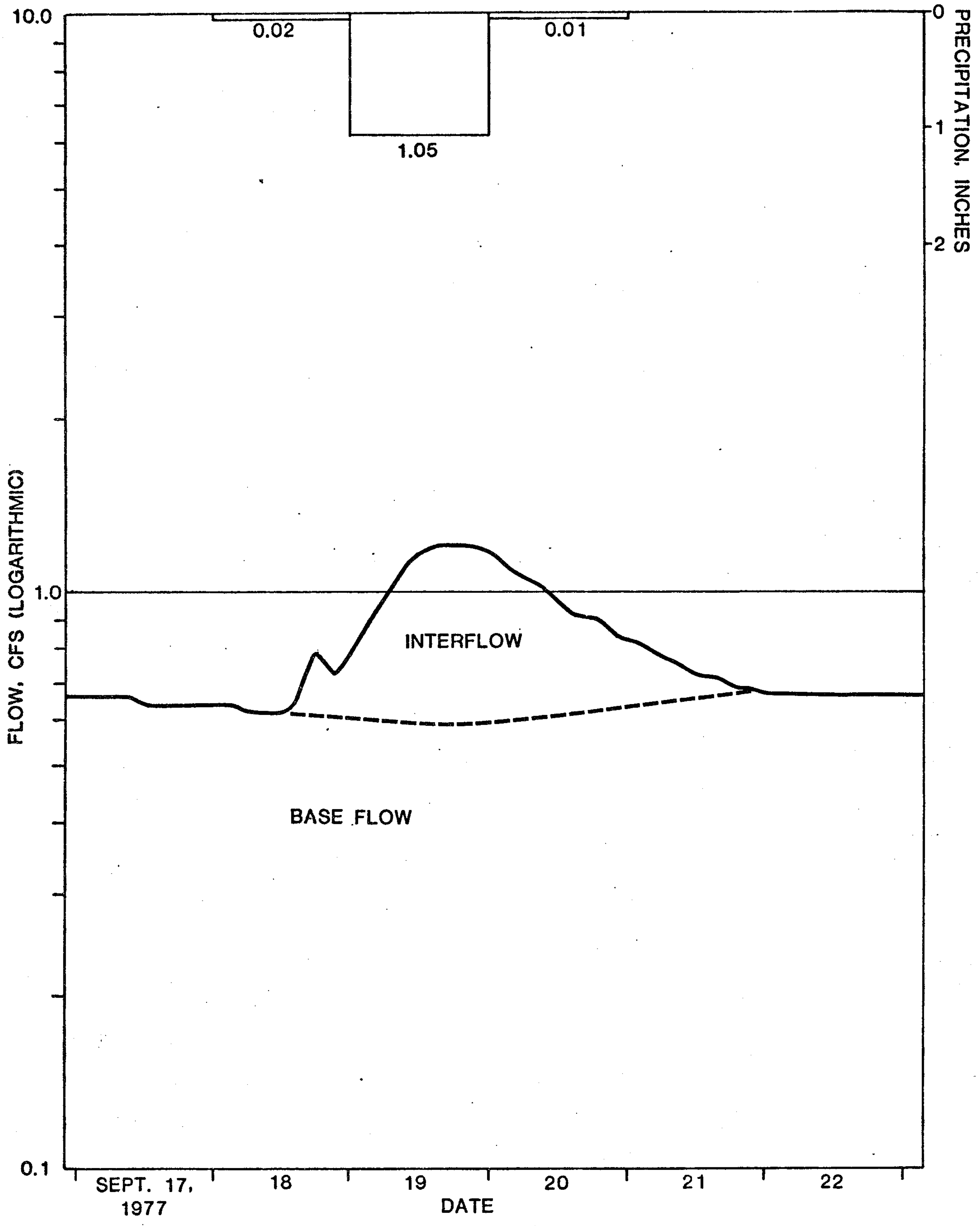
Environmental Significance of Flow Paths--For a stockpile on an impermeable base, the outflow is divided between base flow and interflow (Figure 32), both of which discharge along the margin of the stockpile. For stockpiles on a permeable base, some water will seep into the local groundwater system. Differences among flow paths within stockpiles may affect the release of metals from stockpiles or the impact of a given release. Physical differences which may affect the types and rates of chemical reactions are discussed in section 4.6.

Figure 32

Leachate discharged to surface water may have different effects on aquatic organisms depending on whether the releases are short, sharp pulses of toxicants associated with interflow peaks or the more uniform concentrations associated with base flow. Leachate released into the local groundwater system may move a considerable distance (time) before it is discharged to surface water or to a water well. Toxicants released to groundwater are more difficult to follow and collect, but the large adsorbing surface area and anaerobic conditions in the saturated zone may limit transport (Eger and Lapakko 1979). The significance of these releases also depends on the relative amounts of use of surface and groundwater resources.

Environmentally significant properties of flow paths within stockpiles are summarized in Table 42. Existing field data do not allow an unambiguous determination of how much water will be discharged laterally as interflow, how much as baseflow, and how much as seepage to the groundwater below the pile. Continuous flow records at Erie's Dunka Mine are from a stockpile which blocks a surface drainageway. Base flow is dominated by throughflow from the blocked drainage area which masks the contribution from direct infiltration. Direct infiltration into the mound is estimated to be approximately 5 to 15 percent of the

FIGURE 32 EXAMPLE OF A STOCKPILE HYDROGRAPH SHOWING INTERFLOW AND BASE FLOW



SOURCE: FLOW RECORDS AT EM-8, ERIE MINING CO'S DUNKA MINE. (HEWETT, 1979) precipitation on the stockpile or 20 to 50 percent of the total runoff. Further study may make a more precise estimate possible.

Table 42

The ratio of interflow to baseflow is not likely to be the same in wet or dry years as in average years. For example, outflow from Erie stockpiles in the summer of 1976 was almost entirely baseflow. Interflow made a more significant contribution during the rainy summer of 1977.

Plant Site--The plant site is expected to be largely covered by roofs and pavement. Runoff from such impervious surfaces is high. Average annual runoff from the plant site was assumed to be 75 percent of precipitation, based on runoff from urban areas for storms with 5 to 10 years recurrence intervals (Viessman et al. 1977). This is probably a high estimate. Because of the impervious surfaces, outflow should be entirely due to surface runoff, and seepage to groundwater should be zero.

Open Pit--A schematic diagram of the open pit is shown in Figure 33. Water inputs to the open pit include precipitation, seepage from the bedrock, and seepage from the surficial materials around the pit. Most of the bedrock in the Study Area is massive crystalline rock which contains water only in fractures. Since these fractures amount to only a few percent by volume of the rock and are somewhat dicontinuous (Siegel and Ericson 1979), seepage from bedrock has been assumed to be negligible. This might not be the case if the mine intersects leached zones in the Biwabik Iron formation (Siegel and Ericson 1979). Within the Study Area, unconsolidated materials overlying bedrock are generally

Table 42. Environmentally significant properties of flow paths in stockpiles.

FLOW PATH	GABBRO SURFACE AREA CONTACTED	TIME IN CONTACT WITH GABBRO	OXYGEN AVAILABILITY	TEMPERATURE	WET/DRY CYCLING	LOCATION OF OUTPUT	TIME DISTRIBUTION OF OUTPUT
Surface runoff	small	very short	high	variable	yes	surface water	short, sharp peaks
Interflow	large	short	high	variable	yes	surface water	short, sharp peaks
Base flow	large to very large	long	restricted, depends on wet/dry cycling	low	limited, depends on fluctuations of water table	surface water	steady flow over long periods
Seepage into material below pile	large	1	1	1	1	groundwater	1

1-If the lower part of the pile is unsaturated, water seeping out of the pile will have undergone conditions in the pile similar to those for interflow, while if the lower part is saturated, seepage into the material below the pile will have undergone conditions like those for base flow.

saturated through at least part of their thickness. Once a pit is opened through these materials, groundwater will flow into the pit. Flow depends strongly on the permeability and saturated thickness of the surficial materials. On the basis of a one-dimensional application of Darcy's Law, Siegel and Ericson (1979) estimated that inflow to open pits in the Study Area could range from less than 100 to several thousand gallons per minute. Values used in the water balance were either zero or 870 ft^3 per year per foot of pit circumference. The latter number is a moderate value which gives roughly 200 gpm or 300 ac ft/yr for the 523 acre pit associated with a 20 X 10^6 mtpy mine. Since most of the Study Area is till, it is reasonable to expect flows no more than 100 to 200 gpm. However, if a mine is located in sand and gravel or is in hydraulic contact with a major stream, flows could be an order of magnitude greater.

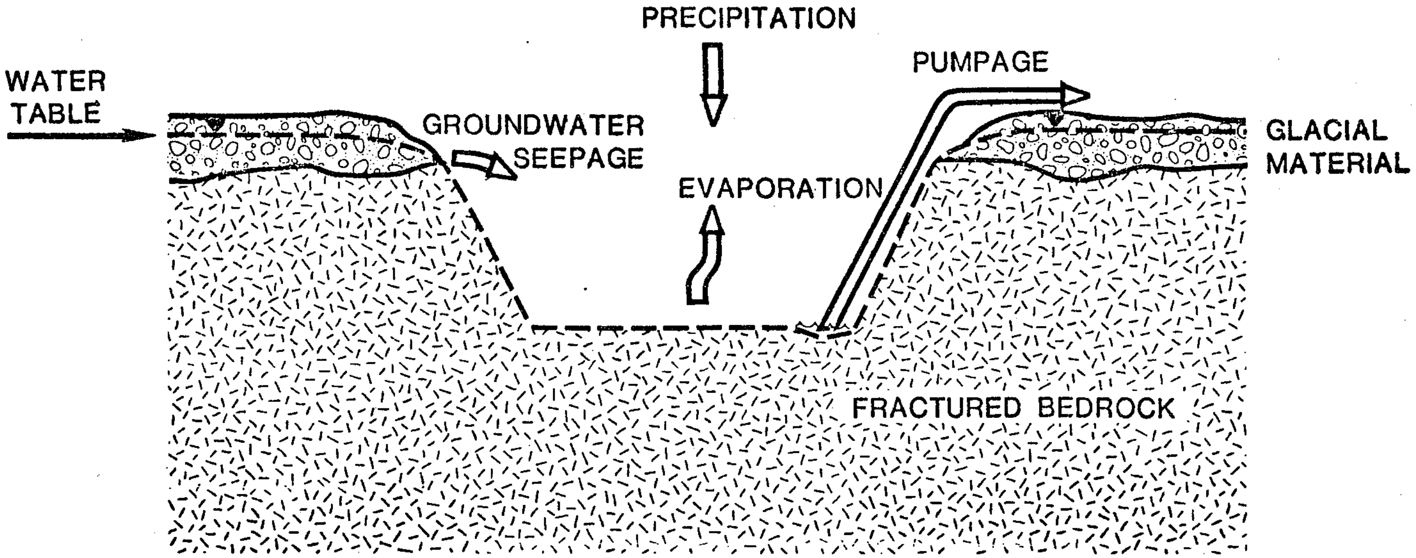
Figure 33

Output from the open pit includes evaporation and pumpage. INCO's (1975, Ul-1-33) estimate of 55 percent evaporative losses is the only available information, and was used for average years. In a dry year, evaporation from the pit can exceed precipitation, since seepage makes additional water available for evaporation.

Underground Mine—The only source of water within an underground mine is seepage from bedrock. Because fractures in the bedrock are discontinuous and sparse, seepage is expected to be less than 25 gpm or 40 ac ft/yr (Siegel and Ericson 1979). Larger flows could occur if the mine encounters leached zones in the Biwabik Iron Formation or if fractures are in hydraulic continuity with surficial aquifers or surface water bodies. For example, the Shebandowan mine in Ontario

FIGURE 33

SCHEMATIC DIAGRAM OF AN OPEN PIT MINE



CROSS-SECTIONAL VIEW

has collected 650 gpm (1,050 ac ft/yr), probably from an overlying lake. In the models, values of 0, 40 and 1050 ac ft/yr have been used.

Undisturbed Watershed Area--This area consists of the border zones between and around various mine elements. Average annual runoff from these areas was assumed to be 12 inches, or 43 percent of precipitation, based on data for watersheds in the Superior National Forest (Garn 1975). Other estimates of average annual runoff for the Study Area are 0.72 cfs/mi^2 or 9.8 inches (Bowers 1977) and 0.79 cfs/mi^2 or 10.7 inches (Siegel and Ericson 1979). Seepage to groundwater was assumed to be zero, implying that any water which seeps into the ground re-emerges within the controlled area and can be collected. In areas where the surficial materials are shallow, this is likely to be the case; in other areas it must be viewed as a simplifying assumption.

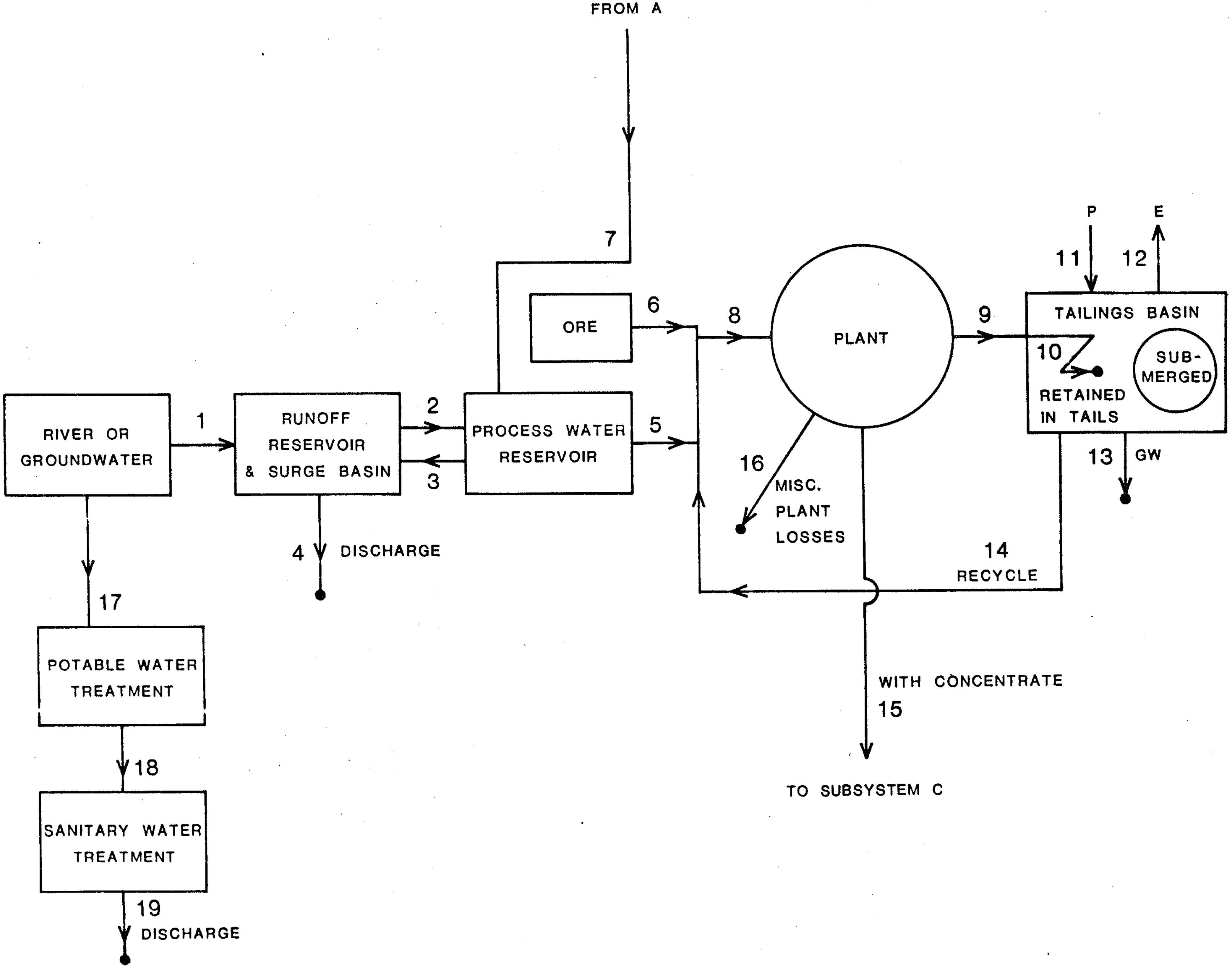
Overburden Piles--Overburden piles were assumed to be intermediate in character and hence in behavior between undisturbed watershed areas and waste rock and lean ore stockpiles. They are unvegetated but are comprised of local soil materials. Average annual runoff was assumed to be 10 inches, or roughly 64 percent of precipitation. Losses to groundwater were again assumed to be zero.

4.4.1.2 Subsystem B. Subsystem B (Figure 34) includes the mill and associated tailing basin and reservoirs. Input to and output from the mill are determined by ore processing needs. Precipitation, evaporation, and seepage in the tailings basin also affect the overall water balance for this subsystem.

Figure 34

Model mill water requirements total 650 gallons for each metric ton of crude ore processed (Volume 2-Chapter 3). Much of this water is continually recycled.

FIGURE 34 FLOW DIAGRAM FOR THE MINE/MILL WATER SYSTEM SUBSYSTEM B



Make-up water to replace that lost in the system can come from precipitation on the tailing basin, appropriation from lakes, streams, or groundwater, or use of the runoff from subsystem A. Losses from the mill system are mainly spills and evaporative losses around the buildings, and range from 2.6 to 4.2 percent of the total water required. Water is used to transport concentrate at 65 percent solids to the smelter (142 gal/mt concentrate) and to transport tailing material to the basin at 29 percent solids (649 gal/mt tailing). In the model tailing disposal system, unthickened tailings are pumped a distance of one mile to the basin. An alternative approach would be to thicken the tailing to 60 percent solids before pumping them to the basin, reducing the water needs to 176 gal/mt tailing. This approach would be used when pumping distances of 5 miles (Volume 2-Chapter 3).

Potable water requirements for the entire complex average 9 gpm for each million mtpy capacity. Potable water is required for sanitary facilities and for some specialized cooling requirements in the smelter-refinery complex. Sanitary water will be treated before discharge.

The minimum amount of water that must be stored in the tailing basin for proper mill operation is a 5 day supply, or roughly 15 acres of pond for each thousand metric tons of tailing discharged per day (Volume 2-Chapter 3). This retention allows the tailing slimes to settle, clarifying the recycle water. Based on standard tailing basin practices, it is estimated that 80 percent of the basin will be covered by water for dust control and water management, which would supply many times the minimum pond area required for proper mill operation (Volume 2-Chapter 3).

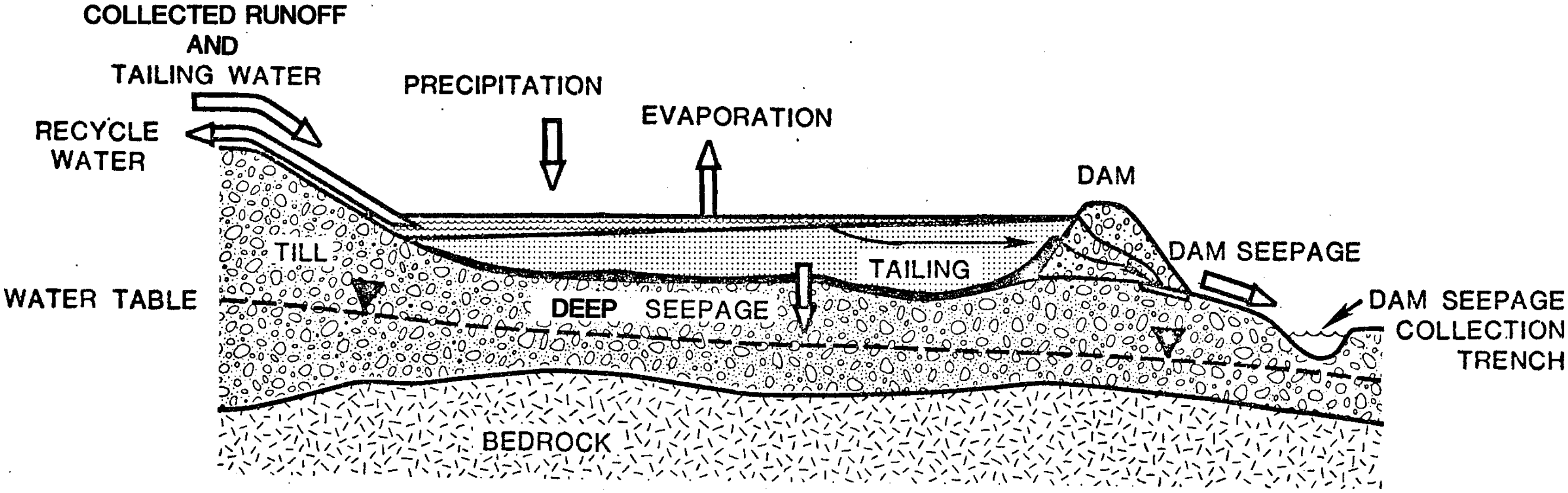
The tailing basin is shown in Figure 35. Input to the tailing basin includes tailing water and precipitation. Some water is retained in interstices between the tailing solids and is not available for recycling or outflow. Outputs consist of recycle water, surface outflow, seepage losses, and evaporation. With standing water continually available over 80 percent of the area, evaporative losses will be substantial. Losses from the ponded area were estimated to be the same as those from ponds and small lakes, while losses from the uncovered area were arbitrarily assumed to be half as great. Surface outflow can occur, but it is expected that such outflow would be prevented during operation by regulating water levels in the basin.

Figure 35

Two seepage losses are possible; one through the basin floor into the underlying surficial material and the other through the toe of the tailing dam. No realistic estimate of seepage through the dams can be made without detailed information on dam length and construction. The model assumes that a seepage collection system surrounds the dams and allows water to be returned to the plant during operation. With such a collection system, dam seepage is wholly controlled until the post-operational phase. Seepage from the base of the tailing basin can vary considerably depending on the nature of the underlying material. Golder Associates (1978) estimated that tailing slimes lining the basin would have a hydraulic conductivity of 2×10^{-6} cm/sec. If the basin is sited on material at least as permeable as this, water will seep out of the basin vertically at 2×10^{-6} cm/sec, or 2.1 ft^3 per year per ft^2 of base area. Materials at least this permeable in the Study Area include Rainy Lobe till, some

FIGURE 35

SCHEMATIC DIAGRAM OF TAILING BASIN



Des Moines lobe till, alluvium, and glaciofluvial deposits. Much of this seepage could be recaptured by a system of collection trenches or wells. If the basin is on impermeable material, such as bedrock or compressed peat, seepage losses will be negligible. On materials of intermediate permeability, such as some Des Moines lobe till, seepage would perhaps be an order of magnitude less than the maximum. All three cases are included in the models, and the variation among them has a significant effect on the overall water balance (Volume 2-Chapter 3).

All tailing basin input and output calculations are based on the area of the basin at the end of the operating life. Building the basin in stages may significantly affect the water balance (Volume 2-Chapter 3).

The model annual water balances for subsystem B do not include consideration of a storage reservoir separate from the tailing basin. Analysis of multiple year dry periods which have occurred in the Study Area indicates that such a reservoir would be a valuable part of an overall water management system (section 4.5).

Water requirements for the milling operations are discussed in detail in Volume 2-Chapter 3 of the Mineral Processing report. Unit water inputs and outputs for subsystem B are summarized in Table 43 and Figure 36.

Table 43, Figure 36

4.4.1.3 Subsystem C--Smelter/Refinery water system. Water requirements in an integrated smelter/refinery complex can be broken into two basic categories: contact water and non-contact water (Figure 37). The distinction is based on the function performed by the water. Contact or process water includes all water which actually comes into contact with the various materials being processed in

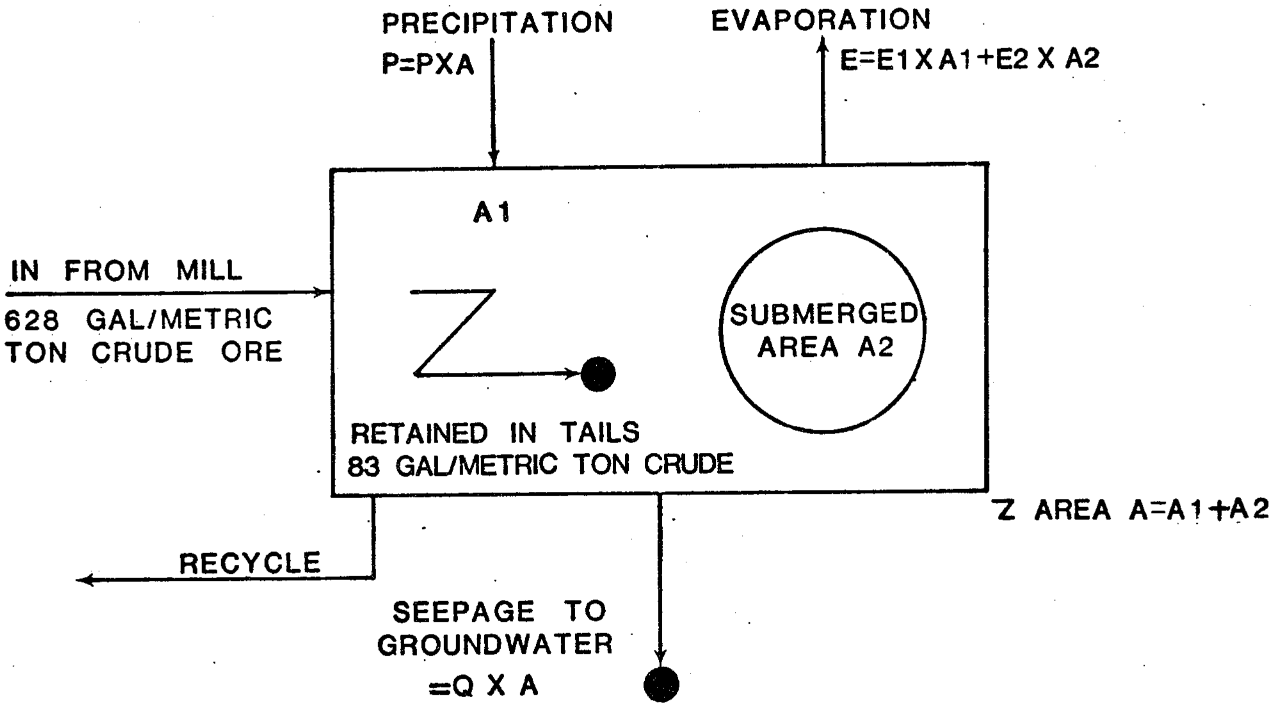
Table 43. Subsystem B: model water requirements and losses.

ITEM	FLOW CHART#	GAL/MT CRUDE ORE
Ore moisture	B6	3
Total mill need	B8	650
Misc. mill losses	B16	17
Concentrate water	B15	5
Tailing water	B9	628
Retained in tails	B10	83

SOURCE: Veith (1978).

FIGURE 36

TAILING BASIN: UNIT WATER INPUTS AND OUTPUTS



METEOROLOGICAL FACTORS,INCHES		AVERAGE	WET YEAR	DRY YEAR
PRECIPITATION	P	28.57"	39"	16"
EVAP. FROM A2	E2	18.7"*	15.3"	22.8"
EVAP. FROM A1	E1	9.35"**	7.67"	11.4"

* FROM ANNUAL EVAPORATION FROM PONDS AND SMALL LAKES

** ESTIMATED AS 1/2 THE EVAPORATION FROM A2

SEEPAGE TO GROUNDWATER*	ON PERMEABLE BASE ($K > 2 \times 10^{6}$ CM/SEC.)	ON SEMIPERMEABLE BASE	ON UNPERMEABLE BASE
VERTICAL FLUX Q	2.07 FT/YR	0.207 FT/YR	0

* FROM GOLDER REPORT

AREA A2 IS AT MINIMUM 15 ACRES/1000 TPD CAPACITY
BUT A MORE PROBABLE VALUE IS 80% OF A

the plant. This water is susceptible to contamination and may require purification before being discharged to the environment. Non-contact water, on the other hand, flows in closed, controlled systems and performs only the function of removing heat. This non-contact cooling function increases the temperature of the water being used, but does not expose it to contamination by substances in the smelter/refinery complex. Bacteriacides, algacides, or fungicides may be introduced to keep the cooling tower clean, and corrosion and scale inhibitors may be used to keep the condensor and piping clean.

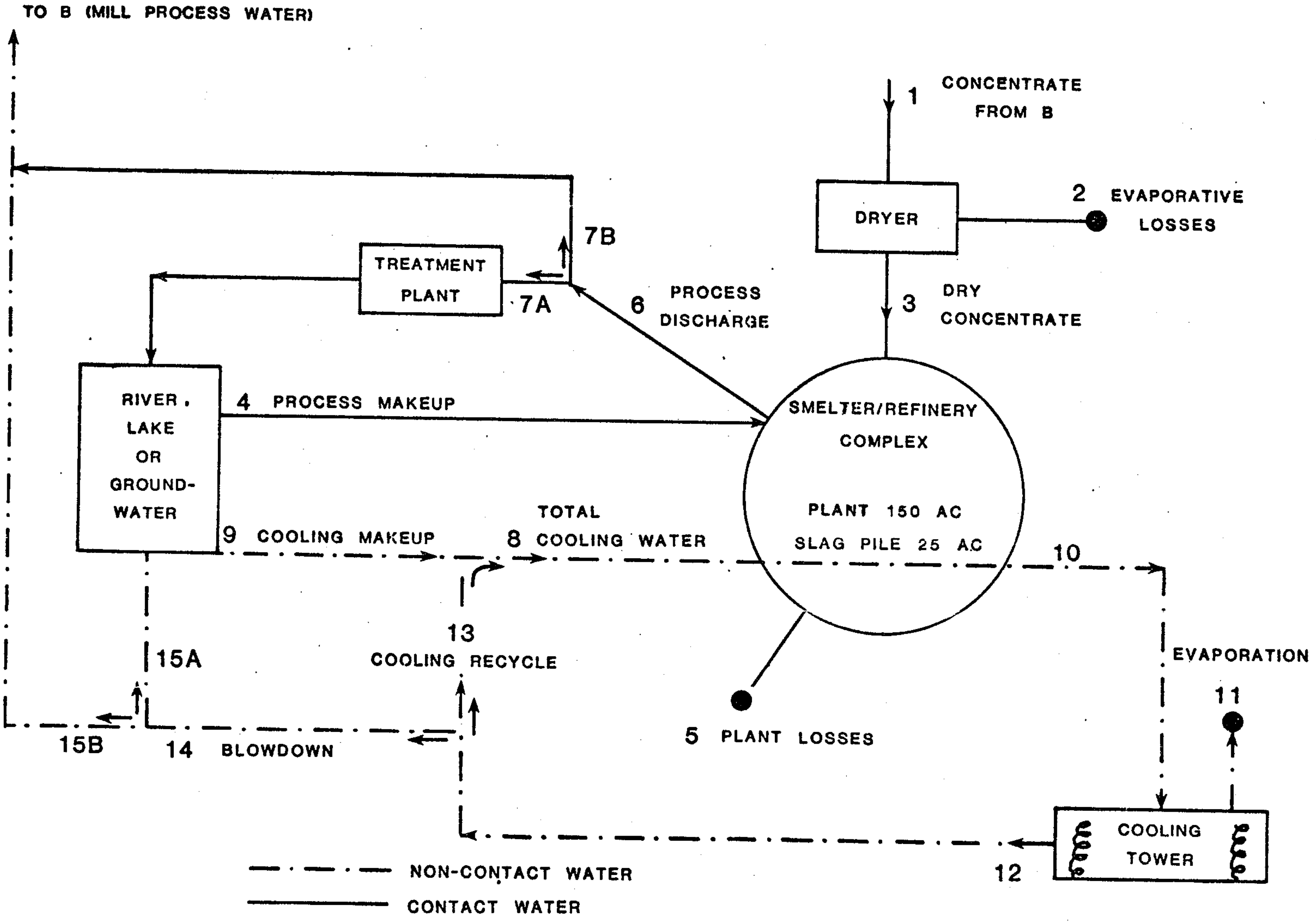
Figure 37

Contact Water--Uses of contact water in a smelter/refinery complex include: scrubbing of gases going to the acid plant; direct cooling of anodes, cathodes, and other products after casting; granulation of molten slag by water immersion; and, electrolytic solution, scrape anode rinsing, and other miscellaneous uses (Volume 2-Chapter 4).

Depending on the specific operations chosen and the degree of internal recycling employed, the total contact water requirements can vary considerably. Tables 44 and 45 show ranges of amounts. Based on an operation producing about 85,000 mtpy of copper and 15,000 mtpy of nickel, estimates of appropriation requirements range from a low of about 700 gpm to a high of about 4,500 gpm. About 500 gpm are actually consumed, primarily through evaporation during contact cooling and as a raw material consumed in the production of sulfuric acid. In addition, the water which enters the smelter/refinery complex with the concentrate is lost to evaporation in the dryer before the concentrate is smelted. These losses are independent of the amount of recycling.

FIGURE 37

FLOW DIAGRAM FOR THE SMELTER/REFINERY WATER SYSTEM
SUBSYSTEM C



Tables 44 and 45

In order to estimate the minimum water requirements necessary to operate the smelter/refinery complex, maximum internal recycling of water is assumed. Using the values from the technical assessment models, the operation would need to appropriate 695 gpm, of which 494 gpm is lost in the plant. The remainder, 201 gpm, must be discharged or treated before re-use in order to prevent the buildup of undesirable constituents in recycle water systems.

Non-Contact Water—Non-contact water is required for: cooling of furnace walls and doors and other refractory equipment; condensing of steam from waste heat turbines; cooling of bearings; and, cooling of the acid plant.

Cooling water flows through sealed heat exchangers which protect it from contamination. For a model smelter/refinery, the heat exchangers require a total flow of 44,500 gpm which is heated 8.9° C during the heat-exchange process (Volume 2-Chapter 4).

The heated water leaving the heat exchange system can be managed in a variety of ways. If allowed by applicable thermal discharge standards, it may be discharged directly to a receiving body of water. Such once-through cooling would require continuous appropriation of water at 44,500 gpm (99 cfs). The large discharge could raise the temperature of receiving waters considerably. Another alternative is to send it to a cooling pond or cooling tower to be cooled by evaporation and then recycled. Heated water will tend to return to its original temperature by dissipating heat through evaporation, diffusion, or convection. To estimate the consumptive use of water in this process, it was assumed that all

Table 44. Itemized water losses and discharges from the model smelter/ refinery 100,000 mtpy capacity (all numbers in gal/min).

PROCESS WATER LOSSES	
Smelter	
Anode casting	33
Slag granulation	220
Acid plant blowdown	47
Potable water	0
Cu refinery	33
Ni refinery	161
TOTAL	494

COOLING WATER LOSSES	
Smelter	
Process cooling	0-154
Turbine condenser cooling	0-161
Acid plant cooling	0-190
Cu refinery	0
Ni refinery	0-125
TOTAL	0-630

PROCESS WATER DISCHARGE	
Smelter	
Anode casting	0-275
Slag granulation	0-2,600
Acid plant blowdown	0-770
Potable water	0-30
Cu refinery	71-260
Ni refinery	130
TOTAL	201-4,065

COOLING WATER DISCHARGE	
Smelter	
Process cooling	616-10,201
Turbine condenser cooling	644-10,864
Acid plant cooling	760-15,000
Cu refinery	0
Ni refinery	67- 8,435
TOTAL	2,087-44,500

SOURCE: Volume 2-Chapter 4, Smelting and Refining.

Table 45. Appropriations and discharges for the model smelter/refinery, 100,000 mtpy capacity (all numbers in gal/min).

ITEM	FLOW CHART#	MAXIMUM RECYCLING	MINIMUM RECYCLING
Plant needs		49,059	49,059
Process make-up	C4	695	4,559
Process losses	C5	494	494
Process discharge	C6	201	4,065
Cooling make-up	C9	2,717	44,500
Cooling losses	C11	630	0
Cooling discharge	C14	2,087	44,500

SOURCE: Volume 2-Chapter 4, Smelting and Refining.

excess heat is dissipated by evaporation. For the model, this results in an evaporative loss of 630 gpm.

Streams and lakes which may supply cooling water contain non-volatile dissolved solids which do not leave the system with the evaporated water, and tend to increase in concentration if a closed-cycle cooling system is used. When concentrations reach saturation, solids precipitate out of the water to clog the cooling system. To prevent this, a certain amount of water, termed "blowdown," is periodically discharged from the cooling system and replaced by fresh water. This water can be cooled to the same temperature as the fresh makeup water, and contains the same constituents as are naturally present in the intake water, although concentrations are elevated by roughly 30 percent. The model blowdown volume of 2,087 gpm will only be required if the make-up water has high levels of dissolved solids. If the make-up water is of high quality, which is the case for many lakes and streams in the Study Area, the blowdown requirement may be as low as 60 gpm.

Table 46 summarizes the contact and non-contact water systems in a 100,000 mtpy smelter/refinery complex assuming maximum recycling. The model requires a total appropriation of 3,412 gpm, of which 1,124 gpm is consumed primarily by evaporation. The remaining 2,288 gpm is not consumed and could be treated and discharged. If the smelter/refinery complex is located close to the mill, this discharge may be used to meet part of the mill water makeup requirements.

Table 46

Table 46. Subsystem C: model water appropriation, discharge, and losses, gpm.

	CONTACT	NON-CONTACT	TOTAL
Appropriation	695	2,717	3,412
Discharge	201	2,087	2,288
Losses	494	630	1,124*

SOURCE: Volume 2-Chapter 4, Smelting and Refining.

*Excludes concentrate drying losses = 179 gpm.

4.4.2 Production Phase Water Balance-Results and Discussion

4.4.2.1 Subsystem A. Annual output from subsystem A for four different mine models under average, wet, and dry conditions is presented in Table 47 and summarized in Tables 48 to 51.

Tables 47, 48, 49, 50, and 51

Because precipitation exceeds evaporation (Watson 1978), there will be runoff from the mine site in an average year. Precipitation moving through the area comes into contact with materials which are potential sources of heavy metals and other contaminants. If the runoff from these elements is not controlled and treated, environmental damage may result (see sections 4.6 and 4.7).

The hydrologic models indicate the pathways water follows through the system, amounts of runoff from each element, and distribution of output to surface water or groundwater. The hydrological models can be combined with chemical models to assess potential impacts. Leachate from lean ore and waste rock piles is expected to provide the greatest mass of contaminants (section 4.6). Mine dewatering discharges may also be of poor quality (section 4.6). Discharge volumes from these elements can be compared with flows from potential receiving waters, as discussed in section 4.5.

Five to ten thousand acres of land may be occupied by the stockpiles, open pit, and other elements associated with a single operation (Volume 2-Chapter 5). If runoff from these elements is controlled and collected, this land is effectively removed from the natural watershed(s), which will lower stream flows and possibly lake levels (see section 4.5).

Table 47. Subsystem A: annual outputs in acre feet (wet year and dry year estimates by method I).

	20 X 10^6 mtpy OP			12.35 X 10^6 mtpy UG		
	Ave.	Wet	Dry	Ave.	Wet	Dry
Surface Runoff						
A2 plant	710	1110	240	460	720	160
A4 open pit	620–920	1240–1540	0–170	—	—	—
A6 overburden piles	150	350	0	—	—	—
A8 & A10 waste rock and lean ore piles	1420–1140	3740–3000	0	70–50	180–140	0
A12 undisturbed watershed area	3070	6320	0	1500	3100	0
A14 underground mine	—	—	—	1050,40,0	1050,40,0	1050,40,0
A15 total surface runoff Case 1	5970	12750	240	3090	5050	1210
2	5530	12000	240	2080	4040	200
3	6270	13050	410	2040	4000	160
4	5830	12300	410	3070	5010	1210
5				2060	4000	200
6				2020	3960	160
Typical Value	5900	12530	330	2070	4020	200
Seepage to Groundwater						
A7 & A9 waste rock and lean ore piles	0–280	0–750	0	0–20	0–40	0

Table 47 continued.

	11.33 X 10^6 mtpy OP			5.33 X 10^6 mtpy UG		
	Ave.	Wet	Dry	Ave.	Wet	Dry
Surface Runoff						
A2 plant	430	660	150	210	330	70
A4 open pit	480–780	950–1250	210	–––	–––	–––
A6 overburden piles	120	280	0	–––	–––	–––
A8 & A10 waste rock and lean ore piles	800–640	2110–1690	0	40–30	100–80	0
A12 undisturbed watershed area	1790	3690	0	670	1380	0
A14 underground mine	–––	–––	–––	1050,40,0	1050,40,0	1050,40,0
A15 total surface runoff						
Case 1	3620	7690	150	1970	2860	1120
2	3460	7270	150	960	1850	110
3	3930	8000	350	920	1810	70
4	3770	7580	350	1960	2840	1120
5				950	1830	110
6				910	1790	70
Typical Value	3700	7640	250	950	1840	110
Seepage to Groundwater						
A7 & A9 waste rock and lean ore piles	0–160	0–420	0	0–10	0–20	0

Table 47 continued.

Notes:

For open pit mines

Case	Seepage into Pit	Seepage out of Stockpile
1	none	none
2	none	max
3	max	none
4	max	max

For underground mines

Case	Seepage into Mine	Seepage out of Stockpile
1	max	none
2	typ	none
3	min	none
4	max	max
5	typ	max
6	min	max

Table 48. 20 X 10^6 mtpy mine/mill water balance, open pit mine (all figures in acre-ft/yr).

KEY TO CASES		1	2	3	4	5	6	7	8	9	10	11	12
Material under tailing basin													
permeable		X	X	X	X								
semipermeable						X	X	X	X				
impermeable										X	X	X	X
Seepage into pit													
zero		X	X			X	X			X	X		
300 acft/yr				X	X			X	X			X	X
Material under stockpiles													
permeable			X		X				X		X		X
impermeable		X		X		X		X		X		X	
CALCULATED VALUES													
Average Year	Flow chart#												
Runoff from subsystem A	A15	6,000	5,500	6,300	5,800	6,000	5,500	6,300	5,800	6,000	5,500	6,300	5,800
Uncontrolled seepage from A		0	280	0	280	0	280	0	280	0	280	0	280
Uncontrolled seepage from tails	B13	8,300	8,300	8,300	8,300	830	830	830	830	0	0	0	0
B make-up needs	B5	11,000	11,000	11,000	11,000	3,200	3,200	3,200	3,200	2,300	2,300	2,300	2,300
B excess	B5	—	—	—	—	—	—	—	—	—	—	—	—
Net make-up needs	B5-A15	4,700	5,100	4,400	4,800	—	—	—	—	—	—	—	—
Net excess	A15-B5	—	—	—	—	2,800	2,400	3,100	2,700	3,600	3,200	4,000	3,600
Sanitary discharge	B19	310	310	310	310	310	310	310	310	310	310	310	310

Table 48 continued.

		1	2	3	4	5	6	7	8	9	10	11	12
Wet Year													
Runoff from subsystem A	A15	13,000	12,000	13,000	12,000	13,000	12,000	13,000	12,000	13,000	12,000	13,000	12,000
Uncontrolled seepage from A		0	700	0	700	0	700	0	700	0	700	0	700
Uncontrolled seepage from tails	B13	8,300	8,300	8,300	8,300	830	830	830	830	0	0	0	0
B make-up needs	B5	6,200	6,200	6,200	6,200	—	—	—	—	—	—	—	—
B excess	B5	—	—	—	—	1,300	1,300	1,300	1,300	2,200	2,200	2,200	2,200
Net make-up needs	B5-A15	—	—	—	—	—	—	—	—	—	—	—	—
Net excess	A15-B5	6,600	5,800	6,900	6,100	14,000	13,000	14,000	14,000	15,000	14,000	15,000	14,000
Sanitary discharge	B19	310	310	310	310	310	310	310	310	310	310	310	310
Dry Year													
Runoff from subsystem A	A15	240	240	410	410	240	240	410	410	240	240	410	410
Uncontrolled seepage from A		0	0	0	0	0	0	0	0	0	0	0	0
Uncontrolled seepage from tails	B13	8,300	8,300	8,300	8,300	830	830	830	830	0	0	0	0
B make-up needs	B5	16,000	16,000	16,000	16,000	8,600	8,600	8,600	8,600	7,800	7,800	7,800	7,800
B excess	B5	—	—	—	—	—	—	—	—	—	—	—	—
Net make-up needs	B5-A15	16,000	16,000	16,000	16,000	8,400	8,400	8,400	8,400	7,500	7,500	7,500	7,500
Net excess	A15-B5	—	—	—	—	—	—	—	—	—	—	—	—
Sanitary discharge	B19	310	310	310	310	310	310	310	310	310	310	310	310

Table 49. 12.35 X 10^6 mtpy mine/mill water balance, underground mine (all figures in acre-ft/yr).

KEY TO CASES		1	2	3	4	5	6	7	8	9	10	11	12
Material under tailing basin													
permeable		X	X	X	X								
semipermeable						X	X	X	X				
impermeable										X	X	X	X
Seepage into mine													
40 acft/yr		X	X			X	X			X	X		
1050 acft/yr				X	X			X	X			X	X
Material under stockpiles													
permeable			X		X				X		X		X
impermeable		X		X		X		X		X		X	
CALCULATED VALUES													
Average Year	Flow chart#												
Runoff from subsystem A	A15	2,100	2,100	3,100	3,100	2,100	2,100	3,100	3,100	2,100	2,100	3,100	3,100
Uncontrolled seepage from A		0	14	0	14	0	14	0	14	0	14	0	14
Uncontrolled seepage from tails	B13	4,800	4,800	4,800	4,800	480	480	480	480	0	0	0	0
B make-up needs	B5	6,400	6,400	6,400	6,400	2,100	2,100	2,100	2,100	1,600	1,600	1,600	1,600
B excess	B5	—	—	—	—	—	—	—	—	—	—	—	—
Net make-up needs	B5-A15	4,300	4,300	3,300	3,300	10	24	—	—	—	—	—	—
Net excess	A15-B5	—	—	—	—	—	—	1,000	980	470	460	1,500	1,500
Sanitary discharge	B19	170	170	170	170	170	170	170	170	170	170	170	170

Table 49 continued.

		1	2	3	4	5	6	7	8	9	10	11	12
Wet Year													
Runoff from subsystem A	A15	4,000	4,000	5,000	5,000	4,000	4,000	5,000	5,000	4,000	4,000	5,000	5,000
Uncontrolled seepage from A		0	36	0	36	0	36	0	36	0	36	0	36
Uncontrolled seepage from tails	B13	4,800	4,800	4,800	4,800	480	480	480	480	0	0	0	0
B make-up needs	B5	3,800	3,800	3,800	3,800	—	—	—	—	—	—	—	—
B excess	B5	—	—	—	—	510	510	510	510	990	990	990	990
Net make-up needs	B5-A15	—	—	—	—	—	—	—	—	—	—	—	—
Net excess	A15-B5	250	210	1,300	1,200	4,500	4,500	5,600	5,500	5,000	5,000	6,000	6,000
Sanitary discharge	B19	170	170	170	170	170	170	170	170	170	170	170	170
Dry Year													
Runoff from subsystem A	A15	200	200	1,200	1,200	200	200	1,200	1,200	200	200	1,200	1,200
Uncontrolled seepage from A		0	0	0	0	0	0	0	0	0	0	0	0
Uncontrolled seepage from tails	B13	4,800	4,800	4,800	4,800	480	480	480	480	0	0	0	0
B make-up needs	B5	9,500	9,500	9,500	9,500	5,200	5,200	5,200	5,200	4,700	4,700	4,700	4,700
B excess	B5	—	—	—	—	—	—	—	—	—	—	—	—
Net make-up needs	B5-A15	9,300	9,300	8,300	8,300	5,000	5,000	4,000	4,000	4,500	4,500	3,500	3,500
Net excess	A15-B5	—	—	—	—	—	—	—	—	—	—	—	—
Sanitary discharge	B19	170	170	170	170	170	170	170	170	170	170	170	170

Table 50. 11.33 X 10^6 mtpy mine/mill water balance, open pit mine (all figures in acre-ft/yr).

KEY TO CASES		1	2	3	4	5	6	7	8	9	10	11	12
Material under tailing basin													
permeable		X	X	X	X								
semipermeable						X	X	X	X				
impermeable										X	X	X	X
Seepage into pit													
zero		X	X			X	X			X	X		
300 acft/yr				X	X			X	X			X	X
Material under stockpiles													
permeable			X		X				X		X		X
impermeable		X		X		X		X		X		X	
CALCULATED VALUES													
Average Year	Flow chart#												
Runoff from subsystem A	A15	3,600	3,500	3,900	3,800	3,600	3,500	3,900	3,800	3,600	3,500	3,900	3,800
Uncontrolled seepage from A		0	160	0	160	0	160	0	160	0	160	0	160
Uncontrolled seepage from tails	B13	4,900	4,900	4,900	4,900	490	490	490	490	0	0	0	0
B make-up needs	B5	6,100	6,100	6,100	6,100	1,700	1,700	1,700	1,700	1,300	1,300	1,300	1,300
B excess	B5	—	—	—	—	—	—	—	—	—	—	—	—
Net make-up needs	B5-A15	2,500	2,700	2,200	2,300	—	—	—	—	—	—	—	—
Net excess	A15-B5	—	—	—	—	1,900	1,700	2,200	2,000	2,400	2,200	2,700	2,500
Sanitary discharge	D10	160	160	160	160	160	160	160	160	160	160	160	160

Table 50 continued.

		1	2	3	4	5	6	7	8	9	10	11	12
Wet Year													
Runoff from subsystem A	A15	7,700	7,300	8,000	7,600	7,700	7,300	8,000	7,600	7,700	7,300	8,000	7,600
Uncontrolled seepage from A		0	420	0	420	0	420	0	420	0	420	0	420
Uncontrolled seepage from tails	B13	4,900	4,900	4,900	4,900	490	490	490	490	0	0	0	0
B make-up needs	B5	3,500	3,500	3,500	3,500	—	—	—	—	—	—	—	—
B excess	B5	—	—	—	—	900	900	900	900	1,400	1,400	1,400	1,400
Net make-up needs	B5-A15	—	—	—	—	—	—	—	—	—	—	—	—
Net excess	A15-B5	4,200	3,800	4,500	4,100	8,600	8,200	8,900	8,500	9,100	8,700	9,400	9,000
Sanitary discharge	B19	160	160	160	160	160	160	160	160	160	160	160	160
Dry Year													
Runoff from subsystem A	A15	150	150	350	350	150	150	350	350	150	150	350	350
Uncontrolled seepage from A		0	0	0	0	0	0	0	0	0	0	0	0
Uncontrolled seepage from tails	B13	4,900	4,900	4,900	4,900	490	490	490	490	0	0	0	0
B make-up needs	B5	9,300	9,300	9,300	9,300	4,900	4,900	4,900	4,900	4,400	4,400	4,400	4,400
B excess	B5	—	—	—	—	—	—	—	—	—	—	—	—
Net make-up needs	B5-A15	9,100	9,100	4,500	4,500	4,800	4,800	4,600	4,600	4,300	4,300	4,100	4,100
Net excess	A15-B5	—	—	—	—	—	—	—	—	—	—	—	—
Sanitary discharge	B19	160	160	160	160	160	160	160	160	160	160	160	160

Table 51. 5.35 X 10^6 mtpy mine/mill water balance, underground mine (all figures in acre-ft/yr).

		1	2	3	4	5	6	7	8	9	10	11	12
Material under tailing basin													
permeable		X	X	X	X								
semipermeable						X	X	X	X				
impermeable										X	X	X	X
Seepage into mine													
40 acft/yr		X	X			X	X			X	X		
1050 acft/yr				X	X			X	X			X	X
Material under stockpiles													
permeable			X		X				X		X		X
impermeable		X		X		X		X		X		X	
CALCULATED VALUES													
Average Year	Flow chart#												
Runoff from subsystem A	A15	960	950	1,970	1,960	960	950	1,970	1,960	960	950	1,970	1,960
Uncontrolled seepage from A		0	7	0	7	0	7	0	7	0	7	0	7
Uncontrolled seepage from tails	B13	2,200	2,200	2,200	2,200	220	220	220	220	0	0	0	0
B make-up needs	B5	2,800	2,800	2,800	2,800	850	850	850	850	630	630	630	630
B excess	B5	—	—	—	—	—	—	—	—	—	—	—	—
Net make-up needs	B5-A15	1,900	1,900	900	900	—	—	—	—	—	—	—	—
Net excess	A15-B5	—	—	—	—	110	99	820	1,100	330	320	1,300	1,300
Sanitary discharge	E10	80	80	80	80	80	80	80	80	80	80	80	80

Table 51 continued.

		1	2	3	4	5	6	7	8	9	10	11	12
<u>Wet Year</u>													
Runoff from subsystem A	A15	1,800	1,800	2,900	2,800	1,800	1,800	2,900	2,800	1,800	1,800	2,900	2,800
Uncontrolled seepage from A		0	19	0	19	0	19	0	19	0	19	0	19
Uncontrolled seepage from tails	B13	2,200	2,200	2,200	2,200	220	220	220	220	0	0	0	0
B make-up needs	B5	1,600	1,600	1,600	1,600	—	—	—	—	—	—	—	—
B excess	B5	—	—	—	—	350	350	350	350	570	570	570	570
Net make-up needs	B5-A15	—	—	—	—	—	—	—	—	—	—	—	—
Net excess	A15-B5	210	190	1,200	1,200	2,200	2,200	3,200	3,200	2,400	2,400	3,400	3,400
Sanitary discharge	B19	80	80	80	80	80	80	80	80	80	80	80	80
<u>Dry Year</u>													
Runoff from subsystem A	A15	110	110	1,100	1,100	110	110	1,100	1,100	110	110	1,100	1,100
Uncontrolled seepage from A		0	0	0	0	0	0	0	0	0	0	0	0
Uncontrolled seepage from tails	B13	2,200	2,200	2,200	2,200	220	220	220	220	0	0	0	0
B make-up needs	B5	4,300	4,300	4,300	4,300	2,300	2,300	2,300	2,300	2,100	2,100	2,100	2,100
B excess	B5	—	—	—	—	—	—	—	—	—	—	—	—
Net make-up needs	B5-A15	4,200	4,200	3,200	3,200	2,200	2,200	1,200	1,200	2,000	2,000	950	950
Net excess	A15-B5	—	—	—	—	—	—	—	—	—	—	—	—
Sanitary discharge	B19	80	80	80	80	80	80	80	80	80	80	80	80

Surface outflow from subsystem A could be used as make-up water for the milling process. The amounts available from subsystem A can be compared with the make-up needs for subsystem B. If the make-up need is less than the runoff, it may be possible to segregate the runoff from subsystem A, so that the worst quality water is used in the milling operation, and the best is discharged to the environment.

4.4.2.2 Subsystem B. Annual balances for subsystem B are presented in Table 52.

Table 52

In an average year, water gained from rainfall on the tailings basin and ore moisture is less than water lost as concentrate water, tailings retention, tailings basin evaporation and seepage, and miscellaneous plant losses. Hence, even though the process water is recycled, fresh make-up water is needed.

Make-up water could be appropriated from streams or lakes in the area. The suitability of a given stream or lake as a source and the seriousness of impacts from appropriation depend strongly on how appropriations are made. A reservoir in the operation can smooth out the effects of seasonal variations in water availability and of extremely dry or wet years. This makes it possible to rely on smaller drainage areas than would be needed if storage were not available. In a system with reservoir storage it may be possible to appropriate water at a rate proportional to streamflow or to appropriate spring peak flows. Without significant storage, water must be appropriated at a constant rate or on an "as needed" basis. These methods of appropriation will have differing impacts on stream systems (section 4.5).

Table 52. Subsystem B: annual balance in acre feet (wet year and dry year runoff by method I).

ITEM	FLOW CHART#	20 X 10^6 mtpy OP			12.35 X 10^6 mtpy UG		
		Ave.	Wet	Dry	Ave.	Wet	Dry
Ore moisture	B6	160	160	160	110	110	110
Plant needs	B8	39,900	39,900	39,900	24,640	24,640	24,640
Misc. plant losses	B16	1040	1040	1040	640	640	640
Concentrate water	B15	310	310	310	190	190	190
Tailings water	B9	38,550	38,550	38,550	23,800	23,800	23,800
Retained in tails	B10	5,090	5,090	5,090	3,150	3,150	3,150
Tailings basin precip	B11	9,560	13,050	5,360	5,500	7,500	3,080
Tailings basin evap	B12	5,630	4,610	6,870	3,240	2,650	3,950
Tailings basin seepage	B13						
impermeable base		0	0	0	0	0	0
semipermeable base		830	830	830	480	480	480
permeable base		8,310	8,310	8,310	4,780	4,780	4,780
Recycle water	B14						
impermeable base		37,390	43,400	34,230	22,910	25,510	19,790
semipermeable base		36,560	42,570	33,400	22,430	25,030	19,310
permeable base		29,070	35,090	25,920	18,130	20,730	15,010
Make-up needs	B5						
impermeable base		2,290	-2,190*	7,740	1,610	-990*	4,740
semipermeable base		3,130	-1,360*	8,570	2,090	-510*	5,220
permeable base		10,610	6,130	16,050	6,390	3,790	9,520
Potable water needs	B17	310	310	310	170	170	170

Table 52 continued.

ITEM	FLOW CHART#	11.33 X 10^6 mtpy OP			5.33 X 10^6 mtpy UG		
		Ave.	Wet	Dry	Ave.	Wet	Dry
Ore moisture	B6	100	100	100	50	50	50
Plant needs	B8	22,620	22,620	22,620	10,660	10,660	10,660
Misc. plant losses	B16	590	590	590	280	280	280
Concentrate water	B15	170	170	170	80	80	80
Tailings water	B9	21,850	21,850	21,850	10,300	10,300	10,300
Retained in tails	B10	2,890	2,890	2,890	1,360	1,360	1,360
Tailings basin precip	B11	5,590	7,630	3,130	2,540	3,470	1,420
Tailings basin evap	B12	3,290	2,690	4,020	1,500	1,220	1,830
Tailings basin seepage	B13						
impermeable base		0	0	0	0	0	0
semipermeable base		490	490	490	220	220	220
permeable base		4,860	4,860	4,860	2,210	2,210	2,210
Recycle water	B14						
impermeable base		21,260	23,900	18,080	9,980	11,180	8,540
semipermeable base		20,780	23,420	17,600	9,760	10,960	8,320
permeable base		16,400	19,040	13,220	7,770	8,980	6,330
Make-up needs	B5						
impermeable base		1,250	-1,390*	4,440	630	-570*	2,080
semipermeable base		1,740	-900*	4,920	850	-350*	2,300
permeable base		6,110	3,470	9,300	2,840	1,640	4,280
Potable water needs	B17	160	160	160	70	70	70

*Negative value indicates excess or discharge.

Runoff from subsystem A can be used to meet the make-up needs for subsystem B. Tables 48-51 give the net make-up need or net surplus that results from combining balances for subsystems A and B. For example, Table 48 gives the results for the 20 X 10^6 mtpy operation. The top third of the table deals with an average year. If the tailings basin is on a permeable base, runoff from subsystem A does not provide enough water to meet the make-up needs of subsystem B in an average year. A net demand of 4,600 to 5,100 acre feet is still required. If the tailing basin is on a semipermeable or impermeable base, the make-up need in an average year is small enough to be met by using runoff from subsystem A, and a net excess of 2,400 to 4,000 acre feet of water from subsystem A remains to be discharged. Most of this discharge (3,700 acre feet) could come from undisturbed watershed areas and the plant site, which have comparatively high quality runoff. However, the undisturbed watershed areas consist of buffer zones around the various mining elements, and it may not be economically feasible to separate runoff from this area from the rest of the site runoff.

Variations in the volume of seepage from the tailing basin have a large effect on the overall water balance for the mining and milling operation, and hence deserve attention in any site specific study. The water lost also constitutes a large uncontrolled discharge to the groundwater system, and its quality must be considered. Water lost by tailings basin seepage can be retrieved using trenches or collection wells.

4.4.2.3 Subsystem C. The annual balance for the smelter/refinery is shown in Table 53. Only the 100,000 mtpy metals capacity model is evaluated. The numbers in Table 53 assume maximum recycling of both process water and cooling water.

Table 53

Table 53. Subsystem C: annual balance in acre feet.*

ITEM	FLOW CHART#	ANNUAL AMOUNT
Water in concentrate	C1	280
Losses in dryer	C2	280
Contact Water		
Process make-up	C4	1,080
Losses in processing	C5	760
Process discharge	C6	310
Non-Contact Water		
Cooling make-up	C9	4,200
Evaporative losses	C11	970
Cooling blowdown	C14	3,230
TOTAL		
Appropriation		5,280
Losses		1,740
Discharge		3,540

*Smelter/refinery with 100,000 mtpy metal capacity assuming maximum internal recycling of water.

Consumptive uses of water in the smelter/refinery are small. Fresh water must be continually appropriated for both processing and cooling, but most of it moves through the plant for cooling purposes and is discharged.

A minimum of 1075 acre ft/yr must be appropriated for processing. Seven hundred sixty-four acre feet of this are lost in consumptive uses. Buildup of undesirable chemicals in the remaining 311 acre feet requires that it be treated before being reused by the smelter/refinery or released to the environment.

Cooling can require up to 99 cfs if once-through cooling is used, and thermal impacts could be severe. Recycling through cooling towers or ponds can reduce cooling appropriations and discharges by at least an order of magnitude. The minimum appropriation for cooling water make-up is 4,200 acre ft/yr, of which 974 acre feet are lost to evaporation in cooling, and 3228 acre feet must be used as blowdown to prevent precipitation of chemicals in the cooling towers.

The total annual appropriation need is 5,278 acre feet. This water must be low in particulates and dissolved ions, so recycled water from the smelter/refinery system or from the mill would not be suitable without treatment. This demand can be compared with streamflows or with the seasonal input into lakes in the area (see section 4.5).

Minimum smelter/refinery discharges include 311 acre ft/yr of contact water and 3,228 acre ft/yr of cooling water. If this water is returned to the same source from which it was appropriated, the net quantitative impacts are lessened. However, both contact and non-contact discharges will contain constituents detrimental to water quality. Discharge volumes and concentrations have to be compared with the volume of receiving waters to estimate quality impacts.

If the smelter/refinery complex is located away from the mining and milling complex (i.e. an "offsite" location such as Duluth) some form of water treatment or purification will be necessary prior to any process water discharge. If the smelter/refinery is located near the mining and milling operation, its discharges can be used without treatment as make-up water for the milling process. Table 54 shows some possible combinations of the model smelter/refinery with 20 X 10^6 mtpy mine model under average meteorological conditions.

Table 54

Example 1 considers a mine/mill site with a tailings basin on a permeable base. The make-up need for subsystem B is partially met by subsystem A and C discharges. The remaining 831 acre feet required by subsystem B and the 5,278 acre feet needed by subsystem C must come from outside the system. The only discharge is tailings basin seepage, which is expected to be of fairly good quality.

Example 2 has a tailing basin on a semipermeable base. The mill make-up need is smaller, and one management option is to meet that need with the poorest quality discharges, which could be detrimental if released to the environment. The example assumes that the worst quality water will come from stockpiles, the open pit, and smelter/refinery process water. These three together supply all but 509 acre feet of subsystem B's need, and this is met with subsystem C cooling water. The net appropriation from outside the system is 5,278 acre feet for smelter/refinery make-up. Surpluses include uncontrolled site runoff, tailing basin seepage and cooling water blowdown, and total 7,479 acre feet. Most of this water is fairly clean. Example 2 is illustrated in Figure 38.

Table 54. Examples of annual water balance for total integrated mine, mill, and smelter/refinery system. (20 X 10^6 mtpy open pit mine model; 100,000 mtpy smelter/refinery model. Examples assume particular seepage conditions and management options. All volumes are in acre-ft/yr.)

EXAMPLE 1

Tailings basin on permeable base, subsystem A and C output used for B make-up

Internal Cycling:	
subsystem B make-up	10,640
subsystem A runoff	6,270
subsystem C discharge	3,539
Net subsystem B make-up	831
Net Appropriations:	
subsystem B make-up	831
subsystem C make-up	5,278
Total	6,109
Net Discharges:*	
subsystem A	0
subsystem B (tailings seepage)	8,310
subsystem C	0
Total	8,310

EXAMPLE 2

Tailings basin on semipermeable base, subsystem A waste rock and lean ore runoff, open pit runoff discharges, subsystem C contact discharges & some non-contact discharge used for B make-up

Internal Cycling:	
subsystem B make-up	3,160
waste rock & lean ore runoff	1,420
open pit runoff	920
contact water discharge	311
part of non-contact discharge	509
Net subsystem B make-up	0
Net Appropriations:	
subsystem B make-up	0
subsystem C make-up	5,278
Total	5,278
Net Discharges:*	
subsystem A	3,930
subsystem B (tailings seepage)	830
subsystem C non-contact	2,719
Total	7,479

EXAMPLE 3

Tailings basin on impermeable base, subsystem A waste rock and lean ore runoff, subsystem C contact discharge, and some non-contact discharge used for B make-up

Internal Cycling:	
subsystem B make-up	2,320
waste rock & lean ore runoff	1,420
contact water discharge	311
non-contact water discharge	589
Net subsystem B make-up	0
Net Appropriations:	
subsystem B make-up	0
subsystem C make-up	5,278
Total	5,278
Net Discharges:*	
subsystem A	4,850
subsystem B (tailings seepage)	0
subsystem C non-contact	2,639
Total	7,489

---

*Excludes sanitary discharge of 310 ac ft.

Figure 38

Example 3 is similar to example 2, but the tailing basin is on an impermeable base.

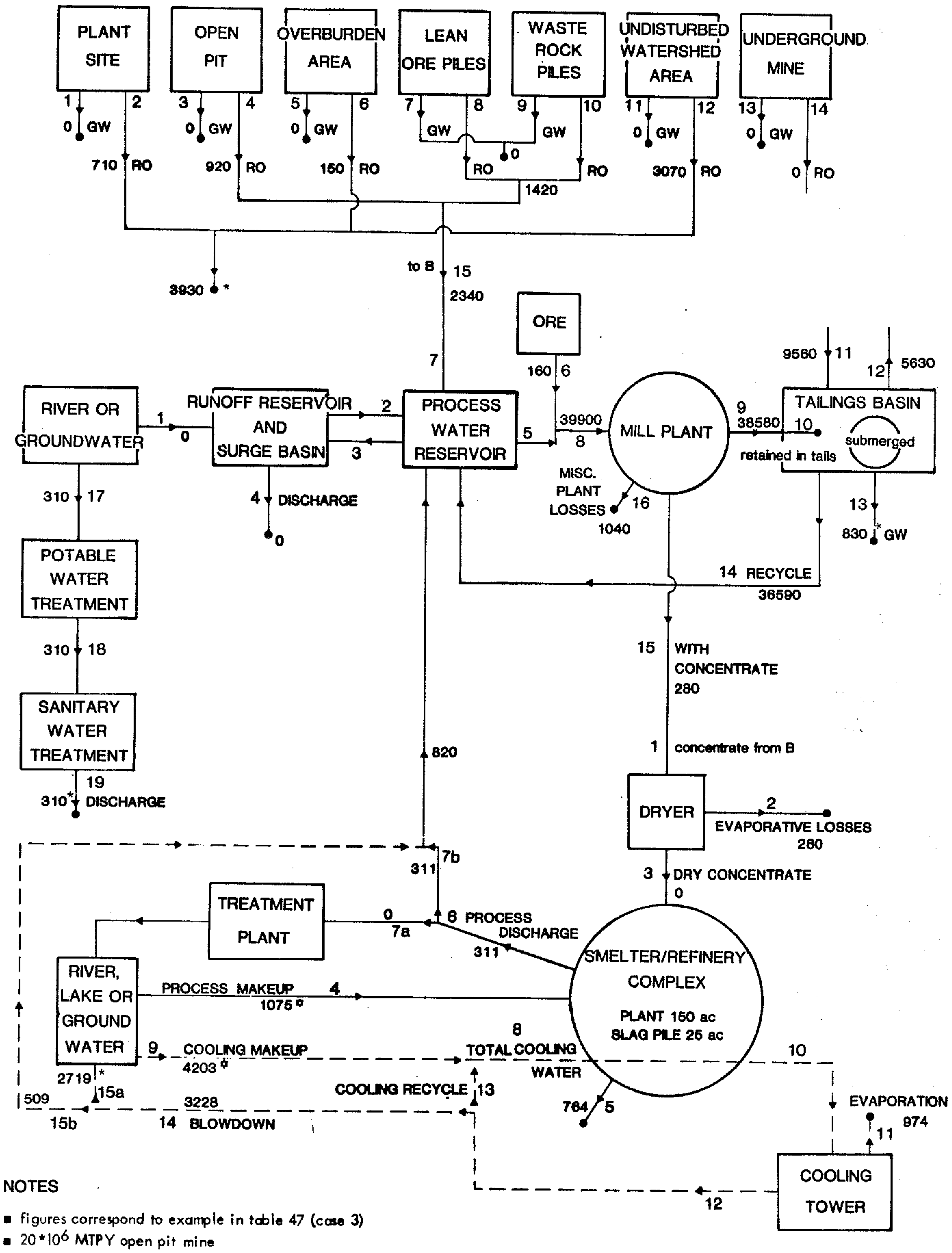
4.4.3 Multiple Year Water Balance

The annual model predicts a net balance for the 20 X 10^6 mtpy mine/mill system ranging from a 5,100 acre foot deficit to a 4,000 acre foot excess. If the tailing basin is on semipermeable or impermeable material, or if most of the seepage loss to a permeable material is recovered by wells or trenches, then the mine/mill area collects enough water in an average year to meet its processing needs. Milling operations generally store at least one year's supply of water in their tailing basins (Volume 2-Chapter 3) so that a single dry year or a single wet year can be handled readily. However, if a series of dry or wet years occurs, the operation could be forced to appropriate or discharge large amounts of water, even though it is close to self-contained on an average basis. Such appropriations or discharges would be likely to have an impact on water resources. Multiple year water balances are useful in assessing the extent of this impact and considering possible water management measures.

A five year design period was chosen to assess the mine/mill operation's deficit under the worst conditions of record. Water balances were calculated for the 3, 5, 6, and 10-year dry periods of record. For example, the 5-year drought of record is defined as the driest 5-year period observed to date. For the Study Area this is the period from June, 1921 to 1925, during which precipitation at Babbitt totaled 106.65". A five-year water balance was calculated using this

FIGURE 38

AN EXAMPLE OF AN ANNUAL WATER BALANCE FOR A TOTALLY INTEGRATED MINE/MILL AND SMELTER/REFINERY SYSTEM



NOTES

- figures correspond to example in table 47 (case 3)
- 20 * 10^6 MTPY open pit mine
- 100,000 MTPY smelter/refinery
- tailings basin on semipermeable base
- average year precipitation and evaporation
- for further assumptions, refer to the text
- actual discharges to the environment marked with *
- actual appropriations from outside the system marked with ✲
- all figures in acre-feet

value for precipitation and assuming average evaporation rates throughout the period. A similar procedure was followed for the 3, 6, and 10-year droughts of record. As shown in Figure 39, the total expected deficit increases as the water budgeting period is increased from 1 to 5 years. For periods longer than five years, dry years tend to be offset by average and above average years, and the total expected deficit for the period declines.

Figure 39

Tables 55 and 56 and Figure 40 show five-year water balances for the 20 X 10^6 mtpy and 12.35 X 10^6 mtpy operations. For a 20 X 10^6 mtpy operation with the tailings basin on a semipermeable base, recurrence of a drought like the 5-year drought of record would cause a water deficit of 16,200 acre feet. The annual excess of 2,400 to 3,100 acre feet in average years would have to be collected over a 5 to 7-year period to have enough water in reserve for this event. Stored in the tailing basin, this much water would cover the entire basin to a depth of 4 feet. If the deficit were appropriated from some external source throughout the 5-year drought, the constant rate of withdrawal would be 4.5 cfs.

Tables 55 and 56, Figure 40

For the 5-year wet period of record, a 20 X 10^6 mtpy operation with a tailings basin on a semipermeable base would generate 27,000 acre feet of excess water (Table 57, Figure 40). This would fill the entire tailings basin to a depth of 6.7 feet, or could be discharged at a constant rate of 7.5 cfs during the 5-year period. The 5-year wet period balance for a 12.35 X 10^6 mtpy operation is given in Table 58.

FIGURE 39

MINE / MILL WATER BALANCES FOR DRY PERIODS OF RECORD

20 X 10^6 MTPY MODEL

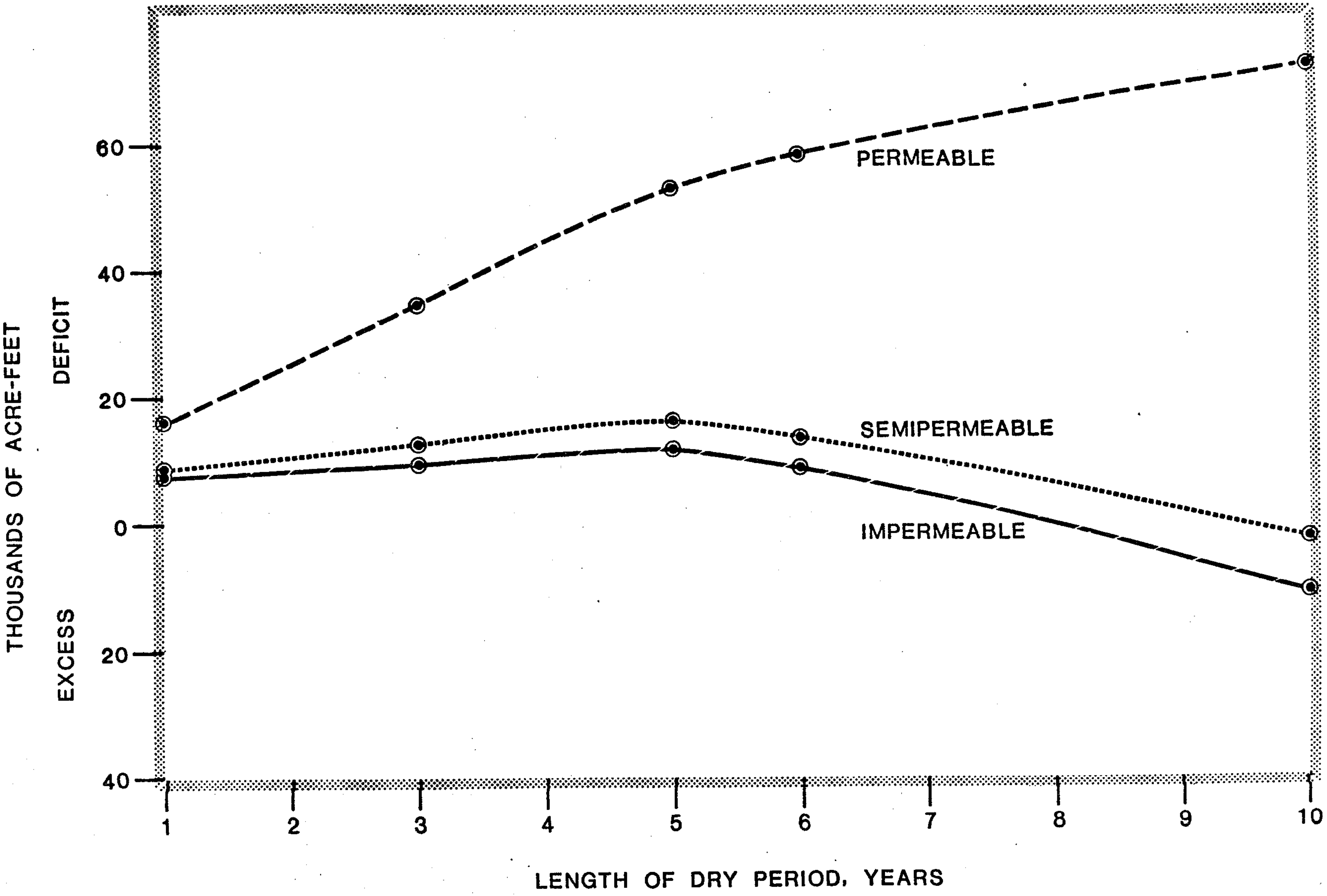


Table 55. Five year drought balance, 20 X 10^6 mtpy mine/mill.

SUBSYSTEM A precip = 106.65"

Element	Five Year Drought of Record Precip, ac-ft	Five Years of Average Evap, ac-ft	Predicted Five Year Drought Runoff, ac-ft
Plant	3,560	1,190	2,370
Open Pit	5,000	3,620	1,390
Overburden piles	1,540	1,300	240
Stockpiles	17,670	16,550	1,120
Undisturbed area	26,000	19,500	6,500
TOTAL			11,620

(groundwater seepage into pit could increase total by 1,500)

SUBSYSTEM B

tailing basin precip-evap for 5-year drought period = 7,580 ac ft

	Five Year Drought Make-up	Net Make-up, Subsystems A & B
Tailings Base:		
impermeable	23,690	12,070
semipermeable	27,840	16,220
permeable	65,250	53,630

Table 56. Five year drought balance, 12.35 X 10^6 mtpy mine/mill system.

SUBSYSTEM A precip = 106.65"

Element	Five Year Drought of Record Precip, ac-ft	Five Years of Average Evap, ac-ft	Predicted Five Year Drought Runoff, ac-ft
Plant	2,310	770	1,540
Stockpiles	850	800	50
Undisturbed	12,760	9,570	3,190
Mine	---	---	40
TOTAL			4,820

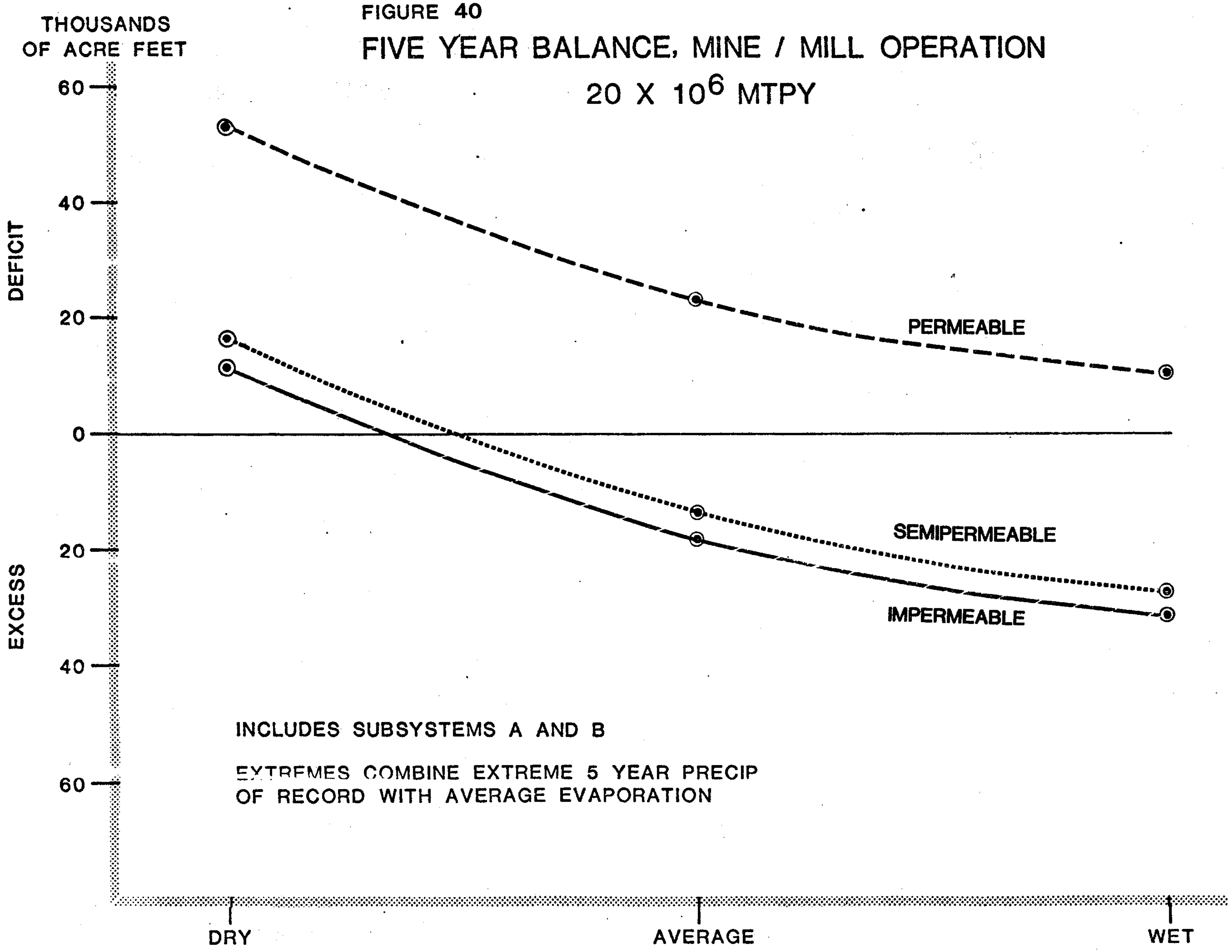
SUBSYSTEM B

tailing basin precip-evap for 5-year dry period = 4,360 ac ft

	Five Year Drought Make-up	Net Make-up, Subsystems A & B
Tailings Base:		
impermeable	14,970	10,150
semipermeable	17,370	12,550
permeable	38,870	34,050

FIGURE 40

FIVE YEAR BALANCE, MINE / MILL OPERATION
20 X 10^6 MTPY



INCLUDES SUBSYSTEMS A AND B

EXTREMES COMBINE EXTREME 5 YEAR PRECIP
OF RECORD WITH AVERAGE EVAPORATION

Tables 57 and 58

A more complete assessment of the implications of dry and wet periods is presented in section 4.5.

4.4.4 Post-Production Water Balance

The water balance following the close of the mining/milling operation is considerably different from the production phase balance. In the post-production phase the mine/mill and smelter/refinery areas have two principal effects on water resources:

1) They continue to yield water of degraded quality.

2) They differ from natural areas in terms of annual outflow, proportions of surface runoff, interflow and baseflow, and timing of flow.

The quality, timing, and volume of outflow from these areas must be compared with the flow properties of receiving waters to assess the nature of long-term impacts and the possibilities for mitigation.

4.4.4.1 Subsystem A. Runoff from the plant site stays the same as during the production phase. Precipitation and groundwater seepage will continue to go into the open pit, but will not be discharged by pumping. For the 20 X 10^6 mtpy mine, precipitation minus evaporation plus groundwater inflow will fill the pit in about 340 years. Without groundwater inflow, 500 years are required. The pit walls will contain some fractures through which water can seep out. The amount of seepage would probably be small, and the distance it would travel would probably be short. Once the water in the pit rises to the level of the

Table 57. Five year wet period balance, 20 X 10^6 mtpy mine/mill.

SUBSYSTEM A precip = 157.92"

Element	Five Year Wet Period of Record Precip, ac-ft	Five Years of Average Evap, ac-ft	Five Year Wet Period Runoff, ac-ft
Plant	5,260	1,190	4,070
Open Pit	7,410	3,620	3,800
Overburden piles	2,280	1,300	980
Stockpiles	26,160	16,550	9,610
Undisturbed area	38,510	19,500	19,010
TOTAL			37,470

(groundwater seepage into pit could increase total by 1,500)
(groundwater seepage from stockpiles could decrease it by 5,000)

SUBSYSTEM B

tailing basin precip-evap for 5-year wet period = 24,700 ac ft

	Five Year Make-Up ac-ft	Net Make-up, Subsystems A & B
Tailings Base:		
impermeable	6,500	-30,900*
semipermeable	10,720	-26,750
permeable	48,130	10,660

*Negative makeup denotes a discharge.

Table 58. Five year wet period balance, 12.35 X 10^6 mtpy mine/mill system.

SUBSYSTEM A

Element	Five Year Wet Period of Record Precip, ac-ft	Five Years of Average Evap, ac-ft	Five Year Wet Period Runoff, ac-ft
Plant	3,420	770	2,650
Stockpiles	1,260	800	460
Undisturbed	18,900	9,570	10,230
Mine	---	---	40
TOTAL			13,380

SUBSYSTEM B

tailing basin precip-evap for 5-year wet period = 14,220 ac ft

	Five Year Wet Period Make-up	Net Make-up, Subsystems A & B
Tailings Base:		
impermeable	5,110	-8,270*
semipermeable	7,510	-5,870
permeable	29,010	15,630

*Negative makeup denotes a discharge.

surrounding surficial materials, it can migrate into surficial aquifers and eventually to surface waters. Overburden piles may be spread as cover material over other parts of the site. Waste rock and lean ore piles will continue to function as they did in the production phase although covering and revegetation could reduce runoff somewhat. The undisturbed watershed area will operate as it did during production. The underground mine would be sealed and will not contribute water. Subsystem A post-production runoff is summarized in Table 59.

Table 59

4.4.4.2 Subsystem B. Only tailings basin precipitation, evaporation, and seepage need to be considered in the subsystem B post-production water balance. The runoff to be expected is difficult to predict, since it will depend on the properties of the tails and the nature of the revegetation and recontouring program. In an average year runoff will probably be 30-50 percent of precipitation. Runoff can leave the tailings basin by surface flow, seepage through the bordering dikes to surface waters, vertical seepage to the groundwater system, or a combination of these. The amount of direct surface runoff will be controlled by final contouring of the basin and the properties of the tailings. Water which infiltrates will be split between dike seepage and vertical seepage depending on the permeability of the surficial materials on which the basin is located. If the base is impermeable, all the infiltration will leave through the dikes. If it is permeable or semipermeable infiltration will leave by some combination of the two. Tailing basin output is given in Table 59.

4.4.4.3 Subsystem C. Runoff from the smelter/refinery site and slag piles has been ignored in the production phase balance and is not included in the post-

Table 59. Model post production water balances.

ELEMENT	AVERAGE YEAR OUTPUT, AC FT 20 X 10^6 mtpy	 12.35 X 10^6 mtpy
Plant	710	460
Open Pit	0	---
Overburden Piles	---	---
Waste Rock and Lean Ore Piles	1,420*[a]	70**[a]
Undisturbed Area	3,070	1,500
Underground Mine	---	0
Tailing Basin	2,810-4,690[b]	1,620-2,690[b]
TOTAL OUTPUT TO SURFACE AND GROUNDWATERS	8,010-9,890	3,650-4,720

*Up to 280 ac ft to groundwater, the rest to surface runoff.
**Up to 20 ac ft to groundwater, the rest to surface runoff.

[a] Could be much greater if surface drainageways are blocked by stockpiles.

[b] Divided among seepage through basin floor, seepage through dikes and direct runoff, as discussed in text.

production balances. The smelter/refinery runoff coefficient would be about the same as that for the milling plant. The hydrologic behavior of slag piles is probably similar to that of waste rock and overburden piles, although slag is quite inert and is not expected to produce runoff with elevated chemical concentrations (Volume 2-Chapter 4).

4.5 HYDROLOGY IMPACTS

Copper-nickel mining, processing, and refining will change the hydrology of the Copper-Nickel Study Area (Study Area). Hydrologic changes could be caused by:

--direct appropriation of water from streams or lakes;

--indirect appropriation by control of runoff from a watershed, or;

--discharge of water to lakes, streams or groundwater, either from point sources or non-point sources mine site runoff or tailing basin seepage.

Appropriation of streamflow and collection of runoff may compete with other users of the water resource. Reductions in low flow of streams decrease the available habitat for aquatic organisms, while the reduction of flooding at spring may eliminate valuable spawning areas. Changes in streamflow or lake levels may be aesthetically undesirable and could decrease the recreational value of the resource.

Discharges to streams could cause scouring and bank erosion or create current velocities too high for existing aquatic communities. Discharge quality may be poor, exceeding tolerance limits for aquatic organisms and standards for drinking water. Various factors, both natural and those related to a copper-nickel mining operation, influence the nature and extent of impacts. The factors in effect during the operational phase would be:

1) Climatic conditions. Although the water requirements for milling or smelting/refining are relatively constant, water availability varies each year in response to precipitation, evaporation, and the resulting runoff in the lake or stream watershed. Larger streams and lakes will be required to provide suf-

ficient water for operation during dry years without major adverse impacts to aquatic communities and other water users.

2) Processing and cooling water requirements. The major factor governing annual water use in milling is the tonnage of ore processed per year. Since an open pit mine in the Study Area must produce approximately 1.6 times as much ore as an underground mine to obtain the same tonnage of metals, water use also depends on the type of mining operation. Other factors of lesser importance may include the volumes of water retained by tailings and used in the concentration of ore. The extent of internal recycling of water is the most important factor governing water needs for the smelter/refinery.

3) Storage. Use of a reservoir, allows storage of water during wet years for use in dry years, lessening wet and dry year impacts and reducing the size of the stream that can provide sufficient water or receive discharges. Storage can be provided by lakes, on-channel reservoirs, or reservoirs located from the water source.

4) Land area from which runoff is collected. Site runoff can be contained and used to supply water needs. The larger the containment area, the larger the amount of runoff collected. Models developed by the Copper-Nickel Study indicate that collection of all mine site and tailing basin runoff would provide more water than needed in the milling operations in an average year. An open pit mine would yield more runoff than an underground mine capable of producing the same amount of metals, because the open pit mine site is larger.

5) Seepage control and soil permeability. The volume of seepage from the tailing basin to groundwater depends on the permeability of the material on which

the pile is sited. If not controlled and collected, seepage can substantially increase losses and increase appropriation requirements.

6) Timing of appropriation or discharge. Timing affects the impact of water appropriation and discharge. Appropriation at a constant rate places a great stress on the water source during low flow periods. If appropriation occurs only during spring flooding, a smaller stream can be used. However, the loss of flow may be detrimental to spawning. Appropriation proportional to streamflow generally minimizes adverse hydrologic impacts, since the amount appropriated depends on available stream flow. The last two appropriation/discharge modes require storage reservoirs, since little or no water will be appropriated at certain times.

The timing of discharges also affects impacts. Discharge proportional to streamflow provides high dilution throughout the year. Discharge only during spring runoff eliminates discharge during much of the year; however, aquatic organisms in the Study Area are most susceptible to stress in the spring (Volume 4-Chapter 1, section 1.4.4.4). Constant discharge leads to varying dilution which is especially poor during periods of low streamflow. Although of short duration, these periods of low dilution can have significant effects on aquatic communities.

In the post-operational phase, different factors will determine impacts than during the operational phase. The size and nature of the area disturbed by copper-nickel development will govern total annual runoff, timing of runoff and distribution among surface runoff, interflow, and baseflow. Residual effects from the operational phase may be in evidence as streams recover from siltation, bank and bed erosion, or other changes in morphology and aquatic communities can be re-established. Reclamation of the disturbed areas can minimize post-operational impacts.

4.5.1 Methodology

This section assesses the ability of water sources in the Study Area to supply water for copper-nickel development, and analyzes hydrologic impacts with respect to natural hydrologic variation, aquatic organisms, and current water users. The models used in this analysis were developed by the Regional Copper-Nickel Study (Volume 2-Chapters 2-5; and section 4.4). They were chosen to illustrate the expected range of hydrologic conditions. The models include:

--mill without storage, dry year and wet year

--mill with storage, average year, three appropriation modes

--mine/mill without storage, dry year and wet year

--mine/mill with storage, average year, three discharge modes

--smelter/refinery without storage, dry year, maximum and minimum recycling

--smelter/refinery with storage, average year, appropriation proportional to flow and constant discharge, maximum and minimum recycling.

Both the 20 X 10^6 mtpy open pit mine/mill and the 12.35 X 10^6 mtpy underground mine/mill area analyzed. The 100,000 mtpy smelter/refinery model is used. The open pit/mill models occupy more area than the underground mine/mill models (Table 37) and cause larger impacts; thus, discussion focuses on the former, with reference to the latter for comparison. The smelter/refinery would probably not be permitted to use minimum recycling under Minnesota's thermal discharge regulations, so the model using maximum recycling is given more emphasis.

The following assumptions were made:

--models for the mill assume only the collection of tailing basin runoff, unless otherwise stated

--mine/mill models assume collection of runoff from the entire mine site

--models assume a semi-permeable base to the tailing basin (seepage rate of 0.2 ft/yr), which is considered more likely to occur than a permeable or impermeable base.

Much of the analysis is based on equations relating streamflow and lake discharge to watershed area (Tables 5 and 60) rather than on data from specific streams and lakes, in order to direct attention to the relationship between scale of watershed and significance of impacts. Because streams in the Study Area are better characterized than lakes, the analysis emphasizes impacts on streams. Impacts on lakes can be equally or more significant than impacts on rivers, but more information on seasonal and annual variations in lake inflow and outflow is needed to address them fully.

Table 60

Additional analysis has been done on certain streams which are large enough to be considered as possible sources of appropriation or receiving waters for discharge and are in or adjacent to the development zones (Figure 1). These streams are the South Kawishiwi, Dunka, Stony, Partridge, and St. Louis rivers (Figure 41). The Shagawa, Bear Island, and Embarrass rivers were not considered, since other major streams are between them and the mineralized zone. The Isabella River is within the Boundary Waters Canoe Area, a federally protected Wilderness Area, prohibiting its use for these purposes. The Whiteface River and Water Hen Creek were not considered, since very little of their watersheds lie within the

Table 60. Areas of watersheds in the vicinity of copper-nickel development zones.

WATERSHEDS	AREA (mi^2)
Unnamed Creek at BB-1	4.2
Filson Creek at F-1	10.4
Keeley Creek at KC-1	11.2
Second Creek at SC-1	26.6
Waterhen Creek at W-1	45.6
Whiteface River at WF-2	47.9
Dunka River at D-1	49.4
Bear Island River at BI-1	68.5
Embarrass River at E-1	88.3
Shagawa River at Sh-1	99.0
Partridge River at P-1	129.3
Stony River at SR-1	244.0
St. Louis River at SL-1	277.
Isabella River at I-1	341.
Kawishiwi River at K-1	1347

SOURCE: USGS (1979).

development area. The option of using several small streams for appropriation or discharge has not been considered here.

Figure 41

Groundwater is not discussed, since it is not a likely appropriation source. The Embarrass-Dunka Rivers Sand Plain area is the only large area with well yields consistently greater than 100 gpm (0.22 cfs) (Siegel and Ericson 1979). This yield is well below model appropriation needs. Yields as high as 1,000 gpm occur only locally in the Study Area (Siegel and Ericson 1979).

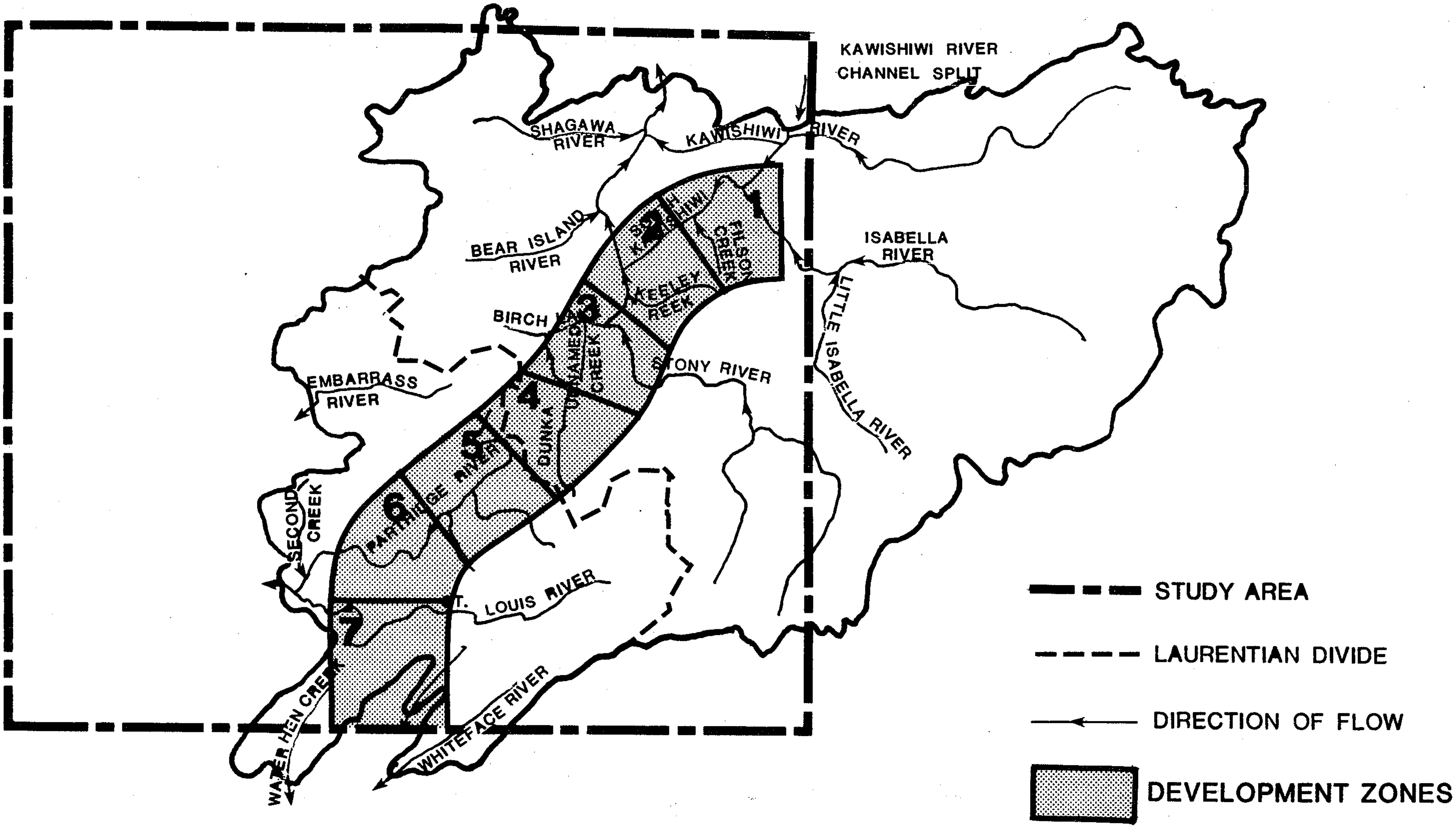
4.5.2 Criteria for Assessing Significance of Hydrologic Impacts

There are no standard criteria cited in the literature for assessing the significance of hydrologic impacts. The effects of hydrologic changes depend upon the morphometry and morphology of individual lakes and streams and on the sensitivity of aquatic species in the water source to the particular change. In this section, the following criteria have been used as guides for determining significance of hydrologic changes resulting from copper-nickel development.

1) Comparison of probable induced changes in streamflow and lake levels with natural variations. Information on streamflows in the Research Area has been compiled (USGS 1976, 1977, 1978) and statistically analyzed for flow duration and flow frequency (Siegel and Ericson 1979). Small changes in stream flow or lake levels would probably not greatly affect stream morphology, lake morphometry, or aquatic species. Changes in the same order of magnitude as natural variations may have impacts immediately or after several years, depending on the severity of the change. Large changes would have immediate impacts.

FIGURE 41

SURFACE DRAINAGE IN THE WATER QUALITY RESEARCH AREA



For this discussion, a large change in streamflow is defined as one which would change flows by 50 percent or more. A small change is one which would affect streamflow by 5 percent or less. A moderate change is between these limits. Levels of significance cannot be associated with these changes without site specific studies of stream characteristics and aquatic species.

Key streamflow parameters were selected to assess the magnitude of streamflow changes. For models without storage, modeled appropriation and discharge needs are most severe during extreme climatic conditions. The key parameters for these models were the 30-day 20-year low flow for dry conditions, and the 30-day 100-year high flow for wet conditions. Models with storage can assume storage of water during wet conditions for use during dry conditions, so average apropriations and discharges during average conditions are considered. Key parameters for these models were the average annual streamflow, for models using appropriation or discharge proportional to flow; the 7-day 2-year low flow (average low flow), for models using constant appropriation; and the average April-May flow, for models using appropriation only during spring runoff. The 7-day 2-year low flow rather than annual flow is used for constant appropriation models since flow changes will be larger (and presumably have more severe impacts) during recurring low flow periods.

1) Rough comparisons of lake level changes to natural variation were made. Lakes with predicted 30-day 20-year low flows are greater than appropriation needs during the 100-year dry year are not expected to experience changes in level. Other lakes will experience some changes in levels, if used as a combination of water source and natural storage reservoir. Lakes with an average annual inflow less than the average demand are not considered suitable for long-term water sources.

2) Assessment of possible competition for water resources between existing users and copper-nickel development, by comparing the combined demand with streamflows.

3) Assessment of impacts on aquatic organisms by considering the magnitude and timing of flow changes. Small changes in flow would probably not greatly affect aquatic communities. If changes are of the same order of magnitude as natural variations, effects may occur immediately or after several yars. For example, an appropriation could reduce the average flow of a stream to a level which occurred naturally only once in 5 years. The impact would not be visible immediately, since the stream system would already be adjusted to periodic incidents of this level of flow. Over a number of years, however, the decreased flow could cause gradual changes in stream morphology or aquatic communities. If flows were reduced to a level which occurred naturally only once in 25 years, fairly rapid measurable physical and biological changes could result.

The persistence of stress on an aquatic community, from either the operational or post-operational phase of copper-nickel development, may determine the significance of the impact. A stress that occurs often, such as during the average low flow of a stream, may not allow the community to recover between episodes. The effects of various discharges and appropriations on the 7-day 2-year low flow are examined in this section for this reason. A community would probably recover between stress episodes if the episodes occurred only during the 7-day 25-year low flow.

4.5.3 Mitigation Measures

This report discusses several measures that would minimize the hydrologic impacts of copper-nickel mining. For the operational phase, measures include: selection of water sources with sufficient water to meet needs with little flow change; type of mine; type of appropriation or discharge; maximum recycling of water for the smelter/refinery; use of site runoff to minimize withdrawal; release of excess water to the watershed in which the site is located; and phased construction of tailing basins and stockpiles. For the post-operational phase, the major mitigative measure is recontouring and revegetation of the disturbed area.

4.5.4 Model Results--Operational Phase

The major hydrologic impacts during the operational phase result from water appropriations and discharges. Collection of site runoff reduces appropriation needs.

4.5.4.1 Mine/Mill System. Process water needs for the mine/mill depend on type of mine. The 20 X 10^6 mtpy open pit model uses more process water than the 12.35 X 10^6 mtpy underground model (Table 61). Only the open pit mine model is discussed in this section; the underground model is included in tables and figures for comparison. Assuming collection of tailing basin runoff, the open pit mine/mill model system would require 3,180 acre-feet in an average year, 8,620 acre-feet in a dry year, and have an excess of 1,330 acre-feet in a wet year (Table 61). With collection of all mine site runoff, the figures are an excess of 2,820 acre-feet, a need of 8,380 acre-feet, and an excess of 14,300 acre-feet, respectively (Table 61).

Table 61

Mine/Mill System Without Storage--The annual water balance of a mine/mill operation is dependent on climatic conditions. Water deficits or excesses can occur

Table 61. Subsystems A and B appropriations and discharges, tailing basin on semipermeable base (all volumes in acre-feet per year)

	20 X 10^6 mtpy open pit						12.35 X 10^6 mtpy underground					
	Average Year		Wet Year		Dry Year		Average Year		Wet Year		Dry Year	
	subtotals	totals	subtotals	totals	subtotals	totals	subtotals	totals	subtotals	totals	subtotals	totals
A. Consumptive Use												
Plant loss	1,040		1,040		1,040		640		640		640	
Concentrate water	310		310		310		190		190		190	
Tailing basin retention	5,090	6,440	5,090	6,440	5,090	6,440	3,150	3,980	3,150	3,980	3,150	3,980
B. Ore Moisture		160		160		160		110		110		110
C. Tailing Basin Runoff												
Precipitation	9,560		13,050		5,360		5,500		9,500		3,080	
Evaporation	5,630	3,930	4,610	8,440	6,870	-1,510	3,240	2,260	2,650	4,850	3,950	-870
D. Tailing Basin Seepage		830		830		830		480		480		480
E. Subsystem B Make-up Need (A-B-C+D)		3,180		—		8,620		2,090		—		5,220
F. Subsystem B Excess (B+C-A-D)		—		1,330		—		—		500		—
G. Runoff From Mine Site		6,000		13,000		240		2,100		4,000		200
Net Make-Up Need (appropriation)(E-G)		—		—		8,380		10		—		5,020
Net Excess (discharge) (F+G or G-E)		2,820		14,330		—		—		4,500		—

SOURCE: Section 4.4.

in extreme years, even if the operation is almost self-sufficient in an average year (Table 61). Assessing impacts for a system without storage requires comparison of extreme wet and dry year conditions.

Extreme Dry Year--The mine/mill water balance for the 100-year dry year is used to assess the hydrologic impacts of an extreme dry year. The calculated deficit for this case is 8,380 acre-feet (11.6 cfs) for the 20 X 10^6 mtpy open pit mine model (Table 61).

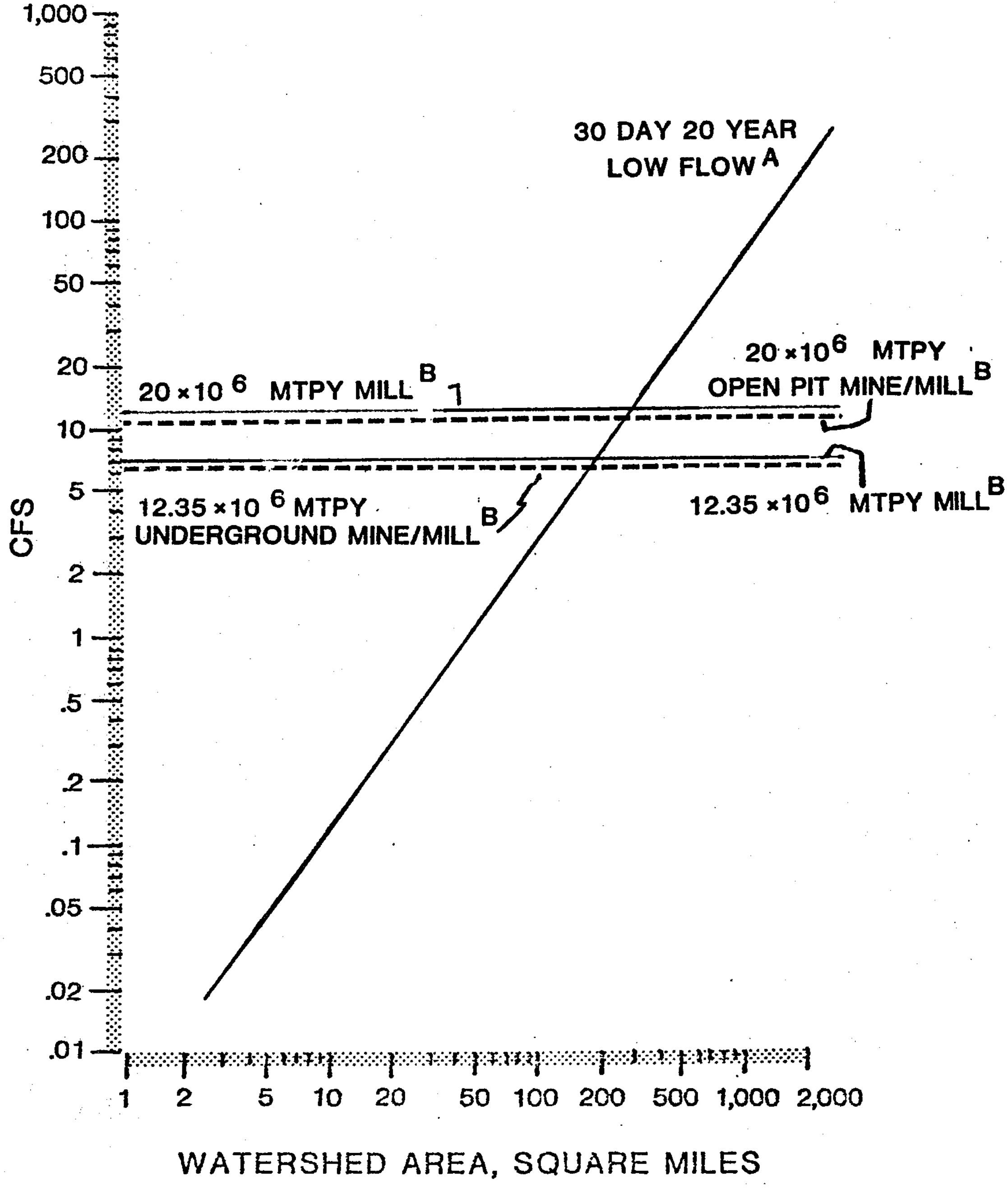
The 30-day 20-year low flow was used in determining the adequacy of streams as appropriation sources for the 20 X 10^6 mtpy open pit mine model. It was assumed that the mill would shut down or use stored water for low flow periods of less than 30 days. The 20 year recurrence interval was selected because statistics for the 100-year recurrence interval could not be developed with the available data. This procedure results in generous estimates of a stream's ability to suply the needed water during an extreme event, since 100-year low flows will be smaller than 20-year low flows. Low flows experienced in 1976 are listed in Table 7.

Comparisons of the draft rate with streamflows shows that streams in watersheds of less than about 270 mi^2 would not be able to meet the appropriation need for the large open pit model (Figure 42). The St. Louis River at SL-1 (watershed area of 277 mi^2) has an estimated 30-day 20-year low flow just large enough to meet the appropriation need (Table 62). The largest river in the Study Area, the Kawishiwi at K-1 (watershed area of 1,347 mi^2), has an estimated 30-day 20-year low flow of about 80 cfs, or about 7 times the appropriation need (Table 7).

Figure 42, Table 62

FIGURE 42

DRY YEAR APPROPRIATION FOR MILL AND MINE/MILL WITHOUT STORAGE



A. BROOKS AND WHITE, 1978

B. TABLE 61

Table 62. Effect of dry year appropriation on streamflow for 20 X 10^6 mtpy mine/mill without storage.[a] Example showing use of Figure 42.

	30-day, 20-yr Low Flow[b]	100-yr Dry Year Appropriation[c]	Low Flow Appropriation	% Reduction in Flow
Kawishiwi River at K-1 (A = 1,347 mi^2)	79.4	11.6	67.8	15
St. Louis River at SL-1 (A = 277 mi^2)	12.4	11.6	0.8	93

[a] Assumes tailing basin on semipermeable base; collection of runoff.
[b] Brooks and White (1978).
[c] Based on Table 61.

Appropriation for the mine/mill model without storage would be 8,380 acre-feet or 2,700 million gallons of water during the 100-year dry year. This would be the second largest consumptive appropriation in the Study Area, exceeded only by Erie Mining Company's process water requirement of 5,900 million gallons per year (Table 10).

The mine/mill water need is small compared with use for power generation and would probably not interfere significantly with this use if the same streams were used. Competition with municipal supply systems is possible, though avoidable. As shown in Figure 42, the 30-day 20-year low flow of the Partridge River is less than the drought demand rate. Competition for water with the Village of Hoyt Lakes would be likely during low flow periods if the river were used as a make-up source. Aurora and Babbitt use groundwater, which is not likely to be used as a milling make-up source. Winton withdraws from the Kawishiwi River near K-1, where flows are high enough to make conflict unlikely.

Hickok (1977) has suggested that dewatering discharges from existing taconite mines could be used to meet copper-nickel mine/mill water needs. Reserve Mining Company's Peter Mitchell Mine or Erie Mining Company's combined mines provide adequate flows for this purpose, even in dry years (Table 10). Most pit water is currently discharged to Unnamed Creek and the Dunka River, or to the Partridge River and Second Creek. Appropriating pit water for consumptive use would reduce the flows of these streams, especially during low flow periods (Siegel and Ericson 1979). This may be preferable to appropriating from streams which are not already impacted. However, process water is appropriated from the Partridge River by the Erie Mining Company. Use of pit water for another mining operation would cause a conflict with Erie's use of the Partridge River flow.

100-Year Wet Year--Discharges for the mine/mill model during the 100-year wet year are 14,330 acre-feet (19.8 cfs) for the 20 X 10^6 mtpy open pit mine model (Table 61).

If released proportional to streamflow, discharge from the 20 X 10^6 mtpy model would approximately double the flows in streams with watersheds of 10 mi^2 (Figure 43). Significant scouring and bank erosion could occur in streams of this size. For streams with watersheds larger than about 150 mi^2, the discharge would increase high flows by 10 percent or less and would probably not have significant effects on stream morphology.

Figure 43

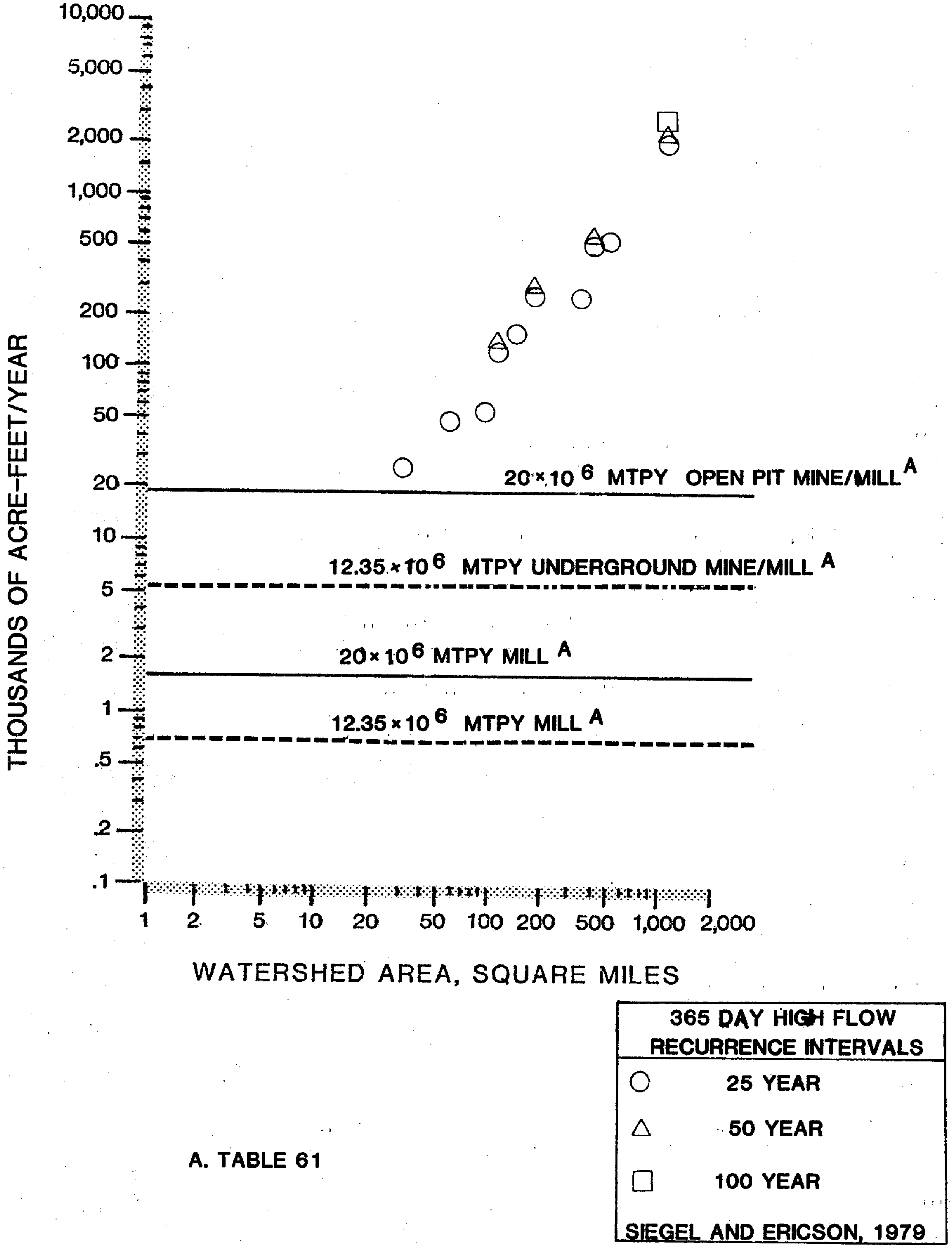
Mine/Mill With Storage--Collection of Tailing Basin Runoff Only--Water excesses and deficits can be reduced by the use of stored water. Excess water in wet years can be stored to prevent a deficit in dry years, thus reducing appropriations and discharges in extreme conditions. Therefore, only impacts of appropriation during average flow conditions are considered in this section.

The average annual appropriation need for the 20 X 10^6 mtpy mill with the tailing basin is 3,180 acre-feet; this figure assumes collection of tailing basin runoff (Table 61). The effect of an appropriation of this size on streams in the Study Area depends on the type and timing of appropriation.

A stream with a watershed of at least 10 mi^2 could meet the average annual need of this model if the entire flow of the stream were appropriated. One way to meet the appropriation need would be to construct a storage reservoir with a catchment area of 10 mi^2. The impacts on the host watershed would be signifi-

FIGURE 43

WET YEAR DISCHARGE FOR MILL ALONE AND MINE/MILL WITHOUT STORAGE



SIEGEL AND ERICSON, 1979

A. TABLE 61

cant. Above the dam, an artificial lake with fluctuating water levels would replace the stream network. Immediately below the dammed area streamflows would drop to near zero because most runoff would be controlled.

A second alternative would be to withdraw water from a stream in a larger watershed for storage in an off-channel reservoir. Three types of appropriation could be used: appropriation proportional to flow, appropriation from spring runoff, and constant appropriation.

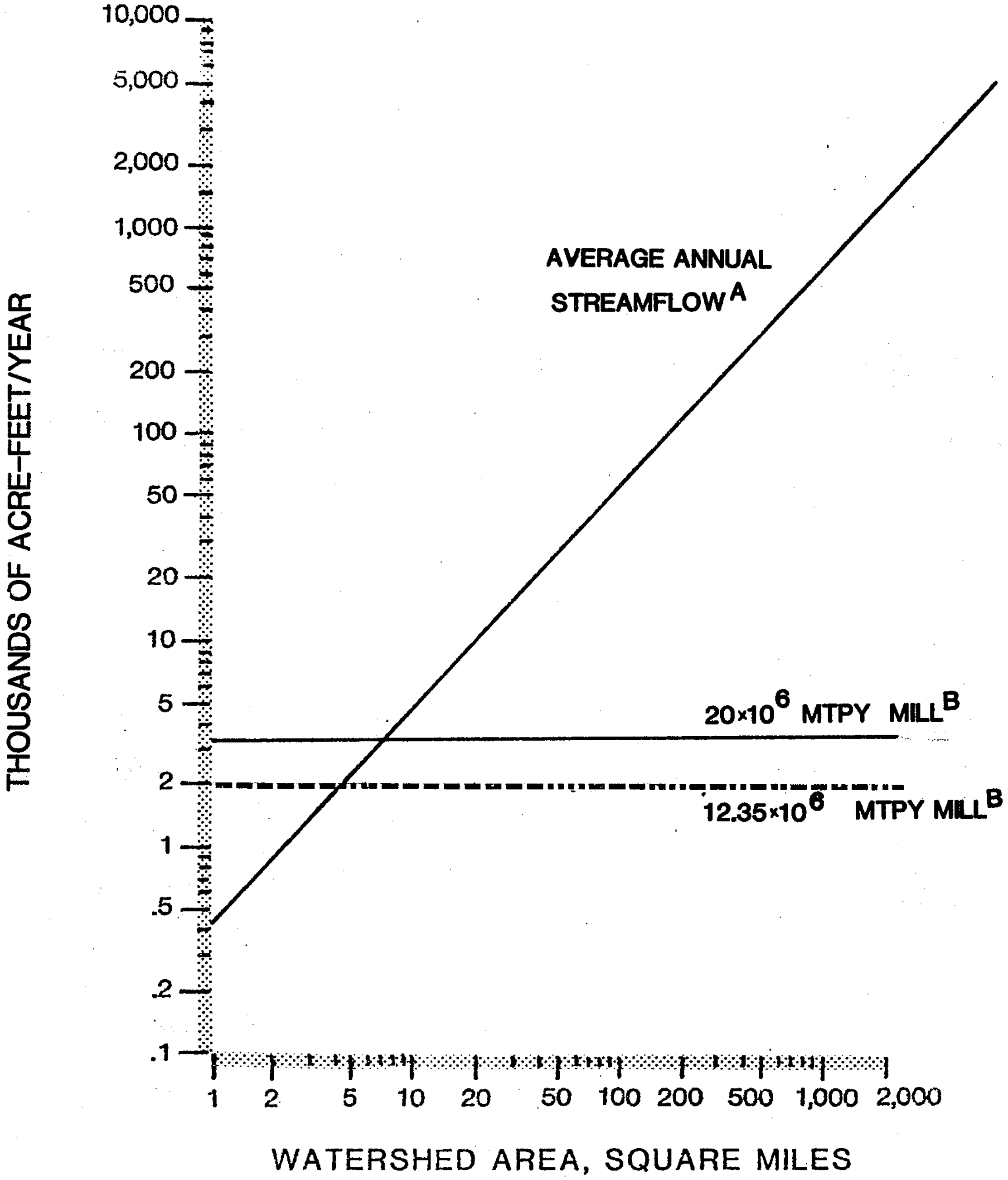
In streams with watersheds over 100 mi^2 area, reductions in annual flow caused by appropriation proportional to flow would be small compared with natural variations, and probably would not cause measureable impacts on stream morphology or aquatic communities. For streams with watersheds of 10 to 100 mi^2, the changes in flow could be large to moderate. Streams in smaller watersheds in this range would show the effects of appropriation immediately, whereas larger streams may exhibit measurable impacts only after several years of appropriation. Figure 44 and Table 63 show how this appropriation would affect the average annual flow of streams. This method would cause the smallest flow reduction on the Dunka River (Table 63).

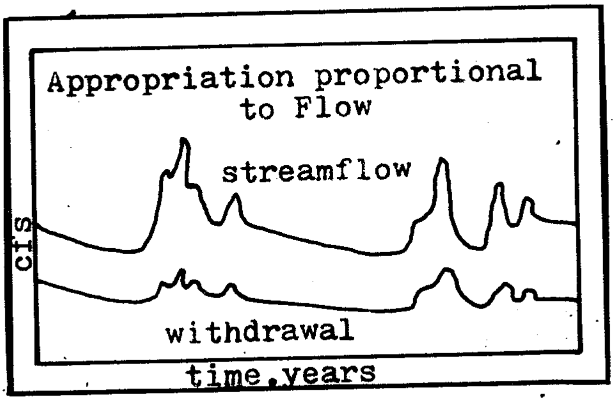
Figure 44 and Table 63

Appropriation from spring runoff would require the entire flow of a stream with a watershed area of about 15 mi^2 (Figure 45). Small watersheds may experience moderate to large flow reductions. For example, the average April-May flow of Dunka River (watershed area of 49.4 mi^2) would be reduced about 27 percent (Table 63). Impacts on the morphology of streams this size may be visible after several

FIGURE 44

APPROPRIATION PROPORTIONAL TO FLOW FOR MILL WITH STORAGE.





A. FROM SIEGEL AND ERICSON, 1979

B. TABLE 61

Table 63. Effect of appropriation on streamflow—20 X 10^6 mtpy mill with storage, with tailing basin or semipermeable base. Example showing use of Figures 44, 45, and 46.

Appropriation Mode	Streamflow Parameter	Dunka River Flow at D-1 (A = 494mi^2)	Average Year Apropriation	Streamflow Appropriation	% Reduction in Flow
proportional to flow	average annual yield[b]	28,255[e]	3,200[e]	25,055[e]	11
with spring runoff	April & May flow[c]	11,726[e]	3,200[e]	8,526[e]	27
constant rate	7-day, 2-yr low flow[d]	3.53[f]	4.42[f]	——	over 100

[a] See Table 61.
[b] Siegel and Ericson (1979).
[c] Calculated as 41.5% of annual flow from Siegel and Ericson (1979).
[d] Brooks and White (1978).
[e] Acre-feet.
[f] Cubic feet per second.

years of spring withdrawal. The model predicts appropriation of about 5 percent of the April-May flow of rivers with watershed areas of 250-300 mi^2 would be required (e.g. the Stony and St. Louis rivers). This appropriation might not have a measurable effect on stream morphology or aquatic communities.

Figure 45

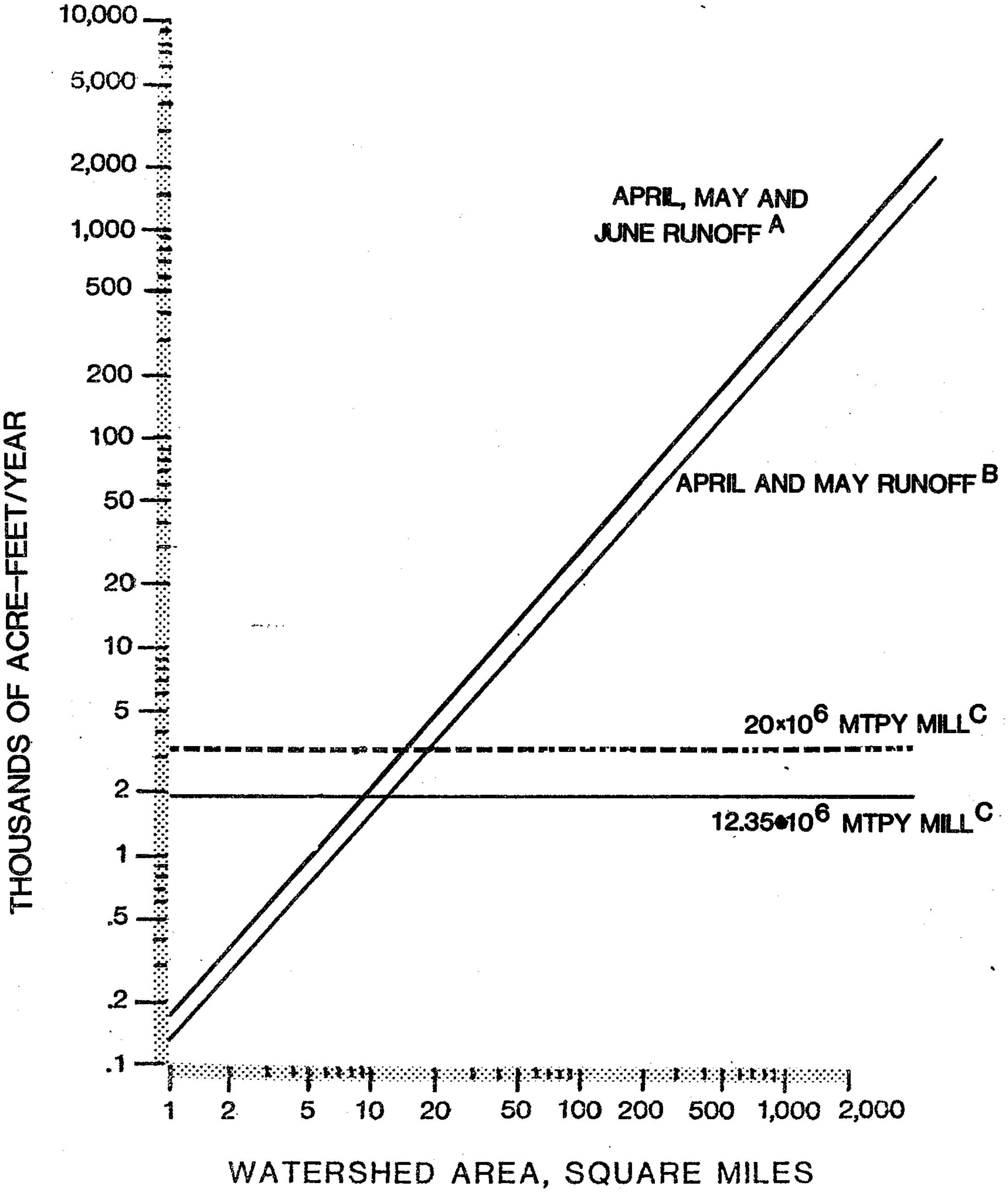
Appropriation at a constant rate requires streams with larger watershed areas. The draft rate for constant appropriation is approximately equal to the 7-day 2-year low flow of a stream with a watershed of 60 to 90 mi^2 (Figure 46 and Table 63). The Dunka River could not supply the needed water (Table 63). Appropriation would cause a large change in low flows of streams in watersheds up to about 200 mi^2 in area. Changes would be small only for streams in watersheds of at least 500 or 600 mi^2. Appropriation at a constant rate can be avoided if storage is used.

Figure 46

Lakes may also be used as water sources for a copper-nickel milling operation. Many lakes in the Study Area are on the channel of rivers; they receive significant inflow and have significant discharges. Data on seasonal inflow and outflow of lakes in the Study Area are not generally available. However, it is assumed that discharges from lakes are relatively comparable to stream flow. Using the equation developed by Ramquist (Table 8) for the mean annual discharge from lakes, it is estimated that discharge from a lake with a drainage area of about 10 mi^2 would be sufficient for the appropriation need of a mine/mill with storage. If such a lake also served as the storage reservoir, lake levels could

FIGURE 45

APPROPRIATION FROM SPRING RUNOFF FOR MILL WITH STORAGE



A. CALCULATED AS 57.9% ANNUAL FLOW, FROM SIEGEL AND ERICSON, 1979

B. CALCULATED AS 41.5% ANNUAL FLOW, FROM SIEGEL AND ERICSON, 1979

C. TABLE 61

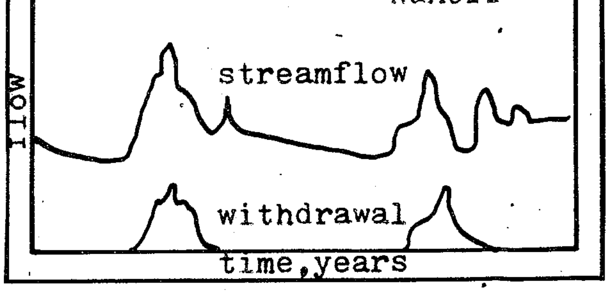
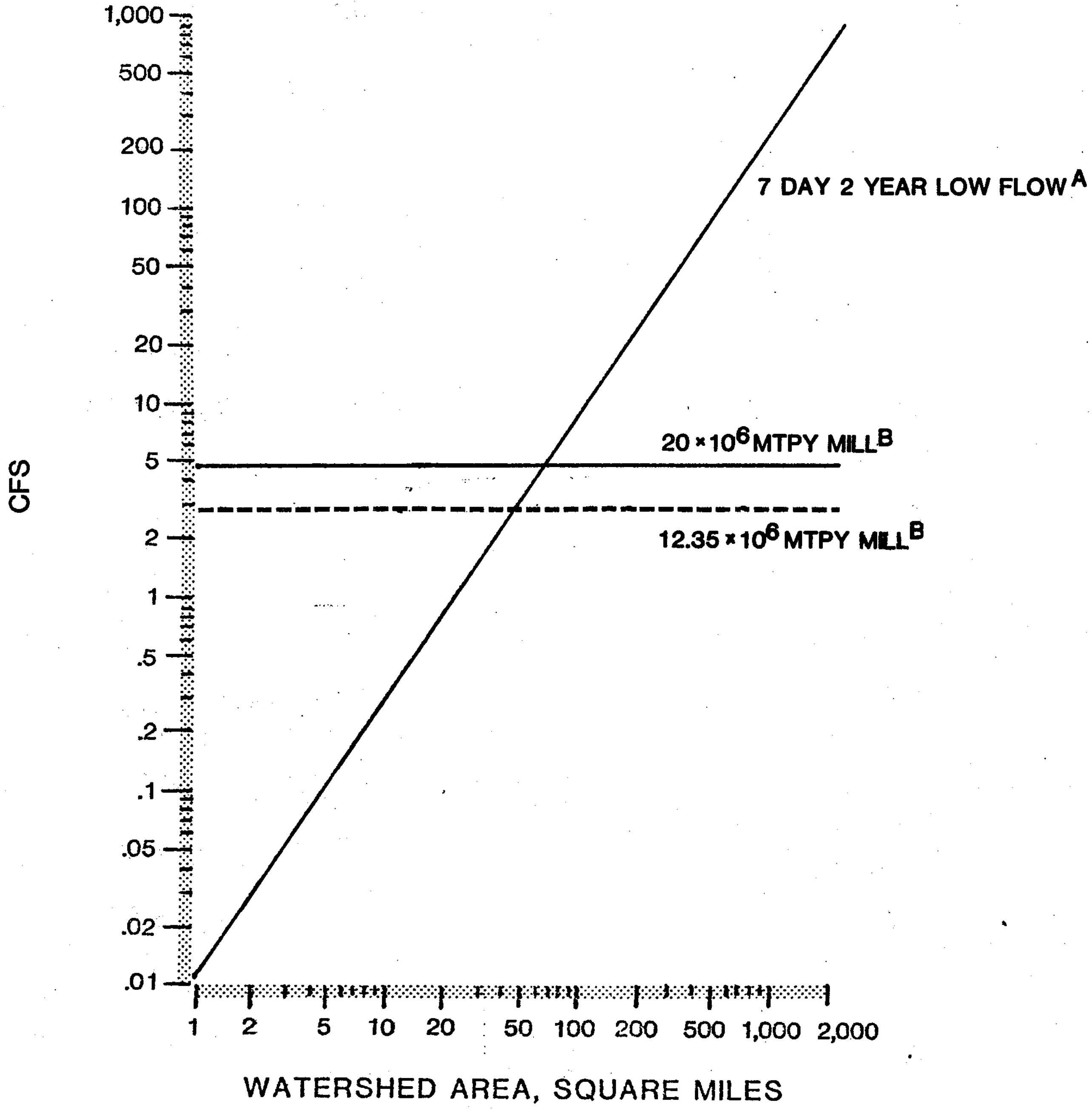


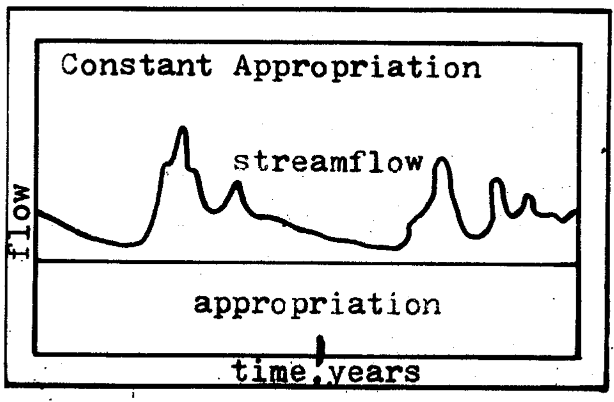
FIGURE 46

CONSTANT APPROPRIATION FOR MILL WITH STORAGE



A. BROOKS AND WHITE, 1978

B. TABLE 61



be expected to fluctuate in an average year (Honetschlager and Hewett 1979). If a separate reservoir were used, withdrawals synchronous with the natural pattern of outflow from the lake would reduce the effects of withdrawal on lake levels.

Based on analogy with streamflows, on-channel lakes with drainage areas less than about 270 mi^2 probably have 30-day low inflows smaller than the dry year demand rate for a mine/mill without storage. If these lakes were used as appropriation sources and natural storage reservoirs, additional lowering of lake levels would occur during dry periods because of evaporation. Only six lakes in the Study Area have drainage areas exceeding 300 mi^2 (Table 64). All are in the Kawishiwi River Watershed. Bald Eagle and Gabbro Lakes, which receive the flow of the Isabella River, would not be suitable water sources, since they are located in the BWCA. Birch, White Iron, Farm and Fall lakes are all on the channel of the Kawishiwi River and drain 980 to 1,350 mi^2. However, only Birch is within a copper-nickel development zone.

Table 64

The 30-day low inflow of record to Birch Lake, which is the lake closest to the mineralized zone, has been estimated at 55.7 cfs (Bowers 1977). This is larger than appropriation needs for models without storage. Monthly evaporation can exceed precipitation by 83 mm or more in dry years, causing a loss of 2.9 cfs per square mile of lake surface (Honetschlager and Hewett 1979). For Birch Lake, with a surface area of 11.6 mi^2, the net evaporative loss in a dry summer month could be as much as 33.6 cfs, reducing discharge considerably.

It could be possible to use several small lakes as sources, rather than one large lake.

Table 64. Lakes in the Study Area with drainage areas exceeding 300 mi^2.

LAKE	DRAINAGE AREA (mi^2)	NOTES
Bald Eagle	340-400	receives flow of Isabella River
Gabbro	399	receives flow from Bald Eagle Lake
Birch	980	receives flow of So. Kawishiwi River, Dunka River and Stony River
White Iron	1,073	on channel of South Kawishiwi River below Birch Lake
Farm	1,070	receives flow of South Kawishiwi River below White Iron Lake and flow of Kawishiwi River
Fall	1,347	receives flow of Kawishiwi River below Farm Lake and of Shagawa River

SOURCE: Table 8.

Selected pit dewatering discharges would be adequate to meet the make-up need for the mill with storage. This would have an impact on the water resources of the Study Area, since pit dewatering discharges currently help sustain flows to Birch Lake and the Partridge River.

Evaluation of the other criteria for significance shows that the mill alone with storage has little adverse impact. The appropriation needs for this model are much less than any other current water use (Table 10). Competition with other users would be unlikely. For example, the combined demand of municipal users and the model mill with storage falls well below the annual flow of the streams used as appropriation sources (Table 65).

Table 65

Water seeps from the tailing basin to groundwater at a fairly constant rate of 1.15 cfs, or 830 acre-feet/year in the mill model. This would double the 7-day 2-year low flow in watersheds of 20 mi^2. Such increases in low flow would be beneficial to aquatic organisms, provided that the quality or temperature of the water were not detrimental.

Mine and Mill With Storage--*Collection of All Mine Site Runoff*--If part of a watershed is used by a copper-nickel operation, and the runoff from the area is collected instead of being allowed to join a stream, the streamflow in the watershed will be reduced. A copper-nickel milling operation could use this collected water to help meet make-up needs, thereby reducing appropriation needs. Containment of the entire mine site would yield about 6,000 acre-feet in an average year. This is 2,820 acre-feet more than is needed to meet the deficit

Table 65. Comparison of current water demands and model mill demand with the flow of source streams.

User	Annual Use 10^6 gal	Stream Source	Annual Flow 10^6 gal[a]
Municipal Supply Systems			
Winton	8.8[b]	Kawishiwi at K-3	242,000
Ely	409.4[b]	Shagawa at Sh-1	23,000
Hoyt Lakes	149.2[b]	Partridge at P-1	24,800
Mine Processing			
Erie Mining Company	5,900[b]	Partridge at P-1	24,800
Model Copper-Nickel Mill	1,020[c]		

[a] USGS (1978).
[b] Siegel and Ericson (1979).
[c] See Table 52

for the mill (Table 61). Either the excess water must be discharged, or a smaller area should be contained.

This water management plan would have the following effects on water resources:

1) Containment of site runoff would reduce the flow of the host watershed. The entire model mine/mill occupies a 16 mi^2 site (Table 37). Assuming the effects of containment of site runoff on streamflow are directly proportional to area, containment of the site runoff could significantly decrease streamflows in much larger watersheds (Figures 47 and 48). Changes are likely to be small in streams with watersheds of 300 mi^2 or more, and effects on stream morphology and aquatic organisms would probably not be measureable. If the mine/mill site occupied bogs or lakes which previously sustained low flows and damped flood flows in the watrshed, or if the open pit diverted flow from the stream, changes in flow could be greater than predicted. Table 66 indicates that site containment would cause a significant decrease (24-41 percent) in Dunka River flows.

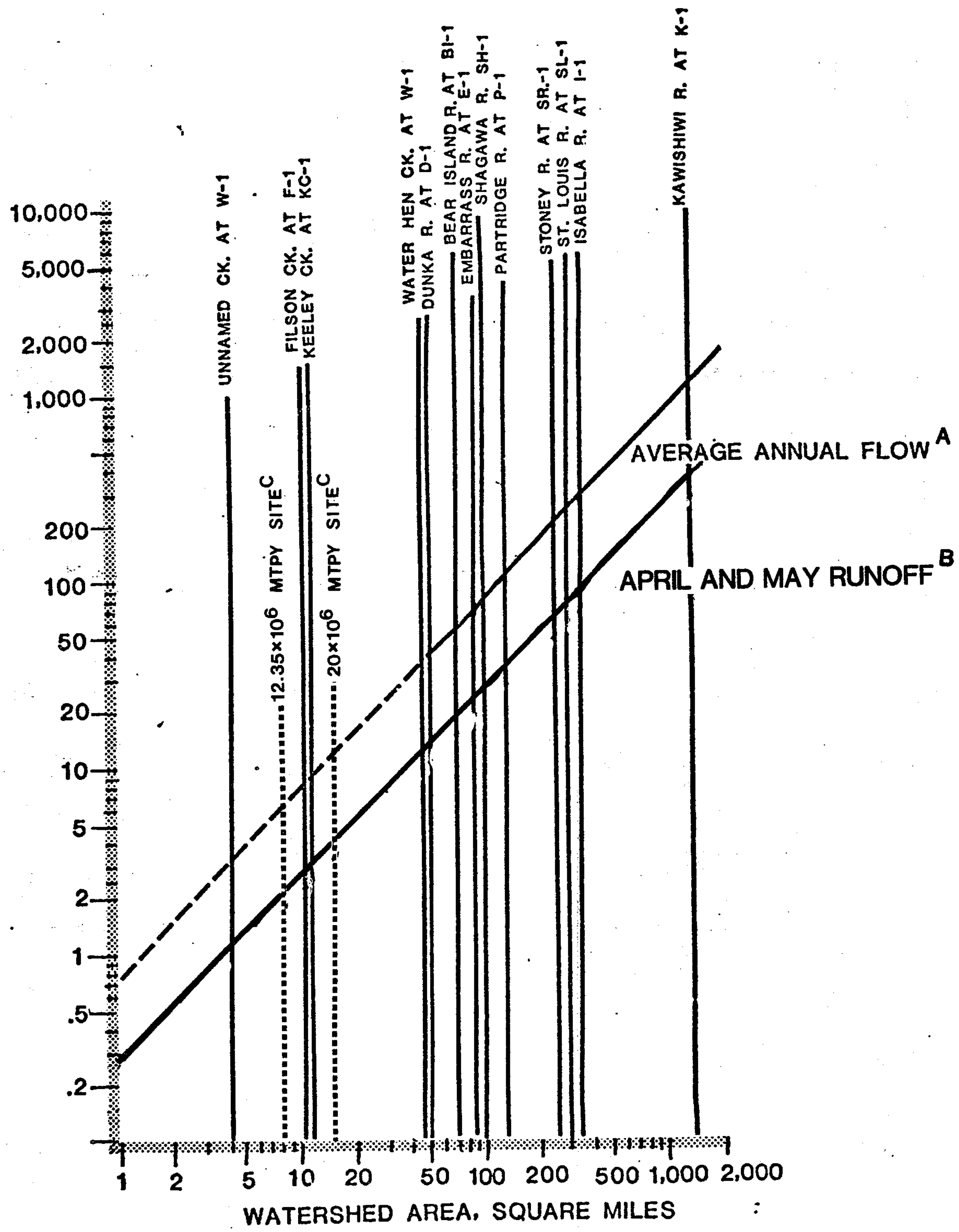
Figures 47 and 48, Table 66

2) Discharges, if released to a watershed other than the one in which the mine-site was located, would increase flow of the receiving watershed. The layout of the site relative to watershed boundaries could result in discharge to a watershed other than the one in which the runoff was collected. This would decrease streamflow in the host watershed and increase streamflow in the receiving watershed.

Figures 49, 50, and 51 compare the mine/mill model discharge (2,820 acre-feet) to streamflows in the Study Area. Excess water is variously assumed to be

FIGURE 47

EFFECT OF CONTAINMENT OF SITE RUNOFF ON ANNUAL STREAMFLOW AND SPRING RUNOFF



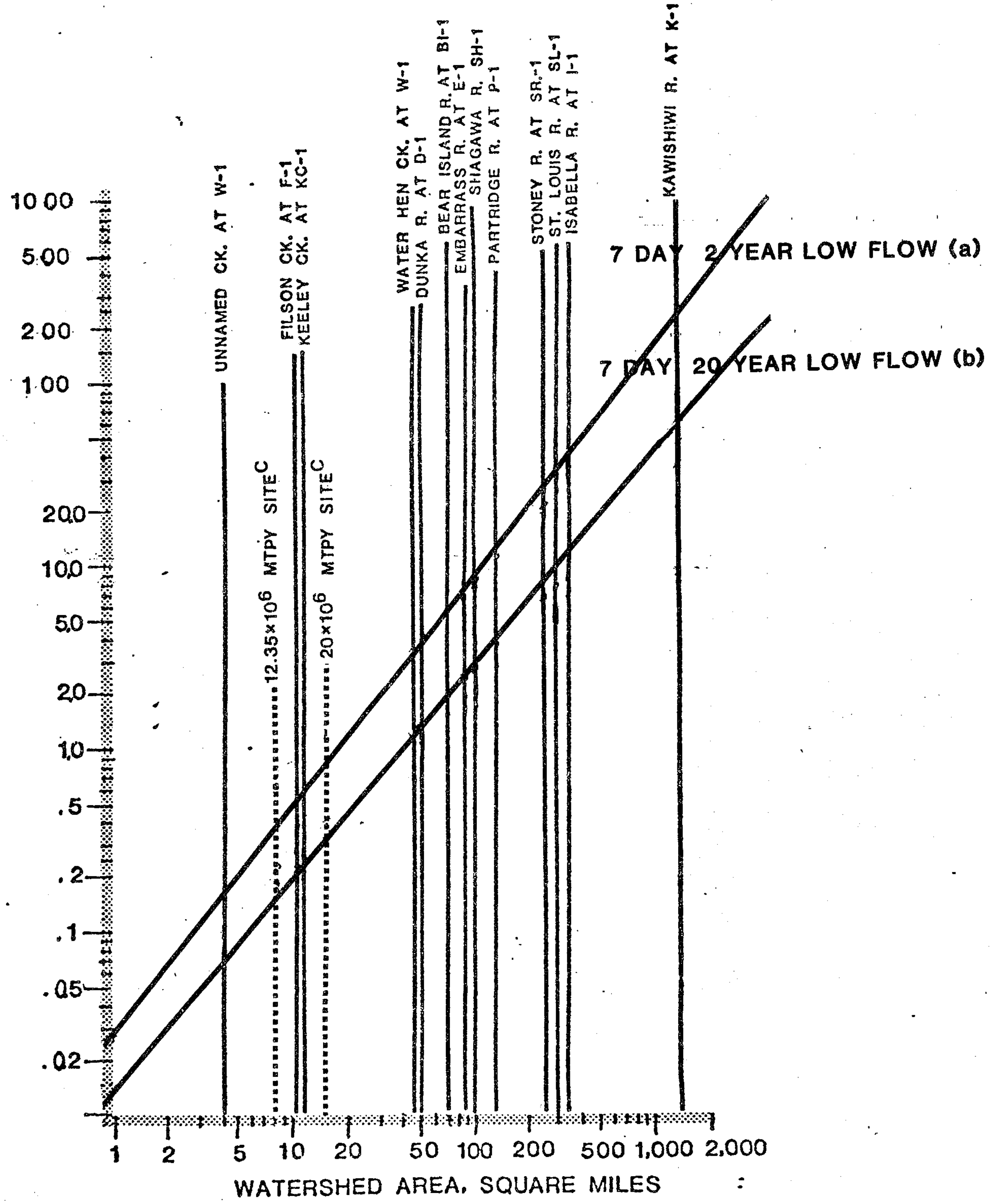
A. FROM SIEGEL AND ERICSON, 1979

B. CALCULATED AS 41.5% OF ANNUAL YIELD, FROM SIEGEL AND ERICSON, 1979

C. SEE TABLE 61

FIGURE 48

EFFECT OF CONTAINMENT OF SITE RUNOFF ON LOW FLOWS OF STREAMS



(a)CALCULATED FROM DATA IN BROOKS AND WHITE 1978

(b)FROM DATA IN BROOKS AND WHITE 1978

(c)SEE TABLE 61

Table 66. Containment of site runoff: effect on streamflows. Example showing use of Figures 48 and 49.

Streamflow Parameter	Units	Dunka R. at D-1	20×10^6 mtpy OP	Dunka-20×10^6 OP	Percent Decrease in Flow	12.35×10^6 mtpy UG	Dunka-12.35×10^6 UG	Percent Decrease in Flow
Area, mi^2		49.4	16.0	33.4		7.85	41.6	
7-day 2-year low flow $\log Q = -1.62 + 1.28 \log A$[a]	cfs	3.53	.83	2.1-2.7[e]	24-41[e]	.34	2.83-3.19[e]	10-20[e]
7-day 20-year low flow $\log Q = -1.7336 + 1.1951 \log A$[b]	cfs	1.23	.32	.77-.91[e]	26-37[e]	.14	1.00-1.09[e]	11-19[e]
Average annual yield $Q = 572 A$[c]	acre-feet	28,300	9,200	19,100	33	4,500	23,800	16
April and May runoff $Q = 237 A$[d]	acre-feet	11,700	3,800	7,900	32	1,900	9,800	16

[a] Calculated from Brooks and White (1978).

[b] From Brooks and White (1978).

[c] From Siegel and Ericson (1979).

[d] Calculated as 41.5 percent of annual yield from Siegel and Ericson (1979).

[e] High estimate subtracts mine site flow from river flow; low estimate is the flow of watershed area minus mine site area.

discharged proportional to flow, during spring runoff, or at a constant rate. All discharge methods would cause large changes in flow in streams with watersheds of 20–30 mi^2 or less. Impacts on stream morphology and aquatic communities in these streams might well be significant. For streams draining 100 mi^2 or more, the change in flow is small for discharge proportional to flow. For streams draining 200 mi^2 or more, change would be small if discharge occurs during spring runoff, and probably would not have a measurable impact on stream morphology or aquatic organisms.

Figures 49, 50, and 51

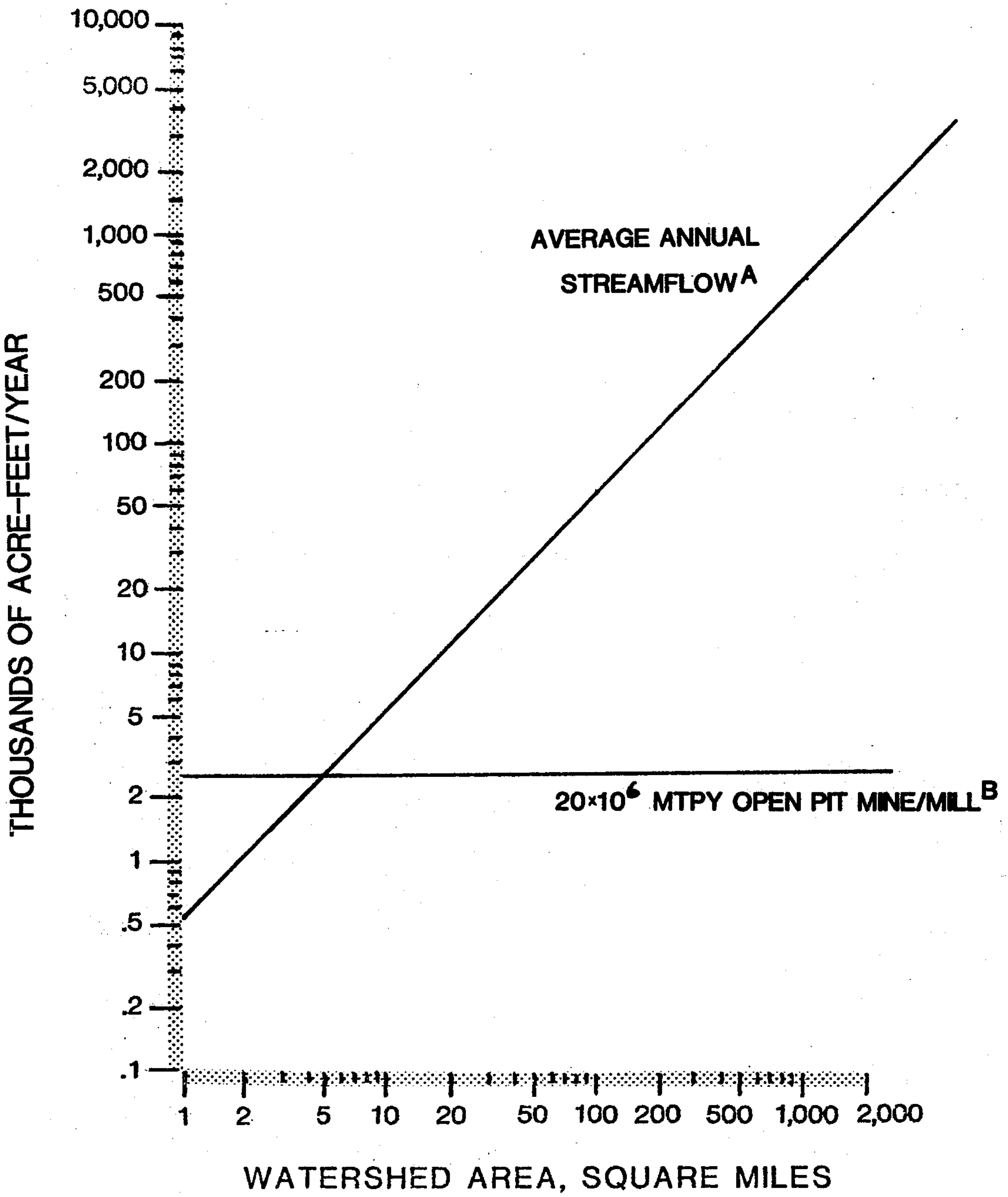
Constant discharge affects streamflows most during low flow periods. The model discharge would approximately double the 7-day 2-year low flow of a stream draining 50–70 mi^2. This would help stabilize the volume and velocity of the stream and may be beneficial to aquatic organisms, quality considerations aside.

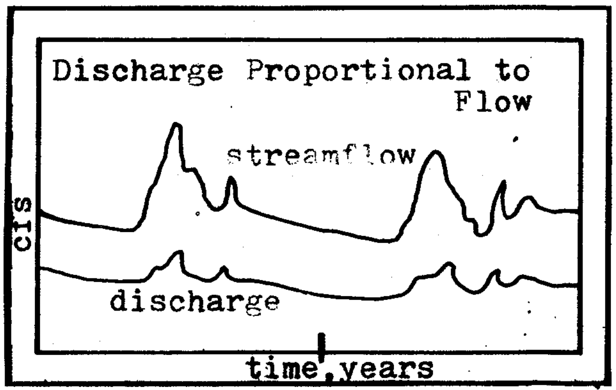
The model discharge is much larger than current mine processing discharges in the Study Area, and is of the same order of magnitude as existing mine pit dewatering discharges (Table 10). Discharge to Unnamed Creek from the Dunka Pit fluctuates widely. This fluctuation may be detrimental to aquatic organisms (Volume 4-Chapter 1).

3) Discharges, if released to the same watershed from which runoff is collected would partially mitigate flow reductions due to containment. Flow reductions can also be mitigated by reducing the size of the area from which runoff is collected. Undisturbed areas within the model mine site account for 40 percent of the land area and about 3,070 acre-feet of runoff (Table 47) in an average

FIGURE 49

DISCHARGE PROPORTIONAL TO FLOW FOR MINE/MILL WITH STORAGE



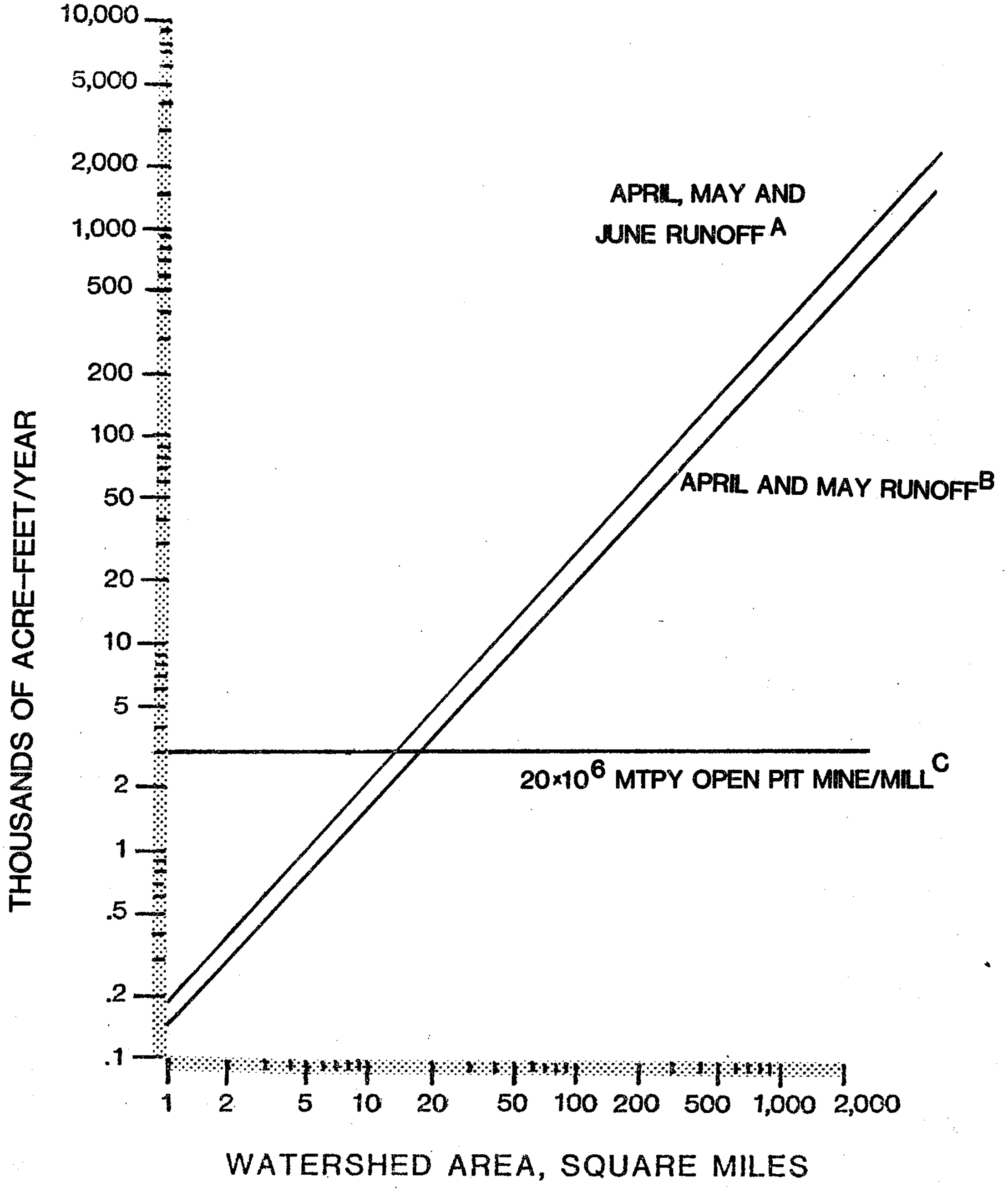


A. FROM SIEGEL AND ERICSON,1979

B. TABLE 61

FIGURE 50

DISCHARGE DURING SPRING RUNOFF FOR MINE/MILL WITH STORAGE



A. CALCULATED AS 57.9% ANNUAL FLOW, FROM SIEGEL AND ERICSON,1979

B. CALCULATED AS 41.5% ANNUAL FLOW, FROM SIEGEL AND ERICSON,1979

C. TABLE 61

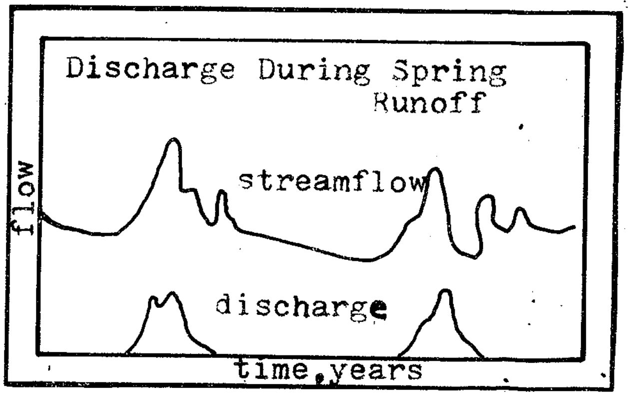
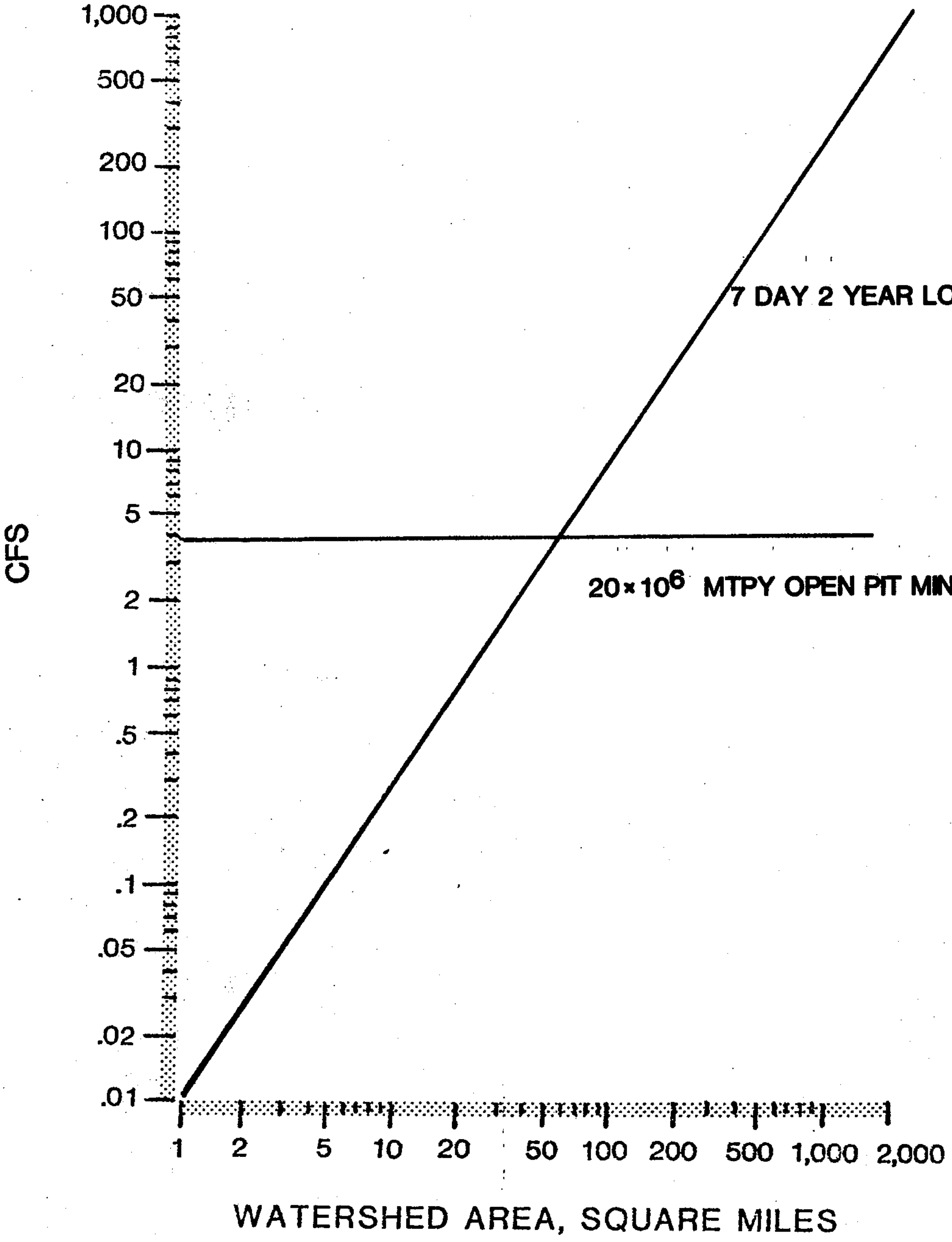
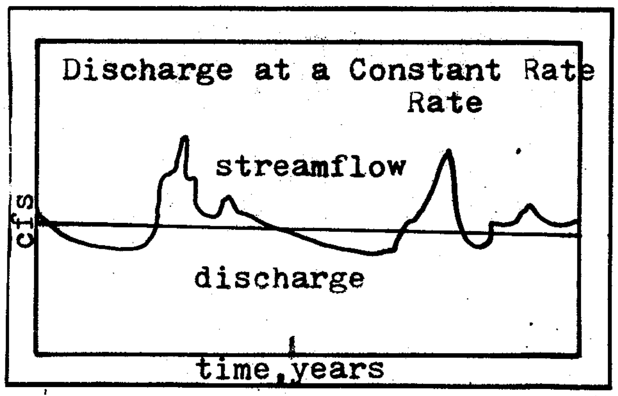


FIGURE 51

DISCHARGE AT A CONSTANT RATE

FOR MINE/MILL WITH STORAGE





A. CALCULATED FROM BROOKS AND WHITE, 1978

B. TABLE 61

year. If it is possible to separate this runoff from that coming from other sources, the discharge can be completely eliminated in an average year. Construction of tailing areas or stockpiles in cells, followed by effective reclamation, and higher stockpiles with smaller base areas could also reduce the area contributing runoff at any given time (section 4.4).

4) Discharges could be of poor quality, requiring dilution. Discharge water can have high concentrations of heavy metals, suspended solids, process chemicals, and other pollutants which may be harmful to aquatic organisms or render the receiving waters unfit for drinking, fishing, or other human uses.

Discharge proportional to streamflow throughout the year provides a constant and relatively high dilution ratio (Table 67). Discharge only during spring runoff would eliminate discharge during much of the year, although the dilution ratio is not as good. Aquatic organisms in the Study Area are most susceptable to stress in the spring (Volume 4-Chapter 1, section 1.4.4.4). Constant discharge leads to a varying dilution ratio which is especially poor during periods of low streamflow (Table 67). Although of short duration, these low dilution periods can have significant effects on aquatic communities. If harmful levels are reached during 7-day 2-year low flows, aquatic communities probably will not be able to recover completely before the next such period, and will show the effects of the recurring stress at least for the life of the operation (Volume 4-Chapter 1, section 1.4.4.4). Any discharge would have to meet Minnesota water quality standards.

Table 67

Table 67. Dilution of mine/mill discharges and effect of discharges on streamflow; 20×10^6 mtpy mine/mill with storage; tailing basin on semipermeable base. Example showing use of Figures 49, 50, and 51.

Discharge Mode	Streamflow Parameter	Units	Dunka River Flow at D-1 ($A=49.4$ mi^2)	Average Year Discharge	Flow+ Discharge	Dilution Ratio (B/C)	% Increase in Flow
Proportional to Flow	Average Annual Yield[b]	acre-feet	28,300	2,800	31,100	.09	10
With Spring Runoff	April & May Flow[c]	acre-feet	11,700	2,800	14,500	.19	24
Constant Rate	7-day, 2-yr low flow[d]	cfs	3.53	3.87	7.40	.52	110

[a] See Table 61.

[b] Siegel and Ericson (1979).

[c] Calculated as 41.5% of annual flow from Siegel and Ericson (1979).

[d] Brooks and White (1978).

Models of the quality of mine site runoff suggest that runoff from waste rock and lean ore stockpiles and mine dewatering discharges will require collection and treatment (section 4.7). If the mine site is adjacent to the mill, using this water for milling is a cost-effective technique to reduce low quality discharge during the operational phase (section 4.4). These two sources yield about 2,000 acre-feet/year in an average year. This would reduce direct appropriation needs from 3,200 acre-feet/year to 1,200 acre-feet/year on the average (Table 47) and leave only relatively clean sources of site runoff (section 4.4).

4.5.4.2 Smelter/Refinery System. Water use in the 100,000 mtpy smelter/refinery models is largely nonconsumptive. The rate of appropriation and discharge depends greatly on the extent of internal recycling of process and cooling water (Table 68). With maximum recycling, one-third of the total appropriation is consumed, and the rest discharged, with minimum recycling, which uses once-through cooling, only one percent of the water appropriated is consumed. Appropriation needs would be 7.3 cfs using maximum recycling of 104.8 cfs using minimum recycling.

Table 68

Once-through cooling is not considered to be a viable water management option for a smelter/refinery in Minnesota, because applicable thermal discharge standards could not be met. Consequently, it is not discussed in detail in this analysis.

The models assume that water needs will be met by appropriation, since the smelter/refinery requires water low in particulates and dissolved ions (section 4.4).

Table 68. Appropriations and discharges for the model smelter/refinery of 100,000 mtpy capacity.

ITEM	MAXIMUM RECYCLING		MINIMUM RECYCLING	
	ac ft/yr	cfs	ac ft/yr	cfs
Process make-up[a]	1,070	1.50	7,050	9.8
Process losses[b]	770	1.05	770	1.05
Process discharge	310	.43	6,290	8.69
Cooling make-up[a]	4,200	5.80	68,800	95
Cooling losses[b]	980	1.34	0	0
Cooling discharge	3,230	4.46	68,800	95

SOURCE: Section 4.4.

Numbers may not balance due to independent rounding.

[a] Total need.
[b] Consumptive use.

The water requirements for the smelter/refinery are constant, but the availability of water from streams and lakes in the Study Area varies from year to year. If storage is not provided, a given stream will be a suitable source only if it can meet the make-up need under dry conditions. If storage is provided, average streamflow conditions can be used in assessing suitability.

Smelter/Refinery Without Storage--Streams which drain about 200 mi^2 or more would be able to meet the combined process and cooling water needs for a smelter/refinery with maximum internal recycling even during the 30-day, 20-year low flow (Figure 52). The decrease in flow due to such an appropriation would be moderate to high in streams draining less than about 2,000 mi^2. All Study Area watersheds are less than 2,000 mi^2. Lakes with watersheds of several hundred square miles could probably provide sufficient water.

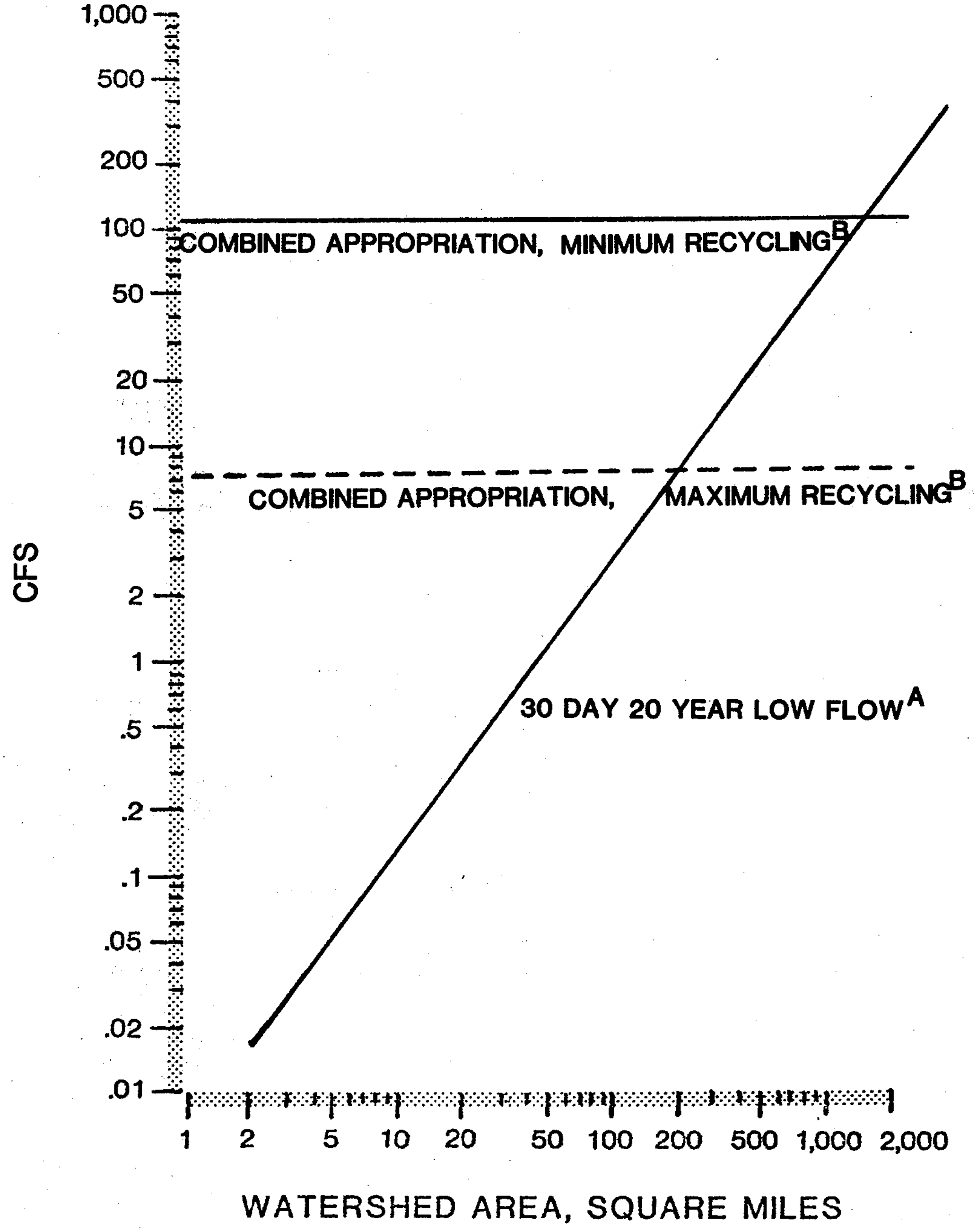
Figure 52

No single stream in the Study Area could meet the demand for the model smelter/refinery with minimum internal recycling during the 30-day 20-year low flow (Figure 52). The combined process and cooling draft rate exceeds the combined 30-day 20-year low flows of the three largest rivers, the Kawishiwi, Isabella, and St. Louis (Table 7). A minimum recycling smelter/refinery without storage is probably not a practical option in the Study Area, even if it could meet thermal discharge standards.

Smelter/Refinery With Storage--If storage is provided, the drainage area required to meet the maximum recycling smelter/refinery water needs using appropriation proportional to flow is reduced to 10 to 15 mi^2 (Figure 53). The water demands

FIGURE 52

APPROPRIATION DURING DRY PERIODS FOR THE SMELTER/REFINERY WITHOUT STORAGE



A. BROOKS AND WHITE, 1978

B. TABLE 68

for the model with minimum recycling would require the entire annual stream flow from a drainage area of 150 mi^2, using appropriation proportional to flow.

Figure 53

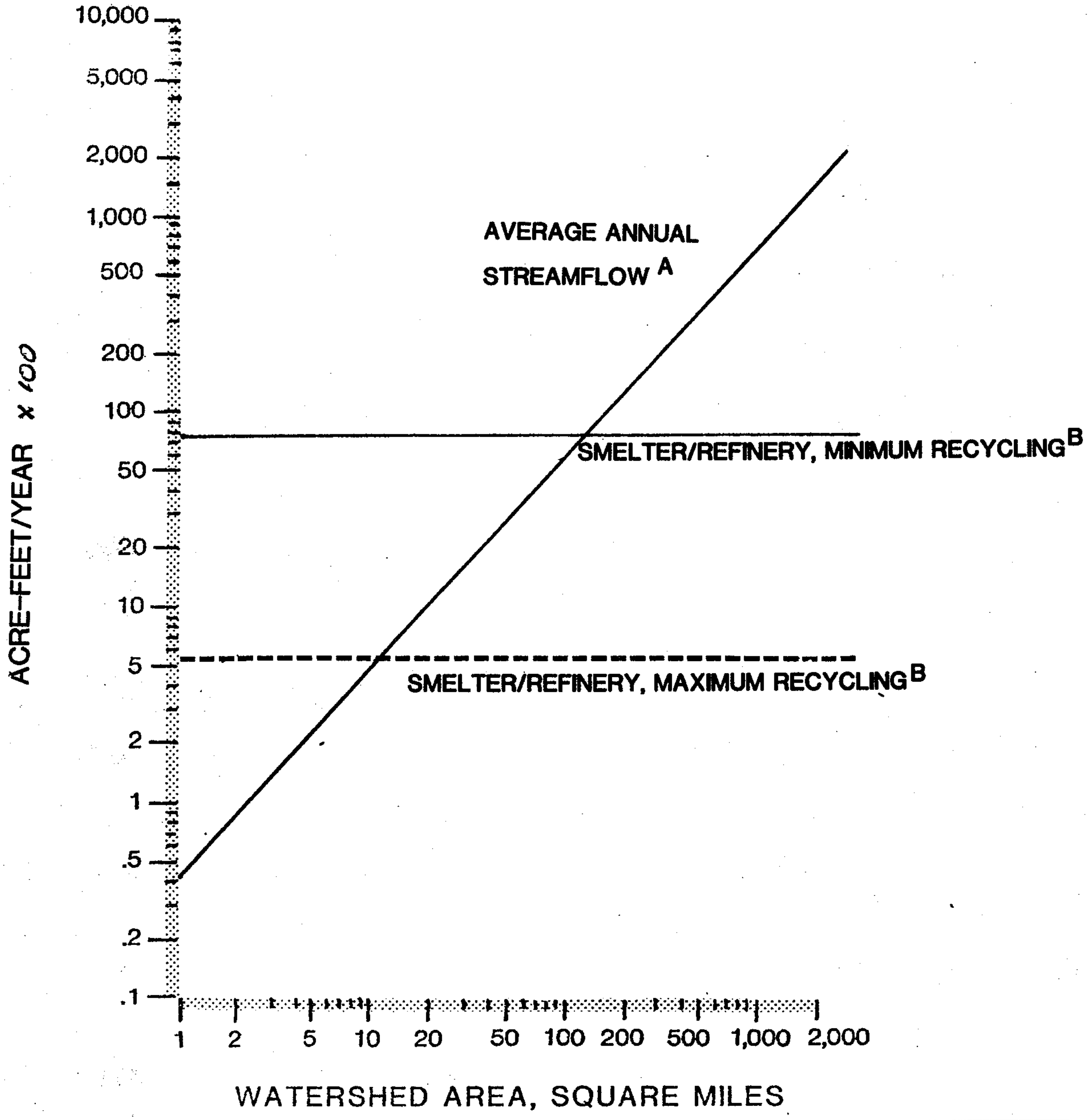
Several design options could be used to meet the appropriation need of the maximum recycling model. One alternative would be to use an existing lake as a storage reservior. Lakes having drainage areas of less than about 200 to 300 mi^2 have 30-day 20-year low inflows smaller than the model draft rate, based on analogy with streamflows. Since lake evaporation and seepage to groundwater further reduce the total amount of water available in storage, an even larger watershed area would be required to assure that the net inflow rate to the lake always exceeded the draft rate. If discharge water is not returned to the lake, fluctuations in lake levels would be induced for lakes with watershed areas less than several hundred square miles.

Another option would be to construct an on-channel reservoir located to collect the flow of a 10 to 15 mi^2 area. A third alternative would be to provide an off-channel reservoir and fill it by appropriation from a large stream or lake. Whether the reservoir was located on-channel or off-channel, the extent of impact on streamflow would be governed by the relative timing of appropriation and discharge.

Smelter/refinery discharge would normally occur at approximately a constant rate. Appropriation proportional to flow coupled with constant discharge would have the net effect of increasing base flows and decreasing peak flows (Figure 54). In a 15 mi^2 watershed, the spring flow would be substantially reduced, while winter

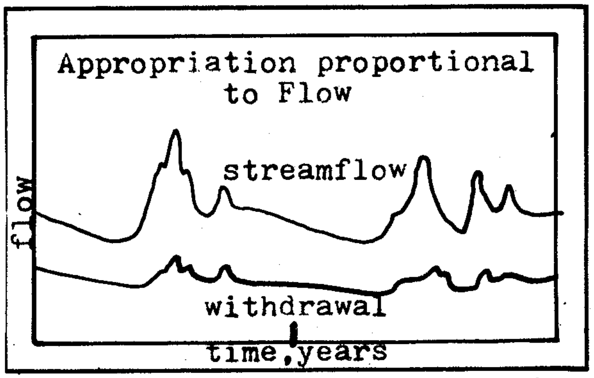
FIGURE 53

APPROPRIATION PROPORTIONAL TO FLOW FOR SMELTER/REFINERY WITH STORAGE



A. FROM SIEGEL AND ERICSON, 1979

B. TABLE 68



flows would be doubled. These changes in flow patterns could eliminate spawning areas, change the stream morphology, create open water in areas previously frozen over, or have other effects on the stream system. For streams in watersheds over 100 to 150 mi^2, effects on flow and consequent impacts would probably be small.

Figure 54

Using holding ponds, discharge could be timed to follow the same patterns as appropriation. For appropriation and discharge proportional to flow, consumptive use would decrease streamflow by less than 5 percent for watersheds over about 70 mi^2.

Dilution of discharge from the smelter/refinery would vary depending on the management of discharges and time of the year, as for the mine/mill. Figure 55 shows how the dilution ratio would vary over a year using appropriation proportional to flow and constant discharge.

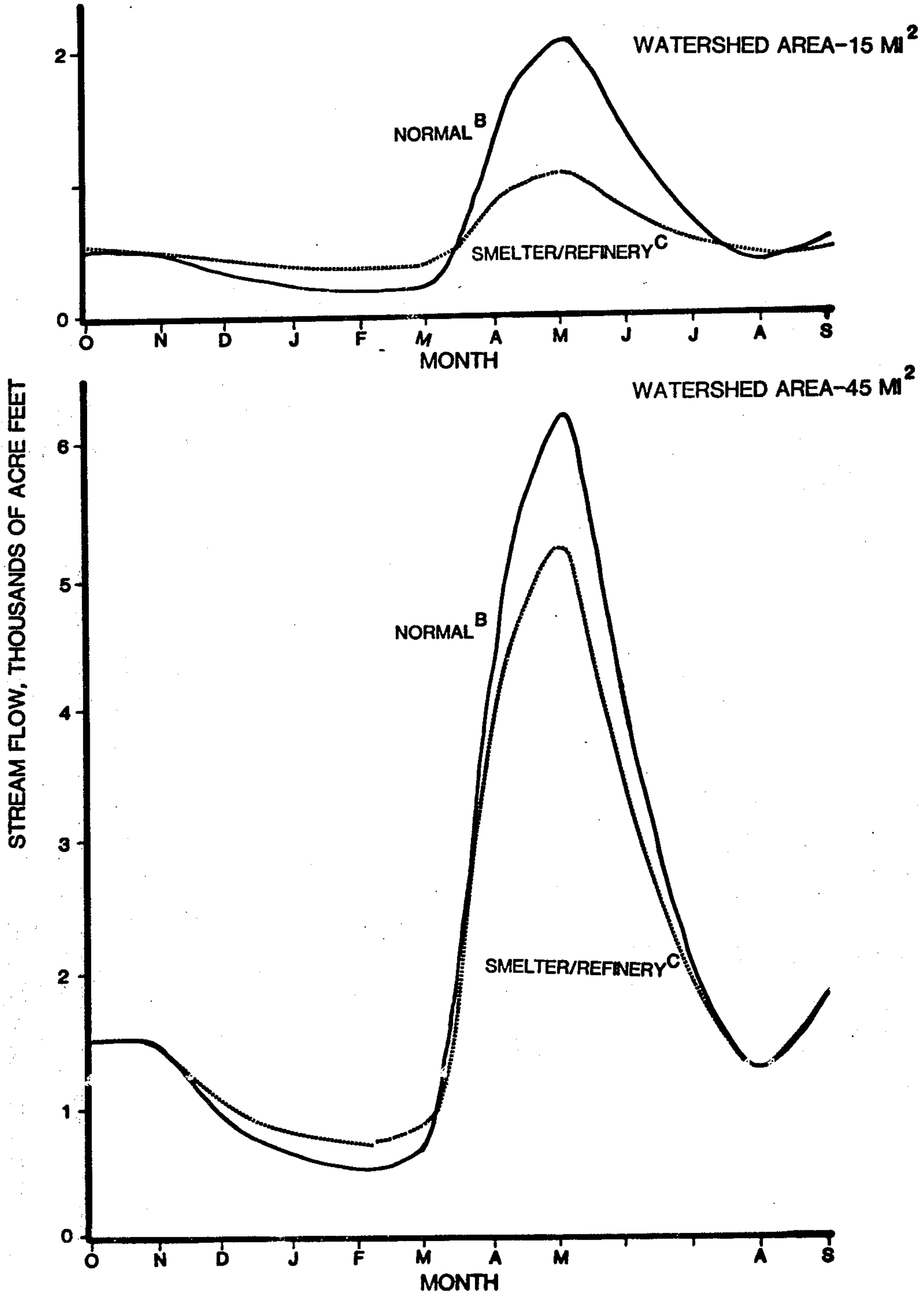
Figure 55

With maximum internal recycling, smelter/refinery consumes 570 million gallons annually. This is about one tenth as large as consumptive use by Erie Mining Company's taconite processing plant, but larger than any other consumptive use in the area.

Summary of Streamflow Impacts During Operation Phase--Figure 56 and 57 summarize the impacts of the appropriations and discharges on streamflow. The probability of a large change in the key streamflow parameter is indicated for each model. The probabilities are qualitative assessments made by Copper-Nickel Study staff.

FIGURE 54

EFFECT OF SMELTER/REFINERY ON AVERAGE STREAMFLOW PATTERN^{A}



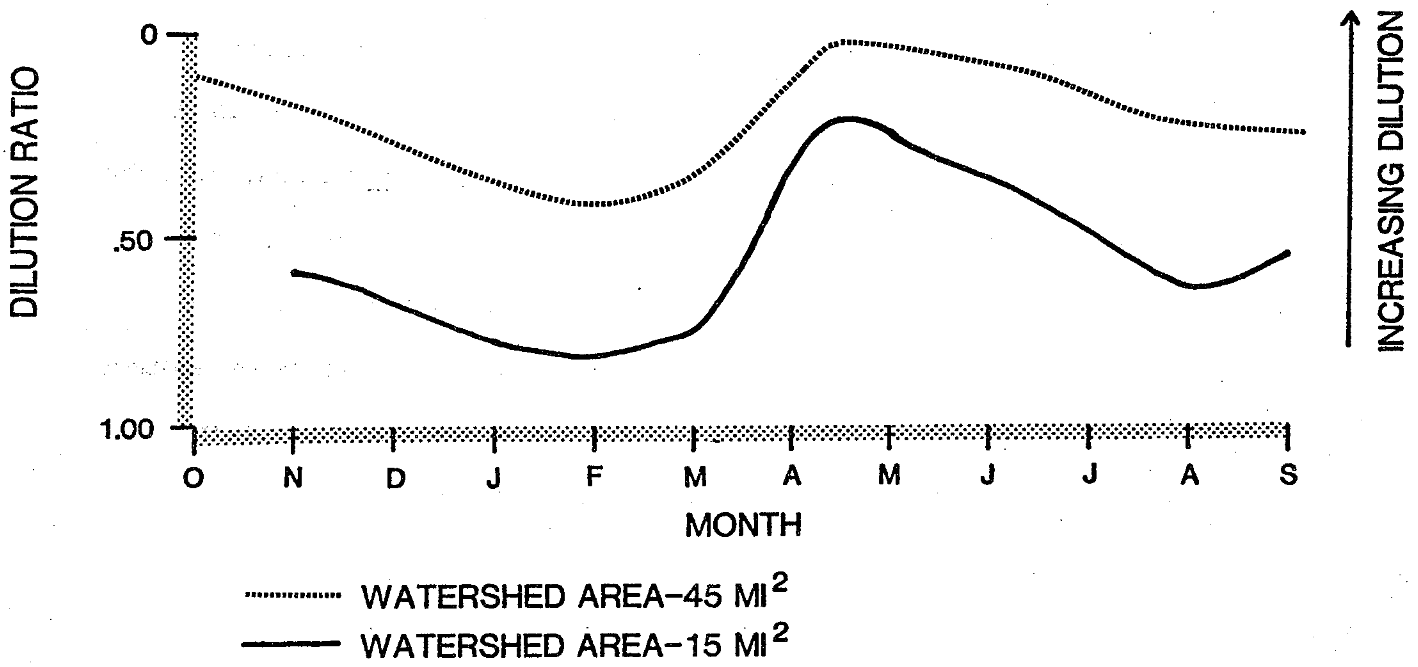
A. CALCULATED FROM SIEGEL AND ERICSON 1979

B. HONETSCHLAGER AND HEWITT, 1979 N, 1979

C. CALCULATIONS ASSUME APPROPRIATION PROPORTIONAL TO FLOW AND CONSTANT RATE DISCHARGE: MAXIMUM RECYCLING IS USED

FIGURE 55

DILUTION RATIO OF SMELTER/REFINERY DISCHARGE PER MONTH [A,B]



A. CALCULATED FROM SIEGEL AND ERICSON, 1979

B. CALCULATIONS ASSUME APPROPRIATION PROPORTIONAL TO FLOW AND DISCHARGE; MAXIMUM RECYCLING IS USED

The models with storage which use appropriation or discharge proportional to flow appear to have the least likelihood of causing large changes in streamflow.

Figures 56 and 57

4.5.5 Model Results--Post-Operational Phase

The abandoned mine site will not have the same hydrologic behavior as the pre-mining undisturbed watershed. The two principal changes will be runoff of degraded quality and different patterns of annual outflow, timing of flow and proportions of surface runoff, interflow and baseflow.

Post-operational impacts on hydrology will depend on the nature and size of the disturbed area, residual effects of the operational phase, and the extent and type of reclamation. Table 69 summarizes the expected hydrologic behavior of unreclaimed mined land compared with the behavior of undisturbed areas. The net hydrologic impact is difficult to determine, since: a) the behavior of any mining element listed in Table 69 will depend on its size and on site characteristics; b) the effects of one element may offset the effects of another element; and c) the elements may be in different watersheds. The following discussion is based on section 4.4 and Honetschlager and Hewett (1979).

Table 69

For an open pit mine and mill in the same watershed, the total annual runoff after abandonment is likely to decrease. Although total runoff from the stock-piles and plant site is higher than from undisturbed watersheds, the open pit mine contributes no runoff, and in fact may capture local groundwater flow. The

FIGURE 5b Probability of large change in Stream Flow due to appropriation

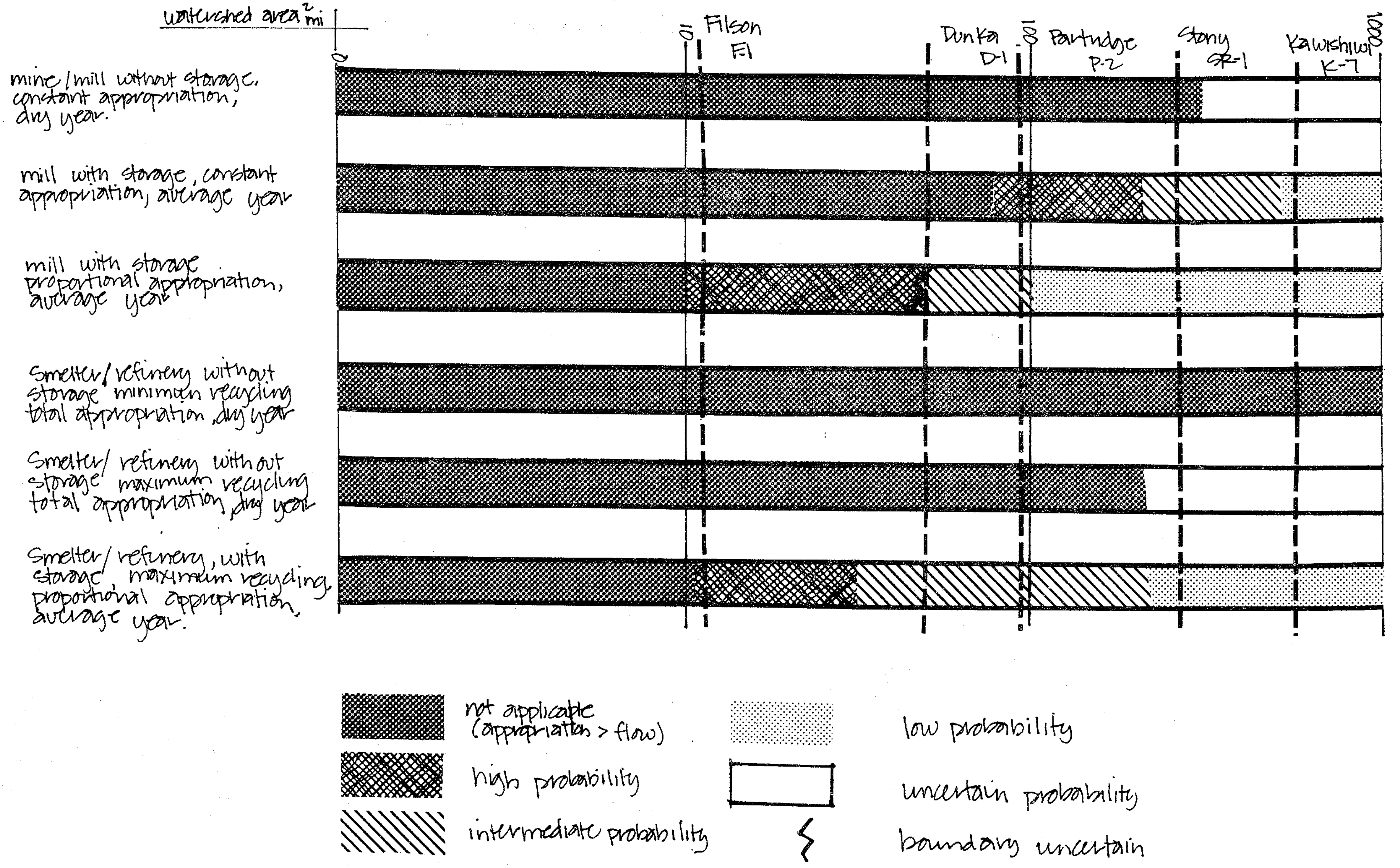


FIGURE 57 Probability of Large change in Stream Flow due to discharge.

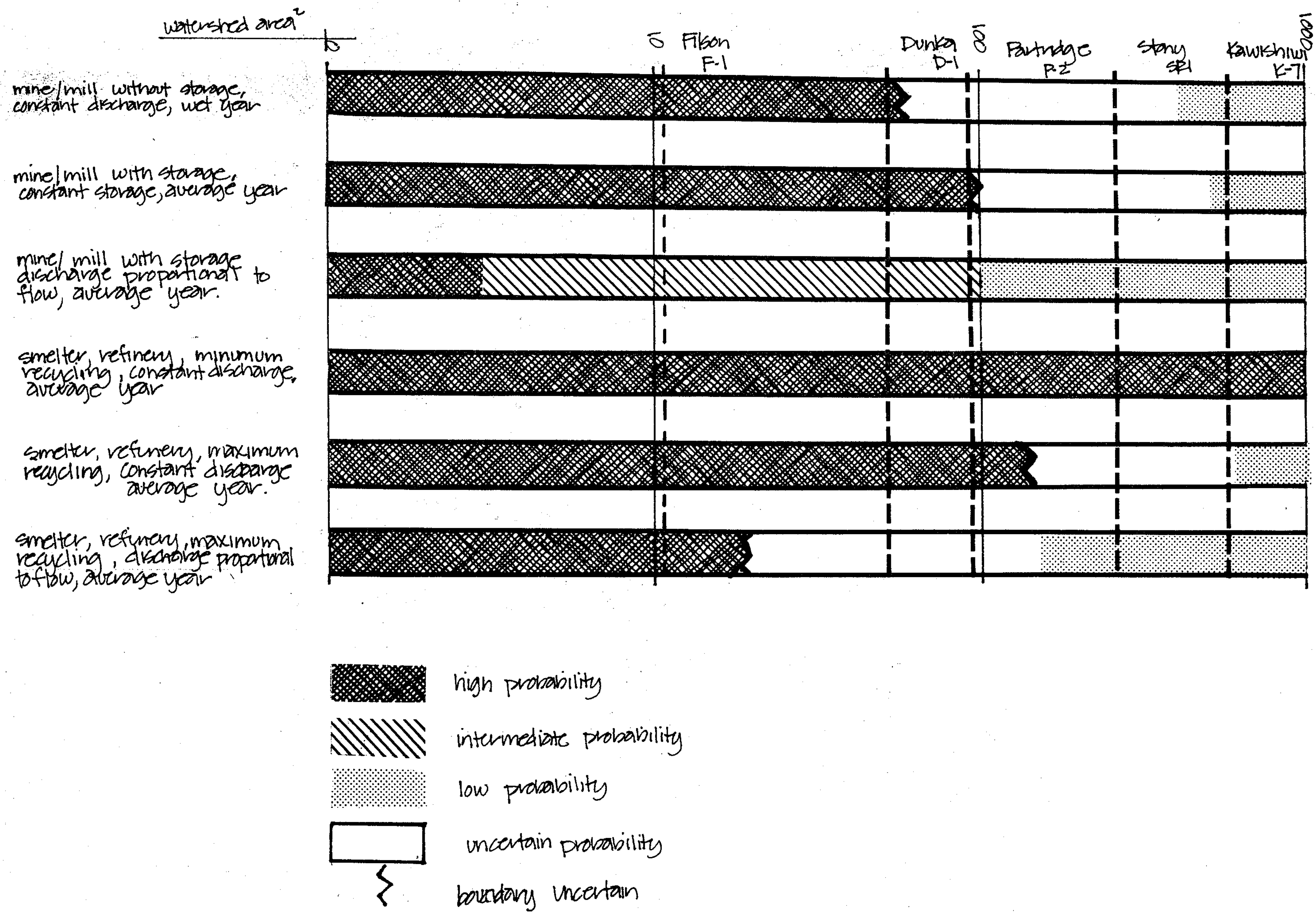


Table 69. Estimated hydrologic behavior of unreclaimed mined land compared with behavior of undisturbed areas in northern Minnesota.

Element	Average Annual Runoff	Surface Runoff	Interflow	Baseflow	Rate of Runoff
Open Pit	Output is approximately zero until filled. The pit is likely to capture groundwater flow from nearby areas	reduced to zero	reduced to zero	Possibly minor seepage to groundwater through bedrock	not applicable
Overburden piles	probably similar	?	?	?	?
Waste rock & lean ore piles	increased	reduced to zero	increased	Groundwater storage within piles may be substantial, especially if they block natural drainage ways. Baseflows may be higher than from natural areas.	slower
Undisturbed watershed area	same	same	same	same	same
Plant site	increased	increased	reduced to zero	reduced to zero	faster
Tailing Basin	Depends on tailing infiltration rates and extent of ponding	Depends on final contouring and on tailing infiltration rates.	Water which infiltrates emerges through tailing dams (interflow or baseflow) or through the basin floor (baseflow). Division between the two depends on the permeability of the material underlying the basin and of the tailing dams, and on layering within the tailings.		Depends on division between surface runoff, dam seepage, and flow seepage.
Smelter/ Refinery Site	increased	increased	reduced to zero	reduced to zero	faster
Slag Piles	?	?	?	?	?

SOURCE: Section 4.4.

open pit and stockpiles contribute no surface runoff, but this may be more than offset if the tailing basin is recontoured to allow surface runoff. Baseflows could increase if seepage from stockpiles and tailing basin is high, but if the mine site occupies the site of a former bog or lake, flow would probably decrease.

The underground mine and related development would have a lesser effect, since they occupy less space. Average annual runoff from the site may increase, since the high plant site runoff and stockpile runoff are not offset by an open pit. Changes in annual yield, surface runoff, and baseflow would depend primarily on the tailing basin, since the stockpiles associated with underground mining are small in area.

Recontouring and revegetation may help restore the disturbed area to more nearly natural hydrologic behavior (see Volume 2-Chapter 2).

The effects of the disturbed area on streamflow would be progressively less perceptible moving downstream from the site. Considering the natural variations in streamflow in the Study Area, changes in the hydrologic behavior of the minesite probably would not be significant beyond a point when the ratio of undisturbed area is about 10 to 1.

The quality of runoff from the abandoned site could be a serious problem. Levels of both dissolved solids and suspended sediments may be elevated (sections 4.6 and 4.7). Dilution would vary depending on streamflows at the point of interest. Post-operational water quality impacts are discussed in sections 4.6 and 4.7.

4.5.6 Water Supply in Copper-Nickel Development Zones

4.5.6.1 General Discussion. The seven development zones have different limitations for water use (Table 70). The adequacy and availability of water supply for copper-nickel development have been determined for each zone.

Table 70

The development models used in this analysis are the 20 X 10^6 mtpy open pit model (maximum recycling, tailing basin on semipermeable base) and the 100,000 mtpy capacity smelter/refinery (maximum recycling). Water needs for the models are from Tables 61 and 68. Stream flow values have been determined by equations listed in Table 7. The criteria for assessing water adequacy are: for cases without storage, the 30-day 20-year low flow is compared to appropriation needs during the 100-year dry year and, for cases with storage, either the average annual flow or the average low flow is compared to average year appropriation needs. (It is assumed stored water will be used during dry years.)

For this analysis, water source is considered adequate if the specified flow exceeds the appropriation need, as calculated in Table 71. Extreme flow reduction would occur in some cases. These may not be allowed under present regulations. Cases of small flow reduction (5 percent or less) are circled on Table 71.

Table 71

The smelter/refinery total appropriation need is the largest water requirement in Table 70. Only three zones have an adequate water supply for this operation if

Table 70. Adequacy[a] of water source for copper-nickel operations by development zone.

	ZONE						
	1	2	3	4	5	6	7
Adequate[a] water source for mine/mill or mill only without storage in dry year	X	X	X	O	O	O	O
Natural storage available	O	X	X	O	O	O	O
Adequate[a] water source for mill only with storage-constant appropriation during average year	X	X	X	O	?	X	X
Adequate[a] water source for mill only with storage-proportional appropriation during average year	X	X	X	X	X	X	X
Adequate[a] water source for mine/mill with storage in average year	X	X	X	X	X	X	X
Adequate[a] water source for smelter/refinery (total appropriation need) with maximum recycling and without storage in dry year	X	X	X	O	O	O	O
Adequate water source for smelter/refinery (consumptive use only) with maximum recycling and with storage-constant appropriation during average year	X	X	X	O	?	X	X
Adequate water source for smelter/refinery (consumptive use only) with maximum recycling and with storage-appropriation proportional to flow during average year	X	X	X	X	X	X	X
Lack of conflict with current municipal water users[b]	X	X	X	X	O	O	X
Lack of conflict with current industrial water users[b]	X	X	X	X	O	O	X

[a] "Adequate" water source is one that can meet the appropriation need; however, extreme flow reduction may result. See development zone discussion in text for magnitude of flow reduction.

[b] Lack of conflict with recreational water users has not be considered.

X = yes; O = no; ? = unknown because of lack of streamflow data.

Table 71. Water source by development zone--adequacy for copper-nickel operations (volumes in cfs).

			Zone 1			Zone 2[a]						Zone 3[b]		
Case	Approp. Need	Flow Param.	K-7 Flow 569	Flow-Approp.	% Reduction in Flow	SR-1 Flow 244	Flow-Approp.	% Change	Birch Lake Flow	Flow-Approp.	% Reduction in Flow	D-1 Flow 49.4	Flow-Approp.	% Reduction in Flow
M/M or M w/out storage-dry yr	11.6-11.9	30d[d], 20yr	28.00	16.1-16.4	41-43	10.06	—	—	55.7[f]	43.8-46.8	21	1.46	—	—
M w/storage-constant approp.	4.42	7d[d], 2yr	80.66	76.24	⑤	27.28	22.86	16	111[g]	107	④	3.53	—	—
M w/storage-proportional approp.	4.42	ave.[e] annual	450	446	①	193	189	②	601[h]	597	①	39	35	11
S/R max recycling w/o storage, dry yr	7.3	30d[d], 20yr	28.00	20.7	26	10.06	2.8	73	55.7[f]	48.4	13	1.46	—	—
S/R max recycling w/storage-constant approp.	2.4	7d[d], 2yr	80.66	78.3	③	27.28	24.9	9	111[g]	109	②	3.53	1.1	68
S/R max recycling w/storage-prop. approp.	2.4	ave.[e] annual	450	448	①	193	191	①	601[h]	599	0.4	39	37	6
M/M w/storage	No appropriation need in average year													

Table 71 continued.

Case	Approp. Need	Flow Param.	Zone 4			Zone 5[c]			Zone 6			Zone 7		
			D-2 Flow 17.0	Flow-Approp.	% Reduction in Flow	P-7 & P-5 Flow 30.9	Flow-Approp.	% Change	P-2 Flow 96	Flow-Approp.	% Reduction in Flow	SL-2 Flow 99.0	Flow-Approp.	% Reduction in Flow
M/M or M w/out storage-dry yr	11.6-11.9	30d[d], 20yr	.40	—	—	.71	—	—	3.23	—	—	3.17	—	—
M w/storage-constant approp.	4.42	7d[d], 2yr	.90	—	—	1.60	—	—	8.27	3.85	53	8.02	3.60	55
M w/storage-proportional approp.	4.42	ave.[e] annual	13.4	9.0	33	24.4	20.0	18	76	72	6	74	70	6
S/R max recycling w/o storage, dry yr	7.3	30d[a], 20yr	.40	—	—	.71	—	—	3.23	—	—	3.17	—	—
S/R max recycling w/storage-constant approp.	2.4	7d[d], 2yr	.90	—	—	1.60	—	—	8.27	5.9	29	8.02	5.9	30
S/R max recycling w/storage-prop. approp.	2.4	ave.[e] annual	13.4	11.0	18	24.4	22.0	10	76	74	③	74	72	③
M/M w/storage	No appropriation need in average year													

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[a] Zone 2 may also use K-7 flow as source.
[b] Zone 3 may also use SR-1 or Birch Lake flow as source.
[c] Total flow available in Zone 5 would be greater than the combined flows of P-4 and P-5, but less than the P-2 flow.
[d] From Brooks and White (1978).
[e] From Siegel and Ericson (1979).
[f] Driest month of record gaged inflow (Bowers 1977).
[g] Calculated from Bowers (1977).
[h] From Bowers (1977).

Circled numbers indicate flow reductions less than 5 percent.

no storage is used. The mine/mill without storage would also be restricted to the same three zones.

The number of development zones with adequate water increases if storage is available, either natural or man-made, and if the timing of appropriation is varied. If storage is available, the mill or the smelter/refinery could be supplied by water reservoirs in five or six of the zones if constant appropriation were employed, or in all of the zones using appropriation proportional to flow. The combined mine/mill with storage could be located in any of the zones, since it has an excess of water in an average year.

Table 70 also lists possible obstacles to use of water from each zone. Possible conflicts with current appropriations were determined from Table 65. Only two zones (5 and 6) may have conflicts with current municipal and industrial uses. Five zones do not have natural storage.

4.5.6.2 Water Adequacy in Each Zone. The largest source of water in Zone 1 is the South Kawishiwi River. Gabbro Lake, at the mouth of the Isabella River, cannot be used as a water source or storage reservior because it is located within the BWCA. The South Kawishiwi River at K-7 could supply water for all four cases using storage, with small flow reductions (Table 71). At K-7, the 30-day 20-year flows are adequate to supply the two cases without storage, although major flow reductions would occur: 41 to 43 percent for the mine/mill, and 26 percent for the smelter/refinery.

Possible water sources in Zone 2, besides the South Kawishiwi River, are the Stony River at SR-1 and Birch Lake. All cases with storage could be supplied by the Stony River and Birch Lake with only small flow reductions in most cases.

The mine/mill without storage exceeds the 30-day 20-year low flow of the Stony River. The smelter/refinery without storage could be supplied by the Stony River, although a 73 percent reduction in the 30-day 20-year flow would result. Inflow to Birch Lake exceeds the need for both cases without storage; flow reductions would be moderate. Birch Lake could also be used as a natural storage resevoir.

Copper-nickel development in Zone 3 could also use Birch Lake and the Stony River as a water source and Birch Lake as a natural reservior. The Dunka River at D-1 could not supply three cases—both cases without storage and the mill with storage using constant appropriation. A 68 percent flow reduction would occur for the case of the smelter/refinery with storage using constant appropriation. Moderate flow reductions occur with the remaining two cases.

Most of Zone 4 is located in the watershed of the Dunka River, the largest water source in the zone. The Dunka River at D-2 cannot supply the water needs of any case without storage. There are no lakes in Zone 4 that could provide natural storage. If man-made storage were provided, proportional appropriation for the mill or smelter/refinery would be possible; however this appropriation would reduce average annual flows by about 33 percent. The two cases with storage and using constant appropriation could not be supplied at D-2.

Zones 5 and 6 are located in the Partridge River Watershed. The Partridge River flow is not large enough to supply any system without storage. If appropriation is proportional to flow and storage is provided, the mill or the smelter/refinery could be supplied in most cases; for the smelter/refinery in Zone 6, the flow reduction would be small. Zone 5 may be able to supply a mill or the smelter/refinery with storage if constant appropriation is used. A mill with storage using constant appropriation could be supplied in Zone 6, although 53 percent of the low flow at P-2 would be appropriated; a smelter/refinery using storage in Zone 6 would reduce low flows by 27 percent. No natural storage is available in either zone.

Copper-nickel development in Zones 5 and 6 could encounter conflicts with other users of water in the Partridge River Watershed. Erie Mining Company, which appropriates water for its taconite operation, experienced water supply problems during the 1976 drought. The company has proposed building a water storage reservoir to provide drought protection for its present plant and provide storage for possible future expansion (Hickok 1977).

The Village of Hoyt Lakes takes water from the Partridge River for its municipal water supply. A copper-nickel operation which appropriated from the Partridge River would not have priority over municipal water needs if a conflict arose.

The largest water sources in Zone 7 is the St. Louis River. A system without storage could not be supplied by this river at SL-2. Cases using storage could be supplied, but constant appropriation would reduce the low flow by 55 percent for a mill and by 30 percent for a smelter/refinery. Appropriation proportional to flow would cause only a small flow reduction for the smelter/refinery and a moderate reduction for the mill. There is no natural storage in Zone 7.

From a standpoint of water supply, zones 2 and 3 would be the best areas in which to locate a copper-nickel operation. The South Kawishiwi River, Birch Lake, and the Stony River would be adequate water sources, even without storage, and Birch Lake could be used as a natural storage reservoir. Zone 1 also appears to contain adequate water with little flow reduction for cases with storage.

Zones 4, 5 and 6 appear to be the most poorly suited to support copper-nickel development. The small flow of the Dunka River in Zone 4 could restrict development. In Zones 5 and 6, the small flow of the upper Partridge River and competing current water users pose limitations to development.

4.6 WATER QUALITY SOURCE MODELS

The water quality characterization section (4.3) presented evidence which indicates that water quality of some streams in the Study Area is currently affected by taconite mining. In these streams, specific conductance, calcium, magnesium, and total dissolved solids were most affected.

Impacts of copper-nickel development on water quality are expected to be greater than those experienced with taconite development. Historically, the major problem associated with metal sulfide mining has been the production and release of highly contaminated leachates (Hawley 1972, Eisenreich et al. 1976). In general, this leachate tends to be acidic and contains high levels of toxic trace elements. Leaching has been documented in tailing basins, stockpiles, and mines. There is a significant potential for leaching wherever the oxidation of metal sulfides is likely to occur in the presence of water. Elevated levels of toxic metals have been reported to influence aquatic ecosystems (see Volume 4-Chapter 1).

To evaluate potential environmental concerns, the Copper-Nickel Study developed water quality source models for discharges that might occur from copper-nickel development. These models are comprised of four mine elements (mines, stockpiles, tailing basins, and smelter/refinery). Discharges during the operational and post-operational phases are considered. The water quality parameters presented in these models are based upon field and laboratory studies conducted by the USGS, Amax Exploration, Erie Mining Company, and the Regional Copper-Nickel Study.

Although the models presented here are based on actual measurements, the discussions that follow are based on a single conceptual framework. In each case, the development element (mine, stockpile, tailing basin, or smelter) is viewed as a reactor. Within this reactor the water quality of input waters is physically or chemically altered to that of the output water (see Figure 58). The relative importance of the input and reactor components in determining the quality of output waters varies with the models. For example, reactor stage contributions are expected to be greatest in the case of the smelter and lean ore stockpiles.

Figure 58

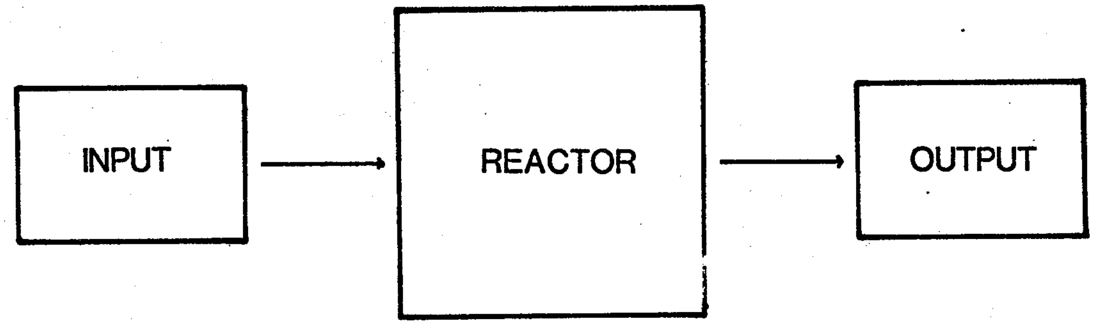
Further details of the theoretical and experimental basis for the conceptual discussions of the models are presented in Eger and Lapakko (1979).

4.6.1 General Discussion of Leaching

Whenever water comes in contact with minerals there is a potential for pH changes and for chemical reactions that will release metals or other chemicals into solution. This potential exists in all phases of mining development. Therefore, a primary concern of environmental analyses of copper-nickel mining was the quality and environmental impacts of the output waters from various development components.

FIGURE 58

CONCEPTUAL FRAMEWORK FOR WATER QUALITY MODELS



PRECIPITATION
    Runoff and Groundwater
APPROPRIATED WATER
RECYCLED WATERS

MINES
STOCKPILES
TAILINGS
SMELTER

DISCHARGE
RUNOFF
SEEPAGE

Leachate production depends on three factors: the water contacting the minerals (the aqueous phase), the minerals themselves (the solid phase), and the reaction environment in which the water and minerals interact. This section discusses these factors in light of theoretical and laboratory findings, and summarizes them in Table 72.

Table 72

The laboratory set-ups are shown schematically in Figure 59.

Figure 59

4.6.1.1 Factors Relating to the Aqueous Phase. The water discussed here may be rainfall, groundwater, mill water, or whatever other liquid is in contact with minerals on the site. For trace metals of special environmental interest, leaching involves two opposing effects: their release into solution and transport to locations where they may adversely affect the environment; and their removal from solution by chemical precipitation. For instance, copper may be released to solution by the dissolution of copper sulfide, but be removed from solution (i.e. the leachate) by precipitation as a non-soluble copper hydroxide or carbonate—depending on aqueous chemical conditions.

Aqueous phase conditions affecting leaching include pH, ionic strength and the presence of dissolved oxygen, or dissolved organics. The pH is a measure of the activity of hydrogen ions in solution, and low pH indicates acidic conditions. Variation in pH can affect mineral dissolution, aqueous phase complexation, oxidation potential, chemical precipitation, and adsorption. Conversely, solid

Table 72. Leaching summary.

Parameter	How Increase in Parameter Affects Trace Metal Concentration in Leachate
pH	decrease
Temperature	increase
Dissolved Oxygen	increase
Stockpile Composition (i.e. sulfide content)	increase
Alkalinity	decrease
Organic Ligands	increase
Ionic Strength of Solution	increase
Surface Area	increase
Rainfall	increase

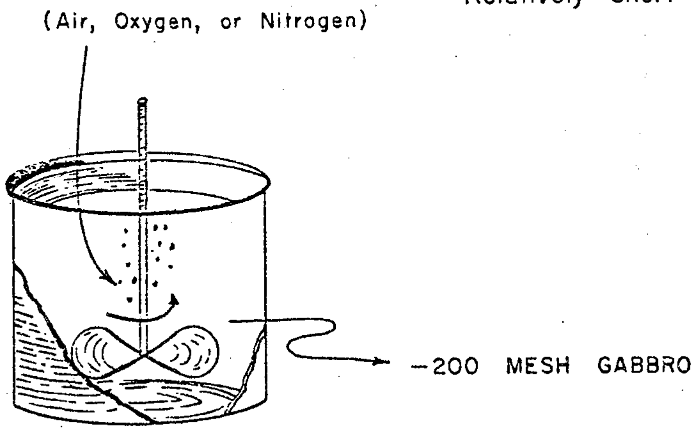
Figure 59

LABORATORY TESTS

1. BATCH REACTOR

Well mixed system, provides maximum contact between solution and rock particals.

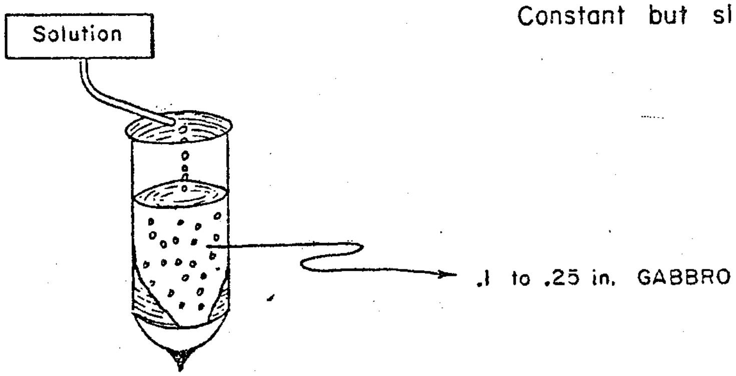
Relatively short term experiments < 1000 hours.



2. COLUMN

Long term, total time : 250 days

Constant but slow, solution addition



phase dissolution may increase or decrease pH, depending on the minerals that are present.

Acidic conditions will increase the solubility of metal hydroxides and carbonate minerals, thus retaining higher concentrations in solution. Since leaching involves the net effect of dissolution (release) and precipitation (removal), a reduction in pH may be expected to lower water quality (i.e. higher metal concentrations).

Low pH increases metal sulfide dissolution, as Figure 60 from a batch reactor test shows. The higher sulfate concentrations associated with lower pH indicate that more metal sulfide dissolution and oxidation occurred at the lower pH values.

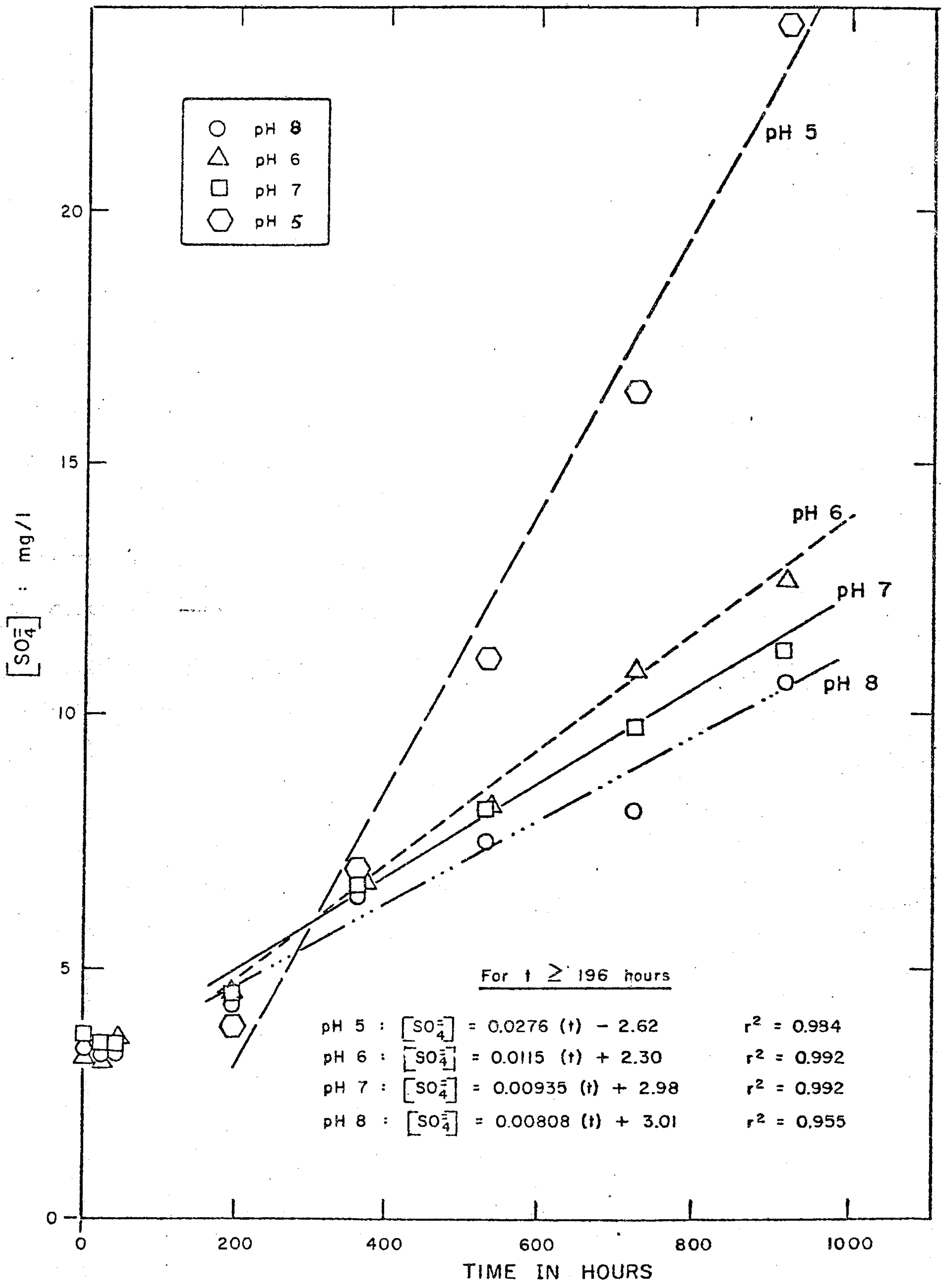
Figure 60

As pH varies, different sulfide minerals behave differently, due to different rates of sulfide dissolution and differing aqueous mobilities of their metal components. For instance, nickel is more mobile than copper because it is less likely to precipitate out of solution once dissolved.

The pH effects on different metals were observed in batch reactor experiments on gabbro. Nickel concentrations rose to levels well over 1,000 ug/l at a pH of 6 (Figure 61). Observed copper concentrations on the other hand, were generally less than 10 ug/l at pH values greater than 6, and only increased significantly as the pH was lowered to less than 6. Therefore, if waters contacting the gabbro are not acidic, nickel leaching will be more predominant than copper leaching. The increasing acidity of the precipitation in the Study Area may tend to

Figure 60

$[SO_4^=]$ VS TIME : EFFECT OF pH



SOURCE: Eger and Lapakko (1979)

increase the relative importance of copper leaching and the release of heavy metals generally, insofar as this acidity is not buffered by the native rock.

Figure 61

Dissolved oxygen concentration also affects leaching. It can directly affect metal sulfide dissolution and indirectly affect silicate mineral dissolution, the latter by enhancing the thermodynamic stability of sulfate over sulfide. Oxygen in solution increases the rate of sulfide oxidation, reduces pH, and enhances silicate dissolution.

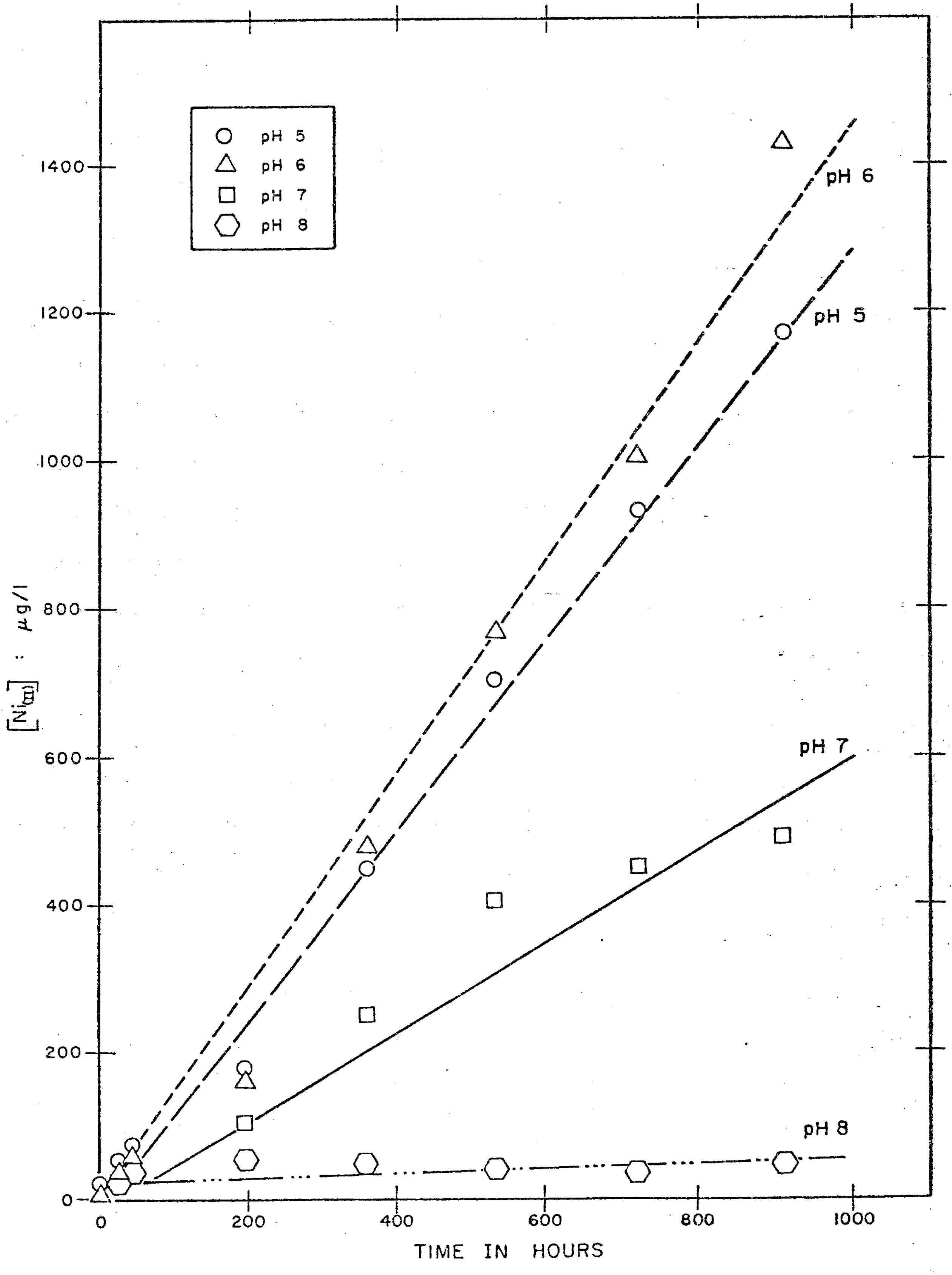
Batch reactor experiments using mineralized gabbro consistently showed that higher dissolved oxygen concentrations yielded solutions of lower pH. Increased concentrations of cations derived from silicate minerals and metals were also observed in waters with more dissolved oxygen. Nickel release was dependent on dissolved oxygen only in the range of 1 to 9.3 mg per liter of dissolved oxygen, whereas copper release varied directly with dissolved oxygen up to 40 mg/l, with a dramatic increase in copper concentration at the maximum level of dissolved oxygen (Eger and Lapakko 1979.)

Increasing <u>ionic strength</u> generally increases solubility, thereby enhancing dissolution reactions and inhibiting the precipitation of metals. Batch reactor experiments illustrated these relationships; the higher the sodium chloride concentrations, the greater the release of calcium. Observed sulfate concentrations increased slightly with increasing ionic strength, suggesting a slight increase in metal sulfide dissolution.

The leaching of nickel as well as calcium was enhanced by increased ionic strength, but copper leaching was not detectably affected. Overall, ionic

Figure 61

EFFECT OF pH ON NICKEL RELEASE



SOURCE: Eger and Lapakko (1979)

strength is a factor of secondary importance.

Organic acids affect leaching, depending on the aqueous chemistry of the organic ligand and the metal being leached. Such acids may enhance leaching or may temporarily bind metals into organometallic complexes and transport them over greater distances than would occur in their absence. Subsequent breakdown of the complexes may release toxic metals into environments far from the source of contamination.

The results of batch reactor leaching experiments using citrate and phthallic acid provide insight into the relative effects of these two organic acids on leaching. Citrate has the greater effect. At pH 7 both nickel and copper concentrations increased with increasing citrate while in the absence of citrate most copper released to solution precipitated. Citrate also enhanced iron mobility. Phthallic acid has a less pronounced effect. Calcium release was slightly enhanced, while metal sulfide dissolution decreased slightly with increasing phthallic acid concentration.

The enhancement of leaching by organic acids may occur if mine components come in contact with surface waters containing them, and may be reduced by siting of stockpiles and other components away from bog waters or by stockpile emplacement on clay pads that isolate the base of the stockpiles from waters rich in organic compounds.

4.6.1.2 Factors Relating to the Solid Phase. These factors include the solids loading, the rock composition, and the particle size of the exposed minerals.

"Solids loading" is the amount of rock surface area available for leaching, expressed as the amount of exposed surface area per unit volume of water. The rock composition pertains primarily to the degree of mineralization of the rock, that is, its percentage composition of sulfide minerals. "Unmineralized" gabbro has lower proportions of sulfide minerals.

The effects of solids loading and rock composition were tested in laboratory batch reactors and leaching columns (Eger and Lapakko 1979), and are summarized here. Actual field data relating leachate water quality to rock composition--specifically of tailings--are discussed in the tailings section (Volume 2-Chapter 3).

In the batch reactor, increased solids loading of unmineralized gabbro raised the pH, which had the expected effect (section 4.6.1.1) of decreasing sulfide-related metal release. Increased loading had the opposite effect with mineralized gabbro. Smaller particles, which have greater available areas for leaching, resulted in lower pHs. Greater nickel release was also noted, apparently due in part to the effect of a greater surface reactive area.

These results are in agreement with theory, which suggests that mineralized gabbro, with its higher proportion of sulfide minerals, results in increased sulfide oxidation and lower pH. The pH effect is related to the iron sulfide oxidation. In unmineralized gabbro the pH increases because silicate dissolution predominates. The worst case leaching situation occurs when there is high sulfide content and high loading, because the possibility of both low pH and high surface availability of trace metals exists.

Column leaching experiments were also performed on mineralized and unmineralized gabbro, but failed to yield the pH effects observed in the batch reactor. Increased sulfide mineralization did not result in significant pH depressions, but did increase metal sulfide dissolution, especially of nickel and cobalt--more so than chemical composition might have suggested. This may relate to surface availability of pentlandite, a mineral in the gabbro containing nickel and cobalt. Copper leaching rates were observed to be less influenced by increased mineralization.

It should be noted that these lab experiments are not totally representative of what might occur in the field. For example, in the batch reactor all available gabbro surface is exposed to leaching. In field situations, the interior of stockpiles may not be entirely exposed to leaching conditions or to water to carry off trace metals. Still the results of batch reactor experiments are useful in understanding the qualitative effects of solids loading.

4.6.1.3. Factors Relating to Reaction Environment. Four factors involving the reaction environment are: temperature, wet-dry cycling, freeze-thaw cycling and length of exposure. Every 10° C temperature increase generally doubles the rates of chemical reaction, so leaching rates will likely vary with temperature. Wet-dry cycling is used in mining for metal recovery from sulfide minerals, and continual exposure of open pits and stockpiles to wet and dry cycling may increase metal release. Freeze-thaw cycles indirectly affect leaching by enhancing mechanical weathering, by exposing new surfaces to chemical reactions. The influence of these three factors on leaching of Duluth gabbro has not yet been investigated in a laboratory situation.

The effects of extended periods of exposure on Duluth gabbro leaching are also not known. Stockpiles observed at the Erie Mining Dunka site are chemically reactive after over ten years, but continued water quality monitoring will be required to determine whether leaching of toxic contaminants will increase, decrease, or remain constant over longer periods.

4.6.2 Mine Water

Mine water is defined as any water discharged from an underground or open pit mine. This section presents water quality models for mines during both operational and post operational phases.

Many site-specific factors influence mine water quality, and cannot be determined with the available data, so additional research and site-specific information is required to improve the accuracy of predictions. Still, it does appear that mine water will be of lower quality than natural surface water in the Study Area.

The quality of mine water is discussed in reference to the schematic presented in Figure 58. The inputs are discussed and chemical reactions and considerations summarized. Detailed information on the chemical reactions and factors affecting them is presented in the leaching section (4.6.1). Additional information describing mining operations is available in the Technical Assessment volume (Volume 2-Chapters 1-5).

4.6.2.1 Conceptual Discussion. The quality of mine waters is dependent upon the quality of water entering the mine and chemical reactions that occur therein. Figure 62 presents a schematic model of mine water flow and the factors affecting water quality. The type and scale of mining operations will also affect the water quality. The mine water discussed here is the water collected and pumped from the sumps, either to be recycled or discharged (see Figure 33 for a schematic of an open pit mine).

Figure 62

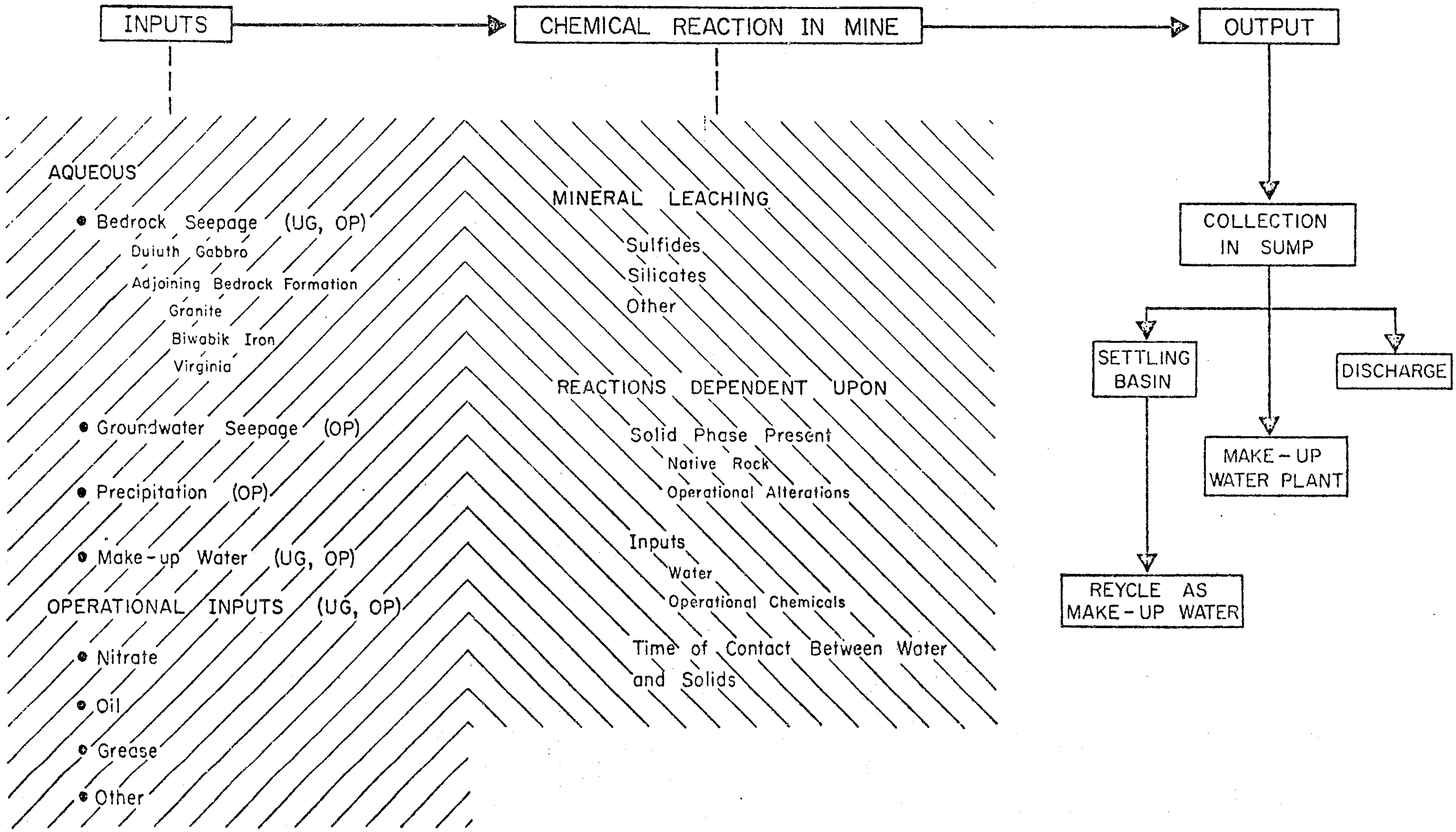
Inputs--Water may enter mines from natural sources such as seepage from bedrock, seepage from surficial materials, and precipitation. Appropriation of make-up water for mining procedures such as drilling and dust suppression may also be required (see Volume 5-Chapters 1-5).

Bedrock Seepage--Aquifers are rock formations containing recoverable quantities of water. Bedrock aquifers occur in joints, fractures, leached zones, and isolated pockets (Siegel and Ericson 1979). There will be little flow unless one or more of these conditions exists. Preliminary mapping of the major fractures and joint systems in the region indicate that fractures are more extensive in the upper 200-300 feet, but some probably extend to considerable depths (Siegel and Ericson 1979). Bedrock aquifers near the ground surface generally are connected to water table aquifers in surficial materials, whereas deeper aquifers are generally unconnected.

Table 73 lists the water bearing characteristics of the various bedrock types. In general, the bedrock water yield in the study area is low, the one exception being the Biwabik Iron Formation, which supplies water for municipal and industrial use. Large quantities of water occur in this formation and the leached zone can provide secondary porosity (through cracks and fissures) as high as 50 percent. Prediction of seepage at a particular location is not possible due to the large variability in secondary porosity. Little is known about the permeability of the Biwabik Iron Formation where it underlies the Duluth gabbro, and it is possible that large quantities of bedrock water may be encountered by

Figure 62

MINE WATER QUALITY : CONCEPTUAL SCHEMATIC



*UG : Underground Mine
OP : Open Pit Mine

mines that intersect it.

Table 73

Pockets of highly mineralized saline water, presumably isolated reservoirs, have been encountered in the AMAX area. Saline water was encountered in two drill holes, and on three separate occasions in the exploration shaft (see section 4.3). Data on the quality of bedrock water, though limited, are summarized in Table 25. Table 26 summarizes data on the saline water encountered in the AMAX area.

Although there are not enough data to perform statistical analysis, it appears that different bedrock units have different major constituents: sodium, chloride, and bicarborate in the Duluth Gabbro; and calcium, magnesium and bicarborate in the others (Siegel and Ericson 1979). Bedrock water has a higher pH and mineral content than the surface water of the area (section 4.3).

The few trace metal analyses of bedrock water available suggest that the concentrations of dissolved copper, nickel, cadium, silver, mercury, and lead are less than a few micrograms/liter (Siegel and Ericson 1979).

Seepage From Surficial Materials—The unconsolidated materials overlying bedrock are usually saturated. They frequently yield more water than does the bedrock, though the availability of water from them varies considerably within the Study Area.

The rate of seepage from surficial materials into an open pit will depend on the thickness of the surrounding soil, its permeability, the cross sectional area of

Table 73. Water bearing characteristics of bedrock units in the Study Area (from Siegel and Ericson 1979).

System	Major Units	Subdivision	Estimated max. thickness	Description	Water Supply and Water Bearing Characteristics
Pre-cambrian	Animikie Group	Duluth Complex	(?)	Largely troctolite	May yield 5-15 gal/min from fractured zones near its upper surface
		Virginia Argillite	2,000±	Thinly bedded, gray to black argilite	May yield up to 30 gal/min from fractured zones near its upper surface. Utilized for numerous domestic supplies.
		Biwabik Iron-Formation	800±	Taconite—dark-colored hard dense iron-bearing silicic rock Ore—black, yellow, or red, soft iron-bearing porous rock.	May yield up to 1,000 gal/min to wells in highly fractured taconite and ore. Utilized for numerous municipal and industrial supplies.
		Pokegama Quartzite	350±	Varicolored vitreous quartize	May yield 5-15 gal/min. from fractured zones near its upper surface.
		Giants Range Granite	(?)	Largely granodiorite	May yield 5-15 gal/min from fractured zones near its upper surface.

flow (exposed area) and the hydraulic gradient. Mines which intersect buried sand and gravel deposits can receive large amounts of water. At Erie Mining Company's Dunka Pit operation, a buried valley yields as much as 500 gpm to the pit; sand and gravel can yield up to 1,000 gpm (Siegel and Ericson 1979).

Groundwater samples collected in the Study Area indicate that, in general, the mean concentrations of major water quality parameters in the till aquifers are significantly higher than in sand and gravel aquifers (section 4.3). Till contains more silt and fine sized material than the sand and gravel deposits, reducing permeability and providing a larger surface area and contact time for chemical reactions. Till samples also contain higher concentrations of dissolved organic carbon which can increase the rate of chemical reactions (Eger and Lapakko 1979).

Trace metal concentrations in surficial aquifers are relatively low, but are nevertheless higher than in the area's surface waters (Tables 20 and 24). In the mineralized zone near the contact, surficial aquifer waters exhibit elevated concentrations of copper and nickel (Figures 22 and 23). Some of the copper values are in the range which could produce biological effects. (A "safe" level of 10 ug/l for copper has been chosen, see Volume 4-Chapter 1, section 1.6.2.2).

In summary, the quantity and quality of groundwater flow into a mine is difficult to predict accurately, but some qualified generalizations can be made. The USGS has divided the region into seven physiographic regions (Figure 11). The major potential for open pit mining is in regions A and C. The USGS predicts that groundwater discharge into open pit mines would be small in region A (shallow bedrock-moraine area) but that significant discharges (up to 1,000 gpm depending on the cross sectional area available for flow) could occur in Region C (The Embarass-Dunka sand plain). It is likely that this water will have copper and nickel levels of 5-20 ug/l (Figure 22 and 23).

Bedrock water is more likely to be encountered in areas which adjoin the Biwabik formation than in either the granite or the Virginia formation. Most of the fractured zones are less than 200-300 feet deep and there are limited data on permeability at greater depths. Bedrock water will likely be high in total dissolved solids, alkalinity, and pH, but low in trace metals.

Make Up Water--In an underground mine, seepage water collected in the shaft would most likely be pumped to a settling basin to remove the fine rock particles. The supernatant would then be recycled to the mine as make-up water for dust suppression or drilling. More make-up water may be needed than is available from bedrock seepage. The quality of the make-up water would initially be determined by its source, while the quality of the recycle water would be a function of the factors discussed in the following sections.

Operational Inputs--Mining operations introduce water contaminants to the mine such as explosive residues (e.g. nitrate, oils), oils from drilling, and vehicle residues (e.g. oil, grease, and trace metals). Blasting and other mining practices may alter the physical nature of the mine walls by producing small particles, thus increasing the available surface area.

It is likely that underground mines would exhibit higher concentrations of operational inputs than open pits. Generally, a higher percentage of the residues would be retained in the enclosed volume, and a smaller volume of water would be available for dilution.

Chemical Reactions in the Mine--The primary chemical process in the mine is leaching, which is discussed in section 4.6.1. Leaching is likely to be more significant in an open pit mine operation than in an underground mine because a greater surface area will be exposed in an open pit. The open pit will also be subject to processes which tend to increase leaching: wet-dry cycles, freeze-thaw cycles, and a continuous supply of precipitation to transport reaction products.

In contrast, an underground mine has a more uniform environment and much less exposed surface area. Parts of the mine may be totally dry, so there would be no water to transport products from the rock surface, except for small amounts absorbed from the air (Smith and Shumate 1971).

To reiterate, it is difficult to predict the quality of mine water beforehand. Uncertainties include the amount of bedrock seepage, the possibility of encountering saline water, and any number of factors relating to the leaching process.

4.6.2.2 Mine Water Quality Models. Although the proceeding qualitative discussion did not yield quantitative mine water quality models, such models are required to assess environmental impacts in section 4.7. Therefore, models have been generated on the basis of analogous mine situations.

Underground Mine Water Quality Model--This model represents the water quality that might be collected in an underground mine. The best available data are from the AMAX copper-nickel exploration project. The specific data used for the model were taken from the AMAX main settling basin in 1977. Most of the water was from the mine, where exploration activities occurred throughout the year. Some test plot runoff was also added to the basin. The model concentrations are shown in

Table 74. Consistent with the conceptual discussion, increases in trace metals, sulfate, and nitrate and ammonia levels were observed. Trace metals and sulfates may be associated with the increased mineralization and solids loading in the mine, while nitrates and ammonia are associated with residues of explosives.

Table 74

Several unexpected occurrences have greatly influenced the AMAX mine water. The first is the previously noted encounter with saline groundwater. The second is a high level of zinc, which may be caused by interaction of saline water with the galvanized mesh installed in the mine to prevent loose rock from falling down the shaft. However, data from the physically discrete AMAX leaching test piles also showed significant zinc release.

Open Pit Mine Water Quality Models--Two open pit water quality models have been developed, based upon two different existing pits. The first gives the "best case" model (i.e. lower concentrations of chemical parameters), and is based upon data from the AMAX exploration site and the Erie Mining Company Dunka Pit (Table 75). (In addition to the water quality model, average concentrations and ranges are shown for different locations at Dunka and AMAX.) Although the Dunka Pit's east wall is in exposed gabbro, it is a taconite operation and has less exposed gabbro than an actual copper-nickel mine would. Water quality at the Dunka Pit is also improved by a large groundwater discharge, which tends to dilute the concentrations of the mine water.

Table 75

Table 74. Underground mine water quality model.

pH	7.9
Alkalinity (mg/l as $CaCO_3$)	44
Specific Conductance (mg/l as Ca)	4700
Sulfate mg/l	59
Chloride mg/l	1575
Copper mg/l	.012
Nickel mg/l	.068
Cobalt mg/l	.003
Zinc mg/l	.034
Nitrate-N mg/l	.31
Ammonia-N mg/l	9.8
Oil mg/l	1
Cadmium ug/l	.28
Lead ug/l	4
Arsenic ug/l	7
Silver ug/l	.25
Chromium ug/l	8.0
Mercury ug/l	.15
Selenium ug/l	1

Table 75. Open pit water quality Model A (better case)—based on Dunka open pit taconite operations and Amax holding basin (in mg/l, except pH).

		Dunka Pit North Pit		
Parameter	Model	average	range	Amax Holding Basin Inflow(a)
pH		7.9	6.9-8.4	
Sulfate	11	274	140-400	11
Copper	0.004	.005	.002-.019(b)	0.004
Nickel	0.060	.009	.002-.009(b)	0.060
Cobalt	0.003			0.003
Zinc	0.058			0.058

[a] Lapakko (1979)

[b] Concentrations after filtration.

The second model, the "worst case," is based upon a U.S. Steel bulk sample site which is a small (100' long x 50' wide x 10' deep) abandoned pit that has filled with rain and surface runoff. Due to its small size, the surface area to volume ratio is much larger than in an operating mine (Eger and Lapakko 1979). Table 76 shows the model concentrations, while Figure 63 (field data collected in 1977) illustrates the ranges of pH, alkalinity, and copper and nickel concentrations that were observed. This water was bioassayed and shown to be extremely toxic (see Lind et al. 1978). Conditions approximating those found in Table 76 could exist at water collecting sumps in open pits.

Table 76, Figure 63

Actual open pit mine water will probably lie somewhere between the two models, unless saline water is encountered, in which case higher dissolved solids concentrations may occur. The saline water data indicate that trace metal concentrations are on the order of a few micrograms per liter (Table 26), but the effect of this type of water on the dissolution of the sulfide minerals in the pit walls is not known.

Open Pit Mine Water Quality/Post Operational Phase--Since precipitation exceeds evaporation in the Study Area, an abandoned pit can eventually fill with water. This water may seep into the regional groundwater system, eventually reaching streams and lakes.

The critical factors in determining the rate at which a pit will fill are the rates of surficial and bedrock water seepage which, as mentioned previously, are difficult to estimate. For the 20 X 10^6 mtpy model open pit, the estimate of

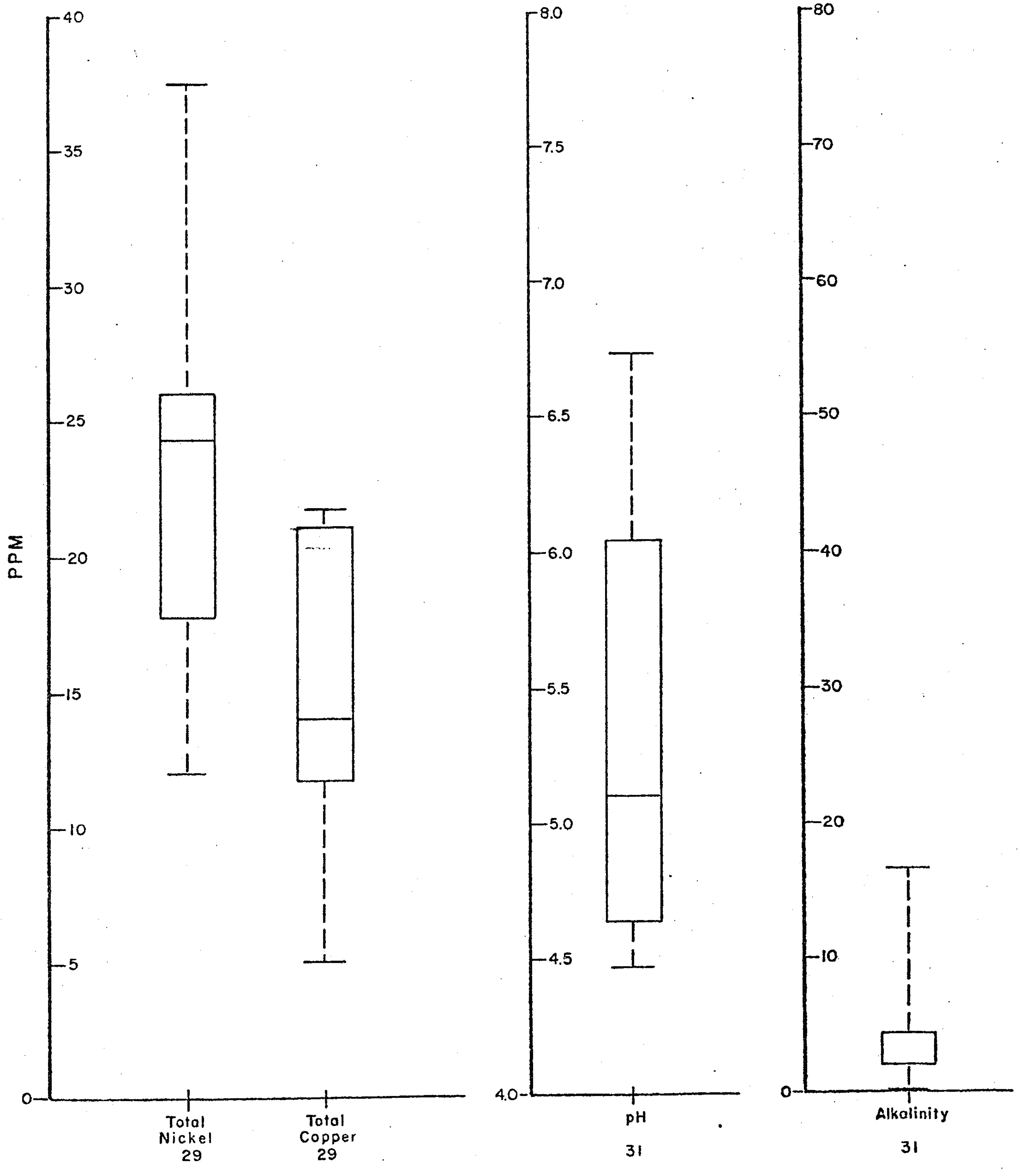
Table 76. Open pit mine water quality Model B (worst case).

Parameter	Concentration (mg/l)
Copper	21
Nickel	25
Cobalt	0.62
Zinc	0.22
Sulfate (SO_4)	438

SOURCE: Based on U.S. Steel pit, Lapakko (1979).

Figure 63

Water Quality Data at the U. S. Steel Site



SOURCE: Eger and Lapakko (1979)

filling time is 300 years, assuming a seepage rate into the pit of 300 gpm (see section 4.4).

The final water quality of an abandoned pit will be a function of the water sources, pit size, the composition of the pit walls and the floor, and the total surface area available for leaching. The total surface area depends upon the degree the pit walls are fractured and allow increased mineral contact with the water.

One method of estimating an ultimate concentration is to assume that all of the metal remaining in the pit walls (to a fixed depth) dissolves and remains in solution (worst case). An example is shown in Table 77, which yields a copper concentration of 2.2 mg/l for a 900-feet deep pit. This this great a concentration could only occur if the pH is less than 5.5. However, the pH will probably be closer to neutral (6-8) if significant amounts of water seep into the pit and/or residual sulfide content in the pit walls is low. On the other hand, acidic precipitation as observed in the Study Area may lower pH in an abandoned pit. This calculation indicates that there may be enough metal left in the pit to cause water quality problems. Even if a neutral pH is maintained in the pit and copper levels are low, nickel concentrations may still exceed toxic levels.

Table 77

4.6.3 Lean Ore and Waste rock Stockpiles

The quality of lean ore and waste rock pile runoff is influenced by many factors. Reactions occurring within such piles will be highly influenced by the physical and chemical nature of the rock itself and by the waters in contact with the rock.

Table 78. Stockpile mass.

Operation	Size (mt/yr)	Mine Life (yr)	Total Stockpile Mass		Estimated Surface Area m^2/ton	Stockpile Grades (%)					
			Lean Ore (mt)	Waste Rock (mt)		Lean Ore			Waste Rock		
						Cu	Ni	S	Cu	Ni	S
Open Pit	20×10^6	25	325×10^6	325×10^6	50–200	.306	.073	.655	.10	.023	.207
Underground	12.35×10^6	23	28.2×10^6 (total)		300–500						
Dunka Pit*		12	6.0×10^6 tons	15.6×10^6 tons	50–200	.28	.08	no data	.050+	.014+	no data

SOURCE: Eger and Lapakko (1979).

*Values are totals for the 12 years of mine operation; stockpile masses are as of January, 1977.

+Average.

puts specific to stockpiles are illustrated schematically in Figure 64. General observations about the leaching process, which is the predominant process here, have been discussed in section 4.6.1.

Figure 64

Inputs--Precipitation is the major input to stockpiles, although stockpiles sited in wetlands could receive basal seepage from surface waters. The chemical composition of regional precipitation is discussed in section 4.3.4. In general, the rainfall in the study area tends to be acidic, with low concentrations of nutrients, cations, anions, and trace metals (Eisenreich et al. 1978).

Reactions Within the Stockpiles--Leaching has been discussed generally in section 4.6.1, but a few points have special relevance to stockpiles.

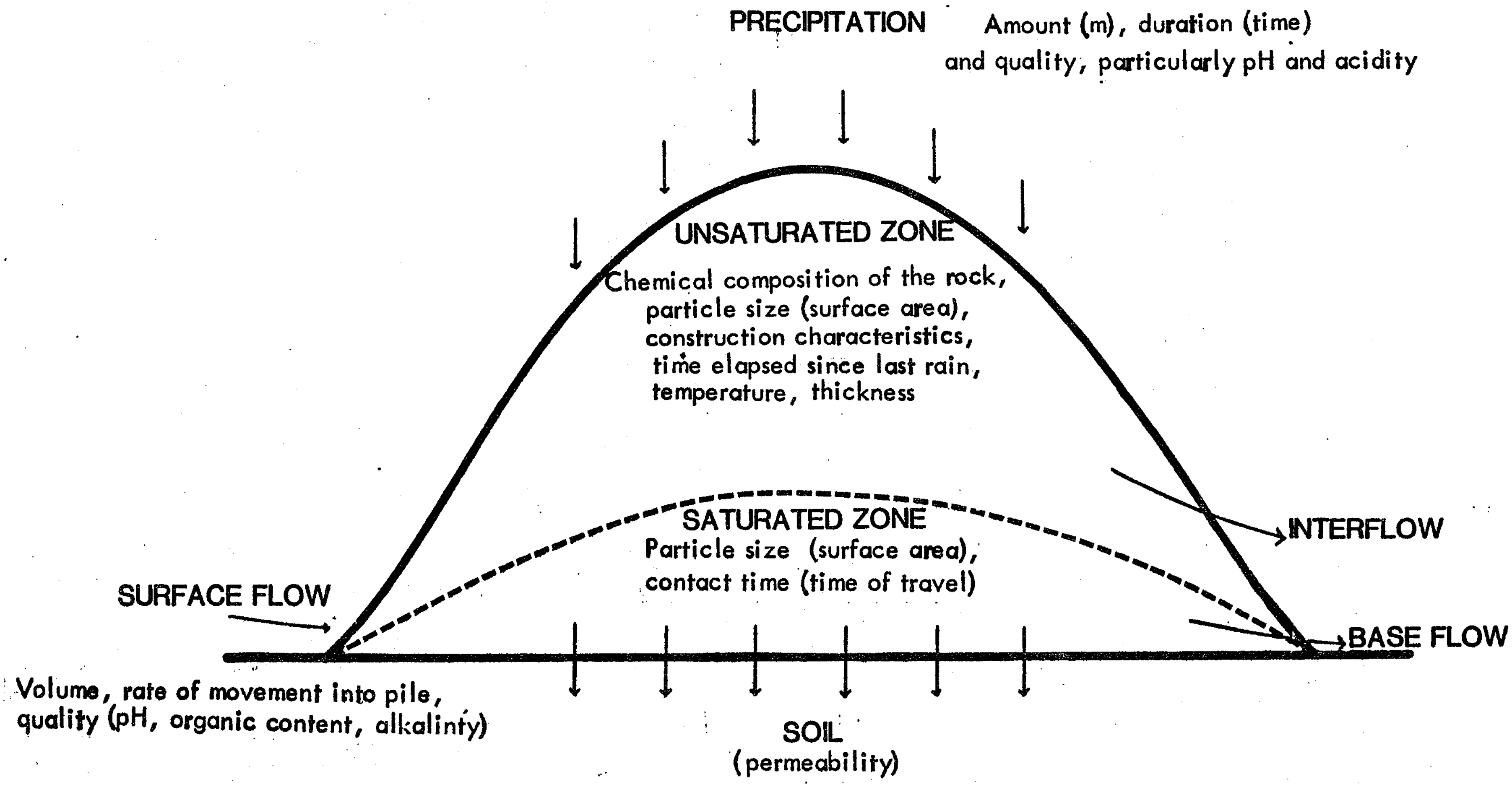
First, the more mineralized the stockpile, the greater its potential for increased acidity upon leaching. Non-mineralized waste rock piles will be of less concern. (It is important to note that a pile low in copper sulfide mineralization may still have a significant amount of iron sulfide mineralization. The relevant consideration is the degree of sulfide, not copper, mineralization.

Second, leachate production per unit mass is expected to be greater from stockpiles derived from underground mines because the particle size of constituent rocks will be smaller and solids loading greater. The surface area per ton for material from an underground mine is about 2.5 times that from an open pit mine.

Third, organic acids can assist leaching by increasing metal mobility, so stockpiles should be isolated from bog waters.

FIGURE 64

FACTORS AFFECTING THE QUALITY OF STOCKPILE RUNOFF



Fourth, reduction of water flow through stockpiles will reduce metal transport, so stockpile design should encourage runoff rather than infiltration.

4.6.3.2 Lean Ore Stockpile and Waste Rock Pile Water Quality Models. The water quality models presented here are based upon actual concentrations measured in the course of field studies of gabbro stockpiles at the Erie Mining Company's Dunka Pit (Table 79). Model I, based on EM-8 (Table 80), is a model of water quality from a wasterock pile. This leachate has relatively low metal concentrations. Model II (Table 80), on the other hand, is based on leachate from a lean ore stockpile. It is a composite of the measured concentrations at seep 1 and seep 3 at the Dunka site, which come from a waste rock and a lean ore pile, respectively. Maximum trace metal concentrations were chosen, to simulate the worst case. Table 80 shows the average readings and the range of readings observed from EM-8 and Seeps 1 and 3.

Tables 79 and 80

A few caveats should be stated. First, leachate production at Dunka is influenced by precipitation, which may not have been "typical" during the study period. Rainfall during the 1976 sampling period was approximately one half of an average year, while the 1977 sampling period rainfall was over 15 percent greater than average.

A second concern is that the "worst case" chosen--Model II--does not necessarily provide an ultimate upper limit for leachate concentrations. The models were based on a relatively short period of observation, and may not be representative of long-term effects. For example, recent data at EM-8 show that metal con-

Table 79. Stockpile size and composition.

	------- Erie - Dunka - Pit -------			Amax			Based on (20X10^6
Site:	EM-8*	Seep 1*	Seep 3*	FL 1	Inco	Models	mtpy open pit)
Mass (tons)	12.2X10^6	.92X10^6	3.0X10^6	1766	not known	325X10^6	325X10^6
Cu (%)	.04$^+$	.03$^+$	.29	.33-.35	.47	.1	.306
Ni (%)	.01$^+$	.01	.08	.075	.15	.023	.073
S(%)	no data$^+$	no data$^+$	no data$^+$	.6	1.08	.207	.655
Classification of material	waste rock	waste rock	lean ore	lean ore	ore	waste rock	lean ore

*These are average compositions for the entire pile. Both stockpiles are only 70% gabbro. If the assumption is made that the iron formation and Virginia formation contain no copper and nickel, then the composition of the gabbro can be calculated:

$$\frac{\text{Overall composition}}{\text{fraction gabbro}} = \text{gabbro cum position}$$

	Cu (%)	Ni (%)
EM-8	.057	.014
Seep 1	.043	.014

$^+$Sulfur to copper ratio is generally on the order of 2-3:1.

SOURCE: Eger and Lapakko (1979).

Table 80. Waste rock pile and lean ore stockpile model leachates, and average concentrations and range of observed values at EM-8 and at Seep 1 and Seep 3 (concentrations in mg/l unless otherwise noted).

Parameter	Model I Waste Rock Pile Model	EM-8		Model II Lean Ore Stockpile Model	Seep 1 and Seep 3	
		Average	Range		Average	Range
DOC	20.9	20.9	11.5-36.3	18.8	18.8	11.6-27.1
Alk as $CaCO_3$	137	137	103-178	79.5	79.5	47.4-114
pH	7.2	7.20	6.50-7.65	6.98	6.98	6.45-7.15
SO_4	1260	1260	708-1680	3620	3620	801-5640
Ni	2.42	1.89	0.580-2.42	39.8	30.6	24.4-39.8
Cu	0.053	0.019	0.010-0.053	1.71	1.09	0.803-1.71
Zn	0.040	0.031	0.018-0.040	2.40	2.10	1.50-2.40
Co	0.021	0.021	0.016-0.029	2.40	1.77	1.00-240
Fe	0.208	0.131	0.084-0.208	7.20	4.73	0.710-7.20
Ca	200	200	64.9-301	346	346	284-388
Mg	123	123	82.0-178	268	268	215-288
Mn	2.85	1.30	0.680-2.85	11.2	9.74	8.41-11.2
Cl	41.3	41.3	2.92-56.5	56.7	56.7	38.5-70.4
SC (mho cm^{-1})	2020			3620		
Cr	not determined			0.123		

SOURCE: Eger and Lapakko (1979).

centrations have increased signficantly: during the period of July, 1976-August, 1977, nickel values ranged from 0.58-2.42 mg/l, compared to nickel values of 4.6-7.1 mg/l during July-September, 1978.

Time variations have also been observed at Erie Mining Seep 3. Average pH values there were 7.2 in 1976, 7.1 in 1977, and 6.7 in 1978. At the present time the cause of the pH reduction is not known.

Six test piles have been established at the AMAX site to ascertain long-term trends of stockpile water quality, as well as the effects of revegetation. Preliminary data for two of the six test piles have shown a trend of decreasing pH (FL-5 and 6). The declining pH can lead to increased metal concentrations. Preliminary results indicate nickel (filtered) concentrations as high as 83 mg/l.

Leachate from Amax test pile FL-5 has been acidic, but the exact cause is not yet known. This pile was covered with overburden, fertilized, and revegetated; the effects of these processes are still being investigated. The pH in Amax test pile FL-6, which received no treatment, has recently begun to decline (Eger et al. 1979).

The Copper-Nickel Study attempted to determine waste rock and lean ore stockpile water quality models using release rates for specific parameters. [This work is described by Eger and Lapakko (1979)elsewhere.] Although the data base did not allow development of discharge models, the laboratory results exhibited the same range of values as the field rates, although they are somewhat higher (Figure 65). Only for sulfate were observed field values greater than the rates measured in the laboratory. Field values are calculated over longer time intervals and over a wider range of environmental variables than most of the laboratory experiments and therfore may better represent actual conditions.

Figure 65

The fact that the laboratory and field rates fall in the same range is significant. The implications are that: a) the gabbro in the field study areas, particularly the Erie stockpiles, does not exhibit anomolous leaching characteristics; and, b) the Erie Mining gabbro stockpiled over 10 years shows similar leaching characteristics to fresh material, so there is no reason to believe that leaching is only a short term problem.

Lean Ore and Wasterock Piles/Post-Operational Phase--In the post-operational phase the mineralized lean ore piles will likely have been processed through the mill. If not, they may constitute leachate sources for several hundred years, according to an approximate calculation by Eger and Lapakko (1979), where all contained metal is assumed to leach at the current rate.

In any case, waste rock piles will remain after mining and may be leachate sources for many years.

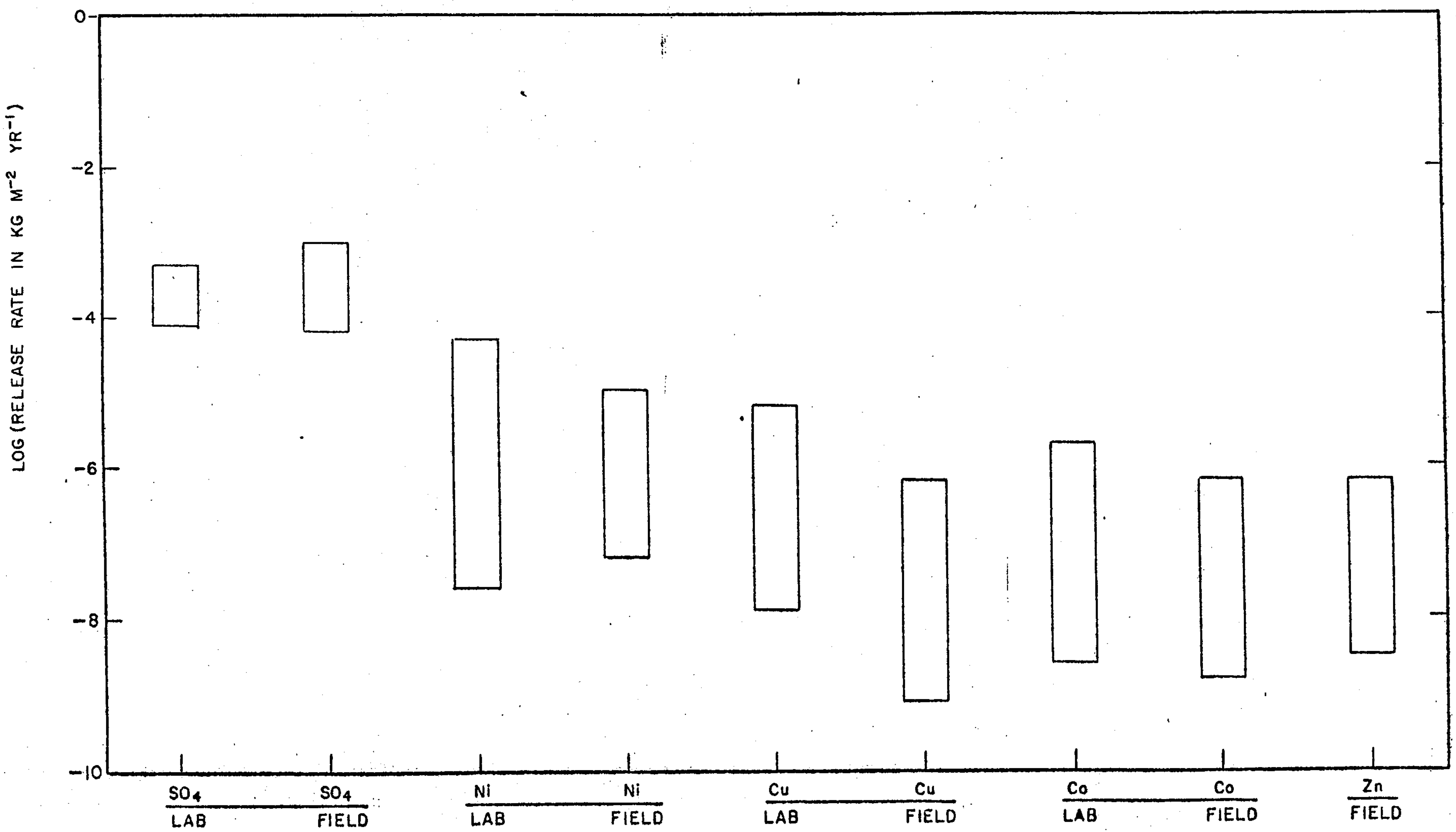
4.6.4 Tailing Basin Water

Tailing basins have historically been sources of water quality problems, particulary in sulfide mining operations (Hawley 1972). Large quantities of unwanted iron sulfides are often present in the tailings providing conditions conducive to the formation of acid leachate containing high concentrations of trace metals. Tailing basins remain as potential sources of pollution after mining operations cease.

Figure 65

LABORATORY AND FIELD RELEASE RATE

(Box indicates observed range of values)



Predictions of water quality from copper-nickel tailing basins are difficult to make, because there are presently no field data on leaching of Duluth gabbro tailings. This section presents three tailing basin water quality models based upon extrapolations. Two models are worst case, in that they assume the tailing basin water will be of no better quality than the runoff collected from the rest of the mining operation. The third model is based on pilot plant studies performed at the University of Minnesota's Mineral Resources Research Center, and is a best case in that it assumes the tailing basin system will improve the quality of water from other parts of the mining operation.

This section also discusses input flows to the basin, reactions within the basin, and seepage modes by which water can leave the basin.

4.6.4.1 Tailing Basin Inputs and Water Quality Models. A schematic diagram of a tailing basin is shown in Figure 35. It is assumed in this section that the tailing basin receives all runoff and stockpile leachate generated on the site (Subsystem A, see section 4.4.1.1). This runoff will be of poor quality in the case of an open pit operation, and uncontrolled discharge could produce environmental problems (Lind et al. 1978). It all runoff is collected and channeled to the tailing basin, it can be used as makeup water and be neutralized by chemical processes in the basin and at the mill. Runoff is not usually directly collected at most of Minneosta's taconite operations. Specific runoff components that would be collected at a Minnesota copper-nickel mine will depend on the water management plan for that operation.

Another assumption about the mine configuration is that a closed system operation is used, as recommended by Kealy et al. (1974) (Figure 66). In closed system operation, water is recycled from the tailing basin to the mill complex. The tailing basin acts as a reservoir and settling basin. In accord with this closed system concept, the tailing basin and mill are discussed jointly as the tailing basin-mill system.

Figure 66

Figure 66 indicates there are three "inputs" to the tailing basin: net precipitation directly on the basin; water from the mill; and, collected runoff from "subsystem A," which consists of the plant site, stockpiles, undisturbed watershed, and mines (including mine dewatering) (section 4.4.1.1).

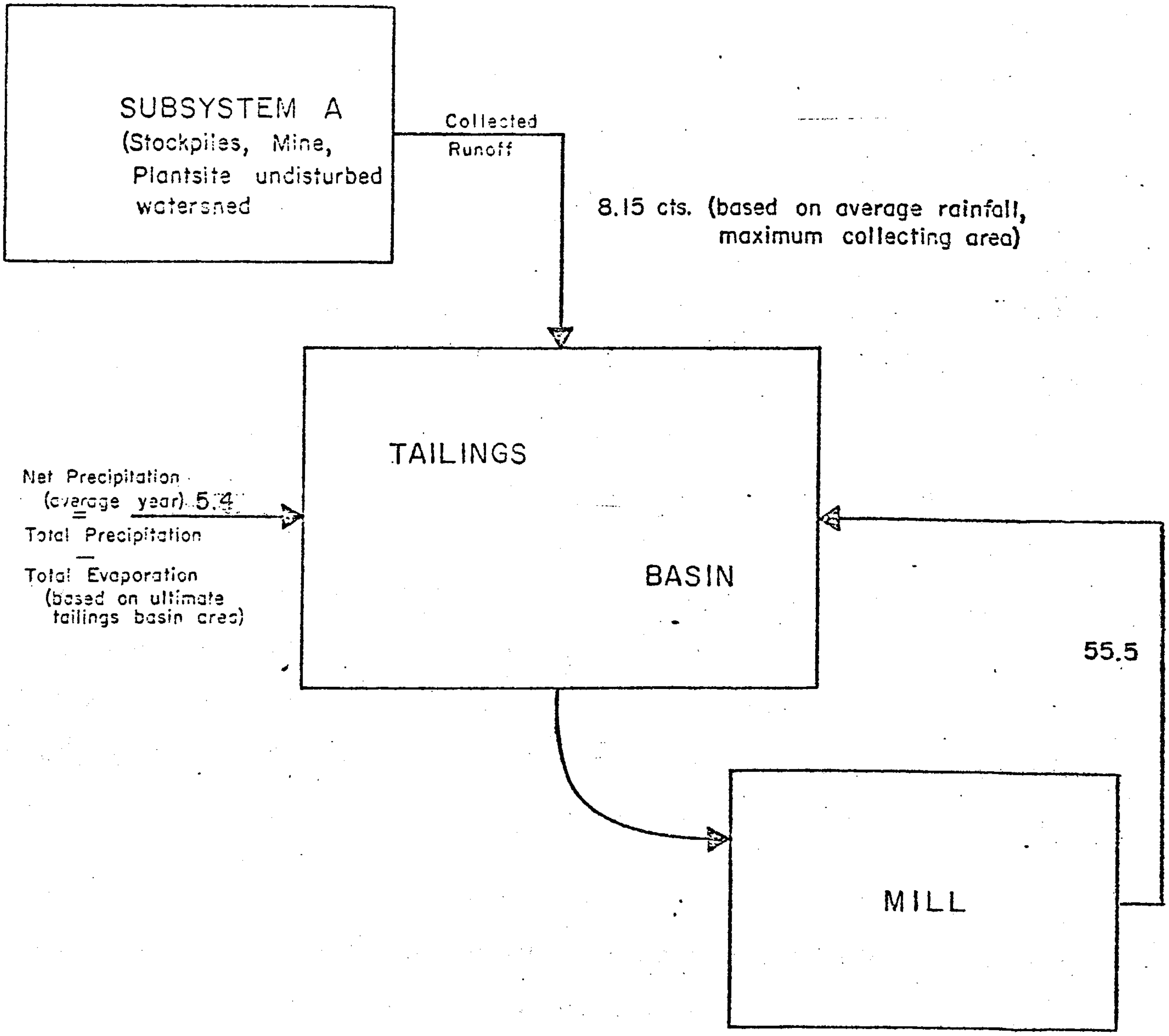
Eighty percent of the yearly "input" volume is from the mill in the 20 X 10^6 mtpy open pit mine during an average preciptation year. But the mill is not a true input, per se, because it only recycles water out of and back into the basin; the real inputs are precipitation and Subsystem A. Still, these two inputs are not expected to dictate the final tailing basin water quality because reactions should occur in the tailing basin-mill system that will improve water quality.

The first two models of tailing basin water are worst cases, in that they assume that the tailing basin/mill system has no effect on the original water quality of the runoff. To develop these models, the conservative mass balance technique was used (Lapakko 1979). The total input of each of 5 parameters (Cu, Ni, Co, Zn, and sulfate) was calculated from each runoff component, and then divided by the total runoff volume. This calculation provides a "worst case" concentration for each parameter, because it assumes no removal reactions (e.g. chemical precipitation or adsorption) occur.

Figure [illegible]

FLOW RATES -- AVERAGE YEAR FOR MODEL OPEN PIT

20×10^6 mtpy



Production Rate = 20×10^6 mtpy

The models assume inputs from stockpiles, the plant site, mine dewatering, and undisturbed watershed areas, the last having the best quality runoff. The amount of runoff generated from each source is a function of source area. As the mining operation progresses, increasingly larger areas will be taken up by mining developments, so that increasing amounts of runoff will be derived from mining-impacted areas. The worst case situation will occur when the runoff contributions from the open pit and stockpiles are at their maximums. Table 81 lists the volume of runoff for an average year of precipitation for the 20 X 10^6 mtpy open pit mine model, assuming maximum source areas.

Table 81

The quality of stockpile runoff and mine water is discussed in the preceding sections. The first model (Model A) is based on mine water quality similar to that of the U.S. Steel bulk sample site (section 4.6.2), and the second (Model B) is based on measurements made on a holding basin at the AMAX site, which are similar in magnitude to the water quality model for the Dunka open pit (section 4.6.2). If large amounts of saline mine water are encountered and this water is pumped to the tailing basin, chloride concentrations in the basin will be higher than those projected by these models and could pose operational problems for the mill, if recycling is used (section 4.6.4).

Since it is impossible to predict if, when, or how much saline water may be encountered, chloride concentration in the basin must be monitored and treatment applied if an acceptable concentration level is exceeded.

To calculate tailing basin Models A and B, stockpile leachate models from section 4.6.3 were used to represent the concentrations in the waste rock (Model I) and

Table 81. Runoff components, volumes (average year of precipitation 20 X 10^6 mtpy open pit mine model).

SOURCE	VOLUME+ l (yr^{-1}) x 10^{-6}
Plant Site	880
Open Pit	760
Overburden	180
Waste rock	880
Lean ore	880
Undisturbed watershed	3800

+ maximum source areas are assumed.

net precipitation input on basin (precipitation - evaporation)	4800

SOURCE: Section 4.4.

lean ore (Model II) stockpile runoff. Data on overburden pile runoff are limited and plant runoff data for the type of operation that might occur in Minnesota do not exist. In the calculation, their effects were assumed to be negligible.

Table 82 presents the results of these calculations for each of five parameters during a wet and average year, and represents the model of runoff water quality used in this Study. These models are used in section 4.7 to determine potential water impacts of copper-nickel mining.

Table 82

The third model (Model C) is developed using a different set of assumptions, namely that the tailing basin/mill system is the dominant force on the basin water quality and that pilot plant mill water generated in Mineral Resources Research Center (MRRC) experiments will represent the basin water in actual practice. This is a best case model, and the actual results will likely lie between Models A and B, and Model C.

It is reasonable to assume that the basin/mill system will influence the tailing basin water, since four times as much basin water will cycle through the mill each year as will enter the basin/mill system each year from runoff and precipitation. It is also reasonable to assume that the tailings--being ground to a small size (high loading) and separated from sulfides in the mill--will increase pH as noted in the leaching section (4.6.1).

Within the mill both release and removal reactions may occur, and output water quality will reflect the net effect of these two types of reactions. Releases were observed in data from bench scale tests and pilot plant operations performed

Table 82. Tailing basin water quality models (concentrations in mg/l).

Model	Average Year					Wet Year				
	(Cu)	(Ni)	(Co)	(Zn)	(SO_4)	(Cu)	(Ni)	(Co)	(Zn)	(SO_4)
A	1.5	4.7	0.22	0.19	380	1.4	5.4	0.25	0.23	460
B	0.13	3.1	0.18	0.18	360	0.15	3.7	0.22	0.22	420
C	.038	.050	.010	.009						

SOURCE: Lapakko (1979).

by the MRRC (Iwasaki et al. 1978) which indicate that in the mill cycle the concentration of dissolved solids increases and a pH around 8 is produced. In addition, the crushing and grinding processes can result in the liberation of mineral fibers (Stevenson 1978).

Removal reactions are a factor due to the finely ground siliceous materials comprising the tailings. In the processing circuit, 30 percent (by weight) of the solution is solids. Given a pH of 8 and a solution containing an estimated adsorbing surface area of 10-25 m^2/liter of solution, substantial amounts of trace metals may be removed by precipitation or adsorption. Residual xanthates (see below) as well as the silicate matrix of the gabbro may absorb trace metals from solution (Eger and Lapakko 1979).

Organic chemicals in the form of frothers (e.g., MIBC) and collectors (e.g., xanthates) are added in the mill for the flotation process. A description of the nature of these compounds, the various types of additives, and the role they play in the flotation process is presented in Volume 2-Chapter 3. Residual concentrations of these chemicals will remain in the mill water. Samples from pilot plant operations (Interim report MRRC 1969-19) contained residual concentrations on the order of 1-5 mg/l.

The net result of release and removal reactions will probably produce mill recycle waters with a pH around 8. This pH is unfavorable for the release of heavy metals to solution, and favors metal removal reactions, indicating that trace metal concentrations may decrease as water flows through the mill. Although concentrations of trace metals are expected to be low, elevated levels of dissolved solids, residual organic process chemicals, and mineral fibers are expected.

Table 83. Comparison of tailing basin water at two locations with maximum concentrations observed in laboratory experiments (for comparison with models A, B, and C, Table 82)(all units but pH measured in mg/l).

Parameter	Eveleth Taconite Tailing Basin[a]	Shebandowan Tailing Basin[b]	Laboratory Tailing[c]
pH	6.8-8.2(5)	6.7-8.3	8.15-8.34
Iron	0.1-0.6(3)	0.06-0.54	0.091, 0.350
Copper	0.001(1)	0.001-0.014	0.017, 0.032
Nickel	0.005(1)	0.046-0.077	0.005, 0.016
Zinc	0.005(1)	0.001-0.054	
Total Dissolved Solids	0.16-439(5)	341-751	N/A[d]
Sulfate (SO_4)	19-82(5)	122-447	N/A
Ammonia	---	0.1-3.7	N/A
Nitrates	1.81-2.66(3)	0.2-3.75	N/A
Nitrite	0.04(1)	0.01-0.08	N/A
Total Phosphorus	---	0.01-0.29	N/A

SOURCE: Eger and Lapakko (1979).

[a] Data collected during 1967-1975 period; number in parenthesis denotes number of samples. Impacted runoff was not collected.

[b] Data collected during 1974-1977 period; resource is a massive nickel sulfide and a basic host rock. The nickel reading was based on limited data, namely five samplings. The iron, copper, zinc, and nitrite had large apparent outlies, respectively: 42, 0.23, 0.17, and 0.28.

[c] Tailings were leached with groundwater and with bog water.

[d] N/A means no data available.

The MRRC pilot plant results are presented in Table 82, labelled as "Model C." Models A, B, and C will be used in section 4.7, to determine water quality impacts of copper-nickel mining.

4.6.4.2 Tailing Basin Water/Post-Operational Phase. The three models for tailing basin waters A, B, and C are logically the bounds on post-operative waters. At best, the tailing basin would continue to exert a neutralizing influence on the runoff from the site, and lean ore piles will have been processed and removed. Also, reclamation efforts, such as revegetation or contouring, may have helped divert precipitation from sulfide-bearing materials.

At worst, the tailing basin would have no effect, and runoff from the mine and piles will be the primary discharge from the site in the post-operational phase.

4.6.4.3 Comparison of Results With Other Tailings Data. There are few data on the effects of processing Duluth gabbro which could be used to predict accurately tailing basin water quality. It is useful to search for even slightly analogous situations, given the importance of the tailings to lessen the pollution potential of other mine components. For comparision purposes, there are data from: tailing basins at Shebandowan, Ontario, and Eveleth, Minnesota; from batch reactor experiments at MRRC; and from acidification measurements on Canadian tailings. Neither of the tailing basins receives stockpile runoff or open pit water, the two major sources of heavy metals; but the results show the low concentrations in the tailing basins themselves (Table 83).

Table 83

The Shebandowan operation is an underground mine in a massive nickel-copper sulfide deposit (1.06% nickel, 0.8% copper). The host rock is peridotite, an ultramafic rock whose mineralogy is dominated by pyroxene and olivine, two minerals also present in the Duluth gabbro. The host rock at Shebandowan has shown a substantial buffering capacity. Observed copper concentrations in the tailing basin water are lower, and nickel concentrations of the same order of magnitude as Model C.

The Eveleth operation is a taconite mine, and its basin water shows a neutral to basic pH, and lower trace metal concentrations than even Shebandowan.

Finally, batch reactor experiments (Figure 59) performed on mineralized Duluth gabbro show basic pHs, and copper and nickel concentrations that are lower than model C. These results support the conclusion that tailing basin water will have high levels of dissolved solids, a pH in the range of 7 to 8, and trace metals concentrations in the range .01-1 mg/l. Although metal concentrations are expected to be low, they will be above background values and may approach levels of biological concern (Eger and Lapakko 1979).

Another way to gauge the effect of Duluth gabbro tailings is to compare their sulfur content with that of tailings that may have caused acid conditions to occur elsewhere. Hawley (1972) has reported the range over which acid mine drainage problems have been observed in Canada, and found that tailings greater than 2.5 percent sulfur fall in this range. This percentage is much higher than the Copper-Nickel Study model tailings (about 0.3 percent) (Volume 2-Chapter 3), and higher than most of the AMAX deposit. Still, lean ore test piles (not tailings) at AMAX--with sulfur content as low as 0.8 percent--have shown declining pH trends, although test piles at 0.6 percent have not (Eger and Lapakko 1979). This is consistent with Hawley's observation that acid conditions even may be a problem with tailings that are less than 2.5 percent sulfide. He recommended "that to prevent an acid drainage situation from developing in any particular tailing area, the (iron) sulfide content of the mass must be kept substantially below 2.5 percent and probably as much below 1 percent as possible". As it is, if the richest ores are mined first ("high grading"), the higher residual sulfide concentration in the tailngs could enhance acid production.

4.6.4.4 Discusison of Tailing Basin Discharge Via Seepage. Water leaves the tailings basin by four principle routes: a) direct discharge or overflow of water in the basin; b) seepage through the dams; c) deep seepage to the groundwater system; and, d) evaporation. The quality of direct discharges would depend upon the inputs and reactions already discussed, and the tailing basin water quality models presented in 4.6.4.2. This section discusses dam seepage and deep seepage as well as additional chemical reactions influencing water quality.

As discussed in Section 4.6.1, many factors affect the water quality of seepage. Of special interest in the tailing basin are these: the dissolved oxygen concentration, pH, and the metal adsorptive capacity of the tailings.

The pH of the seepage (through the dam) is expected to be comparable with that of the water in the basin, which laboratory tests indicate may be buffered at a pH around 8 by the tailings. Laboratory experiments indicate that at a pH of 8 heavy metal release is very low and that any metals in solution would most likely be adsorbed onto the tailings as the water seeps through the tailings and the dam, or metals may precipitate as metal carbonates and hydroxides.

The dissolved oxygen concentration is significant because the mobilty of iron and manganese will increase as oxygen levels drop. Since deep seepage will pass from oxygen rich into oxygen-poor zones, water that seeps down to the groundwater will have increased levels of these two metals. Other metal concentrations may be similar to the basin concentrations.

Tailing basin seepage can be mitigated. Dam seepage to the environment is highly dependent on dam design, and can be designed to be very little. Either a low permeability clay liner could be put on the inner face of the dam or a drain can be placed at the toe of the dam to collect what seepage there is, for treatment or return to the basin.

Groundwater seepage may also be controlled by location on a natural or imported low permeability base. In the water budget section (4.4), it was estimated that seepage for the model open pit operations (20 X 10^6 mtpy) tailing basin would be between zero and 8,300 acre-feet in an average rainfall year, depending on whether the base was impermeable or permeable. This is equivalent to hydrologic permeabilities of 2 feet a year, at most, and due to an assumption that a very fine tailing fraction, "slimes", will cover the entire basin floor and constitute the limiting permeability (section 4.4.1.2).

4.6.5 Smelter/Refinery Waters

Although the extraction of copper-nickel ore within the Study Area may not necessarily involve the operation of a smelter within the area, the addition of a smelter to other mining developments presents a "worst case" for possible environmental impacts. For this reason the Regional Study has developed a smelter/refinery water quality model which is presented in Volume 2-Chapter 4, section 4.9.2.

Unlike the water quality models developed for mine waters, stockpiles, and the tailing basin-mill systems in the previous sections, no field data were available from which to estimate water quality from a smelter/refinery system. Rather, this discussion relies heavily on information available in the literature, which deals principally with the domestic copper industry. The water quality model was developed by scaling data from domestic copper operations to produce a hypothetical smelter/refinery model capable of processing 100,000 mtpy of metal. Studies of the domestic copper industry (EPA, 1975), reflect the particular conditions of the mines and include problems (notably involving arsenic) not likely to occur in Minnesota operations. On the other hand, parameters of particular concern in Minnesota are nickel and cobalt, which do not occur at significant levels in most existing domestic copper operations. The Regional Study's smelter/refinery water quality model attempts to take nickel and cobalt into consideration. The lack of data for a nickel refinery presented a serious problem in developing the model. In the absence of such data, model waters for a nickel refinery were based on data for electrolytic copper refineries. Details of model development are presented in Volume 2-Chapter 4, section 4.9.2.

It should be noted that a smelter/refinery operation may be integrated into the total extractive operation in such a way that smelter/refinery discharge water can be recycled through the tailing basin. "Off-site" smelter development (in another part of the state or in another state) would necessitate the development of separate treatment facilities to handle smelter/refinery discharge waters. The nature of necessary treatment facilities cannot be anticipated without more information regarding the smelting and refining methods likely to be used in a Minnesota copper-nickel industry.

4.6.5.1 Inputs. If a smelter is built within the Study Area, the most likely source of input water is from streams. The average water quality of minimally disturbed streams in the Study Area is presented in Table 1. In addition to water quality parameters for undisturbed streams, the quality of waste rock-lean ore pile leachate presented in section 4.6.3 can be used to approximate a worst case model for stream water quality in the immediate vicinity of a mining operation.

The quality of recycle water in an integrated smelter/refinery/mine/mill system is likely to be influenced by the quality of water in the tailings basin. Models of water quality for a tailings basin are discussed in section 4.6.3.1 and summarized in Table 82.

The nature of processing additives is dependent on the method of processing and cannot be projected at this time. For this reason processing additives are not considered in the smelter/refinery water quality model.

As was suggested earlier, the nature of the ore will influence potential output water quality. Minnesota smelter feed would be lower in lead and arsenic but higher in nickel and cobalt than in previous domestic operations. The adjustments made in the model to compensate for these differences are discussed below.

4.6.5.2 Reactions Within the Smelter/Refinery. Two major classes of reactions occur during the smelting and refining processes: evaporation of cooling waters and chemical alteration of process waters. As is discussed in Volume 2-Chapter 4, section 4.9.1, nearly ten times as much cooling water as process water is used. Although evaporation may result in the concentration of some of the constituents originally present in the input water, it is not expected to alter the quality of cooling waters significantly. On the other hand, process waters will be altered by addition of process chemicals and by chemical reactions in both the smelter and refinery. Specific reactions cannot be anticipated at this time.

4.6.5.3 Output Waters. Major sources of output waters include anode casting water, slag granulation water, acid plant blowdown, treated sewage water (potable water), copper refinery water, and nickel refinery water. Potable water is assumed to be uncontaminated and represents a very small proportion of the total volume of water produced. Table 84 summarizes available data for process water quality in the various process flow streams, along with the modeled volume of flow assigned to each stream. No data are available in the literature for nickel refinery water so the quality of this water was assumed to be the same as that for electrolytic copper refineries. In order to approximate the higher levels of nickel and cobalt in Minnesota smelter feed than in the literature, the nickel concentration from worst case waste rock lean ore leachates (Table 80) was substituted for values given for existing domestic operations. Because no data are available for cobalt in smelter/refinery effluent the value of 2.4 mg/l from the leachate model was used.

Table 84

In comparison with intake waters, anode casting water could be expected to exhibit increased levels of suspended and dissolved solids and elevated levels of some metals, especially copper. Data from three domestic smelters reveal high levels of lead, zinc, and arsenic with pH values just above 7. Acid plant blowdown from three domestic smelters indicated depressed pH values with elevated

Table 84. Water quality data summary for process water streams.

PARAMETER	ANODE CASTING WATER	SLAG GRANULATION WATER	ACID PLANT BLOWDOWN	Cu REFINERY WATER	Ni REFINERY WATER[a]
PH	7.8	7.6	2.0	6.9	6.9
TDS (mg/l)	17,770	50,000	244,000	3700	1900
$SO_4^=$ (mg/l)	230	5,900	36,000	22,650	22,650
As (mg/l)	0.5	187	59	30	30
Cd (mg/l)	0	0.7	9.7	0.1	0.1
Co (mg/l)[b]	2.4	2.4	2.4	2.4	2.4
Cu (mg/l)	11	14	1.0	70	70
Fe (mg/l)	0.5	5	38.2	70	70
Hg (mg/l)	0	0.01	0.1	0.1	0.1
Ni (mg/l)[b]	39.8	39.8	39.8	39.8	39.8
Pb (mg/l)	3	130	89.8	10	10
Zn (mg/l)	0	640	218	20	20
Modeled flow (gpm)	275	2600	770	260	130
Percent of total process water flow	7	64	19	6	3

SOURCE: Volume 2-Chapter 4.

[a] Assumed to be the same as the copper refinery water.
[b] Value based on worst case model of waste rock/lean ore leachate.

levels of sulfate, arsenic, cadmium, iron, lead, and zinc. On the basis of data from eight domestic refineries, copper refinery water can be expected to exhibit elevated levels of zinc, iron, copper, lead, nickel, and sulfate. A wide variety of processes are available for treating the copper-nickel matte likely to be produced from a smelter using Minnesota concentrate. It is therefore important that reliable data on nickel refinery effluents be produced in the event that a specific refinery installation is proposed.

A single smelter/refinery effluent water quality model was generated by combining the models given for the various streams. All constituents were assumed to behave conservatively, so that their final concentrations could be computed as a weighted average based on the volume of output water from each stream. A small potable water contribution with zero values for each parameter was also included. Table 85 presents the overall smelter/refinery water quality model. Detailed discussions of the overall model can be found in Volume 2, section 4.9.2. In Table 86 the concentrations of parameters listed in Table 91 are expressed as mass loadings in metric tons per year. In general, model values for arsenic, mercury, lead, and sulfate may be higher than need be expected from a Minnesoa operation because of their higher proportion in domestic smelter feeds on which the model is based. The low pH of the model waters is the result of the weak acid blowdown from the acid plant. In reality, this stream would most certainly be neutralized prior to combining it with other process streams to prevent acidification of the overall process effluent stream.

Tables 85 and 86

Table 85. Integrated water quality model for a smelter/refinery process water effluent stream.[a]

PARAMETER	MODELED VALUE
Flow (gpm)	4,065
pH	2.7
TDS (mg/l)	79,700
$SO_4^=$ (mg/l)	12,800
As (mg/l)	3.0[c]
Cd (mg/l)	2.3
Co (mg/l)	2.40[a]
Cu (mg/l)	16.6
Fe (mg/l)	17.2
Hg (mg/l)	0.017[b]
Ni (mg/l)	39.8[a]
Pb (mg/l)	5.2[c]
Zn (mg/l)	450

SOURCE: Volume 2-Chapter 4.

[a] Value based on worst case model of waste rock/lean ore leachate.

[b] Unless otherwise noted, model values are based on data from selected domestic operations (EPA 1975).

[c] Values adjusted downward to reflect 100% of the constituent present in the modeled smelter feed.

Table 86. Mass loadings and recovery of constituents implied by the smelter/refinery process water quality model.[a]

PARAMETER	MASS LOADING (mt/yr)	PORTION OF INPUT ACCOUNTED FOR
$SO_4^=$	33,000 (as S)	20% (as S)
As	22	100%[b]
Cd	18	70%
Co	19	2%[c]
Cu	130	0.1%
Fe	130	0.07%
Hg	0.13	100%[b]
Ni	310	2%[c]
Pb	40	100%[b]
Zn	350	50%

[a] See Volume 2-Chapter 4.
[b] 100% recovery assumed (see discussion).
[c] Based on value from worst case waste rock/lean ore leachate model.

4.7 ENVIRONMENTAL IMPACT OF COPPER-NICKEL MINING ON REGIONAL WATER QUALITY

A major environmental concern is the potential environmental impact of copper and nickel mining on natural water bodies in the Study Area. Significant changes in water quality due to mining operations have been observed at the Erie Mining Dunka Site, AMAX test stockpiles and the U.S. Steel Pit (Section 4.6). Elevated trace metal concentrations in Unnamed Creek also indicate the potential for mining related impacts on natural waters (section 4.3).

This section considers possible environmental impacts on water resources within the Study Area, especially on streams. Primary emphasis is given to trace metals. The analysis considers impacts in the operational and post-operational phases, and draws on information from earlier sections, including water budgets (section 4.4), mine water quality models (section 4.6), and aquatic biology (Volume 4-Chapter 1).

4.7.1 Chemical Parameters of Concern

Section 4.6 presented water quality models for mining discharges in the operational and post-operational phases (e.g. Tables 75 and 77). Many of the chemicals contained in these discharges appear in greater concentrations than are now found in the unimpacted waters of the Study Area, and in greater concentrations than are allowed by state and federal regulations. This section discusses chemical parameters of concern, namely trace metals, total dissolved solids (hardness), pH, total suspended solids (sediment loading), residual processing reagents, and mineral fibers. Criteria are developed for trace metals and for sulfate, a component of total dissolved solids. Trace metals and sulfates are emphasized in the subsequent impact analysis.

4.7.1.1 Trace Metals. Four trace metals are of primary interest: copper, nickel, cobalt, and zinc. These four were selected for impact assessment based on results of laboratory (Eisenreich et al. 1977 and 1978) and field observations (Eger et al. 1979) which indicate that these are the major trace metal constituents of mineralized gabbro (Volume 3-Chapter 1, Table 25) and of projected effluents from copper-nickel development. Also, their potential toxic effect on aquatic life in the Study Area is greatest (Volume 4-Chapter 1). Other trace metals, such as arsenic, lead, cadmium, and silver, are not expected to significantly contribute to the toxicity of potential water effluents because of their very low concentration in Duluth gabbro.

Various criteria can be used to evaluate the seriousness of trace metal discharge for mining operations. Two examples are the water quality standards promulgated by MPCA and the U.S. EPA, shown in Table 87.

Table 87

These standards can be compared with Table 88, which shows water quality models developed in Section 4.6. All five models have copper concentrations in excess of the MPCA standards, and four have sulfate concentrations greater than MPCA's standard. (No sulfate concentration was developed for the fifth model, Model C.)

Table 88

Another criteria for comparison is the median concentration of each parameter in undisturbed (Group C) streams in the Study Area (Table 1). All four trace metals of interest appear in greater concentrations in the water quality models.

Table 87. Various criteria for selected chemical parameters.

Parameters	Current MPCA Standards[b]	EPA Criteria	Cu-Ni Guidelines[c]	Study Area Streams (undisturbed) Median Value	Composite Standard[d]
Copper (Cu) (ug/l)	10[e]	1000[g]	10-100[i]	1.3	---
Nickel (Ni) (ug/l)	NA	NA[g]	100-1000[i]	1.0	---
Cobalt (Co) (ug/l)	NA	NA	10-100[i]	0.4	---
Zinc (Zn) (ug/l)	5000	5000[g]	100[i]	2.0	---
CEU[a] (ug/l)	—	--	5-30	—	10
Sulfate (SO_4) (mg/l)	250[f]	NA	NA	6.6	250
Mercury (Hg) (ug/l)	NA	0.05[h]	NA	.08	.05
Mineral Fibers					

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[a] CEU is "copper equivalent units," a measure developed by the Copper-Nickel Study staff to evaluate the combined biological impacts of the trace metals copper, nickel, zinc, and cobalt. It is calculated by the formula:

$$[CEU] = 1x[Cu] + 0.1[Ni] + 1x[Co] + 0.1[Zn].$$

The impacts range from "no effect" (0-5) to "definite acute effects" (over 600).

[b] Minnesota State Regulations, WPC 14 and 15, 1973 supplement.

[c] Regional Copper-Nickel Study, Volume 4-Chapter 1.

Table 87 continued.

[d] This is a composite standard for comparison in this section with water quality models derived in section 4.6. Each standard is the most stringent of the three standards tabulated here, except for copper, nickel, cobalt, and zinc, for which a composite standard based on "copper equivalent units" has been developed.

[e] MPCA has different standards for water to be used for domestic purposes and for fisheries and recreation. Here the more stringent fisheries and recreation standard is used. It is also more stringent than the Copper-Nickel Study "CEU" guideline.

[f] MPCA sets this tabulated standard for domestic use. A more stringent standard, 10 mg/l, is applied under certain circumstances if the water is to be used for wild rice production.

[g] In addition to any listed, fixed concentration criteria, EPA has an additional criteria for this parameter that involves the measurement of lethal concentrations on a biological population.

[h] This criteria applies to aquatic life; a less stringent criteria prevails for water intended for domestic use.

[i] For aquatic life.

Table 88. Water quality source models for copper-nickel development.[a]

	Copper ug/l	Nickel ug/l	Cobalt ug/l	Zinc ug/l	CEU(a) ug/l	Sulfate mg/l	Flow Rate (cfs)
Operative Phase (tailing basin discharge)							
Model A	1500	4700	220	190	2200	380	4.5
Model B	130	3100	180	180	640	360	4.5
Model C[b]	38	50	10	9	54	---	4.5
Post-Operative Phase (waste rock pile and lean ore stockpile discharges)							
Model I	53	2420	21	31	320	1260	.98
Model II	1710	39800	2400	2400	8300	3620	.98

[a] Assumes the 20 X 10^6 mtpy open pit mine model.

[b] Model C is the same as Discharge I displayed in Figure 35a, of Volume 4-Chapter 1.

MPCA and U.S. EPA have not promulgated standards for all trace metals, and individual standards for each metal do not take account of additive effects that may occur on biological organisms when more than one metal is present. Use of unimpacted stream concentrations as criteria may be unnecessarily restrictive, since a water body may be able to accommodate greater metal concentrations than are already there.

The method that the Copper-Nickel Study developed to evaluate the impact of trace metal discharges is based on the combined toxic effects of the trace metals: copper, nickel, cobalt, and zinc (see Aquatic Biology, Volume 4-Chapter 1). The concentrations of the trace metals in ug/l are assumed to be additive and are normalized to "copper equivalent units", [CEU], by the formula

$$1 * [Cu] + 0.1 * [Ni] + 1 * [Co] + 0.1 * [Zn] = [CEU].$$

(Nickel and zinc are 1/10 as toxic as copper and cobalt, e.g. 100 ug/l of nickel or zinc has the same toxic effect as 10 ug/l of copper or cobalt.)

The potential impact for a given CEU concentration is then evaluated based on ranges established in Volume 4-Chapter 1, section 1.6.3 of aquatic biological impacts. The ranges are summarized below.

0-5 CEU	no effect
5-30 CEU	low probability of measurable impact
30-100 CEU	probable chronic effects
100-600 CEU	potential acute effects dependent upon total organic carbon and hardness present in receiving water
600	definite acute effects

The table indicates that the likelihood of impact increases with increasing concentration, rather than occurring only after a specific threshold is reached.

The likelihood of impact is also dependent on the chemical nature of the specific receiving water. The presence of total organic carbon reduces the toxic effects of copper, and hardness reduces the toxic effects of nickel (see Volume 4-Chapter 1).

For the purpose of subsequent analysis, the criteria for CEU to indicate environmental acceptability is chosen to be 10 ug/l (see composite standard column, Table 87). This level is equivalent to that of any of the four metals individually.

4.7.1.2 Total Dissolved Solids. Total dissolved solids (TDS) are of concern because of the cost and difficulty in controlling such wastes and because of the potential for significant concentrations of TDS in copper-nickel development effluents. TDS is composed of a variety of ions; the major ones of concern associated with possible copper-nickel mining are: sulfate and chloride.

Sulfate originates from the oxidation of sulfides in waste piles, tailing, and mill process water. In addition, sulfates can be added to effluent streams by trace metal treatment systems utilizing the sodium sulfide method. Most sulfate salts are very soluble in water and are very difficult to remove from waste discharges with conventional treatment methods. To a large degree, sulfate concentrations in waste water will parallel trace metal concentrations, since they are products of the same reaction. But while metals can be removed by precipitation or adsorption, sulfates will stay in the aqueous phase. Sulfate concentrations in the 1,000 to 3,000 mg/l range can be expected in leachates based on Copper-Nickel Study field and laboratory studies, as well as measurements made at non-ferrous sulfide metal mines in the U.S. and Canada. This is the same range of concentrations developed for the waste rock pile and lean ore stockpile water quality models in section 4.6 (Table 88). Should contaminated waste water discharges occur, even following treatment for trace metals, sulfate concentration 2-3 orders of magnitude (100 to 1,000) greater than background stream concentration could occur. Once discharged, dilution is the only significant factor controlling stream concentrations because natural removal processes are not expected to affect sulfate concentrations.

Except at the point of discharge, high sulfate concentrations are not expected to be toxic but will reduce the value of the impacted resource for domestic consumption.

The criterion chosen to evaluate sulfate concentrations in this section is the same as the current MPCA standard for sulfate, 250 mg/l.

Chloride concentrations in discharge waters are more difficult to predict since its primary source is believed to be highly saline bedrock groundwater of unknown spatial distribution and magnitude. Elevated chloride levels have been encountered at the AMAX exploration site near Babbitt, Minnesota (section 4.3). Road salt is another potential source of chloride, but of lesser concern than saline groundwater. Unless significant quantities of highly saline groundwater are encountered by the mine, stream chloride concentrations due to copper-nickel development should be of the same order of magnitude as are presently found in disturbed watersheds in the Study Area: 5-10 times higher than streams in undisturbed watersheds. Therefore, if copper-nickel development occurred in undisturbed watersheds (e.g. Kawishiwi River), median chloride concentrations in the 5 to 20 mg/l range are expected (median background concentration is in the 1 to 2 mg/l range).

If large quantities of highly saline waters are encountered the resulting mine waters probably could not be used as make-up water for the mill, and would have to be discharged without receiving the beneficial effect of the mill cycle. If treatment is required prior to discharge, lower cost conventional methods would not be effective and higher cost systems such as reverse osmosis or ion exchange would be necessary. If mine water could not be used in the mill, the mill's water appropriation needs would increase.

Sulfate and chloride discharges are not a significant water pollutant on an aquatic biology or public health basis, but can result in significant water quality reductions in the Study Area. They are also of significance because unlike some of the other parameters discussed, they are very difficult (and costly) to remove from contaminated waste streams. Application of treatment systems effective in removing these ions would likely be considered economically unfeasible (EPA 1975).

4.7.1.3 pH. During the operating phase, the pH of contaminated waters from individual water pollution sources within the mine/mill complex could vary significantly, from acid waters (pH less than 5) to alkaline waters (pH greater than 10). The major concern about pH is its effect on trace metal mobility. Federal effluent regulations for the ore mining and dressing industry requires that waste discharges be controlled within the range of 6 to 9 pH units.

If contaminated discharges occur during operation, they would likely be on the alkaline side, not the acid side. Regional surface water pH ranges from 4.7 to 8.8, with streams having a median pH of 6.9 and lakes having a median pH of 7.1.

4.7.1.4 Total Suspended Solids. Historically, mining areas were noted for their impact on increasing the sediment loading of streams draining the affected area.

While total suspended solids concentrations of several hundred mg/l have been recorded in mining areas (Down and Stocks 1977), such discharges can be effectively controlled with the use of sediment traps and reclamation practices to reduce erosion. Federal effluent requirements require that TSS concentrations be maintained at or below 20 mg/l.

4.7.1.5 Chemical Reagents. Chemical reagents are utilized in the flotation process (Volume 2-Chapter 3, section 3.2.3.4). Depending on the type and amount of reagents added to the system, residual reagent concentrations will exist in tailing basin water and in discharge effluents from the tailing basin. Many of the compounds used are very toxic; others are less toxic. Some are persistent and hence will eventually escape a tailing area. Others are unstable and will break down in a tailings area.

The toxicity of organic flotation agents--particularly collectors and their decomposition products--is an area of considerable uncertainty, particularly in the complex chemical environment present in a typical flotation-mill discharge. Data available on the potential toxicities of many of the reagents indicate that only a broad range of tolerance values is known. Table 89 is a list of some of the more common flotation reagents and their known toxicities as judged from organism tolerance information (EPA 1975).

Table 89

The Minnesota Mineral Resources Research Center (MRRC) performed bulk flotation tests (pilot plant scale) on Minnesota copper-nickel ore and studied the fate of processing reagents, specifically Potassium amyl xanthate (KAX)(collector), MIBC

Table 89. Known toxicity of some common flotation reagents used in ore mining and milling industry.

TRADE NAME	CHEMICAL COMPOSITION	FUNCTION	KNOWN TOXIC RANGE (mg/l)	TOXICITY*
Aerofloat 25	Essentially aryl dithiophosphric acid	Collector/Promoter		
Aerofloat 31	Essentially aryl dithiophosphric acid	Collector/Promoter		
Aerofloat 238	Sodium di-secondary butyl dithiophosphate	Collector/Promoter	1,000 to 10,000	Low
Aerofloat 242	Essentially aryl dithiophosphric acid	Collector/Promoter	10 to 1,000	Moderate
Aerofroth 65	Polyglycol type compound	Frother	1,000 to 10,000	Low
Aerofroth 71	Mixture of 6-9 carbon alcohols	Frother	1,000	Low
Aero Promoter 404	Mixture of sulfhydryl type compounds	Collector/Promoter	1 to 100	Moderate
Aero Promoter 3477	Unknown	Collector/Promoter	100 to 1,000	Moderate
AROSURF MG-98A	Unknown	Collector/Promoter		
--	Chromium salts (ammonium, potassium, and sodium chromate and ammonium, potassium, and sodium dichromate)	Depressing agent	10 to 1,000	Moderate
--	Copper sulfate	Activating agent	0.01 to 1.0	High
--	Cresylic acid	Frother	0.1 to 1.0	High
Dowfroth 250	Polypropylene glycol methyl ethers	Frother	1,000	Low
Dow Z-6	Potassium amyl xanthate	Collector/Promoter	0.1 to 200	Moderate to High
Dow Z-11	Sodium isopropyl xanthate	Collector/Promoter	0.2 to 2.0	High
Dow Z-200	Isopropyl ethylthionocarbamate	Collector/Promoter	10 to 100	Moderate
Jaguar	Based on guar gum	Flocculant		
--	Lime (calcium oxide)	pH modifier and flocculant	10 to 1,000	Moderate
M.I.B.C.	Methylisobutylcarbinol	Frother	1,000	Low
--	Pine oil	Frother	1 to 100	Moderate
--	Potassium ferricyanide	Depressing agent	0.25 to 2.5	Moderate to High
--	Sodium ferrocyanide	Depressing agent	1 to 1,000	Moderate
--	Sodium hydroxide	pH modifier	1 to 1,000	Moderate
--	Sodium oleate	Frother	1 to 1,000	Moderate
--	Sodium silicate	Depressing agent	100 to 1,000	Moderate
--	Sodium sulfide	Activating agent	1 to 100	Moderate
--	Sulfuric acid	pH modifier and flocculant	1 to 100	Moderate
Superfloc 16	Polyacrylamide	Flocculant	1,000	Low

*Toxicity	Tolerance Level
High	1.0 mg/l
Moderate	1.0 to 1,000 mg/l
Low	1,000 mg/l

NOTE: Toxic range is a function of organism tested and water quality, including hardness and pH. Therefore, toxicity data presented in this table are only generally indicative of reagent toxicity. Although the toxicity ranges presented here are based on many different organisms, much of the data are presented in relation to salmon, fathead minnows, sticklebacks, and Daphnia.

(frother), and MG500 (flocculant). The collector and frother were added to the flotation system and the flocculant was used to remove fine tailing material from the recycle water. These particular reagents are not necessarily the ones that would be used in a Minnesota copper-nickel operation.

Residual reagent levels in the recycle water (equivalent to the water transported to the tailing basin in a full-scale operation) averaged: 1.7 ppm KAX, 2.3 ppm MIBC, and 0 ppm MG500. This constituted extraction rates of 97 percent, 87 percent, and 100 percent, respectively. Part of the observed rates may actually be due to reagent decomposition prior to recycling.

Because the literature shows MIBC toxicity levels of 100 to 1,000 ppm, expected levels of MIBC in the tailing water would be significantly below toxic levels. The flocculant also appears to pose no problem.

The KAX collector situation is not so clear. The literature reports toxicity levels of 0.01-0.1 ppm for similar collectors, but Regional Study tests showed toxicity levels for one of these collectors to be 22-38 ppm. The MRRC results (1.7 ppm) falls between these two levels. Depending on the actual toxicity level, KAX could be a problem (Volume 2-Chapter 3).

When reagents are being chosen for a mine-mill circuit, the toxicity of compounds should be considered. Included in the definition of "least" toxic compounds are those toxic compounds that break down rapidly (into innocuous substances) in a waste stream or those toxic substances which can be removed easily from a waste stream using recognized waste treatment technology.

In general, compounds having known or suspected nutrient properties should be avoided if possible. Compounds that are persistent (that is, compounds that do not break down easily in a natural environment) should be avoided. Compounds that will significantly increase hardness or total dissolved solids content should also be avoided.

4.7.1.6 Mineral Fibers. Asbestiform fibers have been identified as a potential public health concern in northeastern Minnesota. Present information indicates that the concentration of asbestiform amphibole minerals in Duluth Complex ore is expected to be quite low—on the order of 0.1 ppm by weight (Volume 3-Chapter 1, section 1.4.3.5). On the other hand, amphibole minerals in non-asbestiform habits are expected to be present in significant amounts, possibly ranging as high as 13 percent by volume and averaging 2-3 percent by volume based on Regional Study data. The concern is that milling these amphibole minerals will result in the creation and subsequent release of fiber-like cleavage fragments.

Analysis was performed on samples of pilot plant tailing slurries to estimate mineral fiber concentrations in water from the mill (Volume 3-Chapter 2). The average values indicate that total fiber concentrations could be 1.61 to 4.95 X 10^{12} fibers/liter depending on the degree of grinding utilized in the milling process. Because of the difficulty of measurement, these and other fiber measurements should be considered order of magnitude estimates.

Section 4.3.1.4 of this chapter presents data on background fiber concentrations in Study Area surface waters and Ely drinking water (tap water). Ambient fiber concentrations were found to be six orders of magnitude below projected tailing basin water.

Settling and decanting experiments performed on tailing material suggest that regardless of treatment to control the release of fibers, the tailing material itself retains a significant fraction of the fibers generated (Volume 3-Chapter 2). If tailing material is exposed to wind erosion, the resultant fugitive emissions will most certainly contain mineral fibers. If the tailing material is subject to water erosion, the resulting discharges will most certainly contain mineral fibers. In terms of water treatment for fiber removal, continuous pilot plant work at MRRC indicates that the use of a flocculant in the clarification of process water prior to recycling reduces the fiber content by 4-5 orders of magnitude. However, this means the fibers are then essentially all retained in the tailing material, and pose the potential for future release when active control practices cease.

Information generated by the above studies and those presented in Volume 3-Chapter 2, presents quite a dilemma when an attempt is made to use it in the assessment of potential environmental impacts. As currently defined, mineral fibers will most certainly be present in the products of mineral processing. Typical tailing slurries may contain from 10^{12} to 10^{13} fibers/liter of which some 20-30 percent or more may be amphibole fibers. This corresponds to some 10^9 to 10^{10} fibers/gm of dry tailing material in a basin. Processing of Duluth Complex material may produce roughly 1/3 the concentration of amphibole fibers present in Reserve's tailing material at Silver Bay (Stevenson 1978). It should be reiterated that the fibers observed in gabbro, and at Reserve, do not originate from minerals which are present in asbestiform habits. The occurrence of such habits in gabbro is expected to be rare. The aspect ratios of the fibers from gabbro are quite low in comparison to those formed from truly asbestiform minerals. In fact, it has been observed that a large fraction of fibers from gabbro are plagioclase, a common mineral in the earth's crust. It is expected that such fibers may naturally occur in most areas as a result of cleavage fragment formation by the forces of wind and water acting in nature. Still, the city of Duluth has taken precautionary measures to remove these fibers from their water supply.

Since the mechanisms by which some fibers are harmful to human health are not yet clearly understood, this study points out the importance of continued research into the pathology of mineral fibers. If it is important to control these fibers, or fibers of selected mineralogy or aspect ratios, the pathology must be known to allow a specific control program to be designed and instituted.

4.7.2 Method of Evaluating Stream Impacts

Mining discharges of low quality will not be released to the environment without treatment. Mitigative techniques are discussed in sections 4.7.1 and 4.7.7, while this section and next indicate the level of stream impacts if dilution was the only mitigative technique.

This section identifies the data and techniques to be used in section 4.7.3 to evaluate stream impacts. The conservative mass balance technique is the primary analytic tool, and is used to determine trace metal (CEU) impacts on streams from copper-nickel mining discharges and the size of the watersheds that would be necessary to dilute stream CEU concentrations to the composite criteria (Table 87).

This is not to say that "dilution is the only solution;" other mitigative techniques, such as water collection, treatment, and controlled release, are available and should be used. Dilution is used in this analysis to indicate how near or far the different water quality models are from meeting the standard, by indicating the size of the dilutional watershed needed if dilution was the only mitigative approach. This analysis will demonstrate the need for additional methods, especially for some of the "worst case" discharge models. The analysis below also suggests how stream location can ameliorate the pollution problem if other mitigative techniques fail.

4.7.2.1 Conservative Mass Balance Technique. This technique was used in section 4.6 to develop water quality models for mine "subsystem A" runoff. It is a method for calculating the resulting concentration of a chemical parameter when two or more different flows are combined.

The conservative mass balance equation for two flows is:

$$C_f = \frac{C_M Q_M + C_R Q_R}{Q_M + Q_R}$$

where: C_f = concentration of parameter in receiving water after input of mining discharge (mg/l)

C_M = concentration of parameter in mining discharge (mg/l)

Q_M = flow rate of discharge (cfs)

C_R = concentration of parameter in receiving water (mg/l)

Q_R = flow rate of receiving water (cfs)

The impact analysis will determine dilutional watershed areas needed for different model discharges to meet a predetermined concentration criterion, C_f. First, the above formula is solved by algebraic manipulation for Q_R, the flow rate of the receiving water. Then the required flow rate can be used to calculate the watershed area needed to generate that flow rate, using other equations introduced in section 4.2. The conservative mass balance equation is simplified by assuming that $C_R Q_R$ is much less than $C_M Q_M$ and can be ignored.

When this is not the case, the simplified formula underestimates the dilutional flow needed.

Two other major assumptions are integral to the mass balance technique: the conservation of chemical mass in the aqueous phase, and complete mixing of mining discharge and receiving water flow. The mass conservation assumption assumes there is no mass added to the receiving water other than mining discharge and no mass removed from the mining discharge or the receiving water. In fact, mass may be added by additional leaching reactions or atmospheric deposition, or be removed by chemical precipitation, adsorption, or biological assimilation. Trace metals that are removed may accumulate in streams or lake sediments, and be redissolved later if aqueous conditions change (e.g. if pH drops). Atmospheric deposition is discussed in section 4.3.4 and removal mechanisms are discussed in section 4.6.1. The degree to which mass will be added to or removed from the system has not been quantified.

The assumption of no chemical precipitation tends to overestimate the degree of impact. The removal rates of copper, nickel, cobalt, and zinc are most likely not equal, and further research is necessary to determine their magnitude in the environment. Because nickel is more mobile in solution than copper, the conservative mass assumption is more valid for it.

The complete mixing assumption is a simplification of the real situation, though it is more valid for streams than for lakes due to the turbulence of flow. The degree of mixing will increase with distance from the point of discharge. At the point of discharge, considerable variability in concentration may occur.

4.7.2.2 Mining Discharge Variables. Model values of concentration (C_M) and flow (Q_M) are based on analyses described in section 4.6 (Water Quality Models) and section 4.4 (Water Budget), respectively. This information is summarized in Table 88, and is based on the best available information applicable to the Minnesota situation. The results were developed so that some impact analyses could be performed, and are not intended to be predictive.

Two time periods are analyzed, the operational phase and the post-operational phase. During the operational phase it is assumed that all site runoff is collected and routed to the tailing basin; excess system water is discharged to a stream. The projected average discharge from a tailing basin located on an impermeable base during average annual precipitation conditions is 4.5 cfs. The tailing basin input and discharge models are based on the 20 X 10^6 mtpy open pit operation (section 4.4).

Three different water quality models were chosen for the operational phase, to simulate the range of likely discharges from an integrated mine-mill operation's tailing basin (see section 4.6 and Table 88). The modeled CEU's, the primary parameter for subsequent analysis, range from Model A's 2,200 ug/l for a runoff dominated by a "worst case" open pit resembling one observed at the U.S. Steel site, to Model C's 54 ug/l for a hypothetical facility whose mill/tailing basin circuit neutralizes all mine waters to the concentration levels that were observed in mill pilot plant studies performed at the University of Minnesota's Mineral Resources Research Center. Model sulfate values are also shown in Table 88, but only for Models A and B. It will be seen that the modeled sulfate levels require much less dilution to achieve the sulfate criteria.

These models assume that concentration levels do not vary. This is inconsistent with observations at existing mine sites. Still, no consistent temporal pattern has been observed and variations on a seasonal or yearly basis have not been quantified. The model concentrations employed are not atypical of the observed concentrations, but do represent the upper end of the concentration range for the worst case.

As discussed in section 4.7.1.1, trace metal concentrations and sulfate concentrations in the modeled discharges are in excess of MPCA and U.S. EPA standards, and far in excess of existing concentrations in the area's surface waters. If they entered the receiving waters without mitigation, significant changes in the quality of the receiving waters could occur, depending on the volume of dilutional flow available in the receiving waters.

Two water quality models (Models I and II in Table 88) are used for the <u>post--operational phase</u> to simulate the discharge from waste rock pile and a learn ore pile, respectively. These two mine components will dominate after the mill processing circuit is no longer exerting its neutralizing influence. Ideally, in the post-operational stage, the lean ore piles will have been processed and not be a factor in the water quality of the region.

The quantity of flow from the waste rock pile is assumed to be 0.98 cfs, and is dependent on the stockpile size and the amount of precipitation. A runoff coefficient of 0.3 is used, although subsequent analysis indicates this is low (see section 4.4). Calculations assume an average precipitation year as well as stockpile dimensions that would occur at the end of operations. Only the impacts of an open pit are exhibited here, since an underground mine would have much less impact. The stockpile area projected for a 12.35 X 10^6 mtpy underground mine is about 1/20 that of the 20 X 10^6 mtpy open pit, consequently the ratio of the flows from the stockpiles is in the same ratio.

4.7.2.3 Receiving Water Quantities (streams). The conservative mass balance approach presented above can be used to calculate the dilutional flow of water required to reduce a mine discharge to the level specified in the composite standard (Table 87). Once determined, this flow can be used to calculate and identify watershed areas that would generate such a flow.

To perform these calculations, the following formulae were statistically derived to express the average stream flow and the 7-day, 2-year low stream flow as a function of watershed area:

$Q_{AVE} = 0.790\ A$ (Siegel and Ericson, 1979)

$Q_{7D2Y\ low} = 0.024\ A^{1.28}$ (Brooks and White, 1978)

Q is expressed in cubic feet per second, and A is expressed in square miles. On the average, a watershed of area A will generate a flow of Q_{AVE}, but for a one-week period approximately once every two years the flow will be as low as $Q_{7D2Y\ low}$. These formulae can be used to determine flows if drainage areas are known, so final stream concentrations can be calculated with the mass balance equation. They can also be used to calculate needed areas if one knows what flow is required to dilute a discharge to the composite standard.

These formulae were calculated using linear regression analyses of watersheds in the Study Area. The results are statistical, and should not be thought to accurately represent the watershed area-stream flow rate relationship in any particular stream at any particular time.

The table below shows some values of Q_{AVE} and $Q_{7D2Y\ low}$ for a few different values. For a given area, the average flow is greater than the 7-day, 2-year low, so a constant mine discharge would have a greater effect during a low flow period, when there was less stream water to dilute it. A stream with double the watershed area will have double the average flow of another stream, but will have more than double the flow of the other stream during the low flow period. In other words, the larger the watershed, the more protection it provides against adverse impacts during low flow periods.

		Watershed Area	
		$100 mi^2$	$200 mi^2$
Flow Rates	Q_{AVE} (cfs)	79	158
	Q_{7D2Y} low (cfs)	8.7	21.2

4.7.3 Stream Results

The information presented in section 4.7.2 can be used to estimate stream impacts from different mining discharges in the Study Area, as well as the dilutional watershed areas required to achieve water quality criteria.

4.7.3.1 Stream Impacts. Table 90 shows the effect that each of the five different mining discharges would have if they occurred at Station E-1 on the Embarrass River, in terms of the CEU concentration at that point (section 4.7.1.1). The effects of Model A (operational phase) and Model II (post-operational phase) are most severe, both having potential acute effects on aquatic life during average periods, and definite acute effects when the low flow period occurs. Model C, on the other hand, would likely have no effect during average flow periods and a low probability of impact even during a low flow period. Similar calculations can be performed for other watersheds.

Table 90

Table 90. Resultant concentrations at Embarrass River station E-1, for various models (in ug/l CEU) (a).

OPERATIONAL PHASE						POST-OPERATIONAL PHASE			
Model A		Model B		Model C		Model I		Model II	
Ave.	7D,2Y low	Ave.	7D,2Y low	Ave.	7D,2Y low	Ave.	7D,2Y low	Ave.	7D,2Y low
160	965	47	281	4	24	5	47	140	1207
potential acute effects	definite acute effects	probable chronic effects	potential acute effects	no effect	low probability of impact	no effect	probable chronic effects	potential acute effects	definite acute effects

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[a] Calculation is performed using the mass balance equation, and equations for average and 7-day, 2-year low flow. The dilutional watershed area used to determine these flow rates is the actual watershed area above station E-1, minus 16 square miles, that is, 88.4-16, or 72.4 square miles. This adjustment is made because the 20 X 10^6 mtpy open pit model requires 16 square miles of area, and the unimpacted watershed above station E-1 would be diminished by this amount.

Stream impacts will be less if the mining discharge is located downstream from a larger watershed area. Table 91 shows selected stream stations in the Study Area, their watershed areas, and their average and 7-day, 2-year low flows. Table 92 shows the resulting concentrations if the mine and its discharge is located at these various stations, assuming the discharge resembles Model B (640 ug/l of CEU). The smaller streams, such as Unnamed Creek (already impacted) and Filson Creek would be most affected, while larger rivers such as the St. Louis and Kawishiwi would have the greatest capacity for absorbing the discharge. Again, the most severe impact coincides with the 7-day, 2-year low flow period. Higher concentrations and even worse impacts could occur during frequent low flow periods, for instance, the lowest 7-day flow which statistically occurs every 10 years.

Tables 91 and 92

Location on a stream also affects the magnitude of the impact from the discharge. As distance downstream increases, the watershed area drained by the stream increases, thereby increasing the quantity of available dilutional flow. If mining discharge occurs near the source of a stream, the CEU concentration resulting would be higher than if discharge occurred further downstream. This can be seen for a hypothetical discharge on the Partridge River, using data in Table 92. A 640 ug/l CEU discharge at station P-3 (see Figure 4), yields a CEU concentration of 468 ug/l during an average flow period, with a potential for acute effects on aquatic wildlife. If the mine were placed farther downstream, near Station P-1, the greater average dilutional flow available would result in a concentration of 31 ug/l, on the borderline of a low probability of measurable impact.

Table 91. Profiles of selected streams in Study Region.

STREAM AND STATION		N or S[a]	Present[b] State	Dilutional Watershed Area[c] (square miles)	Average Flow[d] (cfs)	7-day, 2-yr Low Flow[d] (cfs)
Unnamed Creek:	BB-1	N	A	0	0	0
Filson Creek:	F-1	N	C	0	0	0
Keeley Creek:	KC-1	N	C	0	0	0
Waterhen Creek:	W-1	S	C	29.6	23.4	1.83
Dunka River:	D-1	N	B	33.4	26.4	2.14
Embarrass River:	E-1	S	B	72.4	57.2	5.76
Partridge River:	P-1	S	A	113	89.3	10.19
	P-2	S	B	85.9	67.9	7.17
	P-3	S	C	2.1	1.66	0.06
Stony River:	S-1	N	C	228	180.1	25.02
St. Louis River:	SL-1	S	A	275	217.2	31.81
Kawishiwi River:	K-1	N	C	1331	1051.5	239.42

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[a] North or south of Laurentian Divide.

[b] A=highly impacted; B=intermediate; C=very clean.

[c] Area for the 20 X 10^6 mtpy open pit model (16 mi^2) is subtracted from actual watershed area (see note (a) of Table 90).

[d] The statistically derived equations used to calculate these numbers were: $Q_{AVE} = .079A$ and $Q_{7D2Y\ low} = .024\ A^{1.28}$, where Q's are in cfs and A's in square miles.

Table 92. Resultant stream concentration and impact if Model B mining discharge (640 CEU) occurs upstream from station.

STREAM AND STATION		CEU Concentration (ug/l)	Impact Level	CEU Concentration (ug/l)	Impact Level
Unnamed Creek:	BB-1	640	definite acute effects	640	definite acute effects
Filson Creek:	F-1	640	definite acute effects	640	definite acute effects
Keeley Creek:	KC-1	640	definite acute effects	640	definite acute effects
Waterhen Creek:	W-1	103	potential acute effects	455	potential acute effects
Dunka River:	D-1	93	probable chronic effects	434	potential acute effects
Embarrass River:	E-1	47	probable chronic effects	281	potential acute effects
Partridge River:	P-1	31	probable chronic effects	196	potential acute effects
	P-2	40	probable chronic effects	247	potential acute effects
	P-3	468	potential acute effects	632	definite acute effects
Stony River:	S-1	16	low probability of impact	98	probable chronic effects
St. Louis River:	SL-1	13	low probability of impact	79	probable chronic effects
Kawishiwi River:	K-1	3	no effect	12	low probability of impact

4.7.3.2 Mitigating Effect of Discharges Proportional to Flow. As section 4.7.3.1 demonstrates, the 7-day, 2-year low flow period constitutes a recurring maximum impact on aquatic life, assuming the discharge rate is constant. But discharge rates can be varied with stream flow, at least during the operational phase when the discharge rate can be more readily controlled.

During the operational phase, the amount of discharge can be kept proportional to the streamflow: greater during high flow periods and lesser during low flow periods. This method can keep the stream concentration constant and just equal to the result the mass balance equation would yield when the average flow, Q_{AVE}, is used as the receiving stream flow, Q_R. Thus, a proportional discharge strategy averages out the impact and avoids worse impacts otherwise associated with low flow periods. For the streams in Table 92, the year-round impacts would be the ones displayed under the average flow column. Smaller dilutional watershed areas are required to meet criteria, if proportional discharges are used instead of constant discharges (see 4.7.3.3). Whether discharge proportional to flow can be applied in a given instance will depend on the design and location of the mining development (e.g. sufficient water storage capacity, ability to collect and control various discharge components).

An additional factor to be considered in timing mining discharges is seasonal variations in biotic sensitivity, since aquatic organisms may have greater sensitivity to toxins during certain periods, such as springtime spawning, than during other periods (Volume 4-Chapter 1).

4.7.3.3 Dilutional Watershed Requirements for Various Models. Calculations were performed to determine the sizes of dilutional watershed that would be necessary to dilute the model mine discharges to the composite criteria displayed in Table 87: 10 ug/l for CEU, and 250 mg/l for sulfate. This calculation was performed for Models A, B, and C in the operational stage, and Models I and II in the post-operational stage. The results are shown in Tables 2 and 3. Model A requires the greatest dilution, 4,022 square miles of runoff if it is discharged at a constant rate. This can be reduced to 1,247 square miles if the rate of discharge is varied proportionally with fluctuations in stream flow.

The sulfate concentration of the discharge is of much less environmental concern than CEU, as seen by Table 2. Any watershed area large enough to dilute CEU to an acceptable level will do the same for sulfate, with area to spare.

Discharge C requires much less area than Discharge A. It is uncertain as yet which of the two models the tailing basin water will most resemble.

The implications of these results can be seen by comparison with the available dilutional watersheds displayed in Table 91. Even using discharge proportional to flow, not even the Kawishiwi River station K-1 has sufficient dilutional watershed available to dilute Model A discharges to the 10 ug/l CEU standard. On the other hand, a Model C discharge proportional to flow could be accommodated by all but the three smallest creeks listed in Table 91.

Table 3 displays the situation in the post-operational phase. Since discharges may be harder to control than during the operational phase, the constant discharge results may be a credible "worst case" which may reoccur at the 7-day low flow period every two years. Also, the 7-day 2-year low flow case is most applicable for a conservative estimate of environmental impact, since stockpiles can generate significant flows even in dry periods (section 4.4 on stockpile hydrology). If a high degree of impact recurs every 2 years, populations of organisms may not be able to fully recover (Volume 4-Chapter 1).

The worst situation would occur if the discharge resembled lean ore stockpile Model II, in which case no stream listed in Table 91 has a sufficient dilutional watershed to dilute the discharge to the desired 10 ug/l CEU. The Kawishiwi's 1,331 square miles comes closest to the needed 3,459 square miles, and would reduce the concentration to 34 ug/l CEU.

If lean ore piles are removed before mine closure, the resulting water quality will be better. If the discharge resembles Model I, then the two largest rivers listed in Table 91 can accommodate the load. In this case, Model I's post-operational discharge will constitute less of a problem than either Model A or B during the operational phase even if proportional discharge occurs then (266 mi^2 of dilutional watershed required, compared to Model A's 1,247 mi^2 or B's 359 mi^2-Table 2). It is impossible to predict what discharge concentrations will occur. The discharge flow rates are also critical assumptions, but neither can they be predicted with certainty.

4.7.4 Lake Results

This section discusses impacts on lakes from mining discharges occurring anywhere upstream from a lake, including on feeder streams.

4.7.4.1 Analysis Method. Impacts on lakes are evaluated with some of the same techniques and criteria as were applied to streams. To calculate the concentration of the inflow to a lake downstream from a discharge, the mass balance equation is used again, and complete mixing is assumed. Q_M is again taken to be the mining discharge while the receiving waters flow rate Q_R in this case is taken to be equal to lake inflow. In effect, the lake inflow concentration is calculated as though the lake received two flows: the mine discharge and the total unimpacted runoff from the rest of its watershed.

A statistical formula is available to relate the watershed area of a lake to the dilutional flow:

$$Q = 0.960\ A^{0.9504}$$

where Q is the 10-year average discharge in cubic feet per second, and A is the watershed area in square miles (section 4.2). Since over long periods lake outflow is likely equal to lake inflow (Siegel and Ericson 1979), this expression can be substituted into the mass balance equation as the inflow Q_R. The unimpacted lake inflow is assumed to have zero CEU concentration, as in the case of stream. This yields:

$$C_I = \frac{C_M\ Q_M + C_R\ Q_R}{Q_M + Q_R} = \frac{C_M\ Q_M}{Q_M + 0.96A^{0.9504}}$$

C_I = average concentration in total lake inflow
C_M = CEU concentration in mining discharge anywhere upstream of the lake
Q_M = flow rate of mining discharge anywhere upstream of the lake
C_R = CEU concentration in unimpacted lake inflow
Q_R = flow rate unimpacted lake inflow = $0.960A^{0.9504}$

The conservative mass balance assumption is more questionable when analyzing lakes than for streams. Trace metals may be removed from solution before or after they reach the lake, and may concentrate in stream or lake sediments.

The complete mixing assumption used in the mass balance technique is also more questionable in the case of lakes than of streams. Actual concentrations will tend to be higher near the inflow of the mining discharge, since mixing of lakes is neither instantaneous nor necessarily complete (Figure 67), and involves consideration of advection, dispersion, diffusion, biological activity, stratification, etc. Stratification, for instance, influences how well a lake will mix (and dilute) the mining discharges that enter it (Figure 68). As the number of turnovers increases, the degree of mixing also increases, e.g. dimictic lakes will tend to mix more readily than monomictic lakes. The effects of mixing have not been developed quantitatively for this presentation.

Figures 67 and 68

A lake's volume can buffer the impact of a discharge. A measure of this buffering capacity is its "flushing rate." This is the ratio of annual discharge (or net annual inflow) to lake volume and represents the number of lake volumes discharged per year. If the flushing rate of a lake is relatively small, the time required for lake water quality to equal that of the inflow is relatively long. As the flushing rate increases, the time required for lake water quality to equal that of the inflow decreases (Lorenzen et al. 1976). Similarly, the flushing rate determines how long it takes for a lake to recover after all mining discharges have ceased.

The concentration buildup and decline in a lake follows exponential laws. A lake with a flushing rate of 2 will reach 86 percent of inflow concentration in one year, while lakes with rates of 0.5 and 0.1 will take 4 years and 20 years, respectively, to achieve this level. This is based on the assumption that the parameter--CEU in this case--is conservative, and is not removed from solution. A more accurate analysis would account for precipitation reactions leading to a build-up of the parameter in lake sediments.

FIGURE 67

CONCENTRATION DISTRIBUTION SHORTLY AFTER INITIATION OF MINING DISCHARGE

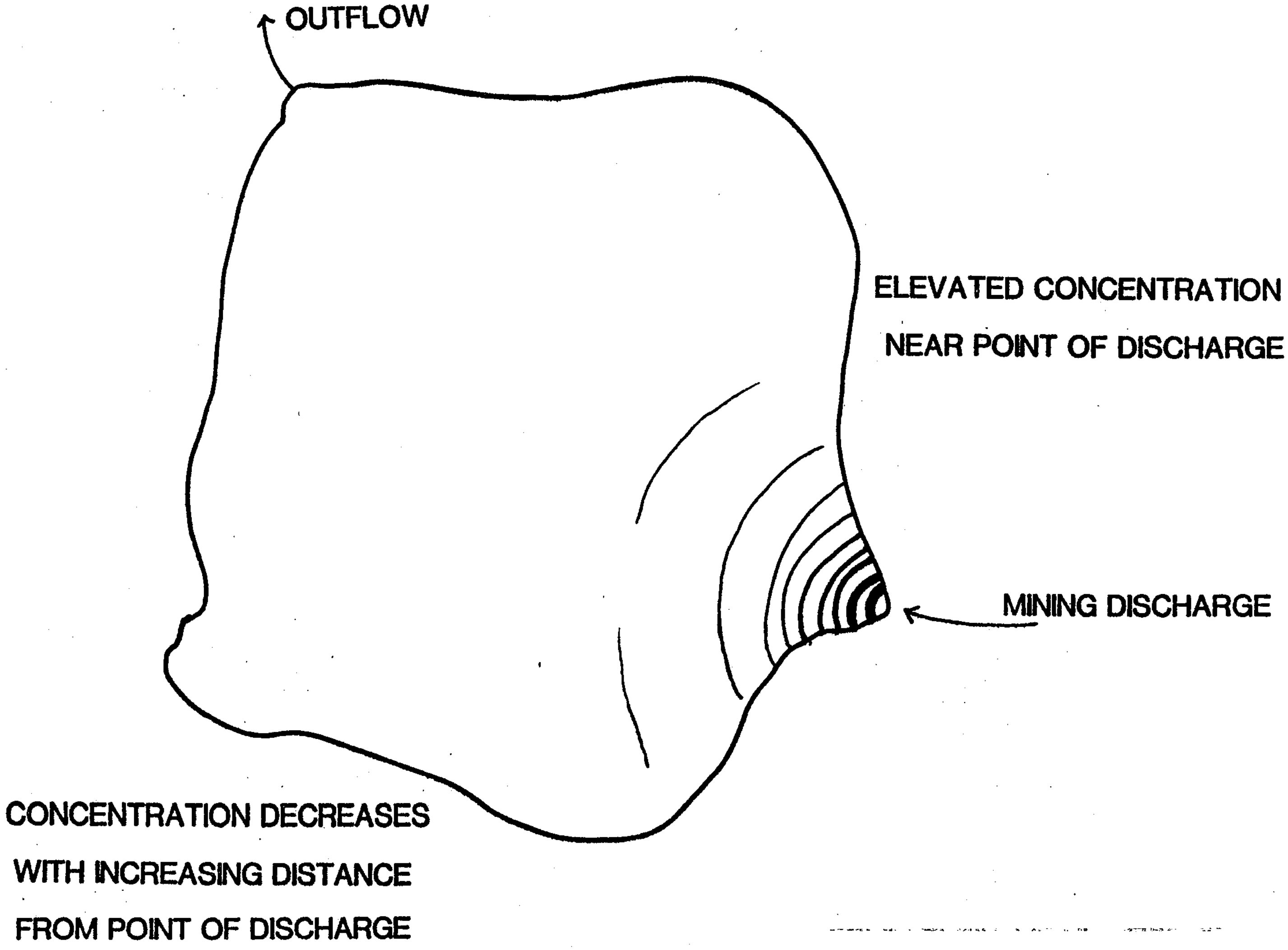
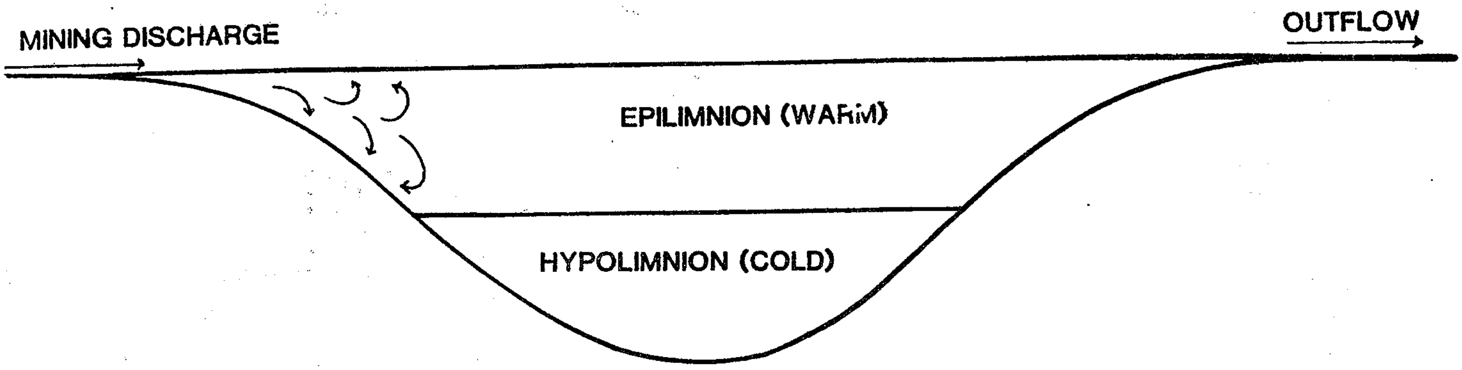


FIGURE 68

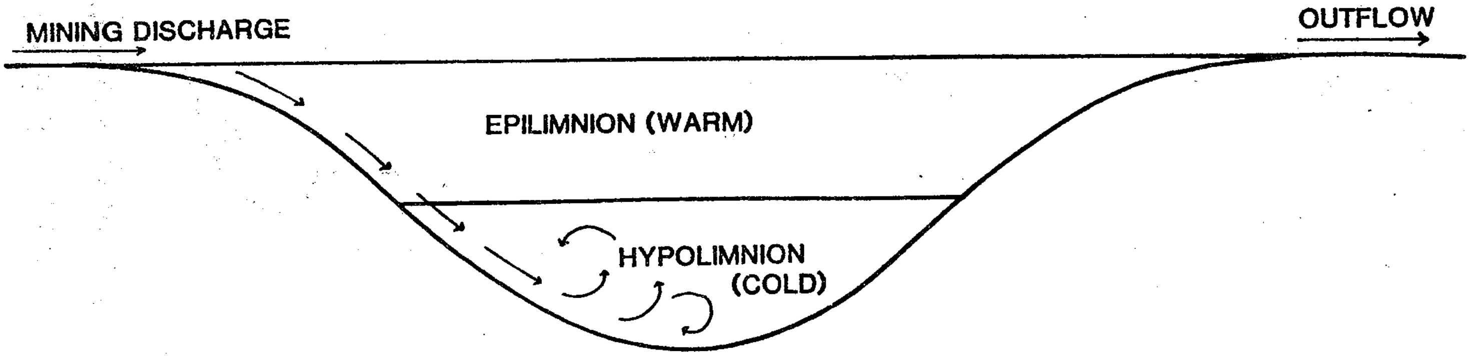
DISCHARGE INTO STRATIFIED LAKES: SUMMER

WARM MINING DISCHARGE



POTENTIAL FOR ENTRAPMENT OF TRACE METALS IN EPILIMNION

COLD MINING DISCHARGE



POTENTIAL FOR ENTRAPMENT OF TRACE METALS IN HYPOLIMNION

4.7.4.2 Lake Impacts. Table 93 provides information on monitored lakes in the Study Area, including dilutional watershed, flushing rate, and tendency to stratify.

Table 93

Table 94 displays the likely impacts on a few monitored lakes for the operational phase models A, B, and C, and the post-operative phase models I and II. These results occur only after the lake concentration reaches the level of the inflow concentration, and how long this takes depends on the flushing rate.

Table 94

As in the case of streams, the larger the dilutional watershed, the less the probability of adverse impact. For instance, for Model B, lakes with large watersheds like White Iron and Fall show little impact, while lakes with small watersheds like Perch or Tofte would experience definite acute effects from an upstream mining operation.

An alternative way to consider the results of the mass balance technique is to calculate the dilutional area needed to achieve a level of 10 ug/l CEU for each model discharge. This is shown in Table 95 and is similar to Tables 2 and 3 for streams. If a worst case Model A occurs, no lake in Table 93 could dilute it to the desired concentration. Many lakes could accommodate a Model C discharge.

Table 95

Table 93. Characteristics of monitored lakes in the Copper-Nickel Study Area.[a]

LAKE	WATERSHED	DRAINAGE AREA(mi^2) Dilutional	FLUSHING RATE (yr^{-1}) 10-yr ave.	FLUSHING RATE (yr^{-1}) 3/1/76-2/28/77 ave.	STRATIFICATION
Greenwood	Stony River	24	4.53	2.80	Does not stratify
Sand	Stony River	0	3.97	2.56	Does not stratify
So. McDougal	Stony River	0	19.02	10.72	Does not stratify
Slate	Stony River	160	82.20	58.07	Does not stratify
Bear Island	Bear Island River	16	.31	.19	Strongly dimictic
Perch	Bear Island River	0	1.04	.47	Weakly dimictic
Birch	Kawishiwi River	940	5.62	4.61	Does not stratify
Gabbro	Kawishiwi River	370	19.16	14.54	Does not stratify
White Iron	Kawishiwi River	1100	7.83	6.48	Weakly dimictic
August	Kawishiwi River	0	1.35	.67	Does not stratify
Clearwater	Kawishiwi River	0	.15	.07	Does not stratify
Lake One	Kawishiwi River	220	4.83	3.51	Strongly dimictic
Turtle	Kawishiwi River	0	1.22	.63	Does not stratify
Fall	Kawishiwi River	1280	22.62	19.13	Weakly dimictic

Table 93 continued.

LAKE	WATERSHED	DRAINAGE AREA(mi^2) Dilutional	FLUSHING RATE (yr^{-1}) 10-yr ave.	FLUSHING RATE (yr^{-1}) 3/1/76–2/28/77 ave.	STRATIFICATION
Colby	Partridge River	110	12.33	8.46	Weakly dimictic
Big	Partridge River	0	.58	.29	Weakly dimictic
Seven Beaver	St. Louis River	44	5.14	3.29	Does not stratify
Pine	St. Louis River	0	1.09	.56	Does not stratify
Long	St. Louis River	0	7.14	3.83	Does not stratify
Whiteface Reservoir		110	1.62	1.11	Weakly dimictic
Tofte		0	.11	.05	Monomictic
Triangle		0	.33	.16	Strongly dimictic
Bass		0	1.4	.54	Strongly dimictic
Bearhead		0	.33	.17	Weakly dimictic
Wynne		120	7.57	5.24	Strongly dimictic
Cloquet		0	2.95	1.40	Does not stratify

[a] See Mustalish et al. (1978) for additional morphometric data.

[b] To determine the dilutional watershed, the approximate size of a 20 X 10^6 mtpy open pit mine (16 mi^2) has been subtracted from each lake's total drainage area.

Table 94. Impacts on selected lakes for modeled discharges (CEU in ug/l).

LAKE	OPERATIONAL PHASE Model A	Model B	Model C	POST-OPERATIONAL PHASE Model I	Model II
Greenwood	409	119	10	15	394
Perch	2200	640	54	320	8300
Birch	15	4	0.4	0.5	13
White Iron	13	4	0.3	0.4	11
Fall	11	3	0.3	0.4	9
Colby	112	33	3	4	96
Tofte	2200	640	54	320	8300

Table 95. Minimum dilutional watershed area required to reduce CEU concentrations to composite standard (in mi^2).

	OPERATIONAL PHASE			POST-OPERATIONAL PHASE	
	Model A	Model B	Model C	Model I	Model II
To achieve CEUs less than 10 ug/l	1,474	397	24	38	1,203

NOTE: Actual watershed would be tabulated number plus 16 mi^2, to account for area required for 20 X 10^6 mtpy open pit mine model.

4.7.5 Impacts on BWCA Surface Waters

The methods used to analyze impacts on streams and lakes (sections 4.7.2 and 4.7.3) are also applicable for streams and lakes in the BWCA. Potential for impacts on the BWCA can be high, medium, or low depending on the proximity of development to the BWCA and location with respect to the Laurentian Divide (Figure 4).

Development south of the Laurentian Divide (zones 5, 6, 7, and part of 4) is classified as a low impact potential because mining discharges would probably go into streams also south of the Divide and eventually drain into Lake Superior via the St. Louis River.

Development in zone 1 would be classified as having either high or medium impact potential. If discharges were to occur in the eastern part of zone 1, within the subwatershed called K-7 by the Study, there would be little (if any) water for dilution before these waters reached the BWCA. Being on the edge of the BWCA, the impacted waters would soon flow out again. Once any such discharges reached the main channel of flow there would be water (upstream drainage area over 1,447 km^2 or 570 mi^2) for dilution; however, high concentrations would occur within the boundaries of the BWCA.

A medium impact potential is indicated for the rest of zone 1, zones 2, 3, and part of 4. Discharges into surface waters in those areas would eventually enter the BWCA near monitoring station K-1. Before entering the BWCA, discharges in these areas would benefit from the substantial dilution due to the Kawishiwi River (drainage area of 3,489 km^2 or 1,347 mi^2). Because such dilution may not be sufficient to eliminate all risk of impacts from mining discharges, these areas have been classified as having a medium impact potential.

4.7.6 Groundwater Impacts

Although no quantitative analysis was performed on the possible impacts on groundwater, some qualitative conclusions can be drawn. Mining impacted water may seep into groundwater if it flows over permeable material. Among the various mining components, tailing basins and stockpiles provide the greatest potential for significant seepage. The resultant concentration of trace metals is difficult to predict, since it depends on the rate of infiltration, the rate of groundwater flow, and the degree of metal removal by soils.

The potential extent of groundwater impacts is greatest in the high permeability Dunka-Embarrass sand plain and the Aurora area buried sands south of the Stony River. Groundwater in these areas can travel long distances, whereas in most parts of the Study Area flow is restricted by bedrock topography and peat formations. Most groundwater flow in the Study Area north of the Stony River is limited to distances of 1 to 2 miles (Siegel and Ericson 1979).

Groundwater use in the Study Area is generally small, limited to individual homes with the exception of Babbitt (Siegel and Ericson 1979) and Aurora, where groundwater is used as a municipal supply. These sources may become contaminated if they are connected to the mine site by an aquifer of sufficient permeability. Sand and gravel outwash is particularly conducive to providing this unfavorable flow condition.

Groundwater impacts can be minimized by preventing seepage of mining discharges, and is especially important in areas where groundwater is the source of domestic water. Seepage to groundwater could be minimized by siting and construction techniques. Siting components on impermeable materials such as bedrock or peat would limit seepage to groundwater below these materials. Techniques for tailing basin construction which limit seepage have also been developed (see Volume 2-Chapter 3).

4.7.7 Mitigation

Mitigation techniques will be required in the operational and post-operational phase, and include various water management techniques, trace metal removal, and othr techniques including some discussed in section 4.7.1. Continuing research on mitigative techniques is being performed by the Minnesota Department of Natural Resources (MDNR) and others.

4.7.7.1 Water Management. Operational phase water impacts can be tempered by the method of discharge. Using the closed system approach (Kealy et al. 1974) and discharge proportional to stream flow, calculated trace metal concentrations are significantly lower than for uncontrolled discharge. The closed system approach helps mitigate CEU effects in collected water by cycling through the mill, and reduces the need for appropriations from streams. Discharge proportional to stream flow avoids significant mining discharges during low stream flow periods, which would cause relatively high concentrations of chemical parameters. A comparison of dilutional watershed areas required for uncontrolled (constant) and controlled (proportional) discharge is presented in Table 3.

Control of water flow through waste rock piles is another important technique, and is being studied by the MDNR. Revegetation is one such technique; others are the placement of peat or tailings with the piles to remove metals from the leachate (Eger et al. 1979).

Thoughtful location of mining discharges within a watershed is also a mitigative tool. If a sufficiently large upstream watershed is chosen, it ensures sufficient dilutional flow. It also protects against the effects of an accidental release if routine treatment or containment procedures of a mine fail.

4.7.7.2 Treatment of Aqueous Mine Waste for Trace Metal Removal. Treatment methods discussed are based on information from Iwasaki et al. (1975), EPA (1975), Huck and LeClair (1978), and Gott (1978) on treatment of mining waste water. The methods presented are: lime precipitation; lime precipitation and effluent polishing; xanthate precipitation; cementation; and activated carbon adsorption. Additional trace metal removal methods are available and are discussed in the aforementioned sources.

Lime treatment to increase pH is effective largely due to the decrease in metal hydroxide solubility with increasing pH (Iwasaki et al. 1976). Field results indicate the feasibility of industrial application of the technique. Based on published sources, industry data, and analysis of samples, it appears that the concentrations given in the tabulation below may be routinely and reliably attained by hydroxide precipitation in the ferro alloy-ore mining and milling industry (EPA 1975).

Metal	Concentration (mg/l)
Cu	0.03
Ni	0.05
Zn	0.15

Combined, these concentrations would yield a CEU of 50 ug/l, less than Model C's CEU and easily handleable by dilution. Supportive data from copper mining operations have been obtained (Gott 1978; EPA 1975).

Secondary treatment or polishing can be incorporated in addition to lime precipitation, as was demonstrated by a pilot plant for treatment of acid mine drainage. It employed lime and polymer addition, flocculation, clarification, filtration, and sludge recycle. Results are presented below (Huck and LeClair 1978):

Extractable Metal Concentration in mg/l

	Cu	Zn
Input	5-76	22-1590
Clarifier overflow	0.05	0.36
Sand filtration	0.04	0.19

The Climax Molybdenum Company conducted pilot plant studies in which lime precipitate was conditioned in an electrocoagulation cell, then mixed with a polymer flocculant, and finally floated in an electroflotation basin by "microbubbles." Feed concentrations of copper and zinc were reduced from 0.19 and 0.29 mg/l, respectively to 0.050 mg/l (Gott 1978).

Iwasaki et al. (1976) investigated the feasibility of copper and nickel removal by metal-xanthate precipitation, cementation, and adsorption onto activated carbon. Results indicate that concentrations of free copper and nickel can be significantly reduced by metal-xanthate precipitation.

Cementation of copper and nickel onto sponge iron appears to be the most effective of the three methods tested, capable of reducing initial metal concentrations of 10 mg/l to less than 0.01 mg/l. Another possible technique is activated carbon adsorbtion of copper and nickel, but this may not be feasible in field application due to the amount of carbon required (Iwasaki et al. 1976).

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