MINE, WATER & ENVIRONMENT. 1999 IMWA Congress. Sevilla, Spain

THE LIMNOLOGY OF AN OPEN PIT FISH FARM

Kimberly McNaughton[1,] Peter F. Lee[1], D. Lindsay[2], and Michael P. Sudbury[3]

[1]Department of Biology, Lakehead University
Thunder Bay, Ontario P7B 5E1. Canada
Phone: + 1 8073438588, Fax: + 1 8073467796
e-mail: Kamcnaug@ice.lakeheadu.ca

[2]Snow Lake Fish Farms
Atikokan, Ontario, Canada

[3]Falconbridge Ltd.
95 Wellington St. West
Toronto, Ontario M5J 2V4. Canada
Phone: + 1 9053392733, Fax: + 1 9053393465
e-mail: msudbury@cgo.wave.ca

ABSTRACT

The unique geology and physical features of an open pit mine site that contributes to the successful establishment of an aquaculture operation were examined. Located under Steep Rock Lake near Atikokan, Ontario, the high grade hematite ore was exposed by diverting water from the lake and excavating 205 million cubic meters of overburden. Open pit mining took place from 1944 to 1979 and over 85 million tonnes of ore were extracted from the Caland and Steeprock Pits, located in the east and middle arms respectively of the original lake bed. After closure, the pits were allowed to fill with water from rainfall, snowfall and groundwater seepage reaching present depths of over 150 meters. The occurrence of limestone deposits at the site counters the production of acid from waste rock and the water in the pits remained above neutrality. In 1988, Snow Lake Fish Farms began raising trout and salmon species in the Caland Pit. Detailed water quality testing was conducted during 1998. Water chemistry in the two pits was found to be largely dependent on the type of proximal waste rock and surficial geology. The water in the pits differed in metal, anion, cation, conductivity, hardness and dissolved oxygen concentrations. Although there was nutrient loading from excess fish food and feces, phosphorus levels were not elevated in the water column. It was hypothesized that the increases of phosphorus in the Caland Pit were suppressed by the deposition of phosphorus with iron compounds in this deep meromictic basin. The current expansion of the fish farm operation is not expected to increase phosphorus concentrations in the water column, but the volume of usable water may be diminished due to the increased oxygen demand.

INTRODUCTION

Newly scoured surfaces from open pit mining presents a unique opportunity to study the effects of the chemically active rock walls, waste rock, and tailings on these man„made closed lake systems. Generally the composition of the water depends on the minerals present in the exposed rock, their relative abundance, their weatherability, the actual weathering reactions involved, and the drainage condition (Eugster and Hardie, 1978). The utilization of abandoned open pit mines for aquaculture adds additional new chemical variables that increases lake productivity in these unsettled environments.

In northern Minnesota's Mesabi Range, intensive aquaculture operations were established in several abandoned open pits that had moderately hard water (Axler et al., 1996a). In Quebec, a rainbow trout rearing facility was located at Lac Du Passage and was also characterized by slightly basic water (Cornel and Whoriskey, 1993). The acid buffering capacity of these flooded pits can therefore be suitable for fish cultivation. Unfortunately a second problem that often arises from the actual aquaculture operation is the development of anoxic conditions in the hypolimnion caused by the BOD of fish food and feces that settles to the bottom of the pits. In the absence of oxygen, P is released at the sediment:water interface, mixed throughout the water column at spring and fall turnover and results in eutrophic conditions. Any discharge from the pits will adversely affect the water quality of the receiving water body. This was essentially the situation in Minnesota and the inability of the aquaculture company to meet discharge standards ultimately caused its bankruptcy (Axler et al., 1992).

Non compliance of environmental regulations has therefore limited the use of open pits for aquaculture. Nevertheless, the premise of utilizing an abandoned mine site for aquaculture remains attractive from both an economic and social sense. The challenge is to devise a set of criteria for identifying suitable open pits for this purpose and to develop the needed techniques that will limit any detrimental effects on the environment. Falconbridge Inc., Lakehead University and Snow Lake Fish Farms have embarked on a major research program that should result in the successful utilization of abandoned open pits for aquaculture.

GEOLOGY OF THE STUDY SITE

The Study Site is located at the southern margin of the granite- greenstone Wabigoon subprovince of the superior province of the Canadian Shield (Ontario Ministry of Northern Development and Mines, 1994). The Steep Rock area (Figure 1) contains Archean metavolcanic, metasedimentary and intrusive rocks which have been displaced by a series of faults (Shklanka, 1972). These rocks lie on weathered granite rocks which separate the main sections of the ore bodies. The ore is bordered by "Paint Rock", a soft clay-like material eroded from the limestone, and by "Ash Rock" formed from volcanic ash. There are also small patches of conglomerates made up of Archean sand and gravel deposited by an ancient sea (Pye, 1968). The displacement of the granitic masses along the faults caused folding and tilted the ore body and associated rocks to a near vertical position. The ore extended to a depth of 760 m, width of 50 m, and length of over 4 km. The ore consisted mostly of geothite and hematite and averaged 56.5% Fe, 3.42% Si, 0.17% P, 8% Al, and 0.21% Mn (Steep Rock Mines, 1943). Although it is possible the iron originated from volcanic action, the most accepted theory for iron deposition in the region is that the iron was precipitated as oxides in the shallow waters of a Precambrian sea when oxygen became abundant in the water column (Cloud, 1973; Ojakangas and Matsch, 1982). The occurrence of large fossilized blue-green algal mounds at the Hogarth Pit give credence to this hypothesis.

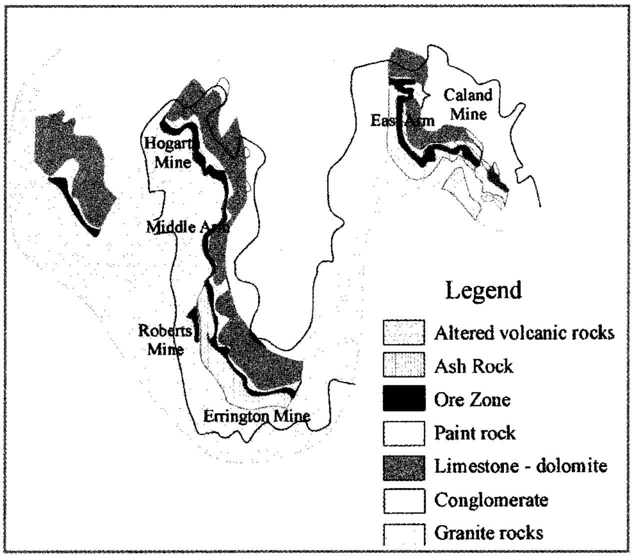

Figure 1. Geological map of the former Steep Rock Lake. The main ore bodies were displaced from each other along large faults (modified from Pye, 1968).

MINING HISTORY OF STUDY SITE

The occurrence of iron bearing rocks in the Atikokan region was first recognized by in 1891, but it was not until 1930 that the ore bodies were located below Steep Rock Lake (Steep Rock Mines, 1943). Since the iron ore body was located under Steep Rock Lake, the lake had to be drained. This was accomplished by diverting the inlet, the Seine River, to flow through Finlayson Lake and installing a series of dams (Figure 2). The Middle and East Arms of the lake were pumped dry and about 205 million of overburden were removed. Steep Rock Iron Mines mined the Middle Arm of Steep Rock Lake (Hogarth Errington, and Roberts Pits), while Caland Ore mined the East Arm of Steep Rock Lake (Caland Pit). Both companies had ore pelletizing plants. From 1944 until 1979 when the mines were closed, over 85 million tons of ore were removed (Pye, 1968). After mining ceased, the rights to the land reverted to the Government of Ontario and the pits began to naturally fill with water.

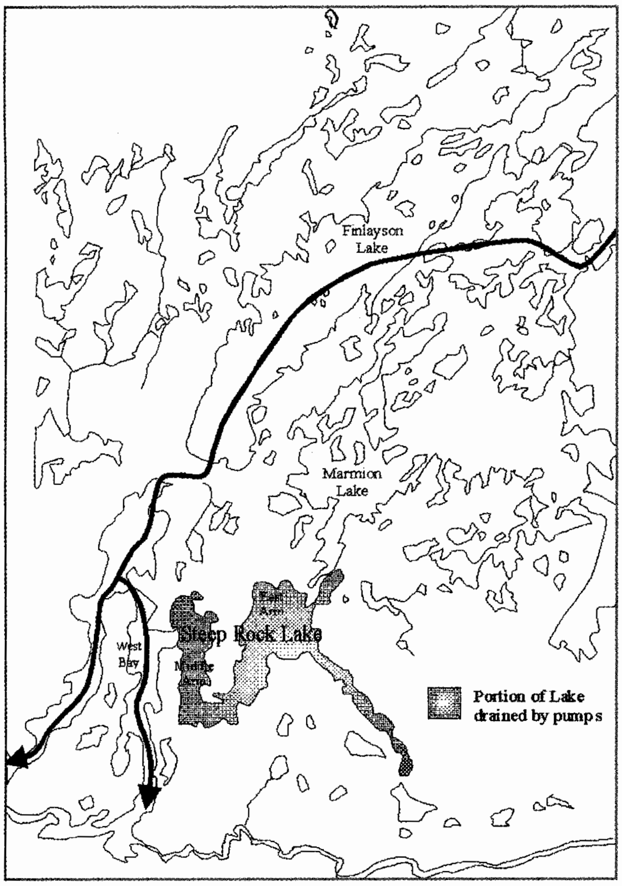

Figure 2. Location of open pits (Caland and Hogarth) that were utilized after Steep Rock Lake was drained. The arrows indicate the flow of water after Steep Rock Lake was drained (modified from Pye, 1968).

SNOW LAKE FISH FARM

Snow Lake Fish Farm was established in 1988 in the Caland Pit. It uses cage culture to raise primarily Rainbow Trout. The cages are extended in the water column to a depth of 20 m. The fish are raised throughout the year but growth occurs primarily in the summer. The normal procedure is to place trout fingerlings in smaller 7.6 m diameter cages in the spring where they remain until they are 10 cm in length. The fish are then transferred first to cages 15 m in diameter and finally to 23 m diameter cages where they are grown to market size (1-2 kg). The larger cages have a capacity of 20,000 kg in the summer and 40,000 kg in winter. Processing of the fish was done on site in a floating building until recently when a processing plant was built in the nearby town of Atikokan. Until 1998, maximum production on the lake was 52,000 kg/yr. In 1998, a major expansion of the facility was undertaken to gradually increase production to 225,000 kg/yr (Snow lake Fish Farms, 1997). The major concern with the fish farm is the effect on water quality caused by wasted feed and fish excretion. An assessment of the carrying capacity of the pit by Chapman (1997) determined that increased P inputs could have a severe impact on water quality and lead to oxygen depletion.

STUDY SITE

The study site consists of an open pit used for aquaculture and a similar nearby open pit that has no aquaculture. These pits are located at the former site of Steep Rock Mines at Steep Rock Lake (48º 48'N, 91º39'W) near Atikokan, Ontario, Canada (Figure 2). Caland Pit, located in the former East Arm of the lake, has an active aquaculture operation. It currently has a depth of 180 m with an area of 1.5 km^2 and acts as the test site. Hogarth Pit, located in the northern part of the former Middle Arm, contains no fish and acts as our control site. Hogarth has a depth of approximately 155 m and an area of 1.6 km^2. Both pits continue to increase in depth from rainfall and runoff, and, by the year 2030, Caland Pit will be connected to Hogarth Pit. At that time, the maximum depth of the newly connected pits will be 425 m with a combined area of 13.4 km^2 (Chapman, 1997). Currently, the Caland and the Hogarth Pits have a bowl/cone shaped basin morphology with very low surface area to depth ratio. These lakes are steep sided and well sheltered from winds thus promoting a meromictic environment.

METHODOLOGY

The Ontario Ministry of Environment (MOE) collected water samples from both the Caland and Hogarth pits from 1988 to 1993 inclusive. Their water chemistry analysis followed the Ontario Ministry of Environment Laboratory Guidelines (MOE, 1988-93).

More currently, June and July 1998, Caland and Hogarth were sampled for the corresponding water chemistry parameters at depths: epilimnion (1m), metalimnion (approx. 6 m), hypolimnion (30 m) and (1 m) off-bottom (175 m and 155 m respectively). The water samples were analyzed in the Lakehead University Environmental Laboratory (1998) following their Standard Operating Procedures including Quality Assurance/Quality Control protocols. The Caland upper water parameter measurements were quite similar and thus combined over the two month sampling period, similarly the lower two sampling depths were combined over the same period. In Hogarth, there was no significant difference among the depths thus the 4 sampling depths were combined over the two months. A combined mean summary of the earlier MOE and current data are included in Table 1.

RESULTS AND DISCUSSION

The MOE results (Table 1) show that Hogarth had higher concentrations of Ni, Fe, Mn, Conductivity (EC-$uS.cm^{-1}$), hardness, Mg, Ca, Na, K, and particularly SO_4 compared to Caland. In the summer of 1992, four years after fish farming commenced, dissolved O_2 levels were similar in both pits at a depth of 1 m, but at the 10 and 40 m depths, Caland had substantially lower oxygen levels (5.0 mg/l) than Hogarth (9.0 mg/l)

(Figure 3). Combined average P concentrations were below method detection limit, 5 ug/l, but NO_3 concentrations were substantially higher in the Caland pit. Recent findings are similar in the comparison between the two pits (Table 1).

Currently, the majority of the measured parameters in the upper waters of Caland have decreased in concentration over the past several years even with the increase in farming production. Alternately, the lower waters have increased in anion, cation, and metal concentrations, especially NO_3 (Table 1), but has severely decreased in dissolved oxygen (Figure 3) compared to the MOE data. The characteristics of the main water quality concerns associated with the fish farming practice are discussed below.

Phosphorus

At the fish farm there does not appear to be a problem as yet with the phosphorus levels as they remain below method detection limits (5 ug/l). Chlorophyll readings are also reflective of an oligotrophic environment. Essentially, under oxidized conditions, P precipitates with FeOH complexes, but under anoxic conditions the P is released as Fe^{+++} is converted to Fe^{++} (Mortimer, 1941). In the open pit situation, the continuous supply of oxidized iron from the waste rock should remove P from the water column, but this P is becoming available again for biological uptake and possible eutrophication risk as the redox boundary is currently at the 20 m depth. The released iron rapidly forms an insoluble bond with sulfur at these low redox levels and precipitates (Wetzel,

	1	2	3	4	5	6
Alkalinity	125,45	141,39	169,55	158,94	95,74	65,91
Conductivity	724,25	863,09	1131,58	981,13	2438,08	2081,54
DIC	33,98	na	63,91	na	29,39	na
DOC	4,44	na	4,31	na	2,52	na
Hardness	360,6	490	616,71	552,38	1680,62	1382,08
Cl	8,45	12,43	13,73	13,06	18,04	15,49
NO_3	3,04	3,45	5,3	3,73	1,61	1,1
Ca	83,72	106,36	133,95	122,13	337,14	295
K	4,61	4,62	6,13	4,76	6,98	5,52
Mg	36,8	54,45	68,54	60,13	208,35	166,15
Na	11,91	16,27	18,62	18	24,99	23,08
Al	*	*	*	*	0,02	0,02
B	0,06	0,05	0,06	0,06	0,05	0,05
Be	*	*	*	*	*	*
Cd	*	*	*	*	*	*
Co	*	*	*	*	*	*
Cr	*	*	*	*	*	*
Cu	*	*	*	*	0,01	*
Fe	0,02	0,06	0,03	0,04	0,4	0,29
Mn	0,01	0,04	0,13	0,01	0,16	0,34
Mo	*	*	*	*	*	*
Ni	*	*	*	*	0,07	0,1
Pb	*	*	*	*	*	*
Sr	0,63	0,3	1,05	0,25	1,48	0,28
V	*	*	*	*	*	*
Zn	0,04	*	0,01	*	0,01	*
SO_4	250,92	327,36	475,92	365,25	1902,54	1314,92
NH_4	0,02	*	0,01	*	0,02	*
pH	7,98	8,2	7,08	7,73	7,12	7,39
SiO_2	2,16	3,32	9,41	3,98	9,58	3,53
TDS	435,7	724,45	835,6	834,88	2492,46	2138,38
TKN	0,08	0,58	0,1	0,36	0,02	0,15
TP	*	*	*	*	*	*
TSS	*	*	*	*	*	*

Caland Upper June&July, 1998	1
Caland Upper J/J 88, 90, 92, 93	2
Caland Lower June&July, 1998	3
Caland Lower J/J 88,90,92.93	4
Hogarth June&July 1998	5
Hogarth June/July 88,90,92,93	6

(*) is less than method detection limit

Table 1. Mean values collected and pooled from MOE records in June & July 1988,93, compared to recent data collected from same months in 1998. All parameters are in mg/l except for pH and EC (electrical conductivity umhos/cm).

1983). Axler et al. (1995) suggested that although P-release from anoxic sediments would probably increase it would not likely impact water quality since the increased P-levels would occur far below the euphotic zone (typically 10-20 m).

Nitrogen

The free ammonium levels have remained quite low at the fish farm (0.02 mg/l) despite intense feeding during the fish growth season. Bergheim et al. (1991) stated that only 25-30% of the nitrogen and phosphorus in feed is typically retained in the fish, the remainder being lost to the environment. High rates of nitrogen loading as excreted ammonium may contribute to excessive algal growth, increased rates of oxygen depletion (via nitrogenous BOD), and potentially to unionized ammonia toxicity (Axler et al., 1996). These low ammonium levels leads to a belief that nitrification must be occurring fairly rapidly in the Caland system as neither ammonium toxicity or algal growth are of immediate concern.

Total Kjeldahl Nitrogen and NO_3 levels (Table 1) have decreased in the upper waters of Caland compared to earlier findings which may be due to increased hypolimnion anoxia. Axler et al., (1995) suggested a management option of providing some control of NO_3 buildup by denitrification would require allowing bottom waters to become anoxic for a period of time. Losses of nitrogen occur by reduction of NO_3 gas by bacteria with subsequent return of N_2 to the atmosphere (Wetzel, 1983). In the Caland pit though, monimolimnetic levels of NO_3 have increased which may be caused by insufficient numbers or inhibition of denitrification bacteria due to high concentrations of other elements.

Oxygen

Figure 3 shows that Caland's oxygen concentration has become severely depleted below 20 m depth. Axler et al. (1996) states that in intensive aquaculture systems, organic enrichment comes primarily from uneaten food and fish feces which is dispersed to the surrounding water, and numerous studies have demonstrated hypolimnetic and sediment anoxia due to this organic enrichment. However, it is uncertain at this time if this depletion is the single result of organic enrichment, oxidation to SO_4 and NO_3, or the onset of the meromictic environment as depth: surface area ratio increases.

The Caland site is currently conducive to the description of a meromictic system with its top 20 m of water seasonally mixing and stratifying while its lower waters are stagnant, anaerobic, and more saline (Table 1). Caland's 1998 oxygen profile (Figure 3) as well as its temperature profile (Figure 3) are now reflective of this environment. Hogarth, however, does not fit the norm as this waterbody is oxygenated from top to bottom (Figure 3), has higher concentrations of most elements compared to Caland, and appears devoid of aquatic life.

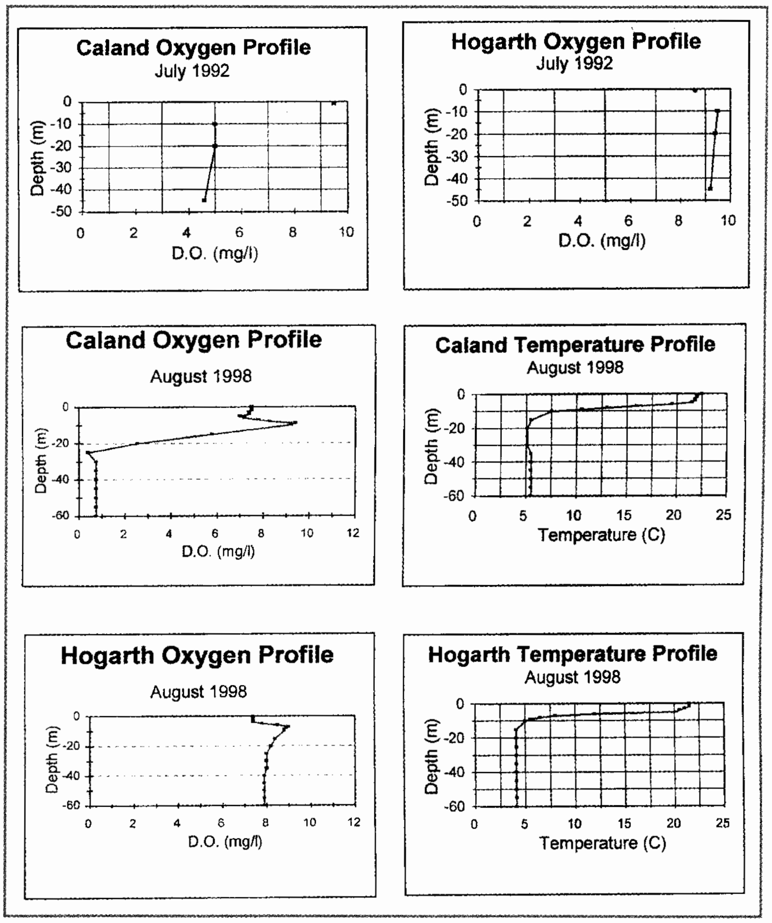

Figure 3. Dissolved oxygen and temperature profiles for Caland and Hogarth Pits.

Sulfate

In Caland, SO_4 levels have substantially decreased in the upper waters (by approx 75 mg/l) and conversely increased in the lower waters (by more than 100 mg/l) compared to MOE data (Table 1). These changes are most likely due to the recent formation of the meromictic environment. Reduction of sulfate to sulfide occurs under anoxic conditions by sulfate reducing bacteria. Cole (1994) states that the monimolimnia may contain appreciable quantities of the very soluble gas H_2S especially in regions high in edaphic sulfate. This gas may be released into the air or re-oxidized to SO_4 in the overlying water column. This re-oxidation increases COD thereby depleting dissolved oxygen. The presence of high concentrations of SO_4 in the anoxic waters of Caland coincides with a theory that there may be too much SO_4 loading for reducing bacteria to reduce to H_2S. A potential problem at the fish farm may be elevated H_2S concentrations which are poisonous to aerobic organisms, by inactivating the enzyme *cytochrome oxidase* (Cole, 1994).

Mortimer (1941) suggest that anoxic sediments rich in organic matter release gaseous hydrogen sulfide. This rotten-egg odor is apparent in the sediment samples below the fish farm, as is the characteristic sapropel.

There are currently substantially higher concentrations of SO_4 in Hogarth compared to Caland and compared to prior

MOE data (Table 1). Since Hogarth is oxygenated for its entire water column, SO_4 remains in its most stable form and its concentration changes little with depth. These elevated concentrations may be due to higher quantities of pyritic hematite in the Middle Arm compared to the East Arm (Ontario Department of Mines and Northern Affairs Map, 1972). The formation of acidic effluents is associated with ore bodies containing the more readily oxidizable iron sulfides, such as pyrite and pyrrhotite (Mining, Mineral and Metallurgical Processes Division, Environment Canada, 1987). Monitored (but unreported) direct drainage into Hogarth is more acidic ie. pH range of 2-5 compared to drainage into Caland pH of 7-8. This lower pH increases leaching from the waste rock and tailings and thus increases concentrations of elements in the water column. With both pits being closed basins, salinity may increase over time (detectable in Hogarth when comparing concentration over time) depending on drainage/rainfall, solute load, evaporation, and precipitation of elements.

Calcium & magnesium

Hogarth and Caland are buffered from acid mine drainage due to naturally occurring limestone and dolomite deposits. In Hogarth, the calcium and magnesium concentrations are 337 mg/l and 208 mg/l respectively, which are much higher than Caland (Table 1). Normally, the concentration in limestone/carbonate area lakes ranges for calcium from 30-100 mg/l and magnesium from 5-50 mg/l (Lind, 1985). These higher concentrations in Hogarth are likely due to dolomite solubilization and the release of Ca and Mg in equal proportions. Dolomite is found in higher quantities around the Hogarth minesite compared to the Caland site, which seems to have more calcium carbonate (Geological Map, 1968 and 1969). In a lake environment, as soon as the $CaCO_3$ threshold is reached with warming epilimnetic temperatures, calcite precipitates reducing the Ca:Mg ratio (Deckker and Last, 1988). Magnesium is required in the chlorophyll molecule but very high levels of magnesium salt produce anaesthesia in both invertebrates and vertebrates (Cole, 1994).

Biotic activity in Caland versus Hogarth

From plankton tows, Hogarth appeared devoid of aquatic organisms even though high concentration of oxygen extended down to the sediment/water interface (>150 m). Possible explanations for the lack of life include: elevated magnesium salt concentrations producing anaesthesia in invertebrates and vertebrates; increasing salinity affecting/disrupting organisms' osmotic capabilities; and/or presence of toxic substances. Ripley et al. (1996) states that one of many minor constituents commonly found in iron ores is arsenic. High levels of arsenic were found in lichen and conifer needle tissue from reports by the Hydro Generating Station on Marmion Lake. Another possible explanation may be the presence of buried toxicants (e.g. PCB's) left behind by Steep Rock Inc. after closure.

Differences between these two pits can be attributed to a variety of factors: presence of the fish farm, geological variations, and, different types and/or different quantities of waste rock at the two mine sites. Changes over time, however, can be attributed to the depletion of oxygen (in the Caland site only), rising water levels submersing new rock/tailing surfaces, and increases in salinity resulting from evaporation in closed basins. Further water sampling, toxicity testing, controlled in-lab experiments, and sediment and rock analysis will be studied to determine the magnitude of effect on these environments.

REFERENCES

Axler, R., S. Yokom, C. Tikkanen, J. Henneck, M. McDonald, 1995. Effects of aquaculture on mine plit lakes near Chisholm, MN: restoration of Twin City-South pitlake fallowing and status of Fraser pit lake. Technical Report: NRRI/TR-95-04. 21 pp.

Axler, R., C. Larsen, C. Tikkanen, M. McDonald, S. Yokom and P. Aas, 1996. Water quality issues associated with aquaculture: A case study in mine pit lakes. Water Environ. Res. 68: 995-1011.

Axler, R., J. Henneck, S. Bridgham, C. Tikkanen, D. Nordman, A. Bamford, and M. McDonald, 1996. Constructed wetlands in Northern Minnesota for treatment of aquaculture wastes. Presented at: Constructed Wetlands in Cold Climates. Niagara-on-the-Lake, Ontario, Canada.

Bergheim, A., J.P. Aabel, and E.A. Seymour, 1991. Past and present approaches to aquaculture waste management in Norwegian net pen culture operations. In C.B. Cowey and C.Y. Cho (eds.) Nutritional Strategies in Management of Aquaculture Waste. Proc. First International symposium on Nutritional Strategies in Management of Aquaculture Waste. June 1990, Guelph, Ontario, CAN. Pp. –117-136.

Chapman, G., 1997. Assessment of the Biological Capacity of Caland Lake. Unpublished Manuscript Prepared for Snow Lake Fish Farms. 16 pp.

Cloud, P., 1973. Paleoecological significance of the banded iron-formation. Econ. Geol. 68: 1135-1143.

Cole, G.A., 1994. Textbook of Limnology. 4th ed. Waveland Press Inc: Illinois. 412 pp.

Cornel, G.E. and F.G. Whoriskey, 1993. The effects of rainbow trout (Oncorhynchus mykiss) cage culture on the water quality, zooplankton, benthos and sediments of Lac du Passage, Quebec. Aquaculture 109: 101-117.

DeDeckker, P., and W.M. Last. 1988. Modern dolomite deposition in continental, saline lakes, western Victoria, Australia. Geology. 16: 29-32.

Eugster , H.P. and L.A. Hardie (in A. Lerman), 1978. Lakes: Chemistry, Geology, Physics. Springer-Verlag. New York. p237-293.

Geological Map, 1968 and 1969 in R. Shklanka, 1972. Geology of the Steep Rock Lake area district of Rainy River. Ont. Dept. Mines and Northern Affairs. Geol. Rep. 93. 114 pp.

Lakehead University Environmental Lab., 1998. Standard Operating Procedures. 1985.

Lind, O.T., 1985. Handbook of common methods in Limnology. 2nd ed. Kendall/Hunt Pub. Co: Iowa. 199pp.

Mining, Mineral and Metallurgical Processes Division, 1987. Mine and Mill Wastewater Treatment. EPS 2/MM/3 Environment Canada. 86 pp.

Mortimer, C.H., 1941. The exchange of dissolved substances between mud and water in lakes. (parts I & II). J. Ecol. 29:280-329.

Ojakangas, R.W. and C.L. Matsch, 1982. Minnesota's Geology. University of Minn. Press. 255p.

Ontario Department of Mines and Northern Affairs. Map 2217, 1970. Steep Rock Lake Area, Rainy River District.

Ontario Ministry of Environment and Energy, 1988-1993. Unpublished data. Thunder Bay, Canada.

Ontario Ministry of Northern Development and Mines, 1994. Rock Ontario. Ontario Ministry of Northern Development and Mines. Rock On Series 1, 89 pp.

Pye, E.G., 1968. Geology and scenery, Rainy Lake and east to Lake Superior. Ont. Dept. Mines, Geol. Guide Book 1, 114 pp.

Shklanka, R., 1972. Geology of the Steep Rock Lake area district of Rainy River. Ont. Dept. Mines and Northern Affairs. Geol. Rep. 93. 114 pp.

Snow Lake Fish Farms, 1997. Snow Lake fish farms business plan. Unpublished Manuscript. 41 pp.

Steep Rock Mines, 1943. The Steep Rock iron ore deposits. A story of patient investigation and development. Can. Mining. J. 63: 437-444.

Ripley E.A., R.E. Redmann, and A.A. Crowder, 1996. Environmental Effects of Mining. St. Lucie Press: Florida. 356 pp.

Wetzel, R.G., 1983. Limnology 2nd ed. Saunders College Publishing: Toronto, Ontario. 767 pp.