Implications of Non-Acidic Metal Leaching on Mine Rock Management at a Nickel Mine in Permafrost Terrain: Environmental Baseline Investigation

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Raglan is a nickel-copper mine in the continuous permafrost region of Quebec that commenced operations in 1997. The potentially-acid mine rock was being stockpiled for later backfill of open pits to freeze in-place for permanent storage, while non-acid generating mine rock was stored on surface permanently. However, it has recently been recognized through laboratory and field investigations that nickel leaching occurs for certain rock types that were considered to be non-acid generating. The pre-existing screening criteria were reexamined to address the issue of nickel leaching and cut-off criteria for reactive waste. The more conservative criteria resulted in a significant change in mine plans to dramatically reduce the quantity of mine rock for the project. In addition, a baseline assessment of the mine claim areas was initiated to better define conditions in areas of planned open pits. Natural levels of nickel in the region are elevated but actual values are watershed specific. Surface water quality is now routinely monitored and nickel loadings are evaluated by sub-watersheds to identify pre-mine and mining operations effects. The results of three years of monitoring are summarized.

INTRODUCTION

The mine-mill complex at Raglan Québec, owned by Falconbridge Ltd. and operated by Société Minière Raglan du Québec Ltée (SMRQ), has been producing nickel-copper concentrate since 1997. The initial mining plan included waste management activities that would protect the environment from the effects of acid generation from exposed tailings and mine rock. Ongoing investigations and assessment of mine rock materials have shown that nickel leaching may also occur in the absence of acidic drainage, and that mine waste management plans must consider the potential for nickel leaching in order to be protective of the environment (Rinker *et al.*, 2003). The identification of nickel leaching from mine rock prompted mine staff to reevaluate previous plans and a change in mine plans that reduced rock production by more than 10 M tonnes. As part of the ongoing commitment of SMRQ to prevent environmental degradation resulting from mining activities at Raglan and to complement existing regulatory requirements, additional baseline monitoring was initiated to assess water quality conditions associated with areas where mining activities have occurred or are planned in the future. This baseline investigation was implemented to develop a survey of water quality across the region and to provide an interpretation of the results related to water quality issues in active mining areas and proposed mine locations. It was on SMRQ's initiative to advance studies further than that specifically required by applicable regulations.

OBJECTIVES AND SCOPE

The primary objectives of the baseline investigation were to identify nickel concentrations for background conditions associated with mineralized zones across the Raglan formation, develop a database of water quality information in areas where mining is planned in the future, and to quantify the loading rates associated with sub-watersheds of the Deception River. The focus of the baseline investigation was the collection of water samples across the Raglan formation, with emphasis in areas where future mining is planned, in areas of mineralization. Because of the nature of terrain and water courses, few surface water locations have accumulated sediments that can be sampled and objectively assessed. Therefore, only surface water was sampled and analyzed for metals and other water quality indicators. Where possible, surface flow rates were also estimated or measured in order to quantify loading rates for nickel in the various sub-watersheds of interest.

BACKGROUND

The Raglan mine is located at Katinniq on the Ungava Peninsula in Northern Quebec, 90 km south of Deception Bay, where the mine's port facility is located. The mine is situated on continuous permafrost the extends to about 500 m depth with minimum temperatures of about –7 ^{o}C. The mine site is located about 1130 miles north of Montreal, or approximately 700 miles north of the start of continuous permafrost and about 300 miles north of the treeline. The mine was developed on the Raglan formation. The Raglan formation is composed of a sequence of mafic and ultramafic rocks including basalt, gabbro, peroxinite and peridotite. The mine-mill complex is located near the head waters of the Deception River that discharges in Deception Bay and in the Hudson Straight on the northern shore of the Ungava Peninsula. Mine development will also occur near Donaldson, which is in the Povungnituk River watershed where discharge occurs to Hudson's Bay on the west side of the Ungava Peninsula. A map showing the location of the mine can be seen in Figure 1.

The rock at Raglan can have a wide range of sulphur contents. The values were as high as 1.6% (mainly as sulphide) with nickel content up to about 0.8%. In general, the nickel to sulphur ratios (Ni/S) in the Raglan mine rock exhibit high values compared to mine rock samples at other nickel deposits. Based on a limited database, the ratio of Ni/S in the rock is about 0.55. The main waste sulphide that is generally associated with nickel sulphide deposits is pyrrhotite with only minor amounts of pyrite. Pyrrhotite (FeS) generally contains a maximum nickel content of about 1% by weight. This means that the nickel content of the Raglan mine rock cannot be attributed to pyrrhotite only, suggesting that a significant fraction of the sulphide in the rock is composed of pentlandite ($\{Fe, Ni\}_8S_9$) with the remaining sulphide likely composed of pyrrhotite. The kinetics of oxidation and of metal leaching of the Raglan rock is presented in more detail in a companion paper in this proceedings (Rinker et al, 2003). Kinetic tests, including pH-modified metal leaching tests, clearly showed that the Raglan rock can leach nickel at neutral pH, and that material shown to be "non-acid generating" from the NP/AP ratios leached nickel at significant rates. The results of the mine rock assessment clearly showed that nickel leaching was a key issue for waste management and potential environmental contamination at the Raglan mine. The geochemical investigations also highlighted the potential for nickel leaching as a result of natural weathering of local mineralized rock and the potential for elevated nickel concentrations in drainage from mineralized areas.

The Deception River

The Deception River represents the primary surface water receiver at Raglan. Baseline investigations were conducted on the Deception River system as part of the Environmental Assessment in support of the Raglan project (Roche, 1992a,b). Water quality and sediment data in the Deception River were collected since the 1980s. Elevated nickel concentrations were observed in both sediment and water in the mid-1990s along the Deception River before the Raglan Mill commenced operations. Before 2000, however, little baseline data existed for the smaller streams, ponds and lakes within the Raglan project area (located across the 40-km project zone from Donaldson in the east to East Lake in the west), data that are necessary to determine the effects of mining on water quality in the Deception River system. Mine development is planned at various points along this zone. A site map showing the location of current (Zone 2 and 3) and proposed (triangles) open pit mines is presented in Figure 2.

APPROACH AND METHODOLOGY

Baseline Surface Water Program

These baseline studies were initiated in 2000 with a broad survey of sampling sites to collect information on ambient nickel concentrations in surface water across the region. The results of the study indicated that elevated nickel concentrations occurred in areas that were both undisturbed and disturbed by mining activities and provided a focus for ongoing monitoring that was conducted in 2001 and 2002.

Surface water samples were collected and analyzed for sulphate (unpreserved) and metals (field filtered and preserved with HNO_3). The samples were kept cool and shipped to Philips Laboratories (Phillip) of Burlington, Ontario. Selected duplicate samples were submitted to the laboratory at Raglan for confirmatory analyses. Field duplicates and blanks (filled with de-ionized (D.I.) water supplied by the Stantec laboratory) were also submitted to Phillip as part of the quality assurance/quality control (QA/QC) program.

The purpose of the initial phase of the baseline program was to differentiate between nickel originating from mine related operations and that from natural processes, if possible, in order to establish "pre-mining" background nickel concentrations in surface waters throughout the project area. It was clearly recognized that, while areas of current mining activities will likely exhibit some evidence of enhanced nickel leaching, these areas are also the zones with the highest background nickel levels and would also be expected to exhibit evidence of natural leaching from the exposed mineralization.

Geological and chemical data on solids were compiled in order to determine typical metal concentrations for various rock types across the property. Historical exploration activities were also reviewed to differentiate areas with past mining-related activities, and assist in determining the degree of associated metal loadings on background water chemistry. Based on this data review, samples of surface water were collected in July 2001 from sites representing a range of potential mining activities; from sites adjacent to the mine site activities (mill, tailings, mine rock storage) designated "High" activity zones, to areas with a variety of geology and exploration history designated as "Medium" to "Low" activity zones, to background conditions where only natural loadings were expected.

Ideally, pristine locations not affected by mining related activities or drilling exploration but containing mineralized rocks, would represent appropriate areas to sample for baseline conditions within the area defined as the Raglan formation. A review by geologists at Raglan, however, found that there were no such areas that were untouched by exploration within the baseline study area, as might be expected. However, three areas were selected for further study because there was little exploration activity associated with these areas in the recent past. These areas, which contained mineralized rock at the surface, were designated as surrogate pre-mine sites and were intended to represent locations with little or no mining related activities for comparison to areas with more intensive mining related activities. Additional water samples were collected at these sites to assess the nickel loadings associated with mineralized areas that had been subject to little or no disturbance. Samples were collected in July and August 2001, and the results were compared to concentrations and loadings observed at other locations.

RESULTS AND DISCUSSION

The primary results of this investigation include concentrations of nickel in surface water samples across the Raglan formation, including those associated with current and planned mining activities. In general, concentrations of nickel were above the detection limit (0.002 mg/L) and ranged up to a few mg/L at some locations. The elevated nickel levels were also observed in regions where little or no mining activities have occurred. Many samples, including some from the Deception River, exhibited concentrations that exceeded the Quebec Provincial nickel objective for the protection of aquatic life of 0.02 mg/L (Environnement Quebec, 1998). In general, however, the highest concentrations observed were those associated with mining activities in the Katinniq area, which along with the Donaldson site, represent the richest nickel sources in the Raglan area. Where stream and river flow rates were estimated, nickel loadings were also calculated. The largest nickel loading rates were generally associated with high flow streams or the Deception River. The nickel loading rates of the few kg/day were commonly observed and are representative of the average loading rates in the Deception River. Detailed descriptions of the results and comparisons among areas across the Raglan formation are presented below.

TABLE 1: Summary of nickel concentrations at two selected locations in the Deception River. Mill operation started in the Fall of 1997. All values in mg/L.

Date	MDL[1]	Deception River	
		Downstream[2]	At Mine-Mill[3]
Aug 90	0.01		0.01
07 Jul 91	0.01	0.01	0.01
23 Jul 91	0.01	0.07	0.09
09 Aug 91	0.01	0.01	0.01
18 Aug 91	0.01	0.01	0.01
31 Aug 91	0.01	0.01	0.05
06 Sep 91	0.01	0.01	0.03
12 Jul 94	0.005	0.005	0.005
10 Sep 95	0.001	0.001	0.016
15 Aug 96	0.005	0.005	0.012
07 Jul 97	0.0003	0.0106	0.0105
05 Aug 97	0.0003	0.0047	0.089
07 Sep 97	0.0003	0.0206	0.0776
04-07 Sep 97[4]	0.0005	0.0194	NA[5]
Jul 2000	0.002	0.008	NA[5]
Aug 2001	0.002	0.046[6]	0.099
Jul/Aug 2002	0.002	0.015[6]	0.033

[1] MDL = Method Detection Limit
[2] DEC 6/DEC 100 – approx 6 km downstream of freshwater reservoir
[3] DEC 9
[4] Leclair (2001) Nunavik Research Centre
[5] NA - Data not available
[6] DEC 22 immediately upstream from DEC 6

Deception River

The Deception River has been monitored and sampled since the early 1990s. Regular sampling of the Deception River commenced in 1994, and available data were compiled for several sampling locations representing the period from 1990 to 2002. These data are shown on Table 1. The data are from various studies and samples have been analyzed at different laboratories with different detection limits. Nonetheless, the data are informative and provide an indication of historical nickel concentrations within the Deception River before and since the Raglan Mill commenced operation in the late summer of 1997. In general, the concentrations observed in the Deception River have been above the detection limit. Elevated nickel concentrations have been observed in the river since the mid 1990s. The 1991 samples exhibited elevated levels of nickel up to about 0.1 mg/L.

Natural vs. Mining Related Effects

Nickel concentrations in surface water, from areas representing a range of potential natural and mining-related activities across the Raglan property (July 2000) are summarized in Table 2**.** Results show that Low to Medium activity zones, representing areas relatively undisturbed by mining or exploration, have low but measurable nickel concentrations (0.0036 mg/L and 0.0056 mg/L, respectively) in surface water. The differences between concentrations inside and outside the Raglan formation do not appear to be significant.

High activity zones have average nickel concentrations approximately a factor of ten higher (0.039 mg/L) than those associated with the Low to Medium activity zones. These zones have not experienced mining activity but are highly mineralized and have been drilled extensively, making it difficult to separate the degree of nickel loading associated with mining and drilling activities from natural loading associated with the exposed bedrock geology. The correspondence of the highest concentrations of nickel to areas of highest mineralization and the mine-mill area is not surprising. Monitoring of this area will continue in order to assess any trends with time.

Nickel Concentrations within Watersheds

Water sampling was conducted once in 2000 and three times each in the years 2001 and 2002. Histograms of the number of samples represented by nickel concentration ranges were produced for three areas across the study region. The resulting histograms are shown in Figure 2 (a to c). The areas include the Donaldson area (representing the headwaters of the Povungnituk River in the eastern area of the Raglan Formation), the headwaters of the Deception

River at Katinniq and the East Lake watershed (near the western extent of the Raglan Mine claims). Each of these areas includes either an active or proposed mine or represents a distinct drainage basin. Nickel concentrations were generally detectable throughout the region, and about 44% of the samples, on average, had concentrations above the provincial water quality objective of 0.02 mg/L (Environnement Quebec, 1998).

The distribution of nickel concentrations in the Donaldson area are shown in Figure 2a. The concentrations range from less than detection (0.002 mg/L) to greater than 2 mg/L. For comparison, the water quality objective for the protection of aquatic life is shown on the figure. Almost 50% of the samples in this area exceeded the water quality objective. This area has been subjected to exploration activity and there has been some test mining conducted in the area as well. The distribution of nickel concentrations in the headwaters of the Deception River at Katinniq is shown in Figure 2b. This area represents a region upstream of the mine-mill complex. In this area, 54% of the samples exceeded the water quality objective. This area receives some drainage from areas around open pits, mine rock stockpiles and other areas associated with mining activity and is also the region with the richest nickel mineralization in the Raglan area. The distribution of nickel concentrations in the East Lake watershed is shown in Figure 2c. The water quality objective for nickel was exceeded in 12% of the samples collected in this area.

While the concentrations of nickel can be informative, the values can also be misleading. Some of the observed concentrations represent standing water (because that was the only sample available) and other samples represented flowing streams or rivers. It would be expected that small bodies of standing water would have higher concentrations than streams with high flow rates even if all samples were collected in the same general vicinity. For this reason, it is useful to compare loading rates that apply to flowing water when the flow rates can be estimated. The loading rates are presented and discussed in the following section.

Nickel Loadings

A loading rate for any dissolved substance can be calculated from the product of the concentration and flow rate. The loading rate is expressed as a mass per unit time and in this case the units of convenience are kg/day. In 2001, the flow rates for streams or rivers were estimated visually using approximate dimensions of the flow channel and a visual estimate of flow velocity. In 2002, stream gauge measurements were made at selected sampling sites and flow rates were calculated. The estimated nickel loading rates varied over a wide range. Loading rates up to almost 90 kg/day were estimated in localized drainage from areas around mining activities. These extreme values, however, are likely to be erroneous because of poor estimates of flow rates, where flow occurred in poorly defined channels or below a layer of broken rock. In addition, these extreme loading rates were never observed in channels with flow of greater than 1 l/s. Outside of the mine-mill complex, nickel loading rates were as high as 4 kg/day. The loading rates in the East Lake watershed were as high as 0.1 kg/day. In general, higher loading rates were generally associated with areas that exhibited higher concentrations, but this was not always observed.

TABLE 4: Summary of average and maximum potential loading rates for nickel in the watersheds of interest.

Watershed	2001 Average (kg. Ni/day)	2002 Average (kg. Ni/day)
Povungnituk River	0.46 (2.01)[1]	1.04 (3.58)[1]
Deception River	4.91 (27.99)[1]	3.08 (7.65)[1]
East Lake	0.18 (1.06)[1]	0.04 (0.08)[1]

[1] Value in brackets equals the geometric mean + 2 standard deviations

In order to eliminate extreme values and to assess the larger scale trends, the average loading rates for nickel were calculated for 2001 and 2002 at all of the locations where flow was estimated in each of the watershed areas. The annual average loading rates are summarized in Table 4. The average of all loading rates for the

Deception River watershed was 4.9 and 3.1 kg/day in 2001 and 2002, respectively. The annual average loading rates in the Povungnituk River watershed were 0.5 and 1.0 kg/day in 2001 and 2002, respectively. The East Lake watershed exhibited the lowest annual average loading rates for nickel of 0.2 and 0.04 kg/day in 2001 and 2002, respectively.

Table 4 also shows the average annual nickel loading rate plus 2 standard deviations, which represents a maximum expected value. Because of the large variability observed for estimated loading rates, the maximum values (includes 95% of the anticipated measurements) can be several times larger than the average values. It is evident, however, that the average loading rates in two regions observed in 2002 were lower than those in 2001, and that the values of the standard deviations for the 2002 data are smaller than those calculated for 2001. The lower values in 2002 and the smaller standard deviations are likely the result of more precise flow rates, that were measured in 2002 compared to those that were crudely estimated in 2001. Nonetheless, the results suggest that loading rates for nickel did not increase from 2001 to 2002. Ongoing monitoring of loading rates should provide a useful index of time trends into the future.

The loading rates exhibited significant variation spatially and with time. There are not many trends apparent from the sampling events to date. However, it appears that the largest loading rates are associated with the higher flow periods. This suggests that, rather than causing dilution of nickel concentrations during high flow, a flushing of the soluble nickel from the weathering rock surfaces appears to occur during the high flow periods.

CONCLUSIONS

The results of this study have shown that elevated nickel concentrations occur across the Raglan formation. In general, the concentrations of nickel are highest in areas of significant mining or exploration activity that coincide with areas containing outcrops of nickel-rich rock. However, concentrations above the provincial water quality objectives of 0.02 mg/L (Environnement Quebec, 1998) were also observed in areas where little or no mining related activities had occurred. Nickel concentrations provide a useful index of the amount of nickel released during the weathering of rock exposed to surface, but loading rates provide a better quantification of nickel release in this area.

The results of the baseline investigation show that both concentrations and loading rates for nickel in surface water samples are quite variable. However, both concentrations and loading rates are generally higher in areas of proposed mine development (around proposed pits) compared to adjacent areas with less exposed mineralization at the surface. The results clearly show that concentrations and loading rates are watershed-specific and the observed values need to be carefully considered, prior to the development of any reclamation targets for nickel loadings.

The highest nickel loading rates were observed at the headwaters of the Deception River near Katinniq. These observations are consistent with the expectation that nickel leaching will be enhanced in this area of mining activity and naturally exposed rock that is highly mineralized with nickel. The head waters of the Deception River are closely monitored.

After several years of monitoring in the Deception River, and three years of monitoring in local subwatersheds, there is no evidence of increasing trends with time. Ongoing monitoring results will ensure that any effect of mining activities on water quality will be clearly evident. The Deception River will therefore be protected from significant incremental impact resulting from nickel release because any significant change will be quickly detected and mitigation can be initiated, if required.

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TABLE 2: Nickel concentrations in surface water related to areas that experienced various degrees of mining related activities.

Drilling Activity		Number of Samples	Average Ni Concentration (mg/L)
"Low" to "Medium"	Outside Raglan Formation	25	0.0056
	Within Raglan Formation	14	0.0036
"High"	Outside Raglan Formation	0	---
	Within Raglan Formation	15	0.039
Near Mine Facilities	Downstream	6	0.105
	Up Stream	8	0.0061

TABLE 3: Summary of water quality for non-mineralized and mineralized (pre-mine surrogates with little or no local past drilling) sites.

Area	Mineralization	Number of Measurements	Concentration (mg/L) Sulphate	Concentration (mg/L) Nickel	Nickel Loading Rate (kg/day)
East Lake	Yes	3	2.53	0.021	0.013
	No	6	1.10	0.0125	0.009
Zones 13/14	Yes	2	1.40	0.0065	0.025
	No	5	1.90	0.056	0.004
Boundary Zone	Yes	3	2.52	0.005	0.026
	No	4	5.25	0.0145	0.024

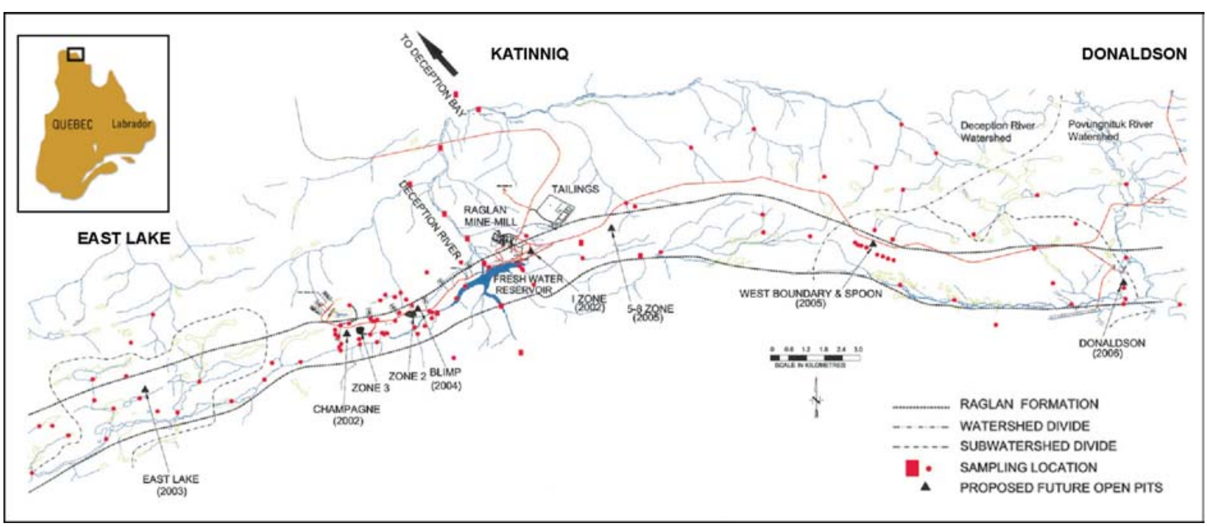

FIGURE 1: Site Map of the Raglan Mine Showing Sampling Locations.

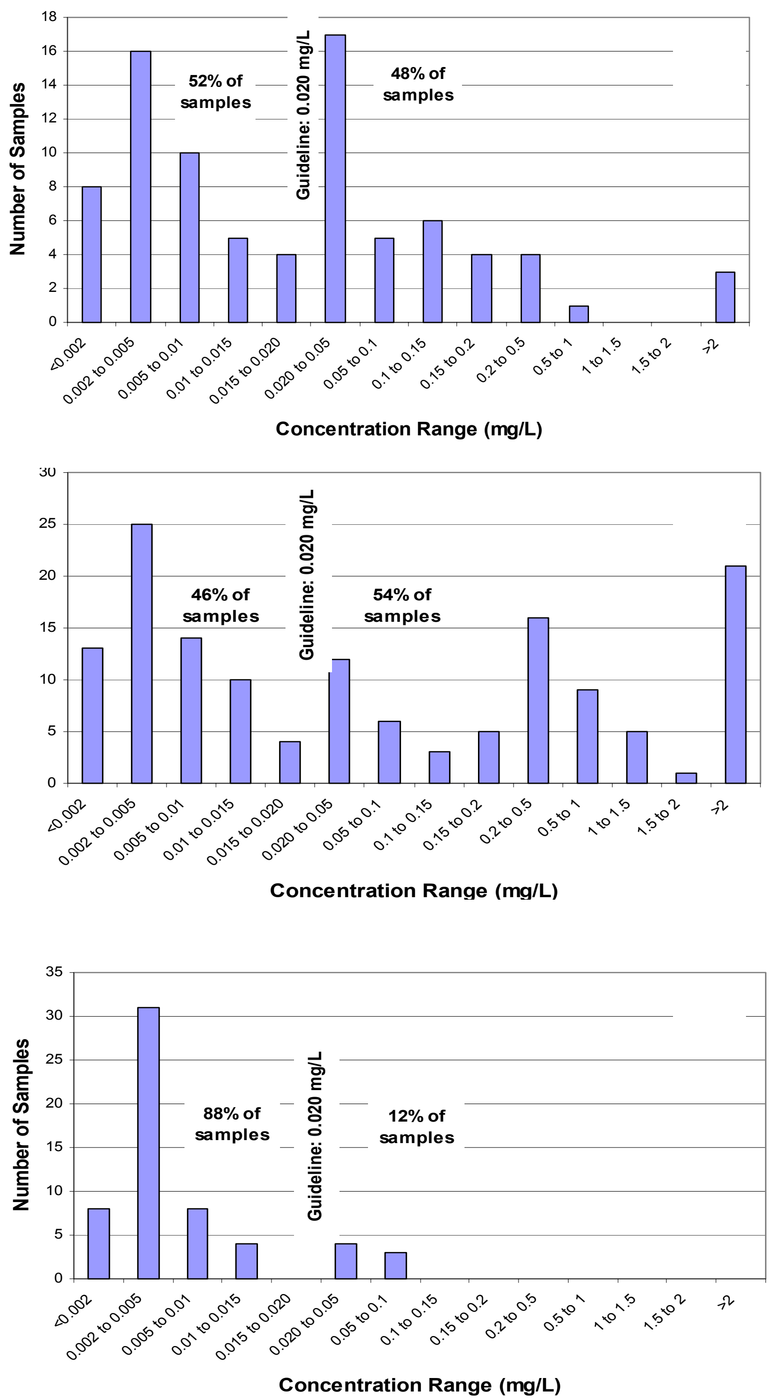

FIGURE 2: Histogram plots of nickel concentrations for the period 2000-2002 by area: A) Povungnituk River Watershed near Donaldson, B) Headwaters of the Deception River at Katinniq, and C) East Lake Sub-Watershed.