Canada's Nuclear Regulator

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Les enjeux de la filière uranifère au Québec

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History of uranium mining in the Elliot Lake region of Ontario and associated effects on water quality and fish intended for human consumption

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Executive Summary

The exploitation of 12 uranium deposits in the Elliot Lake region of Ontario began in the 1950s and 1960s in order to fill military supply contracts and, later, in the 1970s, 1980s and 1990s, to fill supply contracts for nuclear power plants around the world. The low uranium content of the deposits in Ontario compared with those in northern Saskatchewan, combined with lower-than-expected demand for fuel, led to the end of all development activities in the Elliot Lake region. For the most part, mine tailings were deposited in lakes or in valleys with suitable relief to contain the tailings. The large volume of tailings produced necessitated the construction of dams and dikes to contain even larger amounts, so that when the time came to shut down all the mining operations, 9 tailings ponds, all of them formed by dams and dikes, needed to be decommissioned. A multi-criteria decision analysis performed during the environmental assessment process for the decommissioning of the tailings ponds led to the decision to flood 5 tailings ponds and to develop soil covers on 4 tailings ponds in order to minimize acid mine drainage and leacheate containing high levels of metals and radionuclides.

This study reveals that uranium mining in the 1950s, 1960s and 1970s caused irreversible damage to six lakes that were used as tailings ponds. Downstream from these tailings ponds, the mining operations also caused considerable damage to the lakes within the Serpent River watershed. The lakes located downstream from the tailings ponds gradually recovered, and as a result, the ecosystems directly downstream from the tailings ponds are in good health nowadays. The concentrations of ^{226}Ra, uranium and other metals (arsenic, silver, cadmium, chromium, cobalt, copper, molybdenum, nickel, thallium, vanadium and zinc) that are present in the surface waters are generally below the Canadian water quality guidelines for the protection of aquatic life and below the Canadian drinking water quality guidelines. In addition, the general public can safely consume fish from lakes in the region.

It is clear that the tailings management method that was used at Elliot Lake is less and less feasible today. The Canadian Nuclear Safety Commission (CNSC) recommends that tailings be managed in such a way as to minimize long-term monitoring of tailings dams, that is, by depositing radioactive mine tailings, for example, in abandoned open pits or by backfilling underground mine workings to isolate the tailings from overlying ecosystems.

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1.0 Introduction

1.1 History of the development of mining operations

The Cold War in the 1950s led to the discovery of uranium deposits in the Elliot Lake region in northern Ontario. The governments of the day established contracts to supply uranium for military purposes. This led to the construction of 12 uranium mines and 11 associated mills between 1955 and 1958. To support this mining development, in 1954 the Government of Ontario set out to establish a local community to meet the industry's manpower needs. By 1959, the City of Elliot Lake had the infrastructure to accommodate a population of 25,000 people (figure 1).

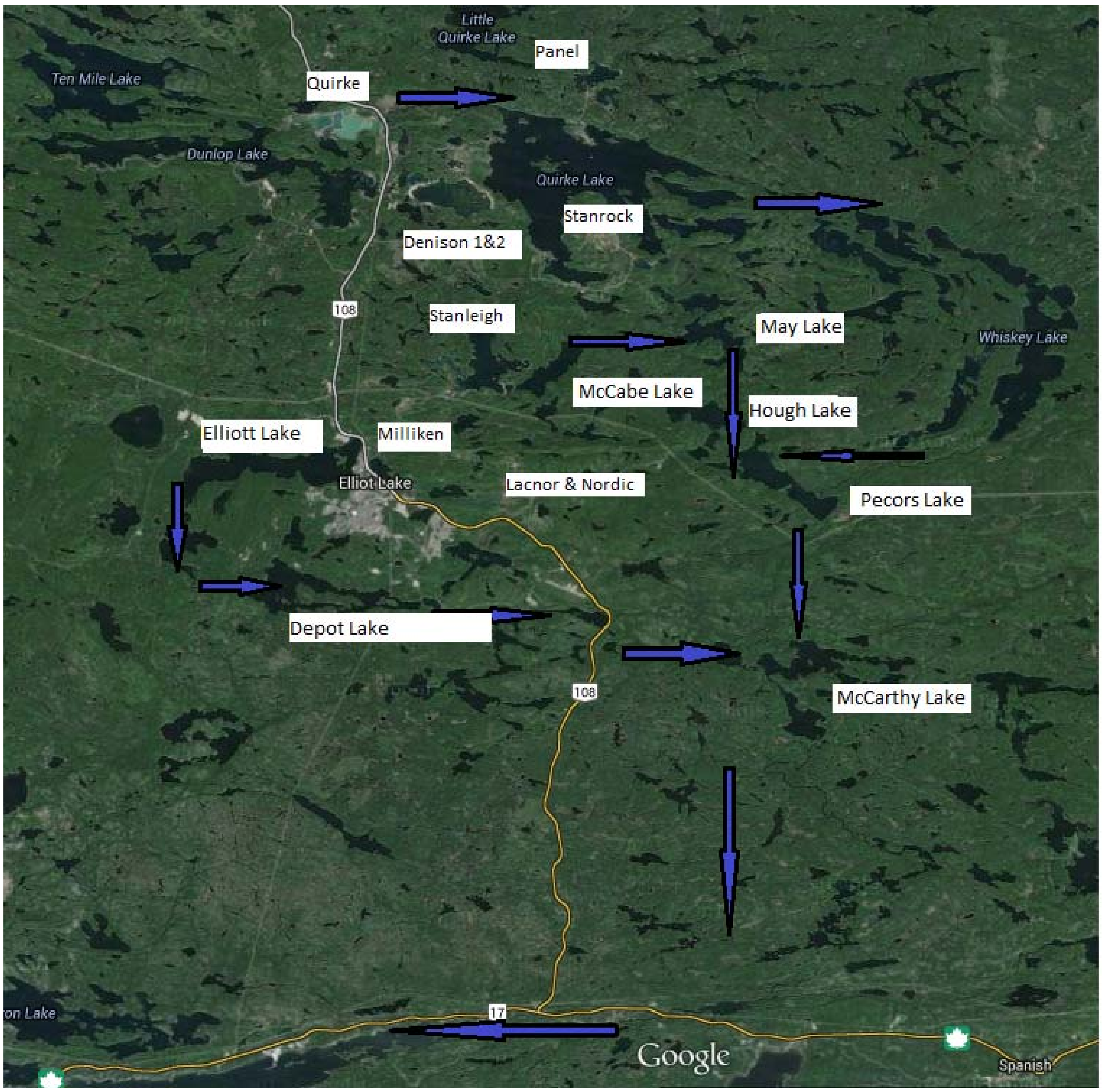

Figure 1. City of Elliot Lake within the Serpent River watershed. The blue arrows indicate the direction of surface water flow.

Most of the uranium extracted from the deposits was supplied to the United States Atomic Energy Commission (USAEC). In 1959, the USAEC announced that it could not extend the supply contracts beyond 1962. At the time, Rio Algom Limited and Denison Mines Inc. were the only companies still working to fill the uranium supply contracts out of the 12 companies originally established some 10 years earlier. In subsequent years, the population of Elliot Lake plummeted to about 7,000 people.

The oil crisis in the mid-1970s created a sudden demand for supplies of uranium fuel for electricity production. Consumers in Western Europe, Japan and the United States wanted to set up supply contracts to meet their long-term needs. Around this time, Rio Algom Limited and Denison Mines Inc. recommissioned the Panel, Stanleigh and Quirke mines.

Toward the end of the 1980s, it became clear that demand for uranium as a fuel for nuclear power plants was much lower than expected and that world supply greatly exceeded world demand. Furthermore, the discovery of high-grade uranium deposits in Saskatchewan made the exploitation of the deposit in the Elliot Lake region economically non-viable. This led to the closure of the Quirke and Panel mines in 1990, followed by the Stanleigh mine in 1996.

1.2 Tailings management during operations and after mine closure

Uranium ore was extracted from the deposits in the Elliot Lake region using sulphuric acid to dissolve uranium from the crushed ore. Ammonia was then used to precipitate the uranium out of solution. This extraction process produced a large quantity of mine tailings containing waste rock, acidic tailings and ammonia residuals to which lime was added for neutralization purposes. This waste was subsequently deposited into tailings ponds. Appendix A provides a more detailed description of tailings management at the different mines in the region.

1.3 Monitoring of tailings dikes and dams

Tailings in the 1950s and 1960s were deposited directly into lakes or natural depressions in the region. This led to the construction of a number of dams to contain the tailings. These dams must be maintained and inspected in perpetuity. The CNSC established the amount of the financial guarantees associated with the licence in order to cover every eventuality.

The dikes and dams in the Elliot Lake area are monitored under a geotechnical inspection program run by Denison Mines Inc. and Rio Algom Limited (licence conditions). The goal of the inspections is to ensure that all structures comply with the 2007 Canadian Dam Association (CDA) Dam Safety Guidelines [1]. Rio Algom Limited and Denison Mines Inc. are required to conduct regular inspections of all dams and dikes from the snowmelt period until the first snowfall the following autumn. The CNSC licence also requires an annual geotechnical inspection by a qualified engineer and a review of the performance data for the different structures. An annual safety review of dams and dikes is also carried out by an independent firm specializing in geotechnics.

In addition, approximately every three years, the CNSC's geotechnical staff conduct geotechnical inspections of the dams to ensure that the licence holders are complying with the dam safety guidelines [1]. The staff also review the annual geotechnical reports and documents concerning dam safety. The inspections carried out by CNSC geotechnical personnel have never identified any serious safety problems with the dams in the Elliot Lake region. In general, the CNSC employees ask licence holders to carry out minor maintenance activities such as the removal of shrubs or young trees whose roots could affect dam stability. These minor maintenance activities are generally carried out in the weeks following the inspections. On the whole, the dams and associated structures are in good condition and are well maintained, in accordance with the CNSC's requirements.

1.4 Decommissioning of tailings ponds

For the decommissioning of tailings ponds, Rio Algom Limited and Denison Mines Inc. considered four decommissioning options: flooding, dry cover, backfilling of tailings in underground workings or backfilling of tailings in Quirke Lake [2]. The companies carried out a multi-criteria decision analysis in order to identify the decommissioning options. This is the approach used nowadays to select a tailings management approach [3] and to identify solutions to environmental problems [4, 5]. The following criteria were taken into account: treatment required in the short and long term, leacheate quality, tailings stability, reuse of tailings, technically feasible construction, practical experience, impacts on future generations, short- and long-term safety of workers and the general public, radiation exposure, costs, short- and long-term responsibilities, effects on the terrestrial and aquatic environment, use of the region in the short and long term, and the possibility of monitoring the performance of the decommissioning option. The multi-criteria decision analysis quickly excluded the option of dumping tailings in Quirke Lake, given the uncertainties related to the long-term impacts and the technical difficulties associated with the dumping of tailings in a lake of its size. Backfilling of tailings was also excluded, mainly because of the costs and the insufficient volume available in the underground mine workings. As a result, decommissioning of the tailings ponds was carried out by the flooding method (i.e., Quirke, Panel, Denison, Milliken and Stanleigh) or by using engineered covers (Lacnor, Nordic, Stanrock).

This tailings management approach based on long-term institutional monitoring of structures such as dikes and dams no longer meets current requirements. Regulatory Guide G-320: Assessing the Long Term Safety of Radioactive Waste Management [6] states that long-term management of nuclear waste should not rely on long-term institutional controls as a safety feature unless they are absolutely necessary. More recently, the CNSC published a regulatory document on the management of uranium mine waste rock and mill tailings [7], which states that the use of natural water bodies frequented by fish should be avoided to the extent practicable for the management of waste rock and tailings and that mine workings such as open pits and underground developments should be used on a priority basis for tailings management. The tailings management practices applied at the sites currently in operation in Saskatchewan meet the CNSC's requirements.

2.0 Environmental issues related to the exploitation of uranium deposits in the Elliot Lake region

Aside from the integrity and stability of the dams at mine tailings ponds, the main issues related to the exploitation of uranium deposits in the Elliot Lake region are acid mine drainage and the mobilization of radionuclides and metals in surface waters downstream from tailings ponds and their impacts on aquatic ecosystems.

2.1 Issues related to terrestrial fauna

The effects on terrestrial fauna were studied by a team of researchers from Laurentian University in Sudbury, Ontario whose work was funded by the CNSC. The studies focused on the radionuclide levels (e.g., ^{226}Ra, ^{210}Po, ^{210}Pb, ^{230}Th) in the tissues of terrestrial animals, specifically the snowshoe hare (*Lepus americanus*) [8, 9], the ruffed grouse (*Bonasa umbellus*) [10], the meadow vole (*Microtus pensylvanicus*) [11, 12], the beaver (*Castor canadensis*) [13] and the muskrat (*Ondrata zibethica*) [14]. The research focused on small game because they have a smaller home range than large herbivores and predators. Small game animals were captured in areas adjacent to one or more tailings ponds in keeping with the species' respective home ranges. The species' limited home range adjacent to the tailings ponds increases their potential exposure to radionuclides compared with the large predators or ungulates, which have a much more extensive habitat, reducing their exposure.

Higher radionuclide concentrations were found in the bones of ruffed grouse [10], snowshoe hare [9] and other species studied [11-14] than in the other tissues examined. Preferential accumulation of radionuclides in bones was also observed in fish [15-17]. This characteristic is associated with a much lower rate of transfer of radionuclides to predators (such as humans) which consume few or no bones. Accordingly, the researchers found very low transfers of radionuclides to humans. Similarly, intakes of radionuclides from the consumption of ruffed grouse tissues, even at exaggerated dietary intake levels, led to doses below the regulatory limit of 1mSv per year. Similar findings were also reported for muskrats [14] and beavers [13], which were eaten in large numbers in the past. Since there was no reason for concern about the consumption of tissues from living animals near tailings ponds, the same conclusion was applied to large ungulates, which have a much larger home range but nonetheless feed on plants. Since those studies were carried out, the environmental assessments conducted by the CNSC have shown that the environmental risks in the Elliot Lake region are associated mainly with the aquatic environment [2]. As a result, monitoring of the quality of tissues from terrestrial fauna has been discontinued. The present report therefore only discusses the impacts on water quality and the quality of fish tissues.

2.2 Issues related to aquatic ecosystems

Until 1965, effluents were released directly into streams without prior treatment. It was not known that the sulphides contained in mine tailings became oxidized upon exposure to air, generating iron salts, metal salts and sulphuric acid. This phenomenon, called acid mine drainage, has been linked to a number of other types of mining. Since 1965, acid mine drainage has been treated with lime to neutralize the acidity of the tailings, maintain the pH of the drainage close to neutral and precipitate certain metals.

In addition to the problems related to acid mine drainage and mobilization of metals, it was not known that radium (^{226}Ra) would be present in large concentrations in the surface water of tailings ponds. Since 1965, the surface water of tailings ponds has been treated with barium chloride in order to precipitate ^{226}Ra. The treated effluents are discharged into the Serpent River watershed. A brief history of tailings management in the Elliot Lake region is provided in appendix A of this report.

Clearly, the practices of the past have given Canadians a bad impression of uranium mining operations. At public hearings held by the CNSC recently, a number of stakeholders stated that the water in the Serpent River watershed is of poor quality as a result of the exploitation of uranium deposits in the 1950s and 1960s and again in the 1980s and 1990s. Although this observation is true for the 1950s, 1960s and 1970s (see below), when there were few regulations in place to protect the environment, the adoption of provincial and federal regulations (*Nuclear Safety and Control Act* adopted in 2000) has helped to improve the state of health of the Serpent River. The purpose of the present study was to prepare an objective report of water quality in the Serpent River as well as of the quality of fish from the river from the standpoint of human consumption.

3.0 Water quality in the Serpent River

This section presents the historical and present effects of discharges from the different mining operations on the quality of the water downstream from the different tailings ponds. It should be noted that from the start of uranium mining operations, water quality monitoring involved measuring the levels of uranium and radium-226 in the water. It was not until the late 1990s that other, non-radioactive substances such as silver, arsenic, cadmium, chromium, cobalt, copper, molybdenum, nickel, selenium, thallium, vanadium and zinc were added to the water quality monitoring efforts on the Serpent River. The concentrations of these metals in the Serpent River are only available as of 1999.

Since the different tailings ponds are located in various subbasins of the Serpent River watershed, water quality will be presented for the following subbasins:

1) water quality in McCarthy Lake and in Serpent River at Highway 17
2) water quality downstream from the Quirke and Denison tailings ponds
3) water quality downstream from the Milliken tailings pond
4) water quality downstream from the Stanleigh tailings ponds
5) water quality downstream from the Lacnor and Nordic tailings ponds

3.1 Water quality in McCarthy Lake and in Serpent River

McCarthy Lake is connected to Pecors Lake and Depot Lake by a tributary (figure 1). Owing to its geographic situation, it could potentially receive contaminants from every tailings pond in the watershed, but the concentrations would be low. The lake has a tributary, the Serpent River, which drains into Lake Huron. This river may also be exposed. Figure 2 shows that during the 1950s and 1960s, the ^{226}Ra levels increased to nearly 1 Bq/L in the Serpent River at Highway 17, in spite of the fact that the highway is more than 20 km from the nearest tailings pond. Those values exceed the present Saskatchewan surface water quality guideline of 0.1 Bq/L and the current drinking water guideline of 0.5 Bq/L. In 1965, when the mines began treating their effluents, the radium concentrations followed a gradual downturn, reaching 0.01 Bq/L in the early 2000s in the Serpent River and in McCarthy Lake. That concentration is 100 times lower than the levels observed 35 years earlier and lower than the current drinking water guideline value.

Despite the increase in the concentrations of ^{226}Ra, the pH of McCarthy Lake and the Serpent River before it empties into Lake Huron remains close to neutral, that is, between Ph 6 and pH 7.

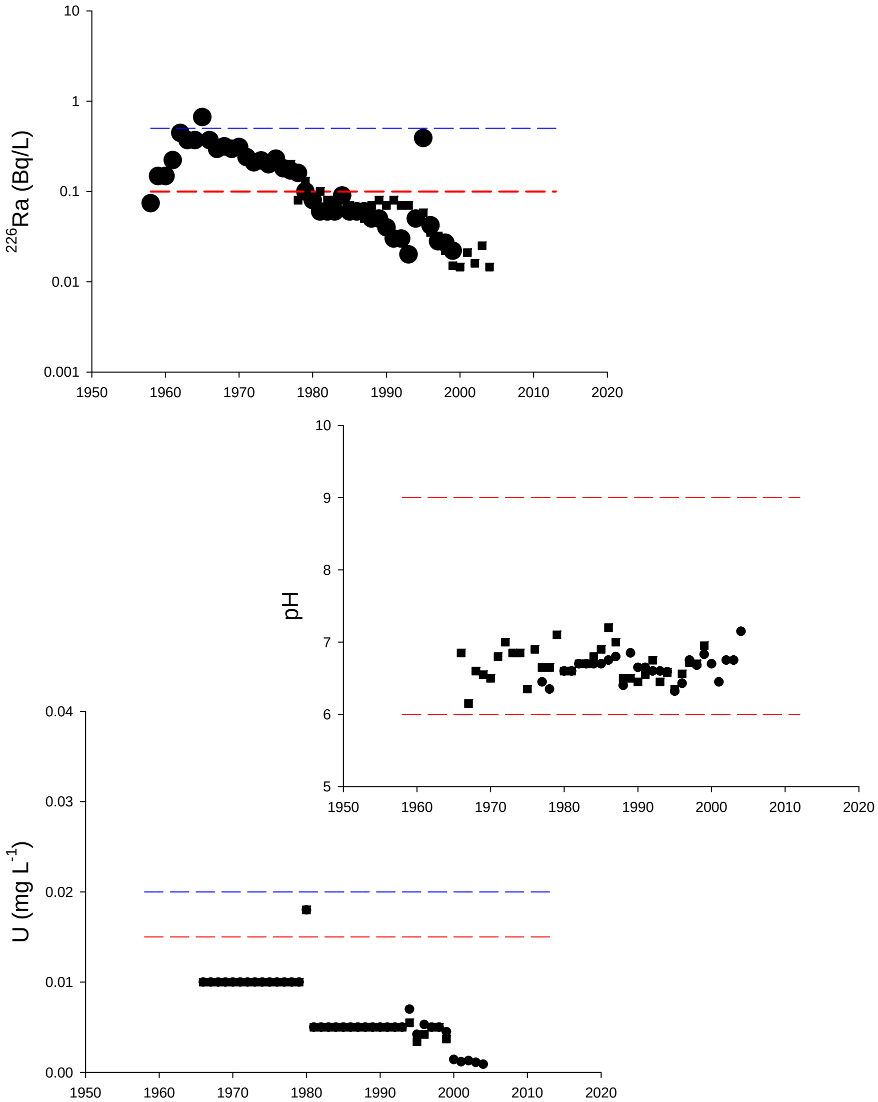

Figure 2. Temporal variation in Radium-226 (upper panel), the pH level (middle panel) and uranium (lower panel) in McCarthy Lake (■) and in the Serpent River at the junction of Highway 17 (●). The red line indicates the Canadian water quality guidelines for the protection of aquatic life. The blue line indicates the Canadian drinking water quality guidelines. The data come from various environmental monitoring reports [18-21, 36].

It can also be seen from figure 2 that the uranium concentrations, although they never exceeded the current Canadian drinking water quality guideline of 20 µg/L and only once exceeded the current water quality guideline for the protection of aquatic life of 15 µg/L, gradually decreased in McCarthy Lake and in the Serpent River farther downstream, reaching levels well below the guidelines for the protection of aquatic life and for drinking water quality.

For the most part, non-radioactive substances in McCarthy Lake were below the detection limits as well as the existing Canadian drinking water quality guidelines and the water quality guidelines for the protection of aquatic life (table 1). Although cadmium levels exceeded the guidelines for the protection of aquatic life, they were below the detection limit.

Table 1. Non-radioactive substances measured in McCarthy Lake in 1999−2000 [18].

	V	Tl	Mo	Cr	Ag	Se	Zn	Ni	Cu	Co	Cd	As
CDWQG*	--	--	--	50	50	--	50	--	1	--	5	10
CWQG**	6	10	73	1	1	0.1	1	25	2	0.9	0.017	5
Detection limit	0.5	0.1	0.8	0.2	0.2	0.06	0.4	0.6	0.1	0.04	0.03	2
McCarthy Lake ***	0.5	0.1	0.8	0.2	0.2	0.1	0.4	0.6	1.1	0.4	0.03	4

* Canadian Drinking Water Quality Guidelines

** Canadian Water Quality Guidelines for the protection of aquatic life

*** Mean measured in 1999−2000

3.2 Water quality downstream from the Denison and Quirke tailings ponds

The Serpent River flows out of Quirke Lake and empties into Whiskey Lake and then McCarthy Lake farther upstream (figure 1). Effluents from the Denison and Quirke tailings ponds located upstream from Quirke Lake empty into the Serpent River, which itself empties into Quirke Lake.

Figure 3 shows the temporal variations in the ^{226}Ra and U concentrations and the pH level in Quirke and Whiskey lakes. A marked increase in the radium concentration was observed in Quirke Lake around 1955: the concentration reached 1.5 Bq/L, which is higher than the current Canadian drinking water guideline. Beginning in 1965, effluent treatment with barium chloride helped to bring about a gradual decline in the radium concentrations in Quirke Lake and consequently Whiskey Lake. Twenty-five years later, in 1980, the levels were below 0.1 Bq/L. Since then, the radium concentrations have remained below the current Canadian drinking water guideline and below the current Saskatchewan surface water quality objective.

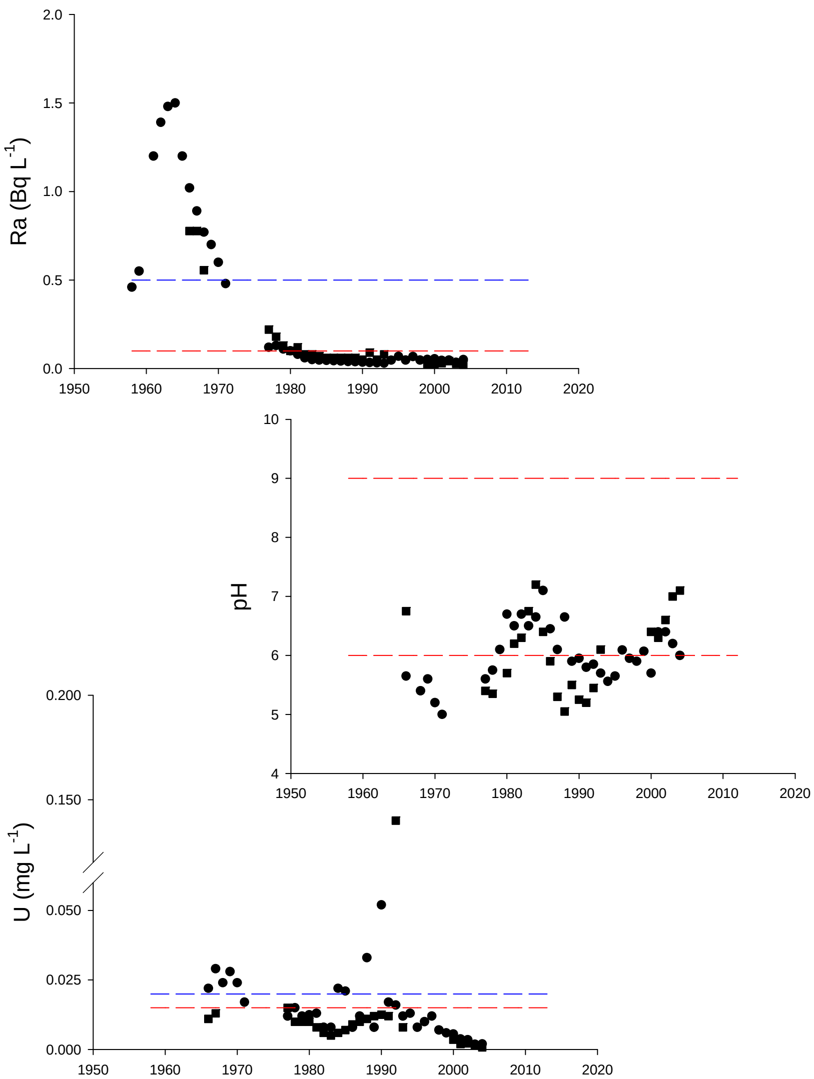

Figure 3. Temporal variation in Radium-226 (upper panel), the pH level (middle panel) and uranium (lower panel) in Quirke Lake (●) and Whiskey Lake (■). The red line indicates the Canadian water quality guidelines for the protection of aquatic life. The blue line indicates the Canadian drinking water quality guidelines. The data come from various environmental monitoring reports [18-21, 26].

The pH level in Quirke Lake was below pH 6.0 during the 1960s (figure 3), in contrast with the situation in McCarthy Lake (figure 2) and Whiskey Lake (figure 3), where the pH level remained neutral. In the 1970s, the pH level remained below pH 6.0 in Quirke Lake and, consequently, Whiskey Lake became acidic as well. The pH returned to a neutral state in the 1980s in both lakes, before dropping back below pH 6.0 toward the end of the 1980s. Since then, the pH in these lakes has returned to a neutral level.

Around the end of the 1960s, the uranium concentrations in Quirke Lake increased to a level higher than the existing Canadian drinking water quality guideline (20 µg/L) and the existing Canadian water quality guideline for the protection of aquatic life (15 µg/L) before falling back below these thresholds as of the mid-1970s. A sudden increase in the uranium levels was noted around the end of the 1980s, just before the sites were decommissioned. Since the 1990s, the uranium levels in these two lakes have remained very low (<0.001 mg/L).

For the most part, non-radioactive substances in Quirke and Whiskey lakes were below the detection limits and below the existing Canadian drinking water quality guidelines and below current Canadian water quality guidelines for the protection of aquatic life (table 2). However, selenium, zinc and cadmium exceeded the water quality guidelines for the protection of aquatic life in 1999−2000. Since then, the selenium and zinc concentrations have fallen back below the water quality guidelines, and cadmium is below the detection limits [19].

Table 2. Non-radioactive substances measured in Quirke and Whiskey lakes in 1999−2000 [18].

	V	Tl	Mo	Cr	Ag	Se	Zn	Ni	Cu	Co	Cd	As
CDWQG*	--	--	--	50	50	--	50	--	1	--	5	10
CWQG**	6	10	73	1	1	0.1	1	25	2	0.9	0.017	5
Detection limit	0.5	0.1	0.8	0.2	0.2	0.06	0.4	0.6	0.1	0.04	0.03	2
Quirke Lake ***	0.5	0.1	0.8	0.4	0.2	**2**	**5**	2	1	1	**0.05**	1
Whiskey Lake	0.5	0.1	0.8	0.2	0.2	**1.5**	**6**	1	1	0.2	**0.18**	1

* Canadian Drinking Water Quality Guidelines

** Canadian Water Quality Guidelines for the Protection of Aquatic Life

*** Mean measured in 1999−2000

3.3 Water quality in Elliot Lake

Elliot Lake is affected mainly by water from the Milliken tailings pond. Although the concentrations of ^{226}Ra and U have always been below the existing guidelines for the protection of aquatic life and below current drinking water quality guidelines, figure 4 indicates that the ^{226}Ra and U levels have decreased since the mid-1960s. The pH level is normal at present, and very close to neutral (figure 4).

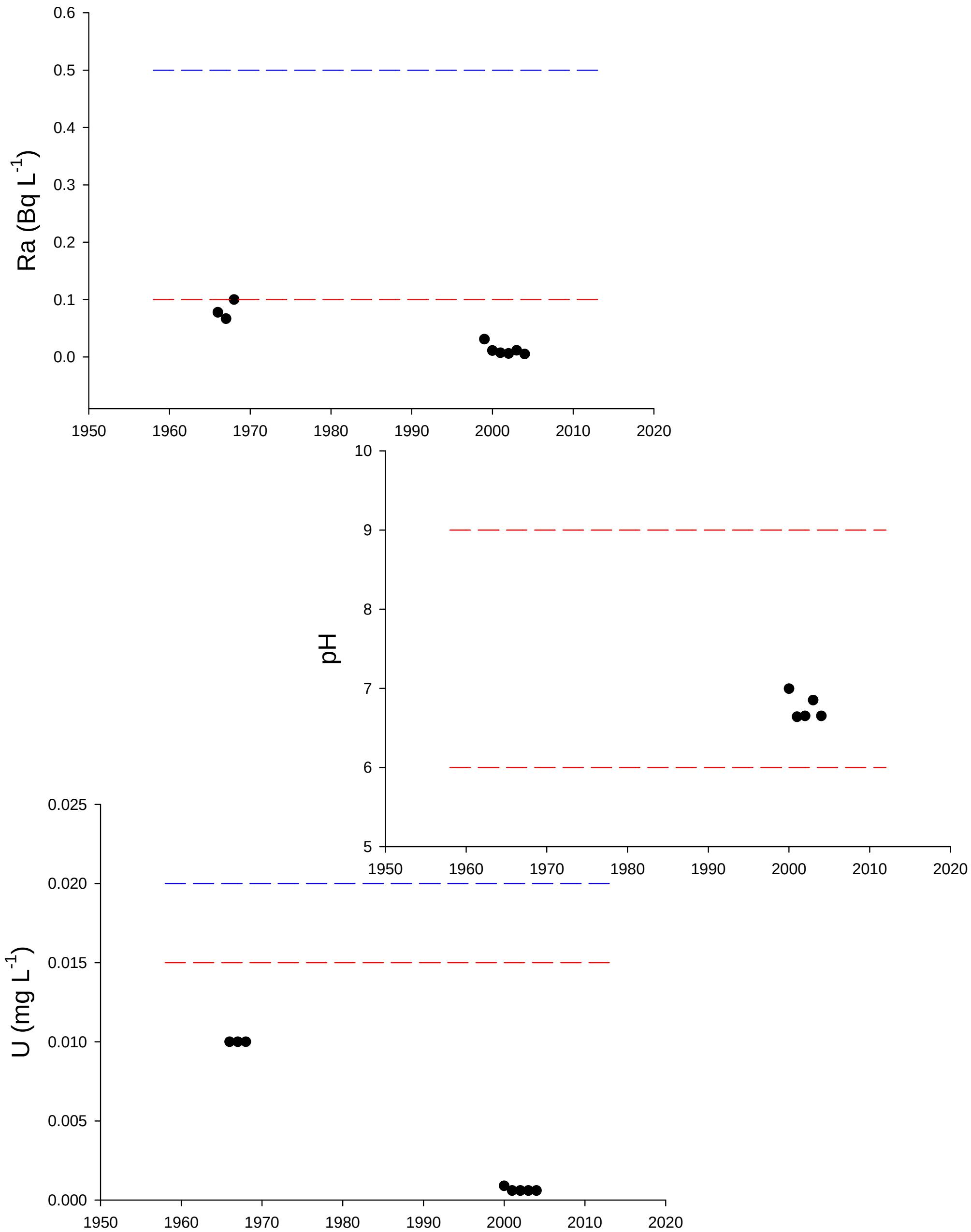

Figure 4. Temporal variation in Radium-226 (upper panel), the pH level (middle panel) and uranium (lower panel) in Elliot Lake (●). The red line indicates the Canadian water quality guidelines for the protection of aquatic life. The blue line indicates the Canadian drinking water quality guidelines. The data come from various environmental monitoring reports [18-21,26].

For the most part, non-radioactive substances in Elliot Lake were below the detection limits and below the existing drinking water quality guidelines and current water quality guidelines for the protection of aquatic life (table 3). Here again, cadmium is below the detection limits but exceeds the water quality guideline for the protection of aquatic life.

Table 3. Non-radioactive substances measured in Elliot Lake in 1999−2000 [18].

	V	Tl	Mo	Cr	Ag	Se	Zn	Ni	Cu	Co	Cd	As
CDWQG*	--	--	--	50	50	--	50	--	1	--	5	10
CWQG**	6	10	73	1	1	0.1	1	25	2	0.9	0.017	5
Detection limit	0.5	0.1	0.8	0.2	0.2	0.06	0.4	0.6	0.1	0.04	0.03	2
Elliot Lake ***	0.5	0.1	0.8	0.2	0.06	0.4	0.4	0.8	1	0.4	**0.03**	1.5

* Canadian Drinking Water Quality Guidelines

** Canadian Water Quality Guidelines for the Protection of Aquatic Life

*** Mean measured in 1999−2000

3.4 Water quality downstream from the Lacnor and Nordic tailings ponds

Runoff and leacheate from the Nordic tailings pond is treated and discharged into Nordic Lake (figure 1). Figure 5 presents the temporal concentrations of ^{226}Ra and U and the pH level in Nordic Lake. In 1965, the ^{226}Ra and U levels exceeded the existing Canadian guidelines for the protection of aquatic life and for drinking water quality. They gradually declined thereafter, falling below the corresponding values in the 2000s. The pH level in Nordic Lake has been normal for a long time, close to neutrality (figure 5).

For the most part, non-radioactive substances were below the detection limits and below the existing Canadian drinking water quality guidelines and current water quality guidelines for the protection of aquatic life in Nordic Lake (table 4). However, the mean Ag and Cd concentrations exceeded the existing Canadian water quality guidelines for the protection of aquatic life. The Ag and Cd levels fell back below the detection limits in 2006 [20].

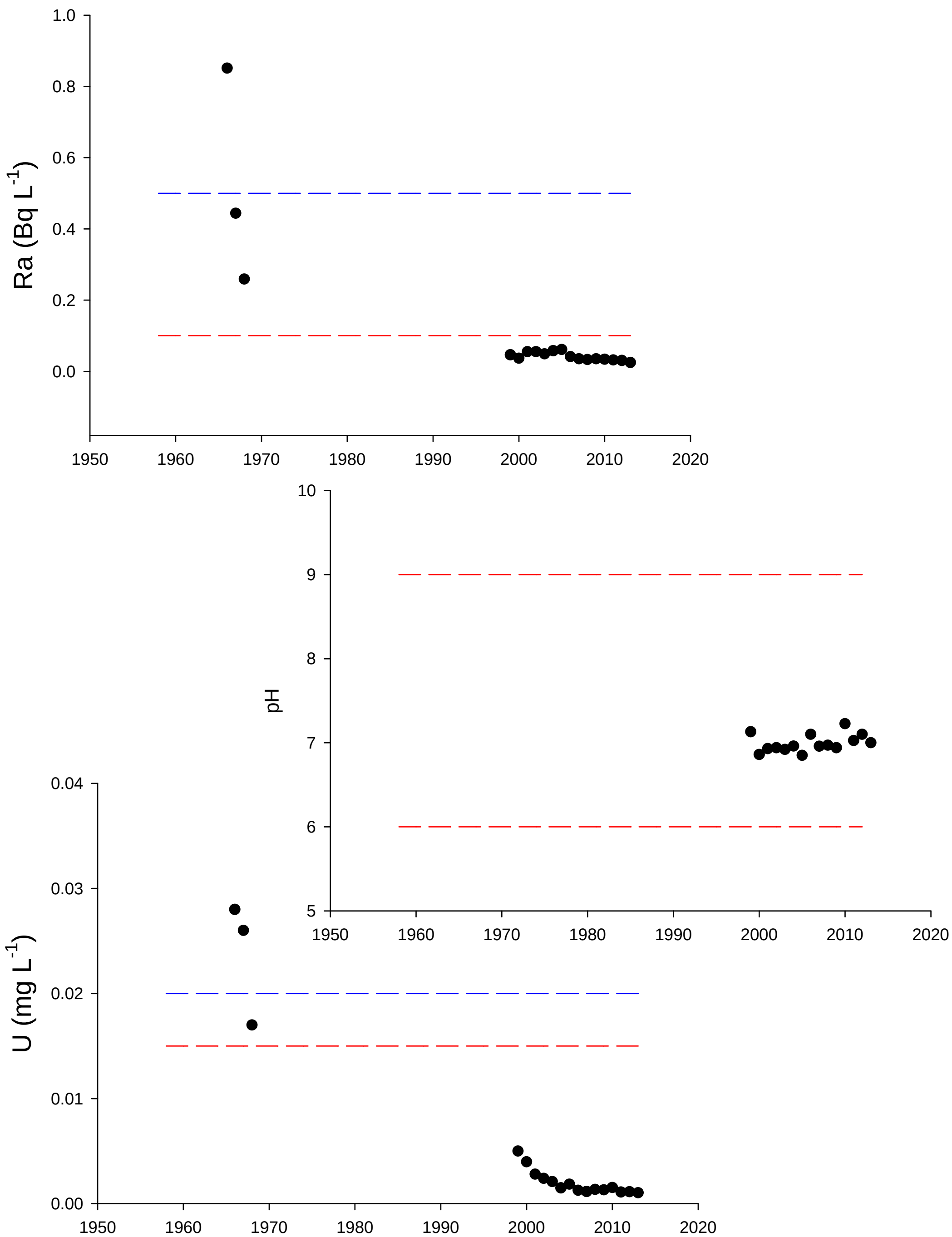

Figure 5. Temporal variation in Radium-226 (upper panel), the pH level (middle panel) and uranium (lower panel) in Nordic Lake (●). The red line indicates the Canadian water quality guidelines for the protection of aquatic life. The blue line indicates the Canadian drinking water quality guidelines. The data are taken from various environmental monitoring reports [18-21, 26].

Table 4. Non-radioactive substances measured in Nordic Lake in 1999−2000 [18].

	V	Tl	Mo	Cr	Ag	Se	Zn	Ni	Cu	Co	Cd	As
CDWQG*	--	--	--	50	50	--	50	--	1	--	5	10
CWQG**	6	10	73	1	1	0.1	1	25	2	0.9	0.017	5
Detection limit	0.5	0.1	0.8	0.2	0.2	0.06	0.4	0.6	0.1	0.04	0.03	2
Nordic Lake ***	0.5	0.1	0.8	0.2	**0.6**	0.8	0.4	0.6	0.5	0.4	**0.03**	2

* Canadian Drinking Water Quality Guidelines

** Canadian water quality guidelines for the Protection of Aquatic Life

*** Mean measured in 1999−2000

3.5 Water quality downstream from the Stanleigh tailings pond

McCabe Lake receives the treated effluent from the Stanleigh tailings pond, which was decommissioned between 1996 and 1998. Figure 6 shows the water quality in McCabe, May and Pecors lakes. In 1965, the radium levels in McCabe Lake were very high, at nearly 3.75 Bq/L, which exceeds the present Saskatchewan surface water quality objective and the current Canadian drinking water quality guideline.

In McCabe and Pecors lakes, the uranium concentrations were just above the Canadian guideline of 15 µg U/L for the protection of aquatic life but below the Canadian drinking water quality guideline (figure 6). The pH level in Pecors Lake, located some 10 km from the Stanleigh tailings pond, became more acidic over time until the beginning of the 1980s (figure 6). After 1965, when effluents began to be treated with barium chloride, the radium levels in McCabe and Pecors lakes gradually declined, reaching values below 0.1 Bq/L, and the levels have remained constant in those lakes ever since. The pH level in Pecors and McCabe lakes has been close to neutral since the 1980s (figure 6).

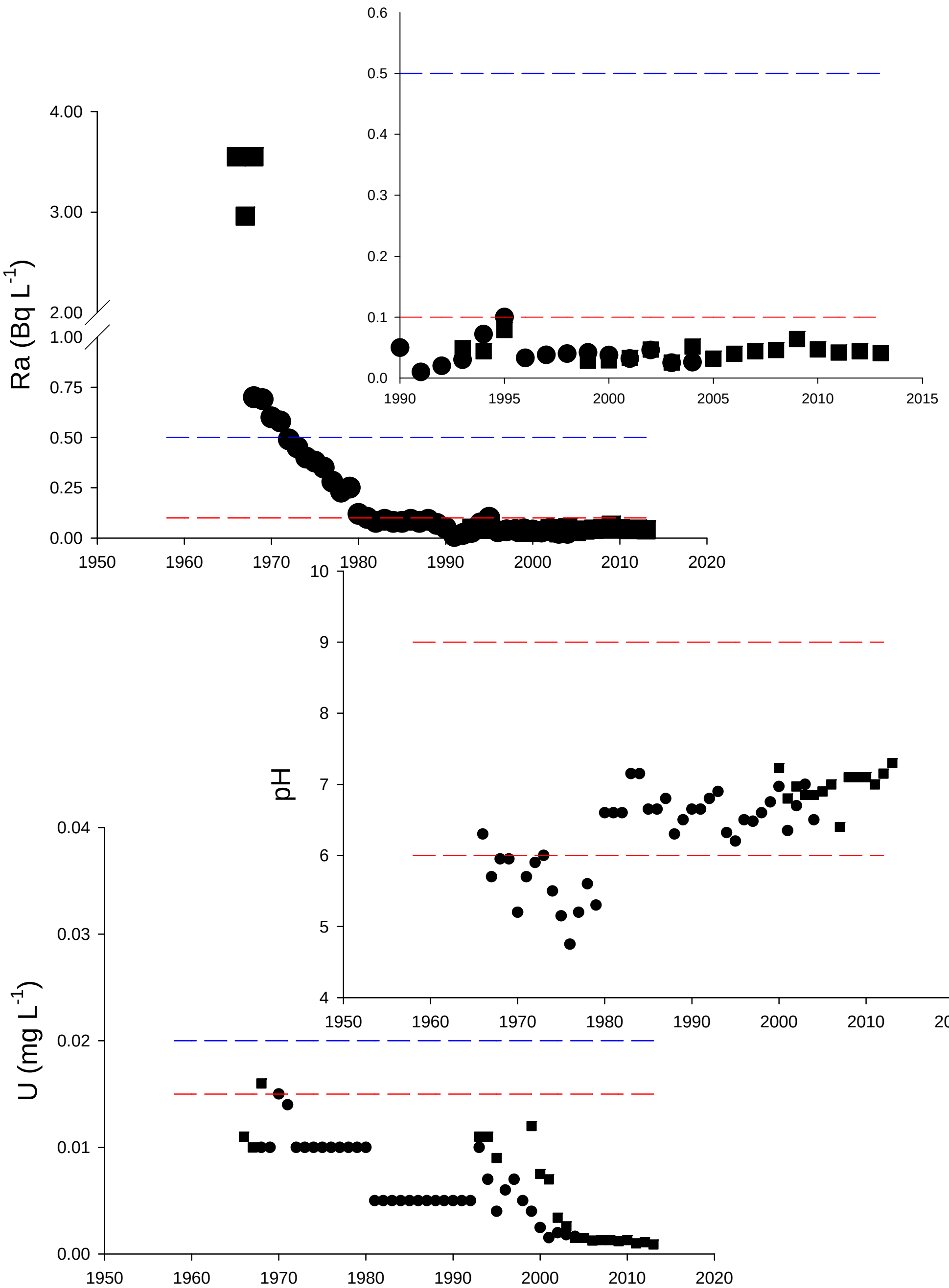

Figure 6. Temporal variation in Radium-226 (upper panel), the pH level (middle panel) and uranium (lower panel) in McCabe (■), May (♦) and Pecors (●) lakes. The red line indicates the Canadian water quality guidelines for the protection of aquatic life. The blue line indicates the Canadian drinking water quality guidelines. The data are taken from various environmental monitoring reports [18-21, 26].

For the most part, the levels of non-radioactive substances in McCabe and Pecors lakes were below the detection limits and below the existing Canadian drinking water guidelines as well as the current Canadian water quality guidelines for the protection of aquatic life (table 5). However, in McCabe Lake, the mean Ag, Se, Cd and As concentrations were below the existing Canadian drinking water guidelines, but above current water quality guidelines for the protection of aquatic life. In Pecors Lake, cadmium alone exceeded the Canadian water quality guideline for the protection of aquatic life. The levels of Ag, Se and As fell back below the water quality guidelines for the protection of aquatic life in 2006 [21]. The cadmium concentrations dropped back below the detection limits [21].

Table 5. Non-radioactive substances measured in McCabe and Pecors lakes in 1999−2000 [18].

	V	Tl	Mo	Cr	Ag	Se	Zn	Ni	Cu	Co	Cd	As
CDWQG*	--	--	--	50	50	--	50	--	1	--	5	10
CWQG**	6	10	73	1	1	0.1	1	25	2	0.9	0.017	5
Detection limit	0.5	0.1	0.8	0.2	0.2	0.06	0.4	0.6	0.1	0.04	0.03	2
McCabe Lake ***	0.5	0.1	0.8	0.2	**1.0**	**1.2**	3.5	1.5	0.8	0.4	**0.1**	**12**
Pecors Lake ***	0.5	0.2	0.8	0.2	0.3	0.9	2.3	1.2	1.7	0.4	**0.04**	2.7

* Canadian Drinking Water Quality Guidelines

** Canadian Water Quality Guidelines for the Protection of Aquatic Life

*** Mean measured in 1999−2000

4.0 Flesh quality of fish in the Serpent River ecosystems

The previous section indicates that water quality in the lakes downstream from the tailings ponds in the Elliot Lake region is of good quality because it complies with the drinking water quality guidelines, the water quality guidelines for the protection of aquatic life, and the Saskatchewan surface water quality objective for ^{226}Ra. Given that the metals, ^{226}Ra and uranium concentrations are below these thresholds, it is likely that the quality of fish tissues is also acceptable. However, it is possible that fish remain exposed to high levels of radionuclides and metals when they forage in historically contaminated sediments.

It should be kept in mind that radionuclides accumulate preferentially in the bony tissues of fish [15-17] rather than in their muscles and that, accordingly, the levels in muscle (or flesh) are much lower. The exposure of members of the general public to radionuclides associated with consumption of fish tissues is therefore lower. There is no preferential accumulation of metals in bones.

In order to determine whether the general public and Aboriginal people are at risk from consuming fish from these water bodies, it is necessary to first estimate the fish consumption rate for the different age groups that are high enough to protect most of the population. To this end, Health Canada [22] recommends using an intake of 220 g of fish per day to represent a high level of fish consumption by Aboriginal populations. As a comparison, Health Canada [22] recommends using an intake of 111 g of fish per day to represent a high level of consumption for the Canadian public at large. We therefore decided to use an intake of 220 g of fish per day in our calculations related to the quality of fish tissues.

For radionuclides, a reference dose of 0.1 mSv per year, that is, one tenth of the CNSC's regulatory dose, was used to calculate the dose associated with the consumption of fish in the Elliot Lake region. This approach is equivalent to the one used by the World Health Organization and by Health Canada to calculate the drinking water guidelines for radionuclides. With regard to non-radioactive substances, for most of the metals, we used the reference doses recommended by Health Canada [22]. For silver, we used the United States Environmental Protection Agency's reference dose (see appendix B). The concentrations in the tissues of fish presented in this study are therefore conservative. The calculation method and the assumptions made to obtain the reference doses are described in appendix B.

4.1 Flesh quality of fish in McCarthy Lake and Serpent River

Figure 7 shows that the uranium and radium concentrations in fish are below the reference levels for a daily intake of 220 g. Similarly, figure 8 shows that the metal concentrations in fish tissues are below the reference levels for daily consumption of 220 g.

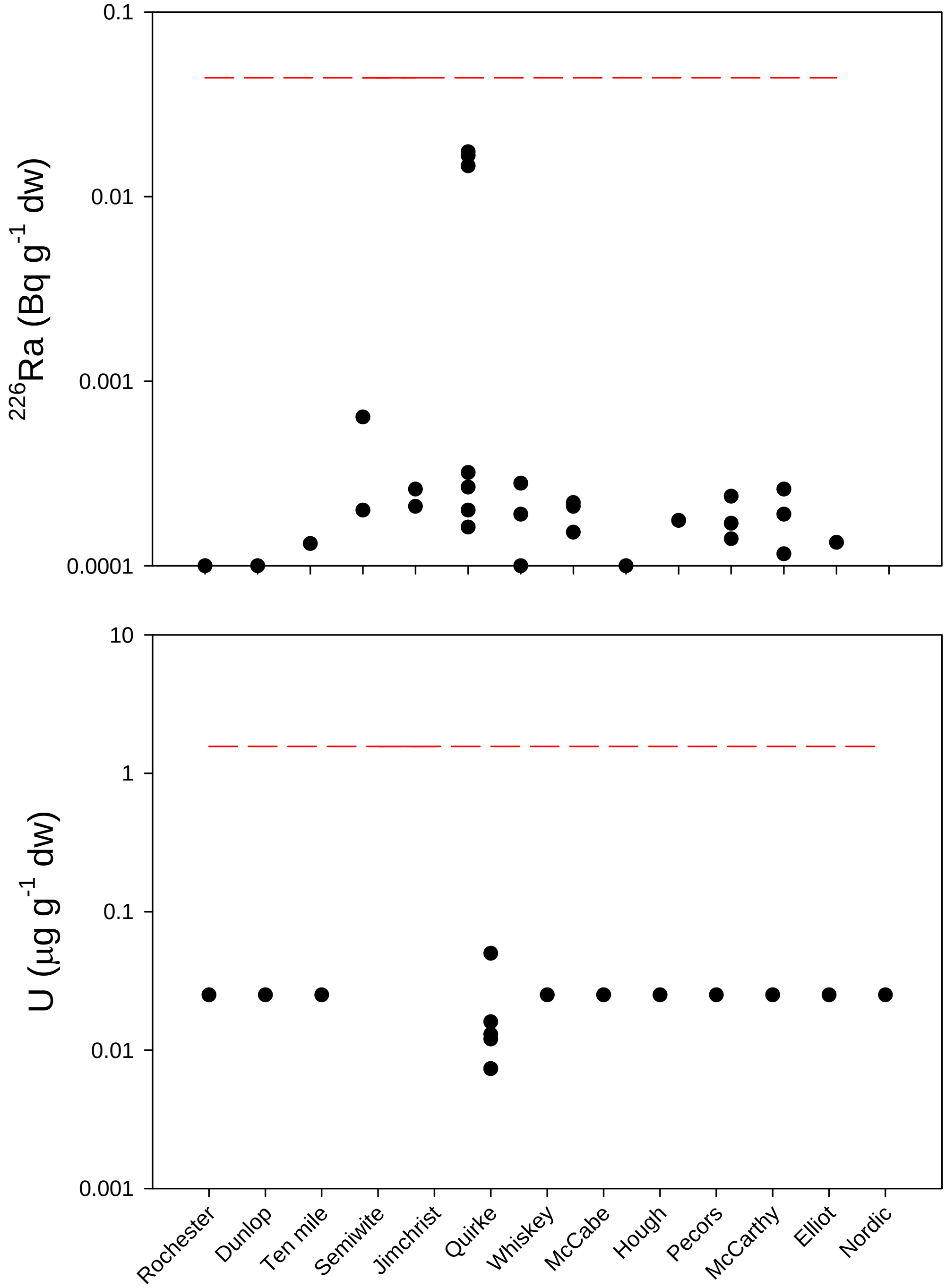

Figure 7. Variation in the U and ^{226}Ra concentrations in fish caught in 1998, 2004 and 2011 in lakes exposed to treated effluents from mine tailings ponds and in unexposed lakes (i.e., Rochester, Dunlop and Ten Mile). The red line indicates concentrations in fish tissues equivalent to a dose of 0.1 millisievert per year (mSv/y) for a daily fish intake of 220 g [22]. The levels in fish tissues are taken from Minnow [18-21, 27].

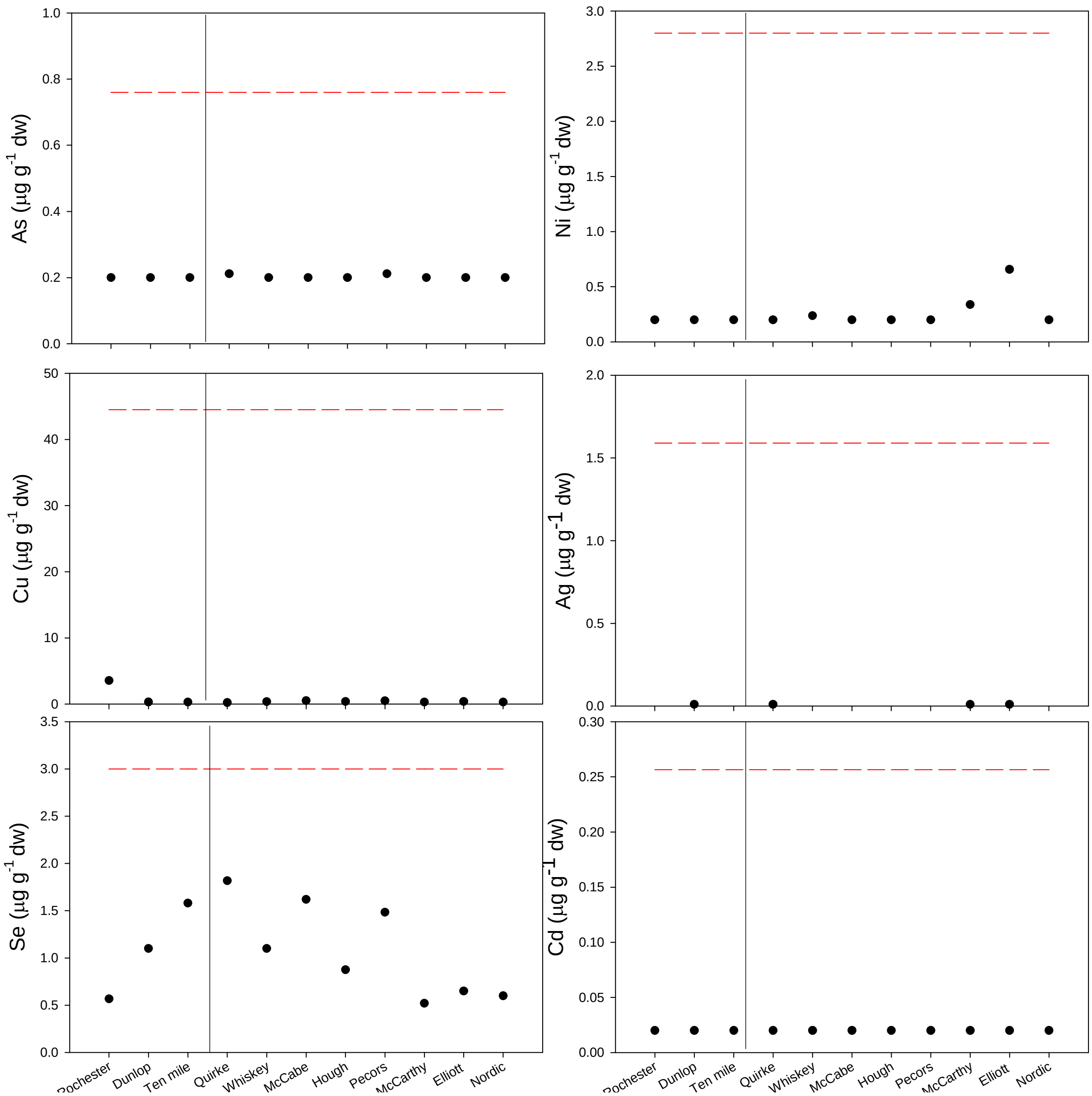

Figure 8. Variation in the concentrations of selenium, cadmium, copper, silver, arsenic and nickel in fish caught in 2004 in lakes exposed to treated effluents from the mine tailings ponds and in unexposed lakes (Rochester, Dunlop and Ten Mile). The red line shows the tolerable intake from daily consumption of 220 g of fish [22]. The levels in fish tissues are taken from Minnow [19].

4.2 Flesh quality of fish in Quirke and Whiskey lakes

Figure 7 shows that the U concentrations in Whiskey Lake are below the reference levels for a daily intake of 220 g of fish. However, the U levels in fish from Quirke Lake vary within an order of magnitude (figure 7). This variation is due to a decrease in the U concentrations in fish flesh from 1999 to 2011 (figure 9). Figure 9 therefore confirms that in Quirke Lake, the U levels have declined and are below the reference levels for a daily intake of 220 g. Figure 8 shows that in Whiskey and Quirke lakes, the metals concentrations in fish flesh are below the reference levels for a daily intake of 220 g.

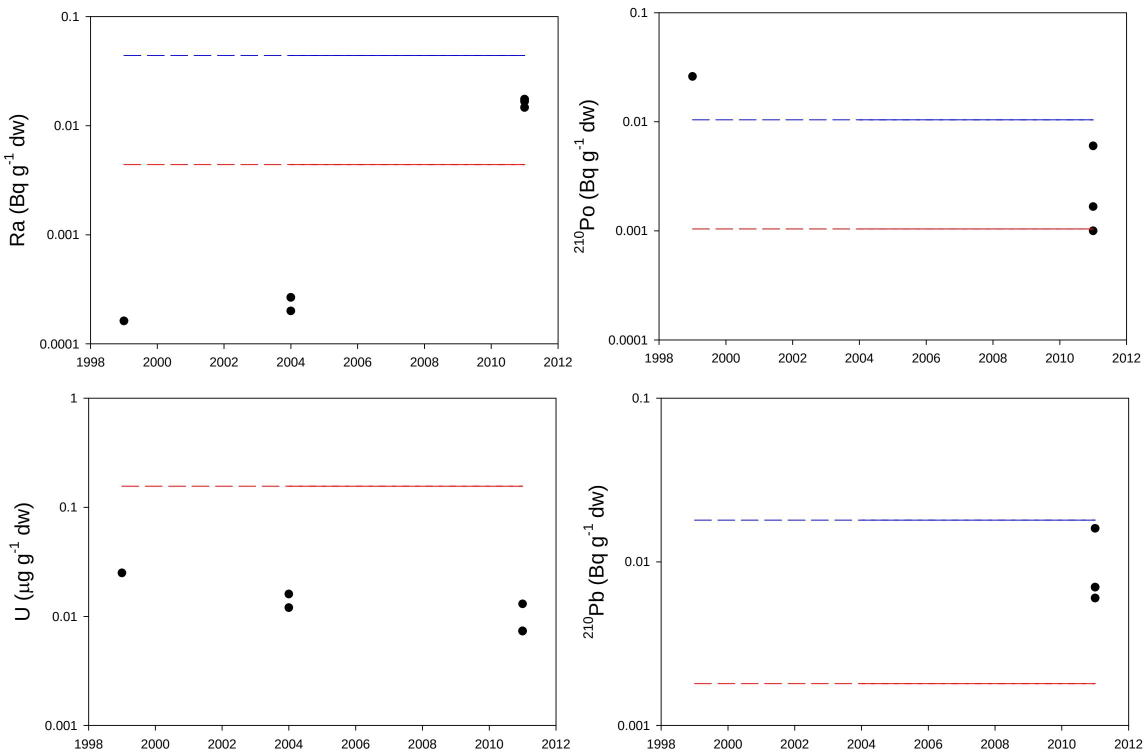

Figure 9. Temporal variation in the uranium and radium levels in fish caught in Quirke Lake. The red line indicates the concentrations in fish flesh equivalent to a dose of 0.1 millisievert (mSv) per year, and the blue line indicates the concentrations in fish flesh equivalent to a dose of 1 millisievert (mSv) per year for an intake of 220 g of fish per day [22]. The concentrations in fish flesh are taken from Minnow [18-21, 27].

For ^{226}Ra, the concentrations in fish flesh in Whiskey Lake are below the reference levels for a daily intake of 220 g of fish (figure 7). By contrast, the ^{226}Ra concentrations in fish in Quirke Lake have increased since 1999 (figure 9) and are now above the reference level leading to a dose of 0.1 mSv. For ^{210}Po and ^{210}Pb, the concentrations in fish caught in Quirke Lake are likewise above the reference levels leading to a dose of 0.1 mSv per year for daily fish consumption of 220 g (figure 7). However, the ^{210}Po levels have decreased since 1999 in Quirke Lake (figure 9). Temporal data for ^{210}Pb were not available (figure 9).

When a reference level leading to a dose of 1 mSv per year—which corresponds to the regulatory dose for public protection in Canada—is used , the reference levels are ten times higher (blue line in figure 9). The ^{226}Ra, ^{210}Po and ^{210}Pb concentrations in the tissues of fish from Quirke Lake are all below this reference limit. The CNSC has nonetheless continued to monitor ^{226}Ra levels in fish in Quirke Lake.

4.3 Flesh quality of fish in Elliot Lake

The uranium and radium levels in fish from Elliot Lake are below the reference levels for daily consumption of 220 g of fish (figure 7). Similarly, figure 8 shows that the metals concentrations in fish tissues are below the reference levels for a daily intake of 220 g.

4.4 Flesh quality of fish in Nordic Lake

The uranium concentrations are below the reference levels for daily fish consumption of 220 g (figure 7). The ^{226}Ra levels were not measured in this water body but should be similar to the values obtained for the other lakes. Figure 8 shows that the concentrations of metals in fish tissues are below the reference levels for a daily intake of 220 g, even though the silver and cadmium concentrations exceeded the water quality guidelines for the protection of aquatic life before 2006.

4.5 Flesh quality of fish in McCabe Lake

The radium and uranium concentrations are below the reference levels for daily fish consumption of 220 g (figure 7). Figure 8 shows that the concentrations of metals in fish tissues are below the reference levels for a daily intake of 220 g, even though the selenium, cadmium and silver levels exceeded the water quality guidelines for the protection of aquatic life before 2006.

5.0 Serpent River ecosystem health

The purpose of this report is to describe the health of aquatic ecosystems downstream from the various mine tailings ponds in the Serpent River watershed. To this end, we have presented the temporal and spatial variations in surface water contamination as well as the quality of fish tissues. A related goal was to determine whether the entire population, Aboriginal people and the general public, and even people with a high intake of fish, can safely consume fish from the Serpent River.

5.1 Impacts of uranium mining prior to 1980 on Serpent River ecosystem health

The untreated effluents that were discharged into the different water bodies of the Serpent River until 1965 caused considerable harm. The ^{226}Ra concentrations in the Serpent River at the junction of Highway 17, which is more than 20 km from the closest tailings pond, fluctuated around 1 Bq/L, which is above the current Canadian drinking water guideline of 0.5 Bq/L (figure 2). However, the pH level remained close to neutral and the uranium concentrations remained below the water quality guideline for the protection of aquatic life and for drinking water (figure 2). Similarly high ^{226}Ra levels in surface waters were also observed in lakes farther upstream (figures 3, 4, 5, 6), and more specifically, in McCabe Lake, where the ^{226}Ra levels reached 3.75 Bq/L (figure 6). It can therefore be confirmed that the deterioration in water quality contributed to a major decrease in the number of fish caught in the watershed, right up until 1977 [23]. Fish consumption was seldom possible during that period. The impacts on Serpent River ecosystems were therefore very severe and encompassed all the lakes extending over a distance of tens of kilometres during a period of 30 years. However, the Elliot Lake ecosystem, which receives drainage waters from the Milliken tailings pond, was essentially spared.

5.2 Impact of uranium mining after the 1980s on the Serpent River ecosystems

Beginning in the 1980s, the quality of surface waters gradually improved until the U and ^{226}Ra levels fell below the Canadian water quality guidelines for the protection of aquatic life and the Canadian drinking water guidelines, and the pH of the surface waters remained close to neutral (figures 2, 3, 4, 5, 6) in the 2000s. The levels of certain metals such as cadmium, selenium, silver and arsenic dropped back below the water quality guidelines for the protection of aquatic life in 2006, following the adoption of the *Nuclear Safety and Control Act*, which required proper management of discharges of radionuclides as well as of non-radioactive substances.

Following the improvement in water quality in the 1980s, the Ontario Ministry of Natural Resources carried out lake trout stocking in Pecors Lake and lakes farther upstream in 1983 [15-16]. A major increase in the number of fish found in surveys was observed between 1976 and 1993 [24, 25]. The reintroduction of fish to support sport fishing nonetheless entailed an evaluation of the risks related to fish consumption. The various results reported here indicate that the general public and Aboriginal people with a high daily intake of fish do not face health risks (figures 7, 8, 9).

However, given the increase in the radium concentrations in fish from Quirke Lake, the CNSC expects the responsible license holder to monitor these concentrations in the coming years. The radium levels in fish tissues do not pose a health risk; the doses associated with daily consumption of 220 g remain within the regulatory limit of 1 mSv per year.

6.0 Conclusions

These results indicate that the exploitation of uranium deposits in the 1950s, 1960s and 1970s caused irreparable harm to certain lakes used as mine tailings ponds. Downstream from tailings ponds, mining operations also caused considerable harm to lakes in the Serpent River watershed. The lakes located downstream from tailings ponds gradually recovered afterwards, and now the ecosystems directly downstream from mine tailings ponds are in good health, because the concentrations of ^{226}Ra, uranium and other metals in the surface waters are below the Canadian guidelines for the protection of aquatic life and the Canadian drinking water guidelines and because members of the public can safely consume fish.

Clearly, the tailings management methods used in the past are no longer feasible today. The CNSC recommends managing tailings in a manner that will minimize long-term monitoring of tailings dams, for example, by depositing radioactive mine tailings in abandoned open pits or by backfilling underground mine workings. At present, radioactive mine tailings from the Rabbit Lake, McClean Lake and Key Lake mines are deposited in abandoned open pits after their walls have been lined with permeable layers of crushed rock in order to permit runoff of groundwater, thereby minimizing contact with radioactive mine tailings. A dry or wet cover is subsequently placed over the tailings. Much less long-term institutional monitoring is required and much lower financial guarantees are required to deal with any eventuality.

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Appendix A – Description of mine tailings management at the different mine sites

A.1 Quirke tailings pond

The tailings pond for the Quirke mine was designed with 4 basins, located one after the other with a total drop in elevation of 14 metres. The pond covers an area of 1.92 km^2 in a valley and contains 46 million tonnes of waste rock and tailings. Since tailings are acid generating, the tailings pond was impounded with a dam. Treated effluent from the tailings pond is released into the Serpent River, which later empties into Quirke Lake (figure A-1).

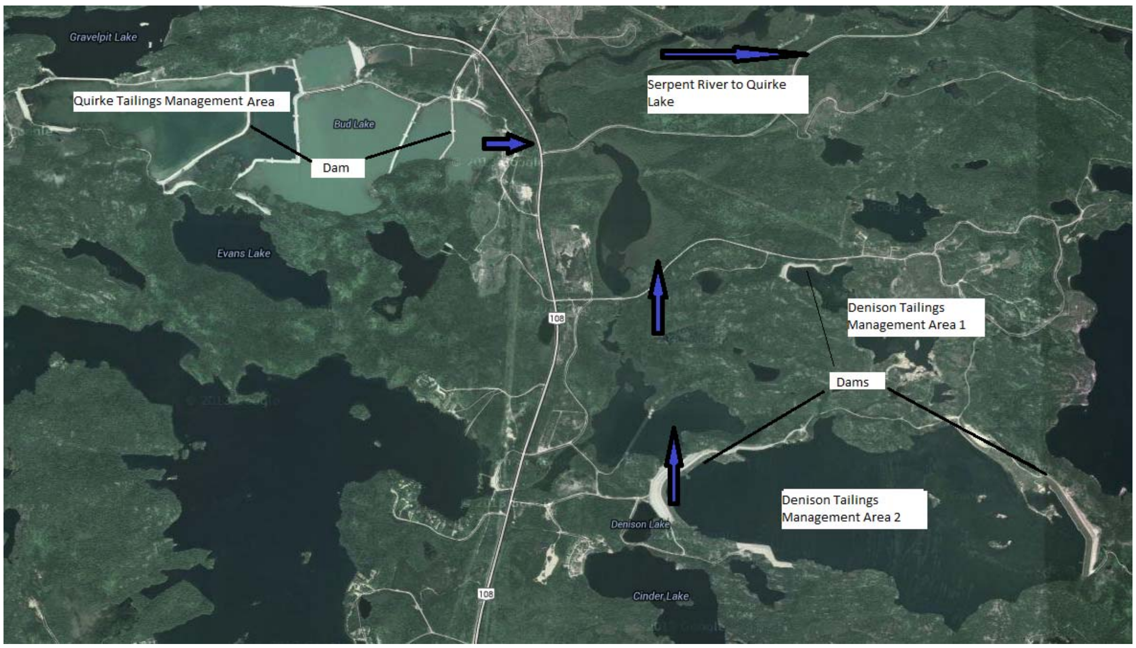

Figure A-1. Tailings ponds at the Quirke and Denison mines. The blue arrows show the direction of surface water flow.

A.2 Panel tailings pond

The Panel tailings pond has a primary basin of 0.84 km^2 to the north and a secondary basin of 0.39 km^2 to the south. Rio Algom discharged 16 million tonnes of mine tailings and waste rock into the primary basin, formerly Strike Lake, where the accumulation of these materials necessitated the construction of four dams to provide increased capacity (figure A-2). Overflow water from the primary basin is channelled to the southern basin formed by two dams and two dikes. The overflow water is then treated and channelled into a small stream which eventually empties into Quirke Lake.

Figure A-2. Tailings pond at the Panel mine. The blue arrows indicted the direction of surface water flow.

A.3 Denison tailings pond

The Denison tailings ponds 1 (TMA-1) and 2 (TMA-2) are located between Dunlop Lake and Quirke Lake (figure A-1). While the Denison Mine was in operation, the tailings were deposited in Smith, Williams, Bear Cub, Stollery and Long lakes. The tailings pond covers an area of 2.58 km^2. At the end of operations in April 1992, there was an estimated 3.3 million tonnes of tailings in TMA-2 and 59.7 million tonnes of tailings in TMA-1. Despite the use of lakes, several dams were constructed to contain mine tailings. TMA-1 is maintained by means of four dams (#9, 16, 17 and 18). In TMA-2, there are four dams (#1, 2, 4 and 12) which separate Williams Lake and Smith Lake. In all, 18 structures have been built since 1957 to contain tailings. Given the acid-generating nature of the tailings, the pond was permanently flooded. Treated effluent from the tailings pond drains into the Serpent River, which eventually empties into Quirke Lake.

A.4 Stanrock tailings pond

The Stanrock and Can-Met mines deposited their mine tailings in a common area. Between 1957 and 1964, 5.7 million tonnes of tailings were deposited in a valley. The tailings were subsequently used to construct dams A, B, C and D, which were reinforced with clean waste rock during decommissioning of the site (figure A-3). The mine tailings pond covers a total area of 0.52 km^2 and is now covered with vegetation. Runoff and leacheate from the tailings pond are channelled to the water treatment plant. Treated effluent is then discharged into the Moose Lake settling pond and flows into Orient Lake for further polishing and eventually to Halfmoon Lake and then May Lake (figure A-3).

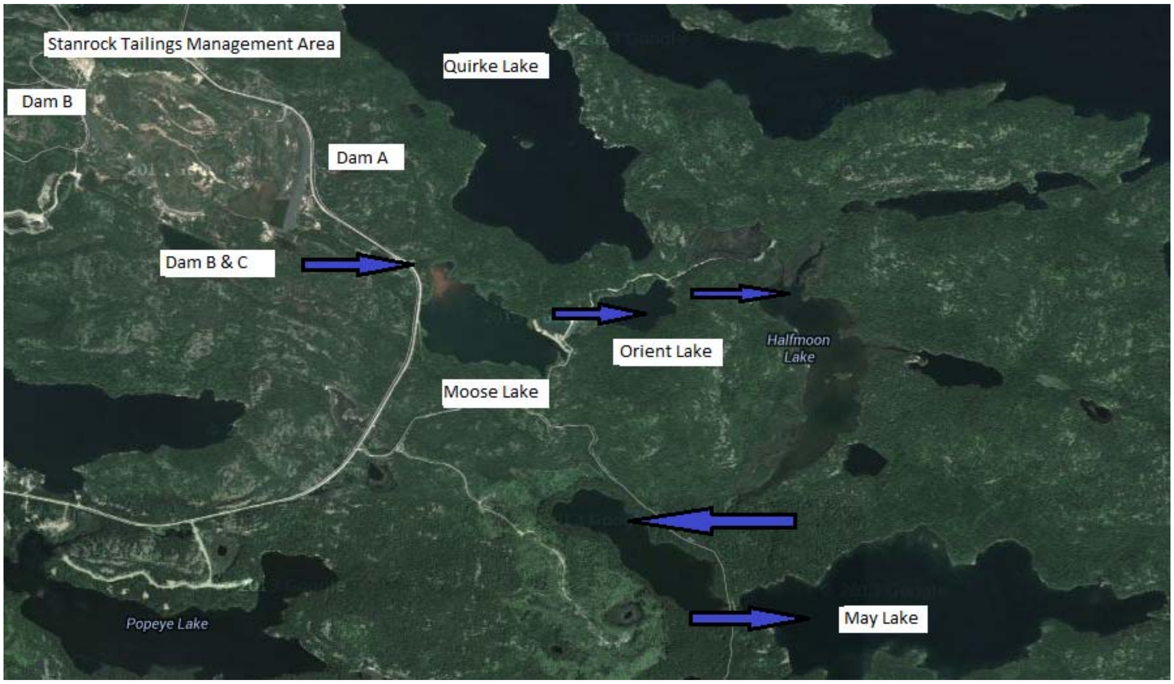

Figure A-3. Stanrock tailings pond. The blue arrows indicate the direction of surface water flow.

A.5 Stanleigh tailings pond

The Stanleigh tailings pond is located 5 km north of the City of Elliot Lake (figure1). It contains 20 million tonnes of mine tailings from the Milliken mine and the Stanleigh mine. From 1958 to 1964, 5.7 million tonnes of tailings were deposited into Crotch Lake from the Milliken mine operations (figure A-4). During the same period (1957−1960) the Stanleigh mine also discharged 1.7 million tonnes of mine tailings into the lake. The tailings pond is strengthened by several dams (figure A-4). In 1980, the Stanleigh mine was reopened and four dams were built to reduce the TMA watershed from 22 km^2 to 13 km^2. From 1983 to 1996, 12.8 million additional tonnes of mine tailings were deposited in the facility. As part of the decommissioning of the mine in 1996, the dams were raised to allow perpetual flooding of the acid-generating tailings in the basin. The tailings pond occupies a total area of 4.11 km^2. The treated effluent is then discharged into McCabe Lake (figure A-4).

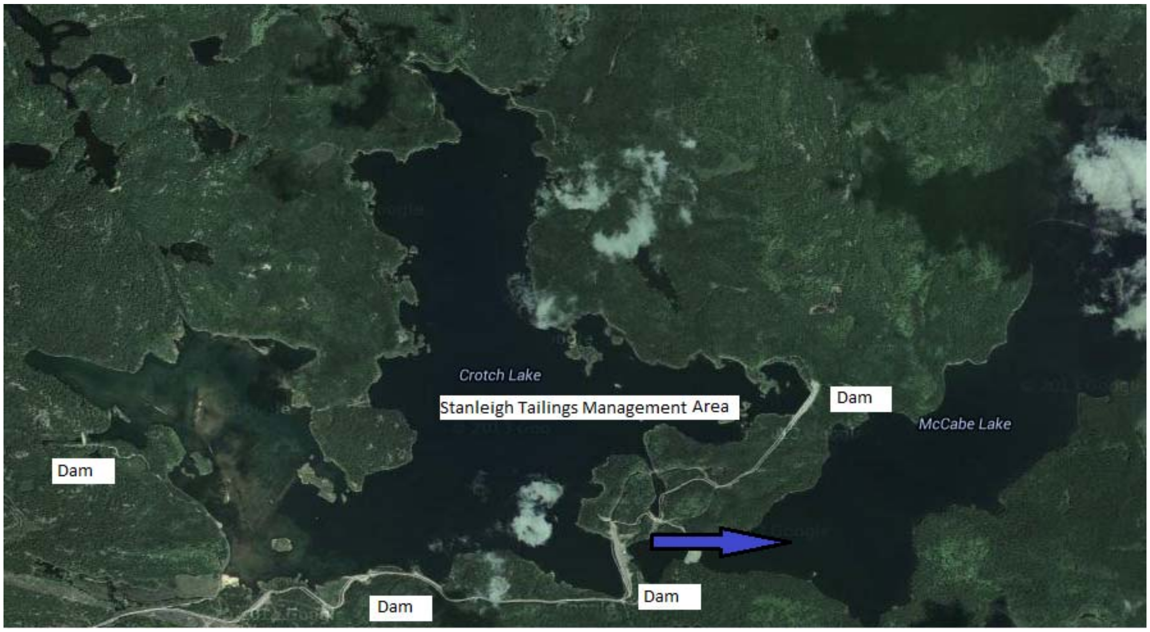

Figure A-4. Stanleigh tailings pond. The blue arrows indicate the direction of surface water flow.

A.6 Milliken tailings pond

The Milliken tailings pond is located 2 km northeast of the City of Elliot Lake. The Milliken mine operated from 1958 to 1964 and discharged 5.7 million tonnes of tailings into the Stanleigh tailings pond (see section A.5). During the same period, about 0.08 million tonnes of tailings were released to Sheriff Creek in an area of 0.17 km^2. In the late 1970s, the mine tailings were covered with a one-metre-thick layer of sandy substrate and then flooded to form a wetland of 0.23 Km^2. In 1997, a berm was constructed to maintain water cover over the tailings. The flow from the Sheriff wetland joins the outflow from Horne Lake before entering Elliot Lake (figure 1).

A.7 Lacnor and Nordic tailings ponds

The Lacnor tailings pond is located about 7 km east of the City of Elliot Lake. The Lacnor mine operated from 1957 to 1960 and deposited 2.7 million tonnes of mine tailings in a valley and were contained by two waste rock dams. The Lacnor tailings pond covers an area of 0.27 km^2. Following the mine's closure, revegetation efforts targeting the tailings began but the acidic conditions prevented the establishment of the plantings (figure A-5). Between 1998 and 1999, 200 kg of limestone was applied per 0.01 km^2 on the tailings, which were subsequently covered with a layer of blast rock to promote groundwater flow and thus limit contact with the mine tailings. The rock cover was later covered with soil and fertilized to encourage vegetation growth. Runoff and leacheate from the tailings pond are collected in a holding pond prior to discharge into the Nordic tailings pond just to the south (figure A-5).

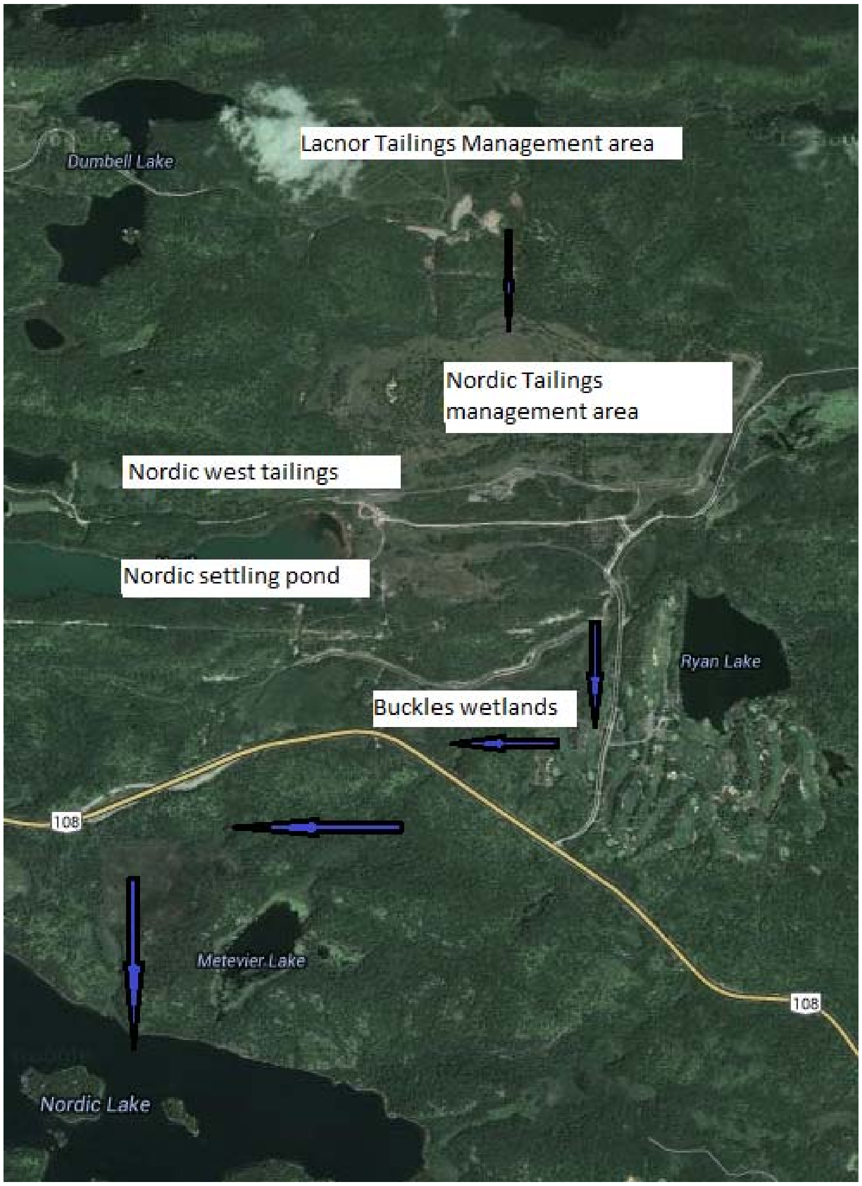

Figure A-5. Lacnor and Nordic mine tailings ponds. The blue arrows indicate the direction of surface water flow.

The Nordic mine operated from 1957 to 1968 and produced 12 million tonnes of mine tailings. The tailings were deposited into the main tailings pond and into a western arm. Dams were constructed with waste rock from the main embankment and another to the west. The tailings pond was decommissioned in the same manner as the Nordic tailings facility. Today, the Nordic tailings pond is completely covered with vegetation. Runoff and leacheate from the Nordic tailings pond are channelled to a treatment plant. The treated effluent is then discharged into Buckles Creek (figure A-5) and flows from there into Nordic Lake (figure 1).

Annexe B – Concentrations in Fish Flesh

Sample Calculations – Concentrations in Fish Flesh

Sample Calculations – Fish Toxicity Reference Values

Fish toxicity reference values, TRV_{fish}, (mg/g) represent the reference concentrations for hazardous substances in fish flesh in terms of their consumption by people. This provides an estimate of the potential exposure of a member of the public to a conservatively-chosen country food diet of mainly fish. Fish were chosen for this type of screening for practical reasons, given the large set of fish flesh data for multiple COPCs. Measured as opposed to modelled data for other country foods (moose, caribou, waterfowl, etc.) are few.

TRV values were calculated using equation B1.

$$TRV_{fish} = \frac{TRV_{hazard} \times BW}{CR_{fish}} \qquad \text{Equation B1}$$

where:

- TRV_{hazard} [mg/kg body weight/day] is the toxicity reference value (Health Canada, 2010; CanNorth, 2014)
- BW [kg] is the body weight associated with the five age ranges in Health Canada (2010)
- CR_{fish} [g] is the fish consumption rate (Richardson, 1997; CanNorth, 2000)

A fish consumption rate of 220 g/day found in Richardson (1997) is recommended by Health Canada (2010) as a value representing native Canadian diets high in fish.

For the contaminants that have different TRV_{hazard} values specified by Health Canada for the five age groups, the adult age group with the most conservative value was used.

Sample Calculations – Nuclear Substances Reference Fish Concentrations

Following the logic of calculations for hazardous substances, reference fish concentrations (C_{fish}) for nuclear substances resulting in an annual dose of 0.1 mSv were calculated for a country foods diet, using equation B2.

The regulatory dose limit to a member of the public is 1 mSv per year. The use of one tenth of this value conservatively allows for intakes of other radionuclides in the uranium decay chain, and intakes from other pathways when examining just one diet item (fish) and one radionuclide at a time. Conceptually, the concentration C_{fish} represents a screening tool to identify situations where a person could approach the public dose limit when pursuing a country foods diet focused mainly on fish, a common lifestyle in northern Canada with its many lakes. The calculation includes a safety factor of ten to accommodate uncertainties in modelling and summing the total intakes of COPCs from all sources.

$$C_{fish} = \frac{D_{reference}}{DC_{ingestion} \times 365.25 \times CR_{fish}} \qquad \text{Equation B2}$$

where:

- $D_{reference}$ [mSv] is one tenth of the public dose limit (0.1 mSv)
- $DC_{ingestion}$ [mSv/Bq] is the radionuclide and age specific ingestion dose coefficient from ICRP Publication 72
- *365.25* [d] is the average number of days in a year
- CR_{fish} [g] is the fish consumption rate (CanNorth, 2000)

A fish consumption rate of 220 g/day found in Richardson (1997) is recommended by Health Canada (2010) as a value representing native Canadian diets high in fish.

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