Long-term trend of uranium concentrations in Beaverlodge Lake, Saskatchewan, Canada, under mine decommissioning

HUAXIA YAO[1], ROBERT KIDD[1] & MICHIO HASHINO[2]

1 *Environmental Protection Branch, Department of Environment, Box 3003, 800 Central Ave, Prince Albert, Saskatchewan S6V 6G1, Canada*
huaxia.yao@gov.sk.ca

2 *Department of Civil Engineering, The University of Tokushima, 2-1 Minami-josanjima, Tokushima 770-8506, Japan*

Abstract The annual mass balance of uranium for Beaverlodge Lake (which is impacted by uranium mining) was analysed using limited observation data. Annual water discharges of the basin, or discharges at the lake outlet are estimated using the discharge ratios of a sub-basin from 1985 to 2006. Uranium loadings are determined using observed concentrations and discharges from two creeks flowing into Beaverlodge Lake. The relationships between inflow loadings, outflow volumes and lake concentration changes are established. Then, given the trends of loading, the long-term trends of outflows from the lake and concentrations in the lake are predicted. Along with a continuous reduction in loadings from 3473 kg/year in 1985 to 0 kg/year in 2092, uranium concentration of the lake decreases from 125 μg/L in 1985 to 10 μg/L in 2118. The natural restoration of the lake water would need 112 years to reach the 10 μg/L Canadian drinking water standard.

Key words trend; uranium; lake; mine decommissioning; Saskatchewan; mass balance; loading; discharge

INTRODUCTION

Past uranium mining and milling activities have been a cause for concern for regulatory agencies and public groups as the removal of contaminants resulting from these operations from impacted waterbodies presents some very significant challenges. Beaverlodge Mine/Mill, the first uranium operation in Canada, was operated between 1951–1982 without strict regulation or sound environmental protection. The mine ceased operations in 1983 and the buildings, underground working and other infrastructure were decommissioned between 1983 and 1985. Since then the mine site has continued to be reclaimed and the surrounding area has been monitored annually. Beaverlodge Lake, downstream from the Beaverlodge Mine/Mill site, which was impacted by metal and radionuclide contaminants during operations, has been in the recovery process. Of the remaining risks, uranium in lake water which meets the close-out objective and is higher than Canadian Drinking Water Quality Objective 10 μg/L, has been selected for our analysis.

There are few studies regarding uranium concentrations in a recovering lake impacted by mining and milling, for two major reasons. First, uranium mines are restricted to very limited locations in the world, so opportunities to collect data or conduct studies are rare. Second, the more significant/measurable impacts occurred mainly during the 1940s–1970s, when environmental monitoring was not required, so the data available for water quality studies was limited. During more recent times, the late 1980s to present day, new regulations and policy were developed. Mine and milling facilities, more heavily regulated, as in Saskatchewan, Canada, are impacting lakes and the environment to a lesser degree.

Many studies on general water quality have been conducted such as the work of Houle *et al*. (2004) and Ekholm & Mitikka (2006). Pinto *et al*. (2004) investigated pollution associated with a Portuguese mine and found high geoaccumulation of uranium and other metals. Peacey *et al*. (2002) undertook a geochemical study of uranium mine tailings near Elliot Lake in Ontario, Canada, which demonstrated the long-term process of dilution of released tailings by precipitation and freshwater. Clulow *et al*. (1998) conducted an earlier study in the same Elliot Lake area to monitor uranium in water, sediment and fish; the results indicated the biological recovery was continuing after mine decommissioning. Gavshin *et al*. (2004) assessed the effectiveness of catch pools for reducing uranium contamination in a very pristine lake in Kyrgyzstan.

The long-term trends of uranium concentrations in a heavily impacted lake have not been well studied or predicted. Therefore, in the present paper, we will report our study results on uranium for Beaverlodge Lake in northern Saskatchewan, Canada.

STUDY BASIN AND DATA

Beaverlodge Lake has a water area of 50.6 km^2 and a drainage area of 230.8 km^2 (Fig. 1). The lake basin is located in northwestern Saskatchewan, Canada, and drains into Lake Athabasca. The two pollutant-contributing watersheds, Ace and Fulton, affected by the mining and milling activities cover a drainage area of 172.4 km^2. The study basin, located within the Taiga Shield ecozone, is characterized by a rugged terrain of rocky ridges and valleys, with local topographic relief approaching 100 m or more. Mean annual temperature is 3.5°C and mean annual precipitation is 362 mm with 197 mm of rainfall in May to September.

Limited hydrological and water quality data are available – one monitoring station in the lake and two stations in the creeks. While there is insufficient data to conduct detailed analysis or simulation modelling of the uranium (U) concentrations in the lake basin, there are adequate data for a case study to plot the trends and provide this as a contribution to the Prediction for Ungauged Basin initiative of IAHS.

Uranium concentration trend is plotted for the 22 years, 1985–2006, with the available data, and then estimated into the future to a point where the U concentration is believed to reduce to the Canadian drinking water objective. Observation data include daily discharges and monthly water quality at Ace Creek and Fulton Creek, and seasonal water quality at the Fulton Bay of Beaverlodge Lake (see Fig. 1). Observed discharges, U concentrations of creeks and lake, and U loadings from the two creeks are displayed in Fig. 2.

METHODS

The basis of the method for analysing U trend in the lake is a mass balance: determining U loadings into the lake, U outflow discharges from the lake, and then determining

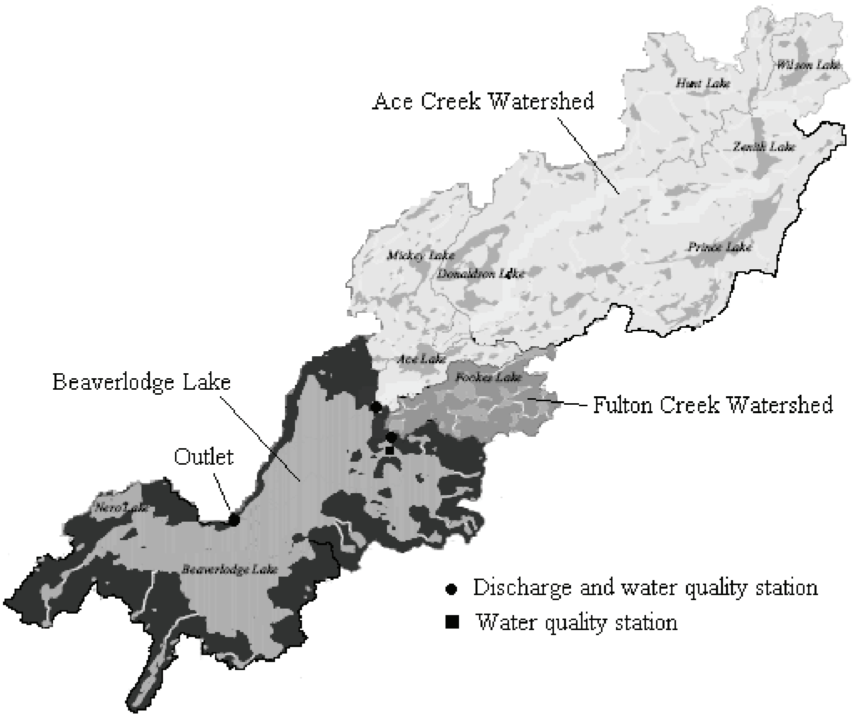

Fig. 1 Beaverlodge Lake basin and observation stations.

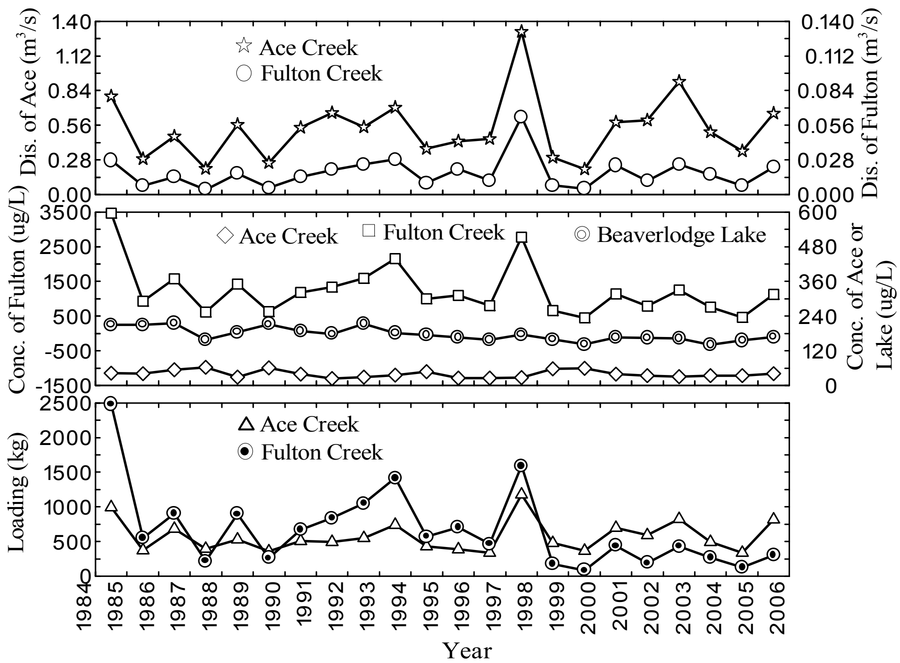

Fig. 2 Observed data of water discharges and U concentrations.

changes of U concentration in the lake. Relationships between annual loading, outflow and concentration were established for 1985–2006 data, and the long-term U trend for the future is predicted. A time step of one year is used for the analysis.

In order to calculate annual U loadings, observed monthly mean water discharges and U concentrations are used to calculate monthly loadings from Ace and Fulton creeks. Monthly loadings are summed to give annual loadings.

To determine annual U outflow discharges, annual mean water discharges at the outlet of Beaverlodge Lake need to be estimated as there were no observations at the outlet. Three approaches were considered: (a) find the ratio of discharge per unit watershed area of Ace Creek watershed, apply the ratio to the whole lake basin area for each month, getting monthly mean discharges of the whole basin (equal to the outlet discharges); (b) use the ratio of Ace Creek watershed to other watersheds draining to Beaverlodge Lake, and calculate monthly or annual discharge of the basin by a water balance method. By assuming the lake water levels do not change, outflow equals inflow plus precipitation on the lake, minus evaporation from the lake. But estimating evaporation is a potential source of errors; and (c) use a hydrological model of the basin to estimate discharge. Using a hydrological model is not recommended as there are limited data. Therefore, approach (a) was chosen for the study. After monthly mean discharges at the outlet are obtained, annual mean ones are estimated.

Annual mean discharge coupled with mean U concentration will give the annual U discharges. The U concentration at the outlet is estimated by using the observed data at the Fulton Bay area which is the receiving bay of the lake. A 40% decrease in U concentration within the lake to the outlet is assumed, and is supported by a good reproduction of the mass balance relations as explained later.

Uranium mass balance analysis is undertaken for each year between 1985–2006. U loading and the mass discharge for a year determine the U concentration change in the lake water. The year's mean concentration is estimated by taking into consideration the concentration change and the last year's concentration. U concentrations in lake water for 22 years were estimated and compared to the actual observed values. If the comparison is satisfied with a reasonable correlation, the assumption of 40% decrease along the lake water body and the estimation methods above are acceptable.

Predictions for uranium concentration trend into the future are made by using the mass balance relationship. Change scenarios of loadings are applied first: reducing stably till zero loading level, and loading levels for each year after 2006 are given. A constant water discharge value at the outlet (the average discharge of 22 years) is used. For 2007, the U discharge is estimated using U concentration of 2006, U concentration change of lake water in 2007 is estimated, and an updated concentration for 2007 is created. Then, continue the step-forward process to 2008, 2009, and so on, until the concentration in water reaches the drinking water criterion. From this, the long-term trend of U concentrations can be plotted and the number of years needed to reach the criterion can be calculated.

RESULTS AND DISCUSSION

U balances for Beaverlodge Lake

Results of mass balance analyses are listed in Table 1 for years 1985–2006. Annual U loading from the Ace Creek equals the annual mean discharge times the annual mean U concentration. Annual loading from the Fulton Creek is estimated similarly. Their

Table 1 Uranium mass balances for Beaverlodge Lake.

Year	[1] Inflow loading (kg)	[2] Outlet discharge (m^3/s)	[3] Outlet U concentration (µg/L)	[4] Outflow (kg)	[5] U change in lake (kg)	[6] Concentration change (µg/L)	[7] Conc. estimated (µg/L)	[8] Error (%)
1985	3473	1.431	126.0	5699	–2226	–1.5	125.1	–0.7
1986	924	0.520	126.0	2070	–1145	–0.8	124.3	–1.4
1987	1581	0.844	129.0	3442	–1860	–1.3	123.0	–4.6
1988	617	0.376	94.2	1119	–502	–0.3	122.7	30.2
1989	1422	1.015	111.0	3562	–2139	–1.5	121.2	9.2
1990	626	0.459	127.2	1846	–1220	–0.8	120.3	–5.4
1991	1179	0.973	112.8	3470	–2290	–1.6	118.7	5.3
1992	1333	1.187	106.2	3985	–2652	–1.8	116.9	10.1
1993	1596	0.981	128.4	3981	–2384	–1.6	115.3	–10.2
1994	2153	1.261	109.2	4353	–2200	–1.5	113.8	4.2
1995	1002	0.670	104.4	2210	–1208	–0.8	113.0	8.2
1996	1093	0.771	99.6	2428	–1335	–0.9	112.0	12.5
1997	800	0.812	94.2	2418	–1617	–1.1	110.9	17.8
1998	2771	2.362	105.6	7888	–5117	–3.5	107.4	1.7
1999	653	0.542	96.0	1645	–991	–0.7	106.7	11.2
2000	452	0.372	85.8	1010	–557	–0.4	106.4	23.9
2001	1139	1.054	99.6	3318	–2178	–1.5	104.9	5.3
2002	783	1.076	98.4	3347	–2563	–1.8	103.1	4.8
2003	1256	1.641	97.8	5075	–3819	–2.6	100.5	2.7
2004	761	0.905	84.0	2405	–1643	–1.1	99.3	18.3
2005	465	0.635	93.0	1866	–1401	–1.0	98.4	5.8
2006	1118	1.177	100.8	3751	–2632	–1.8	96.6	–4.2

sum gives the total loading to the lake (minimal loadings from other drainage creeks are neglected), as listed in column [1]. Annual mean discharge at the lake outlet is estimated using the discharge ratio of Ace Creek watershed, and listed in column [2]. Annual mean U concentration at the outlet is obtained by reducing the observed concentration of the receiving bay area by 40% and is listed in column [3]. The multiplication of column [2] and [3] gives annual U outflow from the lake as listed in column [4].

Annual mass accumulation change in the lake is the inflow loading minus the outflow value, resulting in column [5]. Dividing this by the water volume of the lake gives the change of U concentration in the lake, resulting in column [6]. Adjusting a former year's concentration by using the concentration change of the present year gives an estimated mean concentration for the present year, as listed in column [7].

Comparing columns [7] and [3] gives a percent difference as listed in column [8]. The differences have a high correlation coefficient of 0.723 between the estimated and observed. Therefore, the mass balance relationships as established in Table 1 are reasonable and are used for trend prediction.

U loadings, U mass discharge and in-lake mass accumulation changes, as well as concentrations during the 22 years are plotted in Fig. 3. Before 1983, effluent from the mine and mill while in operation contributed higher concentrations to the two creeks, especially the Fulton Creek which received the tailings water. U loadings from the contaminated creeks depended on both concentration and water discharge. The loading decreases from a level of 3500 kg a year to a level of 1000 kg, although there were

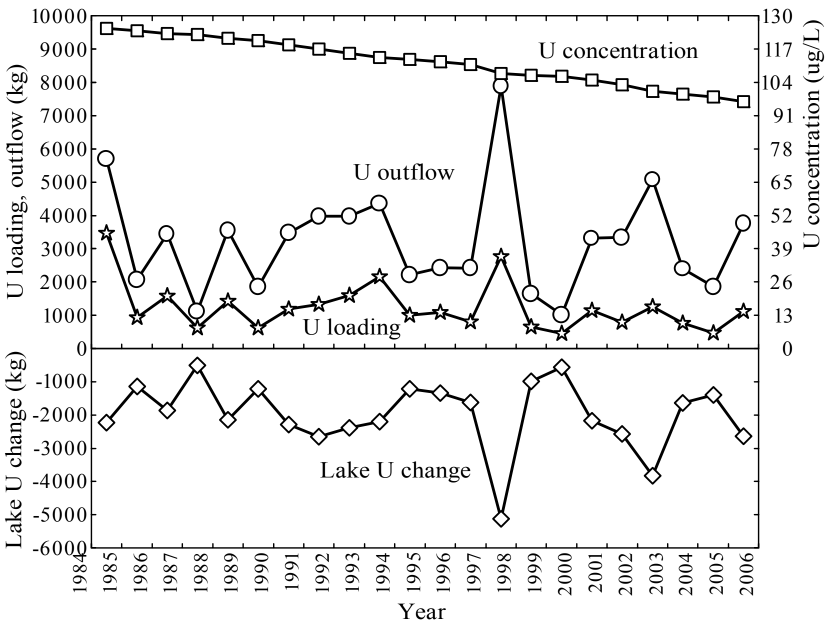

Fig. 3 Mass balances of 1985–2006.

fluctuations during the 22 years. The U discharge from the lake was larger than the loadings, because the loadings were reduced from their operation levels while the concentration in lake water was still high. A weak trend of decrease in the outflows is seen. Along with the decrease of loadings and lake-water concentration, U discharge at the lake outlet will gradually reduce. The lower section of Fig. 3 shows the U mass accumulation changes in the lake water, or the difference of inflow loading and outflow volume; the negative value indicates that inflow was less than outflow.

Prediction of future trends

The annual mean U concentrations between 1985–2006 in the Fulton Creek and Ace Creek were further checked to find their future trends. As shown in Fig. 4, the U concentration of Fulton Creek decreased, more rapidly in the 1980s and 1990s, and then slower in 2000s. A future trend with a constant decrease of 5 μg/L each year is assumed until the concentration reduces to zero. As shown in Fig. 5, U concentration of Ace Creek decreases roughly linearly. A similar linear trend is assumed to continue into the future.

Annual mean water discharge in future is anticipated to be the average value of years 1985–2006. The values are 0.5, 0.017 and 0.899 m^3/s respectively for the Ace Creek, Fulton Creek and Beaverlodge Basin (or water discharge at the lake outlet). The annual concentrations are multiplied by the discharge to give annual loadings from two creeks.

Trends of U discharge from the lake and U concentrations in the lake are predicted year by year starting from 2007. For 2007, the total loading is 772 kg, the mass discharge is estimated using the 2006 concentration 100.8 μg/L and the water discharge at

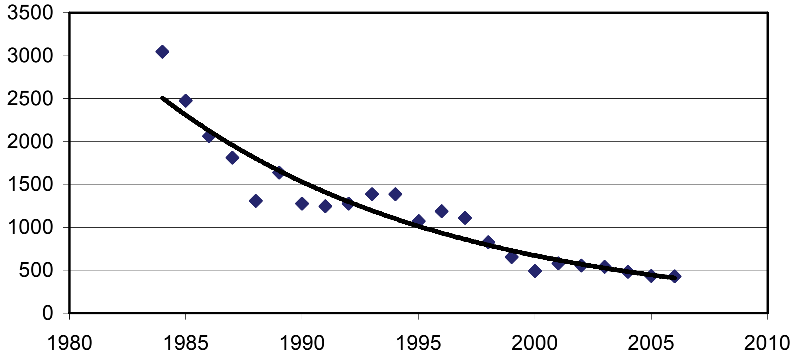

Fig. 4 Trend of U concentration in Fulton Creek.

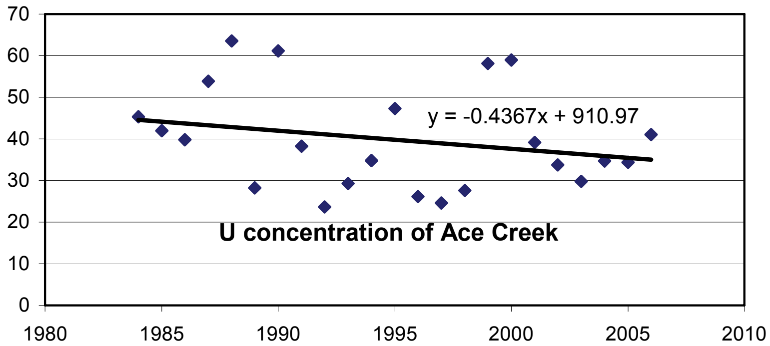

Fig. 5 Trend of U concentration in Ace Creek.

the outlet, and then U mass accumulation change in the lake within the year is obtained, and an updated concentration at the outlet for 2007 is known. Continue this process to year 2008, 2009, and so on, until the concentration reaches a drinking water standard of 10 μg/L. Prediction results for the initial years are listed in Table 2. Prediction results for long-term trends are illustrated in Fig. 6.

Table 2 Predicted U loadings, discharges and concentrations.

Year	Load from Ace (kg)	Load from Fulton (kg)	Total load (kg)	Discharge (kg)	U Change in lake (kg)	Concentration change (μg/L)	Concentration (μg/L)
2007	545	227	772	2856	2084	–1.4	99.4
2008	538	224	762	2997	2234	–1.5	97.8
2009	531	221	752	2953	2200	–1.5	96.3
2010	524	219	743	2911	2167	–1.5	94.8
…	…	…	…	…	…	…	…
2118	0	0	0	471	–471	–0.3	9.9

Estimated U mass balances for 1985–2006 are plotted in thicker lines in Fig. 6; predicted trends for 2007–2118 are plotted in thinner lines. U loading into the lake reduces from 772 kg in 2007 to 0 kg in 2092; the U outflow discharge of the lake reduces from 2856 kg in 2007 to 471 kg in 2118; the mass accumulation change in the

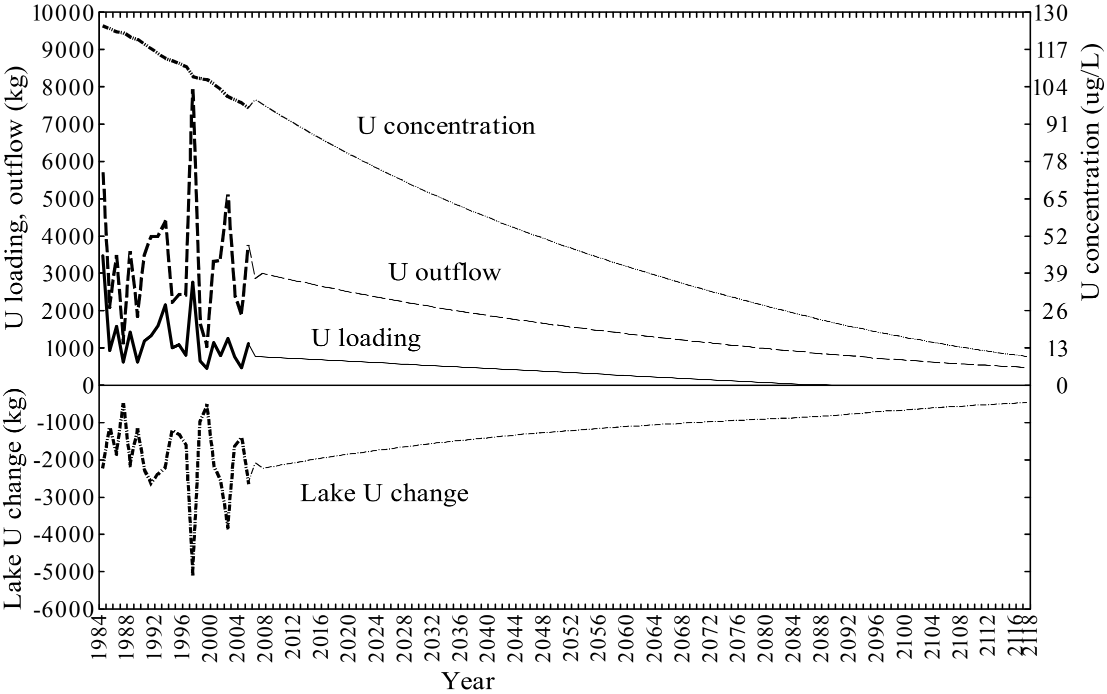

Fig. 6 Trend predictions of U loadings, outflow discharge and concentrations.

lake (the difference of loading and outflow) alters accordingly and gradually comes close to the U discharge value. When there is no loading after year 2092, the absolute value of mass change equals to the outflow level. U concentration of the lake decreases because the outflow volume is larger than inflow loading, and reaches the drinking water standard of 10 μg/L in year 2118. Therefore, it takes 112 years from now for the uranium level in the lake to restore to the standard.

Acknowledgements Hydrological and water quality data used in this study were obtained from the annual reports prepared by Cameco Corporation for the Beaverlodge Project. Their field monitoring and data are appreciated.

REFERENCES

Clulow, F. V., Dave, N. K., Lim, T. P. & Avadhanula, R. (1998) Radionuclides (lead-210, polonium-210, thorium-230, and -232) and thorium and uranium in water, sediments, and fish from lakes near the city of Elliot Lake, Ontario, Canada. *Environmental Pollution* **99**(2), 199–213.

Ekholm, P. & Mitikka, S. (2006) Agricultural lakes in Finland: current water quality and trends. *Environ. Monitor. Assess.* **116**(1-3), 111–135.

Gavshin, V., Sukhorukov, F., Bobrov, V., Melgunov, M., Miroshnichenko, L., Klerkx, J., Kovalev, S. & Romashkin, P. (2004) Chemical composition of the uranium tail storages at Kadji-Sai (southern shore of Issyk-Kul Lake, Kyrgyzstan). *Water, Air, and Soil Pollution* **154**(1-4), 71–83.

Houle, D., Gagnon, C., Couture, S. & Kemp, A. (2004) Recent recovery of lake water quality in Southern Quebec following reductions in sulfur emissions. *Water, Air and Soil Pollution: Focus* **4**(2-3), 247–261.

Peacey, V., Yanful, E. K. & Payne, R. (2002) Field study of geochemistry and solute fluxes in flooded uranium mine tailings. *Can. Geotechnical J.* **39**(2), 357–376.

Pinto, M., Silva, M. & Neiva, A. (2004) Pollution of water and stream sediments associated with the Vale De Abrutiga Uranium Mine, Central Portugal. *Mine Water and the Environment* **23**(2), 66–75.