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Distribution and Transport of Heavy Metals in the Sediments of a Small Northern Eutrophic Lake

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Transport of heavy metals, and their subsequent sorption by sediments in freshwaters, depends on many factors including the reactive organic and sulphide ion content of the sediments, water movements and metal solubility (FORSTNER 1977, ALLAN & BRUNSKILL 1977, OLOFFS et al. 1973). As pointed out by JACKSON (1979) and KUDO & MORTIMER (1979), such factors are often the cause of large scale dispersal of metals through lakes and rivers and are therefore indirectly responsible for introducing pollutants into the food chain. Despite the fact that heavy metal transport is an important aspect of waste disposal schemes and aquatic resource utilization, there is little information on the long term fate of these pollutants in small enclosed ecosystems. The purpose of this study was therefore to measure the concentrations of heavy metals in the sediments of a small, eutrophic lake, which received waste discharges from a gold mine between 1941 and 1949. The data were then used to measure relative rates of movement which were in turn correlated with variations in environmental conditions.

MATERIALS AND METHODS

Sampling was conducted from May to October 1978 in Thompson Lake (Lat. 62°36'N, Long. 113°30'W) in the Canadian Northwest Territories. The lake, measuring 3.7 km long and up to 1.0 km wide, has average and maximum depths of 4.0 and 10.0 m respectively. It is ice covered from October to May, with water temperatures reaching a maximum of 17°C at the surface and 16°C on bottom during July. The lake water is slightly acidic (pH 6.0-6.8) and phytoplankton densities reach 1800 mg m^{-3} during the summer and 400 mg m^{-3} in winter (MOORE 1979). During the study, there were no surface streams flowing into or out of the lake. Gold mining operations began on the south-east shore during 1941 and terminated in 1949. Mill tailings were deposited on shore and in the lake immediately adjacent to the mine. Apart from the mine, there are no other industries or developments along the shore of the lake.

Sediment samples were collected during June and July from 35 stations spaced 400 m apart on a grid throughout the entire lake. The sediments, collected from the upper 1 cm of substrate with a plastic corer, were frozen at -20°C within 3 h of collection. Samples for the analysis of total mercury were digested in nitric

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and sulphuric acids, followed by elemental reduction with stannous chloride and determination by cold vapour atomic absorption spectrometry. Analysis of samples for all other metals involved digestion with hydroflouric, nitric and hydrochloric acids, followed by determination by plasma emission spectrometry. Land based tailings were also collected during June and July on a 20 station grid and preserved, digested and analyzed as outlined for the lake sediments.

Water for chemical analysis was collected from 5 stations running down the length of the lake during June, July, August and September. The samples were taken at the surface with a plastic Van Dorn bottle. Samples for total mercury determinations were preserved through the addition of nitric acid and potassium dichromate, while those for the analysis of other heavy metals were preserved with nitric acid. Determinations were carried out as described by EPA (1974).

Samples for the measurement of the organic content of the substrate were collected with a plastic-lined corer from the 35 sampling stations. The sediments were taken from the upper 1 cm of the substrate, dried to constant weight at 70°C and ashed at 550°C for 24 h.

RESULTS

Tailings contained an average of 190 $\mu g\ kg^{-1}$ of mercury while the corresponding values for Cu, Pb and Zn were 57, 93 and 100 $mg\ kg^{-1}$, respectively (Table 1). Although titanium was also recorded at a high level (2100 $mg\ kg^{-1}$), the concentrations of other metals were generally low. Mercury was much higher in the lake sediments (430 $\mu g\ kg^{-1}$) near the mine and decreased gradually moving away from this area. Although a similar trend was recorded for Cu and Zn, the concentrations of Ti, As, Sr and Cr were lower in the sediments than in tailings.

Variations in the concentrations of heavy metals among the stations were strongly correlated with one another (Table 2). In most instances, correlation coefficients of 0.70 were recorded for Hg, Cu, Pb, Zn, Ti and As. Therefore, changes in the levels of one metal were usually associated with changes in the other heavy metals. The organic content of the lake sediments varied from 20 to 37% dry weight immediately adjacent to the mine. These values increased to 62 to 81% at a distance of 0.2 to 1.0 km from the mine, while the corresponding ranges at 1.1-2.0 and 2.1-3.0 km were 65-87 and 68-91% respectively. There was a strong negative correlation between the concentrations of almost all metals and the organic content of the sediments (Table 3). However, the correlations with As were both positive and significant.

TABLE 1

Mean (± 95% confidence limits) and range in concentrations of metal in the tailings and sediments of Thompson Lake at different distances from the mine. All data are in mg kg^{-1}, except for Hg which is $\mu g\ kg^{-1}$.

	Tailings	Distance from mine (km)		
		0-1.0	1.1-2.0	2.1-3.0
Number of samples	20	16	10	9
Hg	190±54	440±140	110±27	100±19
	(16-590)	(51-1300)	(35-230)	(73-14)
Cu	57±5	84±22	34±3	32±5
	(36-89)	(25-170)	(24-42)	(19-47)
Pb	93±34	29±13	< 2	< 2
	(14-1500)	(2-110)	(-)	(-)
Zn	100±14	11±21	88±5	83±21
	(38-220)	(64-250)	(76-110)	(42-11)
Ti	2100±240	840±380	330±120	270±25
	(780-2900)	(230-3700)	(190-870)	(230-290)
Cr	97±11	38±16	21±5	18±3
	(30-140)	(12-150)	(15-42)	(11-37)
Sr	14±16	65±13	49±13	43±11
	(70-270)	(40-160)	(32-97)	(39-56)
As	29±12	2.5±1.7	2.7±0.5	3.0±1.5
	(0.5-16)	(0.5-18)	(1.0-4.0)	(1.0-5.0)

TABLE 2

Correlation matrix of the concentrations of heavy metals in the sediments of Thompson Lake. Asterisk indicates significant correlation ($P > 0.05$).

	Mercury	Copper	Lead	Zinc	Titanium
Arsenic	0.52	0.26	0.71*	0.79*	0.76*
Mercury		0.87*	0.87*	0.81*	0.87*
Copper			0.77*	0.68*	0.74*
Lead				0.95*	0.97*
Zinc					0.96*

TABLE 3

Correlation coefficients between the concentrations of heavy metals in the sediments and environmental factors. Asterisk indicates significant correlations $(P > 0.05)$.

	Hg	Cu	Pb	Zn	Ti	Cr	Sr	As
Organic matter	-0.81*	-0.87*	-0.90*	-0.83*	-0.64*	-0.70*	-0.67*	0.69*
Distance	-0.60*	-0.65*	-0.51	-0.49	-0.73*	-0.77*	-0.81*	0.9*
Depth	-0.62*	-0.60*	0.91*	-0.63*	-0.52	-0.71*	-0.65*	0.50

There were also negative and generally significant correlations between metal concentrations and the distance from the mine and water depth. In the case of As, the correlations were positive and significant.

Total Hg levels in the water were less than 0.2 mg m^{-3} on all occasions except two, when values of 2.5 and 0.5 mg m^{-3} were recorded immediately next to the mine. As ranged from < 0.01 to 0.040g m^{-3}, while the corresponding values for Cu, Pb and Zn were $<$0.005-0.02, $<$ 0.005-0.35, and $<$ 0.01-0.43 g m^{-3} respectively.

DISCUSSION

The strong negative correlations between the concentrations of most metals and the organic content of the substrate contrast with the findings of JACKSON (1979), KUDO et al. (1977) and others, which indicated that the levels of Hg, Cu, Cd and Zn were positively correlated with organic carbon levels in the sediments of lakes and rivers. These differences are almost certainly due to the fact that the waste discharges at Thompson Lake consisted of crushed rock, associated metals and Hg from the amalgam process. Since, under these conditions, the organic content of the discharged material would be low, the deposition of tailings increased the metal loading to the lake while simultaneously lowering the organic level of the sediments. In contrast, the sources of contamination in the studies by JACKSON and KUDO et al. were effluent from chlor-alkali plants, pulp and paper mills and sewage treatment sites, all of which would release effluents with a relatively high organic content. It is therefore important to assess the physical and chemical characteristics of industrial discharges prior to investigating the extent of heavy metal contamination in lakes.

Since the concentrations of most metals decreased as the distance from mine increased, tailings have not yet spread evenly throughout the lake. This was perhaps surprising given the fact that the lake is small and eutrophic and that wastes were last deposited 30 years ago. Furthermore, since Thompson

Lake is shallow and generally homeothermous, wind-generated currents should be able to transport dissolved and suspended metals throughout the lake. It is therefore apparent that, in cold northern environments, the transport of heavy metals is extremely slow in the absence of flowing water. By contrast, SKEI (1978) showed that tidal action was responsible for the large-scale transport of Hg from a chlor-alkali plant throughout a fjord in Norway. Similarly, Hg levels are generally constant throughout much of the length (120 km) of Lake Paijanne (Finland), a reflection of the north-south flow of water (ŠARKKÄ et al. 1978). Since there was a positive correlation between the concentrations of most metals and water depth in Thompson Lake, it is likely that gravity has little influence on the movements of tailings. This is probably due to the fact that the lake is shallow and that the slopes of the bottom contours are not steep. THOMAS (1972) showed that there was an inverse correlation between mercury levels and water depth in Lake Ontario.

Based on the significant correlation coefficients in Table 2, it is likely that the rates of movements of most metals through the lake were similar. This is consistent with the findings of LUND et al. (1976) which showed that the concentrations of Cd, Cr, Cu, Zn and Ni in soil below sewage disposal ponds varied in constant proportion to each other, regardless of depth. On the other hand, the poor correlation between As and Cu indicates that the dispersal of As through the lake differs significantly from other metals. This is probably due to differences in the chemical binding of the metals (JONASSON & TIMPERLEY 1973). In addition, since As does not accumulate in animal tissues (WAGEMANN et al. 1978), the biotic transport of As through the lake would be much slower than that of Cu.

Hg was last deposited in Thompson Lake 30 years ago and yet total concentrations are still high in the tailings and sediments. Although this indicates that the clearance rate is extremely slow in small enclosed lakes, the OTTAWA RIVER PROJECT GROUP (1979) demonstrated that in open systems (the Ottawa River), Hg has a half life of only one year. The group suggested that desorption of Hg from the disturbed sediments is able to account for most of the observed clearance. Hence, the rates of recovery of aquatic systems from Hg pollution vary widely depending on physico-chemical conditions. This implies that industrial effluent guidelines must consider the nature of potential receiving waters and that broad generalizations may not be made regarding the assimilative capacities of lakes and rivers for mercury additions.

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REFERENCES

ALLAN, R. J. & G. J. BRUNSKILL: In H. L. GOTERMAN (ed). Interactions between sediments and fresh waters. Junk Publ., The Hague. 1977.

ENVIRONMENTAL PROTECTION AGENCY: Methods for chemical analysis of water and waste water. EPA, Cincinatti. 1974.

FORSTNER, U: In H. L. GOLTERMAN (ed.). Interactions between sediments and fresh water. Junk Publ., The Hague. 1977.

JACKSON, T. A.: Environ. Pollut. 18, 131 (1979).

JONASSON, I. R. & M. H. TIMPERLEY: In P. A. KRENKEL (ed.). Heavy metals in the aquatic environment. Pergamon Press, Toronto. 1973.

KUDO, A. & E. C. MORTIMER: Environ. Pollut. 18, 239 (1979).

KUDO, A., R. D. TOWNSEND & D. R. MILLER: J. Environ. Eng. Div. 13128, 605 (1977).

LUND, L. J., A. L. PAGE & C. O. NELSON: J. Environ. Qual. 5, 330 (1976).

MOORE, J. W.: Int. Rev. ges. Hydrobiol. 64, 485 (1979).

OLOFFS, R. C., L. J. ALBRIGHT, S. Y. SZETO & J. LAU: J. Fish Res. Bd. Can. 30, 1619 (1973).

OTTAWA RIVER PROJECT GROUP: Environ. Res. 19, 231 (1979).

SARKKA, J., M. L. HATTULA, J. JANATUINEN & J. PAAIVIRTA: Bull. Environ. Contam. Toxicol. 20, 332 (1978).

SKEI, J. M.: Mar. Pollut. Bull. 9, 191 (1978).

THOMAS, R. L.: Can. J. Earth Sci. 9, 636 (1972).

WAGEMANN, R., N. B. SNOW, D. M. ROSENBERG & A. LUTZ: Arch. Environ. Contam. Toxicol. 7, 169 (1978).