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DISTRIBUTION OF METALS IN DIFFERENT SIZE FRACTIONS OF SEDIMENT FROM THE NIAGARA RIVER

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Executive Summary.

This report contains results of the investigation of the relationship between metals and different particle size fractions in a fluvial sediment exposed to many pollutant sources. The investigation was carried out during 1984-85 under project ECD-236.

Bottom sediments of the Great Lakes connecting channels are composed mainly of coarse particles. The study showed that there is still a significant quantity of silt and clay size particles mixed with sand on the Niagara River bottom. These fine particles contained up to twenty six times higher concentration of lead, zinc, copper, chromium and cobalt than the fine particles from Lake Erie. These fine particles are succeptible to the resuspension and transport from the Niagara River into Lake Ontario. Sand-size particles collected from the Niagara River bottom in the vicinity of a steel plant contained up to sixteen times higher concentration of iron, chromium, cobalt and zinc than sand-size particles from Lake Erie. These may be man-made particles disposed of into the Niagara River. The study showed that the information on total metal concentration of sediment is not sufficient and that some sediment particles can contribute greater metal quantities. Resuspended fine grained particles are an important carrier of metal pollutants within the Great Lakes system.

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RÉSUMÉ ADMINISTRATIF

Le présent rapport renferme les résultats de l'étude ayant pour but d'élucider le lien entre la présence des métaux et la taille des particules que l'on trouve dans les sédiments fluviaux exposés à de nombreuses sources de pollution. Cette étude a été menée en 1984-1985 et désignée par le numéro de projet ECD-236.

Les sédiments de fond que l'on trouve dans les cours d'eau qui relient les Grands Lacs entre eux sont composés surtout de particules grossières. L'étude a révélé qu'il subsiste une quantité appréciable de particules fines, telles que des limons et de l'argile, mêlées à du sable au fond de la rivière Niagara. On a trouvé que ces particules renfermaient des concentrations de plomb, de zinc, de cuivre, de chrome et de cobalt vingt-six fois plus élevées que les particules fines du lac Érié. Ces particules fines peuvent facilement être remises en suspension et transportées par la rivière Niagara jusque dans le lac Ontario. Les particules de sable en provenance du fond de la rivière Niagara à proximité d'une usine sidérurgique renfermaient des concentrations de fer, de chrome, de cobalt et de zinc pouvant être jusqu'à seize fois plus élevées que celles des particules du lac Érié. Il peut s'agir de particules créées par une activité humaine et évacuées dans la rivière Niagara. La présente étude prouve qu'il ne suffit pas de connaître la concentration totale des métaux dans les sédiments puisque certaines particules peuvent renfermer une plus forte proportion de métaux que d'autres. Les particules fines remises en suspension sont un important agent de transport des polluants métalliques dans le bassin des Grands Lacs.

DISTRIBUTION DES MÉTAUX DANS LES PARTICULES DE DIFFÉRENTS CALIBRES DES SÉDIMENTS DE LA RIVIÈRE NIAGARA. Alena Mudroch et George Duncan

ABSTRACT

This study provides information on the relationship between metals and different particle size fractions in fluvial sediment exposed to many pollutant sources.

Concentration of major elements (Si, Al, Ca, Mg, Na, K, Fe, Mn, P. organic and inorganic C) and metals (Cr, Co, Cu, Zn, V, Ni and Pb) and mineralogical composition were determined in six size fractions (<13 µm, 13-19 µm, 19-27 µm, 27-40 µm, 40-54 µm and >54 µm) in bottom sediments collected at eight stations along the Niagara River. Between 32 and 92% of the sediment particles were >63 µm size. The contribution of metals from specific size fractions was calculated from the particle size distribution and metal concentrations. Associations of metals with different particle size in the Niagara River sediment were compared to those in Lake Erie nearshore zone sediment. Except for Pb, the metals were enriched significantly more in the coarse size fraction than in the finest fraction of the Niagara River sediment.

Additional index words: mineralogy, particle size distribution, metal enrichment.

RÉSUMÉ

La présente étude approfondit le lien entre les métaux et la taille des particules que l'on trouve dans les sédiments fluviaux qui sont exposés à de nombreuses sources de pollution.

La concentration des principaux éléments (Si, Al, Ca, Mg, Na, K, Fe, Mn, P. et carbone organique et inorganique) et métaux (Cr, Co, Cu, Zn, V, Ni et Pb) et la constitution minéralogique des sédiments de fond recueillis dans huit stations le long de la rivière Niagara ont été déterminées pour six calibres de particules (>13 µm, 13-19 µm, 19-27 µm, 27-40 µm, 40-54 µm et >54 µm). Entre 32 p. 100 et 92 p. 100 des particules avaient un diamètre supérieur à 63 µm. L'apport en métaux d'après le calibre des sédiments a été calculé à partir de la distribution des diamètres des particules et de la concentration des métaux. Les combinaisons des métaux en fonction de la taille des particules de la rivière Niagara ont été comparées à celles des sédiments de fond en bordure du lac Érié. Pour ce qui est des sédiments extraits de la rivière Niagara, la proportion des métaux était considérablement plus élevée dans les particules grossières que dans les particules fines, à l'exception du plomb.

Autres mots-clés : minéralogie, distribution du calibre des particules, enrichissement (par les métaux)

DISTRIBUTION DES MÉTAUX DANS LES PARTICULES DE DIFFÉRENTS CALIBRES DES SÉDIMENTS DE LA RIVIÈRE NIAGARA. Alena Mudroch et George Duncan

INTRODUCTION

Sediment associated toxic metals and organic compounds can be released in various forms and concentrations into water during dredging operations, and present potential health hazards to society. Studies of metal concentrations in the Great Lakes sediments have shown that metals are associated mainly with fine-grained sediments (Kemp et al., 1976; Mudroch, 1984a). Recently, high concentrations of metals were found in the sediments from the Niagara and Detroit Rivers (Kauss, 1983; Mudroch, 1984b; Thornley and Hamdy, 1984).

The objectives of this study were to investigate the concentrations of metals in different particle size fractions by determination of:

differences in metal concentrations between particle size fractions of the sediments collected at eight sampling stations in the Niagara River;

calculating metal enrichment of the sediments collected from the Niagara River, by comparing the metal concentrations in different size fractions with those of sediments having similar geochemistry and particle size distribution.

MATERIALS AND METHODS

Surface sediment samples were collected by an Ekman dredge at eight stations (Fig. 1) selected on the basis of available information on sediment and metal distribution in the Niagara River (Environment Canada and Ontario Ministry of the Environment, 1981; Kauss, 1983). Possible sources of contaminants in the vicinity of individual sampling stations were considered: steel industry (station 1); shipping channel (station 2); Erie Canal (station 3); combined sewers (station 4); outfall from chemical plants (stations 5 and 6); Cayuga Creek (station 7); numerous industrial and municipal discharges along the Niagara River (station 8). Figure 1

Particle size analyses of bulk sediment samples were carried out by the "Sieve and Sedigraph Method" (Duncan, 1982). Each sediment sample was first wet-sieved through a 150 μm size sieve. Particles <150 μm were further separated by the Warman Cyclosizer (Warman International, Ltd., Artarmon, Sydney, Australia) into following size fractions: 54-150 μm, 40-54 μm, 27-40 μm, 19-27 μm, 13-19 μm and <13 μm. The effective particle separation was calculated after the weight percentages retained in the five cyclons had been determined. Correction factors for water temperature, particle specific gravity, actual flow rate and time of elutriation were calculated according to the cylosizer instruction manual. The smallest size fraction (<13 μm) was recovered from collected water used for the separation by settling, decantation and centrifugation. The efficiency of separation was checked by a sedigraph analysis (Duncan and LaHaie, 1979). All separated size fractions were freeze dried and size fractions >54 µm were ground. Concentrations of organic and inorganic C were determined with a Leco Carbon Analyzer. Concentrations of major elements and metals were determined by X-ray fluorescence spectrometry. The precision of the analysis was determined by analysing five pellets made from a homogenized sediment sample. Relative deviations for major elements in sediment samples can be expected at the following levels: SiO_2 2%, K_2O and Al_2O_3 4%, Fe_2O_3 and CaO 2%, MgO and Na_2O 10%. Absolute deviations of 0.01% to 0.02% were found for MnO, TiO_2 and P_2O_5. For metals (Zn, Cu, Cr, Co, V, Ni and Pb) absolute deviations are to be expected in the range of 3 to 15 µg/g at the determined levels. The accuracy of the analyses was verified by running Canadian Reference Standards Syenite SY-2 and soils SO-2 and SO-4 and comparing the analytical results with the stated reference values for major and trace elements. The mineralogical composition was investigated by powder X-ray diffraction using Cu-target with a Ni-filter.

RESULTS AND DISCUSSION

Particle size distributions of sediment samples determined by sieving and by the cyclosizer are presented in Fig. 2. The Figure 2 greatest portion of the particles between 63 and 2,000 µm was <150 µm and, consequently, classified as fine and very fine sand (Shepard, 1954). Between 30 and 92% of the particles were >63 µm. Sediments collected at the Union Canal (st. 1), Erie Canal mouth (st. 3) and in the lower part of the Niagara River (st. 8) consisted mainly of particles >63 µm.

Mineralogical analyses showed that particles >63 µm were mainly quartz and dolomite. Dolomite, calcite and feldspars were major components of the 13 to 63 µm particle size and particles <13 µm were mainly illite and chlorite with smaller quantities of feldspars and calcite. Some illite was also found in the 13 to 19 µm size fraction.

Concentration of major elements and metals in individual sediment size fractions separated by the cyclosizer are presented in Tables 1 and 2, respectively. Table 1 Table 2

Geochemical Composition of the Sediment

Except at stations 1 and 3 the concentration pattern of SiO_2 was similar in all size fractions at all stations. The lowest concentration of SiO_2 was in the <13 µm size fractions. SiO_2 was abundant as quartz and a constituent of various silicates. The concentration of Al, K and P increased with decreasing particle size, particularly in the <13 µm size fractions. Al and K are constituents of clay minerals such as illite which was detected by X-ray diffraction in all sediment samples. The prefered adsorption of P on clay minerals is known from many past studies (for example Williams et al., 1971). The greatest concentration of Fe was found at station 1 in the >54 μm size fraction. Fe content decreased with decreasing particle size but was still greater than in any other size fraction at the other stations except in >54 μm size fraction at station 3. The source of this high Fe content in sediment at station 1 was most likely the local steel industry. Generally, the concentration of Fe increased slowly with decreasing particle size at stations 2, 4, 5, 6, 7 and 8 suggesting an association with clay minerals. The concentration of Na was between 0.5-1.6 percent and decreased with increasing particle size but there were many exceptions. The results indicated that Na concentration reflected local geology, particularly the presence of sodium feldspar. Increased concentration of Mg in the larger size fraction was due to the presence of dolomite. On the other hand, increased concentration of Mg in <13 μm size fractions was associated with the occurrence of clay mineral chlorite. The concentration of Ti showed a similar pattern in all size fractions: increasing concentration with decreasing particle size and an anomaly in >54 μm size fraction. The overall highest concentration of Ti was in >54 μm size fraction at stations 6 and 8. No explanation is offered for this result. The concentration of Ca in different size fractions was complex and affected by local geology and most likely by some industrial inputs. The greatest concentration was found at station 1 with a steel plant as a possible source and at station 8 which had greatest quantities of dolomite. We have no explanation for increased Ca concentration in 13-40 μm size fractions at station 7. The concentration of organic C increased with decreasing particle size at all stations. However, it was lower than that in the silty-clay sediments of Lake Erie (Thomas *et al.*, 1976). Inorganic C represented the concentration of carbonates in the sediments. The concentration of Mn was related to that of Fe in all sediment samples.

Distribution of Metals

The concentration of Ni was similar in all size fractions at all sampling stations except station 5. Significantly higher concentrations were found in 13-40 μm size fractions at this station. The greatest concentration of Co was in the >54 μm size fraction at stations 1 and 3. Cr and Co showed concentration patterns similar to that of Fe at stations 1 and 3: decreasing concentration with decreasing particle size. This relationship indicates an identical source of Fe, Cr and Co which was most likely a steel plant. High concentrations of these three metals in >54 μm size fraction at station 3 were accompanied by an increased concentration of V. At the other stations concentrations of Cr, Co and V showed patterns similar to those of Pb, Zn and Cu, i.e. increasing concentration with decreasing particle size. The greatest concentration of Pb and Zn was found in <13 µm size fraction at station 1. With the exception of Ni concentrations of metals in almost all size fractions exceeded many times the Ontario Ministry of the Environment guidelines for disposal of dredged sediment into open lake.

Contribution of metals from specific size fractions was calculated from quantities of each size fraction (Fig. 2) and metal concentrations (Table 2), and are presented in Table 3. Total quantities of metals in sediment at each station are summarized in Table 4. For example, at station 2 concentration of Pb in >54 µm size fraction (i.e. 54% of sediment) and <13 µm size fraction (21% of sediment) were 66 $\mu g \cdot g^{-1}$ and 559 $\mu g \cdot g^{-1}$, respectively. Calculated total content of Pb in sediment was 195 $\mu g \cdot g^{-1}$ (Table 4) comprising 18.3% of Pb in >54 µm size fraction, 60.3% of Pb in <13 µm size fraction and 21.4% of Pb in the remaining size fractions (Table 3). About 60% of sediment particles from station 2 could be transported after resuspension into Lake Ontario. The concentration of Pb in these particles was 559 $\mu g \cdot g^{-1}$. Further, about 39% of sediment particles from station 1 with Pb concentration 1,811 $\mu g \cdot g^{-1}$ may be transported by the same route. These small particles with low settling velocity will be dispersed for certain period in Lake Ontario water column until they settle to the bottom. However, it should be noted that total concentration of Pb in sediment from stations 1 and 2 was 324 and 195 $\mu g \cdot g^{-1}$, respectively.

Table 3

Table 4

The sediment collected from the eight stations along the Niagara River had generally similar particle size distribution and geochemical composition to that at the inshore of Lake Erie (Mudroch, 1984a). Consequently, concentrations of metals found in different size fractions of sediment collected at the Lake Erie nearshore zone were compared to those found in the Niagara River sediments. Calculated enrichment of each metal in >54µm and <13µm size fractions is presented in Table 5. With the exception of Ni, concentrations of metals were consistently greater in the Niagara River sediments than in the Lake Erie inshore sediment. Except for Pb, metals were enriched more in >54µm than in <13µm size fraction. The greatest enrichment of >54µm fraction with Cr, Co and V was in the sediment from station 3 at the Erie Canal mouth and that of Zn and Fe in >54µm fraction at station 1 in the vicinity of the steel plant. In addition, the greatest enrichment of <13µm size fraction by Pb was found at this station. Table 5

CONCLUSIONS

The present study shows that fine particles (<13µm) in a river sediment exposed to pollution sources can accumulate great concentrations of metals. In addition, such sediment may also contain man-made metal particles of various sizes or coarser particles (>54µm) which were exposed for an extended period to pollution sources and adsorbed great quantities of metals.

A primary settling area of fine and coarse contaminated particles transported by a river into a lake is the river mouth. Many of these areas in the Great Lakes are used as harbours and small craft marinas and need regular dredging. The suitability of the dredged material for the most economical disposal into the lake is regulated by guidelines based on the sediment bulk chemical composition. It should be recognized that the information on total metal concentration alone is not sufficient and that some sediment particles can contribute greater metal quantities. In addition, only a certain portion of the metals may take part in short-term geochemical processes and become bioavailable. Implementation of guidelines which would recognize the potential availability of metals associated with different sediment size fractions could significantly improve and facilitate the management of the dredged material.

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TABLE 1. Concentration of major elements in separated sediment size fractions (% dry weight)

Sampling Station	Particle Size	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	Inorg-C	Org-C
1	>54	44.9	5.5	36.2	2.7	8.1	0.53	1.00	0.45	0.43	0.27	0.75	0.25
	40-54	55.8	6.8	23.2	2.6	8.3	0.72	1.43	0.57	0.34	0.30	0.81	0.28
	27-40	57.3	7.1	20.8	2.7	8.8	0.63	1.48	0.63	0.34	0.31	0.85	0.58
	19-27	59.7	7.3	17.9	2.6	9.0	0.56	1.58	0.72	0.34	0.33	0.87	0.75
	13-19	60.0	7.7	16.3	2.7	9.6	0.63	1.73	0.78	0.32	0.30	0.91	0.68
	<13	47.7	13.4	17.2	3.4	12.9	0.56	3.10	0.78	0.34	0.76	1.12	0.73
2	>54	75.7	7.5	4.1	3.4	5.4	1.34	1.57	0.70	0.07	0.28	0.92	0.91
	40-54	76.7	8.1	4.2	2.8	4.5	1.20	1.67	0.53	0.07	0.28	0.67	1.93
	27-40	76.1	8.1	4.6	2.8	4.7	1.11	1.61	0.62	0.08	0.28	0.83	2.25
	19-27	74.1	8.8	5.2	3.0	5.1	0.91	1.72	0.76	0.09	0.31	0.88	3.45
	13-19	72.6	9.4	5.9	3.0	5.0	0.89	1.93	0.86	0.10	0.32	0.86	3.51
	<13	57.1	14.3	11.8	3.2	5.1	0.90	3.85	1.03	0.14	2.63	0.88	3.62
3	>54	55.9	5.7	23.9	3.0	4.2	0.91	0.83	0.90	0.34	0.34	0.36	0.15
	40-54	77.9	7.7	3.5	2.5	4.3	1.70	1.61	0.54	0.06	0.24	0.62	0.33
	27-40	77.9	8.0	3.0	2.6	4.6	1.66	1.56	0.48	0.05	0.25	0.65	0.58
	19-27	76.4	7.9	3.8	2.8	5.3	1.28	1.61	0.68	0.06	0.28	0.78	0.95
	13-19	74.6	8.3	4.4	3.0	5.7	1.17	1.67	0.80	0.07	0.26	0.83	1.15
	<13	53.7	16.2	9.7	4.4	7.8	1.53	4.12	0.98	0.25	1.34	0.87	1.25
4	>54	75.8	7.4	5.5	2.6	4.6	1.48	1.53	0.71	0.08	0.27	0.67	0.57
	40-54	75.8	7.8	4.7	2.7	5.1	1.41	1.55	0.55	0.08	0.30	0.75	0.82
	27-40	74.4	7.9	5.3	3.0	5.6	1.25	1.58	0.68	0.08	0.31	0.82	1.10
	19-27	72.7	8.4	5.9	3.1	6.0	1.07	1.73	0.77	0.09	0.32	0.90	1.25
	13-19	70.1	9.3	6.8	3.2	6.4	1.00	1.91	0.87	0.10	0.34	0.93	1.15
	<13	57.1	14.3	12.2	3.9	6.2	0.72	3.83	1.06	0.13	0.94	0.90	1.20
5	>54	74.6	7.2	6.2	2.8	5.3	1.40	1.48	0.64	0.09	0.33	0.91	0.98
	40-54	75.3	8.2	4.3	2.8	5.5	1.36	1.60	0.57	0.07	0.35	0.97	1.65
	27-40	73.8	8.4	4.6	3.0	6.2	1.28	1.65	0.66	0.08	0.35	1.10	2.73
	19-27	72.9	8.5	4.9	3.2	6.6	1.04	1.70	0.76	0.09	0.37	1.18	2.58
	13-19	70.4	9.4	5.9	3.1	6.9	0.98	1.94	0.85	0.11	0.44	1.23	2.49
	<13	56.5	14.4	11.0	3.9	6.9	0.95	3.88	1.05	0.11	1.23	1.23	2.82
6	>54	77.2	7.3	5.0	2.6	3.4	1.44	1.34	1.55	0.09	0.17	0.62	0.26
	40-54	79.3	8.0	2.4	2.7	3.7	1.49	1.62	0.57	0.04	0.18	0.64	0.43
	27-40	78.8	8.3	2.5	2.8	3.9	1.41	1.55	0.61	0.04	0.17	0.70	0.65
	19-27	78.1	8.4	2.8	2.9	4.0	1.19	1.63	0.75	0.04	0.20	0.72	1.10
	13-19	77.0	8.8	3.3	3.0	4.0	1.02	1.78	0.88	0.04	0.20	0.74	1.25
	<13	61.3	15.4	8.8	3.8	3.9	0.93	4.23	1.09	0.07	0.52	0.70	1.18
7	>54	80.1	7.9	2.5	2.3	3.3	1.63	1.47	0.51	0.04	0.20	0.61	0.28
	40-54	77.2	8.0	2.7	3.0	5.2	1.49	1.58	0.54	0.05	0.28	1.15	0.67
	27-40	71.7	8.3	3.4	2.9	9.7	1.29	1.66	0.56	0.06	0.38	1.45	0.95
	19-27	69.2	8.5	4.0	3.1	11.2	1.00	1.79	0.70	0.07	0.47	1.56	1.00
	13-19	68.8	9.0	4.5	3.2	10.3	0.96	1.93	0.80	0.07	0.45	1.49	2.30
	<13	59.8	15.0	9.2	3.4	5.6	0.78	3.93	1.08	0.11	1.34	0.95	1.95
8	>54	68.1	7.7	6.2	4.9	8.0	1.44	1.47	1.61	0.13	0.17	1.43	0.65
	40-54	73.2	7.9	3.0	4.2	8.0	1.09	1.75	0.48	0.07	0.12	1.19	0.93
	27-40	71.6	8.6	3.8	4.0	8.0	0.99	1.96	0.61	0.08	0.15	1.05	1.13
	19-27	71.0	9.3	4.3	3.7	7.4	0.84	2.11	0.76	0.08	0.17	1.00	1.05
	13-19	70.0	10.1	4.9	3.5	7.0	0.77	2.37	0.86	0.08	0.17	0.95	1.20
	<13	58.3	15.2	9.9	4.4	4.9	1.05	4.43	1.09	0.14	0.34	0.70	1.43

TABLE 2. Concentration of metals in separated sediment size fractions

(μg/g dry weight)

Sampling Station	Particle Size	Cr	Co	Cu	Zn	V	Ni	Pb
1	>54	336	267	91	967	90	24	200
	40-54	367	90	89	1,208	88	29	204
	27-40	313	75	103	1,193	86	37	352
	19-27	257	71	106	1,111	86	38	394
	13-19	203	61	99	1,061	88	36	468
	<13	192	51	168	2,337	101	28	1,811
2	<54	57	<5	11	75	41	20	66
	40-54	148	33	6	198	59	34	78
	27-40	136	17	78	262	51	28	84
	19-27	142	13	84	338	67	32	102
	13-19	201	25	98	377	75	35	240
	<13	426	41	292	1,065	134	37	559
3	>54	378	227	13	336	734	17	33
	40-54	89	16	30	168	40	19	10
	27-40	87	9	54	249	37	24	63
	19-27	148	26	49	296	47	31	113
	13-19	150	32	8	198	55	33	111
	<13	214	42	43	409	104	55	177
4	>54	98	4	71	277	52	19	66
	40-54	116	16	89	375	45	26	94
	27-40	164	19	106	433	53	30	120
	19-27	149	22	117	456	62	35	120
	13-19	204	33	97	424	73	38	160
	<13	306	28	311	1,390	121	36	534
5	>54	119	18	95	368	49	26	98
	40-54	116	5	119	419	44	45	108
	27-40	134	20	218	466	47	89	104
	19-27	173	8	332	461	62	167	154
	13-19	201	26	255	466	71	167	192
	<13	326	20	509	1,364	121	53	568
6	>54	83	9	21	97	136	19	15
	40-54	125	18	81	241	43	26	17
	27-40	62	4	16	90	47	23	19
	19-27	70	8	22	99	56	24	21
	13-19	76	11	27	117	70	26	25
	<13	128	36	44	214	139	37	47
7	>54	73	<5	20	229	36	21	33
	40-54	109	7	25	209	36	23	53
	27-40	103	<5	45	302	42	25	74
	19-27	121	<5	61	358	50	26	97
	13-19	172	15	65	365	56	30	231
	<13	289	24	142	850	124	37	274
8	>54	156	12	25	154	127	21	30
	40-54	105	13	32	137	31	26	25
	27-40	137	14	40	163	50	26	35
	19-27	120	14	50	188	67	28	38
	13-19	120	6	65	203	83	30	46
	<13	230	28	151	400	159	44	179

TABLE 3. Contribution of metals from specific size fractions (in percent)

Station/size fraction µm		Fe	Cr	Co	Cu	Zn	V	Ni	Pb
1:	>54	93.1	90.9	96.7	82.6	78.5	86.3	83.6	53.7
	13-54	3.4	4.9	1.5	5.1	6.2	5.9	8.4	7.1
	<13	3.5	4.2	1.8	12.3	15.3	7.8	8.0	39.2
2:	>54	36.5	18.9	16.6	8.1	13.2	32.7	40.1	18.3
	13-54	22.6	26.2	30.4	8.0	13.9	25.8	31.1	21.4
	<13	40.9	54.9	53.0	83.9	72.9	41.5	28.8	60.3
3:	>54	99.2	98.1	99.5	84.5	96.1	99.5	91.4	86.1
	13-54	0.4	1.3	0.3	12.7	2.7	0.4	5.7	8.9
	<13	0.4	0.6	0.2	2.8	1.2	0.1	2.9	5.0
4:	>54	24.0	17.7	5.2	15.2	13.5	22.8	22.7	9.1
	13-54	29.8	23.7	39.0	15.8	15.1	21.1	31.7	13.7
	<13	56.2	58.6	55.8	69.0	71.4	56.1	45.6	77.2
5:	>54	26.7	18.8	32.9	10.8	15.7	20.5	13.6	11.0
	13-54	18.7	21.9	24.7	23.0	17.1	20.9	54.6	15.6
	<13	54.6	59.3	42.4	66.2	67.2	58.6	31.8	74.4
6:	>54	49.3	49.1	31.0	41.2	41.0	43.7	41.9	33.4
	13-54	20.5	15.8	12.1	18.8	16.9	27.3	20.0	17.9
	<13	40.2	35.1	56.9	40.0	42.1	29.0	38.1	48.7
7:	>54	32.5	30.2	28.9	20.3	32.9	33.5	42.7	16.7
	13-54	26.9	29.5	23.3	30.5	25.5	27.4	31.5	36.4
	<13	40.6	40.3	47.8	49.2	41.6	39.1	25.8	46.9
8:	>54	85.6	85.5	81.2	62.5	77.9	85.9	79.1	64.8
	13-54	3.4	4.4	3.2	11.0	5.8	3.2	7.4	4.7
	<13	11.0	10.1	15.6	26.5	16.3	10.9	13.5	30.5

TABLE 4. Total concentrations of metals in the Niagara River sediment ($\mu g.g^{-1}$ dry weight)

Sampling Station	Cr	Co	Cu	Zn	V	Ni	Pb
1	321	240	96	1,072	91	25	324
2	163	16	73	306	68	27	195
3	366	217	14	332	700	18	36
4	198	19	171	740	82	30	263
5	209	18	292	771	79	63	289
6	91	16	28	128	120	24	24
7	129	9	52	368	57	26	105
8	159	13	34	172	128	23	40

TABLE 5. Enrichment of metals in the <13 µm and >54 µm size fractions of the Niagara River sediments

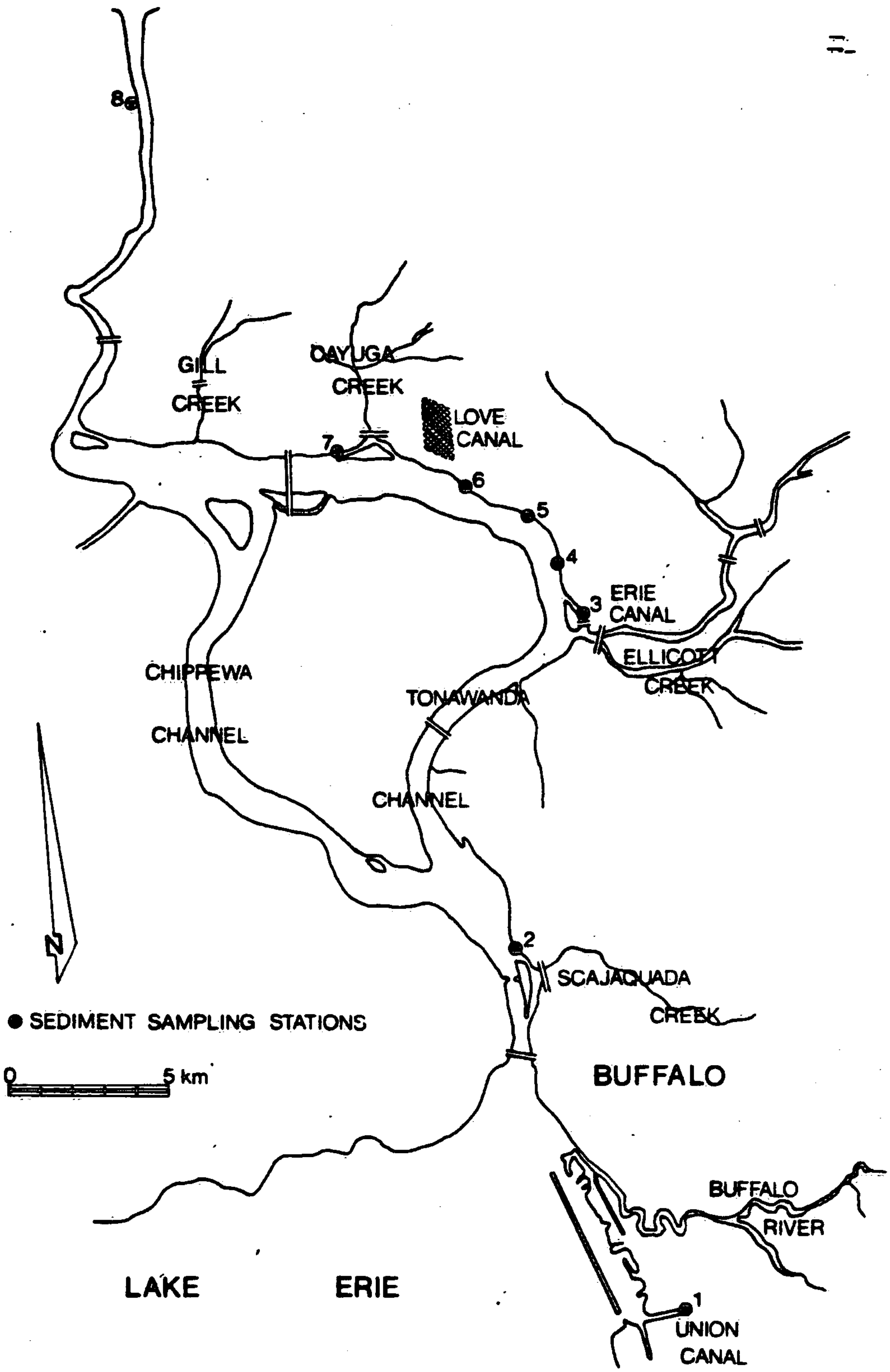
Station No.	Particle Size (µm)	Cr		Co		Cu		Zn		V		Ni		Pb		Fe	
		>54	<13	>54	<13	>54	<13	>54	<13	>54	<13	>54	<13	>54	<13	>54	<13
1		16.8	1.9	13.4	2.0	2.8	*	12.0	6.5	3.1	*	*	*	4.5	26.2	12.5	2.0
2		2.9	4.2	*	1.6	*	1.4	*	3.0	1.4	*	*	*	1.5	8.1	1.4	1.4
3		18.2	2.1	45.4	1.7	*	*	4.1	1.1	25.3	*	*	*	*	2.6	8.2	1.1
4		4.9	3.0	*	*	2.2	1.5	3.4	3.9	1.8	*	*	*	1.5	7.7	1.9	1.4
5		5.6	3.2	3.6	*	2.9	2.4	4.5	3.8	1.7	*	*	*	2.2	8.2	2.4	1.3
6		4.2	1.3	2.0	1.4	2.9	*	1.2	*	4.7	1.1	*	*	*	*	1.7	*
7		3.7	2.8	*	*	*	*	2.8	2.4	1.2	*	*	*	*	4.0	*	1.1
8		7.8	2.3	2.4	*	*	*	1.9	1.3	4.4	*	*	*	*	2.5	2.2	1.2

* = no enrichment

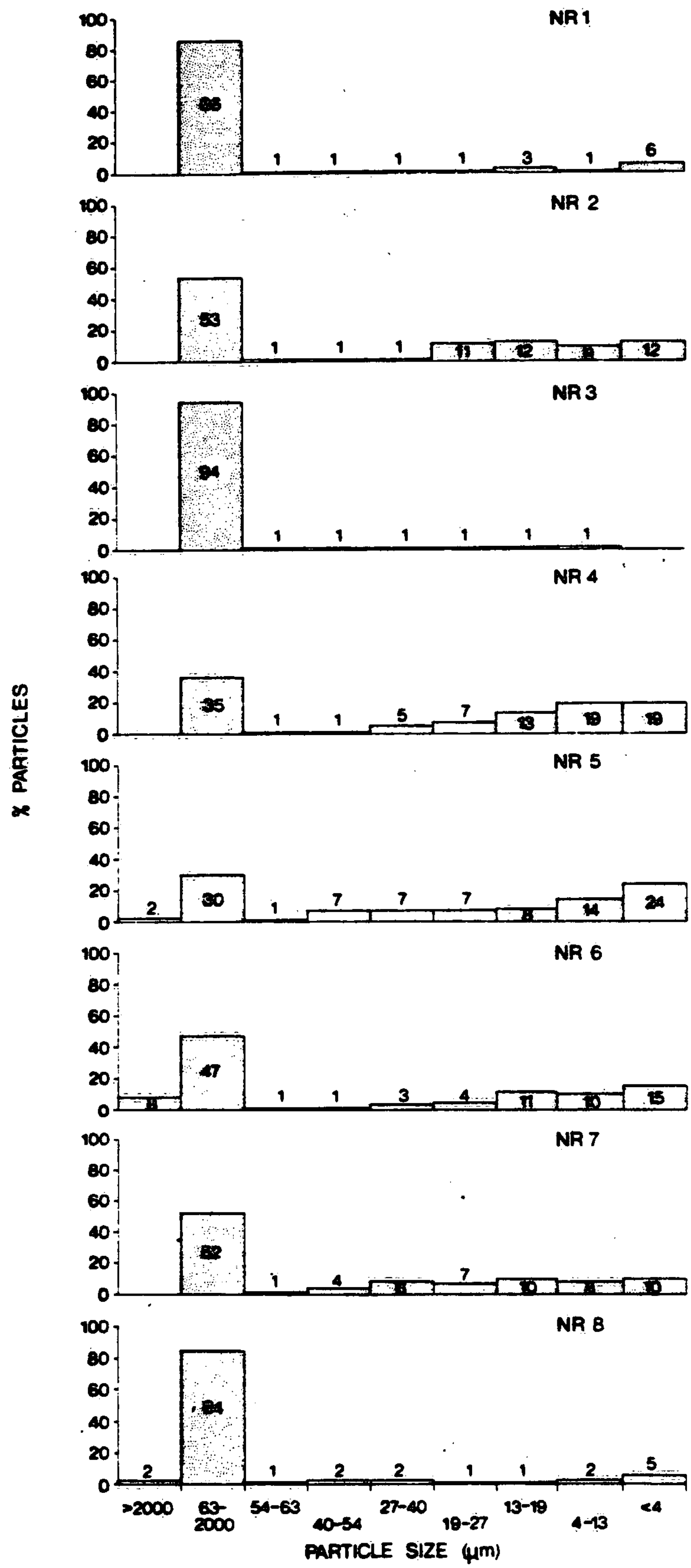
FIGURE CAPTIONS

Figure 1 Surface sediment sampling stations in the Niagara River

Figure 2 Particle size distribution of collected sediment samples



8
GILL
CREEK
CAYUGA
CREEK
LOVE
CANAL
7
6
5
4
3
ERIE
CANAL
ELLICOTT
CREEK
CHIPPEWA
CHANNEL
TONAWANDA
CHANNEL
N
2
SCAJAQUADA
CREEK
● SEDIMENT SAMPLING STATIONS
0
5 km
BUFFALO
BUFFALO
RIVER
LAKE
ERIE
1
UNION
CANAL



NR 1
NR 2
NR 3
NR 4
NR 5
NR 6
NR 7
NR 8
100
80
60
40
20
0
% PARTICLES
>2000
63-
2000
54-63
40-54
27-40
19-27
13-19
4-13
<4
PARTICLE SIZE (µm)

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