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MICROBIAL RESPONSES TO TRACE ELEMENTS AND NUTRIENTS IN ST. LAWRENCE RIVER

by

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EXECUTIVE SUMMARY

Concerns regarding toxic substances input to the Great Lakes basin have generated great interest in integrated ecotoxicological studies to evaluate the fate and long-term effects on sediment biota and biogeochemical processes. The potential toxicity of sediment pollutants to microbes has implications to water management programs. The extent of microbial community structure and their activities in aquatic ecosystems generally determine the types and rate of a number of essential biochemical processes such as organic matter degradation, nitrification and denitrification. The types of microbial communities that thrive in these ecosystems are indicative of microbial processes. Use of bacterial types and densities has been extensively employed in ecological assessment studies. This study provides information on sediment bacterial responses to the in-situ sediment pollutants in Lake St. Louis in the St. Lawrence River, spatial distributions possibly indicating sources and contaminant sinks. The study provides information on the usefulness of microbial communities to evaluate the nature and extent of sediment pollutants in an aquatic ecosystem. The data summarized in this report provide information on the relationship between microbial populations and the concentrations of trace elements in sediments in Lac St. Louis, St. Lawrence River. The information is useful for the evaluation of the response of microbial processes in aquatic sediments to pollutants.

Réactions des micro-organismes à la présence d'éléments trace et de substances nutritives dans les eaux du fleuve Saint-Laurent,
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SOMMAIRE ADMINISTRATIF

Les préoccupations suscitées par l'apport de substances toxiques dans le bassin des Grands Lacs ont éveillé beaucoup d'intérêt pour les études écotoxicologiques intégrées dans le but d'évaluer les effets à longue échéance et la tranformation du biote sédimentaire et des mécanismes biogéochimiques. Les effets toxiques que peuvent avoir les poluants sédimentaires sur les micro-organismes doivent être pris en compte dans les programmes de gestion des eaux. L'étendue et la composition des populations de micro-organismes ainsi que leurs activités dans les écosystèmes aquatiques déterminent en général la nature et le rythme de plusieurs processus biochimiques essentiels tels que la dégradation de la matière organique, la nitrification et la dénitrification. Le type de micro-organisme qui prolifère dans un écosystème donné permet de connaître la nature des processus qui s'y déroulent. On a fondé bon nombre d'études d'évaluation écologique sur l'analyse des types et du nombre de bactéries. Dans la présente étude on décrit les réactions des bactéries aux polluants qui se trouvent mêlés aux sédiments du lac Saint-Louis dans le fleuve Saint-Laurent. La répartition des bactéries dans l'espace fournit des indices quant aux sources de la pollution et aux endroits où elle se concentre. Cette étude nous renseigne sur le rôle utile que peuvent jouer les colonies de micro-organismes pour permettre d'évaluer la nature et l'étendue des polluants sédimentaires dans les écosystèmes aquatiques.

Les données présentées dans cette étude indiquent les liens qui existent entre les populations de micro-organismes et la concentration des éléments trace dans le lac Saint-Louis, le long du fleuve Saint-Laurent. Ces données peuvent servir à évaluer les effets des polluants sédimentaires sur les micro-organismes aquatiques.

ABSTRACT

Over 100 surface sediment samples from Lac St. Louis (St. Lawrence River) were examined for various microbial physiological types and densities. These organisms were correlated to the concentrations of trace elements (Ni, Co, Cr, V, Cu, Pb, Zn, As, Fe, Mn and Ti) and nutrients (P and organic matter). Results indicated a relationship between bacterial densities and trace element concentrations. Data also suggested that there was an apparent indication of bacterial inhibition due to toxic substances in the lake sediment. Generally, high and low bacterial density zones existed in the sediment with low bacterial density zones being associated with high concentration of trace elements. Because of the relationships and the distribution of trace elements and organic matter, the lake bottom exhibited a heterogeneous nature. The availability of trace elements in the surface sediments was assessed by determination of chemical species of the trace elements in solutions obtained by elutriation of the sediment with distilled water. Data and methodology are presented.

SOMMAIRE

On a examiné plus d'une centaine d'échantillons de sédiments provenant du lac Saint-louis (fleuve Saint-Laurent) pour répertorier les divers types physiologiques des micro-organismes qui s'y trouvent et la densité de chaque population. On a établi une corrélation entre ces organismes et les éléments trace (Ni, Co, Cr, V, Cu, Pb, Zn, As, Fe, Mn, et Ti) ainsi que les substances nutritives (P et matière organique). Les résultats ont révélé qu'il existe un lien entre les concentrations d'éléments trace et la densité des populations bactériennes. Il semble également que la présence de substances toxiques dans les sédiments aient un effet inhibiteur sur la croissance des bactéries. Dans l'ensemble, on a décelé des variations importantes de la densité d'une zone à l'autre; les zones ayant les populations de bactéries les moins denses possédaient les concentrations d'éléments à l'état de trace les plus élevées. À cause de la répartition dans l'espace des éléments trace et de la matière organique ainsi que le rapport inverse qui existe entre eux, le fond du lac paraît hétérogène. Pour évaluer la présence d'éléments trace dans les sédiments et identifier leur composition chimique, on a préparé des solutions par élutriation des échantillons de sédiments avec de l'eau distillée. On présente les données et la méthodologie employées dans le rapport.

INTRODUCTION

The St. Lawrence River system has been the subject of extensive studies since 1972 due to concerns about the fate of toxic pollutants released by municipal and industrial sources. In response to these concerns, several studies on the long-term effects of toxicants to biota and to organic biodegradation rates in the sediment have been undertaken actively. Lac St. Louis, a section of the St. Lawrence River, has been recognized as one of the highly contaminated water bodies. In order to determine whether Lac St. Louis acts as a sink for certain contaminants originating from municipal and industrial sources, a major program was initiated by Inland Waters Directorate, Quebec Region. As a part of this program, a study was undertaken to 1) ascertain microbiological response to contaminant loadings and 2) to establish if there is any measurable impact on bacterial ecosystems. Also, recent studies (Kwan and Dutka, 1984) indicated that 80% of the surface sediments (3 cm) and 100% of the relatively deeper layers (10 cm) were found to contain toxicants as measured by the Microtox test in Lac St. Louis.

In order to establish areas with bacterial populations that are sensitive to sediment contaminants in Lac St. Louis, over 100 sediment samples were examined for various bacterial physiological types and densities, trace metals and some nutrients. The data gathered were processed using a computer program to obtain correlation matrix for

the measured parameters at the sediment surface to determine if any relationship existed between bacterial and chemical parameters. Observations are presented in this report.

MATERIALS AND METHODS

Sediment Sampling

During the period of May to October 1984, a total of over 100 sediment samples were collected from Lac St. Louis (Fig. 1) using an Ekman dredge sampler. All sediment samples were placed in 500 mL polypropylene bottles and stored at 4°C until processing. Determinations of heterotrophic bacteria, nitrogen and sulphur cycle bacteria, organic matter, trace elements (Ni, Co, Cr, V, Cu, Pb, Zn, As, Fe, Mn and Ti) and phosphorus were carried out on all sediment samples.

Bacteriological Procedures

Aerobic heterotrophic bacteria were measured in all samples using the spread-plate procedure and a low nutrient medium (peptone, 3 g; K_2HPO_4, 0.2 g; $MgSO_4$, 0.05 g; $FeCl_3$, trace; agar 20.0 g and distilled water 1000 mL) with a pH of 6.8 was used throughout these studies. Incubation of the inoculated plates was carried out for seven days at

20°C (Dutka, 1978). Sulphur cycle and nitrogen cycle bacteria densities were estimated on all samples using the 5-Tube Most Probable Number procedure (MPN). Ammonifying bacteria densities were estimated in casein solution (Allen, 1953) and nitrifying bacterial densities in nitrosomonas broth (Thompson, 1969). Alexander's medium (1965) was used to test for denitrifying bacteria (N_2 production) and nitrate reducing bacteria (NH_3 and N_2 production). All nitrogen cycle bacteria were incubated for 21 days at 20°C.

Density estimates of the sulfur oxidizing bacterial population were made in Postgate's Thiobacillus medium (Postgate, 1966) with incubation at 28 C for 14-21 days. Sulfate reducing bacteria were enumerated in Starkey's medium (Starkey, 1948) with an anaerobic incubation period of 14-21 days at 28 C. For the enumeration of bacteria that reduce organic sulfur to sulfides, an MPN medium described by Gunkel and Oppenheimer (1963) was used, combined with anaerobic incubation at 28 C for 14-21 days.

Determination of Chemical Parameters in the Sediment

All sediment samples for chemical analyses were freeze dried and ground to pass through a 100 mesh size sieve.

The concentration of organic matter was determined as loss on ignition according to a standard procedure (American Public Health Association, 1985).

The concentration of trace elements and phosphorus was determined by X-ray fluorescence spectrometry using powder pellets. Relative deviation for Fe (expressed as oxide) can be expected 2%. Absolute deviations of 0.01% to 0.02% were found for Mn, Ti and P (expressed as oxides). For the rest of the trace elements, 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 computer program "Geochem" developed for the calculation of chemical equilibria in soil solutions and other natural water systems (Sposito and Mattigod, 1980) was used to predict the distribution of free trace element ions in the elutriate test (U.S. Environmental Protection Agency/Corps of Engineers, 1977). The method of calculation of chemical species in the elutriate test was described by Mudroch and Davies, 1985.

RESULTS AND DISCUSSION

The concentration of trace elements, organic matter and distribution of the bacterial population in Lac St. Louis are shown in Tables 1 and 2. The greatest concentration of trace elements was found in the western part of Lake St. Louis south of Ile Perrot, at stations

E1, E2, E3 and E4, in the northwest corner near Ottawa River mouth at station J1 and in the northern part south of Pointe Claire at stations I1 and I2 (Fig. 1). Generally, bacterial populations decreased with increasing concentrations of trace elements. However, there were many exceptions which will be discussed latter in this report. The maximum bacterial populations recorded in Lac St. Louis sediments were in the 10^7 range and the lowest bacterial populations in the 10^2 range. The results obtained by chemical and microbiological analyses of sediments from all sampling stations were statistically examined to ascertain if any relationship existed among microbial populations and concentrations of trace elements and organic matter. Correlation matrix of all parameters from all stations (Table 3) indicated a relationship between organic matter and Ni, Co, Cu, Pb and Zn. Highest positive correlation coefficients were obtained for Ni and Co, Ni and Cu, Pb and Zn and Fe and Mn (Fig. 2 to 5).

Significant differences in the concentration of trace elements and organic matter at all sampling stations indicated the heterogenous nature of sediments in Lac St. Louis. The degree of contamination of the sediment may be affected by numerous point sources along the River as shown by the greater concentrations of trace elements accumulated in the sediment at some areas in the lake, particularly at stations E1, E2, E3 and E4, I1, I2 and J1. Data from these stations were treated separately to investigate the relationship between individual parameters (Table 4). At these stations, organic matter

and all trace elements showed a positive relationship. It was therefore suspected that trace elements were bound to sediment organic matter. In this study, particularly the response of certain physiological types of bacteria to these associations of organic matter and trace elements seems to be noticeable. For example, organic sulphur reducers and sulphate reducers appear to be suppressed in this area. However, sulphur oxidizers and ammonifiers did not appear to be affected to the same extent by the trace element-organic matter association. A further investigation is necessary to assess in detail the effects of different "organic matter-trace element complex" on microbial population in Lac St. Louis.

At station J1 bacterial populations, concentration of organic matter and trace elements, except Mn, were similar to that observed at E-stations, i.e. higher concentration of organic matter (103 mg/g) was generally associated with higher densities of Thiobacillus sp. and ammonifiers at station J1.

A large population of ammonifiers is probably a good indicator of the availability of a complex nitrogenous substances (Dutka et al., 1974). It is generally believed that NH_3 produced by these bacteria stimulates the growth of autotrophic bacteria which obtain energy by oxidizing NH_3 through NO_2 to NO_3. Because of the quantity of O_2 used in this process and that utilized by heterotrophic bacterial population, a drastic reduction in dissolved oxygen concentration may occur. If this process occurs in a stagnant water, the lowering of

the redox potential may bring about dissolution of Fe and trace elements associated with Fe compounds in the sediment. However, in a fluvial system, such as Lac St. Louis, dissolved oxygen is usually abundant and the microbial processes may have only a short time local effect on the redox potential of the surface sediment.

In this study, presence of high densities of ammonifiers and the concentration of organic matter at stations J1 and E1 to E4 suggest that there is a source of nitrogenous substances in the sediment. Elevated concentrations of trace elements had no apparent effect on the growth of ammonifiers in these sediments. The populations of ammonifiers were highest in the sediment at station I1. This is a nearshore area and it is possible that there is an input of nitrogen compounds from domestic wastes which even though may not reside in the sediment are a source for ammonifiers. Nitrifying bacteria in these sediments (Nitrosomonas sp.) are usually indicative of active nitrification process. In addition, the greatest concentration of Fe, Mn and P (12.9% Fe_2O_3, 0.27% MnO and 0.65% P_2O_5) was found at this station.

A large population of sulphate reducing bacteria (Desulfovibrio sp.) indicates a supply of organic material such as algae, and their growth may be related rather to negative redox potential and the availability of carbonaceous energy source (Dutka et al., 1974). Desulfovibrio sp. are potential producers of ready energy for SO_4 reducing bacteria. In acid stressed lake sediments, for example, they

contribute to the overall sulphur concentration of sediment by reducing SO_4 (Thode et al., 1985). In Lac St. Louis, the greatest population of Desulfovibrio sp. existed near or at the centre of the lake.

Data from stations I1, I2 and I3 are summarized in Table 5. The concentration of trace elements at stations I1 and I2 was similar to that of stations E1 to E4. But the trace element concentration decreased at station I3. The concentration of organic matter was significantly lower at station I1 (16 mg/g) than at stations I2 and I3 (86 mg/g and 76 mg/g, respectively). Correlation matrix obtained by statistical examination of the data from these stations is shown in Table 5. A negative relationship was found between organic matter and Cr, As, Fe, Mn and P. There was no relationship between organic matter and the rest of the trace elements.

Elutriation of sediments collected at all sampling stations in Lac St. Louis was carried out by Champoux et al. (1985). One volume of surface sediment was elutriated with five volumes of distilled water and major and trace elements and nutrients were quantitatively determined in the final solution of the elutriate test (Champoux et al., 1985). The greatest concentration of trace elements obtained by elutriation of sediments was found in stations E1, E2, E3 and E4. The concentration of eluted trace elements at this station is compared to that obtained by elutriation of sediments from stations J1, I1, I2 and I3 (Table 6). Generally, greater quantities of Fe, Cu, Ni and Pb

were elutriated from sediments collected at stations E1 to E4 and J1 than from that at stations I1 to I3.

The concentration of free trace elements in each elutriate calculated using the computer program "Geochem" are given in Table 7. Greater concentration of free trace element ions, in particular, Cu and Pb, was found in the elutriates from stations E1 to E4 and J1 than from stations I1 to I3. On the other hand, significantly higher density of ammonifiers and sulphur oxidizing bacteria existed at station I1 than at E1 to E4 and J1. Since free ions are believed to be the most available form of an element to biota (Florence and Batley, 1980), the difference in the chemical form and availaility of Cu and Pb could have influenced the bacterial population at these stations.

Differences in the availability of trace elements and perhaps the nature of their association with the sediment organic matter may contribute to the differences in bacterial population and their growth in sediments with similar concentration of trace elements.

SUMMARY

Microbiological and selected trace element analyses of Lake St. Louis sediments indicated the following:

1. Sediments from Lac St. Louis in St. Lawrence River exhibited high and a low bacterial density zone. Low density zones were

associated with sediments with higher concentration of trace elements. However, there were exceptions evident, particularly in the western and northwestern parts of the lake.

2. At the western and northwestern areas, the concentration of trace elements in sediments was higher than that from the other parts of the lake. A relationship existed between organic matter and trace elements in sediments in these areas.

3. Generally higher concentration of trace elements in the sediment had no apparent effect on the growth of ammonifiers and sulphur oxidizing bacteria. Distilled water elutriation of sediments indicated that trace elements are more available from sediments in the western and northwestern areas than from the rest of the lake. Differences in the availability and the nature of association of trace elements and organic matter in the sediment could contribute to the differences in bacterial growth in sediments with a similar concentration of trace elements.

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REFERENCES

Alexander, M. 1965. Methods of soil analysis. Part 2. In: Black, C.A. (Ed.) Chemical and microbiological properties, Agronomy Service No. 9, American Society of Agronomy Inc., Madison, Wisconsin.

Allen, O.N. 1953. Experiments in soil bacteriology. Borges Publishing Company.

American Public Health Association. 1985. Standard methods for the examination of water and wastewater. 16th Edition. Amer. Pub. Health Assoc., N.Y.

Champoux, L., Ross, P., Jarry, V., Sloterdijk, H., Mudroch, A. and Cuillard, Y. 1985. Composition chimique des elutriates des sediments du Lac Saint-Louis (Fleuve Saint-Laurent). Submitted for publication.

Dutka, B.J. 1978. Methods for microbiological analysis of water, wastewaters and sediments. Inland Waters Directorate, Canada Centre for Inland Waters, Burlington, Ontario.

Dutka, B.J., Bell, J.B. and Liu, D.L.S. 1974. Microbiological examination of offshore Lake Erie sediments. J. Fish. Res. B. Can. 31: 299-308.

Florence, T.M. and Batley, G.E. 1980. Chemical speciation in natural waters. CRC Crit. Rev. Anal. Chem. 9: 219-296.

Gunkel, N. and Oppenheimer, C.H. 1963. Experiments regarding sulphide function in sediments of Texas Gulf Coast. In: Oppenheimer, C.H. (Ed.) Symposium on marine microbiology. Charles C. Thomas, Springfield, Ill.

Kwan, K.K. and Dutka, B.J. 1985. Microbiological studies of Lake St. Louis sediments, 1984. Unpublished Report, National Water Research Institute, Burlington, Ontario, 121-AMD-5-85.

Postgate, F. 1966. Media for sulphur bacteria. Lab. Pract. 15: 1239-1244.

Sposito, G. and Mattigod, S.V. 1980. GEOCHEM: A computer program for the calculation of chemical equilibria in soil solutions and other natural water systems. Dep. of Soil and Environ. Sciences, Univ. of California, Riverside, CA.

Starkey, R.L. 1948. Characteristics and cultivation of sulphur reducing bacteria. J. Am. Water Works Assoc. 40: 1291-1298.

Thode, H.G., Dickmann, M.D. and Rao, S.S. 1985. Effects of acid precipitation on sediment downcore profiles of diatoms, bacterial densities and sulphur isotope ratios in lakes north of Lake Superior. Submitted for publicationin Hydrobiologia.

Thompson, F. 1969. An investigation into the distribution of autotrophic and heterotrophic bacteria in little round lake with particular emphasis on some bacterial agents of sulphur cycle. Bacteriol. Branch Lab. Divn. Ontario Water Res. Com. Can., p. 17.

U.S. Environmental Protection Agency/Corps of Engineers. 1977. Ecological evaluation of proposed discharge of dredged material into ocean waters. Published by Environmental Effects Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

TABLE 1 Concentration of trace elements in sediments from Lac St. Louis ($\mu g.g^{-1}$ dry weight)

Station Number	Ni	Co	Cr	V	Cu	Pb	Zn	As	Fe_2O_3	MnO	TiO_2	P_2O_5
A1	32	13	63	52	23	37	143	3	40,400	700	5,800	2,200
A2	36	18	62	50	30	30	173	8	43,500	800	5,800	1,900
A4	38	16	74	58	34	36	188	9	47,300	900	6,300	2,700
B1	9	6	82	21	10	14	38	<1	15,000	400	3,600	1,200
B2	13	12	120	62	14	16	45	7	44,000	700	7,500	2,200
B3	14	11	109	47	13	25	90	<1	36,000	700	5,800	2,900
B4	8	7	84	29	9	11	24	<1	19,000	500	5,500	1,400
C1	13	10	91	41	14	16	113	<1	33,000	700	4,900	2,500
C2	14	8	92	37	15	17	139	<1	36,000	600	4,100	2,900
C3	12	9	100	30	13	16	81	<1	24,000	600	3,600	1,400
C4	9	5	75	26	10	17	19	2	19,000	500	5,100	1,300
D2	13	13	85	43	10	15	72	12	40,000	700	5,600	2,100
D3	41	16	94	88	38	44	201	8	56,000	900	7,200	2,600
D4	33	19	94	92	25	20	105	5	55,000	1,100	8,000	2,550
E1	52	29	117	99	40	56	322	2	87,300	3,100	9,000	3,700
E2	52	33	118	99	47	60	349	3	87,200	2,600	9,200	3,000
E3	52	30	111	64	57	64	465	6	77,800	1,800	8,800	2,500
E4	23	9	54	40	12	27	109	2	31,900	600	4,800	2,200
F1	14	17	102	69	10	22	89	<1	52,000	900	9,200	3,700
F3	47	24	110	94	39	57	397	<1	61,000	1,100	7,900	2,400
F4	40	16	143	84	41	55	491	6	52,000	1,000	7,200	2,700
G1	49	23	126	92	40	68	533	3	64,000	1,100	7,800	2,800
G2	15	16	122	51	14	39	233	<1	38,000	800	5,800	2,900
G3	9	6	54	24	7	21	57	<1	14,000	300	2,700	1,100
G4	13	13	122	46	15	31	187	<1	35,000	700	5,900	2,700
H1	38	25	107	97	40	48	171	<1	63,000	1,400	8,100	3,500
H2	46	23	117	97	43	46	199	9	70,000	1,400	7,800	2,700
H3	43	21	116	90	40	47	297	<1	64,000	1,200	7,700	2,600
I1	52	26	144	94	48	42	222	19	129,000	2,700	6,400	6,500
I2	51	23	118	93	45	51	403	5	68,000	1,100	7,800	2,500
I3	11	9	100	39	9	18	111	7	30,000	700	5,400	3,100
J1	54	27	116	104	57	59	356	3	77,000	1,600	8,300	3,300
J2	24	12	113	54	21	37	217	<1	44,000	800	6,300	3,400
J3	39	20	108	105	32	19	128	<1	65,000	1,100	9,300	2,400
J4	41	19	126	86	38	53	447	<1	57,000	1,000	7,200	2,600
K1	12	8	91	21	10	19	64	9	20,000	600	3,200	1,700
K4	10	8	112	22	9	14	37	<1	23,000	600	3,300	1,200

TABLE 2 Microbial population and concentration of organic matter in Lac St. Louis

Station Number	Heterotrophs #/ml	Organic Sulphur #/100 ml	Desulfovibrio #/100 ml	Thiobacillus #/100 ml	Ammonifiers #/100 ml	Nitrosomonas #/100 ml	Denitrifiers #/100 ml	Total Bacteria	Respiring Bacteria	L.O.I.* mg/gr dry sed.
A1	$7.0x10^4$	$3.5x10^6$	$1.7x10^4$	$9.2x10^4$	$4.7x10^5$	$7.9x10^2$	$2.3x10^5$	---	---	33 mg
A2	$4.5x10^4$	$1.3x10^6$	$1.1x10^4$	$2.3x10^3$	$2.1x10^6$	$1.3x10^3$	$1.6x10^7$	---	---	61 mg
A4	$3.2x10^5$	$1.3x10^6$	$7.9x10^3$	$4.6x10^2$	$4.6x10^5$	$2.3x10^3$	$7.9x10^5$	---	---	83 mg
B1	$1.6x10^4$	$4.9x10^5$	$1.3x10^3$	$2.8x10^2$	$7.0x10^6$	$4.9x10^2$	$2.3x10^5$	---	---	3 mg
B2	$4.6x10^4$	$1.1x10^5$	$3.3x10^3$	5	$1.4x10^5$	$4.9x10^1$	$4.9x10^4$	---	---	19 mg
B3	$4.2x10^5$	$2.3x10^6$	$3.3x10^3$	$4.9x10^2$	$5.4x10^6$	$4.9x10^2$	$4.9x10^5$	---	---	31 mg
B4	$6.8x10^5$	$7.9x10^5$	$4.6x10^3$	$1.8x10^4$	$2.8x10^6$	$2.3x10^2$	$7.9x10^5$	---	---	8 mg
C1	$1.9x10^5$	$3.3x10^5$	$4.9x10^3$	$9.2x10^4$	$1.4x10^6$	$3.3x10^3$	$3.3x10^4$	---	---	9 mg
C2	$1.3x10^6$	$2.4x10^5$	$7.9x10^3$	$2.1x10^4$	$2.2x10^6$	$4.9x10^3$	$2.4x10^6$	---	---	22 mg
C3	$1.8x10^5$	$4.9x10^5$	$3.3x10^3$	$5.4x10^4$	$1.8x10^5$	$2.3x10^3$	$4.3x10^4$	---	---	9 mg
C4	$4.0x10^5$	$1.1x10^6$	$1.1x10^4$	$2.4x10^4$	$1.4x10^5$	$1.7x10^2$	$2.2x10^5$	---	---	5 mg
D2	$3.2x10^5$	$1.1x10^6$	$7.0x10^3$	$3.5x10^4$	$2.4x10^6$	$7.0x10^2$	$7.0x10^5$	---	---	53 mg
D3	$4.8x10^5$	$2.4x10^6$	$3.5x10^4$	$7.9x10^1$	$9.2x10^6$	$9.2x10^2$	$4.9x10^5$	---	---	87 mg
D4	$4.9x10^5$	$3.5x10^6$	$2.4x10^4$	$4.9x10^1$	$1.4x10^6$	$4.9x10^2$	$1.7x10^6$	---	---	25 mg
E1	$2.1x10^5$	$2.2x10^6$	$5.4x10^4$	$1.1x10^3$	$4.3x10^6$	$4.9x10^2$	$1.6x10^7$	---	---	80 mg
E2	$1.9x10^5$	$2.4x10^6$	$7.9x10^3$	$1.3x10^3$	$9.2x10^6$	$1.7x10^2$	$1.7x10^6$	---	---	85 mg
E3	$1.5x10^5$	$1.7x10^6$	$2.4x10^4$	$3.3x10^3$	$9.2x10^6$	$7.9x10^2$	$2.2x10^6$	---	---	87 mg
E4	$2.9x10^5$	$5.4x10^6$	$5.4x10^4$	$6.4x10^2$	$2.5x10^6$	$4.9x10^2$	$2.5x10^6$	---	---	67 mg
F1	$6.0x10^6$	$1.3x10^6$	$2.8x10^4$	$2.3x10^1$	$1.6x10^7$	$3.3x10^3$	$2.5x10^6$	---	---	17 mg
F3	$5.2x10^4$	$3.5x10^6$	$9.2x10^4$	$1.7x10^3$	$2.8x10^5$	$4.9x10^2$	$6.9x10^5$	---	---	57 mg
F4	$8.4x10^4$	$5.4x10^6$	$9.2x10^4$	$1.1x10^2$	$3.5x10^6$	$4.9x10^2$	$1.6x10^7$	---	---	53 mg

*Loss on ignition.

TABLE 3 Correlation coefficient matrix of parameters from all stations

1.	Heterotrophs	1.00																		
2.	Org. Sulphur Reducers	-.09	1.00																	
3.	Desulfovibrio sp.	-.01	.10	1.00																
4.	Thiobacillus sp.	-.15	.13	.06	1.00															
5.	Ammonifiers	.39	.01	-.00	.04	1.00														
6.	Nitrifiers	.01	-.18	.03	.23	.07	1.00													
7.	Denitrifiers	-.08	.36	-.02	.44	.34	.04	1.00												
8.	Organic Matter	-.18	.23	.16	.16	.22	.16	.39	1.00											
9.	Ni	-.18	.27	-.07	.15	.30	.30	.35	.74	1.00										
10.	Co	-.02	.20	-.07	.12	.39	.27	.33	.67	.91	1.00									
11.	Cr	-.03	.16	.00	.20	.28	.31	.23	.17	.44	.51	1.00								
12.	V	.02	.29	-.04	.19	.31	.33	.33	.60	.88	.87	.58	1.00							
13.	Cu	-.20	.22	-.10	.16	.36	.31	.41	.72	.97	.90	.51	.84	1.00						
14.	Pb	-.18	.37	.14	.25	.23	.30	.40	.74	.88	.83	.52	.74	.88	1.00					
15.	Zn	-.18	.39	.19	.32	.13	.23	.42	.69	.81	.75	.59	.69	.82	.94	1.00				
16.	As	-.10	-.09	-.11	-.18	.38	.22	-.08	.22	.28	.24	.13	.19	.29	.09	.03	1.00			
17.	Fe_2O_3	.03	.20	-.14	.08	.55	.30	.25	.52	.87	.91	.68	.86	.85	.71	.63	.44	1.00		
18.	MnO	-.03	.15	-.11	-.03	.50	.16	.24	.47	.75	.86	.52	.70	.73	.64	.53	.32	.89	1.00	
19.	TiO_2	.23	.21	-.07	.06	.28	.19	.25	.58	.74	.84	.51	.88	.72	.64	.60	.07	.75	.64	1.00
20.	P_2O_5	.26	.28	-.01	.09	.65	.24	.17	.26	.49	.56	.57	.57	.48	.42	.37	.45	.79	.68	.48	1.00
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

TABLE 4 Correlation coefficient matrix of parameters from stations E1, E2, E3 and E4

1.	Heterotrophs	1.00																		
2.	Org. Sulphur Reducers	-.14	1.00																	
3.	Desulfovibrio sp.	-.07	.53	1.00																
4.	Thiobacillus sp.	.82	-.67	-.47	1.00															
5.	Ammonifiers	.27	-.76	-.94	.72	1.00														
6.	Nitrifiers	.89	-.16	.31	.68	-.02	1.00													
7.	Denitrifiers	-.40	-.26	.59	-.28	-.42	.04	1.00												
8.	Organic Matter	.19	-.96	-.74	.72	.91	.07	-.02	1.00											
9.	Ni	-.03	-.98	-.55	.54	.74	-.01	.30	.94	1.00										
10.	Co	-.08	-.96	-.66	.50	.80	-.13	.10	.96	.99	1.00									
11.	Cr	-.13	-.96	-.55	.45	.71	-.11	.33	.92	.99	.99	1.00								
12.	V	-.59	-.71	-.37	-.04	.41	-.50	.50	.64	.82	.84	.87	1.00							
13.	Cu	.29	-.97	-.68	.79	.89	.19	.00	.99	.93	.93	.90	.58	1.00						
14.	Pb	.13	-.99	-.65	.67	.84	.08	.13	.98	.98	.98	.96	.71	.98	1.00					
15.	Zn	.38	-.96	-.62	.84	.85	.30	.02	.97	.91	.89	.86	.51	.99	.97	1.00				
16.	As	.84	-.57	-.55	.98	.74	.63	-.44	.67	.44	.43	.35	-.14	.73	.60	.77	1.00			
17.	Fe_2O_3	-.20	-.94	-.52	.39	.67	-.16	.37	.69	.99	.98	1.00	.90	.86	.94	.83	.29	1.00		
18.	MnO	-.46	-.79	-.26	.07	.38	-.30	.62	.67	.87	.85	.91	.97	.63	.76	.59	-.05	.94	1.00	
19.	TiO_2	-.10	-.97	-.57	.48	.74	-.09	.29	.94	1.00	.99	1.00	.86	.91	.97	.88	.39	.99	.89	1.00
20.	P_2O_5	-.60	-.57	-.08	-.19	.03	-.31	.84	.38	.66	.61	.71	.89	.35	.50	.32	-.34	.75	.93	.68	1.00
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

TABLE 5 Correlation coefficient matrix of parameters from stations I1, I2, and I3

1.	Heterotrophs	1.00																		
2.	Org. Sulphur Reducers	.86	1.00																	
3.	Desulfovibrio sp.	.15	-.37	1.00																
4.	Thiobacillus sp.	.01	-.50	.99	1.00															
5.	Ammonifiers	.87	1.00	-.36	-.48	1.00														
6.	Nitrifiers	.34	.77	-.88	-.93	.76	1.00													
7.	Denitrifiers	.85	1.00	-.39	-.52	1.00	.79	1.00												
8.	Organic Matter	-.74	-.98	.55	.66	-.98	-.89	-.98	1.00											
9.	Ni	-.32	.21	-.99	-.95	.19	.78	.23	-.40	1.00										
10.	Co	-.18	.34	-1.00	-.99	.33	.86	.37	-.53	.99	1.00									
11.	Cr	.28	.73	-.91	-.96	.72	1.00	.74	-.85	.82	.90	1.00								
12.	V	-.32	.20	-.98	-.95	.19	.78	.23	-.40	1.00	.99	.82	1.00							
13.	Cu	-.27	.25	-.99	-.97	.24	.81	.28	-.44	1.00	1.00	.85	1.00	1.00						
14.	Pb	-.58	-.08	-.90	-.83	-.10	.57	-.06	-.12	.96	.91	.63	.96	.94	1.00					
15.	Zn	-.85	-.46	-.66	-.54	-.47	.21	-.43	.27	.78	.68	.28	.78	.74	.92	1.00				
16.	As	.74	.98	-.55	-.66	.98	.89	.98	-1.00	.40	.53	.85	.40	.44	.12	-.27	1.00			
17.	Fe_2O_3	.31	.75	-.89	-.95	.74	1.00	.78	-.67	.80	.88	1.00	.86	.83	.60	.25	.87	1.00		
18.	MnO	.49	.86	-.79	-.87	.86	.99	.88	-.95	.67	.77	.97	.67	.71	.43	.04	.95	.98	1.00	
19.	TiO_2	-.82	-.42	-.69	-.58	-.43	.25	-.40	.23	.80	.71	.32	.80	.77	.94	1.00	-.23	.29	.09	1.00
20.	P_2O_5	.75	.98	-.55	-.66	.98	.88	.99	-1.00	.39	.52	.85	.39	.44	.12	-.27	1.00	.36	.95	-.23	1.00
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

TABLE 6 Concentration of trace elements in sediment elutriates ($M.L^{-1}$)

Parameter/ Station	E1	E2	E3	E4	I1	I2	I3	J1
Mn	$2.29*10^{-5}$	$2.19*10^{-5}$	$1.38*10^{-5}$	$5.62*10^{-6}$	$3.31*10^{-5}$	$5.12*10^{-6}$	$8.71*10^{-6}$	$2.14*10^{-5}$
Co	$5.13*10^{-8}$	$5.13*10^{-8}$	$3.39*10^{-8}$	$5.13*10^{-8}$	$1.70*10^{-8}$	$3.39*10^{-8}$	$1.02*10^{-10}$	$3.39*10^{-9}$
Fe	$8.51*10^{-5}$	$7.08*10^{-5}$	$7.94*10^{-5}$	$9.12*10^{-5}$	$1.58*10^{-5}$	$6.17*10^{-5}$	$1.51*10^{-5}$	$5.37*10^{-5}$
Cu	$1.58*10^{-7}$	$1.41*10^{-7}$	$2.19*10^{-7}$	$2.34*10^{-7}$	$4.67*10^{-8}$	$1.41*10^{-7}$	$7.94*10^{-8}$	$1.41*10^{-7}$
Ni	$1.55*10^{-7}$	$1.20*10^{-7}$	$1.69*10^{-7}$	$1.86*10^{-7}$	$5.13*10^{-8}$	$1.35*10^{-7}$	$6.76*10^{-8}$	$2.24*10^{-7}$
Pb	$6.76*10^{-8}$	$6.31*10^{-8}$	$8.13*10^{-8}$	$8.12*10^{-8}$	$9.55*10^{-9}$	$3.39*10^{-8}$	$9.55*10^{-9}$	$4.37*10^{-8}$
Zn	$7.94*10^{-7}$	$7.56*10^{-7}$	$1.17*10^{-6}$	$1.41*10^{-6}$	$7.76*10^{-7}$	$1.70*10^{-7}$	$6.17*10^{-7}$	$4.90*10^{-7}$
As	$3.72*10^{-8}$	$3.98*10^{-8}$	$3.24*10^{-8}$	$5.13*10^{-8}$	$1.86*10^{-8}$	$3.24*10^{-8}$	$3.09*10^{-8}$	$3.98*10^{-8}$

TABLE 7 Concentration of free trace element ions in sediment elutriates ($M.L^{-1}$)

Parameter/ Station	E1	E2	E3	E4	I1	I2	I3	J1
Mn	$2.14*10^{-5}$	$2.01*10^{-5}$	$1.24*10^{-5}$	$5.00*10^{-6}$	$2.09*10^{-5}$	$4.48*10^{-6}$	$7.64*10^{-6}$	$1.95*10^{-5}$
Co	$4.00*10^{-8}$	$3.70*10^{-8}$	$1.99*10^{-8}$	$3.00*10^{-8}$	$8.56*10^{-9}$	$1.70*10^{-8}$	$5.17*10^{-11}$	$2.25*10^{-9}$
Fe	$1.35*10^{-20}$	$6.76*10^{-21}$	$1.70*10^{-21}$	$1.69*10^{-21}$	$8.51*10^{-22}$	$8.51*10^{-22}$	$8.51*10^{-22}$	$3.39*10^{-21}$
Cu	$2.61*10^{-8}$	$1.79*10^{-8}$	$1.55*10^{-8}$	$1.66*10^{-8}$	$2.41*10^{-9}$	$7.27*10^{-9}$	$4.09*10^{-9}$	$1.35*10^{-8}$
Ni	$1.08*10^{-7}$	$7.48*10^{-8}$	$7.72*10^{-8}$	$8.42*10^{-8}$	$1.87*10^{-8}$	$4.91*10^{-8}$	$2.48*10^{-8}$	$1.22*10^{-7}$
Pb	$1.19*10^{-8}$	$7.99*10^{-9}$	$4.98*10^{-9}$	$4.97*10^{-9}$	$3.96*10^{-10}$	$1.39*10^{-9}$	$3.94*10^{-10}$	$3.89*10^{-9}$
Zn	$6.46*10^{-7}$	$5.83*10^{-7}$	$7.94*10^{-7}$	$9.46*10^{-7}$	$4.73*10^{-7}$	$1.03*10^{-7}$	$3.77*10^{-7}$	$3.58*10^{-7}$
As	$9.34*10^{-17}$	$1.31*10^{-16}$	$9.00*10^{-16}$	$1.29*10^{-16}$	$8.97*10^{-17}$	$9.73*10^{-17}$	$7.66*10^{-17}$	$9.87*10^{-17}$

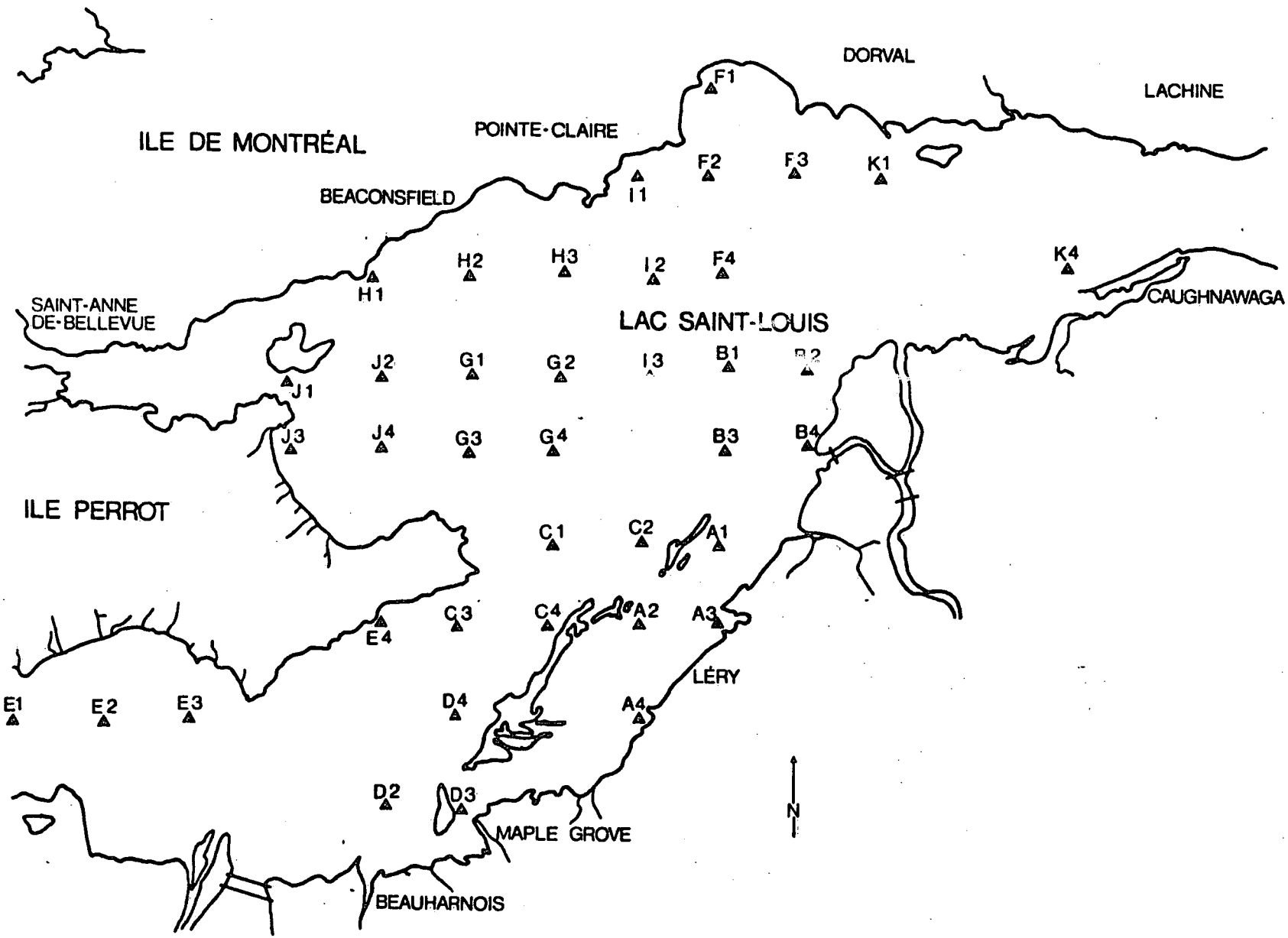
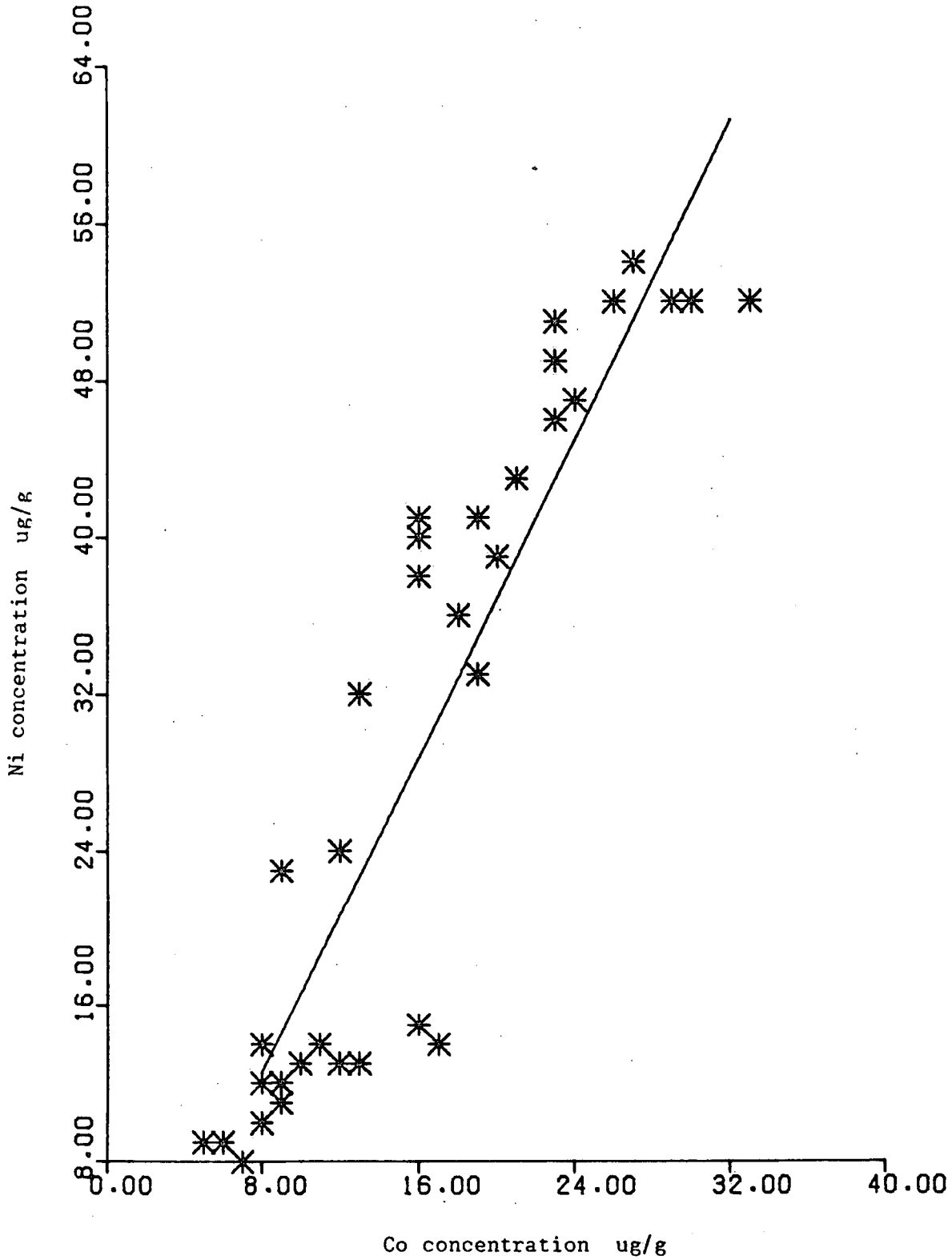
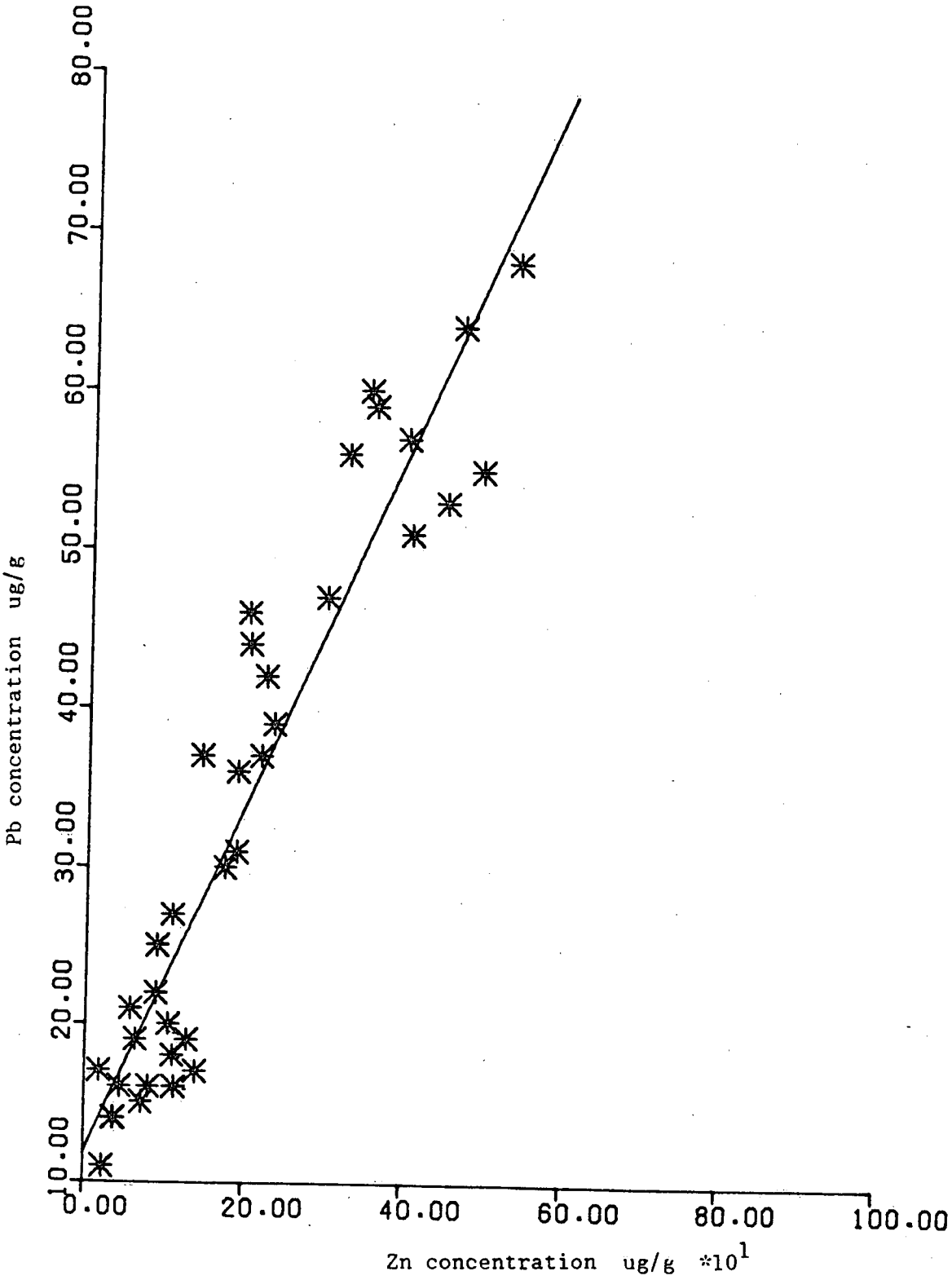
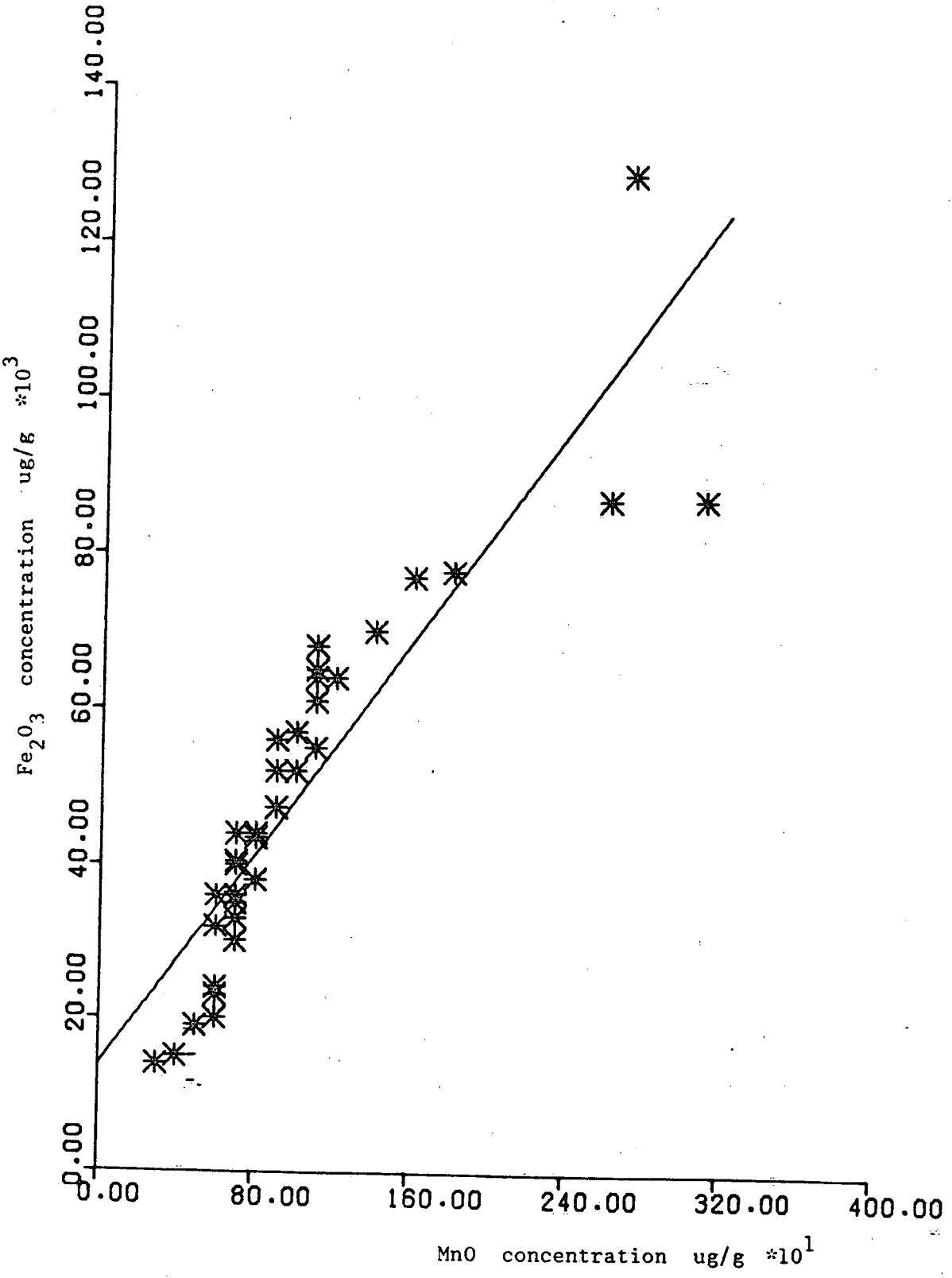
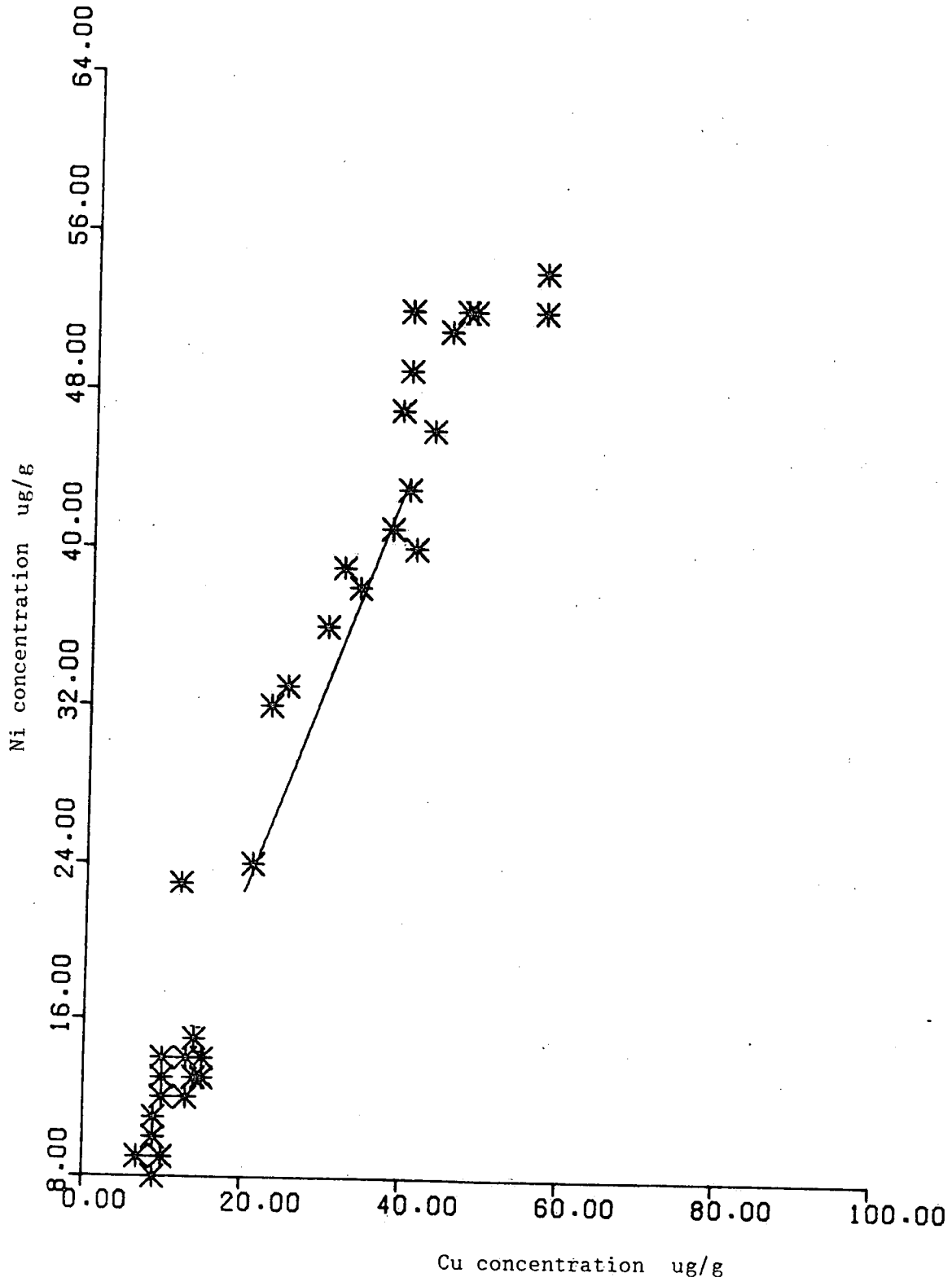


Figure 1 LOCATION OF SAMPLING SITES - LAKE ST. LOUIS


64.00
56.00
48.00
40.00
32.00
24.00
16.00
8.00
Ni concentration ug/g
0.00
8.00
16.00
24.00
32.00
40.00
Co concentration ug/g


Pb concentration ug/g
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
0.00
20.00
40.00
60.00
80.00
100.00
Zn concentration ug/g *10^1


140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Fe_2O_3 concentration ug/g *10^3
0.00
80.00
160.00
240.00
320.00
400.00
MnO concentration ug/g *10^1


64.00
56.00
48.00
40.00
32.00
24.00
16.00
8.00
Ni concentration ug/g
0.00
20.00
40.00
60.00
80.00
100.00
Cu concentration ug/g