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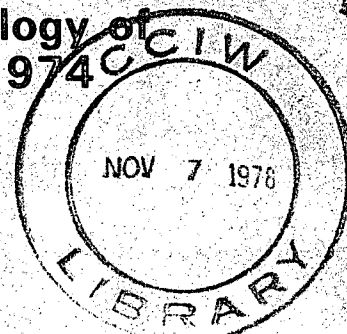
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Chemical Limnology of
Georgian Bay, 1974



N.D. Warry



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(Résumé en français)

INLAND WATERS DIRECTORATE, ONTARIO REGION,
WATER QUALITY BRANCH,
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Cat. No. En36-502/91

ISBN 0-662-10154-5

Contents

	Page
ABSTRACT	v
RÉSUMÉ	v
INTRODUCTION	1
SAMPLING AND DATA PROCESSING METHODS	1
RESULTS AND DISCUSSION	2
Major ions	2
Trace metals	5
Nutrients	7
Silica	7
Phosphorus	10
Nitrogen	10
Oxygen and pH	11
SUMMARY AND CONCLUSIONS	11
ACKNOWLEDGMENTS	11
REFERENCES	11
APPENDIX	13

Tables

1. Georgian Bay concentration vectors for major ions and dissolved reactive silica	4
2. Comparison of mean hypolimnetic concentrations of major ions in Lake Huron and Georgian Bay	4
3. Area-weighted mean concentration of nutrients at 1-m and 50-m depths in segment 10 of Georgian Bay	9
4. Ratios of total particulate P to total P in the surface waters of each Georgian Bay segment	10

Illustrations

Figure 1. Map of Georgian Bay showing station locations and zones	2
Figure 2. Distribution of major ions in the surface waters of Georgian Bay during May 1974	3
Figure 3. Epilimnion concentration differences of chloride and conductance observed in segments 10 and 3 of Georgian Bay	5
Figure 4. Histogram representing the distribution of all trace metal data collected in Georgian Bay during 1974	5

Illustrations (cont.)

	Page
Figure 5. Distribution of Cu, Ni, Fe, Mn, Pb and Zn in the surface waters of Georgian Bay during May 1974	6
Figure 6. Distribution of the nutrients total P, total dissolved P, dissolved reactive P, $\text{NO}_3^- + \text{NO}_2^-$, NH_3 and soluble reactive silicate in the surface waters of Georgian Bay during April 1974	8

Abstract

Seven complete chemical surveys of Georgian Bay were conducted between April 28 and December 6, 1974. The observed distributions and open water concentrations of seven major ions (Ca, Mg, Na, K, Cl^- , SO_4^{2-} , alkalinity), six trace metals (Cu, Ni, Fe, Pb, Mn, Zn), and six nutrients (total P, dissolved reactive P, total dissolved P, $\text{NO}_3^- + \text{NO}_2^-$, NH_3 and reactive silicate) are presented. Comment on the probable causes of the observed concentrations and their distribution patterns has been included. In addition, the overall chemical composition of Georgian Bay is discussed in terms of its controlling variables. In order of importance these are (i) exchange with Lake Huron, (ii) lithology of the drainage basin, (iii) the effect of the French River, (iv) exchange with North Channel and (v) human activity in the drainage basin.

Résumé

Sept études chimiques de la baie Georgienne ont été menées de façon exhaustive, entre le 28 avril et le 6 décembre 1974. Le rapport donne la répartition et la concentration de sept ions importants (Ca, Mg, Na, K, Cl^- , SO_4^{2-} , l'alcalinité), de six métaux à l'état de trace (Cu, Ni, Fe, Pb, Mn, Zn) et de six éléments nutritifs (P total, P réactif dissous, P dissous total, $\text{NO}_3^- + \text{NO}_2^-$, NH_3 , silicate réactif), et contient des observations sur les causes qui les ont probablement produites. Le rapport examine en outre la chimie de l'ensemble de la baie Georgienne en tenant compte de ses facteurs qui sont, par ordre d'importance: (i) les échanges avec le lac Huron; (ii) la pétrographie du bassin versant; (iii) l'influence de la rivière des Français; (iv) les échanges avec le chenal Nord; et (v) l'activité humaine dans le bassin versant.

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N.D. Warry

INTRODUCTION

Chemical descriptions have been provided for Lake Superior (Callendar, 1973; Weiler, 1976), Lake Erie (Burns, 1976), Lake Ontario (Shiomi and Chawla, 1970; Dobson, 1967) and Lake Huron (Crawford, 1976). To complete the requirements for the International Joint Commission (IJC) baseline information collection on the Upper Great Lakes, a thorough investigation of the chemistry, physics, biology and geology of Georgian Bay was undertaken.

The chemical results from this recent (1974) large-scale investigation of Georgian Bay, consisting of seven major surveys for the measurement of basic chemical and biological parameters, are reported here. The data from these surveys are extensive and only the highlights are included. The full data set is available elsewhere (Archives of the Canada Centre for Inland Waters).

This report will characterize the general chemical composition of Georgian Bay and will identify the major mechanisms by which it is controlled.

SAMPLING AND DATA PROCESSING METHODS

The sampling network consisted of 59 stations (Fig. 1). They were selected subjectively, in the absence of any previous extensive survey data; however, experience gained from similar sampling programs on the other Great Lakes was employed in the station selection procedure.

At all stations, temperature was derived by bathy-thermograph and water was sampled using polyvinyl chloride Van Dorn bottles for the following parameters: dissolved reactive phosphorus (DRP), total phosphorus (TP) (filtered and unfiltered), $\text{NO}_3^- + \text{NO}_2^-$, NH_3 , soluble reactive silica (SRS), conductivity, oxygen concentration, chloride, sulphate, Secchi disc and water transparency (beam transmissometer). Sampling depths at all stations (Fig. 1) were 1 m, 25 m, 50 m and 2 m off the bottom during unstratified conditions; 1 m, 5 m, top of thermocline, mid-thermocline, bottom of thermocline, mid-hypolimnion and 2 m off bottom for stratified conditions.

In addition, samples were collected at all stations for major ions (Ca, Mg, Na, K) on two cruises (May and August) at depths of 1 m and 25 m (unstratified conditions) or 1 m, mid-thermocline and mid-hypolimnion (stratified conditions). Filtered trace metal samples (Cd, Cr, Se, Co, Cu, Fe, Mn, Pb, Ni, Zn) were collected on all cruises from all stations at the same depths as the samples for major ions. Details regarding sample collection have been described by Carew and Williams (1975).

The analytical techniques employed in this study have been discussed by Philbert and Traversy (1973). All samples were collected from the windward side of the ship in clean polyethylene bottles. The nutrient samples (total dissolved P (TDP), DRP, SRS, $\text{NO}_3^- + \text{NO}_2^-$, NH_3 , alkalinity, dissolved oxygen, pH, and specific conductance) were filtered through 0.45- μm Millipore filters and analyzed on board ship (AutoAnalyzer) immediately after collection. Total P samples were filtered, acidified and stored at 4°C. Shiomi and Kuntz (1973) provide an excellent summary of nutrient and major ion analytical procedures employed in this study. Trace metal samples were filtered through prewashed (with dilute HNO_3 solution) 0.45- μm membrane filters and then acidified (2 ml concentrated HNO_3 per litre) before being stored. The trace metal samples were extracted with ammonium pyrrolidine dithiocarbamate (APDC) and methyl isobutyl ketone (MIBK) and analyzed by atomic absorption spectroscopy. The detection limit for each trace metal is: Co, 0.2 $\mu\text{g l}^{-1}$; Cd, 0.2 $\mu\text{g l}^{-1}$; Cr, 0.2 $\mu\text{g l}^{-1}$; Cu, 0.5 $\mu\text{g l}^{-1}$; Fe, 0.5 $\mu\text{g l}^{-1}$; Hg, 0.05 $\mu\text{g l}^{-1}$; Se, 0.1 $\mu\text{g l}^{-1}$; Pb, 0.1 $\mu\text{g l}^{-1}$; Mn, 0.2 $\mu\text{g l}^{-1}$; Ni, 1.0 $\mu\text{g l}^{-1}$; and Zn, 1.0 $\mu\text{g l}^{-1}$. The coefficient of variation for any metal at the detection limit is taken to be $\pm 50\%$. At 10 $\mu\text{g l}^{-1}$ the largest variation is $\pm 5\%$. Complete documentation of sampling and analytical techniques is found in the Upper Lakes Reference Group Archives (IJC Regional Office, Windsor, Ontario). Estimates of precision for most parameters have been discussed by Strachan (1973).

It was decided that the most effective way to minimize the vertical variability of the water body was to treat Georgian Bay as a simple one- or two-layer well-mixed lake system. The areal variability was minimized by dividing the lake into 10 relatively homogeneous zones or segments on the basis of each zone's temperature

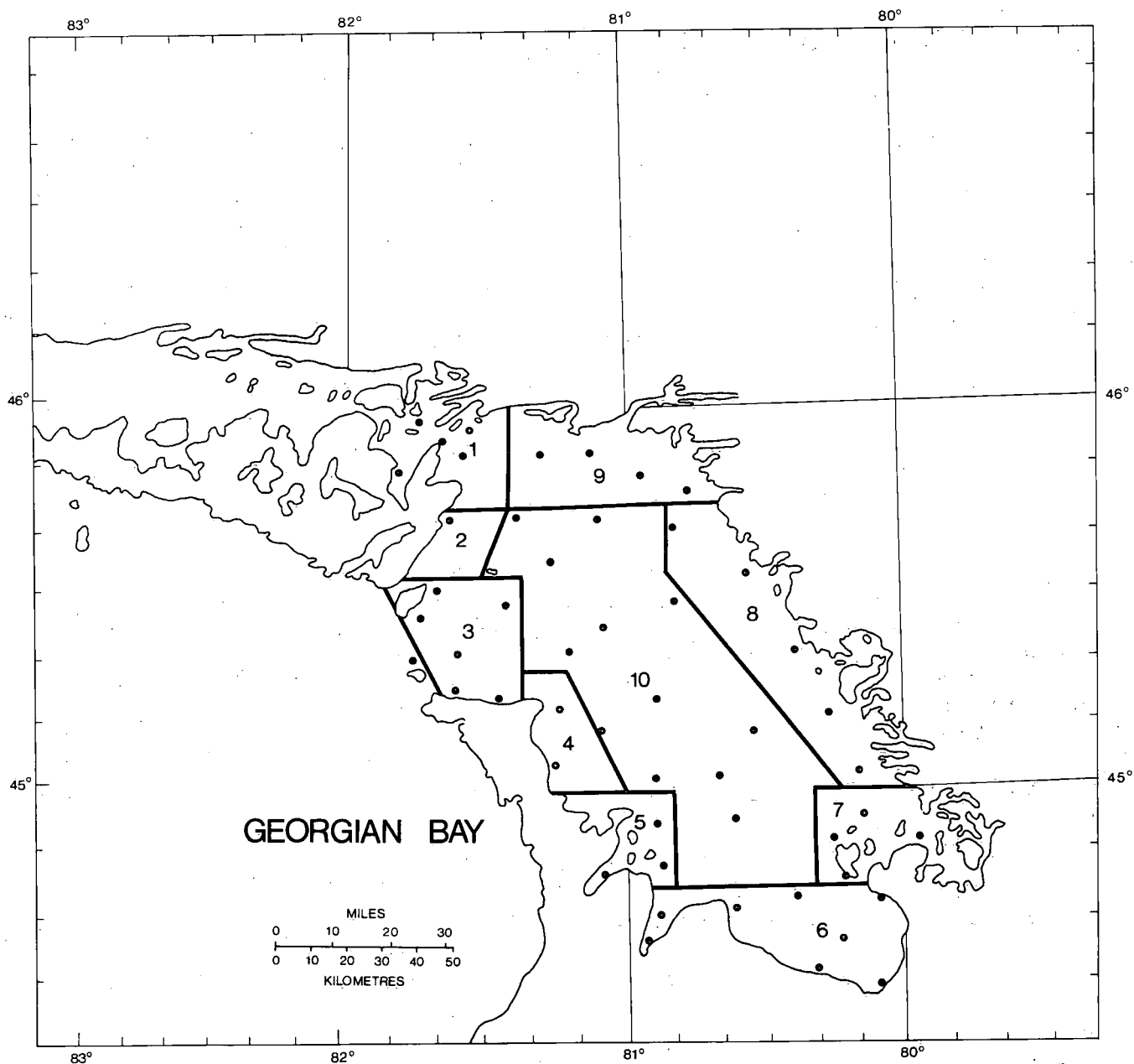


Figure 1. Map of Georgian Bay showing station locations and zones. The numbers represent the zones into which the Bay was divided.

structure (U.L.R.G., 1977, Vol. II). In this way, comparisons between zones are possible. Discussion in this paper will address the whole bay, although, because of space considerations, the data in Table 4 relate only to the open lake zone, segment 10.

The reported concentrations for each parameter in Table 4 are area-weighted mean concentrations. It is assumed that this mean provides a more realistic representation of the chemistry within a segment than does the arithmetic mean, particularly in regions where

samples are few and concentration gradients are large. The method used to calculate the area-weighted means is described in the Appendix.

RESULTS AND DISCUSSION

Major Ions

The May distributions of major ions in the surface waters of Georgian Bay are illustrated in Figure 2. The

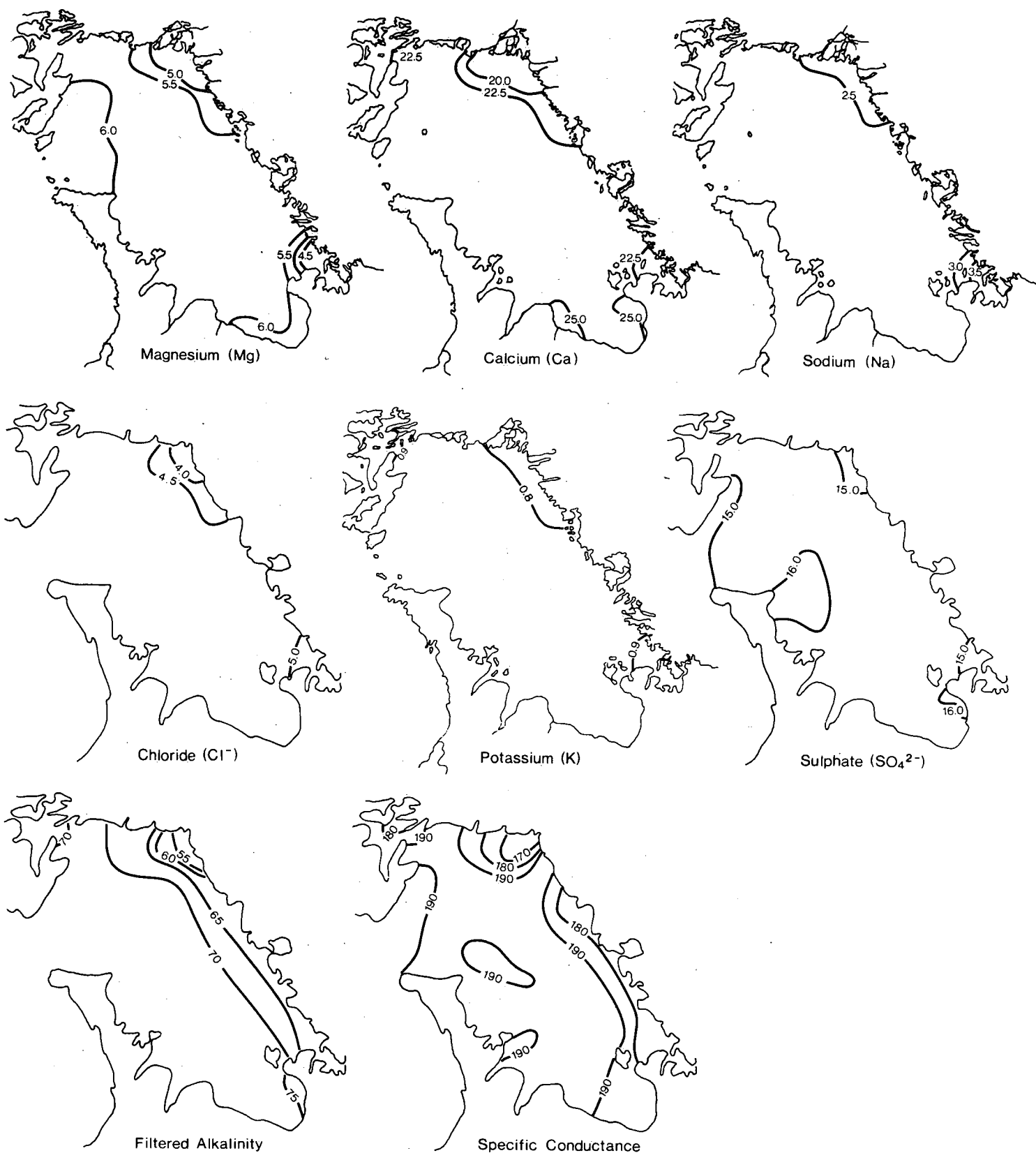


Figure 2. Distribution of major ions in the surface waters of Georgian Bay during May 1974. Concentrations are all in mg l⁻¹; conductance is reported in μS cm⁻¹.

main feature of their distribution is that the concentration minima for most of these ions are found in the vicinity of the northern and eastern shorelines, while their maxima are observed along the west and southwest shores of the bay. The reason for these obvious differences in concentration is apparent when one examines the geology of the Georgian Bay basin.

The northern and eastern coasts of Georgian Bay are underlain by the silica-rich granites and gneisses of the Canadian Shield; the southern and western coasts are composed of the carbonate-rich limestones and shales of the St. Lawrence Platform. As a result, the chemistry of the water running off the land from these two regions is substantially different, especially with respect to its carbonate (measured as alkalinity) content.

In Georgian Bay, the concentration gradients for the major ions are composed of both a magnitude and a direction. The largest gradients are in a direction 160° from true north, from the area of the French River to Collingwood. The largest area-weighted mean concentration gradient is that for alkalinity, which increases 14% (10 mg l^{-1}) from the mouth of the French River to just offshore at Collingwood. For the other major ions, the concentration gradients range from non-existent for potassium to over 10% (2.5 mg l^{-1}) for calcium (Table 1).

The mean hypolimnetic concentrations of the major ions in segment 10 of Georgian Bay are, on the average, only 4% less than the comparable concentrations in Lake Huron (Table 2). This close correspondence implies that

these water bodies are well mixed. The effect of this mixing can be calculated if it is assumed that no Lake Huron water enters Georgian Bay. Given this assumption, and utilizing recent loading data and flow data (U.L.R.G., 1977, Vol. II), a most probable major ion composition for an "isolated" Georgian Bay was calculated. The results of the calculation are presented in Table 2. It is seen that the major ion composition derived for an "isolated" Georgian Bay is quite distinct from the real one, and is further removed from the composition of Lake Huron.

Table 1. Georgian Bay Concentration Vectors* for Major Ions and Dissolved Reactive Silica

	Change in concentration, %
Ca	+ 10.2
Mg	+ 7.8
Na	+ 3.6
K	0
Alk.	+ 14
SO ₄ ²⁻	+ 3.2
Cl ⁻	+ 6.1
SiO ₂	-20

* All gradients are in a direction 160° from true north.

Table 2. Comparison of Mean Hypolimnetic Concentrations of Major Ions in Lake Huron and Georgian Bay

Ion	Conc. in Lake Huron (Crawford, 1976)	Conc. in Georgian Bay (mg l^{-1})	Actual % difference between Lake Huron and Georgian Bay major ion conc.	"Isolated"* Georgian Bay composition (mg l^{-1})	Probable % difference between Lake Huron and "Isolated" Georgian Bay
Ca	25.0	24.4	-2.4	17.5	-30.0
Mg	7.0	6.5	-7.1	4.2	-40.0
Na	3.1	2.8	-9.7	3.1	0
K	0.8	0.8	0	1.2	+50.0
Alk.	76.0	71.3	-6.2	55.0	-27.6
SO ₄ ²⁻	14.0	15.7	+ 12.1	16.8	+20.0
Cl ⁻	5.4	4.9	-9.3	4.9	- 9.3

* "Isolated" — assumes no exchange between Lake Huron and Georgian Bay water.

Further evidence of the exchange of water between Lake Huron and Georgian Bay is provided by Figure 3, where the chloride concentration and specific conductances in the epilimnion of segments 3 and 10 are compared. At all times between May and November, the surface waters of segment 3 (Fig. 1) exhibit higher concentrations of chloride and have higher specific conductances than the surface waters of segment 10. The concentration differences are attributable exclusively to the significant influxes of Lake Huron surface water into Georgian Bay as determined by Schertzer *et al.* (1978).

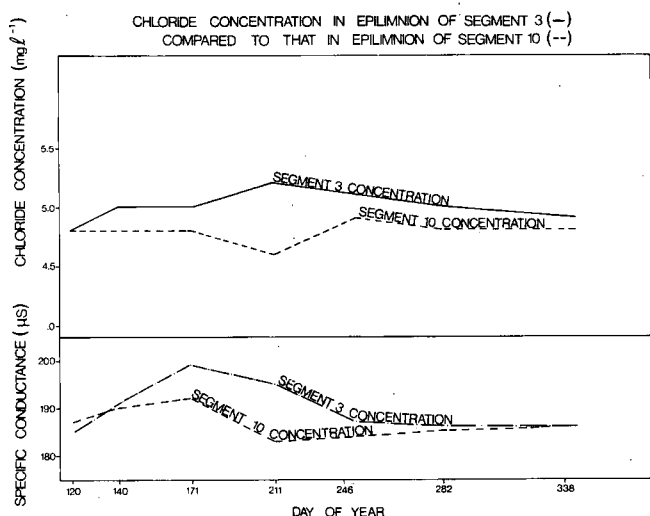


Figure 3. Epilimnion concentration differences of chloride (mg l^{-1}) and conductance ($\mu\text{S cm}^{-1}$) observed in segments 10 and 3 of Georgian Bay. The differences result from the Lake Huron water flowing into segment 3.

Trace Metals

Figure 4 is a histogram depicting the frequency distribution of trace metal data for all of Georgian Bay in 1974. From the observed distribution, the trace metal data were sorted into three groups. The first group consists of Cd, Co, Cr, and Se, which are present in quantities at or below their detection limits. In this group, selenium was never measured above its detection limit of $0.2 \mu\text{g l}^{-1}$, nor was cobalt. Cadmium and chromium occasionally were reported at their detection limit of $0.1 \mu\text{g l}^{-1}$ but never in concentrations greater than $0.2 \mu\text{g l}^{-1}$.

The second group of trace metals includes Fe, Mn, Pb and Zn. They normally occur in measurable but unchanging concentrations.

Filtered iron was not measured during April or May because of a sampling oversight. For the data obtained in

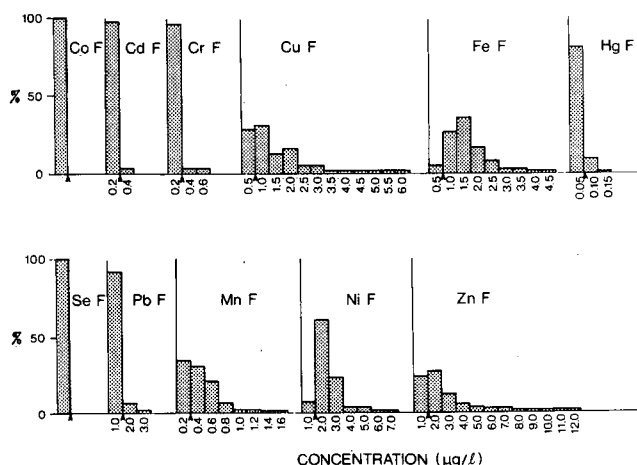


Figure 4. Histogram representing the distribution of all trace metal data collected in Georgian Bay during 1974. The caret denotes the detection limit for each metal. Concentrations are $\mu\text{g l}^{-1}$. F indicates filtered.

the June-December period, it was found that the concentration of iron was relatively constant throughout the whole water column during the entire sampling period, averaging $1 \mu\text{g l}^{-1}$. The distribution of filtered iron in June (Fig. 5) suggests that the French River is the major source of this metal.

The distribution of filtered zinc in June (Fig. 5) resembles that of iron. The annual mean concentration of zinc averages $2.2 \mu\text{g l}^{-1}$ and varies from 1 to $8 \mu\text{g l}^{-1}$. No reliable zinc data were obtained during the April and May cruises because the plastic in the bottle caps was contaminated with zinc. However, from the close correspondence in the distributions of filtered iron and filtered zinc during June, it appears that the French River is a primary source of zinc as well as iron.

Similarly, the distributions of filtered lead and filtered manganese (Fig. 5) suggest a French River source for these two metals. In addition, Lake Huron appears to be a second source of lead. Concentrations of those metals normally range from 0.2 to $0.6 \mu\text{g l}^{-1}$ for filtered manganese and from undetectable ($<1.0 \mu\text{g l}^{-1}$) to $2.0 \mu\text{g l}^{-1}$ for filtered lead.

The third group of trace metals is composed of copper and nickel. These two metals exhibit significant temporal and spatial variations in concentration. The distribution of copper and nickel in April in Georgian Bay is illustrated in Figure 5. It is quite clear that the northeast section of the bay is the area of highest concentration, with its focus being the French River. Concentrations in the surface waters of segments 8 and 9 during the April cruise are almost double those in segment 10, averaging $8 \mu\text{g l}^{-1}$

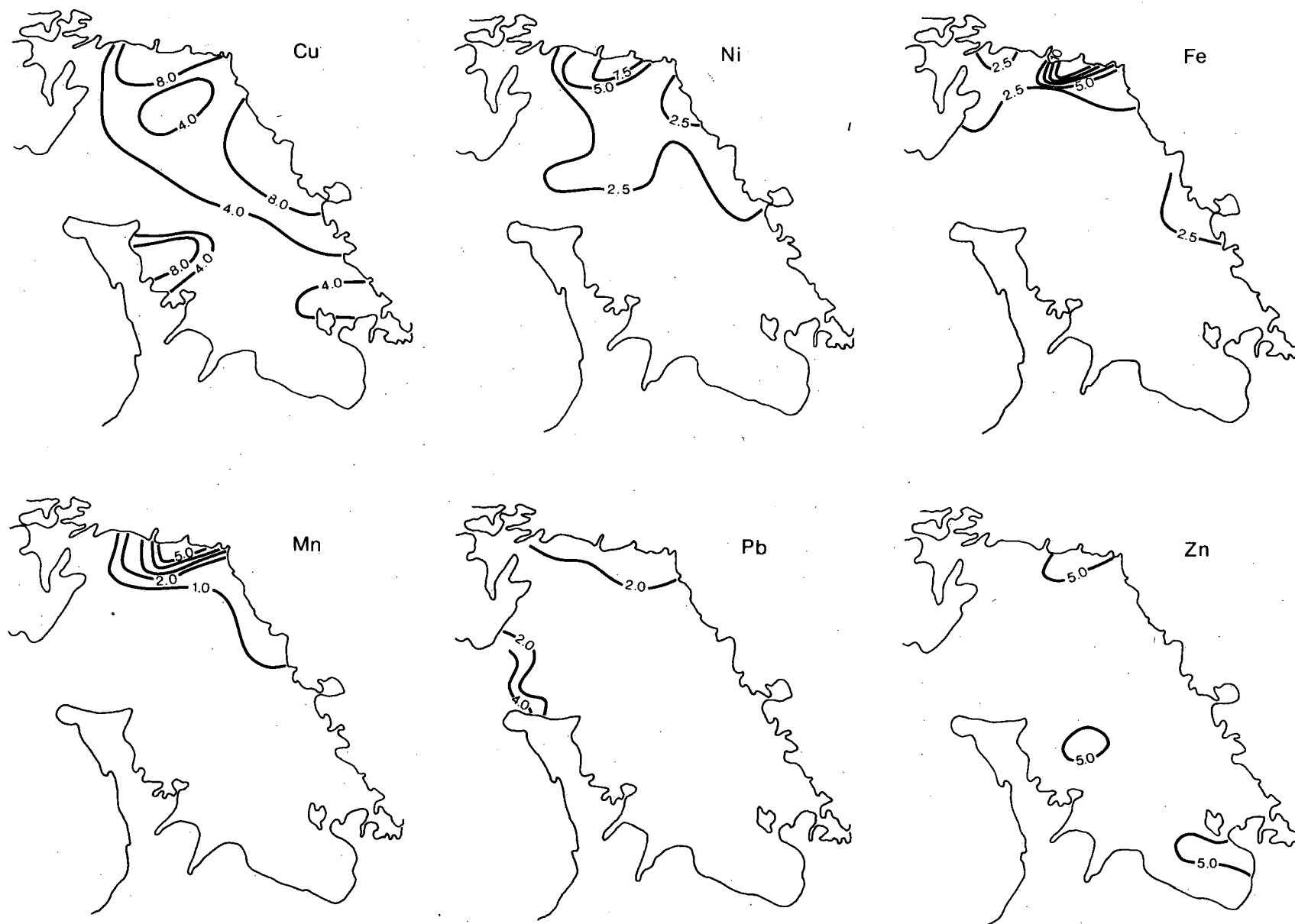


Figure 5. Distribution of Cu, Ni, Fe, Mn, Pb and Zn in the surface waters of Georgian Bay during May 1974. Concentrations are in $\mu\text{g l}^{-1}$.

for copper and $5 \mu\text{g l}^{-1}$ for nickel. Table 3 shows that the concentrations of filtered copper and nickel in segment 10 at the time are near $4 \mu\text{g l}^{-1}$ and $2.5 \mu\text{g l}^{-1}$, respectively. One reason for these differences is that segments 8 and 9 are nearshore areas of Georgian Bay. Concentrations of these metals during spring runoff from streams in Lake Superior are up to 10 times those at any other time of the year (Ryan, 1975). If it can be assumed that the same phenomenon exists in the tributary waters of Georgian Bay, higher concentrations of trace metals should be observed in all nearshore waters during the spring. Unfortunately, the data indicate that this is not the case. As is evident from Figure 5, only the northeastern sections (segments 8 and 9) of Georgian Bay exhibit significant trace metal concentrations, particularly for copper and nickel. A single observation is the basis for the high copper concentration near the Bruce Peninsula; therefore it is not considered significant, although it is included for completeness. The high concentrations in the northeastern sections are the result of at least five observations.

It is not possible to determine the cause of the observed phenomena from the data collected in this study, although the following speculation is suggested: the northeast portion of Georgian Bay is subject to higher-than-average loadings of copper and nickel because of the proximity of this area to a major atmospheric source of these metals at Sudbury.

During the winter, the total atmospheric loading for the previous 4-month period accumulates in the snow. This entire quantity of material is then discharged into the nearshore areas in the northeast portion of Georgian Bay during a 2-week period of spring runoff, resulting in the elevated concentrations of copper and nickel being observed in these waters in early May.

By June, regional differences are no longer apparent and the concentrations of filtered copper and nickel in the whole bay have decreased substantially, ranging from 1 to $2 \mu\text{g l}^{-1}$ for both metals. By December, the bay-wide concentration of filtered copper is $<0.5 \mu\text{g l}^{-1}$ and for nickel it is about $1 \mu\text{g l}^{-1}$.

These data suggest that an annual concentration cycle exists for these elements. The springtime concentration maxima observed for copper, nickel, and also manganese and lead are probably attributable to the sudden large influx of the dissolved metal ions in the runoff water of relatively low pH (pH 7) from the north and east coasts and in particular from the French River. The metal ions become immobilized by sorption reactions with the organic matter in the water and by inorganic

complexation reactions (Florence and Bately, 1976) in the high-pH waters (pH 8) of Georgian Bay. As a result, their filtered concentrations decrease to the levels observed in the other Great Lakes (Crawford, 1976; Weiler, 1976). These data also suggest that the French River is the primary source of all of these metals to Georgian Bay, particularly in the spring. Since the French River has a pH near 7.1 (Hutchinson *et al.*, 1975), and since its drainage basin is subject to a large supply of these ions from the smelting operations at Sudbury (Kramer and Muller, 1977), it is not surprising that this area displays the highest dissolved trace metal concentrations in Georgian Bay.

Nutrients

Silica

The early spring epilimnion distribution of soluble reactive silica (SRS) is shown in Figure 6. The most notable feature is a concentration decrease as one moves south from the northeast portion of the bay to the southwest portion. The concentration gradient for silicate is nearly equal in relative magnitude, but opposite in direction to that exhibited by alkalinity (Table 1). This supports the hypothesis that the early spring variability observed for silicate and alkalinity is induced by the geology of the lake basin. Also apparent from Figure 6 are the other sources of silicate to Georgian Bay. These include the North Channel, the east coast and the Penetang-Midland area.

The annual mean concentration of SRS in the hypolimnion of offshore Georgian Bay is 1.36 mg l^{-1} . During the period June 18 - September 10, the surface waters become depleted in SRS. The calculated depletion rate in the top 10 m of the water column is $5.2 \mu\text{g l}^{-1}$. This rate is comparable to that observed in Lake Huron ($5.5 \mu\text{g l}^{-1} \text{ day}^{-1}$) but lower than that calculated for the North Channel ($7.9 \mu\text{g l}^{-1} \text{ day}^{-1}$). At the time of maximum depletion the SRS concentration in the epilimnion averages 0.6 mg l^{-1} (or 44%) less than the hypolimnetic concentration. This is greater than the 0.4 mg l^{-1} depletion reported for central Lake Huron (Crawford, 1976) but is almost identical with the 0.55 mg l^{-1} observed in the North Channel (Warry, 1978). The trophic state of Georgian Bay, with respect to silicate at least, can thus be characterized as being midway between the extreme oligotrophy of Lake Superior, where the SRS depletion is less than 10% (Weiler, 1976) and the mesotrophy of Lake Ontario, where the SRS depletion approaches 75% (Shiomi and Chawla, 1970).

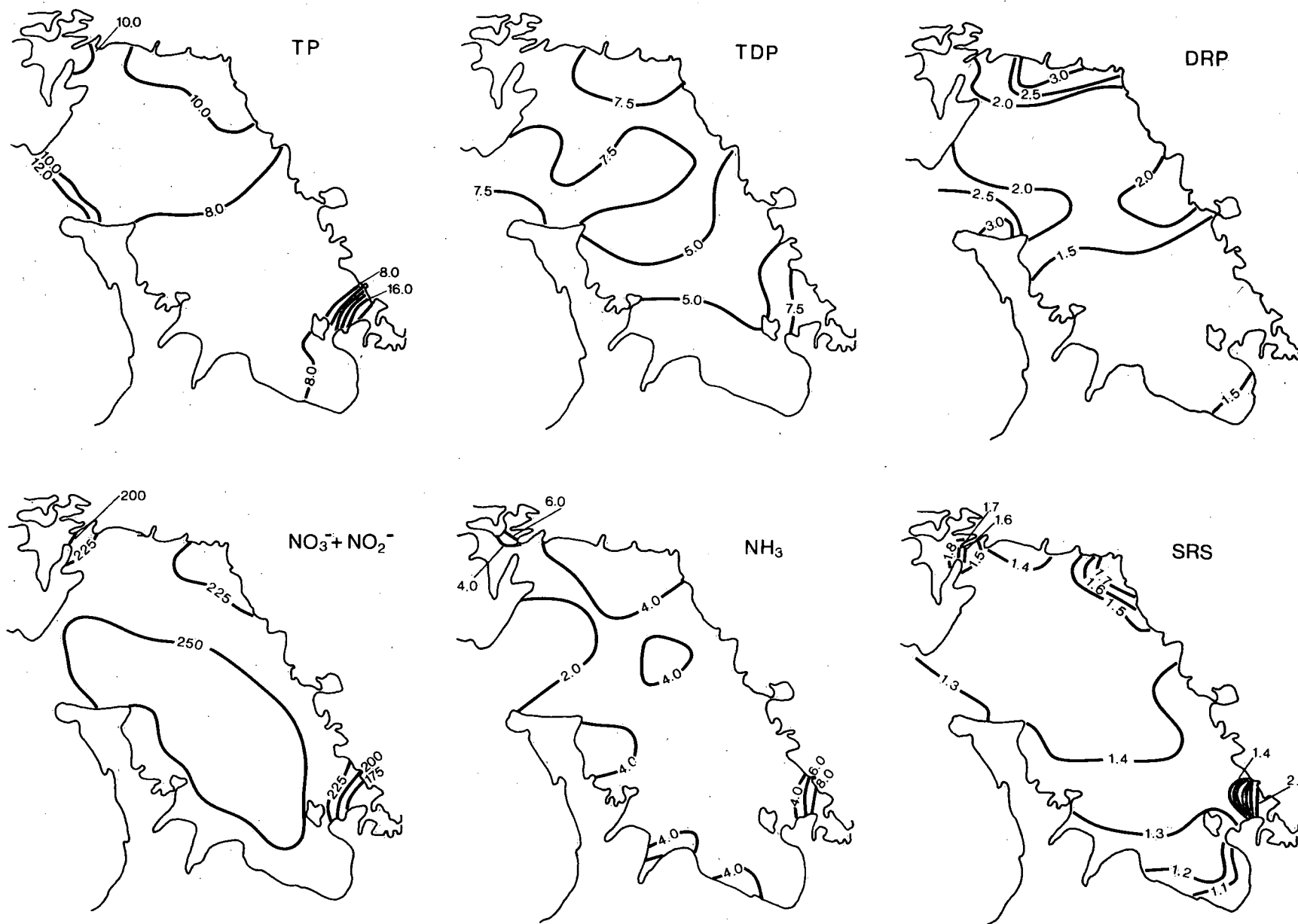


Figure 6. Distribution of the nutrients total P (TP), total dissolved P (TDP), dissolved reactive P (DRP), $\text{NO}_3^- + \text{NO}_2^-$, NH_3 and soluble reactive silicate (SRS) in the surface waters of Georgian Bay during April 1974. Concentrations of SRS and $\text{NO}_3^- + \text{NO}_2^-$ are in mg l^{-1} ; all others are in $\mu\text{g l}^{-1}$.

Table 3. Area-weighted Mean Concentration* of Nutrients at 1-m and 50-m Depths in Segment 10 of Georgian Bay.

Parameter	April	May	June	July	September	October	December
TP ($\mu\text{g P l}^{-1}$)	8.1	4.1	4.6	4.2	3.1	5.1	4.7
	7.5	3.9	4.2	4.3	3.7	4.6	5.2
TDP ($\mu\text{g P l}^{-1}$)	6.4	1.9	2.3	2.6	1.8	3.6	3.0
	5.4	2.2	2.3	2.6	1.8	3.2	2.8
DRP ($\mu\text{g P l}^{-1}$)	1.6	0.5	0.6	0.5	0.7	0.7	1.1
	1.1	0.6	0.6	0.5	0.6	0.7	1.0
$\text{NO}_3^- + \text{NO}_2^-$ (mg N l^{-1})	0.26	0.25	0.24	0.21	0.21	0.21	0.28
	0.26	0.25	0.25	0.24	0.26	0.25	0.29
Diss. NH_3 ($\mu\text{g N l}^{-1}$)	3.0	3.0	4.0	2.0	4.0	3.0	N.M.*
	3.0	3.0	5.0	3.0	6.0	1.0	N.M.
SRS ($\text{mg SiO}_2 \text{ l}^{-1}$)	1.34	1.40	1.29	0.96	0.79	0.96	1.28
	1.34	1.40	1.34	1.35	1.46	1.43	1.32
Diss. O_2 (mg l^{-1})	14.0	13.8	13.1	9.5	9.2	10.7	12.0
	14.0	13.8	13.5	12.9	12.4	11.9	12.0
Filtered Ca (mg l^{-1})		23.9			24.9		
		24.3			25.0		
Filtered Mg (mg l^{-1})		5.9			6.8		
		6.0			6.9		
Filtered Na (mg l^{-1})		2.8			2.9		
		2.8			2.9		
Filtered K (mg l^{-1})		0.8			0.9		
		0.8			0.9		
Filtered Alk. ($\text{mg CaCO}_3 \text{ l}^{-1}$)	72.6	70.8	70.5	68.2	69.5	70.1	71.7
	73.0	71.2	71.3	70.8	70.9	71.4	71.8
Filtered Cl^- (mg l^{-1})	4.8	4.8	4.7	4.7	4.9	4.8	4.8
	4.9	4.9	4.8	5.0	5.1	4.9	4.8
Filtered SO_4^{2-} (mg l^{-1})	15.4	15.7	15.7	15.2	15.8	15.6	15.9
	15.5	15.7	15.8	15.4	16.0	15.5	15.9
Spec. cond. ($\mu\text{S cm}^{-1}$)	187	191	194	179	182	184	186
	188	190	193	183	184	185	186
Filtered Zn ($\mu\text{g l}^{-1}$)	N.M.	N.M.	2.4	1.4	1.8	1.5	3.9
	N.M.	N.M.	4.5	2.0	2.6	2.4	3.3
Filtered Ni ($\mu\text{g l}^{-1}$)	2.0	2.2	1.1	1.5	1.1	1.0	0.9
	2.1	1.4	1.6	1.2	1.1	1.0	0.9
Filtered Mn ($\mu\text{g l}^{-1}$)	0.3	0.1	0.3	0.2	0.4	0.4	0.2
	0.2	N.D.	0.3	N.D.	0.1	0.1	0.2
Filtered Pb ($\mu\text{g l}^{-1}$)	0.2	N.D.	0.3	N.D.	N.D.	N.D.	N.D.
	N.D.	N.D.	0.5	N.D.	N.D.	N.D.	N.D.
Filtered Fe ($\mu\text{g l}^{-1}$)	N.M.	N.M.	1.2	1.1	1.0	0.9	0.9
	N.M.	N.M.	1.4	0.7	1.0	1.0	0.6
Filtered Cu ($\mu\text{g l}^{-1}$)	4.4	2.6	1.9	1.0	0.7	0.6	0.4
	3.0	1.1	2.2	0.9	0.8	0.7	0.4

N.M.—Not measured on this cruise.

N.D.—Below detection limit.

* First row of figures for each parameter is concentration at depth of 1 m; second row is for depth of 50 m.

Table 4. Ratios of Total Particulate P to Total P in the Surface Waters of Each Georgian Bay Segment

Month	Segment No.									
	1	2	3	4	5	6	7	8	9	10
Apr.	0.18	0.24	0.31	0.29	0.30	0.27	0.38	0.23	0.22	0.23
May	0.66	0.58	0.58	0.57	0.56	0.53	0.48	0.45	0.63	0.50
June	0.45	0.44	0.42	0.46	0.46	0.42	0.56	0.45	0.48	0.50
July	0.43	0.44	0.42	0.23	0.36	0.32	0.35	0.35	0.37	0.40
Sept.	0.42	0.41	0.39	0.47	0.53	0.53	0.44	0.39	0.44	0.41
Oct.	0.39	0.39	0.30	0.33	0.41	0.44	0.40	0.36	0.31	0.34
Dec.	0.46	0.50	0.44	0.40	0.45	0.37	0.34	0.35	0.43	0.40

Phosphorus

The April distributions of TP, TDP and DRP in the surface waters of Georgian Bay are illustrated in Figure 6. Concentrations of all forms are at their annual maximum in April, at a time when their distribution is least affected by biological activity. This permits identification of the major sources. From Figure 6, the major sources of TP are the North Channel, the French River and the Penetang-Midland areas of Georgian Bay. Likewise, the North Channel (segment 1) and French River (segment 9) are sources for TDP and DRP.

Segments 1 and 9 exhibit large P concentrations because they are subject to the largest April-May input of surface runoff. These two segments show the lowest TPP/TP ratios¹ in the bay during the April cruise (Table 4). Segment 7 (the Penetang-Midland area) is affected by sewage discharges (Veal and Michalski, 1971) and this results in its high TP concentrations.

By May, the concentrations of TP, TDP and DRP were equal to, or less than, one-half their April concentrations. For the remaining months all three forms of phosphorus remain near their May concentrations of $4.5 \mu\text{g l}^{-1}$, $2.4 \mu\text{g l}^{-1}$ and $0.6 \mu\text{g l}^{-1}$, respectively.

During the period April 28 - May 18, phosphorus depletion throughout the entire bay was very rapid, averaging $0.2 \mu\text{g l}^{-1} \text{ day}^{-1}$. This sudden decrease is the result of uptake by rapid phytoplankton growth during this 3-week period, when the concentration of total

particulate carbon doubles (U.L.R.G., 1977, Vol. II), as does the ratio of TPP and TP. Phytoplankton growth has been shown to be an extremely efficient phosphorus-scavenging mechanism in Lake Erie (Burns, 1976) and apparently also in Georgian Bay.

As evidence of the oligotrophic nature of Georgian Bay, it should be noted that DRP is never exhausted in the epilimnetic waters.

Nitrogen

The May distribution of $\text{NO}_3^- + \text{NO}_2^-$ in the surface waters of Georgian Bay is depicted in Figure 6. Three segments exhibit lower-than-average $\text{NO}_3^- + \text{NO}_2^-$ concentrations, which are generally 10-12% less than those of the reference segment. This is because the inflowing waters of the French River are very low in $\text{NO}_3^- + \text{NO}_2^-$ relative to Georgian Bay. $\text{NO}_3^- + \text{NO}_2^-$ concentration in the river water averages 0.024 mg l^{-1} (U.L.R.G., 1977, Vol. II) compared with the 0.26 mg l^{-1} average in Georgian Bay. In segments 1 and 7 the low $\text{NO}_3^- + \text{NO}_2^-$ concentrations reflect the early onset of phytoplankton growth in these areas, because these waters are shallow, warm and relatively unmixed.

The hypolimnetic concentration of $\text{NO}_3^- + \text{NO}_2^-$ in Georgian Bay is 0.26 mg l^{-1} all year long except in December, when a 20% increase to 0.30 mg l^{-1} is found. The cause of this large bay-wide increase is not apparent.

$\text{NO}_3^- + \text{NO}_2^-$ exhibits a seasonal depletion of 25% (0.05 mg l^{-1}) in the epilimnion, resulting in surface concentrations near 0.20 mg l^{-1} in September in segment 10. This depletion can be expressed in terms of a rate constant of $0.55 \mu\text{g l}^{-1} \text{ day}^{-1}$ in the North Channel.

¹Ratio is calculated as $(\text{TP conc.} - \text{TDP conc.})/\text{TP conc.}$, and determines how much of total P is particulate (TPP).

Some areas of Georgian Bay exhibit nitrate distributions different from those described in segment 10. Segment 1 (North Channel) is affected by a summer influx of nitrate-depleted (0.22 mg l^{-1}) North Channel water. This results in a larger summertime depletion of $\text{NO}_3^- + \text{NO}_2^-$ (0.8 mg l^{-1}) and a greater depletion rate ($6.9 \mu\text{g l}^{-1} \text{ day}^{-1}$). Segment 3 shows a smaller total depletion (0.02 mg l^{-1}) and a small depletion rate ($2.4 \mu\text{g l}^{-1} \text{ day}^{-1}$) because of the large influx of Lake Huron surface water into this area. Summertime concentrations of $\text{NO}_3^- + \text{NO}_2^-$ average $0.23 \mu\text{g l}^{-1}$ in north-eastern Lake Huron and this is reflected in the behaviour of $\text{NO}_3^- + \text{NO}_2^-$ noted above in the surface waters of segment 3 in Georgian Bay.

Ammonia concentrations in Georgian Bay are low and no definable trends exist. The mean ammonia concentration for segment 10 is $3 \mu\text{g l}^{-1}$. Again, the French River is a source of ammonia, as its annual concentration averages $35 \mu\text{g l}^{-1}$ (U.L.R.G., 1977, Vol. II), 10 times the mean ammonia concentration in the Bay. Figure 6 illustrates the distribution of ammonia during the May cruise.

Oxygen and pH

Surface oxygen concentrations decrease only as a result of temperature increases. Hypolimnion oxygen values decrease to 12 mg l^{-1} in response to increasing water temperature. In accordance with the low oxygen demand, oxygen saturation in the hypolimnion is never less than 95% in any part of Georgian Bay. The oxygen depletion rate for Georgian Bay during the period May 1 - December 1, 1974 has been calculated as $0.31 \text{ mg per month}$.

The pH of the main bay lies between 8.0 and 8.2 in the hypolimnion all year long. A surface maximum slightly greater than 8.4 is recorded in September. This is a result of phytoplankton photosynthesis and consequent removal of CO_2 from the water. The highest pH is found in segment 6, where September surface pH values reach 8.6.

SUMMARY AND CONCLUSIONS

A general description of the chemistry of Georgian Bay is presented. Distribution maps of the major chemical species are given, along with the area- and volume-weighted mean concentrations of each species in the offshore segment of the bay (Table 3).

The chemistry of Georgian Bay can be described in terms of its controlling variables. The most important

control of the major ions is the exchange of water between Georgian Bay and Lake Huron, although the influence of lithology on the bay's major ion chemistry also was detected. In particular, for alkalinity and nutrient silica, the rock type of the drainage basin played a dominant role in the elemental distributions.

The trace metal chemistry of Georgian Bay is predominately influenced by the French River and, in particular, the spring runoff from this major tributary.

The nutrient chemistry reflects the oligotrophic nature of Georgian Bay. Maximum nutrient depletion is small, and even at times of maximum production a significant pool of nitrate, phosphate and soluble reactive silica remains in the epilimnion. In addition, oxygen saturation levels are never less than 95%.

Man's activities have effected small though detectable changes in the localized chemistry of Georgian Bay, especially in nearshore areas such as Penetang-Midland (eutrophication), Nottawasaga Bay (slight nutrient enrichment), and the French River region (heavy metal contamination and sulphate loading).

At present, the spatial and temporal variability in the Georgian Bay chemistry is primarily attributed to natural phenomena.

ACKNOWLEDGMENTS

I thank the Technical Operations Section at the Canada Centre for Inland Waters for performing the massive task of collecting the samples. In particular, I wish to thank Dr. W. Wilford, who critically reviewed the manuscript, and C. Pacenza, who typed it.

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APPENDIX

The method for calculating the weighted averages is the following.

- 1) The lake was divided into 2 km by 2 km squares and each square was assigned a depth from the bathymetry measurements of the lake.
- 2) The lake boundaries and zone boundaries were assigned to the appropriate cells.
- 3) Each cell was assigned a station number corresponding to the station closest to the cell.
- 4) The electronic bathythermograph temperature structure was determined for each station.
- 5) Concentrations for every grid cell were derived from the actual observations interpolated vertically by fitting the observed values to the temperature structure.
- 6) The area-weighted mean for each zone is obtained by averaging the concentrations for each grid cell at the specified depth in that zone.
- 7) Volume-weighted means are obtained by averaging all grid cells in a single zone from the surface down to the specified depth. In addition, volume-weighted averages can be calculated for each layer between specified depths.

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