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A Report on Studies of the Effects of Dredging and Disposal in the Great Lakes with Emphasis on Canadian Waters

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Abstract

Dredging in the Great Lakes is undertaken mostly to maintain navigation, although sand and gravel are exploited to a limited extent. Until recently, most dredging activities used open-lake disposal, although the use of confined disposal in Lake Erie and in the Detroit River remain notable exceptions. No major program has been undertaken solely for the removal or treatment of contaminated lake sediments. Following establishment of the Great Lakes Water Quality Agreement in 1972, open-lake disposal activities have been much reduced.

Since 1972, also, a number of unpublished studies have been undertaken to assess the influence of dredging practices on water quality and this report refers principally to studies in the Canadian portion of the Great Lakes which, in most cases, have been undertaken in conjunction with regular dredging operations.

At Port Stanley (Lake Erie) and Bronte Harbour (Lake Ontario), in studies before, during and after maintenance dredging, it was shown that total and reactive phosphorus levels increased rapidly in the receiving waters both at the removal site and at the open-lake dumping site; similar increases in other nutrient elements and heavy metals were also observed. However, as a result of particle settling and dilution, elevated concentrations decreased rapidly and background conditions in the overlying waters were generally re-established within a few hours. Because of the influence of wave activity in Lake Erie the dumped materials were rapidly redistributed and no evidence was obtained to indicate a long term influence on water chemistry.

At Thunder Bay (Lake Superior), however, recent evidence suggests that some harbour materials disposed of in deep water, below wave base, may continue to influence overlying waters for extended periods.

At Mitchell Bay (Lake St. Clair), containment of dredged materials in an artificial island was examined, particularly to assess the significance of sediment water exchange processes. Tests were made both upon pumped slurry and on dumped materials after settlement. Despite seasonal variations in surface materials pore water concentrations below about 1.5 m remained sensibly constant; concentrations of Al, Cd, Cu, Pb and Zn were similar and concentration profiles of Fe, Mn and P showed strong dependence upon pH and redox potential; Hg in pore water remained independent of sediment values.

Dredging effects and ship turbulence are undoubtedly significant contributors to local sediment/water mixing; in the Great Lakes, however, the importance of these events remains small in comparison to lake-wide effects such as the resuspension of sediments as a result of wind-wave action.

Based upon data from field experiments and observations associated with the dredging/dumping activities, upon data from laboratory studies and upon data available in other published works, the significance of environmental impact in terms of the behavior of nutrient and mobile elements, toxic substances and heavy metals, and sediment/water mixing have been drafted in the form of conclusions.

Résumé

Le dragage dans les Grands lacs a pour but principal d'assurer la navigation, bien
que l'on exploite dans une certaine mesure le sable et le gravier. Jusqu'à récemment, on
rejetait le plus souvent les matériaux de dragage dans les eaux libres des lacs, sauf pour
quelques rares exceptions où cette élimination s'effectuait dans des zones restreintes du
lac Érié et de la rivière Détroit. Aucun programme majeur d'élimination ou de traitement des
sédiments contaminés des lacs n'a été élaboré, mais la mise en application de l'Accord de 1972
relatif à la qualité de l'eau dans les Grands lacs a entraîné une importante réduction des
opérations de déversement dans les eaux libres.

Depuis 1972, on a effectué un certain nombre d'études, non encore publiées, visant
à évaluer l'effet des travaux de dragage sur la qualité de l'eau. Le présent rapport traite
avant tout des études menées dans la partie canadienne des Grands lacs lors des travaux de
dragage.

Des études effectuées avant, pendant et après les travaux de dragage d'entretien à
Port Stanley (lac Érié) et à Bronte Harbour (lac Ontario) ont révélé que les concentrations
de phosphore total et de phosphore réactif augmentaient rapidement dans les eaux réceptrices,
à la fois au lieu d'élimination et au point de rejet dans le lac; on a de plus noté une
augmentation semblable dans les concentrations d'autres substances nutritives et métaux
lourds. Toutefois, en raison de la décantation et de la dilution des particules, ces concen-
trations élevées ont rapidement diminué et les conditions naturelles des eaux supérieures se
sont en général rétablies en quelques heures. Puisque les vagues dans le lac Érié dispersent
les matériaux dragués, on n'a pu établir la preuve d'une action à long terme sur la chimie
de l'eau.

En revanche, certaines données récentes recueillies à Thunder Bay (lac Supérieur)
indiquent que les matériaux de port éliminés en eau profonde, sous le niveau de base des
vagues, continuent d'exercer une action sur les eaux supérieures pendant de longues périodes
de temps.

On a étudié à Mitchell Bay (lac Ste-Claire) le déversement des matériaux de
dragage sur une île artificielle afin d'évaluer l'importance du processus d'échange eau-
sédiment. On a effectué les essais sur une boue que l'on avait pompée et sur des matériaux
déversés après décantation. Malgré les variations saisonnières des matériaux de surface,
les concentrations d'eau de porosité inférieures à 1.5 m sont demeurées constantes tout

comme les concentrations de Al, Cd, Cu, Pb et Zn alors que les teneurs en Fe, Mn et P ont indiqué une forte dépendance de pH et du potentiel d'oxydo-réduction. Par contre, les niveaux de Hg dans l'eau de porosité ne sont pas reliés aux valeurs des sédiments.

Il est évident que les effets du dragage et du remous créé par les navires contribuent dans une large mesure au mélange local de l'eau et des sédiments. Ces effets sont toutefois minimes dans les Grands lacs comparativement à ceux entraînés dans un lac par la remise en suspension des sédiments sous l'action du vent et des vagues par exemple.

À partir des données des essais sur place et des observations faites sur les travaux de dragage et de déversement, ainsi que des résultats des essais en laboratoire et des données disponibles dans d'autres publications, on en est arrivé à dresser des conclusions sur les incidences écologiques des substances nutritives et des éléments mobiles, des produits toxiques et des métaux lourds de même que du mélange eau-sédiments.

Following the signing of the Great Lakes Water Quality Agreement, between Canada and the United States, in 1972, a number of research studies have been undertaken related to dredging and associated activities. This work has been required to define the nature of both short and long term effects resulting from various dredging and disposal activities, and to establish their environmental significance.

Under the general topic of sediment/water interaction the thrust of the work has addressed three major questions, noted as follows:

1) Do the activities of dredging, dumping or disposal pose special problems in regard to the availability of nutrient elements and, if so, how?

2) Do these same activities pose special problems in regard to the availability of toxic substances and, if so, how?

3) Does the turbulent resuspension of particulate materials caused by dredging, dumping or disposal activities appear significant when compared with conditions produced by a) the passage of normal seaway traffic (shipping), b) natural wind/wave (storm) disturbance and, if so, under what conditions?

In this contribution the author has drawn mainly on the work which has been undertaken in the Canadian portion of the Great Lakes, where most of the field work has been conducted in association with dredging/disposal activities on an opportunity basis.

Background Description of the Great Lakes

The North American Great Lakes form a unique body of water which holds in reserve about one-fifth of the world supply of liquid surface fresh water. The lakes, which cover an area of 240,000 km^2 (Figure 1), occupy one-third of the surface area of the total drainage basin. The basin is intensively developed by agriculture, industry and urban settlement in the southern part, and supports a total population of nearly 35 million people.

The Great Lakes occur as an interconnected group of deep troughs, structurally controlled, and progressively deepened as a result of repeated glaciation.

Around Lake Superior and the north shore of Georgian Bay the bedrock is dominated by the presence of igneous and metamorphic rocks, whilst elsewhere shales and carbonates (dolomites and limestones) are exposed. Recent sediment remains thin over much of the northern part of the basin but provides extensive cover in the south where rapid erosion of soft materials presents problems in the control of shoreline stability.

In most of the deeper parts of the lakes a thin cover of modern mud (silty clays up to 18 m thick) overlies varved clays and glacial deposits. Modern muds thin towards the shorelines and become noticeably more silty; in regions where current circulation is sufficiently strong, nondepositional regimes may produce substantial exposures of relict glacial and earlier (high and low) lake stage sediments. Sands and gravelly sands charac-

Lake Superior

St. Marys River

N

KEY

▨ Exposed Bedrock
--- Southern Tip of the Canadian Shield
Contour Intervals of :
☐ 0–20 m
   20–40 m
   40–80 m
   80–120 m
   120–160 m
   160–200 m

Scale
0   100 km   200 km

Lake Huron

Georgian Bay

Saginaw Bay

Lake Ontario

Niagara River

St. Clair River

Lake St. Clair

Detroit River

Lake Michigan

Lake Erie

Bedrock exposed at or near lake surface
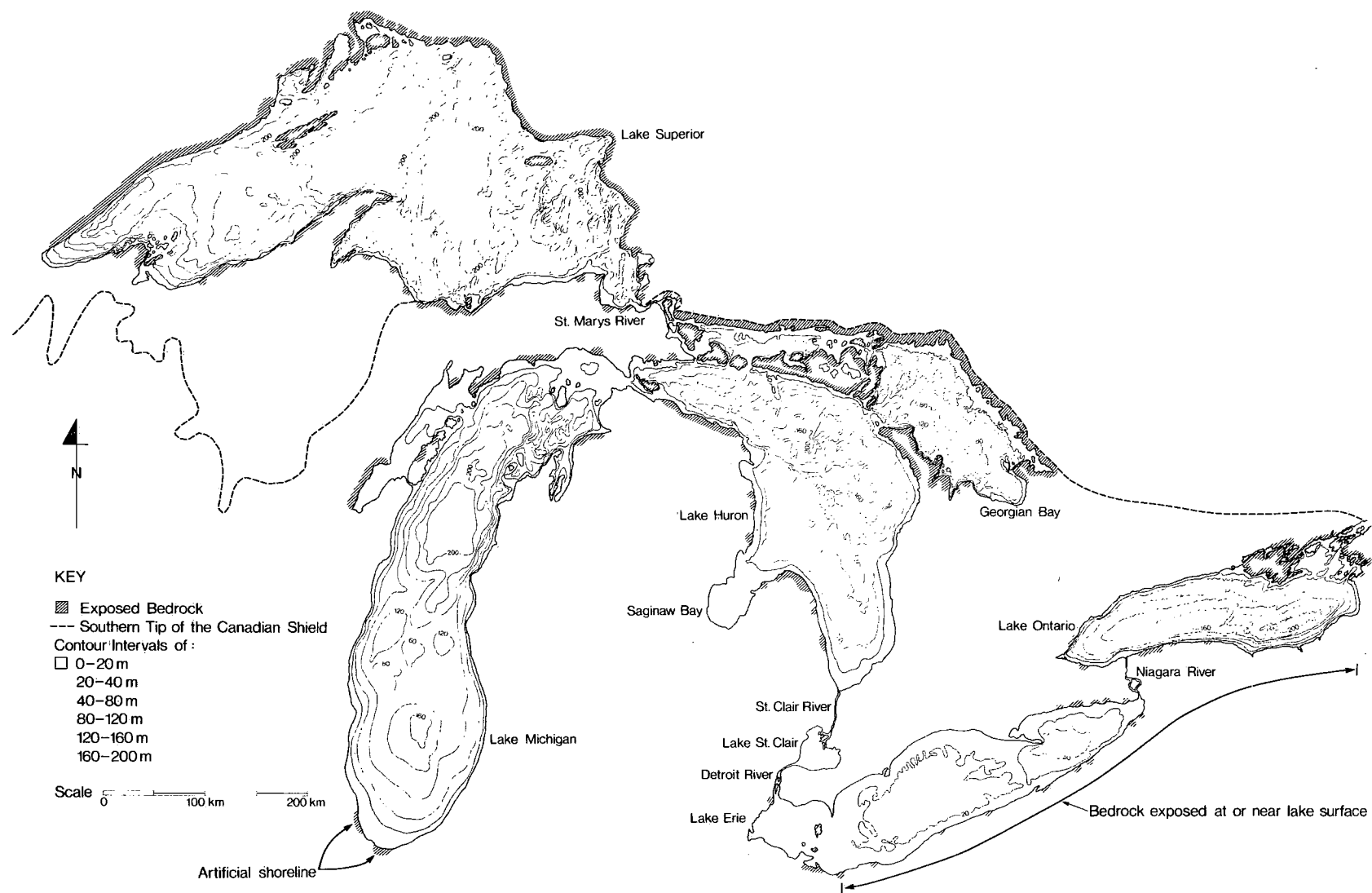
Artificial shoreline

Figure 1. Great Lakes bathymetry showing shoreline control by resistant exposed bedrock.

terize the shallow and nearshore zone where sediment response is dominated by wind/wave action (as a general value, between 0 and 20 m in water depth). This zone, with the notable exception of Saginaw Bay (Lake Huron) and the western and central parts of Lake Erie, is narrow and discontinuous within most of the lakes (Figure 1).

The chemical composition of Great Lakes waters varies from lake to lake and is strongly influenced by the nature of the bedrock. In Lake Superior the water is slightly alkaline (e.g. pH 7.1 - 7.4) whereas in Lakes Michigan and Erie, under the influence of carbonate rocks, pH values range between 8.0 and 8.4. The concentrations of major ions and trace metals in lake waters are generally low and, in many parts of the lakes, well within potable water standards (Matheson, 1975). However, concentration values rise in the nearshore zones under the influence of land runoff, river inflow and point source loadings. Because of the large surface area of the lakes relative to that of the basin, direct atmospheric inputs of both wet and dry precipitation, also, may have a significant and long term effect on the concentration of certain ions.

The concentrations of chloride ions, which may be taken as a coarse guide to the impact of industrial and urban development, show a four-fold increase from Lake Superior to Lake Erie waters.

During periods of thermal stratification, the concentrations of nutrients in epilimnion and hypolimnion waters may become very different because of biological uptake of dissolved substances. On the death or migration of biota nutrients may be transported from the epilimnion to the hypolimnion layer, so that in summer it is not uncommon to find surface waters depleted of nutrients.

The major nutrient elements include nitrogen, carbon, phosphorus and silicon. In terms of primary productivity, nitrogen values (in the forms of nitrate and ammonia) approach zero in the epilimnion waters of Lakes Ontario and Erie during the summer months. Such shortages can affect phytoplankton in these lakes, but elsewhere nitrogen does not appear to be limiting. Levels of dissolved organic carbon and total dissolved phosphorus are lowest in Lakes Huron and Superior. Phosphorus availability in Lakes Huron and Superior appears low in both summer and winter, and may well be limiting in terms of productivity. Concentrations of silicon, as reactive silica, show a sharp drop in the epilimnion layers of both Lakes Erie and Ontario during summer months and strongly suggest that diatom growth could be suppressed as a result of silicate shortage.

Despite the fact that concentrations of total dissolved solids are relatively low in lake waters (60 to 150 ppm), there are important exchange processes taking place between water and sediments and within the sediments themselves. Some of these processes are purely chemical and may depend upon redox potential (Eh) and pH conditions, while others are essentially biochemical and involve microbiological processes.

The more "active" geochemical parameters are associated with the presence of clay particles, hydroxides in colloidal form and particulate organics. The clay minerals, which may act as adsorption sites for various ions or molecular compounds, predominate in the finer silt and clay-sized fractions. If such materials are disturbed they may be

LAKE SUPERIOR

Thunder Bay 141

Navigation   Mining

LAKE ONTARIO   1,832 m³   99 m³
LAKE ERIE   4,637 m³   727 m³
LAKE HURON   533 m³   191 m³
LAKE MICHIGAN 1,310 m³   none
LAKE SUPERIOR 630 m³   45 m³

Parke Township 44

St. Marys River

Port Iroquois 302

GEORGIAN BAY

LAKE HURON

Green Bay 92

Saginaw Bay 191

Bay City 382

LAKE ONTARIO

Toronto Area 601

Oswego 61

Bronte

Hamilton Area 704

Niagara Bar 99

Rochester 275

LAKE MICHIGAN

Muskegon 53

Grand Haven 76

Holland 76

Saugatuck 45

South Haven 57

Benton Harbor 66

Chicago 61

Calumet Harbor 111

Indiana Harbor 153

Nanticoke 64

Welland Canal Area 111

Port Burwell 71

Buffalo 535

St. Clair River 188

Port Stanley 63

Lake St. Clair Channel 153

Detroit 420

LAKE ERIE

Erie 395

Erie 225

Conneaut 61

Ashtabula 137

Fairport 305

Monroe 153

Maumee Bay 76

Toledo 764

Cleveland 688

Sandusky 458

Lorain 88
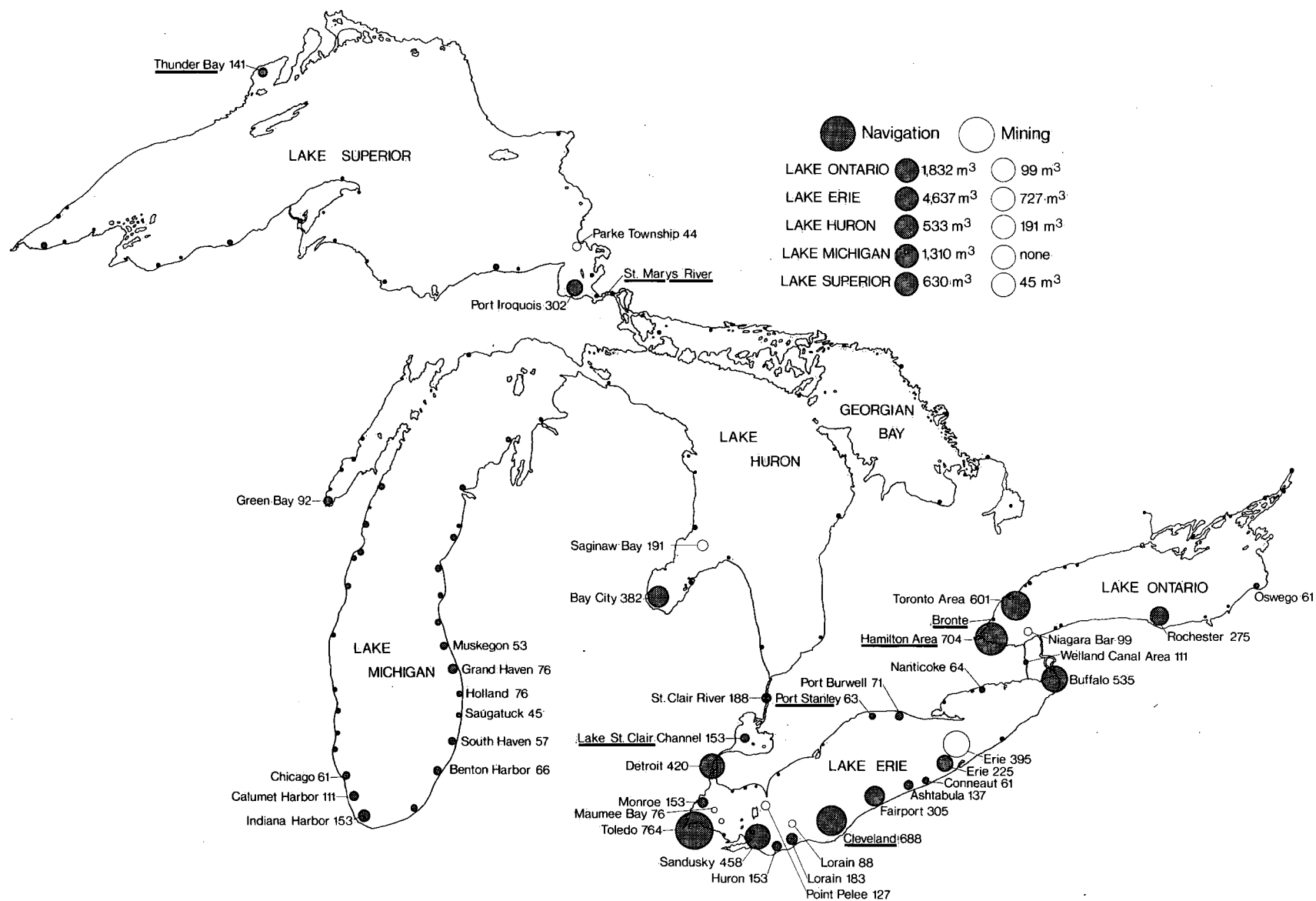
Huron 153

Lorain 183

Point Pelee 127

Figure 2.   Great Lakes dredging activities, average annual quantities (m³), 1975.

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simply redistributed but, if violently agitated, the adsorbed complexes may be partially removed. Such ions may remain in solution or simply re-attach to other adsorption sites after transport to a less turbulent location.

Recent sediments of silty-clay materials are usually loosely consolidated and retain a very high water content, and it is known that such pore waters may retain much higher concentrations of ions in solution than occur in the overlying water. If this pore water is released, as a result of turbulent mixing of the bottom materials, it can locally, and temporarily, increase the total dissolved solids at the site of disturbance.

The chemistry of the bottom sediments and overlying waters in the Great Lakes present complex situations wherein varied input loadings, residence times (e.g. Superior 183 years, Erie 2-8 years), and outputs give each lake and its sub-basins different, though related, characteristics.

Although variations in water level and currents associated with tidal systems are of only limited importance, in other respects and because of their size, the physical behavior of the Great Lakes perhaps may be thought of more easily as freshwater seas than lakes.

Dredging in the Great Lakes

The recovery of resource materials accounts for only a small percentage of the annual dredging activity (about 10 million m^3/year) which is mostly undertaken in support of harbour and channel maintenance. Figure 2 shows the relative quantities of material subject to dredging activities in each of the Great Lakes and clearly demonstrates the focus of activity in the connecting channels between Lake Huron and Lake Erie, along the south shore of Lake Erie, and the major ports of Lake Ontario.

Nearly 80% of all Great Lakes dredging is undertaken by the United States on whose behalf the Corps of Engineers maintains all channels except for the south-east bend cut-off channel in Lake St. Clair and the Welland Canal approaches (which are maintained by the Canadian Department of Public Works).

In the Great Lakes most materials are presently removed using suction dredges, hopper dredges, and cutter suction dredges. The most commonly used mechanical dredge is of the grab or clamshell type, although dragline and dipper dredges have been used for special tasks.

Until recently, most dredging/disposal operations were planned to be as economic as possible based upon direct costs; as a result no dredging plant has been designed or operated in such a way as to minimize environmental effects. Loss of fines and associated local turbulence caused by dredging/dumping is thus a subject of particular attention.

Bearing in mind the geochemical significance of dredged materials, research activities, therefore, have been associated with the impact of harbour and channel maintenance dredging.

In the Great Lakes the principal interest in nutrient elements has focused on the availability of phosphorus, both in respect to its importance to the problem of eutrophication and, in particular, to the control of phosphorus loadings from major industrial and urban sources.

Williams et al (1976), in a study on the form of phosphorus in surficial sediments from Lake Erie, differentiated three major forms:

1) Apatite phosphorus (consisting of orthophosphate present in crystal lattice of apatite grains);

2) Non-apatite inorganic phosphorus - NAIP (which includes all remaining orthophosphate ions, and assumes that non-orthophosphate forms of inorganic phosphorus are either absent or present in very small amounts);

3) Organic phosphorus (all phosphorus associated with carbon atoms via C-O-P or C-P bonds);

Of these forms only NAIP provides a significant amount of biologically available P, and may be derived from orthophosphate ions associated with the particulate and pore water fractions of the surficial sediments.

In the following field observations, evidence strongly suggests that sequential release/precipitation of Mn, P and Fe is related to pH/redox potential controls, as demonstrated by many authors (Cronan and Thomas, 1972; Burns and Ross, 1972; Robbins and Callender, 1975).

Site Observations - Loadings, Port Stanley

At Port Stanley (Figure 2) studies were made in association with dredging during both 1973 and 1974 seasons and the general distribution of sample stations is shown in Figure 3.

The harbour at Port Stanley (population 1,500) forms a partial enclosure at the mouth of Kettle Creek and material loading is largely related to input from the creek (which drains an area of 440 km^2 including the town of St. Thomas, population 22,000) and from the immediate area of the harbour itself. Exchange with open-lake waters is partially limited by the presence of breakwaters.

Ongley (1974) estimates that the average annual suspended load input from the creek (bedload is negligible) is about 6,500 short tons, but cautions that this value may be low by perhaps 50%. If a bulk density of approximately 1.5 is used for this material, the creek may be responsible for contributing between 4,000 and 5,000 m^3 of the harbour muds. Since average annual dredging requirements are in the order of 50,000 m^3/year, it must be assumed that the major portion of the harbour muds are, in fact, brought in from the open lake, as the harbour surrounds cannot be expected to account for more than a few hundred cubic metres of material.

On the basis of Ongley's data (op. cit.) it is estimated that Kettle Creek contributes about 68,000 kg of total phosphorus; this is the same amount of phosphorus

that is estimated to be taken from the harbour by dredging (Chemex, 1975), though the volume of dredged material exceeds the creek input by ten to eleven fold.

The harbour site therefore represents an area in which lake muds enter, become entrapped and mixed with tributary materials.

It is interesting to note that further corroboration of this process may be found in the budget for total iron. Ongley (op. cit.) estimates that the input loading of total iron from Kettle Creek is about 229 short tons per year, or about 208,000 kg/yr. Based upon the total iron content of sediment cores, it may be assumed that the Fe content of the dredged muds averaged about 2.1%; on the basis of the removal of 52,700 m^3 (Chemex, 1975) this is equivalent to about 2,138,000 kg of iron. This value is again more than ten times the available input from the Creek and can only be met from open lake sources.

The Port Stanley harbour muds appear to be similar in composition to the Lake Erie muds reported by Williams et al (1976). Table V compares the averaged characteristics of the pre-dredged harbour muds with total mean lake values (and the closest lake samples N21 and K21); taking into account the extremely fine particle size of the harbour muds, it is perhaps surprising that their concentration values are not higher. The 1973 water column and sediment geochemistry data (Chemex, 1974) is shown in Tables I, II and III.

Water Column (1973)

Water temperature values, before, during and after dredging, followed the normal seasonal variations as observed in Lake Erie (Canada Centre for Inland Waters, CCIW, cruise data 73-22-103, 107 and 109). Values of pH rose slightly during dredging but remained somewhat below open-lake values. Dissolved oxygen values showed a steady increase and by November DO saturation in the harbour waters was the same as in the non-stratified open-lake. Turbidity, although highest during dredging, was undoubtedly affected by the influx of lake sediments under the influence of late fall weather conditions. Phosphorus values in the water column showed a consistent increase from before to after dredging, whilst Mn appeared highest after dredging and Fe appeared highest during dredging.

Pore Water and Sediment Samples (1973-4)

Most measured parameters of pore waters show a general increase in concentration from before to after, dredging; this is particularly noticeable for Mn, but Fe appears highest during dredging (as in the water column).

In the sediments, there appears to be a general increase in concentration values, from before to after dredging, for total P, Mn and Fe.

Dredging and sampling were carried out in the area immediately in front of the harbour mouth during additional studies (Chemex, 1975) when conditions, as observed in 1973, were generally repeated again. Figure 4 shows the general change in sediment composition throughout the area, and the decrease in total P from inner harbour to lake is clearly demonstrated; the phosphate composition of pore waters is also shown. It is interesting to note, however, that the water column showed markedly higher values of total active phosphorus during the 1974 dredging activity than in 1973; 1974 study period being October 29 - November 5, as reported by Chemex (1975). (Note - for convenience active

TABLE I Water quality characteristics, Port Stanley - Before, During,
and After dredging - 1973
(Data after Chemex Ltd., 1974)

Locations	Composite		Temp	pH	Eh+	DO % Sat	Turb (Jackson)	Total P	Reactive P	Total Mn	Total Fe	Total Pb	Total Zn
1, 2, 3,	A	*BEFORE August 2-3*	21.9	7.6	267	82	40	18	6	<1	87	1	12
4 and 5	B		20.6	7.8	300	76	-	25	5	2	240	2	2
6 and 7	C		19.8	7.8	255	80	19	24	8	3	80	4	11
8 and 9	D		20.1	7.5	250	78	18	22	5	5	115	2	3
1, 2, 3	A'	*DURING September 17*	16.5	8.1	365	88	73	33	19	<1	300	12	13
4, 5, 6	B'		16.5	8.0	375	88	71	33	19	<1	320	5	7
7, 8, 9	C'		16.6	8.1	401	86	80	23	17	<1	537	4	8
10,11,12	D'		16.5	8.0	427	86	69	22	16	<1	433	7	9
1, 2, 3	A	*AFTER November 5*	9.4	7.9	412	98	41	85	33	40	48	50	41
4 and 5	B		9.5	7.8	410	98	39	40	20	10	50	44	52
6 and 7	C		9.6	7.8	400	99	40	72	12	10	50	30	38
8 and 9	D		9.6	7.8	410	96	43	87	45	25	40	28	6

——————— All values ppb ———————

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TABLE II   Sediment pore water quality characteristics Port Stanley

Before and After dredging - 1973

(Data after Chemex Ltd., 1974)

Station Location	Depth Segment (cm)		Total P	Reactive P	Total Mn	Total Fe	Total Pb	Total Zn
3	3-9		90	22	1	880	13	7
	25-31		125	35	2	220	18	3
	47-53	BEFORE August 2-3	45	12	13	400	23	3
4	5-11		80	22	2	1150	13	9
	32-38		50	12	2	440	16	7
	56-68		65	12	4	220	16	14
7	2-12		60	22	1	1420	17	2
	28-38		40	18	9	500	21	5
	57-67		22	12	1	550	14	5
8	1-7		45	18	1	720	16	1
	11-17		30	8	1	500	18	3
3	0-8		140	47	118	205	32	5
	63-75	AFTER November 5	187	70	63	580	54	10
4	0-10		225	115	140	130	25	10
	64-75		267	82	73	160	34	9
7	0-10		180	74	112	320	32	9
	45-58		50	12	11	490	22	3
8	0-7		70	22	14	205	28	2
	25-35		165	70	63	625	60	16

———————————— All values ppb ————————————

TABLE III   Sediment core geochemistry Port Stanley - Before and After dredging - 1973

(Data after Chemex Ltd. 1974)

Station Location (see also Fig. 3)		Depth Segment (cm)	Temp °C	pH	Eh mV	Total P	Inorganic P	Total Zn	Total Pb	Total Mn	Total Fe	Mean Phi	Standard Deviation Phi Particle Size	Total Volatiles %
3		3-9	21.5	6.9	+45	656	570	18.0	40	650	22 000	***	***	***
		25-31	20.4	6.7	+30	800	744	94.0	45	580	19 500	7.6	2.2	2.58
	August 2-3	47-53	20.1	6.6	+35	719	620	58.0	50	580	23 500	7.9	2.3	4.06
4		5-11	20.6	6.9	+80	625	560	62.0	32	615	22 500	***	***	***
		32-38	18.7	6.7	+40	960	813	144.0	63	685	24 000	6.8	2.4	3.75
		58-68	18.7	6.8	+75	781	650	54.0	43	800	24 000	8.0	2.4	2.62
7		2-12	21.3	7.1	+70	750	610	84.0	40	580	21 500	8.3	2.2	4.10
	BEFORE	28-38	20.0	6.7	+55	719	620	70.0	50	580	18 000	7.7	2.3	2.48
		57-65	19.2	6.8	+65	813	650	44.0	46	765	18 000	7.3	2.2	3.10
8		1-7	21.7	7.4	+65	844	650	72.0	40	545	22 500	***	***	***
		11-17	21.7	7.1	+70	750	550	38.0	30	500	12 000	6.5	2.1	1.51
3		0-8	6.5	6.6	+55	1 000	650	70.0	35	800	26 500	7.5	2.3	2.32
	November 5	63-75	5.0	6.5	+93	1 050	650	83.0	63	760	31 000	8.2	2.3	2.84
4		0-10	5.4	6.9	+45	1 000	625	70.0	28	900	31 000	7.9	2.2	2.39
		64-75	4.6	6.5	+85	1 050	650	86.0	40	760	31 000	7.4	2.8	2.37
7		0-10	7.0	6.8	+75	950	650	82.0	49	800	30 000	7.6	2.4	2.45
	AFTER	45-58	7.0	7.0	+285	1 000	575	66.0	25	760	41 500	9.1	3.0	1.99
8		0-7	6.0	7.0	+135	1 000	600	58.0	28	740	39 500	7.4	2.7	1.42
		25-35	5.0	6.6	+85	1 150	625	84.0	46	760	40 000	8.2	2.3	3.82

————— All values ppm —————

*** Insufficient sample

TABLE IV   Averages, Port Stanley Chemical Data 1973

(Data after Chemex 1974)

	Sediment Cores					Pore Water					Water Column (Composites)		
	BEFORE			AFTER		BEFORE			AFTER		BEFORE	DURING	AFTER
Segment cm	0-6	6-20	> 20	0-10	> 10	0-6	6-20	> 20	0-10	> 10			
pH	7.0	6.8	6.7	6.8	6.6	-	-	-	-	-	7.7	8.1	7.8
Temp ^{o}C	-	-	-	-	-	-	-	-	-	-	20.7	16.5	9.5
Eh mV	+56.	+50.	+54.	+72.	+129	-	-	-	-	-	+270.	+392.	+409.
DO% Sat'n	-	-	-	-	-	-	-	-	-	-	79.5	87.0	98.0
Turb JTU	-	-	-	-	-	-	-	-	-	-	22.	73.	40.
Chlor a PPB	-	-	-	-	-	-	-	-	-	-	13.5	13.0	11.0
Total P*	726.	795.	797.	1000.	1090.	65.4	56.7	48.4	151.4	170.2	22.0	27.8	73.8
Inor P*†	586.	687.	666.	630.	635.	23.0	18.6	12.0	65.6	65.8	6.2	17.5	29.2
Cu*	23.	23.	19.	26.	28.	9.3	8.5	6.3	12.	16.	3.2	4.6	12.
Zn*	68.	73.	54.	70.	82.	6.1	5.8	10.	9.8	9.6	7.8	8.2	35.
Pb*	40.	45 .	49.	36.	45.	18.	23.	20.	29.	40.	2.0	6.5	40.
Cd*	1.1	1.9	2.0	1.2	1.4	1.5	1.2	1.1	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0
Mn*	608.	604.	657.	808.	778.	2.7	2.4	5.4	104.	61.	2.7	< 1.0	25.
Fe*	22000	17800	20400	31000	34700	939.	790.	359.	221.	444.	118.	409.	47.
Hg*	1.7	0.97	0.91	0.87	0.83	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
As*	1.2	1.7	2.3	1.4	0.6	6.2	4.3	4.1	2.0	3.2	< 1.0	2.2	1.6
Phenols PPB	-	-	-	-	-	24.	14.	30.	100.	117.	2.6	< 1.0	1.0
Total % Volatiles	3.78	2.54	2.69	2.23	2.68	-	-	-	-	-	-	-	-

* Concentration - PPM in sediment, PPB in water

† Reactive P in water

TABLE V   Comparison of averaged mud sample
                 characteristics

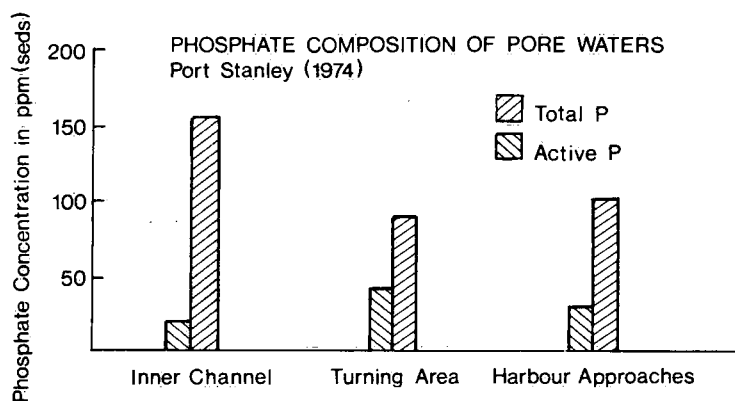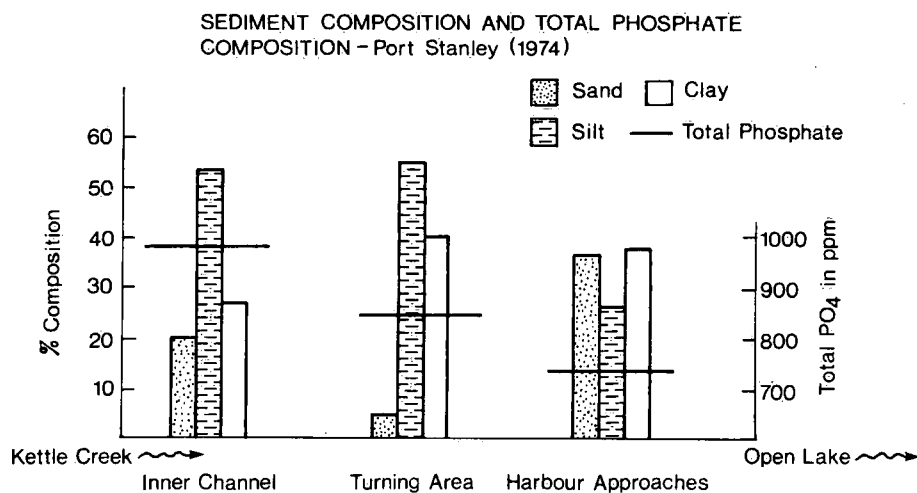|		Port Stanley	Total Lake Erie Mean	Samples N21 and K21 Range
		(Chemex, 1974)	(Williams et al, 1976)	
Total P	PPM	773	879	601-918
Inorganic P	PPM	646	770	538-772
Total Mn	PPM	623	873	540-770
Total Fe	%	2.01	3.84	2.56-2.81
Mean Size	Phi Units	7.5	5.23	4.72-5.49
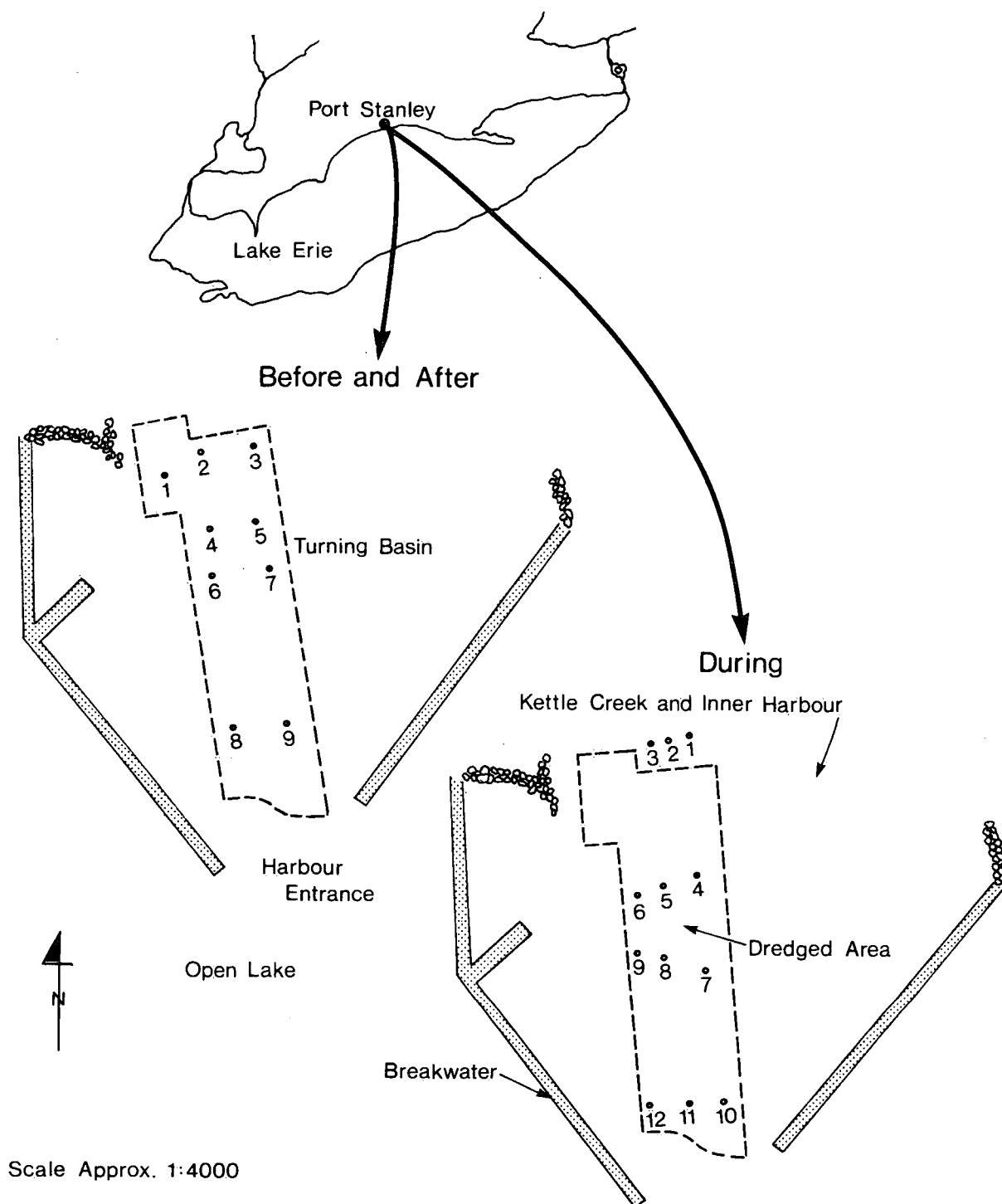
Figure 3. Port Stanley harbour, Lake Erie, showing relative positions of Before, During and After sample sites (See also Table 1).

Port Stanley

Lake Erie

Before and After

Turning Basin

Harbour Entrance

Open Lake

N

Scale Approx. 1:4000

During

Kettle Creek and Inner Harbour

Dredged Area

Breakwater

SEDIMENT COMPOSITION AND TOTAL PHOSPHATE
COMPOSITION – Port Stanley (1974)

Sand   Clay
Silt   —— Total Phosphate

% Composition

Total PO$_4$ in ppm

Kettle Creek

Open Lake

Inner Channel   Turning Area   Harbour Approaches

PHOSPHATE COMPOSITION OF PORE WATERS
Port Stanley (1974)

Total P
Active P

Phosphate Concentration in ppm(seds)

Inner Channel   Turning Area   Harbour Approaches

PHOSPHATE CONCENTRATION IN WATER COLUMN
DURING DREDGING – Port Stanley (1974)

Phosphate Concentration in ppb (water)

Total P

Active P

29   30   2   4   5
Oct.   Nov.
Date of Water Column Sampling

Figure 4.   Phosphate composition of sediment, pore water, and
water column at Port Stanley, 1974, during dredging.

phosphorus may be considered as orthophosphate, and generally equivalent to NAIP, Williams et al, 1976; analytical procedures, however, are not identical.)

Discussion

Burns and Nriagu (1976) have reported, in the Central Basin of Lake Erie, that Fe occurs strongly attached to clay particles rather than as a precipitated oxide; further, where anoxic conditions persist for some time, that large amounts of Fe are potentially releasable from clay materials as a result of resuspension. This situation appears to closely parallel that existing at Port Stanley harbour and would account for the rapid increase in Fe concentrations as a result of disturbance by dredging. The 1973 and 1974 observations suggest that sorption reactions which form amorphous Fe-Inorganic P complexes (Williams et al, 1971, and Williams and Mayer, 1972), after oxidation of ferrous iron to ferric iron (and in the presence of orthophosphates), may help to account for the rapidity with which elevated levels of Fe and P return to normal in the water column at sediment dumping sites, such as at Port Stanley. (See also open-lake disposal).

The changes in concentration of Mn showed similar association with pH/redox potential control (Krauskopf, 1957) but, in part, remain independent of Fe/P response. The sustained high level of Mn in the water column and pore water after dredging appears to be related to the differential dissolution of Mn and Fe oxyhydroxides, resulting in higher levels of Mn relative to Fe, in the water (Delfino and Lee, 1968). The effects of partial oxygen depletion, such as exist in the harbour area, would tend to reinforce this differential (Burns and Nriagu, 1976).

The reasons for the apparent increase in Fe, Mn and P values near the new surface may be exposing concentration levels which had previously existed in the sediment at depth. However, since in all probability Eh levels would have decreased with depth, it would seem more likely that Fe and Mn would have moved into solution and thereby reduced concentration levels in the solid phase at depth. It is suggested, instead, that these sediment cores reflect the early settlement of new material which has had the opportunity to scavenge the elevated concentrations Fe, Mn and P available in the partly entrained harbour waters (Dean, 1970).

Open-Lake Disposal

Studies were also conducted on the open-lake disposal of muds from Port Stanley (Chemex, 1974). The phosphate concentrations at the dump site on three occasions in 1974 (October 30, November 7 and November 25) are shown in Figure 5 and are based upon composite water samples taken 30 to 60 minutes after dumping from a scow; the active phosphate levels at various depths are also shown, giving an indication of the immediate impact of dumping.

The individual composite water samples taken in the dump site showed much variation in the relative concentrations of P, Fe and Mn (variations in concentration of active and total PO_4 are shown as example). The localized variabilities were associated with the turbulent mixing of particulates and water during dumping, as a result of physical mixing. Mn concentrations showed minor variation overall. As a result of

sorption reactions (previously discussed), physical settlement and dispersion by currents, elevated concentrations in the water column persisted for less than two hours under observed conditions.

CCIW monitor cruise data (for a number of years) suggests that at this time of year soluble reactive phosphorus and total phosphorus values in the order of 2 to 3 ppb and about 20 ppb, respectively, might be expected at the dump site area. The values shown in Figure 5 demonstrate a considerable, but local, excess.

Bronte Harbour

A similar study on the impact of harbour dredging was also undertaken in Bronte Harbour, Lake Ontario, in 1973. Bronte Creek (which crosses the heavily urbanized western shore of Lake Ontario) carries an average total suspended solids load (Ongley, 1974) of about 6,180 short tons/year, equivalent to a volumetric conversion of about 4,000 - 5,000 m³/year (bedload being negligible). The estimated quantities of total phosphorus and total iron are 10,000 kg and 177,000 kg per year, respectively.

Records of Public Works Canada show that Bronte Harbour receives only intermittent dredging (once during the period 1966-74) and that material removed has amounted to only about 11,500 m³ during the past 8 to 9 years.

In terms of materials budget, therefore, Bronte Harbour differs significantly from Port Stanley. If one assumes an average annual dredging requirement of about 1,300 - 1,500 m³ (based upon 11,500 m³ over 8-9 years), then Bronte Creek must distribute an excess loading of between 2,500 and 3,500 m³/year. The percentage composition of creek materials (based upon Ongley's data, op. cit.) for total phosphorus and iron are estimated as 0.18% and 3.16%. However, harbour sediment values (from cores) indicate equivalent compositions of only 0.06% and 1.7%.

This apparent contradiction may be explained by examination of the particle size data. In a review of Great Lakes data (Sly and Thomas, 1974) it was demonstrated that P and Fe were typically associated with the finer particulates, particularly the clay fraction (as at Port Stanley); on such a basis lower P and Fe concentrations in association with sand size materials would be expected. The P and Fe values at Bronte, in fact, approach similar concentration values recorded in equivalent sand size materials off the mouth of the Niagara River (author, unpublished data). It therefore seems likely that a portion of the creek's input load in the sand size fraction is preferentially deposited within the harbour area, whilst the finer fraction is distributed into the lake taking with it the higher concentrations of P and Fe.

Coakley (1970), in a study of nearshore sand bodies in western Lake Ontario, demonstrated their likely derivation from local sources. On this basis some sand-sized materials may be carried out into the lake from the Bronte area. However, since the nearshore lake bed is mostly formed of exposed bedrock, it seems unlikely that inward sand transport from the lake is of major importance.

Table VI shows the summarized data from the Bronte Harbour dredging study and, despite slight differences in Eh values and generally lower overall concentrations, the
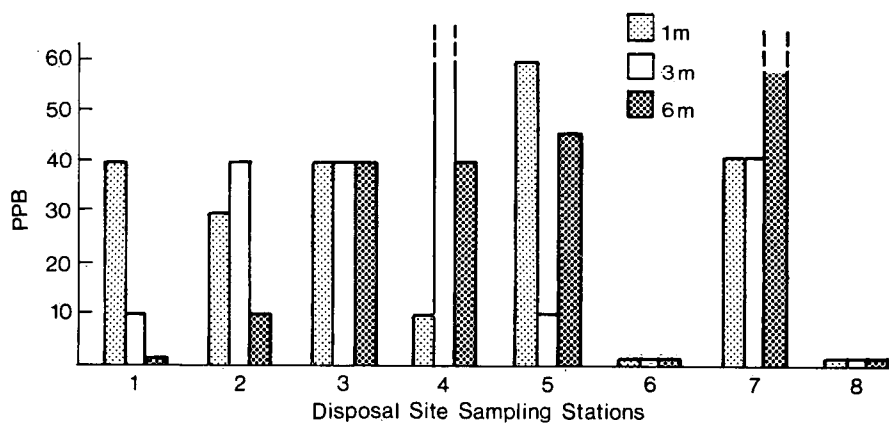
VARIATIONS IN ACTIVE AND TOTAL PO4 AT PORT
STANLEY DISPOSAL SITE 1974 AFTER DUMPINGS
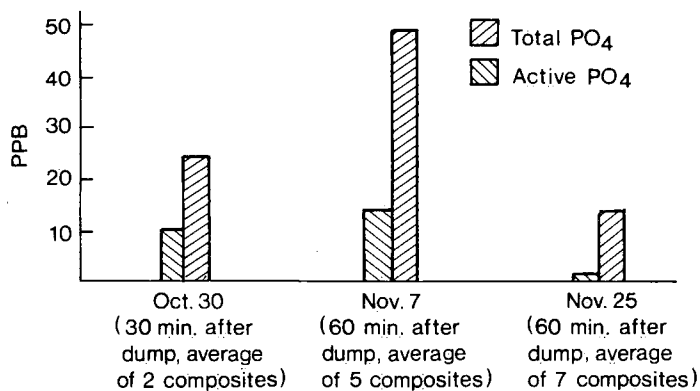
VARIATIONS IN ACTIVE PO4 CONCENTRATION AT DISPOSAL
SITE ON NOV. 7 IMMEDIATELY AFTER DUMPING, AT 3 DEPTHS
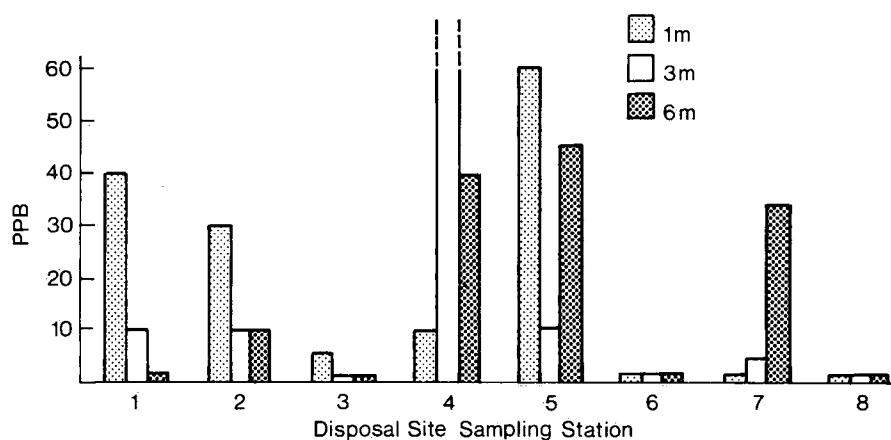
VARIATIONS IN TOTAL PO4 CONCENTRATION AT DISPOSAL
SITE ON NOV. 7 IMMEDIATELY AFTER DUMPING, AT 3 DEPTHS

After Chemex Ltd. ,1975

Figure 5.   Variations in active and total PO4 at Port Stanley
disposal site, 1974, after dumping.

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TABLE VI   Averages, Bronte Harbour Chemical Data - 1973
(Data after Chemex Ltd., 1974)

| | Sediment Cores | | | | | Pore Water | | | | | Water Column | |
	BEFORE			AFTER		BEFORE			AFTER		BEFORE	AFTER
Segment cm	0-6	7-20	> 20	0-10	> 10	0-6	7-20	> 20	0-10	> 10		
pH	6.6	6.8	6.8	7.0	7.1	-	-	-	-	-	7.7	8.1
Temp $^{\circ}$C	-	-	-	-	-	-	-	-	-	-	11.2	6.4
Eh mV	+114.	+87.	+92.	+150.	+150.	-	-	-	-	-	+404.	+327.
DO % Saturation	-	-	-	-	-	-	-	-	-	-	100.2	91.0
Turb JTU	-	-	-	-	-	-	-	-	-	-	11.1	3.2
Chlor a PPB	-	-	-	-	-	-	-	-	-	-	19.	10.
Total P*	635.	586.	573.	740.	730.	62.	43.	62.	173.	165.	9.5	73.4
Inorganic P*†	439.	404.	396.	622.	568.	25.	15.	16.	65.	47.	3.3	10.0
Cu*	12.9	11.7	11.3	22.0	17.0	11.0	6.5	8.8	20.0	19.0	5.6	10.4
Zn*	89.6	79.3	82.8	87.0	115.	12.0	11.0	15.0	16.0	20.0	31.0	17.0
Pb*	29.2	25.0	26.6	41.0	37.0	8.4	5.9	5.4	13.0	13.0	7.3	21.4
Mn*	576.	537.	554.	680.	545.	16.0	18.0	25.0	29.0	26.0	2.2	13.6
Cd*	1.0	1.0	1.0	1.0	1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.6
Fe*	17100	16400	17500	26250	23250	349.	257.	288.	604.	350.	60.	11.0
Hg*	0.08	0.08	0.08	0.18	0.26	0.3	0.2	0.2	0.1	0.2	0.2	0.1
As*	1.5	1.5	1.4	0.5	0.15	2.2	3.6	2.2	2.2	3.4	1.2	1.4
Phenols PPB	-	-	-	-	-	8.9	18.0	9.3	37.6	36.8	1.9	3.8
Total % Volatiles	2.1	1.7	1.7	2.8	2.9	-	-	-	-	-	-	-

* Concentration - PPM in sediments, PPB in water

† Reactive P in water

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trends in before and after dredging data are remarkably similar to those observed at
Port Stanley. It is therefore assumed, despite the difference in origin of particulate
materials (Port Stanley - major sediment influx from lake, Bronte Harbour - retention of
sand size materials from Creek loading), that the geochemical processes of scavenging
and precipitation (Dean, 1970), and Eh/pH control, are essentially the same at both
sites.

Physical Settling of Dumped Materials

At Port Stanley, the unconsolidated silt/clay material settled quickly and
there was little evidence of its persistence at a depth of 6 m or less (Chemex, 1975),
two hours after dumping. The "settling" rate of Port Stanley muds, therefore, must
have exceeded 0.08 cm/sec, equivalent to a particle size of about 5 phi (0.03 mm);
since this is considerably larger than the observed mean (7.7 phi - 0.005 mm) it may be
presumed that the faster settling rate is related to the formation of particle aggregates
in association with flocculation and precipitation, under the influence of well-oxygenated
conditions of the open lake.

At Bronte, sand/silt materials were dumped in 20 m of water and despite an
observed drift of 20-30 cm/sec little extension of the plume was recorded (Chemex, 1973).
The plume appeared to be completely settled within two hours, suggesting that the minimum
settling velocity was about 0.3 cm/sec, equivalent to a particle size of about 4.2 phi
(0.055 mm). Since the mean particle size of the Bronte materials was about 3.2 phi
(0.1 mm), the slowest settlement at this site appears to be associated with individual
silt size particles.

The physical characteristics of the Port Stanley and Bronte plumes appear to con-
form closely to that anticipated from the material composition and their dynamics seem
to be well expressed by existing models (Krishnappan, 1975), although at present, such
models do not incorporate functions associated with flocculation and precipitation and
may therefore contain a bias towards the fine particulates.

Later, attempts were made to relocate the dumped materials, but at both dump sites
it was found that the materials had been completely dispersed as a result of wave
action and nearshore water circulation.

Long Term Materials and Nutrient "Release"

Recently, evidence indicative of persistent effects associated with dumping have
come from Thunder Bay in Lake Superior and from Lake Erie, and the following text has
been modified from the 1975 report by the International Working Group on the Abatement
and Control of Pollution from Dredging Activities.

"In May 1975 an acoustic survey was made at a lake disposal site in Thunder Bay,
Lake Superior. The survey consisted of traverse lines which intersected at the disposal
site marker buoy.

In Figure 6 side-scan sonar records illustrate the lake bed and overlying water
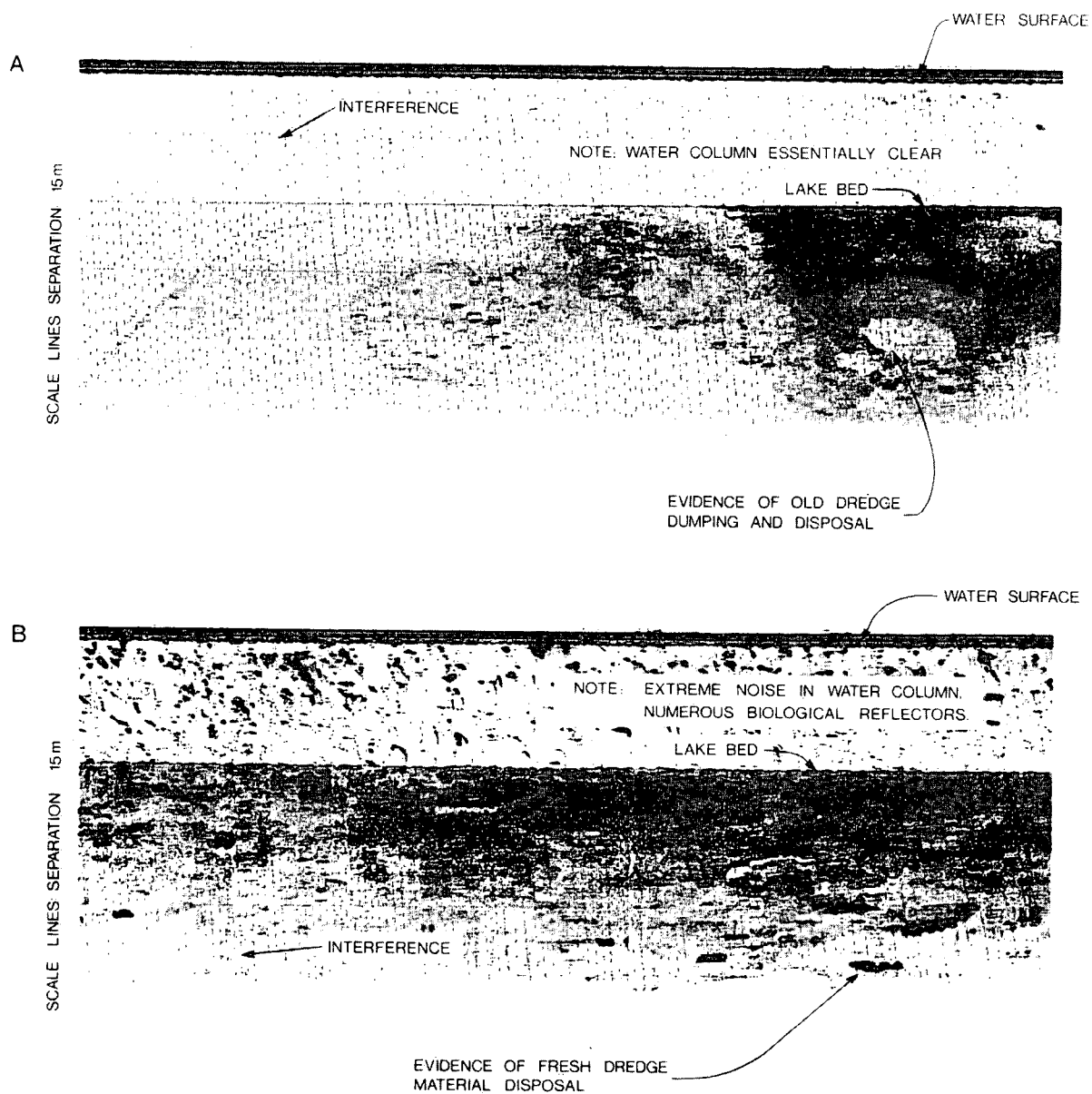column conditions in areas adjacent to the marker buoy.

A

INTERFERENCE

NOTE: WATER COLUMN ESSENTIALLY CLEAR

WATER SURFACE

LAKE BED

SCALE LINES SEPARATION 15 m

EVIDENCE OF OLD DREDGE
DUMPING AND DISPOSAL

B

NOTE: EXTREME NOISE IN WATER COLUMN.
NUMEROUS BIOLOGICAL REFLECTORS.

WATER SURFACE

LAKE BED

SCALE LINES SEPARATION 15 m

INTERFERENCE

EVIDENCE OF FRESH DREDGE
MATERIAL DISPOSAL

Figure 6. A comparison between adjacent areas at a dredged material dump site, Thunder Bay, Lake Superior, May 1975. Comparative starboard hand side-scan sonar records of similar bottom sediment areas at a dump site.

A Lake bed in area where dumping has been undertaken periodically, but not during 1974.

B Lake bed in area where dumping has been undertaken within the last year.

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Record A illustrates an area where dumping has occurred, but not during the last 12-18 months. In this record the water column, overlying the lake bed sediment, is essentially clear (acoustically). The lake bed is generally flat although a slight irregularity with relief of a few centimeters can be made out in part of the record. Evidence of the presence of old dumped materials can be seen in the darker, patchy nature of some of the bottom sediments.

In Record B the water column is seen to contain numerous acoustic reflectors, typical of dense fish populations; and, additionally, the darker patches (and lighter shadow areas) imply evidence of more recently dumped materials on the lake bed. Dumping at this location has occurred within the last 12 months.

Both traverses (A and B) cover adjacent parts of an open lake location. Wave action is minimal (at the time of recording) and circulation is of low intensity. The dumping has occurred in about 30 m of water and reworking of dumped materials as a result of wave turbulence may be considered negligible.

It may be implied, therefore, that some form of food source from the recently dumped materials has directly, or indirectly, attracted a large population of fish. In adjacent lake bed areas, where dumped materials are somewhat older, contributions from such sources are not evident. Hence a sharp distinction may be seen between the adjacent areas (A and B).

This example highlights the effect of dumped materials, acting as a food source for some time after emplacement; the source being associated with nutrients and organics which locally affect productivity and attract fish."

From Lake Erie, Sweeney et al (1975) reported on a 1973 study of an open-lake disposal site in 18 m of water off Cleveland (Figure 2) which had been used for the dumping of dredged materials from Cleveland Harbour and the Cuyahoga River between 1925 and 1968. Samples from adjacent areas provided controls for the comparison between areas subject to dumping and those unaffected. Evidence of previously dumped materials was clearly shown by the persistence of elevated levels of total phosphorus, iron, mercury, cadmium, and oils and greases, and by relatively high BOD and COD values. In addition, population analysis showed the presence of a particularly limited fauna of oligochaetes in areas of dumped materials.

These observations from Lake Erie add further support to those from Thunder Bay, Lake Superior, and strongly suggest that although some dumped sediments disposed of in depths beyond wave influence may provide a continuing source of available materials, persistence of elevated concentrations also may be taken to imply minimal release over extended periods of time.

Carbon and Nitrogen

Although, for continuity of discussion, attention has focused upon P, Fe and Mn to this point, it is appropriate to comment upon the behavior of C and N, as other related nutrient elements affected by the activities of sediment dredging and disposal.

Carbon, as organic carbon, is closely associated with the clay size fraction

(Sly and Thomas, 1974), and typical values in the finer sediments of Lakes Erie and Ontario range up to about 5% (Kemp et al, 1972). Under normal diagenetic processes associated with sediment accumulation there is a slow loss of organic carbon, at a rate of about 15% per century; at such a rate this material may be considered as uninfluenced by processes associated with dredging and dumping (excluding redistribution). Kemp et al (1972) have also shown that about 30% of the organic carbon present at the surface of lake sediments is in the form of fulvic and humic acids and that about 60% is present in the form of humins. Burns and Ross (1972) have further confirmed the rapid degradation of organic matter in the water column and at the sediment surface. On this basis, although most of the organic matter in the sediments from both Port Stanley and Bronte harbours may be supplied from the inflowing streams, it seems likely that much will have been degraded by the time of settlement, or soon after.

As a result of dredging and dumping, therefore, most of the organic carbon will be redistributed as an essentially conservative substance, although a slight increase in fulvic and humic acids may affect metals complexation (Cheam and Sly, 1975). Local increases in BOD as a result of bacterial activity associated with partly degraded organic materials do not seem to have been of concern at either Port Stanley or Bronte, at the time of these studies; however the disposal of large quantities of such material into hypolimnion waters already exhibiting oxygen depletion could well exaggerate the local development of anoxic conditions.

Although organic carbon values were not determined at either Port Stanley or Bronte, percent volatiles were; thereby providing a general indication of the amount of organic material present. The percent volatiles at Port Stanley were higher than at Bronte and correspond to the presence of finer particulates. However, variations in creek loadings at each site may also contribute to such differences.

Table VII shows the averaged values from some forms of nitrogen at Port Stanley, obtained from composite samples and reported by Chemex (1975). Generally, Kettle Creek waters show highest levels of N and, based on Kjeldahl-N and NH_3 data, there is evidence to suggest that a definite increase in some forms occurs as a result of dispersion at the dump site. Recent publications by Byrnes et al (1972), and Keeney (1974), have shown the complexity of establishing quantitative assessments of the various forms of nitrogen in different parts of the N-cycle associated with sediment/water interaction. In the light of such studies it therefore seems improper to read more into the Port Stanley data than has been suggested. However, Burns (1976), in a study of Lake Erie nutrient budgets has shown that soluble inorganic nitrogen - SIN ($NH_3+NO_3^-+NO_2^-$) appears to be of limited availability in central Lake Erie epilimnion waters during the summer growth period, and that phytoplankton uptake is much dependent upon the SIN reserve available at the start of lake stratification. It is recognized that depleted SIN may not, in itself, limit phytoplankton concentrations, although it could cause an increase in the presence of blue-green species because of their ability to fix atmospheric nitrogen.

A local and temporary increase in the concentration of nitrogen in epilimnion

TABLE VII   Forms of nitrogen - Port Stanley site 1974
                 (Data after Chemex Ltd., 1975)

	Kjeldhal-N	NH$_3$	NO$_2$	NO$_3$
Sediment pore water	0.7 - 2.8	-	-	-
Kettle Creek water	0.7	1.1	0.02	0.46
Harbour water (before)	-	0.4	-	-
Harbour water (after)	0.14	0.4	0.02	0.12
Dump site water (before)	0.28	0.008	0.02	0.17
Dump site water (after)	0.4	0.15	0.02	0.11

Values expressed in ppm and based on an averaging of a number of sample composites (as with phosphorus, dump site samples tend to give a wide variability in values).

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waters, such as at Port Stanley, should, therefore, give no major cause for concern.

The effects of N accumulation in Great Lakes sediments and the changes in composition with time have been discussed by Kemp et al (1972), and nitrogen profiles compare closely with those of organic carbon from sediment cores.

TOXIC SUBSTANCES AND HEAVY METALS

Unfortunately, little, if any, information is available from the area of the Great Lakes, about the effects of dredging or disposal on the availability of persistent organic contaminants. Consequently, the following discussion must, of necessity, focus mostly on heavy metals.

Tables IV and VI list the concentration of selected heavy metals and phenols which were measured during the Port Stanley and Bronte Harbour studies. The chemistry of the water columns before, during, and after dredging activities showed little change in composition (excluding particulates) and, with the exception of Fe during dredging at Port Stanley and the content of phenols at both sites, all water quality fell within Canadian drinking water standards (Matheson, 1975) for these measured parameters (Note: NH_3-N in Kettle Creek also exceeded drinking water standards).

The presence of phenols at Port Stanley is probably related to contamination associated with normal vessel usage of the port and contamination at Bronte may be associated with its use by small craft; although additional influence at Bronte may also relate to the presence of a nearby refinery. The data in Tables 4 and 6 suggest that there is a definite increase in the measured concentrations of most parameters in both pore water and the overlying water columns, but, when comparing samples before and after dredging at the two sites, short term effects appear to be of limited impact and may largely relate to release of pore waters as a result of turbulent mixing during dredging activities. The data sets, however, do not provide an adequate basis for assessing the longer term influence of dredging/dumping on the availability of heavy metals and other toxic materials.

Pumped Disposal and Immediate Settlement

Studies on the quality of water returned to the lake after settlement of materials from a pumped slurry at the confined disposal site in Lake St. Clair, Figure 2, (Coastal Engineering Laboratory, Queen's University, 1974 and Termarex/Barringer 1974) showed that, as a result of carefully regulated flow, up to 90% of the mercury contained in the slurry could be retained at sites receiving hydraulic discharge. Returning waters had, for example, mercury concentrations at levels close to those required for drinking water standards. To maintain this quality, however, receiving basins could not become filled to more than 2/3 their capacity without the use of secondary stilling ponds and flow velocities had to be kept below 20 cms/sec to inhibit resuspension of silt materials. The concentration of mercury in the returning waters was undoubtedly affected by the presence of fine particulates, since analyses were made on total samples.

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Contained Disposal and Experimental Studies

Studies on lake sediments disposed of in a contained area (Pilot Island) in Mitchell Bay, Lake St. Clair, (Figure 2) and in connection with elutriate and leaching experiments may, however, provide some indication of longer term effects related to metals availability.

During 1973-4 (Mudroch and Cheam, 1974) studies were undertaken to assess changes in pore water concentration of selected elements in recently dumped sediments forming an island in Mitchell Bay. The walls of the containment area were sealed and sampling began after disposal had ceased. Pore water was sampled using lysimeters placed 0.3 m apart to a depth of 3.0 m below the subaerially exposed surface of the island, which contained approximately 2,000 m^3 of material. The upper 1.2 m of sediment was coupled to the normal subaerial regime and was affected by rainfall, snow, freezing and summer desiccation. Below this, pore water content remained fairly constant and contained high levels of dissolved substances relative to external lake water.

The sediment concentrations of Mn, Zn, Pb, Co, Cr, Cu, Ti, Fe, Org-C, N, and water content showed similar profiles with depth. But the pH of pore water varied both seasonally and with depth (6.8 - 8.0) and the concentrations of the various elements (including Hg) in the pore water remained somewhat independent of sediment composition. The maximum observed values for the composition of pore water were: P, 2.0 ppm; Org-C, 20 ppm; N, 90 ppm; Fe, 100 ppm; Mn, 5 ppm; and Hg, 0.5 ppb. All of these concentrations were higher than those observed in the pore waters in sediment cores from Port Stanley and Bronte (Tables IV and VI) despite the fact that bulk geochemical composition of the sediments was similar.

Whilst it is probable that chemical speciation of the St. Clair sediments differed from that at Port Stanley and Bronte, it seems unlikely that it may fully account for the difference in pore water compositions, especially when such species differences may also occur between Port Stanley and Bronte where pore water characteristics are essentially similar. Other possibilities which might account for these observations include:

1) Relatively high diffusion rates at Port Stanley and Bronte limit pore water concentrations... There is no evidence to indicate that excessively high diffusion rates may control pore water concentrations at either Port Stanley or Bronte, and by comparison with other Great Lakes data (e.g. Bannerman et al, 1975) these sediments seem to have comparable compositional relationships.

2) High pore water concentrations in the St. Clair sediments are additionally influenced by surficial leaching...

On the basis of sediment leaching experiments (Mudroch, 1974) it was demonstrated that elutants derived by mixing air-dried sediments had a higher elemental concentration than the same sediments subjected to an all wet treatment; additionally, Mudroch and Zeman (1975) also confirmed changes in the physiochemical properties of dredged material subject to desiccation which further enhanced materials released.

The relative increase in the release of elements from air-dried materials, as opposed to those maintained wet, is shown in Tables VIII and IX for Hamilton Harbour (Figure 2) and Lake St. Clair sediments; in all these cases release from air-dried materials equals or exceeds that of constantly wet material.

Based upon these case studies therefore it may be suggested that the release of materials subjected to leaching (associated with atmospheric exposure) represents the most severe conditions under which longer term release of contaminants may occur.

Often, however, long term release of contaminants is associated with conditions in which sediments are disposed of into open-lake sites below wave base, and where they may remain largely unaffected by further physical redistribution. In such areas both physiochemical and biochemical processes control the long term distribution and concentration of heavy metals.

In studies on a small eutrophic lake in central Michigan Cline and Upchurch (1973) showed that an upward migration of introduced copper could occur as a result of compaction and undirectional ion migration but was mostly due to bacterial mechanisms. Copper was released as a result of chemi-specific bacterial metabolism and as a result of decreases in Eh and pH values. It was suggested that metals were then transported upwards within the sediment on bubble interface (if associated with gas release) or as a soluble organic complex. On reaching the upper part of the sediment the copper became immobilized as a new complex (by biological activity) or as an inorganic precipitate. It was argued that such a mechanism would provide a means by which heavy metal concentrations would be kept high at or near the sediment water interface, independent of loadings or relative rates of accumulation.

Although Walters et al (1974) have shown that the heavy metal concentrations in lake sediments appear to reflect more the influence of cultural loading than mobilization, due to effects of Eh control, these authors have also suggested that in Lake Erie the order of surface enrichment for heavy metals correlates with the order of ionization potentials, electron affinities and electronegatives and have suggested therefore that some chemical processes are active in influencing their distribution and concentration. The interaction of such complexities as changes in chemical speciation, diffusion, sediment mixing, and changes in input loadings, however, make it extremely difficult to be more specific, especially when it is recognized that Hg, and other heavy metals, can be remobilized following biochemical transformation to methyl compounds.

Methylation

Studies by Saitoh and Cheam (1975) showed that quantities of methyl mercury in sediments from Lake St. Clair, Port Stanley, the Niagara River mouth and Hamilton Harbour varied considerably (from 0.4 to 18.5 ppb) and were independent of total mercury concentrations (0.1 - 3.9 ppm). The upper limit of methyl mercury expressed as a percentage of total mercury approached 1% for samples of Lake St. Clair sediments and these findings appear to conform to the conclusions of Cooley and McCarty (1976), and others, that rates of methylation are primarily related to microbiological activity and the size

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TABLE VIII   Quantities of elements released from Hamilton
Harbour sediments and detected in the water in
leaching experiments (modified after Mudroch, 1975).

| Sediment Content | | Wet Sediment Mixed | | | | Dry Sediment Mixed | | | |
| | | 24 hours | | 48 hours | | 24 hours | | 48 hours | |
Element	Conc ppm	% release	Conc	% release	Conc	% release	Conc	%release	Conc
P	4,000	9×10^{-4}	0.04	2×10^{-3}	0.07	2×10^{-3}	0.07	2×10^{-3}	0.1
Cu	136	0.04	0.05	0.06	0.08	0.05	0.07	0.06	0.08
Zn	4,160	0.06	0.2	0.13	0.8	0.17	0.7	0.27	1.1
Pb	1,100			not detected					
Cd	15			not detected					
Mn	1,600	0.1	1.6	0.17	2.7	0.11	1.8	0.18	2.9
Fe	40,500	9×10^{-5}	0.041	1.4×10^{-4}	0.06	1×10^{-4}	0.06	2×10^{-4}	0.08
Hg	5.3			not detected					

TABLE IX   Quantities of elements released from Lake St. Clair
sediments and detected in the water in leaching
experiments (modified after Mudroch, 1975)

Element	Conc ppm	% release	Conc	% release	Conc
P	500		not analysed		
Cu	38	0.2	0.08	0.18	0.07
Zn	78	0.09	0.07	0.35	0.27
Pb	88		not detected		
Cd	2		not detected		
Mn	405	0.02	0.08	0.02	0.07
Fe	22,200	7×10^{-5}	0.02	1.3×10^{-4}	0.04
Hg	2.5		not detected		

of microbial populations.

Jernelov (1969) suggested that rates of methylation of mercury may range between 1% and 10% per annum, a value which seems generally applicable to the conversion of culturally enriched mercury in Great Lakes sediments (Vernet and Thomas 1972, and Thomas, personal communication). Methylation is also recognized as a potential release mechanism for arsenic and, more recently, Wong et al (1975) have shown that lead from Hamilton Harbour, Lake St. Clair, and other areas can be methylated at rates up to 6% per week (under laboratory conditions); although none of the bacterial isolates were able to produce Me_4 Pb from inorganic lead. The same authors have shown that the isolates could also methylate selenium.

Wolery and Walters (1974), considered the problem of long term mercury release (by methylation) from Lake Erie sediments and concluded that there was a critical depth below which mercury (and other metal) concentrations became largely unavailable as a source for methylation. It was argued that mercury-enriched sediments were subject to bioturbation by tubificids and that this reworking continuously presented mercury to microbial activity close to the sediment surface. In this case the critical depth appeared to be about 3-4 cms below the sediment interface (Jernalov, 1970, has suggested that reworking by lamellibranchs such as Anodonta may extend the critical depth to as much as 9-10 cms). Assuming that mercury enrichment may substantially decrease as a result of regulatory controls, methylation may continue for a period of 10-100 years under steady-state conditions. Under open-lake conditions, however, the effects of sediment accumulation and transport modify the steady state. In areas such as the western basin of Lake Erie, for example, where average accumulation rates exceed 0.4 cm/year, effective burial of a contaminated layer could be accomplished in about 10 years, if uninfluenced by resuspension.

It is recognized, however, that wind/wave turbulence may resuspend sediments at shallow depth (Thomas et al, 1976, and Lam and Jaquet, 1976), and that such influences will tend to increase the effective critical depth. In addition, it is important to note that the concentrations of mercury in the algae Cladophora showed a marked increase following storm activity in Lake Erie (Burkett, 1973), and that this reflected the significance of brief increases in the mercury content of the water mass due to periodic physical disturbance of the sediment surface.

Biological Uptake

Despite implications regarding the longer term availablity of heavy metals in the Great Lakes, and their potential incorporation in the food chain, published research remains limited. McKinnon et al (1975) suggested that uptake of pollutants (methyl mercury) by yellow perch from the Ottawa River was dependent upon ration and respiration necessary to support metabolism and growth (being largely sensitive to body weight); and was largely independent of concentration in food and water. Huckabee and Goldstein (1975) in studies on largemouth bass showed that tissue retention of methyl forms (Hg) was longer than for inorganic forms derived from treated food supplies; they also

implied, since methyl mercury compounds were almost never detected in water, that food chain accumulation mechanisms must predominate. Delisle et al (1975), reported on aquaria experiments with goldfish and catfish and showed that fish exposed to grossly contaminated sediments showed a substantial increase in tissue levels of Zn, Pb, Cu and Cd; maximum concentrations were attained within two months and showed little variation for the remaining three months of the experiments.

Brown and Chow (1975) reported on concentrations of heavy metals in fish taken from Lake Huron (representing an environment essentially free of contaminant loadings) and from Toronto Harbour (an area subject to relatively high urban and industrial loadings). Concentrations of Cd, Cu, Pb, Zn, and Hg in the muscle tissue of Toronto Harbour fish were higher than those from Lake Huron by factors of 2, 4, 9, 8 and 4, respectively. Maximum concentrations, however, remained within health standards.

On the basis of existing evidence, it seems that whilst elevated concentrations of many heavy metals may sustain long term release mechanisms which allow for their incorporation in the food chain, in most cases resulting concentrations do not pose health hazards in edible species.

However, where methylation takes place, bioaccumulation through direct assimilation and via the food chain may show rapid and sustained response resulting in tissue concentrations in excess of standards for human consumption.

SEDIMENT-WATER MIXING: SIGNIFICANCE OF DUMPING, SHIPPING AND STORMS

Krishnappan (1975), as a result of laboratory experiments, suggested that in the Great Lakes region where disposal of dredged materials takes place mostly in shallow waters (less than 100 m and usually in 20 m or so), most dumped materials would fall through the water column in an entrainment phase and that only a small portion would fall in a settling phase with wide dispersal. This implies that the time taken for dumped materials to descend through the water column is mostly less than that required for the fall of discrete particles and in the cases observed it seems likely that the majority of dumped materials take only minutes to fall to the lake bed; complete settlement in depths of 20 m or so would occur in 2-3 hours as confirmed by field observations at Port Stanley and Bronte (Chemex 1973 and 1975), as previously discussed.

The presence of discernible accumulations in Thunder Bay (Figure 6), in water depths of about 30 m, adds further support to Krishnappan's views that material dispersal and fall in settling phase is primarily of concern in areas of ocean dumping (Koh and Chang, 1973) where depths are measured in hundreds or thousands of metres.

Based on such evidence it would seem that only those chemical release processes and reactions with rates measurable in the order of minutes or a few hours appear to have significance as a result of sediment/water interaction associated with turbulent mixing during dumped disposal activities.

The disposal of materials in the form of pumped slurries is usually related to the use of land disposal or containment within dyked or ponded areas. It is not a practice

associated with open-lake disposal.

Dredging, and the disposal of materials by open-lake dumping, represents a special case of sediment/water mixing; in the Great Lakes mixing of the normal sediment/water interface may be induced also by the passage of shipping, and by bioturbation and storm action (associated with both seiching and wind/wave action).

Effects of Shipping

Very little data exists on the effects of the passage of shipping on bottom sediments in shallow areas. However, some estimates may be developed from the observations by Sly (1969) and from the laboratory experiments by Wilson (1973). In a study to define the effects of bottom disturbance, induced by a vessel manoeuvering in shallow water, on surface sediment sampling it was shown that no discernible disturbance of bottom materials took place in water depths greater than about 4.5 m below the axis of the propeller (132 x 86 cm with shaft rotation of 0-500 rpm). At depths of 3.3 m below the propeller axis severe stripping could be induced to a depth of about 2.0 cms in the sediments and to a distance of 4-6 metres on either side of the keel. At depths of 2.0 m below the propeller axis massive stripping to a depth of 7 or 8 cms occurred, to a distance of 6-8 m on either side of the keel.

In laboratory studies (Wilson, op. cit.) it was shown that bottom disturbance by shipping could be induced in: 1) the hull zone, 2) the propeller zone, and 3) the wake zone; disturbance in the wake was of most importance.

Despite the limitations of the laboratory studies due to scale problems it was predicted that lake shipping having a bottom clearance of 1 m or less would induce sediment disturbance (medium-sized sand) to a depth of 0.3 m or more; it was also shown that with repeated passage of vessels the depth of sediment disturbance would increase.

These two sets of observations are in general agreement; the vessel used in the field observations (Sly, 1969) was a deep displacement-hull tug, having a draft of 1.9 m, beam of 5.0 m and length of 19.5 m, and large lake freighters may typically draw more than 8 m and have a beam of 23 m and a length of more than 220 m. On such evidence it may be suggested that large vessels having bottom clearance of 1-2 m will significantly disturb bottom sediments to a depth approaching half a metre over a path 2-3 times the width of the vessel.

The process of lake bottom disturbance induced by shipping is, therefore, only of importance in shallow channels and shallow harbour areas. In most channels (e.g. St. Clair-Detroit River, Figure 2) flow velocities are relatively high so that the main effect of disturbance by shipping is to amplify the rates of existing sediment transport and to cause temporary resuspension of the bed and saltation loads. In harbours, where waters remain partially entrained it may be anticipated that temporary disturbance by shipping has little effect, with resuspended materials falling quickly to the bottom after slight redistribution. Only in areas where contaminants are associated with coarser particulate fractions (Thomas 1971 and 1974; Kudo et al, 1976) does their resuspension by shipping give cause for concern (primarily because of their accelerated

rate of transport and therefore increased rate of spreading and diffusion).

Quantitative estimates of the amount of sediments redistributed as a result of bottom disturbance by shipping in the Great Lakes have not been made, although they must exceed that produced by dredging and disposal by at least an order of magnitude. On this basis and despite the fact that coarser particulates are generally associated with low concentrations of available nutrients, heavy metals and other toxic materials, it seems likely that the passage of shipping in the Great Lakes contributes at least as much, if not more, to the release and redistribution of contaminant materials than dredging/disposal activities. Materials redistributed under relatively high flow conditions in channels are typically transported beyond the channel and become widely dispersed and dilute; on the other hand, unless deposited within the zone of wave-induced influence, dumped materials tend to remain physically immobile.

Storms and Lakewide Effects

Contaminant release from continuing sediment disturbance by biological mechanisms and from disturbance by wind/wave action and storm seiches appears to be by far the most important source of internal loading in the Great Lakes system, though no estimate is available of a release associated with biological process.

Chemex (1973), on the basis of turbidity measurements, estimated that under the conditions prevalent at the time (November) of their study on dumped disposal off Bronte Harbour, at least 1000 metric tons of material were naturally in suspension in the nearshore zone, for every kilometre of shoreline, at any point in time; this loading was many times that derived from the total daily dumping at the Bronte site.

Whilst concentrations of available nutrients and heavy metals were certainly higher in the dredged materials than in the naturally derived materials, such figures help to place the significance of these particulate loadings in perspective.

A more appropriate estimate of the impact of storms in terms of internal loading and nutrient availability, however, may be found in the work of Lam and Jaquet (1976), who developed a model for the physical transport and regeneration of phosphorus for Lake Erie.

In this study it was shown that substantial quantities of phosphorus were regenerated and settled as a result of storm action, with particularly large internal loadings occurring in the central basin of the lake.

In 1976, Kemp et al, estimated that dredged/dumped materials accounted for about 4% of the annual lake loadings of silt/clay sized materials, and since such materials are associated with most of the available phosphorus fraction, and on the basis of the work by Williams et al (1976), it may be estimated that dredged materials could contain something in the order of 300-800 metric tons of nonapatite inorganic phosphorus (NAIP). If such dredged/dumped materials were fully mixed and dispersed during the process of disposal, their total annual contribution would approach the same order of magnitude as the phosphorus regeneration and settling estimated for the 20-day period between cruise and model predictions by Lam and Jaquet (1976).

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As earlier stated, however, unless dredged/dumped materials are disposed of within wave influenced areas, they tend to remain physically immobile and, further, since phosphorus release during dumped disposal in shallow water represents only a part of that potentially available (because of fall within an entrained phase), it appears that short term phosphorus release from dredged/dumped materials represents only a fraction of that induced by lakewide regeneration.

CONCLUSIONS

On the basis of the evidence presented, which may be considered typical of conditions existing in the Canadian portion of the Great Lakes, it is suggested that the following conclusions may be drawn:

1) As an immediate result of sediment disturbance pore waters may be released, thereby adding soluble nutrients and more mobile elements to the water mass.

2) During dredging/dumping activities it is likely that ferrous iron becomes rapidly oxidized to ferric form and through sorption reactions forms iron phosphates.

3) Release/precipitation reactions for P, Fe, Mn appear to conform to the well established pH/redox potential controls, with differential dissolution of Mn and Fe oxyhydroxides resulting in higher levels of Mn, relative to Fe, in water.

4) Nutrient/organics release may persist for some time after open-lake disposal (as attracted fish).

5) N availability appears to be high, especially from sites receiving high N loadings, and locally increased BOD may be caused by the breakdown of additional organic materials.

6) Although heavy metals in soluble form are available in pore waters their early release generally presents little concern since, mostly, concentrations are already within potable water standards and, in any case, the scavenging affects of oxides and hydroxides may rapidly co-precipitate P and other elements in the water mass soon after disposal. However, the occurrence of heavy metals in waters discharged from pumped slurry may give rise to concern. Additionally heavy metals may become available as a result of such physio-chemical effects as leaching and dehydration.

7) Heavy metal availability, both in soluble form and as a source in biochemical conversion is strongly influenced by speciation. Evidence from leaching and elutriate tests suggests that a fairly wide range of solubilities exists, but data is non-specific.

8) Biochemical conversions of certain heavy metals (e.g. Hg, and possibly As, Pb and others), through the process of methylation provide a mechanism for the long term release of toxic species which may be incorporated into the biota.

9) The release of such stable compounds as oils, grease, phenols, etc., depends upon both their original concentration in the sediments, and upon the amount of sediment/ water mixing prior to disposal. In most cases such contaminants fall rapidly to the lake bed in association with the particulates; in areas of frequent dumping,

however, some tainting may occur. Information regarding the fate of other persistent organic contaminants such as PCB's, pesticides and herbicides is not available.

10) On a quantitative basis the contribution of particulates to lake systems by dredging is minor when compared to other loadings and lake-wide resuspension by storms. However, if dumped materials are disposed of in shallow areas subject to wave and current activity, so that they become widely dispersed, it seems certain that they would contribute a measurable percentage to the total nutrient (and toxic) load. Since "dilution should not be the solution to pollution", dumped materials should be placed in as great a depth of water as possible, having sufficient resistance to DO depletion, with the minimum of mixing and dispersal during the activities of dredging and dumping.

11) Harbours and channel areas effectively trap part of the "cultural loadings" to the Great Lakes, thereby lessening their total impact. Although it may be argued that by disposal of this material in open waters there is no significant increase in total loading, such a view should be qualified. Harbour and channel areas trap both materials swept into the nearshore from the lake and from inflowing drainage systems, and by this role they lessen the effect of total loadings to the lake. Open-lake dumping of materials dredged from these locations is a form of reloading to the system where water quality may be effected by long term chemical release, or by the activities of storm action or bioturbation on such dumping. The use of open-lake disposal, therefore, may be seen as a trade-off between limited environmental impact and the expense of more costly disposal alternatives, and on this basis environmental impact assessments must consider each situation on a case-by-case basis. It should be borne in mind, however, that without maintenance dredging the capacity to receive such loadings will rapidly diminish in harbour areas, etc. After steady state is achieved these locations no longer serve as traps. Maintenance dredging and careful disposal is therefore potentially beneficial in terms of reducing lake loadings.

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