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TROPHIC CHARACTERIZATION OF THE U.S. AND CANADIAN NEARSHORE ZONES OF THE GREAT LAKES

TROPHIC CHARACTERIZATION OF THE U.S. AND CANADIAN NEARSHORE ZONES OF THE GREAT LAKES

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DISCLAIMER

The study discussed in this document was carried out as part of the efforts of the Pollution from Land Use Activities Reference Group (PLUARG), an organization of the International Joint Commission, established under the Canada-United States Great Lakes Water Quality Agreement of 1972. Findings and conclusions are those of the authors and do not necessarily reflect the views of the Reference Group or its recommendations to the Commission.

ABSTRACT

A trophic evaluation of the nearshore zone of the Great Lakes has been undertaken. Trophic status is described as a composite of three parameters descriptive of both water quality and trophic conditions. These parameters are total phosphorus, chlorophyll a, and Secchi depth. Phosphorus is assumed to be a primary variable in determining trophic conditions. Chlorophyll a is important as a measure of algal biomass. Secchi depth is a measure of water clarity, inversely related to algal biomass.

The relationship between these three parameters in the Great Lakes nearshore zone is determined with linear regression techniques. These relationships are used as the basis for a Composite Trophic Index (CTI). The CTI is related to trophic conditions in the nearshore zone. The resulting delineation of trophic status in this region is presented.

The nearshore trophic conditions are related to phosphorus contributing areas in the Great Lakes Basin. Nearshore and open water trophic conditions are also compared.

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TROPHIC CHARACTERIZATION OF THE U.S. AND CANADIAN NEARSHORE ZONES OF THE GREAT LAKES

INTRODUCTION

The trophic classification of water bodies, as used in this report, refers to a comparison of the degree of fertility or eutrophication of water bodies, using a common scale or indexing system. This concept of a relative scale for the comparison of water bodies, or conditions within the same water body, is used for most trophic indexing schemes, with the major differences between schemes being the parameters chosen to formulate the index.

As noted by Shapiro (1975), many lake trophic indexing systems have been proposed by numerous researchers over the past several decades for the purpose of trophic state delineation, as well as for justification of nutrient control strategies (in particular, phosphorus). Indices may be descriptive or analytical, simple or complex, relative or absolute, and subjective or objective. Examples of all types are available in the literature, including the trophic indices of Lueschow _et al_ (1970); Shannon and Brezonik (1972); Dobson (1974); U.S. Environmental Protection Agency (1975); Uttormark _et al_ (1975); Carlson (1977); Piwoni and Lee (1977); Dobson and Chapra (1977); and Rast and Lee (1978).

Previously, trophic classification has largely been limited to whole lakes or offshore waters of large lakes. However, very large lakes frequently exhibit a distinct nearshore zone which is separated from the open waters by virtue of its relatively shallow depth. In addition to having higher concentrations of most pollutants, the dynamic mixing of waters in this zone generally produces more variable concentrations of various water quality parameters. This variability results in part from tributary and municipal (urban) pollutant input patterns, as well as from the hydraulic characteristics of this zone. The physical boundaries of the nearshore zone may vary considerably, ranging from essentially zero width, where the offshore waters of the lakes are completely mixed to the shore, to several kilometers distance from the shore. Such factors as wind direction, intensity and duration, as well as shoreline and lake bottom morphology, influence the extent of the zone.

The nearshore zone, by its nature and location, constitutes the transition between nutrient and pollutant loads from the land and the resultant trophic condition and water quality seen in the offshore waters. This zone is also the area in which the immediate effects of nutrients are most visible. This is particularly important for use of the water for water supplies, recreational pursuits and other activities.

Application of any trophic classification scheme to nearshore waters of large lakes, particularly the Great Lakes, has been limited. Gregor (1977) and Gregor and Ongley (1978) qualitatively described trophic conditions for the Canadian nearshore waters of the Great Lakes based on a water quality scale developed by Dobson (1974). However, this scale is based on offshore data (i.e., open water conditions in the lakes) and, therefore, is not necessarily applicable to nearshore waters. In addition, this parametric approach results in contradictions, an example being high turbidity (i.e., low Secchi depths) concomitant with low chlorophyll concentrations (a measure of algal biomass).

Phosphorus is assumed in this analysis to be a primary variable in determining trophic conditions. This is because phosphorus has most often been found to be the nutrient which "limits" or controls the productivity of algae and other aquatic plants (assuming light, temperature and other factors are sufficient for algal growth). In addition, control programs for phosphorus are more technically and economically feasible on a large scale than control programs for other nutrients (e.g., nitrogen, silica).

As part of the activities of Task D of the Pollution from Land Use Activities Reference Group (PLUARG) of the International Joint Commission (IJC), a trophic index was developed for comparison of the nearshore zone of the Great Lakes. This trophic index is based on a modification of Dobson and Chapra's (1977) approach for the offshore waters of the Great Lakes. The development of this index and its application to the nearshore waters is presented in the following sections.

BASIS FOR TROPHIC INDEX

Three parameters, total phosphorus (TP), chlorophyll *a* (Chl*a*) and Secchi depth (SD), have been employed in the development of this nearshore trophic index. The rationale for consideration of total phosphorus was indicated above. Chlorophyll *a* is important as a measure of algal biomass. Secchi depth is a measure of water clarity and is inversely related to the algal biomass, assuming the water bodies do not contain excessive quantities of inorganic turbidity or color. Dobson and Chapra used particulate organic carbon as a second measure of algal biomass. This parameter, however, was not monitored consistently within the nearshore zone of the Great Lakes and was therefore omitted from the trophic index described in this report.

As outlined by Dobson and Chapra (1977), the relationships among TP, Chl*a* and SD can be estimated empirically through linear regressions. Rationalizing that, in the absence of the independent variable, the dependent variable would not be expected to be present, Dobson and Chapra forced their relationships through a zero origin. This assumption may be valid for offshore waters, but does not appear to be true for the nearshore zone. For example, a large portion of the total phosphorus present in nearshore waters will be chemically bound as apatite phosphorus and therefore not available for use by algae. Sources of apatite phosphorus include shore erosion, tributary inputs and resuspension of lake bottom sediments. Consequently, it is reasonable to expect a threshold level of TP below which Chl*a* is not present. As a result, these authors employed least squares linear regression techniques to establish relationships between the paired variables, specifically TP and Chl*a*, and Chl*a* and SD.

The use of Secchi depth as a trophic state indicator warrants further comment because water transparency is affected by factors other than phytoplankton abundance (e.g., suspended inorganic particulates derived from sources indicated above). However, as will be further discussed below, statistically significant relationships between SD and Chl*a* are observed for the nearshore zone of the Great Lakes.

Secchi depth is inversely related to algal biomass (Dillon and Rigler, 1975; Rast and Lee, 1978). Thus, a transformation is required to directly relate these two parameters. A transformation can be achieved using Lambert-Beer's Law for light extinction in water (Verduin et al, 1976), as follows:

$$I_z = I_o e^{-nz} \tag{1}$$

where I_z is the light intensity at depth z, I_o is the intensity at the surface, and n is the extinction coefficient.

Following Tyler (1968), the Secchi depth corresponds to the depth (meters) at which the light intensity is equal to 10 percent of the value measured at the surface of the water. Applying this factor, Equation 1 can be linearized to:

$$\frac{2.3}{SD} = n_s + n_p + n_w \tag{2}$$

where z (from Equation 1) becomes the value of the Secchi depth, n_s is the extinction due to suspended materials (both organic and inorganic), n_p is the extinction caused by materials dissolved in the water and n_w is the extinction due to water alone. In their derivation, Dobson and Chapra (1977) solved for the components of n such that transformed Secchi depth was linearly proportional to plankton abundance, with a zero intercept. However, because of inherent differences among the Canadian nearshore regions of the Great Lakes, a unique solution to Equation 2 was not possible for these data (the necessity for emphasizing the Canadian nearshore data as the primary sources for the trophic index relationship described in this report is discussed in a following section). Therefore, the Secchi reciprocal $\frac{2.3}{SD}$ was used to develop the linear relationships used in this analysis, assuming that:

$$\frac{2.3}{SD} = \alpha \mathrm{Chl}\underline{a} + (n_s' + n_p + n_w) \tag{3}$$

where α is the proportionality constant and n_s' represents the extinction of light due to suspended inorganic materials only (Chla is expressed as µg/L).

The relationships between Chl_a_ and TP and between Chl_a_ and SD (as expressed in Equation 3 above) derived from these nearshore data, and forming the basis of this trophic index, are developed below.

DELINEATION OF REGIONS WITHIN THE NEARSHORE ZONE

The logic of geographical partitioning of the Great Lakes nearshore zone into discrete regions was to denote areas within which average water quality was relatively homogeneous. Geographic regions were initially delineated for the Great Lakes nearshore zone to reflect primarily the presence or absence of significant tributary inputs and concomitant urban, agricultural and natural pollutant loadings. Hence, the resulting geographical partitioning was done prior to any extensive analysis of nearshore data. Intuitively, and as subsequent analysis indicated, average water quality conditions within any one region were not necessarily significantly different from water quality conditions between adjacent regions. This observation does not invalidate the use of nearshore region boundaries chosen _a priori_ since even data from a single water sampling station for a short period of time are unlikely to be representative of a single water quality condition.

The nearshore partitioning was based primarily on the interface of major river mouths with the nearshore zone, with further differentiation based on consideration of the following factors (not necessarily in the order presented):

a) presence of urban area on shoreline;
b) presence of areas of serious erosion on shoreline;
c) presence of extractive areas or mining industries on shoreline;
d) presence of inlets or embayments along shoreline;
e) general nearshore circulation patterns;
f) depth of thermocline; and
g) estimated homogeneous water quality in the nearshore area.

Generally, the U.S. nearshore zone was delineated from the open waters based on a three-kilometer distance offshore, with adjustments for embayment

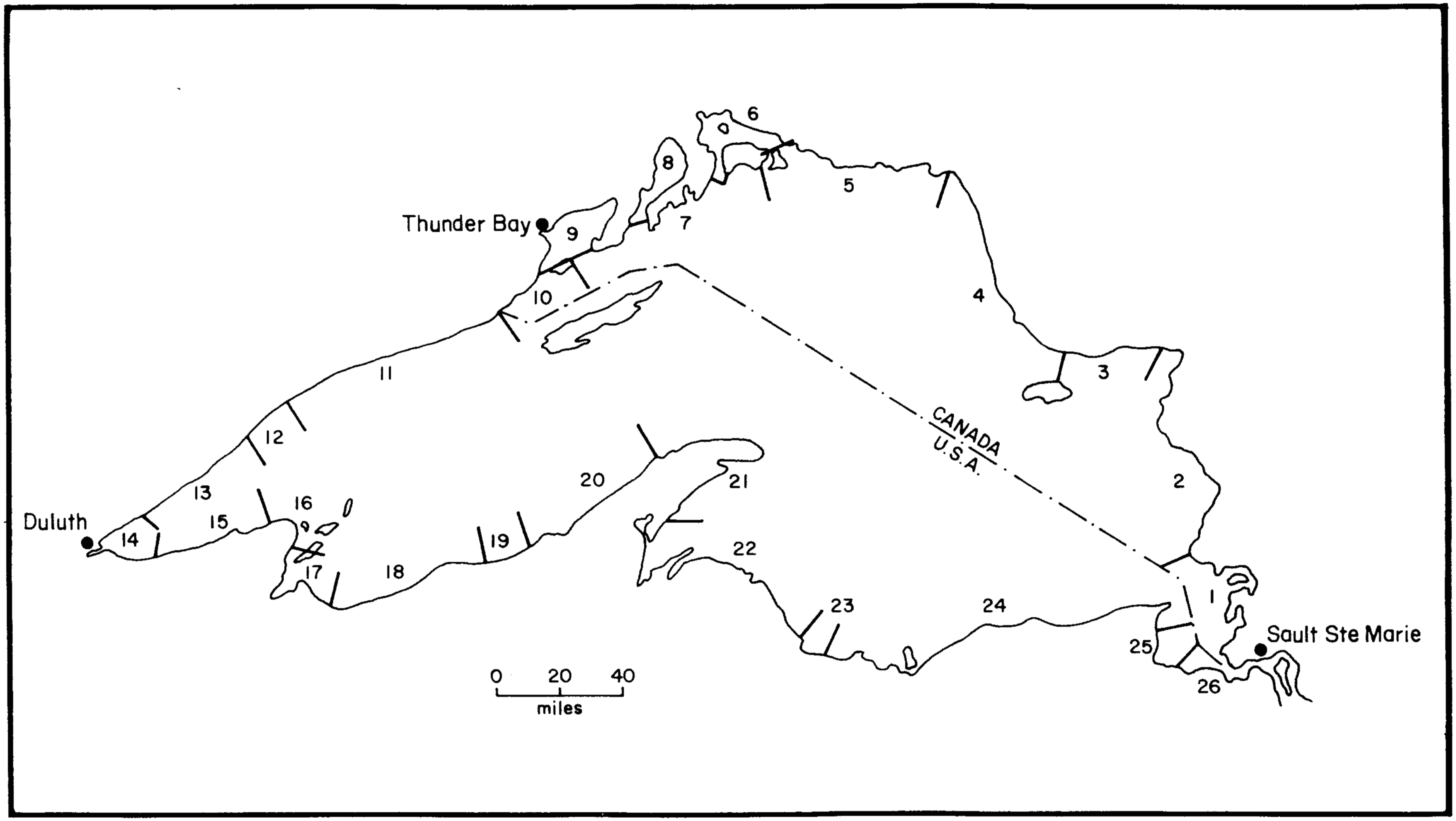


FIGURE 1a: LAKE SUPERIOR NEARSHORE REGIONS

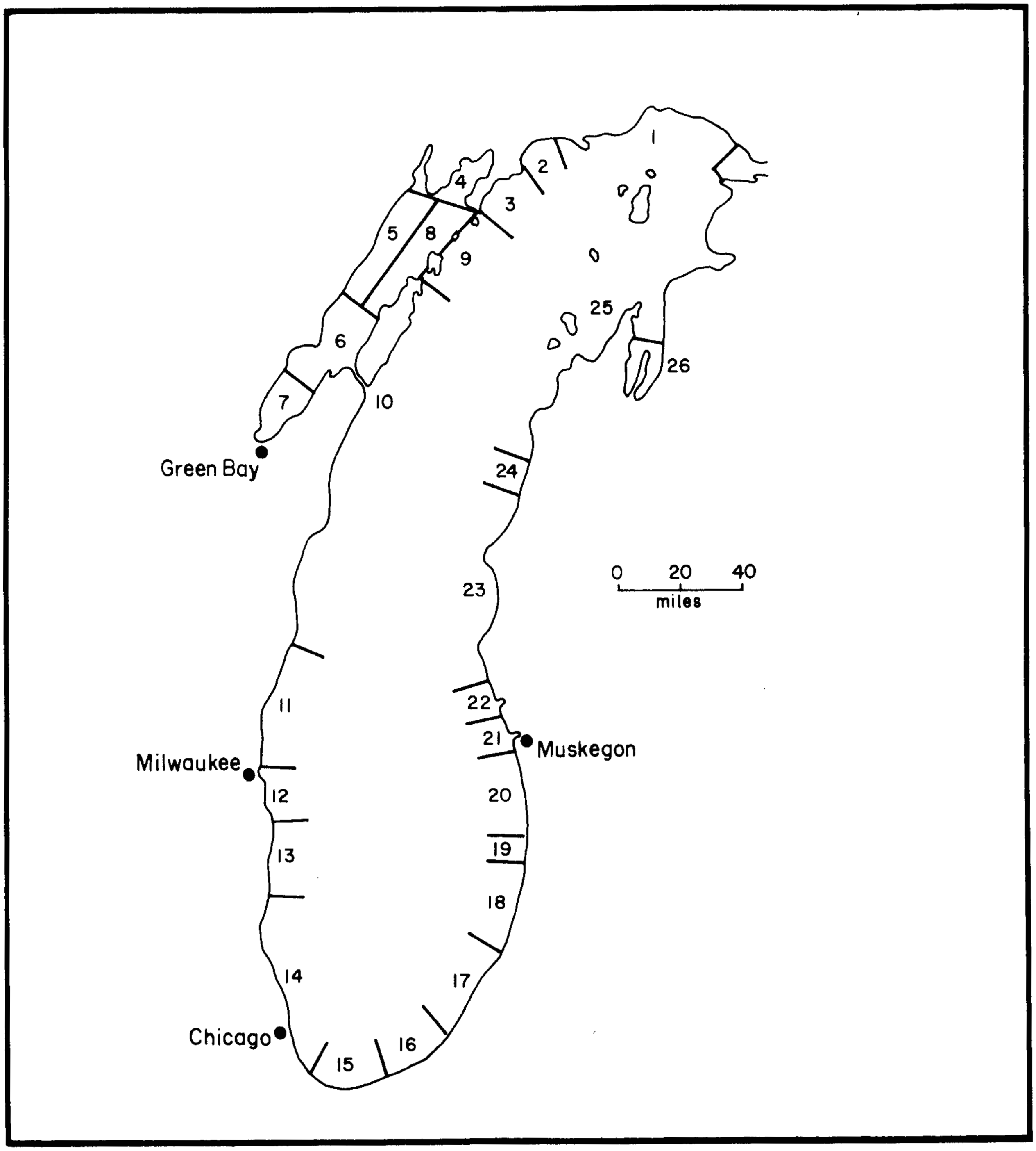


FIGURE 1b: LAKE MICHIGAN NEARSHORE REGIONS

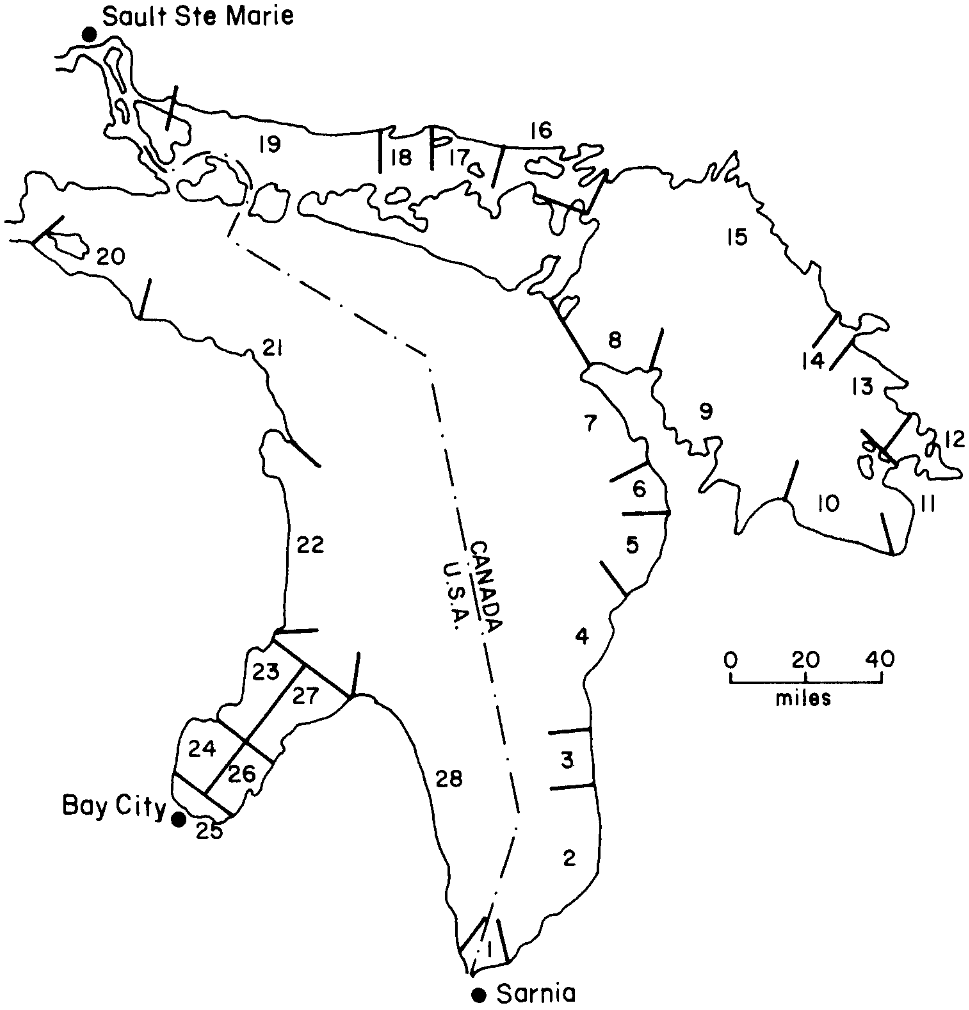


FIGURE 1c: LAKE HURON NEARSHORE REGIONS

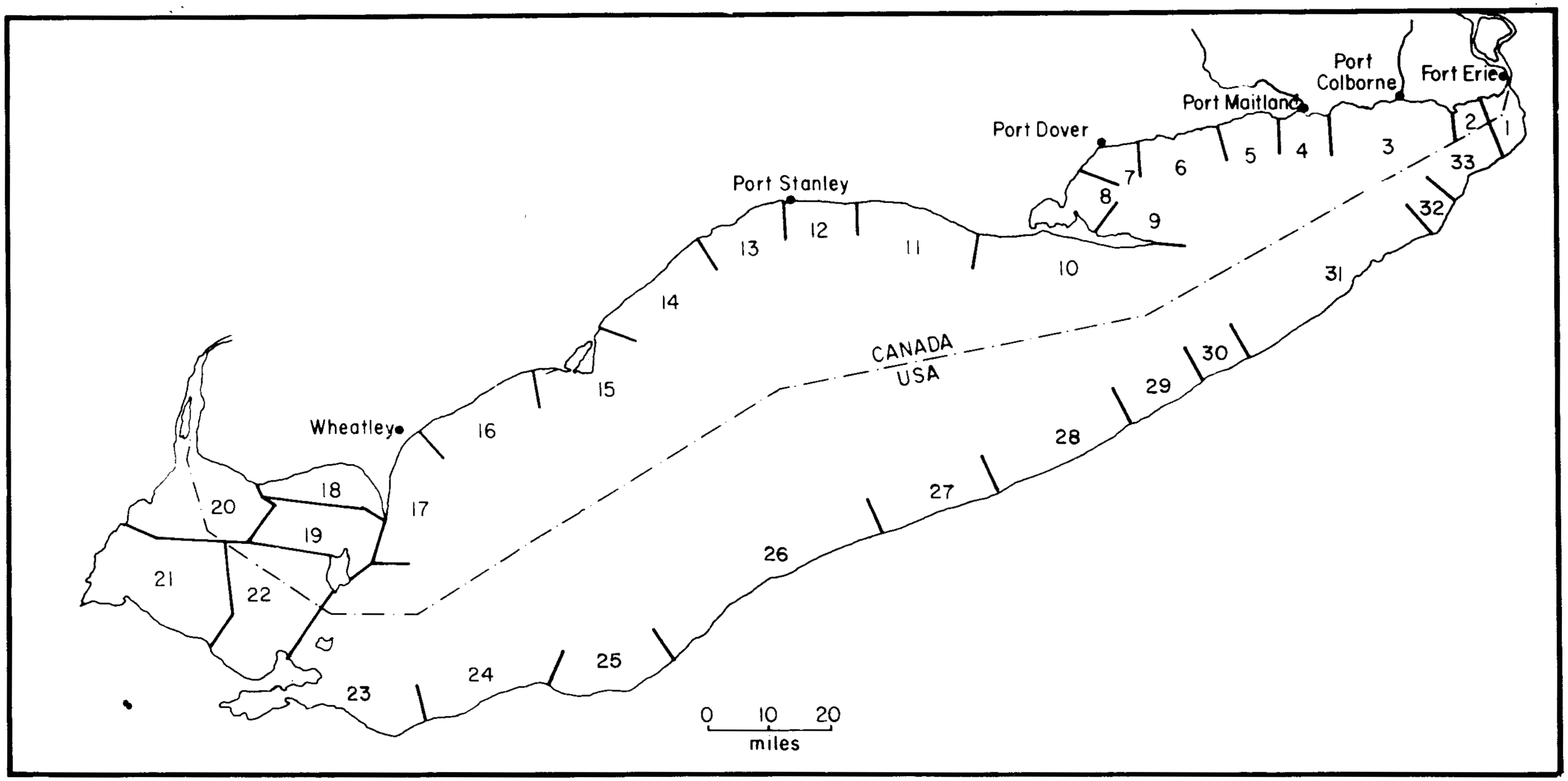
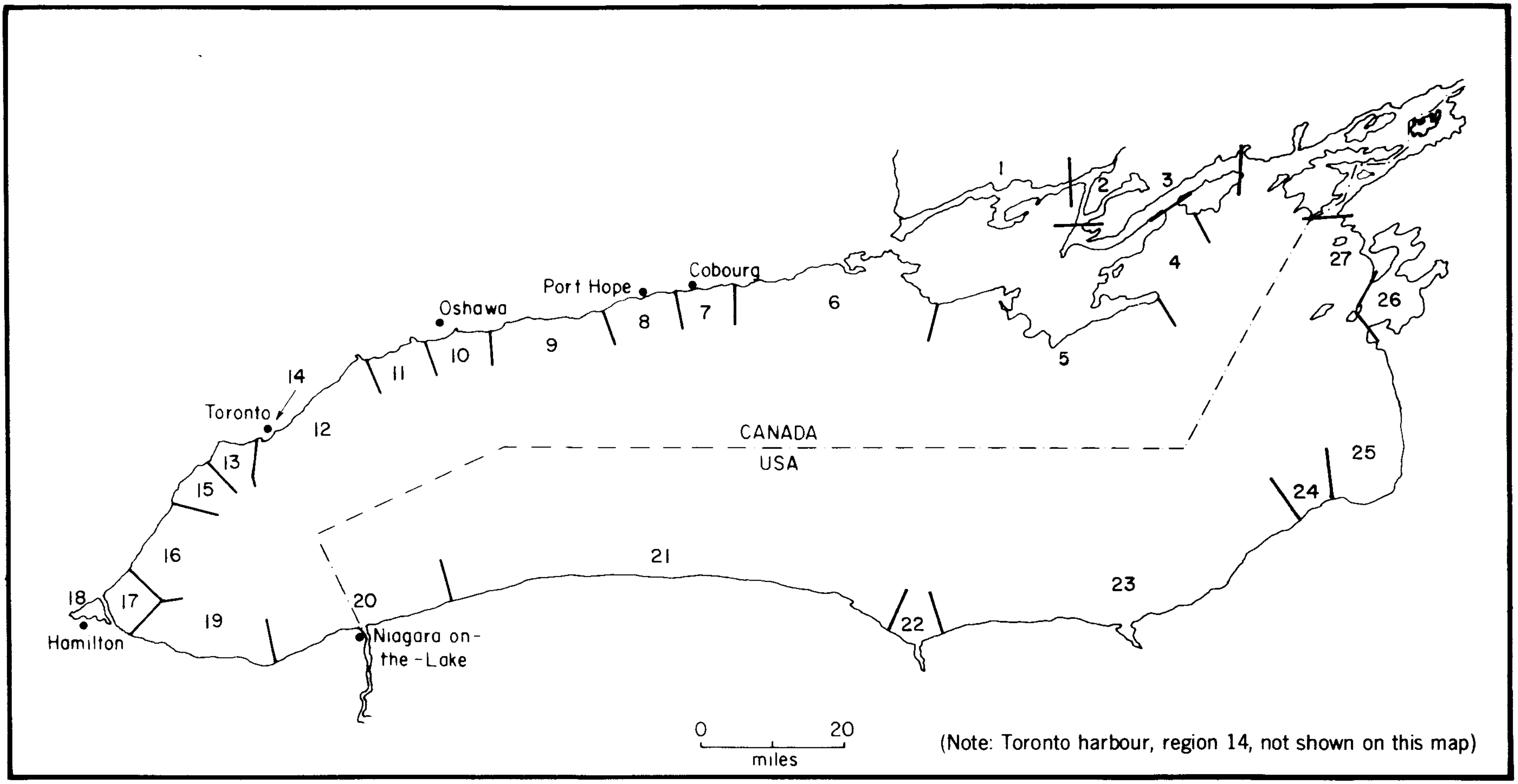


FIGURE 1d: LAKE ERIE NEARSHORE REGIONS



(Note: Toronto harbour, region 14, not shown on this map)

FIGURE 1e: LAKE ONTAIO NEARSHORE REGIONS configurations, although other specific considerations occasionally affected this delineation. The Canadian nearshore zone reflects the local bathymetry, generally extending offshore several kilometers to a depth of 20 to 30 metres.

The resulting Great Lakes nearshore regions are presented in Figure 1.

NEARSHORE DATA SETS

Canada

The Canadian nearshore data are a part of the Ontario Ministry of the Environment's (MOE) Nearshore Water Quality Data File. Details of this data file and the file partitioning employed herein were discussed by Gregor (1977) and Gregor and Ongley (1978). Data file partitioning was necessary to provide:

(i) data subsets containing large numbers of data, with the intent of enhancing statistical confidence;
(ii) an aggregation of data for the purpose of smoothing the effects of variable limnologic processes affecting water quality within the nearshore zone; and
(iii) a separation of periods during which sampling and analytical (laboratory) procedures varied.

On this basis, the data file was partitioned into three discrete periods (time frames) from 1967 to 1973. Each time frame was further differentiated into three limnological seasons (excluding the winter season) and, where appropriate, into surface ($\leq$ 2m sample depth) and subsurface (> 2m sample depth) data sets. This report incorporates only the summer surface data for 1972 and 1973 (time frame 3) for Lakes Ontario, Erie and Superior (including the Bay of Quinte and Toronto and Hamilton Harbours in Lake Ontario, and Thunder Bay in Lake Superior), and the summer surface data for 1970 and 1971 (time frame 2) for Lake Huron, including Georgian Bay and North Channel. A general paucity of data for Lake Huron, Georgian Bay and North Channel for the years 1972 and 1973 precluded the use of identical years among all water bodies. This was not considered a major limitation, however, since average nearshore conditions in these water bodies were not believed to have changed appreciably during the period from 1967 to 1971.

Thus, a single value represents mean surface water quality for each parameter within each nearshore region for a specified season and time frame, assuming this type of data aggregation represents an average condition resulting from the combined effects of the nutrient loading and process variables acting on the nearshore region, as discussed by Gregor (1977) and Gregor and Ongley (1978). The representative values for Secchi depth, chlorophyll a and total phosphorus are summarized in Table 1.

United States

The U.S. data were not as extensive as the Canadian data. Data were taken from several sources, but principally from the Upper Lakes Reference Group (IJC, 1976), the IJC report on the Lower Great Lakes (IJC, 1969) and Argonne National Laboratory (Torrey, 1976; Tarapchek and Stoermer, 1976). The data were collected by different organizations and represented the period principally from 1965 to the early 1970's for the Lower Great Lakes (Erie and Ontario) and the early to mid-1970's for Lakes Superior and Huron. The Lake Michigan data generally span the period from about the mid-1960's to the early 1970's. It was necessary to assume that the U.S. data were essentially comparable to the Canadian data for the time period indicated above, since the U.S. data were not as consistent and complete.

Total phosphorus data were available for virtually all U.S. regions. Chlorophyll a and Secchi depth data were not as readily available. The U.S. nearshore data are also summarized in Table 1.

DEVELOPMENT OF TROPHIC INDEX

As indicated above, the Canadian nearshore data base was more extensive and systematic than that available for the U.S. nearshore zone. For this reason, the parametric relationships developed in this report were derived from the Canadian data base. The U.S. nearshore data sets were then compared to the relationships derived from Canadian data to determine if the Canadian relationships were appropriate for U.S. nearshore waters.

TABLE 1

SUMMARY QUALITY DATA FOR
THE GREAT LAKES NEARSHORE WATERS

Water Body	Region	Group	SD (m)	Chla (μg/L)	TP (μg/L)	CTI**
Lake Ontario	1	A	0.8	19.7	73	29.6
	2	A	0.8	19.8	87	31.2
	3	A	1.9	9.7	31	12.3
	4	A	2.2	6.8	33	10.3
	5	-	-	-	-	INSF
	6	C	1.5	3.1	17	5.1
	7	A	2.6	2.8	17	5.7
	8	A	2.9	2.4	14	4.8
	9	A	2.8	2.4	14	4.9
	10	A	2.7	2.4	17	5.4
	11	A	2.8	2.8	15	5.2
	12	A	2.9	3.0	23	6.1
	13	A	2.5	5.4	34	9.0
	14	A	1.4	9.9	44	15.5
	15	A	3.1	4.7	29	7.5
	16	A	3.3	3.7	22	5.9
	17	A	2.9	5.4	29	7.9
	18	A	0.7	19.3	85	31.3
	19	A	2.5	6.0	23	8.3
	20	A	1.7	6.1	29	10.7
	21	-	-	-	17-20	-
	22	-	-	-	25-40	-
	23	-	-	-	17-20	-
	24	-	-	-	20-30	-
	25	-	-	-	17-20	-
	26	-	-	-	20-23	-
	27	-	-	-	17-20	-

TABLE 1 (cont'd)

SUMMARY QUALITY DATA FOR THE GREAT LAKES NEARSHORE WATERS

Water Body	Region	Group	SD (m)	Chla (µg/L)	TP (µg/L)	CTI**
Lake Erie	1	A	3.7	2.3	18	4.5
	2	A	3.6	2.4	23	5.1
	3	A	4.0	2.6	19	4.5
	4	A	3.0	3.7	34	7.5
	5	A	3.5	2.2	17	4.5
	6	A	4.0	2.0	20	4.3
	7	A	3.9	1.9	21	4.4
	8	C	2.9	1.7	15	3.2
	9	C	2.7	1.7	17	3.6
	10	C	2.3	2.3	21	4.5
	11	C	1.6	2.2	19	4.7
	12	C	1.6	3.3	28	6.3
	13	C	1.1	3.6	24	6.9
	14	A	2.6	3.4	19	6.2
	15	A	2.8	3.9	20	6.3
	16	A	2.9	4.8	19	6.6
	17	A	2.0	5.6	32	9.9
	18	A	1.4	10.3	48	16.2
	19	A	1.8	7.2	42	12.3
	20	C	1.4	2.8	34	6.8
	21	-	-	-	-	-
	22	A	2.0	7.5	42	11.9
	23	-	-	-	60	-
	24	-	-	-	30	-
	25	-	-	-	40-100	-
	26	-	-	-	30	-
	27	-	-	-	INSF	-
	28	-	-	-	INSF	-
	29	-	-	-	INSF	-
	30	-	-	-	INSF	-
	31	-	-	-	INSF	-
	32	-	-	-	INSF	-
	33	-	-	-	23	-

TABLE 1 (cont'd)

SUMMARY QUALITY DATA FOR
THE GREAT LAKES NEARSHORE WATERS

Water Body	Region	Group	SD (m)	Chla (µg/L)	TP (µg/L)	CTI**
Lake Huron	1	C	4.4	.5	10	1.8
	2	B	7.1	.8	8	1.8
	3	B	5.4	1.3	9	2.4
	4	B	4.3	1.3	13	3.0
	5	B	6.2	.8	8	1.8
	6	B	7.9	.5	8	1.5
	7	B	9.8	.4	9	1.5
	8	B	10.8	.4	9	1.4
	9	B	10.2	.6	10	1.6
	10	B	8.9	.6	9	1.6
	11	B	9.5	.5	7	1.3
	12	A	3.6	2.6	19	4.8
	13	B	8.8	.7	8	1.6
	14	B	6.4	1.3	12	2.5
	15	B	8.7	.7	11	1.9
	16	B	7.6	1.0	8	1.8
	17	-	-	-	-	INSF
	18	-	-	-	-	INSF
	19	B	5.2	1.1	7	2.1
	20	-	-	-	-	INSF
	21*	B	6.9	1.9	5	2.1
	22*	B	5.0	3.7	7	3.5
	23*	-	-	3.0	9	-
	24*	-	-	8.0	13	-
	25*	-	-	16.0	26	-
	26*	-	-	25.0	37	-
	27*	-	-	29.0	58	-
	28*	B	5.0	3.7	7	3.5

TABLE 1 (cont'd)

SUMMARY QUALITY DATA FOR THE GREAT LAKES NEARSHORE WATERS

Water Body	Region	Group	SD (m)	Chla (µg/L)	TP (µg/L)	CTI**
Lake Michigan	1	-	-	-	<3	-
	2	-	-	-	<3	-
	3	-	-	-	<3	-
	4	-	-	-	-	-
	5	-	-	-	-	-
	6	-	-	-	-	-
	7	-	-	-	-	-
	8	-	-	-	-	-
	9	-	-	-	INSF	-
	10	-	-	-	3-11	-
	11	-	-	-	8-15	-
	12	-	-	-	40-100	-
	13	-	-	-	9-14	-
	14	-	-	-	10	-
	15	-	-	-	30-240	-
	16	-	-	-	8	-
	17	-	-	-	8	-
	18	-	-	-	11	-
	19	-	-	-	8	-
	20	-	-	-	7-10	-
	21	-	-	-	7-10	-
	22	-	-	-	7-11	-
	23	-	-	-	6-11	-
	24	-	-	-	5	-
	25	-	-	-	10	-
	26	-	-	-	5-10	-

TABLE 1 (cont'd)

SUMMARY QUALITY DATA FOR THE GREAT LAKES NEARSHORE WATERS

Water Body	Region	Group	SD (m)	Chla (µg/L)	TP (µg/L)	CTI**
Lake Superior	1	B	9.3	0.5	6	1.2
	2	B	11.0	0.5	5	1.0
	3	B	10.7	0.6	3	0.9
	4	B	10.7	0.8	6	1.3
	5	B	7.9	0.8	10	1.9
	6	B	4.8	1.2	13	2.8
	7	B	8.2	0.9	8	1.7
	8	C	2.3	1.5	13	3.2
	9	C	3.0	1.6	22	3.9
	10	-	-	-	-	INSF
	11(MINN)*	B	9.4	0.7	20	2.8
	(CCIW)*	-	-	-	7	-
	12(MINN)*	B	9.4	0.7	20	2.8
	(CCIW)*	-	-	-	7	-
	13(MINN)*	B	5.6	0.9	13	2.5
	(CCIW)*	-	-	-	8	-
	14(MINN)*	C	2.8	2.5	10	3.6
	(WISC)*	C	1.5	3.3	26	6.1
	(CCIW)*	-	-	-	13	-
	15(MINN)*	C	2.8	2.5	10	3.6
	(WISC)*	C	1.5	3.3	26	6.1
	(CCIW)*	-	-	-	13	-
	16(WISC)*	-	3.1	-	13	-
	(CCIW)*	-	-	-	7	-
	17(WISC)*	-	3.1	-	13	-
	(CCIW)*	-	-	-	7	-
	18*	B	4.4	2.1	7	2.8
	19*	B	4.4	2.1	7	2.8
	20*	B	4.4	2.1	7	2.8
	21*	B	4.3	1.8	5	2.4
	22*	B	8.7	1.2	4	1.4
	23*	B	8.7	1.2	4	1.4
	24*	B	8.7	1.2	4	1.4
	25*	B	10.5	0.6	4	1.0
	26*	B	10.5	0.6	4	1.0

* Denotes annual values (MINN = Minnesota data; WISC = Wisconsin data; CCIW = Canada Centre for Inland Waters data)

** Dash(-) in CTI column indicates trophic status based on TP value alone; boundary concentrations are presented in Table 2 (see text for further explanation).

INSF = insufficient data available

The general relationship between Chl$\underline{a}$ and SD was developed in Equation 3 above. It is noted that no attempt is made here to define the individual components of the extinction coefficient (i.e., n'_s, n_p and n_w). Rather, the cumulative value of these components is represented by the intercept derived in the relationships for Secchi depth reciprocals ($\frac{2.3}{SD}$) and Chl$\underline{a}$.

The Canadian nearshore geographic regions cluster into the three groups illustrated in Figures 2 and 3. Group A (Fig. 2) is characterized by high Chl$\underline{a}$ concentrations and low Secchi depths (high Secchi reciprocals) and includes the Bay of Quinte, most of Lake Ontario (including Toronto and Hamilton Harbours), most of Lake Erie and the Penetanguishene-Midland embayment area of Georgian Bay (region 12 of Lake Huron). Group B (Fig. 3) is characterized by low Chl$\underline{a}$ concentrations and relatively high Secchi depths (low Secchi reciprocals) and basically includes all regions of Lake Huron (except regions 1 and 12), and Lake Superior (except regions 8 and 9). Group C (Fig. 3) represents the regions characterized by relatively high inorganic turbidity (attributable largely to shoreline erosion), combined with intermediate (relative to groups A and B) Chl$\underline{a}$ concentrations.

The relationships between Secchi reciprocal ($\frac{2.3}{SD}$) and Chl$\underline{a}$ for groups A, B and C are as follows (note: in these and subsequent equations, the units for SD are meters (m), while Chl$\underline{a}$ and TP are expressed as µg/L):

<u>Group A:</u> Lower Lakes (except as indicated in Table 1), plus region 12 of Georgian Bay (Lake Huron):

$$\frac{2.3}{SD} = 0.310 + 0.134\ \mathrm{Chl}\underline{a} \qquad (r^2 = 0.95) \qquad (4)$$

<u>Group B:</u> Upper Lakes (except as indicated in Table 1):

$$\frac{2.3}{SD} = 0.091 + 0.273\ \mathrm{Chl}\underline{a} \qquad (r^2 = 0.76) \qquad (5)$$

<u>Group C:</u> Highly turbid regions (as indicated in Table 1):

$$\frac{2.3}{SD} = 0.119 + 0.486\ \mathrm{Chl}\underline{a} \qquad (r^2 = 0.84) \qquad (6)$$

FIGURE 2: $\frac{2.3}{SD}$ AND CHLOROPHYLL a RELATIONSHIP FOR GROUP A OF THE GREAT LAKES NEARSHORE REGIONS.

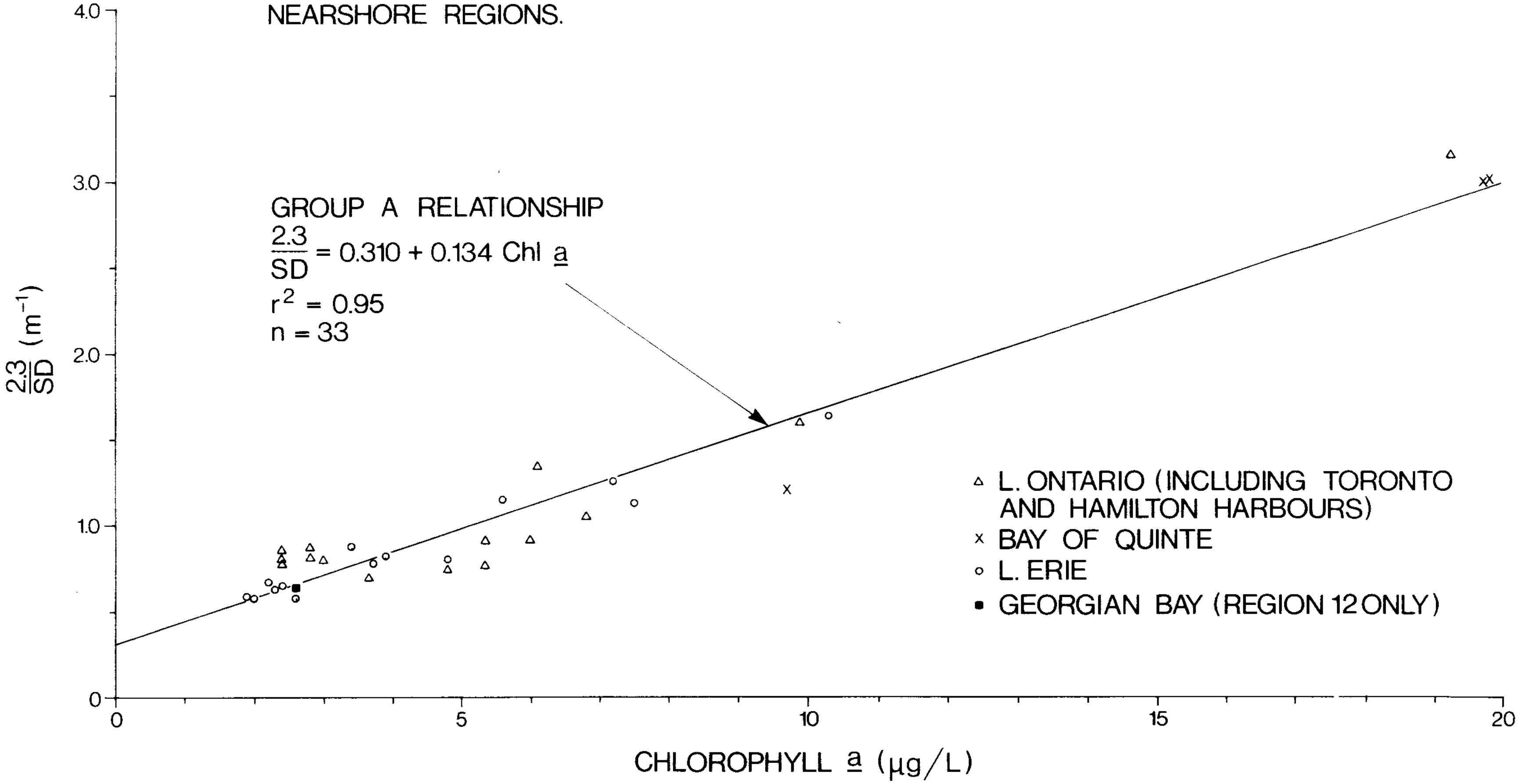
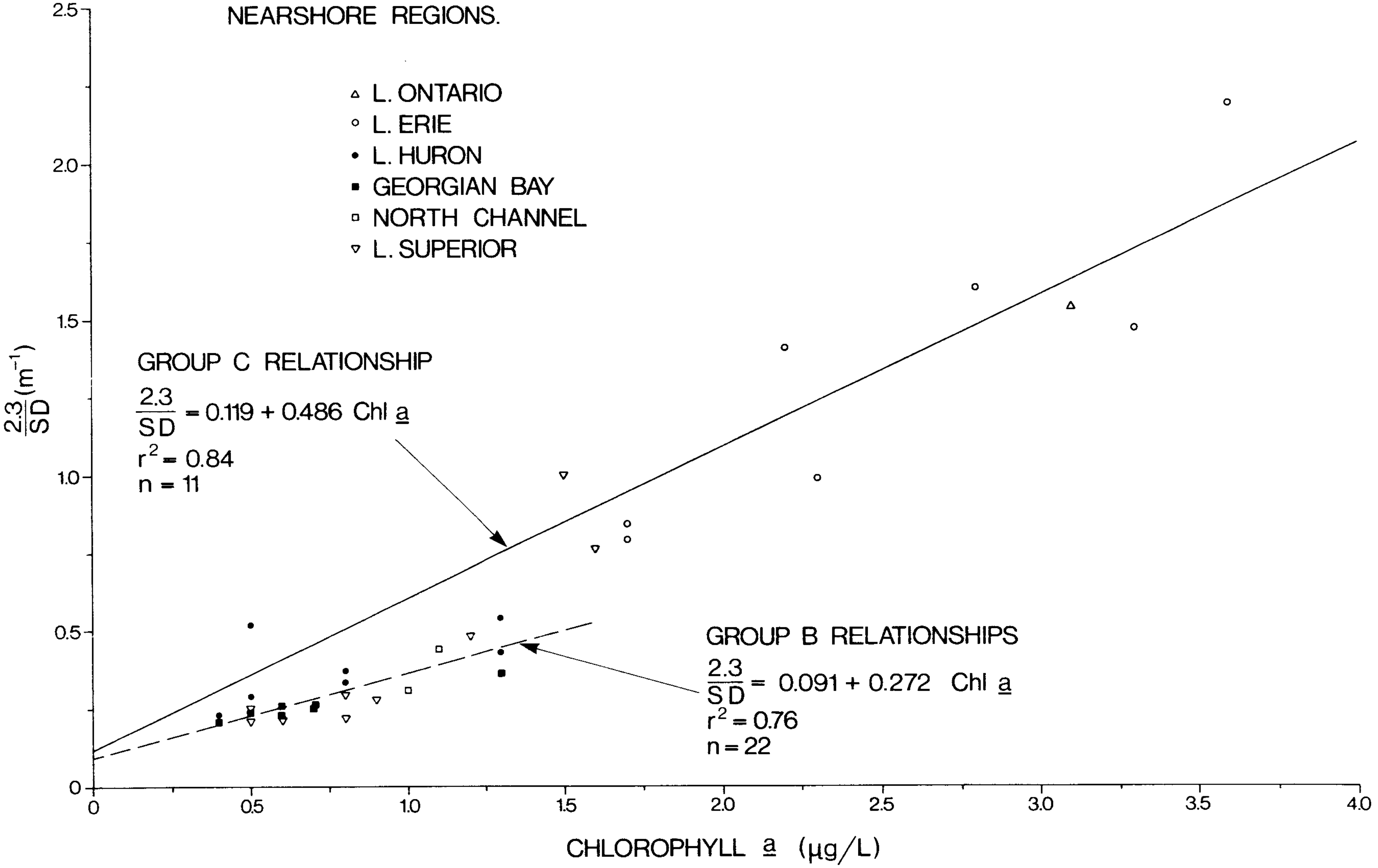


FIGURE 3: $\frac{2.3}{SD}$ AND CHLOROPHYLL a RELATIONSHIPS FOR GROUPS B AND C OF THE GREAT LAKES NEARSHORE REGIONS.



In Equations 4, 5, and 6, the value of the intercept represents the extinction of light due to the presence of suspended inorganic particles (n'_s) and dissolved pigments (n_p) in the water column, as well as that due to the water alone (n_w).

Since the Secchi depths, rather than the Secchi reciprocals, will be used in determination of the trophic index, Equations 4, 5, and 6 can be rearranged as follows:

$$SD_A = \frac{2.3}{0.310 + 0.134\ \mathrm{Chl}\underline{a}} \qquad (7)$$

$$SD_B = \frac{2.3}{0.091 + 0.273\ \mathrm{Chl}\underline{a}} \qquad (8)$$

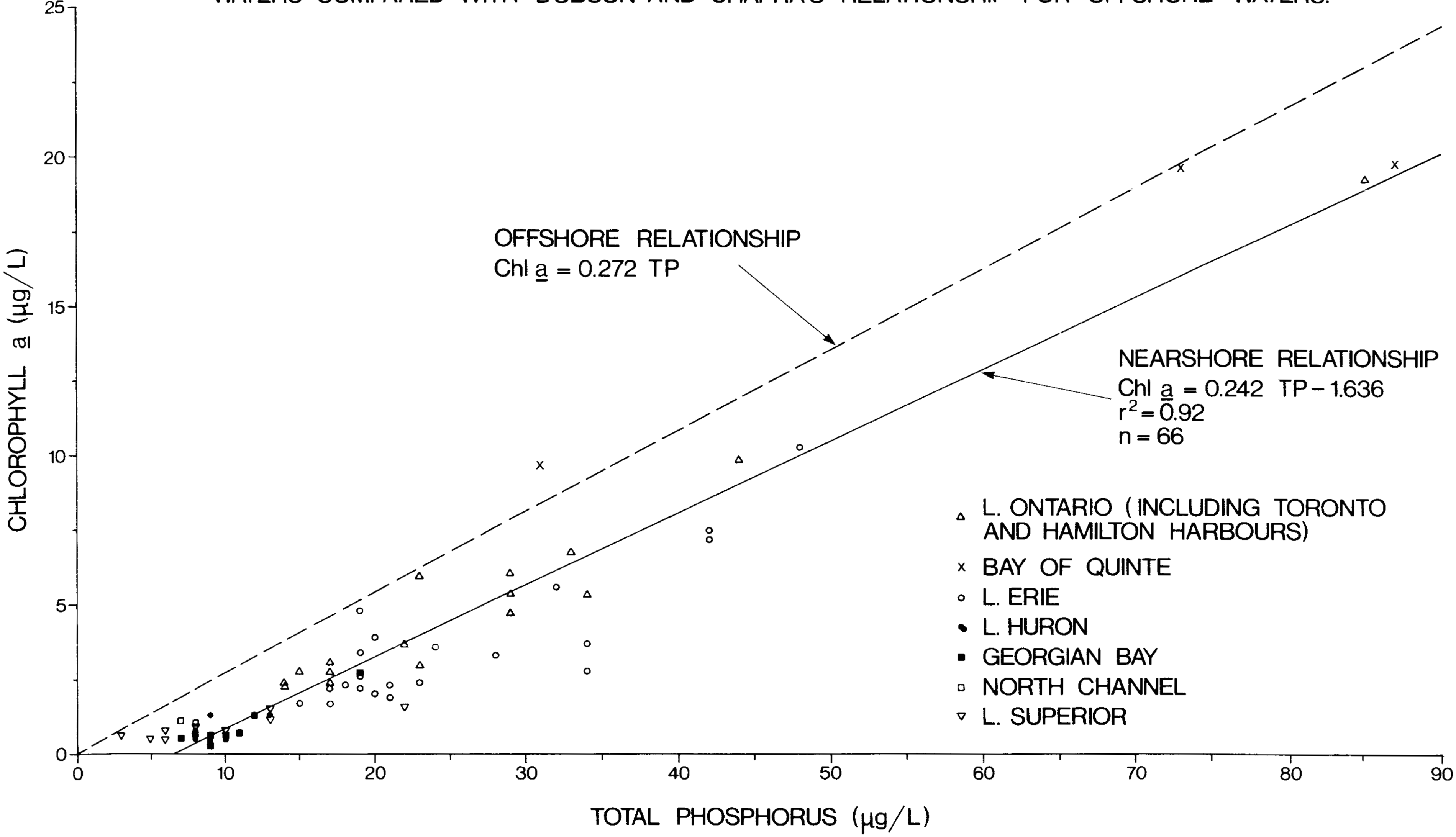
$$SD_C = \frac{2.3}{0.119 + 0.486\ \mathrm{Chl}\underline{a}} \qquad (9)$$

In contrast to the three groups above, a single significant relationship between Chl_a_ and TP was found in all the nearshore regions (Fig. 4) as follows:

$$\mathrm{Chl}\underline{a} = (0.242\ \mathrm{TP}) - 1.636 \qquad (r^2 = 0.92) \quad (10)$$

Having derived relationships between these three water quality parameters, the next step in the development of the trophic index is to determine trophic state boundary conditions based on these parameters. Dobson and Chapra (1977) set trophic boundaries based on specific Secchi depths, and then derived corresponding boundary values for the other two parameters on the basis of their parametric relationships for open waters. This same general approach is used here. However, the open water Secchi depth values chosen by Dobson and Chapra could not be used to establish initial trophic boundaries for nearshore waters because of the higher turbidity exhibited by these waters. Of the three water quality parameters, Chl_a_ is the one for which trophic boundary

FIGURE 4: CHLOROPHYLL $\underline{a}$ AND TOTAL PHOSPHORUS RELATIONSHIP FOR GREAT LAKES NEARSHORE WATERS COMPARED WITH DOBSON AND CHAPRA'S RELATIONSHIP FOR OFFSHORE WATERS.



conditions between offshore and nearshore waters are likely to be most comparable. A survey of the literature indicated considerable similarity among the trophic boundaries established for Chl$\underline{a}$. Concentrations of 2 µg/L and 6 µg/L, as established by Rast (1978; Rast and Lee, 1978), were finally chosen as boundaries between oligotrophic-mesotrophic and mesotrophic-eutrophic conditions, respectively. Substituting these values into Equations 7 through 10 establishes corresponding trophic state boundaries for SD and TP (Table 2). It is noted in Table 2 that only the Secchi depth values vary among the groups identified in this study.

In order to compare the trophic boundaries for all three parameters on a common scale, a Trophic Index (TI) was established. For simplicity, the upper mesotrophic boundary for each parameter was arbitrarily selected to be 10 TI units, following the method of Dobson and Chapra (1977). For Chl$\underline{a}$, this 'standardization' was accomplished by multiplying the Chl$\underline{a}$ concentrations by a factor which, when Chl$\underline{a}$ equalled 6 µg/L, gave a value of 10 TI units (Equation 11). Since the relationship between Chl$\underline{a}$ and TP used to determine the TP concentration corresponding to 6 µg/L of Chl$\underline{a}$ is linear, the TP concentrations were also multiplied by an appropriate factor (Equation 12). Therefore, based on the upper mesotrophic boundary values presented in Table 2, the following TI expressions for Chl$\underline{a}$ and TP were obtained:

$$TI_{Chl\underline{a}} = \frac{10}{6} = 1.67\ Chl\underline{a} \qquad (11)$$

$$TI_{TP} = \frac{10}{32} = 0.31\ TP \qquad (12)$$

However, on the basis of the discussion presented earlier concerning Secchi depth (Equations 1 to 3), it was necessary to transform and linearize Secchi depth such that $\frac{2.3}{SD}$ was proportional to Chl$\underline{a}$ plus an estimate of the sum of the extinction coefficient components, n'_s, n_p and n_w (the reader is reminded that transformation is necessary because Secchi depth is inversely proportional to Chl$\underline{a}$, while linearization is necessary because the relationship between these two parameters is hyperbolic. Therefore, rather than the unaltered Secchi depth, the transformed and linearized Secchi depth was the

TABLE 2

TROPHIC STATE BOUNDARY CONDITIONS FOR CHLOROPHYLL *a*, TOTAL PHOSPHORUS AND SECCHI DEPTH FOR GREAT LAKES NEARSHORE REGIONS

	Trophic State Boundary Conditions		
	Group A	Group B	Group C
Chlorophyll*a* (µg/L)			
upper mesotrophic	6	6	6
lower mesotrophic	2	2	2
Total Phosphorus (µg/L)			
upper mesotrophic	32	32	32
lower mesotrophic	15	15	15
Secchi Depth (m)			
upper mesotrophic	2.1	1.3	0.8
lower mesotrophic	4.0	3.6	2.1

parameter to be standardized. Equations 4, 5 and 6 can, therefore, be rewritten as:

$$SD'_A = (\frac{2.3}{SD} - 0.310) = 0.134 \ Chl\underline{a} \qquad (13)$$

$$SD'_B = (\frac{2.3}{SD} - 0.091) = 0.273 \ Chl\underline{a} \qquad (14)$$

$$SD'_C = (\frac{2.3}{SD} - 0.119) = 0.486 \ Chl\underline{a} \qquad (15)$$

where SD' is the transformed and linearized SD proportional to Chl$\underline{a}$ and equivalent to the extinction of light due to n'_s, n_p and n_w. SD'_A, SD'_B and SD'_C were then standardized to provide the TI expressions as follows:

$$TI_{SD_A} = (\frac{\frac{2.3}{2.1} - 0.310}{10}) \ (\frac{2.3}{SD} - 0.310) = \frac{28.52}{SD} - 3.84 \qquad (16)$$

$$TI_{SD_B} = (\frac{\frac{2.3}{1.3} - 0.091}{10}) \ (\frac{2.3}{SD} - 0.091) = \frac{14.04}{SD} - 0.556 \qquad (17)$$

$$TI_{SD_C} = (\frac{\frac{2.3}{0.8} - 0.119}{10}) \ (\frac{2.3}{SD} - 0.119) = \frac{7.91}{SD} - 0.409 \qquad (18)$$

Having established a TI for each parameter above (and noting that there are three TI values for SD, depending on whether the SD-Chl$\underline{a}$ relationship was derived from nearshore Group A, B or C), a Composite Trophic Index (CTI) based on TP, Chl$\underline{a}$ and SD can now be derived. Derivation of a CTI allows an "averaging" of the data values, thereby smoothing out the effects of atypical relationships in specific nearshore regions. Since three boundary conditions are necessary to define the three groups of nearshore regions having different SD and Chl$\underline{a}$ relationships, it is necessary to define three Composite Trophic Indices for the nearshore zone. The CTI is simply an averaging of the TI of the three parameters for each of these three groups, as follows:

$$CTI_A = \frac{(\frac{28.52}{SD} - 3.84) + (1.67\ Chl\underline{a}) + (0.31\ TP)}{3} \qquad (19)$$

$$CTI_B = \frac{(\frac{14.04}{SD} - 0.556) + (1.67\ Chl\underline{a}) + (0.31\ TP)}{3} \qquad (20)$$

$$CTI_C = \frac{(\frac{7.91}{SD} - 0.409) + (1.67\ Chl\underline{a}) + (0.31\ TP)}{3} \qquad (21)$$

In this manner, the upper mesotrophic boundary for each of the nearshore regions is also established as 10.0 CTI units. Similarly, the lower mesotrophic boundary, corresponding to 2.0 µg/L of Chl$\underline{a}$ (Table 2), was determined to be 3.8 CTI units.

RESULTS

The CTI for each nearshore region was subsequently determined using the appropriate expression (i.e., Equations 19-21). The data and resultant CTI are included in Table 1.

It is noted that it is unrealistic to assume that trophic state boundaries in nearshore waters of the Great Lakes are as clearly defined as suggested by a single CTI value. Consequently, five trophic states were established (Table 3) such that transitional trophic states exist between the oligotrophic, mesotrophic and eutrophic conditions. The range of CTI units for these two transitional trophic states were also arbitrarily selected to provide an approximately equal range of CTI units about the pre-established upper and lower mesotrophic boundaries. Thus, as indicated in Table 3, eutrophic conditions are indicated by a CTI of more than 11.0 units, mesotrophic conditions range from 4.6 to 8.9 CTI units and oligotrophic conditions are indicated by a CTI of less than 3.0. On the basis of the classification scheme detailed in Table 3, the trophic conditions of the Canadian Great Lakes nearshore waters, for the years identified, have been mapped in Figure 5.

TABLE 3

TROPHIC STATE AND ASSOCIATED COMPOSITE TROPHIC INDEX (CTI) VALUES

Trophic State (Water Quality)	CTI
Eutrophic (poor)	≥11.0
Eutrophic/mesotrophic	9.0 - 11.0
Mesotrophic (fair)	4.6 - 8.9
Oligotrophic/mesotrophic	3.1 - 4.5
Oligotrophic (good)	≥ 3.1

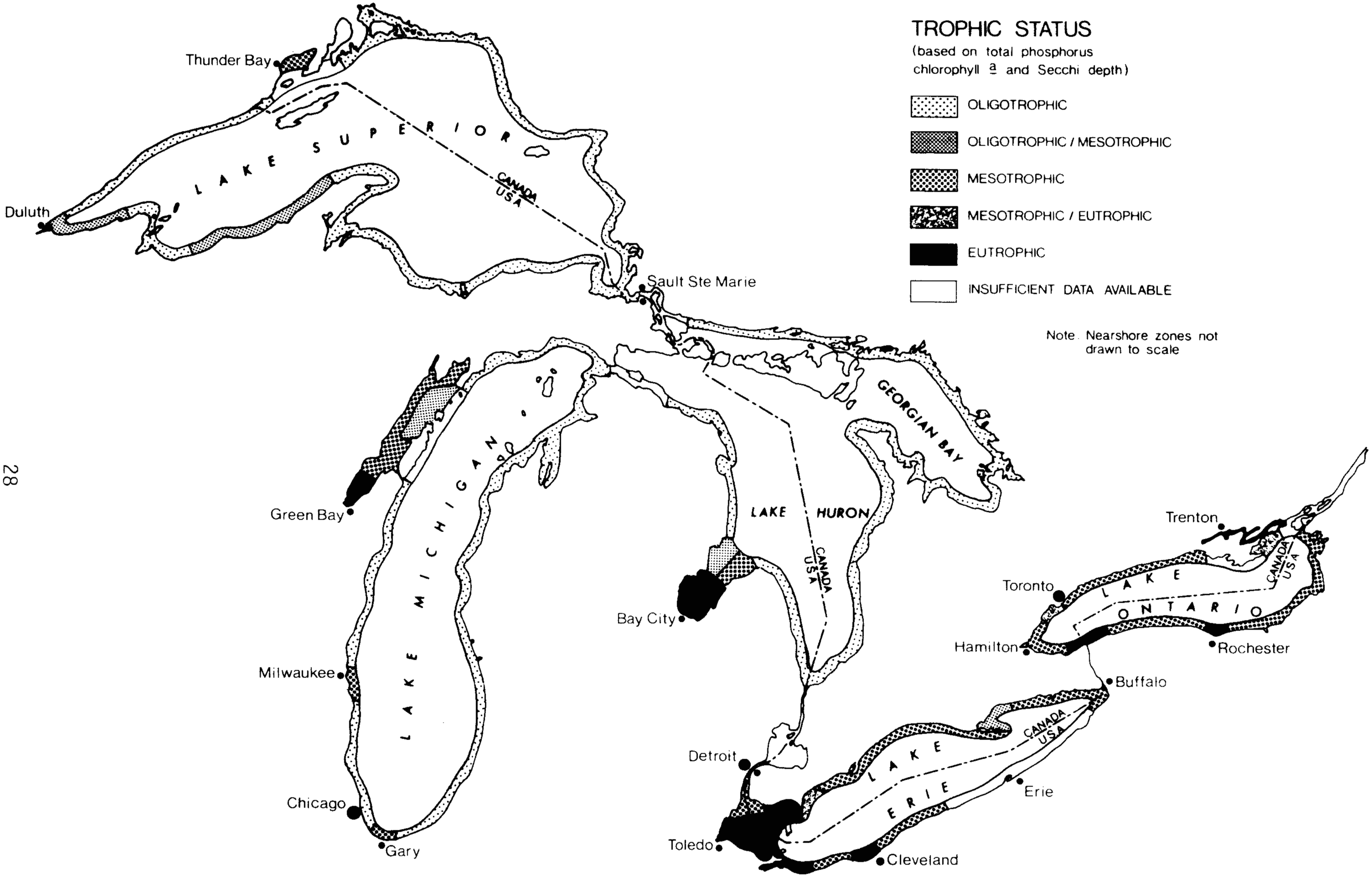


FIGURE 5: NEARSHORE TROPHIC CONDITION OF THE GREAT LAKES

As noted earlier, the U.S. nearshore data were neither as consistent nor complete as the Canadian nearshore data (Table 1). Only total phosphorus data were available for all U.S. nearshore regions. Consequently, for those zones lacking Chl*a* and SD data, the TP concentrations alone were used to delineate the trophic status. This method has been used previously by Dobson (1974) and the Research Advisory Board (IJC, 1978a) to delineate the trophic status of the open waters of the Great Lakes. This approach to delineate trophic state assumes that nearshore TP concentrations adequately define trophic conditions for most nearshore regions.

To illustrate the general adequacy of this assumption, a comparison was made of the trophic status of selected U.S. and Canadian nearshore regions as determined by chlorophyll *a*, Secchi depth and total phosphorus versus that based on total phosphorus alone (Table 4). Examination of Table 4 shows that, although there are a few exceptions, TP alone provides a reasonable delineation of trophic status, compared to that indicated by the Composite Trophic Index. Consequently, although not completely satisfactory, TP concentration alone was used to delineate the trophic status where data for the other parameters were lacking. However, other available data were also used to corroborate the trophic status determined solely on the basis of TP, including locations of point source inputs and data concerning currents and microbiology. As noted in Table 2, the trophic boundary conditions in the Great Lakes nearshore zone are delineated by TP concentrations of 15 µg/L (oligotrophic/mesotrophic boundary) and 32 µg/L (eutrophic/mesotrophic boundary).

DISCUSSIONS AND CONCLUSIONS

Delineation of the basin-wide trophic status of the Great Lakes nearshore waters is difficult because of the need to evaluate a complex system having a relatively limited data base. However, the results of this type of analysis are encouraging and suggest this approach has the potential to provide useful and meaningful results.

TABLE 4

COMPARISON OF TROPHIC STATUS OF U.S. GREAT LAKES NEARSHORE ZONE AS DETERMINED BY CTI AND TP

Lake	Region	Trophic Status Based On CTI**	Trophic Status Based On TP***
Ontario	20	E/M	E
	1	0/M	M
Erie	20	M	E
	22	E	E
Huron	1	0/M	0
	21*	0	0
	22*	0/M	0
	28*	0/M	0
Superior	11(MINN)*	0	0
	13(MINN)*	0	0
	14(MINN)*	0/M	0
	14(WISC)*	0/M	M
	15(MINN)*	0/M	0
	15(WISC)*	0/M	0
	18*	0	0
	19*	0	0
	20*	0	0
	21*	0	0
	22*	0	0
	23*	0	0
	24*	0	0
	25*	0	0

* denotes annual value; data sources indicated in Table 1
** boundary conditions presented in Table 3
***boundary conditions presented in Table 2.

There are obvious limitations within the Canadian nearshore data file (Gregor, 1977; Gregor and Ongley, 1978) and additional restrictions with the U.S. nearshore data. It is interesting that three distinct Canadian data groups are discerned on the basis of the $\frac{2.3}{SD}$ and Chl<u>a</u> relationships (Figures 2 and 3). Indeed, given the dynamics and variability of the nearshore zones of the Great Lakes, it is encouraging that only three groupings are evident and that these can be explained on the basis of known conditions with the nearshore waters. For example, Group A (Figure 2), which includes 32 regions of Lakes Ontario and Erie, as well as region 12 of Georgian Bay, appears to be strongly influenced by both inorganic and organic turbidity. Conversely, the majority of the regions of the Upper Lakes (Group B) demonstrate overall low turbidity. Transformed Secchi depths and Chl<u>a</u> concentrations for Group B are essentially an order of magnitude lower than those noted for Group A. Group C, on the other hand, exhibits a high level of inorganic turbidity, even though possessing Chl<u>a</u> concentrations an order of magnitude below those of Group A. Within Group C, regions 8 and 9 of Lake Superior receive considerable tributary inputs of suspended solids (Ongley, 1974). Region 8 (Black Bay), a shallow, elongated embayment, may also experience resuspension of bottom sediments during wind events. Region 1 of Lake Huron and regions 8 through 13 of Lake Erie experience high shoreline erosion rates and/or longshore transport of eroded bluff material (Gregor, 1977; Gregor and Ongley, 1978; Environment Canada, 1976; St. Jaques and Rukavina, 1973). Region 20 of Lake Erie is directly affected by the highly turbid Detroit River, while region 6 of Lake Ontario is directly affected by its high wave energy environment (located at the eastern end of the lake, which allows considerable fetch for wind wave generation), resulting in bluff erosion and longshore transport of suspended particles as well as erosion of lake-bottom sediments (Rukavina, 1970).

The Chl<u>a</u> and TP relationship for the nearshore waters of the Great Lakes reveal a strong linear relationship which differs from that of the open water (Fig. 3). There is some scatter of the data at very low concentrations of either parameter (primarily for Lake Superior), suggesting that, at least for these waters, some phytoplankton growth occurs at lower phosphorus concentrations than normally required for algal growth in other nearshore regions. It is also noted that considerable scatter about the regression line is evident for most of the regions with TP concentrations less than 35 µg/L. However, there are a sufficient number of regions having higher TP and Chl*a* concentrations to provide reasonable confidence in the regression.

A relationship between Chl*a* and TP has been recognized in limnological studies for some time. An example is the relationship developed by Dillon and Rigler (1974):

$$\ln \mathrm{Chl}\underline{a} = (1.449 \ln \mathrm{TP}_V) - 2.616 \qquad (22)$$

where TP_V is the spring overturn concentration of total phosphorus. The Canadian nearshore data presented in this report can also be expressed nonlinearly in a manner analagous to that of Dillon and Rigler as follows:

$$\ln \mathrm{Chl}\underline{a} = (1.360 \ln \mathrm{TP}) - 3.079 \qquad (23)$$
$$(n = 66, r^2 = 0.86)$$

The relationship expressed in Equation 20 is simply a linear regression of the natural logarithms of the data in Table 1 and is provided here solely for comparison with Equation 21.

Dobson and Chapra (1977) present a linear relationship for Great Lakes offshore waters, using summer surface data, as follows:

$$\mathrm{Chl}\underline{a} = 0.272\ \mathrm{TP} \qquad (24)$$

This relationship (Equation 24) is compared to that determined in this report for the nearshore waters in Figure 4. Although there is considerable parallelism between the nearshore data presented herein and the observations of Dobson and Chapra (1977) and Dillon and Rigler (1974), the nearshore waters have a unique relationship relative to either the Great Lakes' open waters or to inland lakes. This unique relationship indicates that the nearshore waters of the Great Lakes contain a lower chlorophyll concentration for a given total phosphorus concentration than do Great Lakes open waters or inland lakes. Thus, it can be concluded that it is inappropriate to classify Great Lakes nearshore waters using a whole lake trophic index developed for the Great Lakes or smaller inland lakes.

Delineation of the trophic status of the Great Lakes nearshore zone (Figure 5), using the categories defined in Table 3, is intuitively acceptable. The most eutrophic regions occur in areas of relatively restricted circulation and/or high nutrient loadings, including the Bay of Quinte, Toronto and Hamilton Harbours, and portions of Lake Erie's Western Basin, as well as the Cleveland region. High loadings also affect the southwest corner of Lake Ontario (regions 17 to 20), as well as the Toronto and Rochester areas. Surprisingly good water quality (oligotrophic-mesotrophic) is noted for regions 6 through 9 of Lake Erie. This is probably a result of general lake circulation east of Long Point, Ontario. There is a lack of consistent data for the southeast portion of the U.S. Lake Erie nearshore zone. The Upper Lakes are generally characterized by a low trophic status (oligotrophic), with somewhat poorer water quality noted for the Penetanguishene-Midland area (region 12 of Lake Huron), Black and Thunder Bays (regions 8 and 9 of Lake Superior), Saginaw Bay (regions 23 to 27 of Lake Huron), lower Green Bay (region 7 of Lake Michigan), and the Milwaukee, Wisconsin and Gary Indiana areas (regions 12 and 15 of Lake Michigan).

It is also noted that the trophic characterizations of the nearshore regions compare favorably with geographic land areas in the basin described by Johnson *et al*. (1978), which have a high potential for contributing phosphorus and sediment loads to the Great Lakes, based on the soil, land use and hydrologic characteristics of these land areas (Figure 6). The trophic characterizations of the nearshore regions also reflect the proximity of major urban areas to the Great Lakes. Phosphorus sources in urban areas include storm water drainage and municipal wastewater discharges. While no attempt is made here to quantitatively relate land uses, concomitant phosphorus loads and observed nearshore trophic conditions, the qualitative relationships between these components are obvious.

This report does not present a detailed assessment of nearshore trophic state, since the nearshore waters generally exhibit a gradient of improving water quality as one proceeds offshore. This has been illustrated in several recent IJC Great Lakes water quality reports (IJC, 1977; 1978b). However, the rate of dispersion of phosphorus inputs which determine these water quality

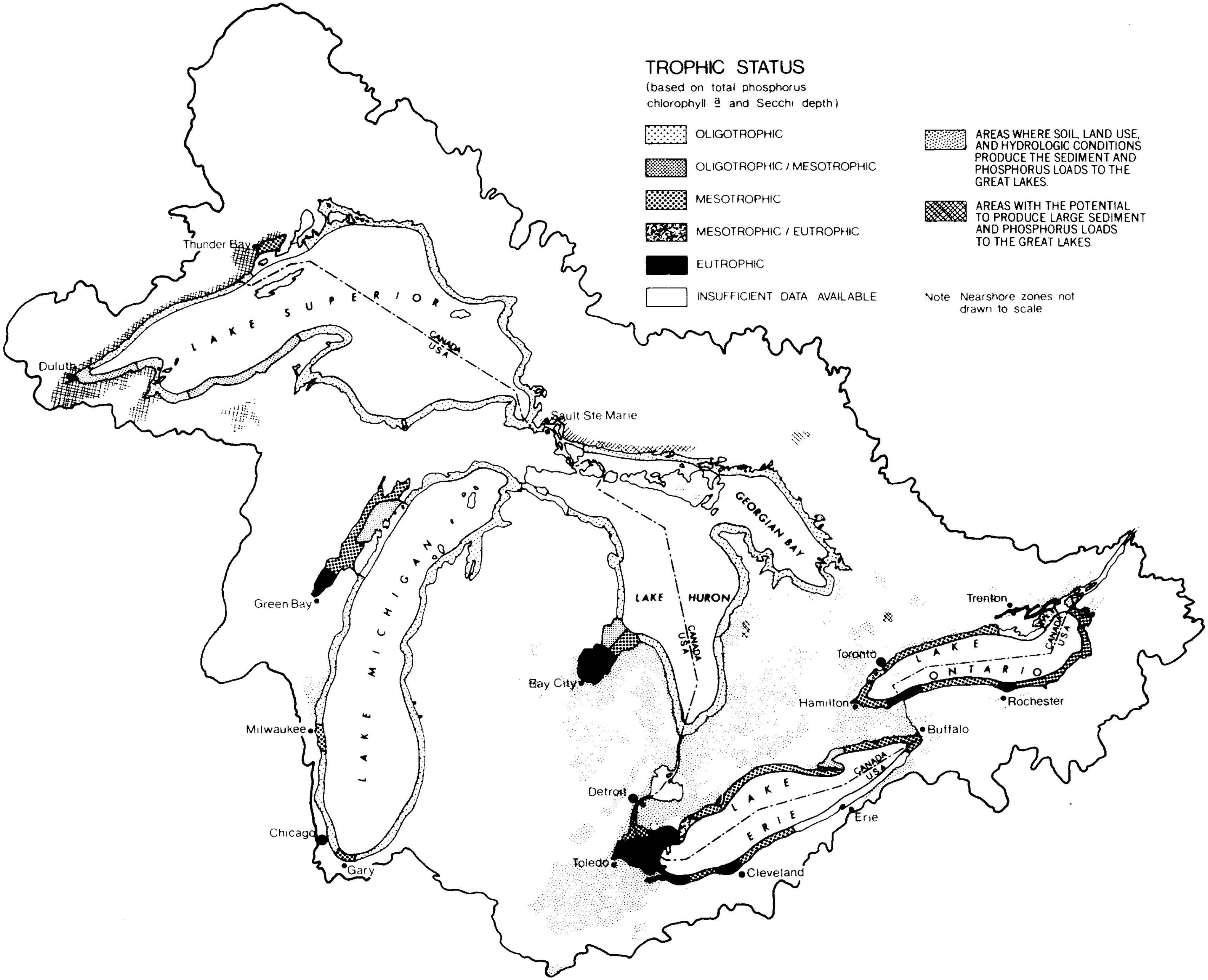


FIGURE 6: PHOSPHORUS CONTRIBUTING AREAS AND NEARSHORE TROPHIC CHARACTERIZATION IN THE GREAT LAKES BASIN

gradients depends upon random processes (e.g., currents, waves) operating in the nearshore zone. Thus, some average or steady state conditions must be determined if the trophic status of the nearshore zone is to be assessed, as was done in this analysis. Further partitioning of the regions used herein could provide more detailed information, but possibly with less statistical confidence. Thus, this approach is considered to be a reasonable compromise in that it uniquely describes nearshore water conditions in commonly accepted terms generally comparable to other water bodies.

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