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PHYSICAL AND CHEMICAL LIMNOLOGY OF FOUR NATURAL LAKES LOCATED WITHIN THE INDIANA DUNES NATIONAL LAKESHORE, NORTHWESTERN INDIANA

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ABSTRACT: Four lakes located in the Indiana Dunes National Lakeshore in northwestern Indiana were evaluated for their physical and chemical limnology. The morphometric characteristics for each lake were measured as were chemical variables, including pH, conductivity and major ions, and nutrients. The study lakes were shallow depressions (z_m = 1.17-3 m; $\bar{z}$ = 0.8-2.51) with steep slopes. Their shallow depths enabled dissolved oxygen to be distributed throughout the entire water column; thus, these lacustrine wetlands never stratify. The pH in these lakes was neutral to slightly alkaline (range = 7.20-10.02), while their conductivity ranged from 40 to 1339 μS/cm. The amount of total dissolved solids ranged from 48.6 to 67.0 mg/L. The oxidation-reduction potential showed a stepwise progression in values ranging from -60 to 475 mv, and more than 90% of the measurements were in an oxidized state. The presence of an oxidized microzone above the sediment interface with the water column prevents metals and nutrients from autochthonous recycling. Total nitrogen levels were similar to those in mesoeutrophic lakes in northeastern and north-central Indiana, while total phosphorus ($\bar{x}$ = 0.121 mg/L) was an order of magnitude higher than in most of the lakes in north-central ($\bar{x}$ = 0.025 mg/L) and northeastern ($\bar{x}$ = 0.052 mg/L) Indiana.

KEYWORDS: Bathymetry, conductivity and major ions, nutrients, pH, trophic status.

INTRODUCTION

Most regional studies of the chemical and physical limnology of glacial lakes have been carried out in Minnesota, Wisconsin, and Michigan (Heiskary, *et al.*,1987; Omernik and Gallant, 1988). Glacial lake limnology along the dunes and nearshore of Lake Michigan has been devoted mainly to the recognition of environmental indicators and the identification of the aquatic biota (Simon, *et al.*,1989; Simon and Moy, 1997; Simon and Stewart, in press). Little attention has been given to the physical and chemical attributes of riverine and depressional wetlands in northwestern Indiana.

The greatest concentration of depressional wetlands in Indiana exists within the Indiana Dunes National Lakeshore (Beaty, *et al.*, 1994). Knowledge of the status and condition of these palustrine and lacustrine wetlands is limited. Many have never been surveyed. The collection of baseline data is necessary for determining patterns in lake trophic status and for analyzing the physical attributes of other natural systems in northwestern Indiana. The morphologic features of these lakes were determined by climatic and edaphic factors that affect the chemical dynamics of the lake, which, in turn, shapes the biota within these ecosystems.

Early investigations of the physical and chemical environment in the natural lakes of Indiana concentrated on the glacial lakes of northeastern Indiana. Classic studies of lake morphometrics in Indiana include the State Geological Survey report on northern lakes (Blatchley and Ashley, 1901), the physical and biological studies of Lake Maxinkuckee (Evermann and Clark, 1920), and numerous lake studies conducted by the Indiana Lakes and Stream Survey (Scott, *et al.,* 1928, 1938; Scott, 1931; Wohlschlag, 1950; Gerking, 1950; Ricker, 1955; Eberly, 1959; Mueller, 1964). The National Eutrophication Survey conducted by the U.S. Environmental Protection Agency in cooperation with the Indiana Department of Environmental Management (formerly a part of the Indiana State Board of Health) during the mid-1970s evaluated 27 lakes in Indiana (numerous individual reports published by U.S. Environmental Protection Agency, 1976). These studies provided data on the chemical and physical characteristics of northern Indiana lakes and discussed their trophic status. The westernmost lake surveyed during that study was Bass Lake in Starke County.

Our objective was to describe the chemical and physical characteristics of four natural palustrine and lacustrine wetlands in northwestern Indiana. While many aspects of their biota can be determined without a knowledge of the physical and chemical characteristics of these lakes, many of the indices of productivity cannot be used without these data. This survey was designed to collect data on the physical and chemical characteristics of four typical palustrine and lacustrine depressional wetlands in the Indiana Dunes National Lakeshore. In addition to discussing the chemical and limnological characteristics of these lakes, our findings will be compared with data from other natural lakes in northern Indiana that were collected during the National Lake Eutrophication Survey.

MATERIALS AND METHODS

Description of the Study Area. The nearshore of Lake Michigan includes a variety of depressional wetlands, such as pannes, ponds, and lakes (Figure 1). Several distinct dune beach complexes were formed during the Pleistocene and Holocene Epochs when Lake Michigan was at higher levels than today (Leverett and Taylor, 1915; Bretz, 1951; Hansel, *et al.*, 1985). The area is part of a province referred to by various scientists as the Calumet Lacustrine Plain (Schneider, 1966), the Central Corn Belt Plain Ecoregion (Omernik and Gallant, 1988), or the Lake Michigan Border Section of the Northwestern Morainal Natural Region (Homoya, *et al.*, 1985). This region is a mosaic of natural and human-impacted areas, including the Indiana Dunes National Lakeshore, the Indiana

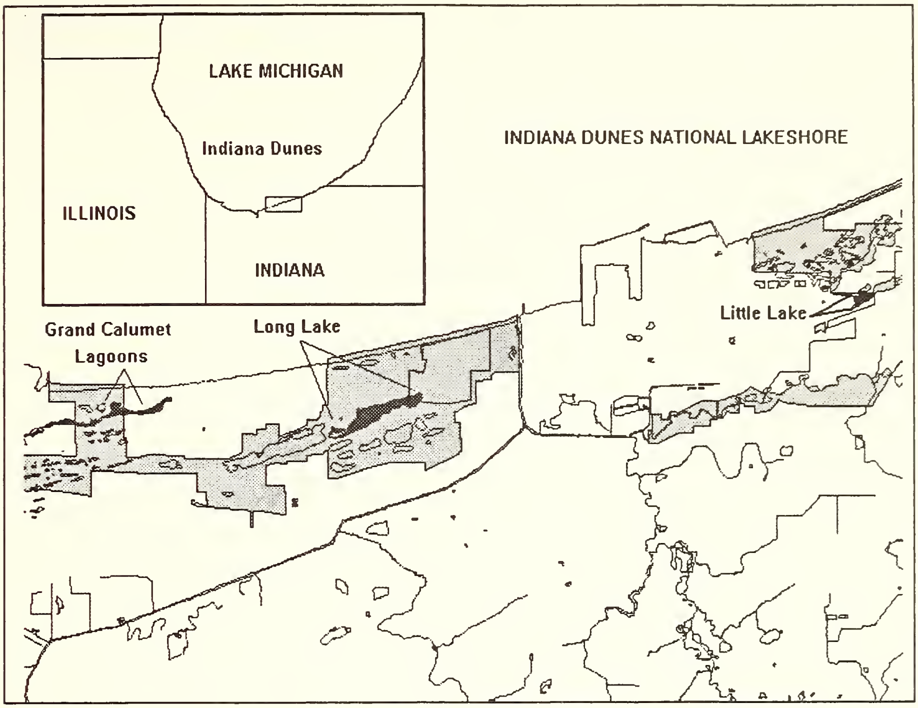

Figure 1. A map of northwestern Indiana showing the location of the four lacustrine wetlands studied.

Dunes State Park, and the Clark and Pine Natural Area. To the west lies one of the most industrialized steel and petrochemical areas in the United States (Moore and Trusty, 1977; Simon, *et al.*, 1989). The four depressional wetlands discussed in this paper are found in the Indiana Dunes National Lakeshore.

Regional Climate and Hydrology. The prevailing climate in northwestern Indiana is temperate continental modified by Lake Michigan so that the climate can take on semi-marine characteristics. The mean annual temperature is 10° C. Average annual precipitation at Gary (the largest nearby city) is about 907.5 mm; normal seasonal precipitation averages 145 mm in the winter, 252.5 mm in the spring, 285 mm in the summer, and 225 mm in the fall (National Oceanic and Atmospheric Administration, 1982). Total monthly rainfall is more variable during warm months that during cold months. The total annual precipitation between 1951-1980 ranged from about 575 mm to nearly 1250 mm. Annual snowfall varies due to the lake effect. Annual average snowfall is 875 mm at Gary with the predominant snow season from November to March. Due to the proximity of the study wetlands to Lake Michigan, early frosts and unusually late spring frosts may be delayed by 2-3 weeks. The coldest month (January) has an average normal monthly temperature of -5.1° C; the average normal monthly temperature during the warmest month (July) is 22.9° C (Beaty, *et al.*, 1994).

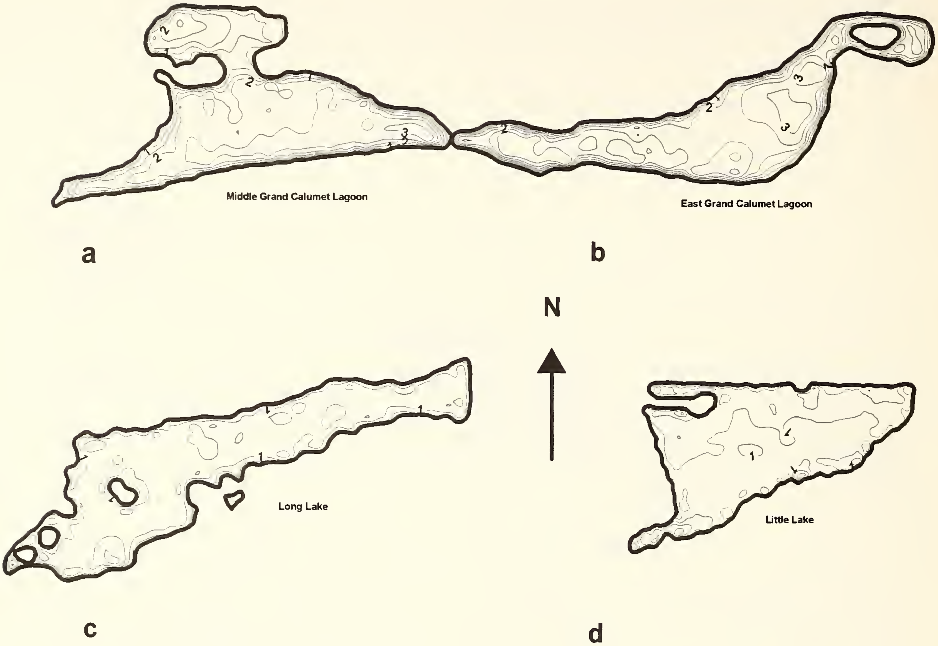

Figure 2. Bathymetric contour maps of the four study lakes: a = Middle Grand Calumet Lagoon; b = East Grand Calumet Lagoon; c = Long Lake; and d = Little Lake. The depth contour line intervals are 0.5 m.

The ponds of West Beach and Miller Woods comprise the last remnant, depressional wetlands in northwestern Indiana along the Lake Michigan dunes in the Indiana Dunes National Lakeshore. These ponds are remnants of geological Lake Chicago that were created by the lowering of lake levels and the shifting of sand dunes (Moore and Trusty, 1977). Long Lake is a large, dunal pond located southeast of Miller Woods in the West Beach Segment. The Grand Calumet Lagoons are riverine wetlands derived from the Grand Calumet River. The Lagoons are the former mouth of the river. They are separated from the river by a covered culvert on adjacent industrial property. The Lagoons are divided into three segments of relatively equal area—the East, Middle, and West Lagoons. This study was confined to the Middle and East Lagoons, the "least disturbed" ponds in the Indiana Dunes National Lakeshore and the City of Gary's Marquette Park. Little Lake is a former portion of Cowles Bog that was separated from the bog by a levee built for an electric utility substation.

Bathymetry, Morphometry, and Chemical Limnology. The bathymetric contour maps of the four lakes (Figure 2) were prepared by tracing the shorelines from perimeter maps obtained from the analysis of aerial photographs and topographic maps (7.5 minute U.S. Geological Survey maps). The size and complexity of each lake determined the number of transects needed to obtain an appropriate bathymetric profile. Little Lake, which is the smallest of the lakes at about 6 ha, was mapped at 20 m transect intervals; Long Lake, which is about 25.9 ha, was mapped using a 30 m interval; and the Middle (30.3 ha) and East Grand Calumet Lagoons (5.1 ha), the largest of the lakes, were studied using 50 m transect intervals. Intervals were measured by determining the perpendicular intersection of adjacent shorelines and then measuring the distance between points using a calibrated line (Cole, 1994). Points were then marked where they would be visible from the water using flagging tape. Depths were recorded to the nearest 0.1 m at discrete points along each transect from a boat. A Hummingbird 3-D depth-finder was used to sample nonwadeable areas, while depths were recorded in centimeters using a Philadelphia rod in wadeable areas. Coordinates were then plotted using Grass 4.0, and a detailed bathymetric map was drawn using Winsurf 5.0 (Golden Software, 1994).

Morphometric parameters were calculated from these maps, following the procedures of Lind (1985) and Wetzel and Likens (1979). Surface morphometric measures included maximum length (l), maximum width (b), mean width ($\bar{b}$), surface area (A), shoreline length (L), shoreline breath, and the shoreline development index (D_L). Subsurface morphometrics included volume (V), maximum depth (z_m), mean depth ($\bar{z}$), relative depth (z_r), and basin slope. Morphoedaphic index calculations followed Ryder, *et al.* (1974). Temperature and dissolved oxygen were measured monthly between February 1992 to August 1997 at near bottom stations at the approximate center of each lake.

The four lakes were too shallow to develop a stratified profile. Most parts of each lake are less than 2 m in maximum depth. A digital meter (Dow Corning Inc., Pocket Meter M90) was used to measure dissolved oxygen (DO; 0.0 to 20.00 ± 0.1 mg/L), temperature (-0.5° to 100° ± 0.1° C), pH (0 to 14 ± 0.1 SU), specific conductance (0.0 to 1999 ± 1 μS), and total dissolved solids (TDS; 0.0 to 1000 ± 0.1 mg/L). The oxidation-reduction potential (E_h) was measured using a digital meter (LaMotte, Inc., ORPTestr, -200 to 1100 ± 5 mv). Dissolved oxygen was calibrated using Winkler titration (American Public Health Association, 1989). Water samples were taken at the deepest level of the water column (near bottom) along predetermined transects using a Kemmerer water bottle sampler. Water samples from each lake were analyzed at the Indiana Dunes National Lakeshore Aquatic Laboratory for nitrite, nitrate, ammonia, hardness, alkalinity, and reactive phosphorous using the appropriate methods (American Public Health Association, 1989).

RESULTS AND DISCUSSION

Origin. The analysis of aerial photographs of the Grand Calumet Lagoons suggests that these water bodies originated following closure of the river's mouth by dune movement. The East and Middle Lagoons were extensive backwaters at the turn of the century when dune movement separated them from the Grand Calumet River. These two ponds are separated by a large lateral dune that arises in the foredune ridge near Lake Michigan, suggesting that the two lakes along

Table 1. Morphometric characteristics of four lakes from northwestern Indiana.

	East Grand Calumet Lagoon	Middle Grand Calumet Lagoon	Little Lake	Long Lake
Maximum length (l)	1730 m	1290 m	437 m	138 m
Maximum depth (z_m)	3.0 m	3.0 m	1.2 m	1.8 m
Maximum width (b)	330 m	370 m	273 m	378 m
Perimeter (L)	4250 m	4060 m	1516 m	4622 m
Shoreline development (D_L)	2.3 m	2.7 m	1.7 m	2.5 m
Surface area (A)	264,090 m^2	318,181.8 m^2	63,029 m^2	272,000 m^2
Volume (V)	663,634 m^3	633,181.8 m^3	5,044 m^3	304,000 m^3
Mean width ($\bar{b}$)	152.7 m	246.7 m	144 m	197 m
Mean depth ($\bar{z}$)	2.5 m	2.0 m	0.8 m	1.1 m
Relative depth (z_r)	0.5 m	1.5 m	0.6 m	0.3 m
Volume development (D_v)	> 1	> 1	> 1	> 1
Basin slope (M)	0.027	0.025	0.024	0.018
Morphoedaphic index (MEI)	25.75	33.28	79.38	53.3

with the Grand Calumet River were once part of a single, continuous watershed. Long Lake is an 8,000-year-old successional lake formed by the regression of Lake Michigan (R. Whitman, pers. comm.). The eastern end of Long Lake has been filled in, creating a separation between Ogden Dunes and the extensive wetlands previously occurring along the Little Calumet River. Long Lake is extensively vegetated and numerous beds of pondweeds (e.g., *Potemogeton*) and water lilies (*Nuphar* and *Nymphea*) have created a vegetated mat that is filling the shallow lake. An increase in nutrients has caused the degradation of this fragile system. Little Lake is the former southwestern corner of Cowles Bog, a large palustrine wetland filled with *Typha*. The levee along its northern shore separates Little Lake from Cowles Bog. To accommodate an electric substation on its northwestern shore, Little Lake was deepened and a narrow access corridor to an electric tower was built into the water. A natural area on the southeastern shore has fallen woody debris, emergent aquatic macrophytes, and submergent stands of *Ceratophyllum demersum* and *Myriophyllum spicatum*. The diversion of groundwater has flooded the area between the South Shore railroad tracks and the levee.

Bathymetry and Morphometrics. Bathymetric maps of the four lakes are shown in Figure 2, and their morphometrics are listed in Table 1. These lakes have surface to volume ratios that are very low, a feature characteristic of the natural lakes found in northwestern Indiana. The deepest lake is the East Grand Calumet Lagoon, whose mean depth is 2.51 m. The shallowest lake was Little Lake, whose mean depth was 1.17 m. The basin slope (M) of these lakes ranges from 0.0184 to 0.027, confirming their shallow depths when compared to their surface area. The shoreline development index (D_L) also shows little variation; the index ranges from 1.703 to 2.73 (Table 1). These values of the shoreline development index are consistent with those from most lakes that develop increased littoral regions (Wetzel, 1983). The lakes trend east to west in latitudinal profile, they are elongate, and they have irregular shorelines.

All four depressional wetlands lack major inflows. All four lakes are subject to atmospheric inputs primarily as a result of air emissions from industrial sources. The majority of the allochthanous input into Middle and East Grand Calumet Lagoon is probably the result of urban and residential development, which generates a higher volume of runoff because of an increase in the area covered by an impervious surface. Little Lake receives leaf litter from the surrounding forest. Inputs of particulate matter in Long Lake are the result of air-suspended material from the adjacent dunes. The shallow depth of all these lakes contributes to their eutrophic condition because dissolved oxygen and light penetrates to the benthic region despite the presence of suspended solids in the water.

Temperature and Oxygen. The four study lakes do not thermally stratify during either summer or winter. Dissolved oxygen is present in the entire water column, and a permanent oxidized microzone is present (Table 2). The mean dissolved oxygen level for the Middle Grand Calumet Lagoon was approximately 62% saturation, while the other three lakes had mean dissolved oxygen levels between 82% to 88% saturation. The amount of dissolved oxygen is strongly linked to temperature. The lowest amount of dissolved oxygen is detected when the temperatures are warmest (0.81 to 0.83 mg/L in Long and Little Lakes, respectively). Supersaturated dissolved oxygen values can occur because of the large aquatic macrophyte population that grows in all portions of the lake. Extreme diel fluctuations may occur because nocturnal respiration by these large plant beds can cause an oxygen deficit.

pH. The pH was highly variable for lakes located in an area of relatively homogeneous geologic and edaphic conditions. The pH ranged from 6.70 to 10.02 (Table 2). All four lakes are found along the edge of Lake Michigan and accept drainage from Oakville Maumee-Brems Soils (Furr, 1981). The dune, beach, and lacustrine silts, sands, and gravel form a thin but laterally extensive surficial aquifer. The sediments of Little and Long Lake arose from drained Adrian muck, while the sediments of East and Middle Grand Calumet Lagoon are Oakville fine sand soils with slopes of 18% to 40% (Furr, 1981). Several sites in East Grand Calumet Lagoon had pH values above 10 SU. Locally elevated pH values may be the result of isolated, narrow belts of slag rock that were buried after the dunes were mined (R.D. Kovach, U.S. Environmental Protection Agency, pers. comm.). Little Lake and the East Grand Calumet Lagoon consistently had the greatest variation in pH (Table 2).

In general, fresh water within the study area is not sensitive to acidification because the water is well buffered (Fenelon and Watson, 1993; Willoughby, 1995; Duwelius, *et al.,* 1996). Fenelon and Watson (1993) reported median pH values from groundwater well samples of about 7.3; four extreme pH values were

Table 2. Mean and standard deviation for monthly field and water chemistry data collected from February 1992 to August 1997 at four lacustrine wetlands in northwestern Indiana. The range is given in parentheses.

Parameters	East Grand Calumet Lagoon	Middle Grand Calumet Lagoon	Little Lake	Long Lake
Alkalinity (mg/L as $CaCO_3$)	128 ± 37.5 (78-298)	138	139 ± 50.0 (44-330)	96 ± 24.4 (52-240)
Hardness (mg/L as $CaCO_3$)	204 ± 39.5 (110-310)	198	194 ± 47.6 (106-282)	132 ± 35.5 (90-342)
pH (SU)	8.2 ± 0.46 (7.2-10.02)	8.34 ± 0.10 (8.17-8.93)	8.1 ± 0.67 (6.7-9.7)	8.0 ± 0.38 (7.0-8.57)
Temperature (° C)	5.3 ± 0.22 (4-20.7)	5.0 ± 0.15 (3.9-20.9)	8.1 ± 5.8 (4.2-23.6)	5.8 ± 0.38 (4.1-22.7)
Chloride (mg/L)	110 ± 35.6 (68-238)	—	74 ± 25.61 (30-147)	30 ± 19.45 (2-106)
Specific Conductance (μS/cm)	609 ± 213.6 (130-1339)	131.5 ± 0.6 (130-1326)	491 ± 195.8 (204-1260)	248 ± 62.1 (40-374)
Dissolved Oxygen (mg/L)	9.02 ± 3.03 (3.4-15.0)	4.50 ± 0.07 (3.4-10.7)	8.52 ± 3.08 (0.83-15.0)	8.00 ± 3.42 (0.81-15.0)
Dissolved Oxygen (% saturation)	88 ± 26.14 (40-155)	62 ± 10.45 (51-100)	87 ± 27.36 (11-150)	82 ± 27.86 (10-132)
NH_3 (mg/L)	0.13 ± 0.15 (0.01-0.65)	0.14 ± 0.28 (0.01-0.5)	0.19 ± 0.35 (0.02-2.2)	0.15 ± 1.87 (0.01-2.3)
Nitrate (mg/L)	0.40 ± 0.60 (0.1-2.5)	0.50	0.3 ± 0.62 (0.01-2.4)	0.3 ± 0.61 (0.01-2.3)
Nitrite (mg/L)	0.003 ± 0.124 (0.001-1.0)	0.005	0.001 ± 0.01 (0.001-0.04)	0.001 ± 0.002 (0.001-0.009)
Reactive Phosphorus (mg/L)	0.030 ± 0.054 (0.01-0.28)	0.07	0.05 ± 0.05 (0.01-0.23)	0.02 ± 0.03 (0.01-0.16)
Total Phosphorus (mg/L)	0.135 ± 0.09 (0.02-0.4)	0.153	0.12 ± 0.26 (0.01-1.58)	0.075 ± 0.08 (0.01-0.35)
Oxidation-Reduction Potential (E_h; mv)	163 ± 115.1 (110-400)	152.5 ± 143.4 (-60-400)	375 ± 141.4 (275-475)	235 ± 82.5 (90-365)
Total Dissolved Solids (mg/L)	66.8 ± 7.49 (48.6-67)	65.85 ± 0.61 (65.3-66.7)	63.5 ± 0.07 (63.4-63.5)	59.5 ± 0.96 (58.4-61.6)

reported from wells screened in slag. Slag is dominantly alkaline-earth-silicate glass, and water in contact with it has an elevated pH. Duwelius, *et al.* (1996) conducted a more extensive survey of the groundwater in area wells and found that the pH ranged from 5.3 to 12.1(median = 7.2). Half of the 118 samples from wells had pH values between 6.9 and 7.6. For most of the groundwater in the United States, pH ranges from about 6 to 8.5 (Hem, 1985). Duwelius, *et al.* (1996) found that samples with an elevated alkaline pH were usually from shallow groundwater wells in contact with slag or industrial waste.

Conductivity and Major Ions. Specific conductance is a measure of the ability of a substance to conduct electricity across a unit length at a specific temperature. Dissolved substances increase the conductivity of water; measurements of specific conductance provide an indication of the amount of dissolved substances in water (Hem, 1985). The specific conductance of pure water is low, less than 10 μS/cm (Hem, 1985). In general, the surface waters of our study had moderate conductance. Conductivity was consistent among wetlands and ranged from 40 to 1,339 μS/cm (mean = 369.9 μS/cm; Table 2), which was considerably lower than the conductivity reported for groundwater wells (106-5,980 μS/cm; median = 828 μS/cm). Half of the 125 well samples had specific conductance values between 450 and 1,540 μS/cm (Duwelius, *et al.*, 1996). The East Grand Calumet Lagoon had the highest conductivity of the four lakes studied.

Alkalinity measures the capacity of a solution to neutralize acids (Hem, 1985). In this study, alkalinities ranged from 44 to 330 mg/L as calcium carbonate (mean = 121 mg/L). Duwelius, *et al.* (1996) recorded alkalinities from groundwater wells in northwestern Indiana that ranged from 24.9 to 1,260 mg/L as calcium carbonate (median = 249 mg/L). Little Lake had the lowest alkalinity (Table 2). Acidity measures a solution's capacity to neutralize bases. Acidity was not detected in any sample.

Water is considered very hard when values exceed 180 mg/L as calcium carbonate. All of the lakes have very hard water (mean = 198.7 mg/L) with the exception of Long Lake (mean = 132 mg/L; Table 2). Fenelon and Watson (1993) found that non-contaminated "natural" groundwater samples from the Indiana Dunes National Lakeshore never exceeded 200 mg/L. Groundwater samples collected from areas adjacent to the heavily industrialized areas surrounding the Grand Calumet River ranged from 400 to 500 mg/L.

Freeze and Cherry (1979) placed groundwater samples into two categories based on total dissolved solids (fresh and brackish water). Fresh water generally contains less than 1,000 mg/L of dissolved solids. Water having between 1,000 and 10,000 mg/L of dissolved solids is called brackish (Freeze and Cherry, 1979). In general, the surface waters in this study represented fresh water. The amount of dissolved solids was similar in each lake and ranged from 48.6 to 67.0 mg/L (mean = 63.9 mg/L; Table 2). Duwelius, *et al.* (1996) found that groundwater wells had dissolved solid concentrations that ranged from 95 mg/L to 6,780 mg/L; the median concentration was 674 mg/L. A comparison of dissolved solid concentrations between paired shallow and deep wells showed that the highest values come from shallow wells.

The oxidation-reduction potential (E_h) of water is an index of the exchange activity of electrons among elements in solution. E_h measures the electric potential, using the potential of a hydrogen electrode as a reference point of zero. A positive potential indicates oxidizing conditions in the water; a negative potential indicates reducing conditions, which determines the valence states of metals (Hem, 1985). The oxidation-reduction potential at the study sites ranged in a stepwise progression from -60.0 to 475 mv (mean = 231.4 mv). Duwelius, *et al.* (1996) found that groundwater from wells was generally reducing (75%), and E_h ranged from -446 to 159 mv (median = -64.5 mv). Reducing conditions increased with increasing well depth. With the exception of the East and Middle Grand Calumet Lagoon, few of our study sites ever showed reducing conditions; more than 90% of the sites were in an oxidized condition.

Chloride is the dominant anion in water, and its concentration ranged from 2.0 to 238 mg/L (mean = 71.3 mg/L; Table 2) in the lakes studied. Duwelius, *et al.* (1996) found that the concentration of chloride in groundwater wells ranged from 1.4 mg/L to 2,600 mg/L (median = 37.8 mg/L). The wells that had the highest concentrations of chloride (greater than 1,000 mg/L) were shallow (less than 4.5 m deep) and were found in areas containing fill near interstate highways. High chloride concentrations indicate contamination by the fill materials and deicing salts. The Secondary Maximum Contaminant Levels are suggested concentration limits for substances in drinking water that do not result in adverse health effects but may limit the use of the water because of unpleasant taste, odor, or color. The suggested limit for chloride is 250 mg/L, a value that was not exceeded in the study lakes.

Nutrients. The concentrations of nitrate plus nitrite, ammonia, and reactive and total phosphorus were determined. Nitrogen concentrations were generally low; NO_3, NO_2, and NH_3 occurred in concentrations of less than 1.0 mg/L. Total phosphorus levels were high (mean = 0.100 mg/L). The surface waters of the study lakes all had high concentrations of nutrients.

Ammonia levels ranged from 0.01 to 0.78 mg/L (mean = 0.15 mg/L; Table 2). This range was lower than that reported from groundwater well samples (0.1-96 mg/L; median = 0.50 mg/L) by Duwelius, *et al.* (1996). Fenelon and Watson (1993) found ammonia concentrations at the Indiana Dunes National Lakeshore to range from 0.05 to 0.20 mg/L. Long and Little Lakes had the highest mean ammonia concentrations. Their mean values were over twice as high as the values observed in the Grand Calumet Lagoons. Duwelius, *et al.* (1996) reported that half of the 125 samples from groundwater wells had ammonia (nitrogen) concentrations less than the detection level (< 0.01 mg/L).

The concentration of nitrate plus nitrite was low, ranging from 0.001 to 2.5 mg/L (mean = 0.38 mg/L; Table 2). These concentrations were higher than those found by Fenelon and Watson (1993). Their values for the concentration of nitrate plus nitrite in groundwater samples from the Indiana Dunes National Lakeshore ranged from below detection level (< 0.01 mg/L) to 0.02 mg/L and were within the range reported for natural groundwater samples (range = 0.02 to 0.96 mg/L; median = 0.06) in northwestern Indiana.

Table 3. A comparison of select physical, spring chemical, and trophic status variables for a variety of natural lakes in northern Indiana (N = nitrogen and P = phosphorus).

	Physical Variables (m)			Chemical Variables		
Lake	Volume (m^3)	Mean Depth	Maximum Depth (z)	N-Total (mg/L)	P-Total (mg/L)	Trophic Status
Northwest						
Middle Grand Calumet Lagoon	0.6 x 10^6	2.5	3.0	0.645	0.217	Eutrophic
East Grand Calumet Lagoon	0.6 x 10^6	2.0	3.0	0.809	0.153	Eutrophic
Little Lake (Porter)	0.05 x 10^6	0.8	1.2	0.863	0.190	Eutrophic
Long Lake (Porter)	0.3 x 10^6	1.1	1.8	0.992	0.100	Eutrophic
North-Central						
James Lake (Kosciusko)	9.348 x 10^6	8.2	19.2	1.854	0.025	Eutrophic
Tippecanoe Lake (Kosciusko)	35.143 x 10^6	11.3	37.5	1.650	0.024	Mesotrophic
Lake Wawasee (Kosciusko)	82.946 x 10^6	6.7	23.5	1.107	0.007	Mesotrophic
Webster Lake (Kosciusko)	4.977 x 10^6	13.7	13.7	1.773	0.029	Eutrophic
Winona Lake (Kosciusko)	20.657 x 10^6	9.1	24.4	2.159	0.041	Eutrophic
Lake Maxinkuckee (Marshall)	55.042 x 10^6	7.3	26.8	0.757	0.024	Mesotrophic
Northeast						
Dallas Lake (LaGrange)	12.303 x 10^6	10.8	29.3	1.582	0.048	Eutrophic
Olin Lake (LaGrange)	4.914 x 10^6	11.7	25.0	1.819	0.011	Mesotrophic
Oliver Lake (LaGrange)	18.300 x 10^6	12.2	27.7	1.287	0.007	Mesotrophic
Sylvan Lake (Noble)	10.879 x 10^6	4.3	11.0	1.397	0.166	Eutrophic
Crooked Lake (Steuben)	19.825 x 10^6	6.1	23.5	0.841	0.017	Mesotrophic
Hamilton Lake (Steuben)	20.475 x 10^6	6.3	21.3	1.352	0.031	Eutrophic
Long Lake (Steuben)	1.887 x 10^6	5.1	9.7	3.460	0.104	Eutrophic
Marsh Lake (Steuben)	1.403 x 10^6	6.1	11.6	1.262	0.084	Eutrophic
Lake James (Steuben)	30.514 x 10^6	7.3	26.2	0.771	0.021	Mesotrophic
Pigeon Lake (Steuben)	1.143 x 10^6	4.6	11.6	4.087	0.033	Eutrophic

The total and reactive phosphorus levels in the lakes of northwestern Indiana were higher than those in lakes from the remainder of northern Indiana (Table 3). The total phosphorus concentrations in the lakes of northwestern Indiana were an order of magnitude higher than those for other lakes measured during the National Eutrophication Survey (U.S. Environmental Protection Agency, 1976). Total phosphorus concentrations in the four study lakes ranged from 0.01 to 1.58 mg/L (mean = 0.1 mg/L; Table 2). The reactive phosphorus in the four study lakes was about 25% of total phosphorous with the exception of East Grand Calumet Lagoon, which was less than 25% (Table 2).

Comparison to Natural Lakes. Ponds and lakes along the nearshore of Lake Michigan are shallow, eutrophic depressions that have steep littoral slopes formed by the erosion and movement of sand dunes. The lakes of northwestern Indiana are significantly different from other natural lakes in northern Indiana. The lakes of northwestern Indiana have an average maximum depth of 2.3 m in contrast to average lake depths of 9.38 m and 7.45 m for north-central and northeastern Indiana, respectively (Table 3). The deeper lakes of central and eastern Indiana stratify and develop thermoclines. The lakes of northwestern Indiana never stratify because they are not deep enough. These lakes rarely attain average depths greater than 2.0 m (mean = 1.6 m; Table 3). The maximum depth of north-central Indiana lakes ranged from 13.7 (Webster Lake, Kosciusko County) to 37.5 m (Tippecanoe Lake, Kosciusko County). Northeastern Indiana lakes ranged from 9.7 m (Long Lake, Steuben County) to 29.3 m (Dallas Lake, LaGrange County) in maximum depth.

Most of the large lakes of northern Indiana are either eutrophic or mesoeutrophic, based on the trophic index developed by the Indiana Department of Environmental Management (1986). The index uses fifteen measurements (based on data from 307 samples collected during the mid-1970s) to characterize the trophic status of inland Indiana lakes. The measurements include broad categories of nutrients, dissolved oxygen, light penetration, total plankton, dominance of blue-green algae, and the abundance of cells in vertical tows from the thermocline and from the littoral zone.

The lakes studied in the Indiana Dunes National Lakeshore are eutrophic or hypereutrophic, exhibit rapid cycling of nutrients, and show predictable crashes in dissolved oxygen during diel cycling. These lakes also had low levels of total nitrogen but high levels of total phosphorus (Table 3). Average total nitrogen for lakes in north-central Indiana ranged from 0.757 mg/L (Lake Maxinkuckee, Marshall County) to 2.159 mg/L (Winona Lake, Kosciusko County), while the lakes in northeastern Indiana had higher concentrations, ranging from 0.771 mg/L (Lake James, Steuben County) to 4.087 mg/L (Pigeon Lake, Steuben County). Total phosphorous for lakes in north-central Indiana ranged from 0.007 mg/L (Lake Wawasee, Kosciusko County) to 0.041 mg/L (Winona Lake, Kosciusko County), while total phosphorous in northeastern lakes ranged from 0.011 mg/L (Olin Lake, LaGrange County) to 0.166 mg/L (Sylvan Lake, Noble County). The total phosphorous in northwestern Indiana lakes is similar to the amount in mesoeutrophic lakes in north-central and northeastern Indiana (Table 3). The presence of an oxidized microzone in the lakes of northwestern Indiana limits autochthonous cycling of nutrients causing permanent loss of phosphorus and nitrogen to the sediments.

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