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PHYSICAL AND CHEMICAL LIMNOLOGY OF THREE LAKES WITHIN HOOSIER NATIONAL FOREST

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ABSTRACT. Three reservoirs, Tipsaw, Indian, and Celina lakes, are located in Hoosier National Forest in Perry County, Indiana, have experienced annual fish kills for over a decade. These lakes were evaluated for patterns in their physical and chemical limnology to characterize morphometrics of length, depth, and width and water quality. Chemical variables, including pH, conductivity, major ions, and nutrients, were measured to evaluate water quality differences among lakes. The study lakes were shallow depressions (Z_{mean} = 3.06–5.60 m; Z_{max} = 7.9–17.0 m) and classified as polymictic. The shallow depths typically enabled dissolved oxygen to be distributed throughout the water column and prevented thermal stratification, although pronounced thermoclines developed during 1989, 1991, and 2001. The Carlson trophic index classified these lakes as mesotrophic with the highest index being calculated for Tipsaw (22–52 TI), followed by Indian (12–13 TI), and Celina (5–14 TI). The highest morphoedaphic index (MEI) was observed in Tipsaw (24.3 (mg/L)/ m), followed by Indian (16.8 (mg/L)/m), and Celina (9.1 (mg/L)/m). The MEI values observed in the three lakes translate to catch yields of 20–30 kg/ha. General chemical patterns are towards a stable state or reduction in nitrogen or phosphorus concentrations. No statistically significant trend based on regression of chemical variable by lake over time was observed for any parameter during the study period (ANOVA, $P > 0.05$). The shallow reservoir depths, changing thermocline and oxycline, and reduction in dissolved oxygen can result in increased potential for continuing conditions promoting fish kills.

Keywords: lake morphometrics, bathymetry, water quality, Morphoedaphic index, Carlson trophic index

INTRODUCTION

The National Lake Survey was originally conducted by the U.S. Environmental Protection Agency (EPA) in the 1970's to evaluate the condition of the nation's lakes. A resurgence of interest in cultural eutrophication (Carpenter et al. 1999; Genkai-Kato & Carpenter 2005; Carpenter & Lathrop 2008) and climate change (Soranno et al. 1999; Moore et al. 2009) has resulted in a more rigorous survey design that has been incorporated during the most recent national sampling efforts (US Environmental Protection Agency [EPA] 2010). Limited studies of small reservoirs (< 1000 ha) have previously been conducted nationally and few studies have been conducted in southern Indiana at mostly public lakes (Thornton et al. 1990; Straskrabová & Talling 1994; Wetzel 2001; Clean Lakes Program, unpublished data). The majority of reservoirs (> 20 ha) in southern Indiana are impoundments of streams or rivers (EPA National Lakes Survey, unpublished data). These reservoirs are important for drinking water, recreation, and flood storage capacity. The collection of baseline information for determining patterns in reservoir lake trophic status and for analyzing physical attributes of lentic systems in southern Indiana is needed (Simon et al. 2011).

The morphologic features of lakes are determined by climatic and edaphic factors

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that affect the chemical dynamics of the lake, which in turn, shape the biota within these ecosystems (Ryder et al. 1974; Carlson 1977; Wetzel 2001; Simon & Simon in review). Investigations of the physical and chemical environment of reservoirs in southern Indiana have not been similarly studied as northern Indiana lakes (Blatchley & Ashley 1901, Evermann & Clark 1920), and are unparalleled in similar intensity or duration. Perhaps the best-studied lake in southern Indiana has been Foots Pond, which is a natural oxbow lake of the Wabash River drainage (Hubbs & Lagler 1942; Lagler & Ricker 1942; Ricker & Lagler 1942). No studies of the physical and chemical limnology of reservoirs in southern Indiana (< 1000 ha) have been conducted during either the 2007 or 2012 National Lake Surveys. Only the State sponsored Clean Lakes Program, which is supported by the State of Indiana Department of Environmental Management, conducts annual monitoring. Chemical measures of public lakes have been conducted annually, with additional support of the National Lake Survey during 2007 and 2012. These studies focus primarily on water quality and trophic state determination.

This investigation was conducted with emphasis on determining contributing factors causing annual fish kills. Our objective was to describe the chemical and physical characteristics of three reservoirs in Hoosier National Forest in southern Indiana focusing on eutrophication, hypoxia, and physical morphometrics. These reservoirs have experienced fish kills for the last decade (Simon 2011; Simon et al. 2011). While many aspects of the biota can be determined without knowledge of the physical and chemical characteristics of these lakes, many of the indices of productivity cannot be determined without this information (Ryder et al. 1974). We compare our results from 2005 and 2012 data to Clean Lakes Program data for these same lakes to determine trophic status and morphometric relationships.

MATERIALS AND METHODS

Description of the study area.—The landscape of southern Indiana has few natural lakes (Omernik & Gallant 1988); however, southern Indiana contains 2,729 impounded lakes that were created by damming small streams and moderate sized rivers. Reservoirs are artificial systems that are built when valley ridges were closed and stream channels flooded these areas. Hoosier National Forest occupies an area that is part of the Mitchell Plain (Schneider 1966) and is considered a portion of the Central Corn Belt Plain and Interior Plateau Ecoregion (Omernik & Gallant 1988). The study area incorporates the Corn Belt and Great Plains nutrient ecoregions (Morris & Simon 2012). The study area in Hoosier National Forest is 820.8 km^2 and is managed by the U.S. Forest Service and is primarily composed of natural watersheds that are without heavy anthropogenic impact in the surrounding watersheds (Figure 1). All lake soils were dominated by Deuchars and Markland soils (USDA 2006). Celina, Tipsaw, and Indian lakes are associated with the damming of streams in the Middle Fork Anderson River (Simon 2011) and were investigated for limnological attributes of physical and chemical parameters following the protocols of the National Lake Survey (EPA 2007).

Regional climate and hydrology.—The prevailing climate in southern Indiana is temperate continental, which is modified by the Ohio River so that the climate can take on semi-marine characteristics (National Oceanic and Atmospheric Administration 2003). The mean annual temperature is 13.96° C (National Oceanic and Atmospheric Administration, NCDC 2012). Average annual precipitation at Tell City (the largest nearby city) from 1981–2010 is about 1230 mm; normal seasonal precipitation averages 94.8 mm in the winter, 122.3 mm in the spring, 93.7 mm in the summer, and 100.1 mm in the fall (National Oceanic and Atmospheric Administration, NCDC 2012). Total monthly rainfall is more variable during warm months than during cold months. The total annual precipitation is 1230 mm. The maximum average precipitation occurs in May with an average of 147.75 mm. Annual average snowfall is 112 mm at Tell City, with the predominant snow season from November to March. The coldest month (January) has an average normal monthly temperature of 2.0 °C; the average normal monthly temperature during the warmest month (July–August) is 31 °C.

The reservoirs of Hoosier National Forest (lat 38.206647°N, lon −86.650334°W to lat 38.121382°N, lon −86.645664°W) comprise the only lakes occurring in Perry County greater than 20 ha surface area. Indian, Tipsaw, and

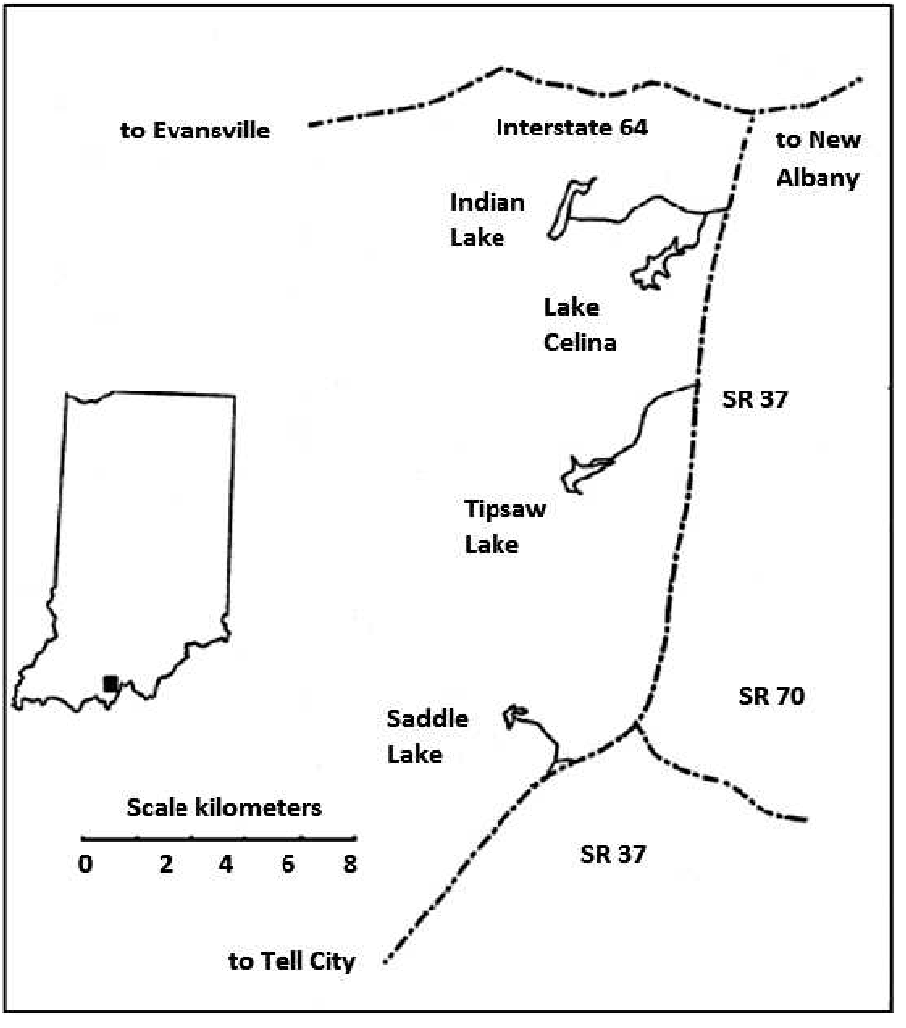

Figure 1.—Study area showing the location of three Hoosier National Forest reservoirs in Perry County.

Celina Lakes are all headwater lakes of the Middle Fork Anderson River drainage. We evaluated three of the largest waterbodies, which were all built during the mid-1960's as recreational lakes.

Bathymetry, Morphometry, and Chemical Limnology.—The bathymetry contour maps of the three lakes (Figures 2–4) were prepared by systematic transect measurement of water column depths using a classical grid design (Wetzel & Likens 1979; Cole 1994). The size and complexity of each lake determined the distance between transects and the number needed to obtain an appropriate bathymetric profile. Tipsaw Lake, the smallest of the three lakes at 53.0 ha, was mapped at 30 m transect intervals. Lake Celina, the largest lake at 66.4 ha, was mapped using a 50 m transect interval as was Indian Lake, which is 61.5 ha. Transect points were established along shore using calibrated measurement tapes to create a square grid profile around the perimeter of each lake. Survey points were marked along shore using flagging at indicated transect distances. Offshore depths were measured at intervals by determining the perpendicular intersection of adjacent shorelines markers and then measuring the distance between points using a calibrated depth finder and Geographic Positioning System (GPS). Transects were measured from a boat under power that was maintained until the latitude and longitude

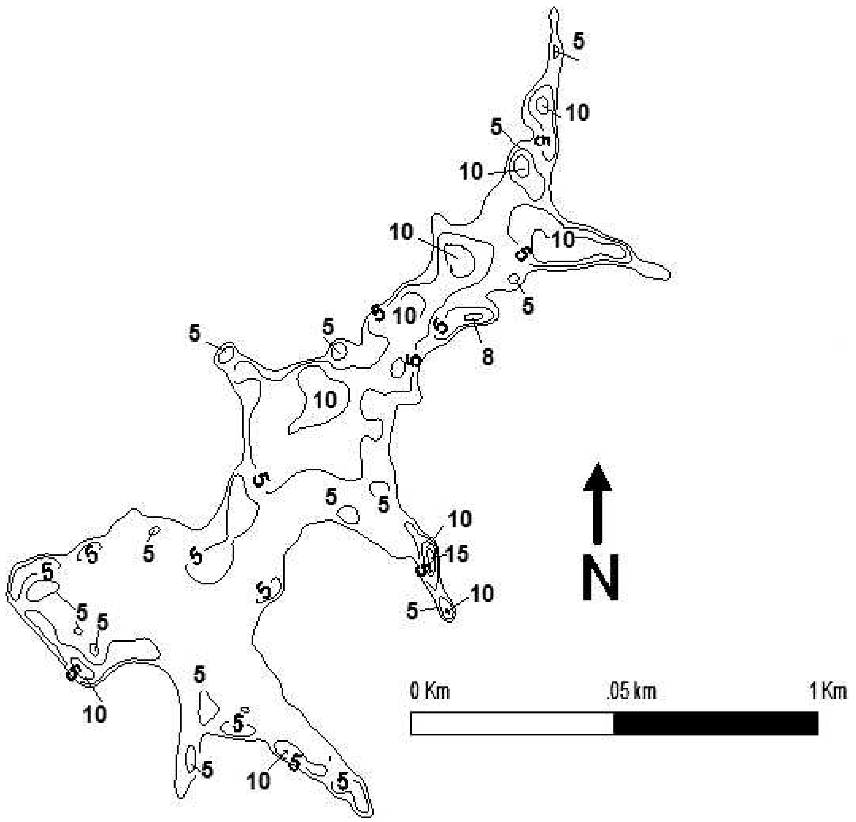

Figure 2.—Bathymetric contour map of Lake Celina based on survey from 16–17 September 2005. Depth contour values in m.

could be recorded and verified along each transect intersection point. A boat mounted Humminbird 3-D depth-finder was used to record depths in non-wadeable areas, while a Philadelphia rod was used to obtain depths in wadeable areas. Depth coordinates were plotted using the GPS reading and a detailed bathymetric map was drawn using Surfer 11.0 (Golden Software 2011). Basin slope was measured using original U.S. Geological Survey 7.5 minute 1:24,000 topographic maps for the length of the reservoir segment. The shoreline perimeter was verified using U.S. Geological Survey 1:24,000 topographic maps and aerial photographs.

Morphometric parameters were calculated from maps following the procedure of Lind (1985) and Wetzel & Likens (1979). Surface morphometric measures included maximum length (l), maximum width (b_{max}), mean width (b_{mean}), surface area (A), shoreline length (L), shoreline breadth and the shoreline development index (D_L). Subsurface morphometrics included volume (V), maximum depth (z_{max}), mean depth (z_{mean}), relative depth (z_r), and basin slope. Edaphic factors are measured by the Morphoedaphic index to evaluate fish productivity, while eutrophication is measured using the Carlson's trophic index based on TP and chlorophyll. Morphoedaphic index calculations followed Ryder et al. (1974) and Carlson's trophic index (TI) followed Carlson (1977). Temperature and dissolved oxygen were measured at the deepest point in each waterbody at 1-m intervals. Chemical measurement, sampling period, and number of samples followed the National Lake Survey protocols with samples completed during a single sample period between June and September (EPA 2007; Clean Lakes Program 2012).

Water samples were taken from the epilimnion and hypolimnion in the deepest portion of the lake using a Kemmerer sampler (Clean Lakes Program 2001; EPA 2007). A digital

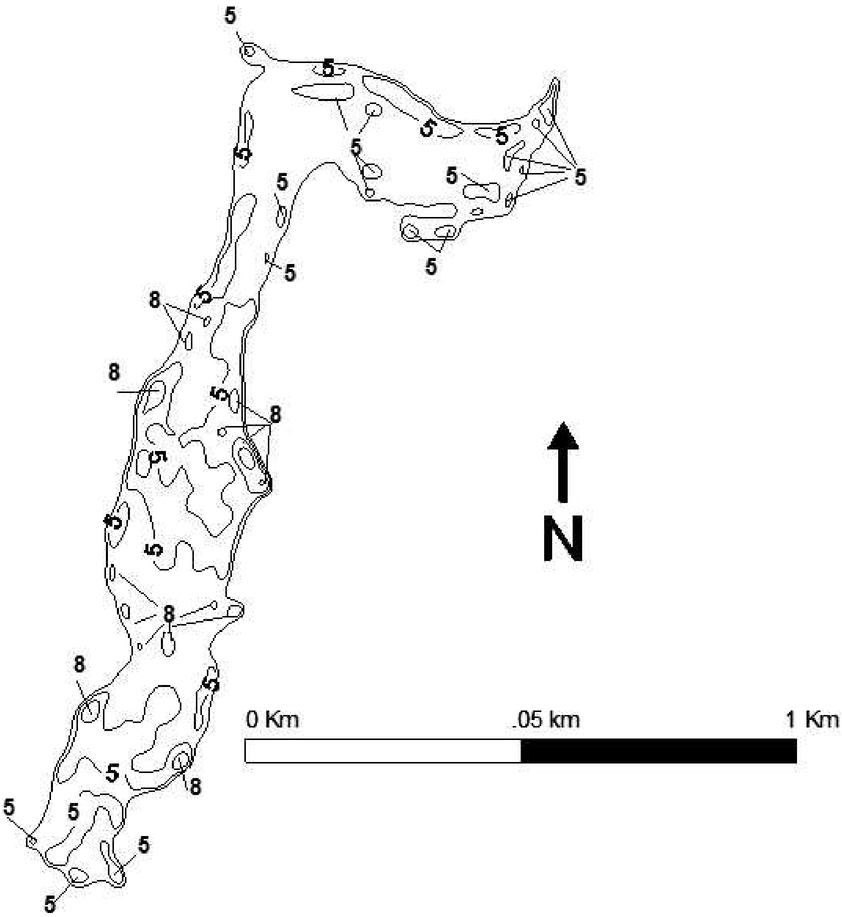

Figure 3.—Bathymetric contour map of Indian Lake based on survey from 16–17 September 2005. Depth contour values in m.

meter (Dow Corning, Inc, Pocket Meter M90) was used to measure dissolved oxygen (DO 0.0–20.00 ± 0.1 mg/L), temperature (−0.5 °C to 100 °C ± 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 a Winkler titration (American Public Health Association 1989) based on Kemmerer sample from the epilimnion and hypolimnion. This parameter was taken from the deepest portion of the lake during all sampling years. During 2005 additional samples were collected from random nearshore areas within each lake as single grab samples. Water samples (n = 10) were taken from within and among each reservoir following the National Lake Survey protocol (EPA 2007). This same protocol is used by the Indiana Clean Lakes Program, which includes a single epilimnion and hypolimnion sample. Laboratory procedures following National Lake Survey procedures (EPA 2007) and quality assurance included field duplicates, blanks, and replicate samples measurement after every 20 samples (Indiana Department of Environmental Management 1986; Clean Lakes Program 2012).

RESULTS AND DISCUSSION

Physical characteristics.—Celina Lake is on the Winding Branch River and is used for recreation and flood control purposes. Its construction was completed in 1969 and it has a normal surface area of 61 ha (153 acres). It is owned by the Department of Agriculture, U.S.

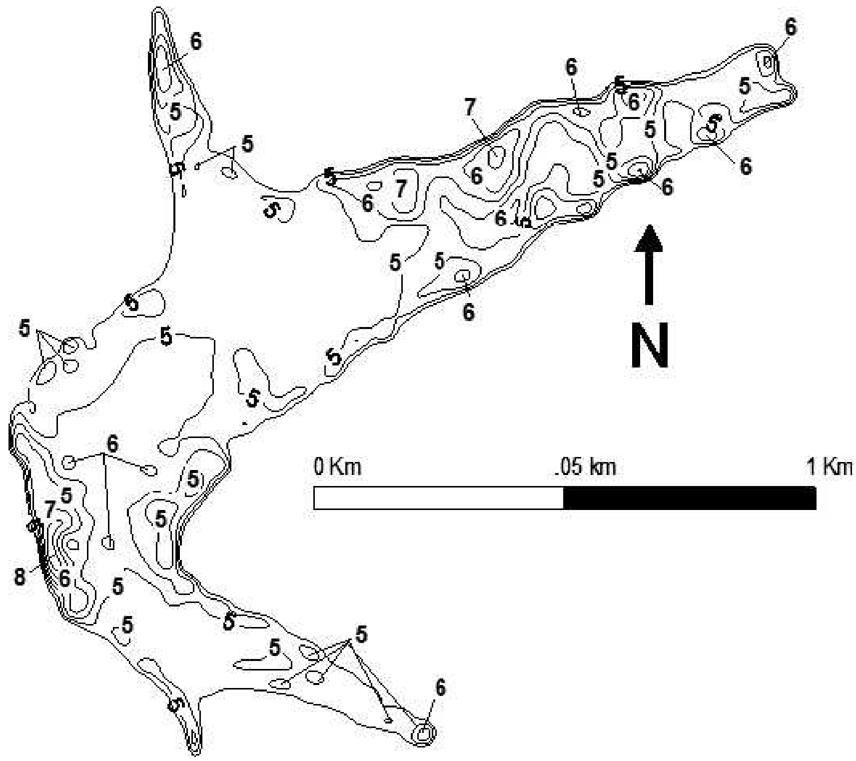

Figure 4.—Bathymetric contour map of Tipsaw Lake based on survey from 16–17 September 2005. Depth contour values in m.

Forest Service. Celina Lake has a dam of earthen construction. The foundation is rock with a soil core. Its dam height is 26.2 m (86 ft) with a length of 310.9 m (1020 ft). Maximum discharge is 2.55 m^3/sec (90 ft^3/sec). Its capacity is 589.97 ha m (4783 acre ft). It drains an area of 7.77 km^2 (3 $miles^2$).

Indian Lake is on the Middle Fork-Anderson River and is used for recreation and flood control purposes. Construction was completed in 1968. It has a normal surface area of 60 ha (149 acres) and is owned by the Department of Agriculture, U.S. Forest Service. The Indian Lake dam is of earthen construction with an earthen core and a rock foundation. Its height is 24.1 m (79 ft) with a length of 289.6 m (950 ft). Maximum discharge is 8.16 m^3/sec (288 ft^3/sec). Its capacity is 471.2 ha m (3820 acre ft). Normal storage is 210.7 ha m (1708 acre ft). It drains an area of 44.03 km^2 (17 $miles^2$).

Tipsaw Lake is used for recreation and flood control purposes. Construction was completed in 1967. Tipsaw Lake has a dam created from earthen construction. The core is earth with a foundation of rock and soil. Its length is 376.4 m (1235 feet). It drains an area of 23.3 km^2 (9 $miles^2$).

Bathymetry maps of the three reservoirs are shown in Figure 2–4, and lake morphometrics are listed in Table 1. All three reservoirs have surface area-to-volume ratios that are very low, a feature uncharacteristic of reservoirs in southern Indiana. The deepest lake was Lake Celina (z_{mean} = 5.6 m), followed by Indian Lake (z_{mean} = 3.50 m), while the shallowest lake was Tipsaw Lake (z_{mean} = 3.06 m). The basin slope (M) of these lakes ranges from 22.4 to 32.1, confirming the shallow depths when compared to the lake surface area. The shoreline-development index (D_L) also shows little variation; the index ranges from 2.07 to 2.91 (Table 1). This index reflects the potential for greater development of littoral communities in proportion to the volume of the lake (Wetzel 2001). The shoreline development index values observed from the three Hoosier National Forest reservoirs are consistent with those from

Table 1.—Morphometric characteristics for three lakes in Hoosier National Forest calculated from bathymetry mapping in September 16–17, 2005. All measurements are in m unless otherwise specified. Shoreline development is unitless.

Measurement	Lake Celina	Indian Lake	Tipsaw Lake
Maximum length (l)	1667	1857	1536
Maximum depth (z_m)	17.0	8.8	7.9
Mean width (b)	341	328	364
Mean depth (z)	5.60	3.46	3.06
Relative depth (z)	2.00	0.78	0.97
Maximum width (b)	1007	688	872
Perimeter (L)	7,776.0	5,982.6	5,548.4
Shoreline Development (D_L)	2.91	2.07	2.18
Surface Area (A) (ha)	66.4	61.5	53.0
Volume development (D_v)	1.29	1.50	1.16
Basin slope (M) (%)	31.0	32.1	22.4
Morphoedaphic index (MEI)	9.1 (mg/L)/m	16.8 (mg/L)/m	24.3 (mg/L)/m

most lakes that develop increased littoral regions (Wetzel 2001). The lake orientation is from east to west in latitudinal profile, possessing elongate basins, with a moderately irregular shoreline.

All three lakes are subject to atmospheric inputs primarily as a result of atmospheric deposition. The majority of the allochthonous input into the lakes comes from runoff from the sloped forested, riparian shoreline. All three lakes exist in a forested landscape, thus leaf litter is received from the adjacent deciduous oak-hickory forest. The shallow littoral zones of all of these lakes contribute to their eutrophic condition because dissolved oxygen and light penetrates to the benthic region despite the presence of suspended solids in the water column.

The three lakes did not thermally stratify during 2005, but did display weak thermocline development in 2011 and 2012 and strongly stratified during 1989, 1991, 1996, and 2001 (Figure 5). Dissolved oxygen was present in the entire water column, although at low levels in the hypolimnion, and a permanent oxidized microzone was present based on nearly 90% of water quality redox measurements (Table 2–4). The mean dissolved oxygen level for Lake Celina and Indian Lake was 6.3 mg/L, while Tipsaw Lake had a mean dissolved oxygen level of 4.7 mg/L. The amount of dissolved oxygen is strongly linked to temperature. The lowest amount of dissolved oxygen was detected in the hypolimnion (0.01 in Lake Celina, and 0.2 mg/L in both Indian and Tipsaw). Supersaturated dissolved oxygen levels occurred in Tipsaw Lake in response to the primary productivity of the large aquatic macrophyte community that was found in the littoral zone. These diel fluctuations occurred because supersaturated diurnal and nocturnal respiration in the large plant beds caused an oxygen deficit, which was observed in both Indian and Tipsaw lakes (Simon et al. 2011).

Chemical characteristics.—The range of pH for each reservoir ranged from 6.4 to 10.9 (Table 2–4). The range of pH values observed during the annual studies had the highest range from Indian Lake (6.4–10.9 SU), followed by Tipsaw (6.9–9.3 SU), and lowest in Celina (6.4–8.3 SU). Extreme pH value shifts were observed in Indian Lake during 2005, which showed the largest range between the epilimnion and hypolimnion (Table 3).

Specific conductance is a measure of the ability of a substance to conduct electricity across a unit length at a specific temperature. Dissolved ions 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, usually less than 10 μS/cm (Hem 1985). In general, the surface waters of our study lakes had moderate conductance. Conductivity was consistent within lake and ranged from 54.7 to 150.3 μS/cm. The lowest conductivity was observed in Lake Celina (mean=99.5 μS/cm), followed by Indian (116.1 μS/cm), and Tipsaw (150.3 μS/cm) exhibited the highest level (Table 2–4).

Alkalinity measures the capacity of a solution to neutralize acids (Hem 1985). In this study, alkalinities ranged from 64 to 164 mg/L

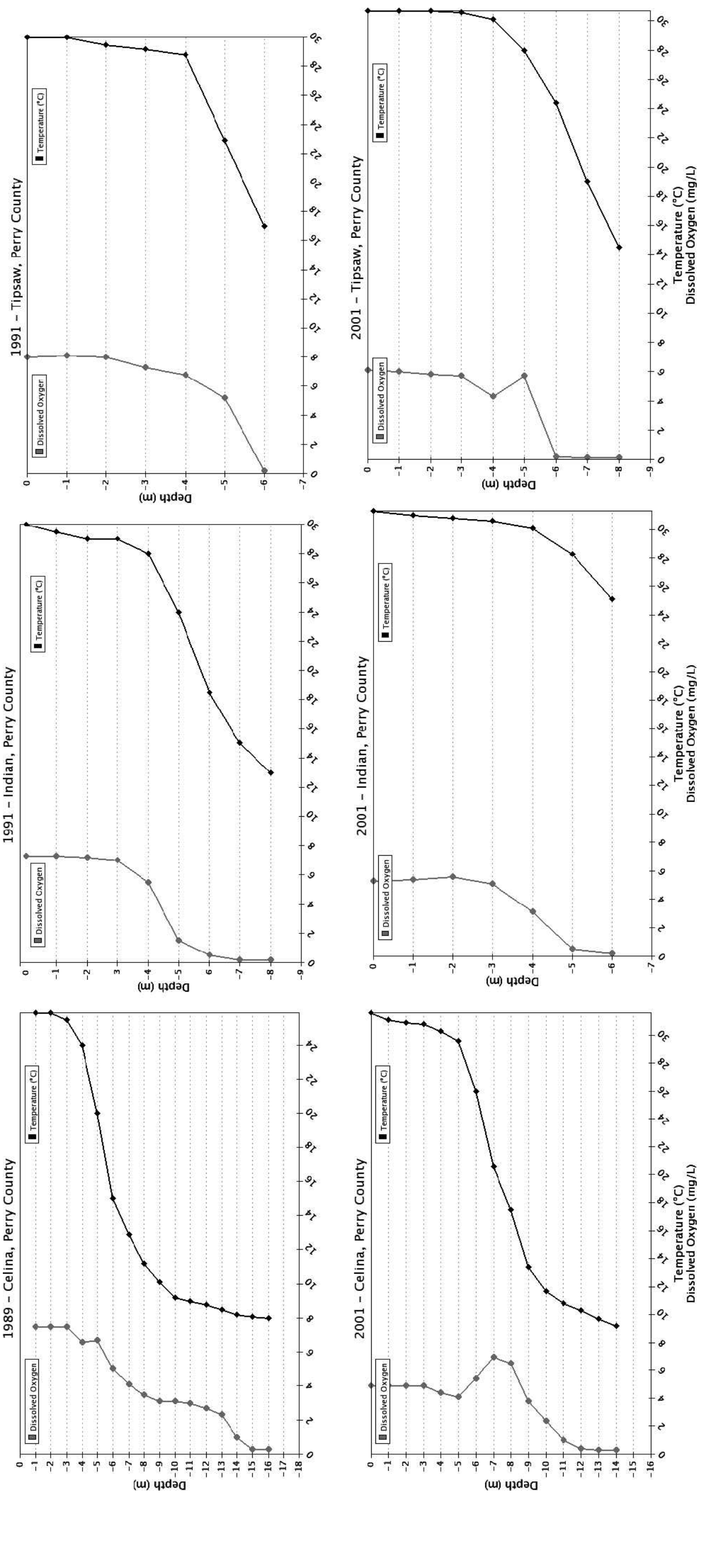

Figure 5.—Depth related dissolved oxygen and temperature thermocline profiles for Lakes Celina, Indian, and Tipsaw for 1989–1991 and 2001 study periods.

Table 2.—Mean, standard deviation, and range in parentheses for field and water chemistry data collected during July 9, 1989, July 22, 1996, August 7, 2001, September 16, 2005, and September 3, 2012 at Lake Celina in Hoosier National Forest. N = samples for each lake collected from the epilimnion and hypolimnion at the deepest portion.

Parameters	1989 (n = 2)	1996 (n = 2)	2001 (n = 2)	2005 (n = 10)	2012 (n = 2)
Alkalinity (mg/L as $CaCO_3$)	39.3 ± 0.92 (38.6–39.9)	36.1 ± 6.08 (31.8–40.4)	30.5 ± 2.12 (29–32)	64 ± 5.65 (60–68)	51 ± 4.2 (48–54)
Hardness (mg/L as $CaCO_3$)	–	–	–	91.5 ± 12.02 (83–100)	89.5 ± 52.1 (83–96)
pH (SU)	6.7 ± 0.42 (6.4–7.0)	7.43 ± 0.88 (6.8–8.1)	7.6 ± 0.99 (6.9–8.3)	7.08 ± 0.29 (6.5–7.6)	7.24 ± 1.11 (6.5–8.0)
Temperature (°C)	13.6 ± 7.2 (8.0–25.9)	17.3 ± 7.2 (10.6–28.1)	19.3 ± 9.4 (9.2–30.9)	25.1 ± 1.9 (22.8–26.8)	21.0 ± 2.7 (9.2–31.6)
Salinity (ppt/L)	–	–	–	0.0 ± 0.0 (0.0–0.0)	0.0 ± 0.0 (0.0–0.0)
Specific Conductance (µS/ cm)	126 ± 22.6 (110–142)	120 ± 15.6 (109–131)	160.5 ± 41.7 (131–190)	102.1 ± 32.6 (75.7–186.3)	143.6 ± 2.12 (98.7–188.5)
Dissolved Oxygen (mg/L)	3.8 ± 2.5 (0.3–7.5)	2.3 ± 3.4 (0.1–7.7)	3.5 ± 2.2 (0.3–7.0)	6.3 ± 1.27 (4.2–8.8)	3.7 ± 2.7 (0.3–6.5)
Dissolved Oxygen (% saturation)	92	97.1	66	79.6 ± 19.0 (50–110%)	87.7
NH_3 (mg/ L)	0.224 ± 0.27 (0.035–0.412)	0.091 ± 0.10 (0.018–0.164)	0.029 ± 0.01 (0.02–0.037)	< 0.0001 ± 0.0 (< 0.0001)	0.022 ± 0.01 (0.015–0.028)
Nitrate + Nitrite (mg/L)	0.36 ± 0.08 (0.303–0.412)	0.10 ± 0.09 (0.039–0.164)	0.08 ± 0.09 (0.013–0.144)	0.30 ± 0.14 (0.20–0.40)	0.30 ± 0.14 (0.20–0.40)
Total Kieldahl Nitrogen (mg/L)	0.58 ± 0.18 (0.447–0.703)	0.31 ± 0.06 (0.27–0.35)	0.45 ± 0.06 (0.41–0.49)	0.55 ± 0.07 (0.5–0.06)	0.42 ± 0.11 (0.34–0.50)
Total Phosphorus (mg/L)	0.02 ± 0.006 (0.015–0.024)	0.03 ± 0.01 (0.023–0.043)	0.02 ± 0.004 (0.016–0.023)	0.045 ± 0.007 (0.039–0.05)	0.038 ± 0.018 (0.025–0.05)
SRP (mg/L)	0.02 ± 0.007 (0.015–0.025)	0.006 ± 0.001 (0.005–0.007)	0.01 ± 0.0 (0.01–0.01)	–	–
Oxidation-Reduction Potential (E_h; mV)	–	–	–	569 ± 255.9 (241–960)	569 ± 255.9 (241–960)
Total Dissolved Solids (mg/L)	–	–	–	50.9 ± 16.5 (37.5–93.1)	50.9 ± 16.5 (37.5–93.1)

as calcium carbonate. Lake Celina had the lowest alkalinity (mean 52.9), followed by Indian Lake (102.9) and Tipsaw Lake (118.5) had the highest alkalinity (Table 2–4).

Water is considered very hard when values exceed 180 mg/L as calcium carbonate. Lake Celina had hard water (mean = 91.5 mg/L calcium carbonate), while Lake Tipsaw (mean = 232 mg/L) and Indian Lake had very hard water (mean = 334 mg/L).

The dissolved solids ranged from 27.7 to 188.9 mg/L, while the mean dissolved solids was lowest for lakes Celina (49.6 mg/L), followed by Indian (58.2 mg/L), and Tipsaw (74.3 mg/L) had the highest levels.

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 state of metals (Hem 1985). The oxidation-reduction potential of the study lakes ranged in a stepwise progression from −66 to 1020 mv, while the mean for lakes was lowest in Indian (376.9 mv), followed by Celina (417.8 mv), and highest in Tipsaw (558.4 mv). Reducing conditions have been observed

Table 3.—Mean, standard deviation, and range in parentheses for field and water chemistry data collected during July 23, 1991, August 7, 2001, September 16, 2005, and September 3, 2012 at Indian Lake in Hoosier National Forest. N = samples for each lake collected from the epilimnion and hypolimnion at the deepest portion.

Parameters	1991 (n = 2)	2001 (n = 2)	2005 (n = 10)	2012 (n = 2)
Alkalinity (mg/L as $CaCO_3$)	79.8 ± 31.2 (58–102)	62.0 ± 7.08 (57–67)	119 ± 0.00 (119–119)	86 ± 33.9 (62–110)
Hardness (mg/L as $CaCO_3$)	–	–	232 ± 0.0 (232–232)	142.5 ± 62.1 (98–187)
pH (SU)	7.8 ± 0.99 (7.1–8.5)	8.25 ± 1.34 (7.3–9.2)	7.33 ± 0.96 (6.8–10.9)	8.15 ± 1.34 (7.2–9.1)
Temperature (°C)	24.6 ± 6.6 (13.0–30.0)	29.8 ± 2.1 (25.1–31.3)	25.4 ± 0.9 (24.3–27.3)	25.85 ± 8.4 (13.4–31.1)
Salinity (ppt/L)	–	–	0.0 ± 0.0 (0.0–0.0)	0.0 ± 0.0 (0.0–0.0)
Specific Conductance (μS/ cm)	212.5 ± 3.5 (210–215)	232.5 ± 17.7 (220–245)	116.1 ± 46.36 (77–188)	232.5 ± 30.4 (211–254)
Dissolved Oxygen (mg/L)	4.4 ± 3.3 (0.2–7.3)	3.8 ± 2.3 (0.2–5.0)	4.71 ± 2.12 (0.8–6.7)	2.9 ± 2.9 (0.2–5.6)
Dissolved Oxygen (% saturation)	98.3	74	61.6 ± 27.24 (9–94%)	74.2
NH_3 (mg/ L)	0.269 ± 0.35 (0.018–0.52)	0.074 ± 0.072 (0.023–0.125)	< 0.0001 ± 0.0 (< 0.0001)	0.074 ± 0.07 (0.023–0.125)
Nitrate + Nitrite (mg/L)	0.184 ± 0.06 (0.143–0.225)	0.013 ± 0.0 (0.013–0.013)	< 0.001 ± 0.0 (< 0.001)	0.02 ± 0.007 (0.015–0.025)
Total Kieldahl Nitrogen (mg/L)	1.323 ± 0.80 (0.757–1.889)	0.537 ± 0.17 (0.417–0.657)	< 0.001 ± 0.0 (< 0.001)	0.528 ± 0.18 (0.40–0.66)
Total Phosphorus (mg/L)	0.54 ± 0.02 (0.039–0.069)	0.035 ± 0.02 (0.020–0.049)	< 0.001 ± 0.0 (< 0.001)	0.033 ± 0.02 (0.015–0.05)
SRP (mg/L)	0.01 ± 0.0 (0.01–0.01)	0.01 ± 0.0 (0.01–0.01)	–	–
Oxidation-Reduction Potential (E_h; mV)	–	–	644 ± 250.6 (270–1020)	569 ± 255.9 (241–960)
Total Dissolved Solids (mg/L)	–	–	58.2 ± 23.1 (39.2–94.4)	50.9 ± 16.5 (37.5–93.1)

previously during nocturnal periods in Lakes Celina and Indian (Simon et al. 2011), while oxidized conditions were always observed in Tipsaw Lake. In a simultaneously conducted study, both Lakes Celina and Indiana were in an oxidized condition during 90% of the diel measurements (Simon et al. 2011).

The concentration of nitrate plus nitrite, ammonia, and total nitrogen and total phosphorus were determined. Nitrogen concentrations were generally low; NO_3, NO_2, and NH_3 occurred in concentrations of less than 0.3 mg/L. Ammonia concentrations ranged from below detection limits in all three lakes to the maximum measured highest concentrations in Indian (0.269 mg/L), followed by Celina (0.224 mg/L), with the lowest maximum concentrations in Tipsaw (0.057 mg/L). Total Kieldahl Nitrogen was highest between 1989–1991 with the highest concentrations in Indian (mean 1.323), followed by Tipsaw (mean 0.08 mg/L), and lowest concentrations in Celina (0.58 mg/L). Mean total phosphorus concentrations were lowest for Lake Celina (0.04 mg/L), followed by Tipsaw (0.045 mg/L), and highest in Indian (0.54 mg/L). The surface waters of the three study lakes all had low concentrations of nutrients. Ammonia concentrations were less than concentrations that would be toxic to aquatic life. The concentration of nitrate plus nitrite was low, ranging from below detection limits < 0.001 to 0.3 mg/L. Indian Lake had the lowest mean concentration of nitrate plus nitrite (0.184 mg/L), followed by Tipsaw Lake (mean

Table 4.—Mean, standard deviation, and range in parentheses for field and water chemistry data collected during July 23, 1991, August 7, 2001, September 16, 2005, July 18, 2011, and September 3, 2012 at Tipsaw Lake in Hoosier National Forest. N = samples for each lake collected from the epilimnion and hypolimnion at the deepest portion.

Parameters	1991 (n = 2)	2001 (n = 2)	2005 (n = 10)	2011 (n = 2)	2012 (n = 2)
Alkalinity (mg/L as $CaCO_3$)	59.3 ± 0.71 (59–60)	80.0 ± 46.7 (47–113)	164 ± 0.00 (164–164)	45 ± 1.41 (44–46)	62 ± 8.49 (56–68)
Hardness (mg/L as $CaCO_3$)	–	–	334 ± 0.0 (334–334)	–	142.5 ± 62.9 (98–187)
pH (SU)	8.0 ± 1.41 (7.0–9.0)	8.4 ± 1.27 (7.5–9.3)	6.97 ± 0.17 (6.8–7.6)	8.0 ± 1.27 (7.1–8.9)	8.0 ± 1.56 (6.9–9.1)
Temperature (°C)	27.2 ± 4.7 (17.0–30.0)	26.9 ± 5.8 (14.5–30.7)	24.5 ± 1.5 (21.8–26.9)	30.2 ± 3.0 (25.7–32.5)	26.1 ± 8.0 (16.5–32.6)
Salinity (ppt/L)	–	–	0.1 ± 0.0 (0.1–0.1)	–	0.1 ± 0.0 (0.1–0.1)
Specific Conductance (µS/ cm)	200.0 ± 14.1 (190–210)	219.5 ± 16.3 (208–231)	150.3 ± 44.98 (78–189)	129.6 ± 4.17 (127–133)	130.9 ± 13.8 (121–141)
Dissolved Oxygen (mg/L)	6.5 ± 2.7 (0.2–8.1)	4.0 ± 2.7 (0.15–6.1)	6.26 ± 1.76 (4.0–10.2)	5.3 ± 3.6 (0.4–8.4)	4.5 ± 3.9 (0.2–7.9)
Dissolved Oxygen (% saturation)	107.7	78.6	69.6 ± 19.86 (49–102%)	98.3	104.5
NH_3 (mg/ L)	0.023 ± 0.0 (0.023–0.023)	0.057 ± 0.77 (0.018–1.118)	< 0.0001 ± 0.0 (< 0.0001)	0.028 ± 0.01 (0.018–0.036)	0.031 ± 0.01 (0.022–0.040)
Nitrate + Nitrite (mg/L)	0.081 ± 0.08 (0.023–0.139)	0.013 ± 0.0 (0.013–0.013)	0.20 ± 0.0 (0.200–0.200)	0.127 ± 0.13 (0.036–0.217)	0.066 ± 0.013 (0.056–0.075)
Total Kieldahl Nitrogen (mg/L)	0.97 ± 0.55 (0.58–1.365)	1.219 ± 1.23 (0.348–2.09)	0.55 ± 0.07 (0.50–0.60)	0.75 ± 0.03 (0.729–0.773)	0.78 ± 0.06 (0.74–0.82)
Total Phosphorus (mg/L)	0.041 ± 0.02 (0.026–0.056)	0.044 ± 0.03 (0.02–0.068)	0.04 ± 0.008 (0.039–0.050)	0.034 ± 0.02 (0.020–0.048)	0.045 ± 0.02 (0.032–0.058)
SRP (mg/L)	0.019 ± 0.01 (0.01–0.03)	0.011 ± 0.002 (0.01–0.013)	–	–	–
Oxidation-Reduction Potention (E_h; mV)	–	–	571.6 ± 169.9 (320–920)	–	569 ± 255.9
Total Dissolved Solids (mg/L)	–	–	74.3 ± 23.2 (31.1–90.9)	–	50.9 ± 16.5 (37.5–93.1)

0.2 mg/L), and Celina (0.36 mg/L) had the highest level (Table 2–4).

The Carlson trophic index evaluates the three independent variables including chlorophyll, total phosphorus, and secchi disk depth (Carlson 1977). The Carlson trophic index classified these lakes as mesotrophic with the highest Tipsaw (22–52), followed by Indian (12–13), and Celina (5–14) as the lowest and most oligotrophic. The quantities of nitrogen, phosphorus, and the total weight of algal biomass are indicators of water body trophic levels. The EPA recommends that the Carlson index should only be used with lakes that have relatively few rooted plants and non-algal turbidity sources An excessive amount of rooted vascular plants was associated with Lakes Indian and Celina, which may affect TI calculations.

Annual comparison.—General patterns in chemical and physical measures is towards a stable steady state or reduction in nutrients. No statistically significant (ANOVA, $P > 0.05$) trend based on regression of parameter by lake over time was observed for any parameter during the study period. Tipsaw Lake showed the greatest variation in nitrogen and phosphorus levels from the earliest 1991 measured value to current 2012 levels, while Celina and Indian were stable over the same period (Table 2–4).

Over the last two decades, the mean temperature trend is toward increasing levels in Indian and Celina, while stable in Tipsaw. The trend in dissolved oxygen is declining in Tipsaw and Indian, while stable in Celina. Stable conditions in all lakes were observed in pH. Declining trends in conductivity were observed for Tipsaw, increasing in Celina, and stable for Indian. Alkalinity trend is increasing in Indian, Celina, and stable in Tipsaw. Salinity has increased in Tipsaw, while stable in the other lakes.

Depth profiles showed a strong thermal profile for Lake Celina during 1989, 1996, and 2001 (Figure 5). The thermocline in 1989 was observed at 5 m, 4 m in 1996, and 8 m during 2001. A strong thermocline was observed in Indian lake in 1991, while less conspicuous in 2001 (Figure 5). In Tipsaw Lake, no oxycline was observed in 1991, but was apparent in 2001 (Figure 5), and recently in the 2011 survey. Dissolved oxygen was present in the deepest portion of each lake, which suggests that the sediment-water column microzone is typically in an oxidized condition. Measurement of oxidation-reduction potential substantiates this observation with 90% of the measurements in a positive state.

Trophic status and fish yield.—The Carlson trophic index has increased between 1989–2012. Tipsaw Lake shows the highest increase with an index rise from 23 to 52. Response in both Indian and Celina did not show similar rises; however, the change in littoral aquatic macrophytes is a possible reason for this change. Trophic levels for these lakes should be classified as mesotrophic (Carlson 1977).

The morphoedaphic index (MEI) is a predicator of fish yield that is based on three hierarchial levels including global scales related to area and temperature, regional scales are dependent on nutrient and mean depth as area and temperature are held constant, and within regional level at which either nutrient or depth variable can be a predictor while the remaining variable is constant (Ryder 1982). Higher MEI values are directly correlated with higher fish yield. The highest MEI value was observed in Tipsaw (24.3 (mg/L)/m), followed by Indian (16.8 (mg/L)/m), and lowest in Celina (9.1 (mg/L)/m; Table 1). The MEI values observed in the three lakes translate to catch yields of 20–30 kg/ha (Ryder et al. 1974).

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