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RESEARCH ARTICLE

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Hydrologic connectivity and land cover affect floodplain lake water quality, fish abundance, and fish diversity in floodplain lakes of the Wabash-White River basin

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Abstract

Floodplain lakes are important aquatic resources for supporting ecosystem services, such as organismal habitat, biodiversity, and the retention of nutrients and sediment. Due to geomorphic alteration of river channels and land-cover change, degradation to floodplain lakes in the Ohio River basin is occurring at a rate that will escalate as climate change causes increased flood intensity and the seasonal redistribution of rainfall. A better understanding of the local drivers that affect oxbow lakes is needed for targeted floodplain restoration efforts designed to slow degradation. We examined the effects of land cover, topography, and hydrologic connectivity on water quality and fish diversity and abundance in nine floodplain lakes with potentially high remnant ecological function in the Wabash-White watershed (Indiana, Ohio, and Illinois). Data collection included water-quality parameters; stable water isotopes; total phosphorus, total nitrogen, and chlorophyll-*a*; and fish community diversity and abundance. Results indicate that hay/pasture land cover and decreased topographic relief in the local oxbow watersheds, along with reduced river hydrologic connectivity, were related to an increase in total phosphorus, total nitrogen, and chlorophyll-*a*. Greater biodiversity and abundance in fish assemblages were evident in oxbow lakes that were more disconnected from the main channel. The results of this study suggest that hydrologic connectivity of oxbow lakes with the contributing drainage area and the main channel influence nutrients and fish communities. Knowing the influencing factors can help ecosystem managers better protect these valuable floodplain lake ecosystems and prioritize restoration efforts amidst increasing stressors due to climate and land-use changes.

KEYWORDS
agriculture, hydrologic connectivity, nutrients, oxbow lakes, restoration, stable water isotopes, wetlands

1 | INTRODUCTION

Arcuate floodplain lakes, also known as oxbow lakes, occur amidst a mosaic of floodplain features in moderate to large river systems when meander bends are cut off as the river migrates across the floodplain (Ward, Tockner, Arscott, & Claret, 2002). Oxbow lakes can provide a myriad of ecosystem services, such as nutrient processing and retention (Jones, Kult, & Laubach, 2015; Schilling, Kult, Wilke, Streeter, &

Vogelgesang, 2017), flood and sediment storage (Wren, Davidson, Walker, & Galicki, 2008), carbon sequestration (Hoffmann, Glatzel, & Dikau, 2009; Mitsch, Zhang, Waletzko, & Bernal, 2014), and habitat for aquatic flora and fauna (Jones et al., 2015; Miranda, Andrews, & Kröger, 2014). Threats to these ecosystem services are abundant and include geomorphic alteration (Schindler et al., 2014), eutrophication (Glińska-Lewczuk, 2005), increased sedimentation tied to changes in climate and land cover (Bianchi et al., 2015; Bird et al., 2019), and invasive species (Spalek, 2015; Wilk-Woźniak, Ligęza, & Shubert, 2014). These threats can be dampened or enhanced by hydrologic connectivity of the oxbow to the main river channel (Amoros & Bornette, 2002; Wang et al., 2020). Providing natural resource managers with tools and information to address threats to floodplain oxbow lakes is useful to improve chances of restoration success.

Floodplain lakes may provide disproportionately large benefits to floodplain ecosystem structure and function in relation to their size. For example, variability of floodplain structure through time begets biodiversity benefits (Amoros & Bornette, 2002). New lakes are generally deep with substantial hydrological river exchange that provides connective habitat for large-river fish. Once disconnected from the main channel, organic matter accumulation, filling, and decreased proximity to the river over time reduce hydrological and biological exchange but may provide habitat for a different set of organisms, including amphibians (Ramalho, Andrade, Matos, & Vieira, 2016; Wang et al., 2020). Variability in floodplain erosion and deposition patterns leads to differences in overbank flow to, and sedimentation rates in, oxbow lakes that increases vegetation patchiness and biodiversity (Piégay et al., 2000). This differentiation of lake function based on age implies that oxbow lakes provide periodic refuge to different sets of organisms through time, thereby supporting biodiversity at the floodplain ecosystem scale. As a result, further study into floodplain lake structure and function is warranted.

Floodplain lakes are also of socioeconomic importance. Recreational fishing brings in substantial tourism dollars (Hoffman, 2004), but degradation over time has lessened recreational use (Knight & Welch, 2004). On a watershed scale, oxbow lakes play a role in nutrient retention and reduction downstream (Gordon, Dorothy, & Lenhart, 2020; Knight, Locke, & Smith, 2013; Lizotte, Knight, Locke, & Bingner, 2014) that is of economic benefit in reducing dead zones in receiving waters (Rabotyagov, Kling, Gassman, Rabalais, & Turner, 2014). Lastly, oxbow lakes reduce flood risk and excess sedimentation but are filling at a faster rate than in the past due to land clearing (Bird et al., 2019) and increased storm intensity and shifting precipitation patterns driven by climate change (Demaria, Palmer, & Roundy, 2016). Shifting rainfall patterns are likely to increase sedimentation in areas with greater storm intensity and may amplify the need for erosion mitigation of surrounding landscapes.

Climate change and land clearing compound other existing threats to ecosystem function, such as artificial levees and bank armoring that separate rivers from floodplain features and reduce development of new oxbow lakes. Conversion of forest to agricultural land cover leads to eutrophication in oxbow lakes, particularly when land-cover change occurs in the riparian zone along lake shorelines (Miranda et al., 2014). Research relating land cover to water quality and biological production in floodplain lakes in large, subtropical rivers has shown that surrounding land-use can have a substantial effect on water quality, but the effect on the biological community is less resolved (Dembkowski & Miranda, 2014; Miranda et al., 2014; Zablotowicz et al., 2010). Biological effects may be specific to the hydroclimatic regime to which the organisms are adapted such that responses to land-use change are not uniform geographically or at various stream orders. Additionally, biological threats are prevalent in floodplain lakes, which can harbor rare and endemic species. For example, substantive human impacts have been implicated in a shift in phytoplankton communities toward lesser niche differentiation and lower biodiversity (Wilk-Woźniak et al., 2014). Invasive species, particularly the exotic silver carp and bighead carp, in the Mississippi River basin have altered food webs (Pongruktham, Ochs, & Hoover, 2010; Pyron et al., 2017; Pyron, Muenich, & Casper, 2020). Understanding ecosystem dynamics at each of these scales is important for prioritizing conservation efforts.

Floodplain mosaics and oxbow lakes in the subtropical lower Mississippi River basin have been studied widely, but less research has focused on the Ohio River basin in the hot-summer humid continental climate zone where oxbows may still exist with high remnant function due to lesser levying and armoring despite the negative effects that dams and agriculture have had on the hydrology (Pyron & Neumann, 2008). More information is needed in medium-sized river systems, such as the Wabash-White in the Midwest of North America (Figure 1) to guide and prioritize conservation efforts. To this end, we studied nine floodplain lakes in the Wabash-White watershed in the Ohio River basin using water-quality and fish sampling, stable water isotopes, and geospatial data analysis. We asked the question: what are the drivers of water quality and fish abundance and diversity in floodplain lakes of moderately sized rivers? In particular, we were interested in examining: (a) how local land use and hydrological river connectivity influence water quality and fish diversity in oxbow lakes of the Wabash-White watershed, and (b) how we can use this understanding of the major drivers to guide floodplain conservation and restoration efforts.

2 | METHODS

2.1 | Overview

The potential drivers of water quality in oxbow lakes that were examined in this study included land cover, connectivity to the main channel measured using stable water isotopes, and topographic relief in the local oxbow watershed influencing connectivity in the contributing local drainage area. Water quality in oxbow lakes was assessed using the following response variables: total phosphorus (TP), total nitrogen (TN), chlorophyll-*a*, turbidity, pH, specific conductance, temperature, dissolved oxygen, and Secchi depth. Drivers of fish diversity and abundance included the same hydrologic connectivity and land-cover variables plus the water-quality parameters.

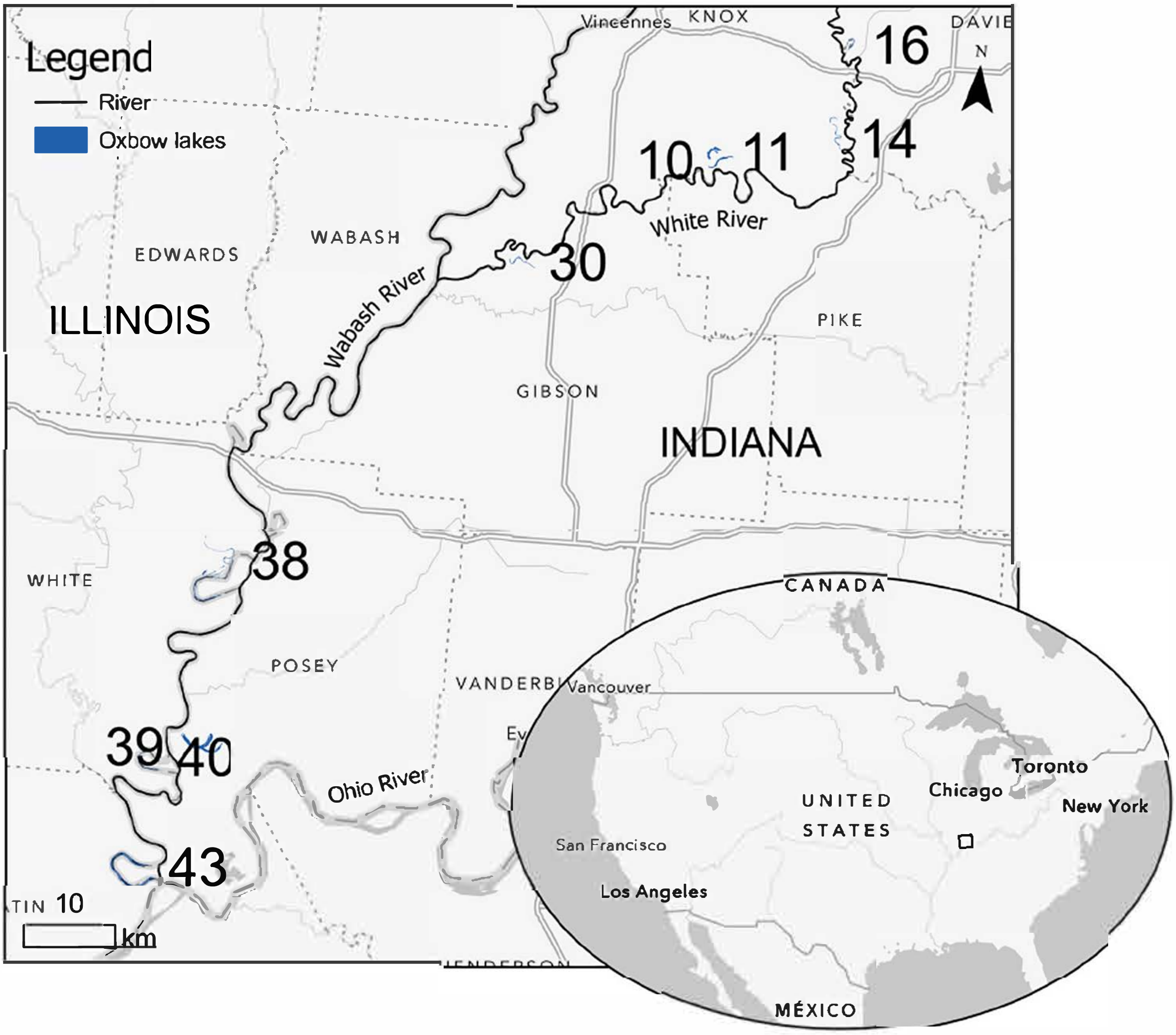

FIGURE 1 Map of the nine oxbow lakes in the study located in the Wabash-White watershed in the midwestern United States (inset). Numbers refer to oxbows listed in Table 1 (*Map data sources*: ESRI, HERE, FAO, NOAA, USGS) [Color figure can be viewed at wileyonlinelibrary.com]

2.2 | Site description and selection

The Wabash River basin covers 86,000 km^2 in east-central Illinois, a small area of west-central Ohio, and north-central to southwest Indiana in the midwestern United States (Figure 1). Land cover in this area is predominantly agricultural, with widespread row cropping on floodplains. The river's mainstem runs for 809.5 km, of which the lower 659.8 km are free flowing. The floodplain of the lower 273.6 km of the Wabash varies from approximately 8–16 km wide and covers approximately 279,233 ha. In addition, the lower 160.9 km of the White River (the main tributary of the Wabash) is contained within a floodplain ranging in width from 1.6 to 6.4 km. Within these two floodplain areas are the majority of the over 100 floodplain lakes. Mean annual temperature for the basin is 10.5–13.3°C (north to south) with annual precipitation ranging from 91 to 112 cm (northeast to southwest). Annual mean discharge for the Wabash River at New Harmony, Indiana, for water years 2011–2020 was 1,072.9 cms, with a maximum daily mean of 8,919.8 cms and a minimum daily mean of 77.6 cms. The Wabash and White rivers are relatively flashy with high flows typically in the spring due to snow melt and spring storms, with low flows occurring in late summer and fall (Figure 2).

Site selection was initiated by identifying floodplain lakes in the Wabash-White watershed that (a) were connected to the river channel and (b) had over 16 ha of open water as measured using aerial imagery. Of the 15 floodplain lakes that qualified, nine had water year-round and access permission from landowners and were, therefore, selected for this study (Figure 1 and Table 1).

2.3 | Geospatial data collection

Floodplain lakes effectively have two watersheds, the local watershed, when the main channel is below bankfull discharge, and another when connected to the main channel at or above bankfull. In this study, we were most interested in describing effects of the local watershed. Therefore, oxbow lake boundaries and local watershed delineations

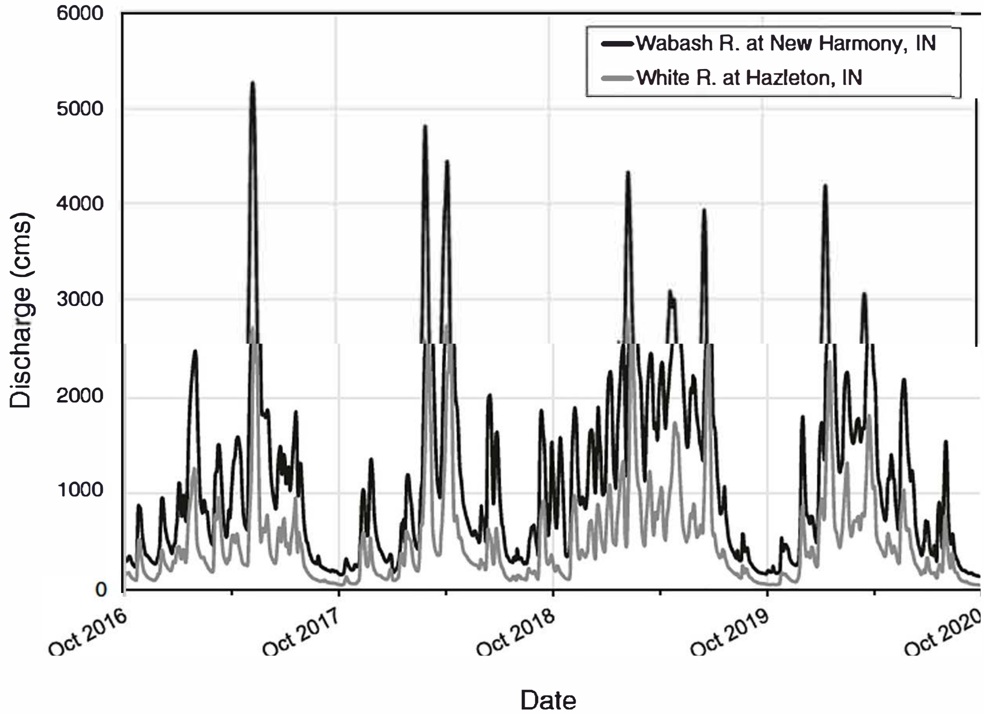

FIGURE 2 Hydrograph of the Wabash River at New Harmony, IN (03378500) and the White River at Hazleton, IN (03374100) over the 2017–2020 water years of the study showing the flow regime, including flow timing and magnitude, at the gaging stations furthest downstream on each of the two main stems (*Data source*: USGS)

TABLE 1 Characteristics of the nine Wabash-White watershed oxbow lakes in the study, including surface area of the oxbow lake, local watershed area draining to the outlet of the oxbow at the main channel, mean land-surface slope within the contributing drainage area as a proxy for topographic relief, and deuterium excess (d-excess) derived from stable water isotopes collected in July 2018 as an indicator of connectivity to the main channel during low river flow

Oxbow ID	Oxbow name	Latitude (deg)	Longitude (deg)	Watershed	Surface area (km^2)	Local watershed area (km^2)	Mean slope (%)	d-excess
10	Long pond Knox	38.545	87.410	White	0.453	4.54	4.64	2.28
11	Half moon pond	38.558	87.417	White	0.557	5.12	4.49	2.55
14	Long pond Anson	38.579	87.262	White	0.352	7.29	2.22	0.48
16	Hyatt	38.677	87.246	White	0.201	2.90	2.94	5.41
30	Long pond Gibson	38.441	87.643	White	0.283	8.62	3.17	10.06
38	Ribeyre	38.100	88.015	Wabash	1.705	37.73	0.89	7.05
39	Pitcher Lake	37.944	88.013	Wabash	2.162	35.96	0.44	10.69
40	Greathouse	37.932	88.061	Wabash	0.568	13.93	0.24	10.41
43	Mackey	37.809	88.071	Wabash	3.354	37.09	0.53	9.86

Note: A more positive d-excess value indicates a signature more like that of river water and, therefore, a more open oxbow lake system.

were performed using LIDAR-based digital elevation models circa 2012–2013 with 6.1 cm vertical accuracy in ArcGIS 10.2.2 using NRCS GIS Engineering Tools (version 1.1.7) that created a shaded depth grid, flow paths, contour lines, an outlet area, and the watershed delineation for the lowest outlet of the oxbow to the river, typically at the tie channel. Lake surface area, local watershed area, and mean topographic slopes (percent) as a proxy for topographic relief within the watershed boundaries were measured in ArcGIS 10.2.2. Local watersheds with steeper slopes indicated the presence of terrace-floodplain topographies, whereas shallower slopes indicated floodplain-only topography. Land-cover data from the 2016 National Land Cover Database (Homer et al., 2020) were clipped to the local oxbow watersheds and summarized in ArcGIS Pro 2.4.0 to obtain percent of watershed occupied by a given land cover class (Table 2).

2.4 | Field data collection and laboratory analysis

Water-quality data included specific conductance (μS/cm), dissolved oxygen (mg/L), turbidity (FNU), pH, and temperature (°C) collected approximately monthly using a calibrated YSI Pro-DSS from July 2017 to August 2020. To determine the sampling regime, samples were

'ABLE 2 Nationa Land Cover Database (NLCD) characteristics of the oca oxbow watersheds, standardized by watershed area. Low, medium, and high intensity and cover categories have ɔeen combined, and evergreen forest and shrub/scrub have been removed due to very ow incidence (<0.03%)

Dxbow D	Dxbow name	Dpen water (%)	Developed, open pace (%)	Developed, low/med/ nigh intensity (%)	Barren land (%)	Deciduous forest (%)	Mixed forest (%)	Emergent herbaceous wetlands (%)	Woody wetlands (%)	Pasture/ hay (%)	Cultivated crops (%)
.0	.ong pond Knox	3.37	2.92	).238	0.119	11.3	).337	0.258	5.34	0.32	69.56
.1	Ha f moon pond	5.22	1.02	).123	ɔ	13.9	0.931	0.070	7.98	2.69	63.92
.4	.ong pond Anson	2.51	1.48	).012	0.012	2.6	).074	0.025	5.69	0	86.36
.6	Hyatt	5.06	2.26	).806	ɔ	13.3	ɔ	0.062	6.45	12.99	57.25
30	.ong pond Gibson	3.17	1.68	).115	0.021	19.8	2.840	0.626	4.44	7.58	59.06
38	Ribeyre	3.95	3.67	).747	1.019	10.2	).458	0.005	15.52	0.95	61.88
39	Pitcher Lake	2.82	3.99	).443	0.568	11.9	).581	0.023	14.04	2.85	61.09
10	Greathouse	3.70	2.57	).343	2.443	7.5	).136	0.110	30.50	0.25	52.00
13	Mackey	3.41	1.12	).352	2.218	7.4	).104	0.403	22.12	0.19	57.18

collected from three randomly selected locations in each lake and selected to minimize localized effects from tributary inputs, near-shore influences such as vegetation, or groundwater upwelling. At each location, samples were collected from two depths: approximately 10–30 cm below the lake surface and half of the total depth. Bottom samples were not collected systematically due to confounding dynamics at the sediment–water interface, identified in reconnaissance sampling, that were outside the scope of the study. Data collected from the near-surface and at mid-depth were similar at various locations within each lake, likely due to lake size and resulting fetch making the lakes reasonably well mixed (e.g., differences in specific conductance values between near-surface and mid-depth were on the order of 2–4 μS/cm, with the exception of Oxbow 43 that showed a greater range around 20 μS/cm in two of the three locations in August, 2017). Lateral variability in near-surface samples was minimal, as well (e.g., the largest observed standard deviation in near-surface specific conductance values was 5.7 for a mean of 432.1 μS/cm at Oxbow 39 in August, 2017). Therefore, single surface samples were deemed sufficient for the aims of the study. Sampling locations were identified and geolocated to ensure that repeated samples were collected at the same locations. This approach allowed us to sample multiple lakes during a single sampling campaign to minimize the impacts of short-term hydroclimatic changes.

TN, TP, and chlorophyll-*a* were collected monthly from June to October 2019 and analyzed by the Indiana Clean Lakes Program (https://clp.indiana.edu/). Water samples for TN and TP were acidified using H_2SO_4 and stored at 4°C until analysis by digestion using alkaline persulfate standard methods (*Standard Methods for the Examination of Water and Wastewater*, 22nd edition. Section 4500-P J.). Chlorophyll-*a* water samples were filtered through a Whatman GF/F filter, stored at less than 0°C for no more than 3 weeks, and analyzed using acetone extraction, grinding, and spectrophotometry (Evolution 220) using standard methods (*Standard Methods for the Examination of Water and Wastewater*, 21st edition, Section 10200 H).

Connectivity to the main channel was assessed using stable water isotopes (e.g., Babka, Futó, & Szabó, 2011). Water samples were collected and analyzed for δ^2H H_2O and $\delta^{18}O$ using a Picarro L2130-i cavity ring-down spectroscopy analyzer coupled to an autosampler and high-precision water vaporizer unit at Indiana University-Purdue University, Indianapolis (van Geldem & Barth, 2012). Laboratory measurement uncertainty indicated by standard deviation in relation to reference waters was minimal for isotopes, with a maximum value of 0.28‰ for δ^2H and 0.07‰ for $\delta^{18}O$. Connectivity was determined by evaluating whether the $\delta^{18}O$ and δ^2H values of samples plotted on the Global Meteoric Water Line (GMWL; representing the average global relationship between δ^2H H_2O and $\delta^{18}O$ in precipitation; connected to the river) or the Regional Evaporation Line (REL; reduced connection to the river and hence evaporative enriched).

Additionally, the deuterium-excess value (d-excess) was calculated following Dansgaard (1964) using Equation (1) as a single metric for the degree of connectivity with the main channel, where greater d-excess values (near 10) indicate greater prevalence of meteoric water and, therefore, greater connection to the river. Deviations below 10 are due to evaporation or differing environmental conditions under which precipitation occurred and have been used successfully in prior studies as an estimate of evaporation (Ala-Aho et al., 2018; Gat, 1996; Hu et al., 2018).

$$d \quad \text{excess} \quad \delta^2H \quad 8*\delta^{18}O. \qquad (1)$$

2.5 | Fish sampling

Sampling of all habitats present in the nine lakes in the study occurred by boat electrofisher (60 Hz DC, Midwest Boat Management, Inc.) in 2018 during high water levels in spring and early summer and again during low water levels in fall with identification, measurement, and release occurring on-site (Ball State University IACUC #126193). Mean collection effort was 36.5 min per lake and ranged from 25 to 50 min per lake, depending on lake size and habitat complexity. Side-scan sonar indicated similar habitat in all lakes, primarily silt and sand substrates with little structure. Shannon-Weiner diversity index, species richness, abundance, and catch-per-unit-effort (CPUE) with collection time of the overall fish community were used to summarize the data. The species richness and abundance of large-river specialist fishes (Hocutt & Wiley, 1986) (e.g., channel catfish, flathead catfish, river carp, and quillback) were extracted and analyzed separately.

2.6 | Data analysis

Linear regressions were fit in IBM SPSS Statistics 26. Dependent variables included TN, TP, chlorophyll-*a*, Shannon-Weiner Index, CPUE (fish/minute), and species richness and abundance of large-river specialist fishes. Independent variables included the average slope in the local watershed as a proxy for topographic relief; percent land-cover in each of the NLCD categories; d-excess in July 2018; and annual averages across 2017–2020 for specific conductance (μS/cm); dissolved oxygen (mg/L), turbidity (FNU), pH, and temperature (°C). Regression models were examined graphically for normality and homoscedasticity, for autocorrelation by verifying a Durbin–Watson statistic near 2.0, and for fit using Akaike Information Criterion and significance at the α .05 level of confidence. Multicollinearity among independent factors in regressions was assessed using the variance inflation factor (VIF). All VIF values were less than 2.5, indicating no more than marginal multicollinearity that did not warrant correction. Interaction terms in the regressions were tested, but significant interactions were not detected.

3 | RESULTS

3.1 | Lake River connectivity

Degree of connectivity between each oxbow lake and the main channel was evident in the stable water isotope data (Figure 3, d-excess in

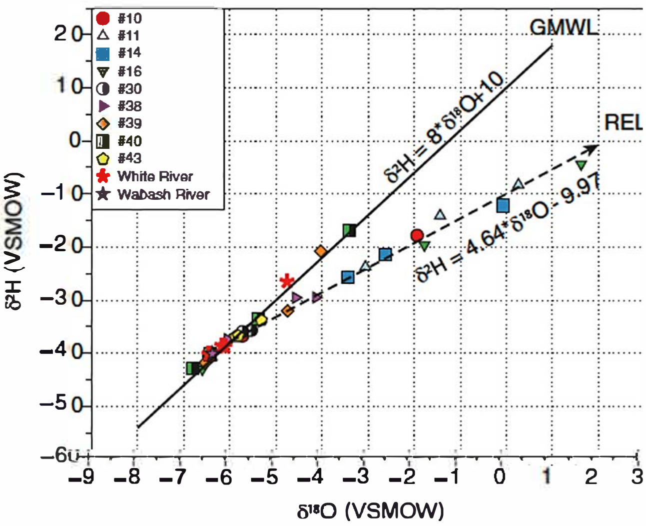

FIGURE 3 Stable water isotope data collected from April through October of 2018 for the nine oxbow lakes in the study and the Wabash and White Rivers. Solid line indicates the Global Meteoric Water Line (GMWL). Dashed line indicates the Regional Evaporation Line (REL) [Color figure can be viewed at wileyonlinelibrary.com]

Table 1). River samples fell along the GMWL, and oxbow samples plotting closer to the meteoric water line, and therefore similar to water from the main channel, suggested they were more hydrologically connected to the river. Spring samples (lower left points in Figure 3) plotted more closely to the river line, and as river stage declined over the summer months (Figure 2), stable water isotope data evolved along the Regional Evaporation Line (REL, Figure 3). Similar variability in connectivity was evident from the d-excess data from July, 2018, where a more positive d-excess value indicates a signature more like that of river water and, therefore, a more open oxbow lake system (Table 1).

3.2 | Water quality

Little variability was observed among oxbow lakes in turbidity, pH, specific conductance, temperature, dissolved oxygen, or Secchi depth (Figure 4). Some lakes showed greater temporal variability than others. Oxbow 16 showed greater TN, TP, and chlorophyll-*a* values than the other lakes but was included in subsequent statistical analyses because visual inspection of partial regression plots indicated that this site did not artificially influence regressions as an outlier.

Nutrients and primary production were significantly related to land cover, topographic relief (as measured by average watershed slope), and connectivity to the main channel (Table 3). Cultivated crops were not significantly related to the nutrient response variables due to the high prevalence across all watersheds and lack of variation among watersheds (Table 2). TN, TP, and chlorophyll-*a* were positively related to the hay and pasture land cover (%) and negatively related to mean slope (%) of the oxbow local watershed, where watersheds with greater topographic relief that included terrace and valley wall areas

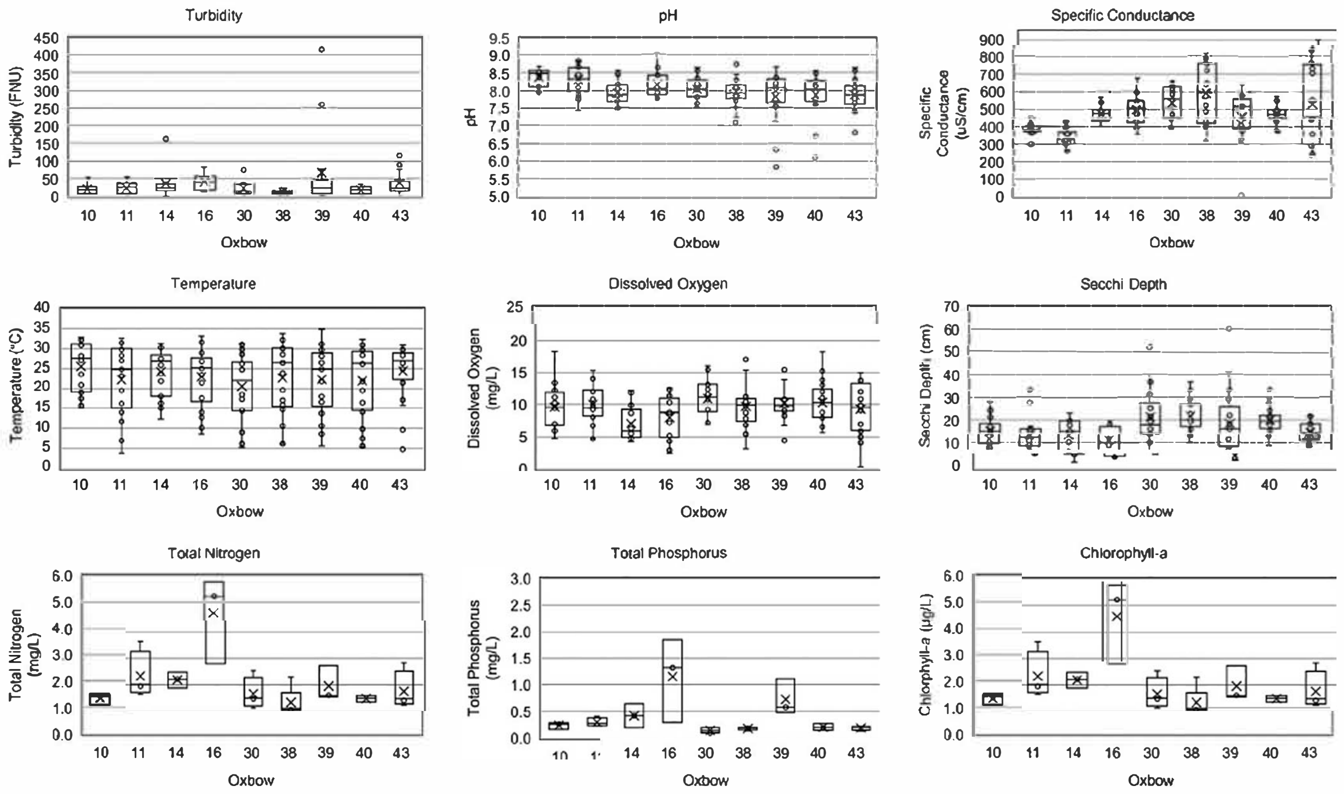

FIGURE 4 Water-quality measurements over the 2017–2019 study period for the nine oxbow lakes in the study showing the degree of variability within an among lakes

TABLE 3 Linear regressions of drivers of mean total nitrogen (TN), mean total phosphorus (TP), and chlorophyll-*a* measured monthly from June to October 2019, in nine oxbow lakes within the White-Wabash watershed of Indiana and Illinois, USA (*df* 3,5,8)

Dependent	Independent	Coefficient	R^2	*F*	*t*	*p* value
Mean TN (ppm)			.948	30.64		.001
	Constant	2.86			9.65	.0002
	Land cover: Hay and pasture (% of oxbow local watershed)	0.16			6.68	.001
	d-excess in July 2018	0.12			5.33	.003
	Mean slope of local oxbow watershed (%)	0.35			3.95	.011
Mean TP (ppm)			.797	6.543		.035
	Constant	0.73			3.68	.014
	Land cover: Hay and pasture (% of oxbow local watershed)	0.05			3.08	.028
	d-excess in July 2018	0.04			2.63	.047
	Mean slope of local oxbow watershed (%)	0.15			2.51	.054
Chlorophyll-*a* (µg/L)			.913	17.44		.004
	Constant	203.32			3.68	.01
	Land cover: Hay and pasture (% of oxbow local watershed)	9.04			2.51	.05
	d-excess in July 2018	9.28			3.08	.03
	Mean slope of local oxbow watershed (%)	37.12			2.63	.05

in addition to floodplain showed lower levels of nutrients and primary production in the lake (Table 3 and Figure 5). When hay and pasture lands were in an upland region of the watershed, nutrients in the oxbow lake tended to be lower (Figures 5 and 6). For example, comparing Oxbow 10 and Oxbow 30 to Oxbow 16 in Figure 6, the hay and pasture lands in 10 and 30 are on a river terrace, whereas in Oxbow 16, the hay and pasture lands are on the floodplain, potentially resulting in greater nutrient concentration in Oxbow 16 (Figure 4).

The d-excess values were negatively related to TN, TP, and chlorophyll-*a*, where lakes with greater d-excess values, and therefore

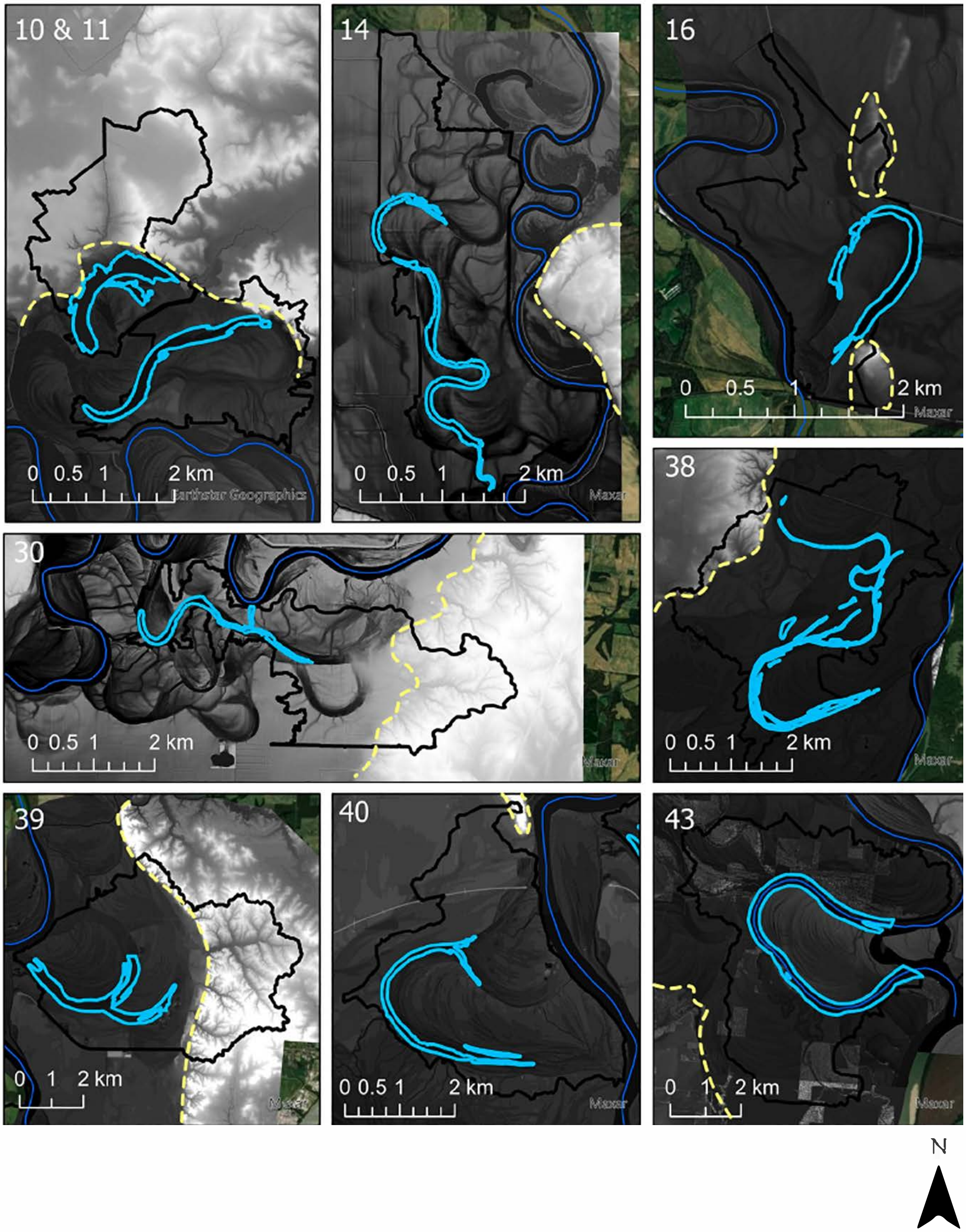

FIGURE 5 Digital elevation models showing relative elevations at the nine oxbow lake sites. Index numbers refer to Figure 1. Lighter grays indicate higher elevation relative to darker grays of lower elevation. Turquoise outlines are the floodplain lake boundaries. Dark blue lines indicate the main channel. Black outlines refer to the local watershed boundaries, with the outlet at the tie channel. Dashed yellow lines indicate approximate location of the valley wall where the topography transitions rapidly to river terrace or upland [Color figure can be viewed at wileyonlinelibrary.com]

more open to the main channel, showed lower levels of nutrients and chlorophyll-*a* (Table 3).

3.3 | Fish diversity and abundance

Fish diversity and abundance were related to local watershed characteristics, water quality, lake dimensions, and connectivity to the main channel. Shannon-Weiner indices of fish diversity showed oxbows with greater turbidity having lower diversity (Table 4). Greater diversity was related to greater proportions of developed open space land cover—consisting primarily in this area of farm roads and driveways—and woody wetland land cover, as well as greater lake surface area (Table 4). Fish abundance in the total fish community as catch-per-unit-effort (CPUE) was positively related to chlorophyll-*a* ($F_{1,7}$ 17.837, p .004). Lesser local watershed slopes indicating greater

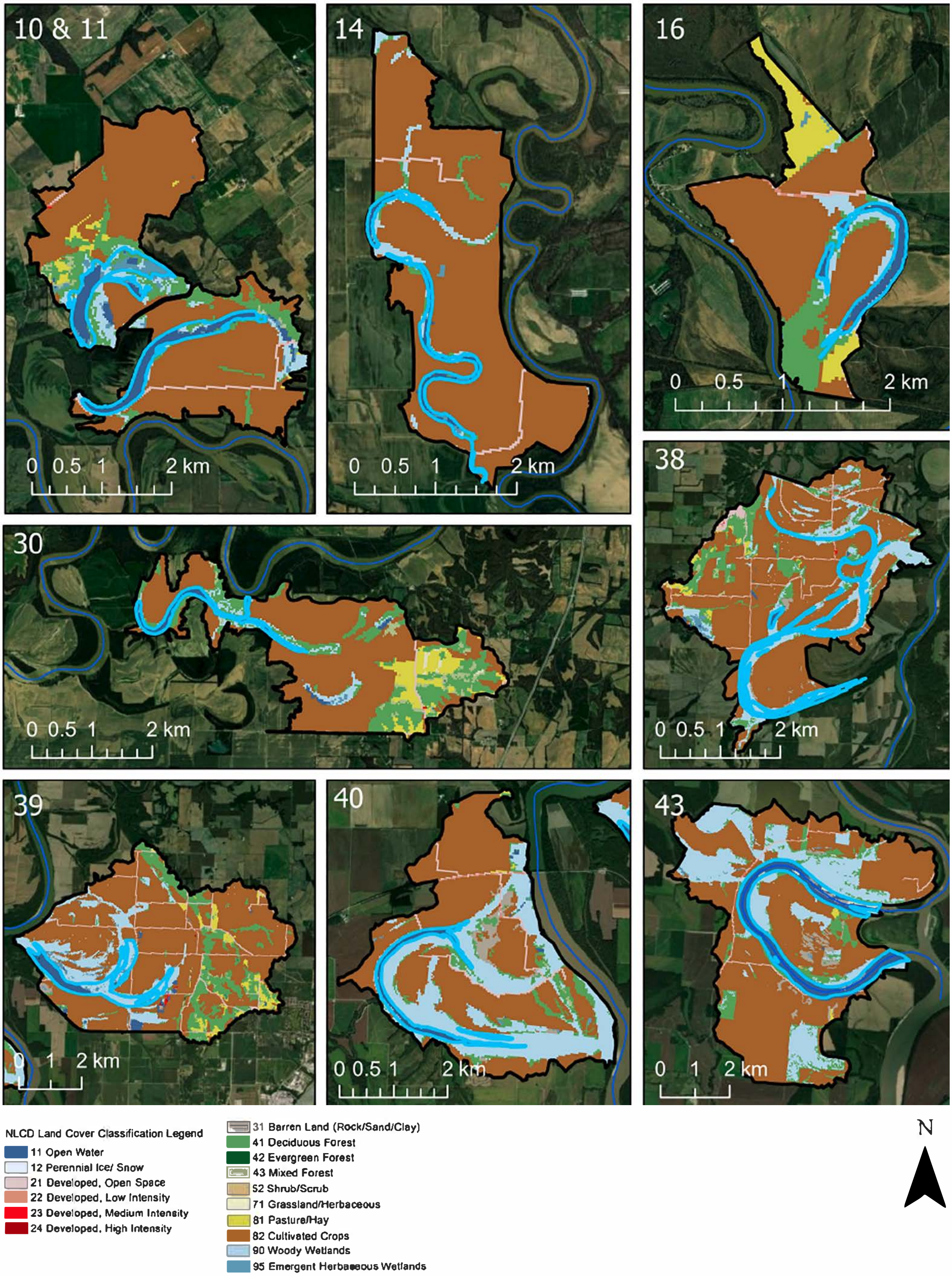

FIGURE 6 National Land Cover Dataset (NLCD) land-cover classes for the watersheds of the nine oxbow lakes in the study, showing a predominance of cultivated crops (brown) with some hay/pasture (yellow), forest (greens), and wetlands (light blues). Turquoise outlines are the floodplain lake boundaries. Dark blue lines indicate the main channel. Black outlines refer to the local watershed boundaries, with the outlet at the tie channel [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Linear regression results of drivers of Summer 2018 fish community metrics in nine oxbow lakes within the White-Wabash watershed of Indiana and Illinois, USA

Dependent	Independent	Coefficient	R^2	F	t	p value
Shannon-Weiner index			.964	27.02		.004
	Constant	2.76			13.29	.0002
	Mean turbidity (FNU)	0.02			4.96	.008
	Developed open (pct)	0.36			5.49	.005
	Woody wetlands (pct)	0.04			4.52	.011
	Surface area (km^2)	0.29			3.60	.023
CPUE (fish/min)			.755	3.975		.080
	Constant	3.535			5.89	.001
	d-excess	0.12			2.58	.041
	Mean slope of local oxbow watershed (pct)	0.50			2.68	.036
Species richness of Large-River specialist fishes			.882	12.45		.009
	Constant	14.19			11.42	.000
	d-excess	0.20			2.76	.040
	Emergent herbaceous wetland (pct)	1.64			4.16	.009
	Developed open (pct)	1.62			4.21	.008
Abundance of Large-River specialist fishes			.959	38.82		.001
	Constant	199.03			4.83	.005
	Specific conductance (μS/cm)	0.44			5.54	.003
	Chlorophyll a (μg/L)	0.52			6.72	.001
	Mean slope of local oxbow watershed (pct)	12.50			3.63	.015

prevalence of floodplain were related to greater CPUE, and lakes that showed greater summertime exchange with the river (greater d-excess) had lower CPUE, although not significantly (Table 4).

For the large-river specialist fishes, species richness and abundance were used as metrics, as diversity indices and CPUE are, by definition, calculated on the entire community and therefore were not quantifiable on this subset of the fish community. Oxbows with greater summertime river exchange (positive d-excess values) showed lesser species richness of large-river fish (Table 4). Emergent herbaceous wetland land cover was negatively related to large-river fish richness, whereas developed open space land cover was associated with large-river fish diversity. Greater specific conductance, chlorophyll-*a*, and steeper slopes were associated with greater abundance (Table 4).

4 | DISCUSSION

Oxbow lakes are major features of floodplain mosaics that provide multiple ecosystem services, including nutrient processing and fish habitat (Naus & Reid Adams, 2018; Winemiller, Tarim, Shormann, & Cotner, 2000). Anthropogenic influences on land cover and floodplain connectivity, however, can degrade oxbow lakes and diminish lake function. The results of this study suggest that local land cover, topography of the local contributing drainage area, and connectivity to the main channel influence nutrients and fish habitat. Knowing the influencing factors can help ecosystem managers better protect valuable oxbow lake ecosystems.

In this study of nine oxbow lakes in the Wabash-White watershed in the Ohio River basin, percent of the local watershed occupied by hay and pasture land cover was related to increases in nutrient and algae concentrations in the lakes, but effects of cropland were not detected. Cultivated crops were far more prevalent in the floodplain and did not vary among local watersheds. While row crops likely contribute nutrients to the floodplain lakes, the effect is similar among the lakes in the study. Hay and pasture areas that support livestock and may contribute nonpoint source pollution were less prevalent in comparison but more variable. The unexpected influence of hay and pasture land on nutrient status of the lakes warrants further investigation. In Oxbow 16, where higher nutrient values were observed, the hay and pasture was adjacent to the lake, whereas in other watersheds, the hay and pasture lands were primarily in terraces above the floodplain. Watersheds with a more variable topography containing a portion of the valley wall and terraced upland areas in addition to floodplain (and therefore steeper average watershed slopes) were associated with lower nutrients in the oxbow lake, as well. While these may be connected by ditches or other routing pathways, biochemical processes, and/or vegetative uptake may reduce the ultimate transport to the floodplains. These results support the idea that keeping agricultural land uses out of the floodplain are beneficial for maintaining water quality in floodplain lakes. Elucidation of the mechanisms or farming practices relating hay and pasture lands to increases in nutrient and algae concentrations would assist in conservation efforts of these lakes.

Efforts to preserve and restore wetlands within floodplain mosaics will help maintain fish diversity. The positive relationships observed between oxbow fish metrics and the wetland land cover classes indicated that wetlands within the oxbow watershed were associated with greater species diversity in the overall fish community and in the large-river fish populations, respectively, a finding that is commonly observed in studies of land cover effects on fish assemblages (e.g., Diana, Allan, & Infante, 2006; Stauffer, Goldstein, & Newman, 2000). Because remnant wetlands in these floodplain ecosystems comprise a small portion of the oxbow watersheds, minor improvements to wetland area are likely to have a disproportionately beneficial effect on diversity of fishes in these ecosystems due to nutrient retention, hydrologic regulation, and habitat (Cheng, Van Meter, Byrnes, & Basu, 2020). Maintaining diversity is particularly important in oxbows for promoting ecosystem function in the face of invasions by silver and other bighead carps that have occurred (Pongruktham et al., 2010; Pyron et al., 2017; Pyron et al., 2020). Increasing bank stabilization and construction of levees threaten to decrease rates of formation of oxbow lakes compared to historic rates (Matthes, 1948; Miranda, 2005).

Hydrologic connectivity to the main channel at various scales has been shown to be important for maintaining ecosystem function in rivers and floodplains. At the watershed scale, Hansen, Dolph, Foufoula-Georgiou, and Finlay (2018) showed that watershed restoration effectiveness on nutrient export depends on having more prevalent and more connected nonfloodplain wetlands in the watershed. Multiple studies showed that increased connectivity at the local scale between oxbows and the main channel led to lower nutrients in the lake with a shift in ecological regime moving laterally away from the main channel (Bhattacharya, Hausmann, Hubeny, Gell, & Black, 2016; Kufel & Leśniczuk, 2014; Wang et al., 2020). The results of this study suggest that the main channel may have a diluting effect on nutrient concentrations when oxbows are well-connected to the river through tie channels or flooding. Additionally, although disconnected oxbow lakes showed higher nutrient concentrations in this and other studies, nutrient processing of pollutants from upslope by the more distal lakes may be of benefit in floodplain landscapes.

River connectivity is also related to fish diversity and abundance in complex ways. Unlike floodplain lakes in the lower Mississippi River that experienced a reduction in fish diversity and abundance with disconnection from the main channel (Dembkowski & Miranda, 2011; Miranda, 2005), connected oxbows in this study showed lower overall fish abundance and species richness of large-river specialist fishes. Owing to the smaller alluvial valley in the Ohio River basin and study design targeting oxbows that had a surface connection, the oxbows in this study were in closer proximity to the channel than other studies, again highlighting the importance of scale and positioning in the greater floodplain landscape. Lakes situated further away from the main channel tend to be more stable hydrologically and therefore reflect different processes related to biodiversity. Floodplain lakes located very far from the main channel experience shallowing with time due to organic matter accumulation and reduced flood pulse frequency that excludes certain fish species while supporting amphibian communities (Miranda, 2005; Ramalho et al., 2016). In this way, oxbow lakes of various ages and localities within the floodplain provide a suite of different ecosystem services (Amoros & Bornette, 2002).

The mosaic of ecosystem services that comprises floodplain landscapes that include oxbow lakes highlights the importance of conservation and preservation. In the United States, the Clean Water Act protects waters, such as floodplain lakes, having a significant nexus to a permanent river feature. However, as oxbow lakes become disconnected from the main channel and incorporated into agricultural landscapes, legal protection becomes less clear. Conservation measures that include wetland preservation (Bolpagni & Piotti, 2016) and afforestation or reforestation of land area adjacent to the oxbow lakes (Cullum, Locke, & Knight, 2010) where slopes are shallow are likely to reduce sedimentation and nutrient loading (Knight et al., 2013). Maintaining connectivity in floodplain lakes that are close to the river is also important in the face of alteration of river flows due to climate change, with greater discharge in flood stage and lower low flows (Demaria et al., 2016). Resulting changes to sedimentation and cycles of erosion and deposition may affect connectivity in tie channels (Rowland, Lepper, Dietrich, Wilson, & Sheldon, 2005). Hydrology and habitat heterogeneity influence fish recruitment and should also be managed effectively to maintain biodiversity (Zeug & Winemiller, 2008), recognizing that degree of connectivity changes through time and leads to changes in community assemblage and water quality. Integrating best management practices in a holistic approach to ecosystem-based management that reduces sedimentation can have substantial benefits to oxbow lakes and floodplain landscapes overall (Cullum, Knight, Cooper, & Smith, 2006; Kröger et al., 2013; Lizotte et al., 2014).

5 | CONCLUSION

The examination of the effects of land cover and hydrologic connectivity to the main channel and of the contributing local drainage area on water quality and fish diversity and abundance in nine oxbow lakes in the Wabash-White watershed revealed that increased land cover in hay and pasture and floodplain-dominated topographies in the local oxbow watershed, along with lesser hydrologic connectivity to the main channel, were related to an increase in TN, TP, and chlorophyll-*a*. Greater biodiversity and abundance in fish communities, however, were evident in oxbow lakes that were more disconnected from the main channel. This apparent trade-off underscores the importance of maintaining water quality and riparian habitat as oxbow lakes age. The results of this study suggest that local land cover and hydrologic connectivity to the main channel influence nutrients and fish communities in important ways. Inundation mapping and analysis of connectivity frequency in future studies would be a valuable contribution to better understanding floodplain lake dynamics, particularly as higher resolution LiDAR mapping becomes available. Knowing the influencing factors can help ecosystem managers better protect these valuable oxbow lake ecosystems and prioritize restoration efforts amidst increasing stressors due to climate and land-use changes.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in PURR, the Purdue University Research Repository, at https://doi.org/10.4231/B3M8-0767 (Carlson Mazur et al., 2021).

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