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RESEARCH ARTICLE

Nutrient retention in tile-fed and non-tile reconstructed oxbows in north central Iowa

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Abstract

Nutrient export from the agricultural Midwest threatens the Gulf of Mexico and new conservation practices are needed to reduce the loss of nutrient from subsurface tile drainage systems. Oxbows are natural waterbodies formed when a river cuts off a meander loop and water quality benefits of reconstructed oxbows are being increasingly recognized. In this study, we monitored four reconstructed oxbow sites (two tile-fed, two non-tile) over a 2-year period in north-central Iowa and assessed their capacity for NO_3-N and dissolved reactive phosphorus (DRP) reductions. Water flow and quality monitoring of tiles, shallow groundwater, oxbow and receiving streams documented that the oxbows were dominated by tile drainage inputs. NO_3-N concentrations were highest in the drainage tiles flowing into the tile-fed oxbows (mean 8–10 mg/L) and much lower in floodplain groundwater (<1–2 mg/L). Annual NO_3-N loads into the tile-fed oxbows were substantially larger than input loads into the non-tiled oxbows. For the two tile-fed oxbows, the 2-year NO_3-N retention efficiencies were very similar (0.76–0.77) and on a monthly basis, greater retention efficiencies were measured in summer and fall. DRP concentrations and loads into the tile-fed oxbows were too low to allow for meaningful estimates of retention. Reconstructing oxbows to receive tile drainage water should be considered a sustainable conservation practice for tile drainage treatment in agricultural areas.

KEYWORDS
oxbow, nitrate, dissolved reactive phosphorus, tile drainage, nature-based solutions, conservation practices

1 | INTRODUCTION

Widespread nutrient loss from agricultural areas of the U.S. Midwest is negatively impacting aquatic ecosystems at local and regional scales (Rabalais & Turner, 2019; USEPA, 2013), including development of a seasonal hypoxic (dead) zone in the Gulf of Mexico (Turner et al., 2008). The U.S. Environmental Protection Agency (USEPA) has called for a 45% reduction in both nitrate-nitrogen (NO_3-N) and phosphorus (P) loading to the Mississippi-Atchafalaya River Basin to reduce the size of the hypoxic zone by 2035 (HTF, 2015). In an effort to meet this goal, many states have adopted strategies to reduce nutrient export (Christianson et al., 2018) and new best management practices (BMPs) are being developed that serve to enhance nutrient processing while minimizing loss of crop production (McLellan et al., 2015). Newer BMPs include

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Research Impact Statement

Riverine oxbows reconstructed to receive inflow water from subsurface tile drainage reduce nitrate-nitrogen loads while providing ecosystem services for aquatic life.

blind inlets (Smith & Livingston, 2013), prairie strips (Zhou et al., 2014), saturated buffers (Jaynes & Isenhart, 2014) and oxbow lakes (Schilling, Wilke, et al., 2019).

Oxbows are natural floodplain features formed when a river cuts off a meander loop as it migrates within its floodplain. Natural oxbows are among the most biologically diverse aquatic systems in the world (Goetz et al., 2015; Ward, 1998), but accumulation of sediment and organic material often fill the oxbow over time and the systems transition from a lentic to terrestrial habitat (Piegay et al., 2000). Removing the oxbow fill material and restoring the lentic habitat is considered oxbow reconstruction. To date, reconstruction of oxbows in agricultural areas of the U.S. Midwest has primarily focused on creating habitat for the federally endangered Topeka Shiner (*Notropis topeka*) (Bakevich et al., 2013) and other Species of Greatest Conservation Need (SGCN; Iowa Department of Natural Resources, 2015; Simpson et al., 2019; Zambory et al., 2019), as well as creating prime habitat for waterfowl (LaGrange & Dinsmore, 1989). The US Fish and Wildlife Service and others have completed over 150 such reconstructions in Iowa, primarily in the north-central Des Moines Lobe region (Schilling, Wilke, et al., 2019).

Furthermore, the water quality benefits of reconstructed oxbows are being increasingly recognized. Schilling et al. (2017) and Schilling, Kult, et al. (2018) monitored nitrate within a reconstructed oxbow in north-central Iowa that was configured to receive flow and nutrients from subsurface field tiles. NO_3-N load reductions provided by the oxbow in 2014, 2015 and 2017 were similar and ranged from 35% to 47%, with a mean value of 42%. At a second study in eastern Iowa, Schilling, Haines, et al. (2018) reported that an oxbow reconstructed to receive inputs from flooding reduced NO_3-N by 76%. A 2-year study comparing a reconstructed oxbow to a degraded oxbow in Iowa reported that the reconstructed oxbow reduced NO_3-N concentrations by 54% compared to the incoming flows from a field tile (Kalkhoff et al., 2016). Overall, research to date suggests that oxbows reconstructed to receive inputs from tile drainage receive considerably more NO_3-N than oxbows fed simply by groundwater discharge or overbank flows. Based on monitoring conducted for multiple years at a site in north-central Iowa, Schilling, Wilke, et al. (2019) proposed a new conservation practice termed a “multipurpose oxbow” that specifically recognized oxbows reconstructed for multiple purposes, including NO_3-N reduction and conservation habitat.

However, despite research to date highlighting the NO_3-N reduction benefits in reconstructed oxbows, there remains several unanswered questions. Previous work was focused on a single tile-fed oxbow without site replication and there were no direct comparisons in water balance and nutrient reductions among paired non-tile fed sites across a similar climate period. This has led to uncertainty in the magnitude and range of annual and seasonal nutrient reductions in tile-fed versus non-tile oxbows. Another question relates to the potential impacts of tile inflow on oxbow temperatures and water quality. Oxbows fed by tile drainage will likely receive greater nutrient loads (e.g., Ikenberry et al., 2014) but it is uncertain what effects the cooler, high nutrient influent tile water will have on oxbow ecosystems, including populations of Topeka Shiner (Osterhaus et al., 2022; Simpson et al., 2019). Lastly, previous work was focused solely on NO_3-N reductions and the effects of oxbow reconstructions on dissolved reactive phosphorus (DRP) have not been examined. Dissolved P retention in wetlands is known to vary considerably and wetlands can be a net source or sink for DRP delivered with tile drainage (e.g., Kovacic et al., 2000; Kynkäänniemi et al., 2013; Tanner & Sukias, 2011).

In this study, we intensely monitored four reconstructed oxbow sites (two tile-fed, two non-tile) over a 2-year period in north-central Iowa and assessed their function as a BMP for nutrient reduction. Specific objectives were to: (1) characterize the hydrogeology and water budget of four new reconstructed oxbows that capture the range of input water and nutrient sources, including groundwater seepage, overbank flooding and tile drainage; and (2) evaluate the nutrient reduction capacity (NO_3-N and DRP) of the individual oxbows and quantify their capacity for nutrient mass load reduction.

2 | METHODS AND MATERIALS

2.1 | Site locations and setting

Four oxbow monitoring sites were established within the 2370 km^2 Boone River watershed in north-central Iowa (Figure 1). The watershed is located in the Des Moines Lobe ecoregion of Iowa, a landscape region of recent glaciation (<12,000 years old) that is dominated by silty and loamy soils formed in flat glacial till and pothole wetland terrain (Schilling, Haines, et al., 2018). Land cover in the Boone River watershed overwhelmingly consists of row crops of corn and soybean production that comprise 89% of the total watershed area. Over 75% of soils are characterized as “hydric” or “partially hydric” (Gassman et al., 2017) and much of the watershed has been artificially drained using networks

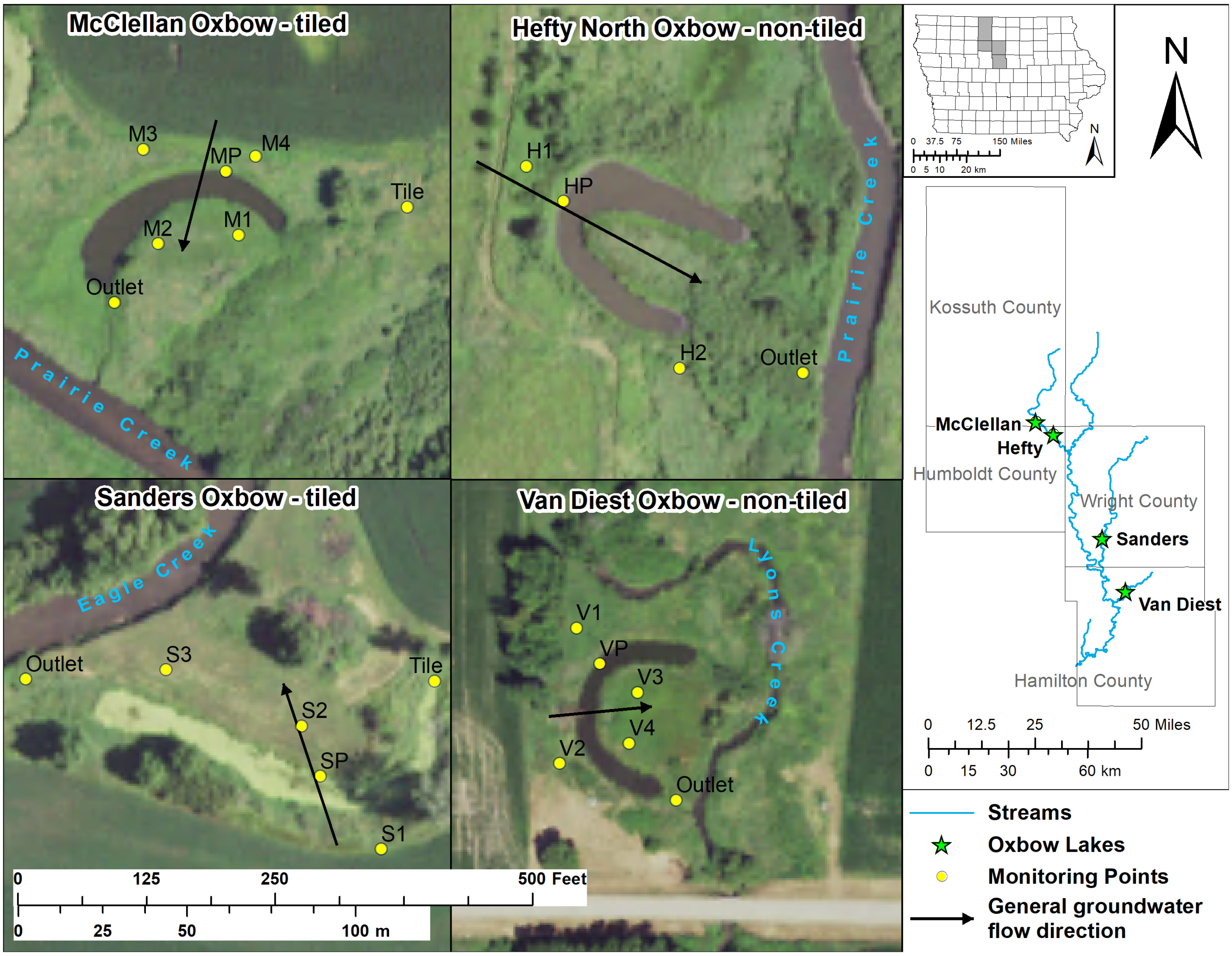

FIGURE 1 Location of the four study oxbow sites in north-central Iowa.

of subsurface drainage tiles and surface ditches. Hence, river NO3-N concentrations, which receive the tile drainage contributions, are very high, and often exceed the EPA Maximum Contaminant Level (MCL) of 10 mg/L. Over a 5-year period, flow-weighted concentrations in the Boone River averaged 10.8 mg/L and exceeded the MCL approximately 25% of the time (Ikenberry et al., 2014). The river is a major tributary of the Des Moines River, a source of municipal drinking water supply for the Des Moines metropolitan area that is threatened by high levels of NO$_3$-N (Schilling & Wolter, 2009).

The four oxbow sites include two sites in the north and two in the south regions of the Boone River watershed (Figure 1). The Van Diest and Sanders oxbows are located in the floodplains of Lyons Creek and Eagle Creek, respectively, whereas the Hefty and McClellan sites are both located adjacent to Prairie Creek. The north and south pairs of sites consist of two oxbows that are at least partially fed by tile drainage (Sanders and McClellan) and two that do not have any tile inputs (Van Diest and Hefty). Both tile-fed oxbows receive flow from 8-inch outlets that drain adjacent agricultural fields. The tiles dump into a small channel before entering the oxbow.

The four oxbow study sites are similar in size ranging from 72–97 m long, 4.9–8.7 m wide and have a depth of approximately 0.35 to 0.5 m (Table 1). All four oxbow sites were reconstructed between 2018–2019 using a similar process (Schilling, Wilke, et al., 2019). Post-settlement sediments were excavated to intersect the bottom of the oxbow with coarse-textured alluvium. Excavated spoils were spread in a nearby agricultural field. The outlets of the oxbows were configured to connect to the nearby receiving stream during high flow events to allow fish passage into them.

2.2 | Field investigation

An electromagnetic terrain conductivity (EM) survey of the oxbow areas was initially conducted using a Geonics EM-31 unit to evaluate local patterns in subsurface geology (Schilling, Streeter, et al., 2020). The EM-31 maps changes in ground conductivity (inverse of resistivity)

TABLE 1 Characteristics of oxbow geologic settings, hydraulic properties and dimensions.

		Floodplain sedimentology			Groundwater hydrology			Oxbow dimensions				
	Site name	Mean % sand	Mean % silt	Mean % clay	Water table depth (m)	*K* (m/day)	Hydraulic gradient	Length (m)	Width (m)	Depth (m)	Surface area (m^2)	Volume (m^3)
Tiled	Sanders	54.9	28.5	16.6	1.58	11.2	0.018	95.6	7.2	0.45	300	126.1
	McClellan	52.7	27.4	19.9	1.10	3.2	0.011	72.1	8.6	0.49	636	217.7
Non-tiled	Hefty	69.9	16.4	13.7	1.18	15.2	0.010	96.7	8.1	0.34	1170	367.4
	Van Diest	35.4	40.8	23.8	1.67	0.93	0.029	74.45	4.9	0.36	235	62.3

using an electromagnetic induction technique with an effective depth of penetration of approximately 6 m (www.geonics.com). Values were recorded with coordinate locations in a continuous manner and stamped with the coordinate locations using a high-precision GPS. The survey points were contoured with the kriging routine in ArcGIS (Figure 2).

Monitoring wells were installed at the oxbow sites using a truck-mounted Giddings drilling rig. The 3.8 cm diameter wells were installed to a depth of 4.5 m and consisted of a 3.0 m well screen with a 1.5 m riser that extended the well to the land surface. A silica sand filter pack was poured around the screen and bentonite chips were added to provide a seal. Following well installation, the wells were developed by surging and overpumping using a Waterra sampling system. An upgradient well at each oxbow site was instrumented with a non-vented miniTROLL transducer (30 psi; In-Situ, Inc) to measure hourly water table fluctuations. Oxbow surface water stage was also monitored hourly using a non-vented miniTROLL transducer secured to a post hand-driven into the oxbow bed. Regional precipitation data were downloaded from the Iowa Environmental Mesonet (http://mesonet.agron.iastate.edu/).

Relative land surface elevations were measured using differential leveling. No reference bench mark elevations were available so datums were surveyed to a site-established benchmark. The precise dimensions (area, depth, volume) of the oxbows (as-built) were determined by manually measuring water depths within the oxbow. A stage-volume relation was then constructed for each oxbow based on the continuous oxbow water level measurements.

The monitoring wells and surface water sites were sampled approximately bi-monthly from June to November in 2020 and from March to November in 2021 (max $n = 24$ over 2 years). Sampling was delayed in 2020 due to COVID-19 travel restrictions. Water levels in wells were measured to the nearest 0.01 foot at the time of sampling. Water samples from wells were collected using a peristaltic pump whereas water samples were collected as grab samples from input tiles, oxbow and the receiving stream. All water samples were analyzed in the field for temperature, specific conductance (SC), pH, dissolved oxygen (DO) and oxidation–reduction potential (ORP) using a YSI

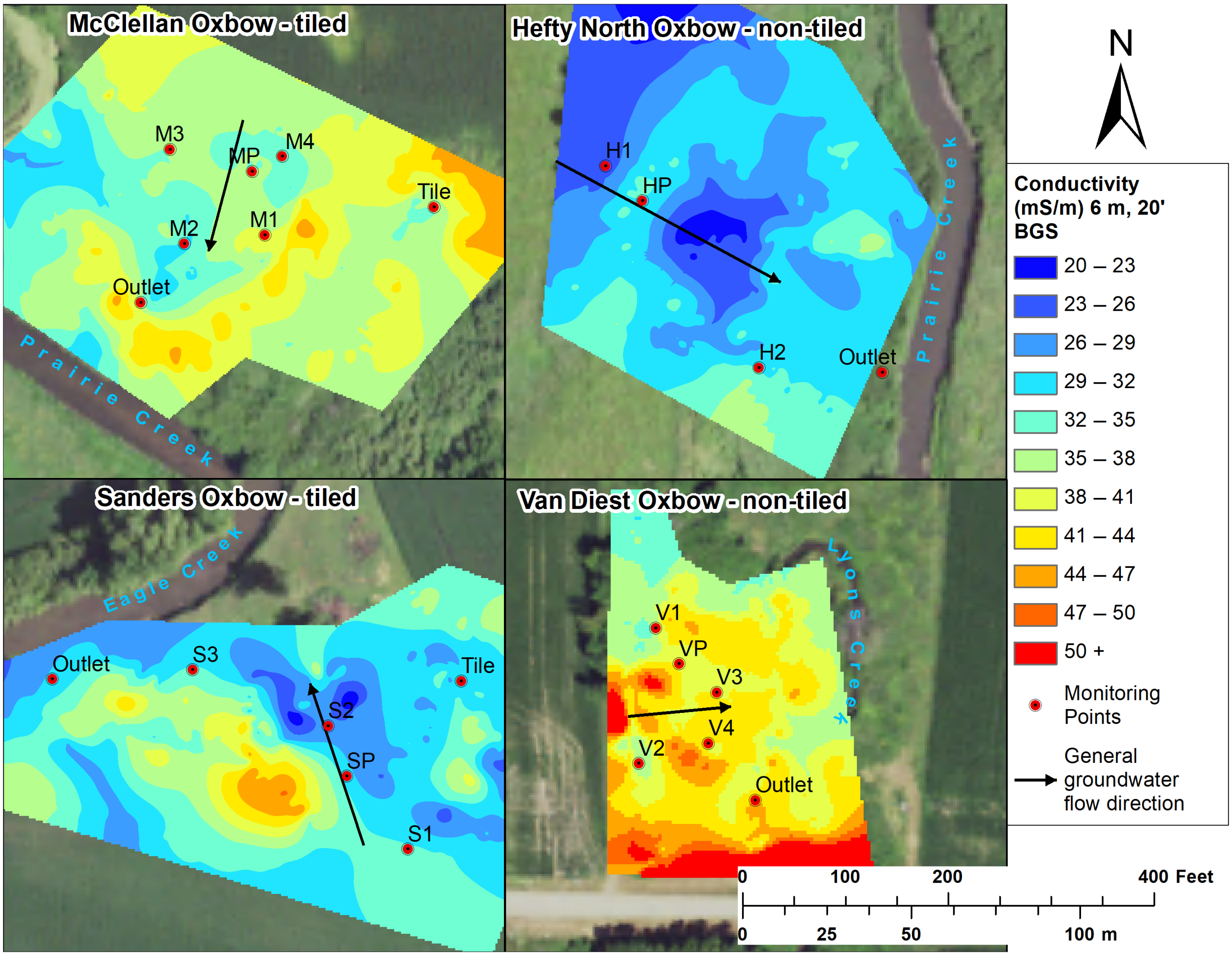

FIGURE 2 Geophysical results using electromagnetic terrain conductivity at the four oxbow sites.

Model 556 water quality meter. Falling head tests were conducted in the wells and results were analyzed using the methods of Bouwer and Rice (1976).

Discharge from input drainage tiles at the McClellen and Sanders sites was measured by ISCO 2150 Area Velocity (AV) Flow Modules. AV sensors were secured to expansion rings placed approximately 2 meters into the tiles from the outlet. The AV sensors use a pressure transducer to measure water depth and ultrasonic sound waves to measure water velocity. Measurements were stored in the module at 5 min increments and used to calculate tile discharge. Ultrasonic velocity measurements require particles or bubbles in the water to reflect the waves back toward the sensor. Sensors were calibrated by the factory prior to installation, and calibrated to a staff gauge quarterly following installation. Tile water is generally clear so many velocity measurements were not detected, especially at lower flows. For this analysis, measurements of depth without a corresponding velocity measurement or a spurious negative value were deleted and the remaining values used to calculate a daily mean discharge.

2.3 | Laboratory analysis

Water samples from the oxbow sites were hand-delivered to the Iowa Soybean Association laboratory on the day of collection. The Iowa Soybean Association maintains a certified testing laboratory in Ankeny, Iowa. Samples were immediately analyzed on the day of collection using Environmental Protection Agency method 300.0 (Pfaff, 1996). Quality assurance/quality control procedures including blanks, fortified samples (spikes), replicates, and known concentration samples, were analyzed with each analytical batch. Concentrations of NO_3-N, DRP, and Cl are reported as mg/L.

2.4 | Load reduction calculations

Nitrate-chloride (N:Cl) ratios in input water to the oxbow were compared to N:Cl ratios in the oxbow itself to estimate nutrient retention in the oxbows. Cl is a conservative tracer that does not undergo transformation or removal in solutions, so variations in Cl concentrations track water flow and the combined effects of dilution, dispersion and diffusion processes. Loss of N relative to Cl concentrations suggests removal of N from the aqueous system from biophysical processes such as assimilation or denitrification (e.g., Garcia-Garcia et al., 2009; Sabater et al., 2003; Simmons et al., 1992).

Monitoring data were used to develop an estimate of daily N and Cl loading to the oxbows from tile discharge, groundwater flow and precipitation. At the two tiled sites, mean daily tile discharge was used along with periodic grab samples to estimate daily N and Cl input loads. Linear interpolation was used to estimate concentrations on unmeasured days. The rate of groundwater flow into the oxbow was estimated from Darcy's Law:

$$V = Ki / n, \tag{1}$$

where K is the hydraulic conductivity (m/s), i is the hydraulic gradient, and n is effective porosity. The mean hydraulic gradient was estimated using the wells and oxbow piezometer heads. The average K of the aquifer was estimated using slug tests and assuming an effective porosity of 0.25 for the alluvium. The rate of groundwater flow (v) was multiplied by the upgradient saturated thickness of the oxbow to estimate the daily groundwater discharge rate into the oxbow. N and Cl concentrations measured in upgradient wells were used to estimate input groundwater loading rates. Overall, daily N and Cl loads into the oxbow were calculated as follows:

$$\text{Daily N or Cl input loads (kg / day)} = \Sigma(\text{Tile} + \text{GW} + P). \tag{2}$$

Daily nitrate retention efficiency (%R) was calculated using the equation (Garcia-Garcia et al., 2009; Schilling et al., 2017):

$$\% R = \left(1 - \frac{\left(\frac{\text{N}}{\text{Cl}}\right)_{\text{ox}}}{\left(\frac{\text{N}}{\text{Cl}}\right)_{\text{in}}} \right) \times 100\,\%, \tag{3}$$

where N/Cl_{ox} is the daily ratio measured in the oxbow and N/CL_{in} is the daily N/Cl ratio of total daily N and Cl loads into the oxbow. %R is the daily percentage of the inflow N load removed by the oxbow.

3 | RESULTS

3.1 | Geology

The four oxbow sites are located in the floodplains of 3rd–4th order tributary streams of the Boone River and subsurface sediments largely consist of sandy loam (Table 1). Conditions were slightly sandier at the Hefty site (~70% sand) and siltier at the Van Diest site (41% silt) and these patterns were reflected in the EM geophysical surveys (Figure 2). Higher conductivity is indicative of a greater fraction of silt and clay in the sediment whereas sand is typified by low conductivity (Schilling, Streeter, et al., 2020). The EM surveys revealed more consistently sandy environments at the Hefty and Sanders sites with values less than 32 mS/m and more fine-textured subsurface at the Hefty and McClellan oxbow sites with EM values greater than 40 mS/m.

3.2 | Hydrology

Hydrologic conditions in north-central Iowa during the 2-year monitoring period were exceptionally dry and well-below normal for the region (mean approximately 905 mm; https://www.weather.gov). Annual precipitation measured nearest to the Van Diest oxbow site (Webster City) totaled 444 and 233 mm in 2020 and 2021, respectively, whereas precipitation at Clarion (nearest to Sanders oxbow) totaled 448 and 567 mm, respectively. The Algona station nearest to the two northern oxbow sites had annual precipitation of 332 and 370 mm in 2020 and 2021, respectively. Overall, annual precipitation was less than one-half of normal at all four sites for both monitored years. Despite low overall precipitation during the project period, the month leading into the start of monitoring was normal to slightly wet (May into June 2020). Due to COVID travel restrictions monitoring began in June 2020, but rainfall in May 2020 ranged from 119 to 160 mm across the four sites. When monitoring was initiated, several oxbows were flooded by overbank flows from the nearby creek and began at very high water levels.

Tile drainage inputs to the two tile-fed oxbows reflected typical wet conditions in spring and dry conditions in the summer and fall (Figure 3). Tile flow into the Sanders oxbow peaked at 224 m^3/day on May 28, 2020 when monitoring began and decreased to 6 m^3/day over the next 2 weeks and was less than 1 m^3/day by July 1. The tile resumed flowing again in early March 2021 and continued flowing into the Sanders oxbow until mid-August and again in mid-September. Tile flows were higher at the McClellan site in 2020 and peaked at 662 m^3/day on June 26 and decreased to <1 m^3/day by August 2 (Figure 3). Tile flow into the McClellan oxbow resumed again on March 24, 2021 following a rainy period to 502 m^3/day and averaged between approximately 50–200 m^3/day until late June. Tile flows resumed again briefly in September 2021 but were otherwise non-flowing through much of the summer and fall.

Water table depths were shallow in the floodplain environments averaging approximately 1.1 to 1.6 m below ground surface at the four oxbow sites (Table 1). Groundwater flow directions at the oxbows are consistent with flow entering the lake on one side and exiting the other toward discharge in the receiving stream. Based on site-specific elevation surveys, hydraulic heads in the upgradient water table wells were found to be consistently above the oxbow water level surface indicating groundwater flow into the oxbow (Figure 4). The daily horizontal hydraulic gradients in the floodplain ranged from 0.01 to 0.029 at the four sites (Table 1). The larger gradient at the Van Diest site is likely due to much steeper bluff topography immediately upgradient of the oxbow. Based on slug tests, the hydraulic conductivities of the alluvium were estimated to range from approximately 1 to 3 m/day at the Van Diest and McClellan sites and 11 to 15 m/day at the Sanders and Hefty sites (Table 1). The higher hydraulic conductivity at the Sanders and Hefty sites is consistent with more coarse-textured alluvium indicated by the EM surveys (Figure 2).

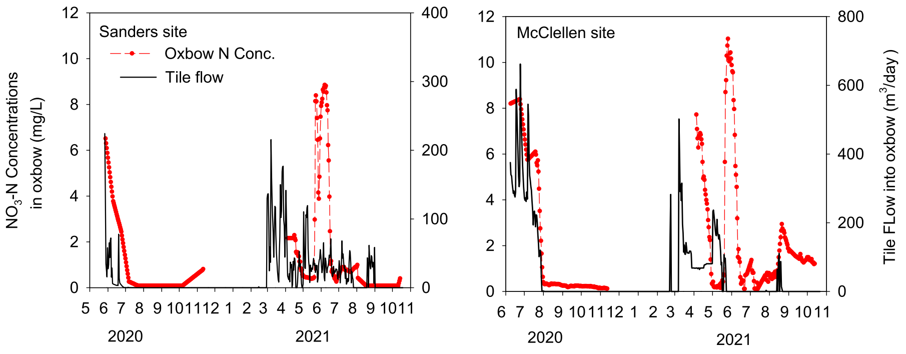

FIGURE 3 Drainage tile flow in the Sanders and McClellen oxbows and daily average oxbow NO_3-N concentrations measured using Nitratax sensor.

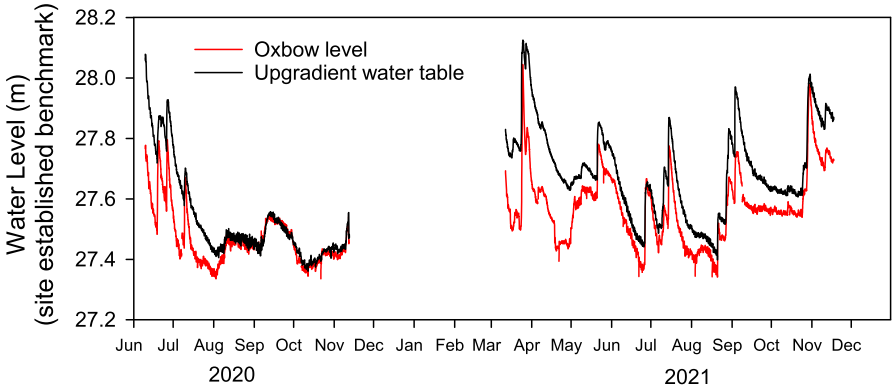

FIGURE 4 Relative daily hydraulic head of upgradient well H1 to oxbow surface water at piezometer HP at the Hefty oxbow site. Heads were surveyed to a locally established benchmark.

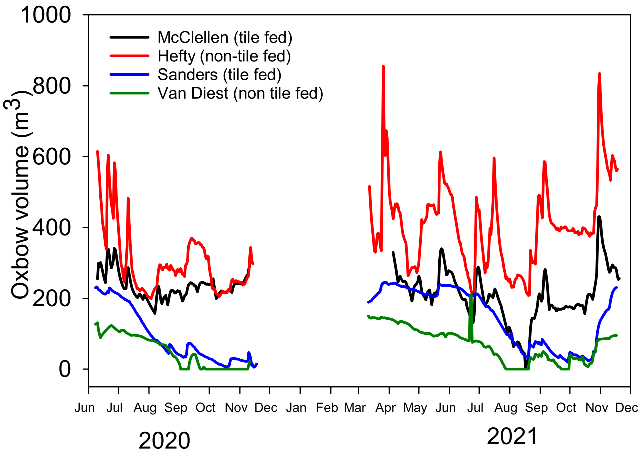

FIGURE 5 The daily volume of water in the oxbows.

We used Darcy's Law to estimate groundwater seepage into each oxbow. If groundwater is assumed to enter the oxbow across the saturated depth along the upgradient edge of each oxbow (approximately 0.3–0.5 m), groundwater discharge into the oxbows was estimated to be 0.6 and 1.2 m^3/day at the Van Diest and McClellan sites, respectively. With a longer upgradient length (~95 m) and higher *K*, more groundwater discharge into the oxbows was estimated at the Hefty and Sanders sites (6.5 and 6.9 m^3/day, respectively). At the tiled sites, groundwater flow contributed significantly less average daily inflow to the oxbow compared to the tile discharge when the tiles were flowing.

Due to variable precipitation and tile inputs to the oxbows, the water storage volumes in the oxbows varied considerably during the 2-year monitoring period (Figure 5). For example, the Sanders oxbow was largely full in late spring 2020 but nearly dry in the fall following an extended dry period (Figure 6). Daily oxbow volumes and levels were highly correlated with daily water table fluctuations with correlation coefficients ranging between 0.83 to 0.94 at all the oxbow sites. Groundwater connection between the oxbow to the alluvial aquifer maintains the water level in the oxbow and as local water table levels decrease during drought, oxbow volumes and levels also decrease.

3.3 | Water quality

Water samples collected from the oxbows, wells, tiles (when flowing at two oxbow sites) and the receiving stream showed variable concentrations throughout 2020 and 2021 (Table 2). NO_3-N concentrations were highest in the drainage tiles flowing into the Sanders and McClellan oxbows with mean values of 7.7 and 9.6 mg/L, respectively. In contrast, mean groundwater concentrations in the floodplain wells were less than 2 mg/L and often less than 1 mg/L. Hence, NO_3-N concentrations in the oxbows receiving tile drainage were notably higher than the two non-tiled oxbows (Figure 7). Concentrations at the tile-fed sites fluctuated considerably and were observed to increase to near 10 mg/L following an influx of tile flows (Figure 3). When tiles were not flowing, oxbow NO_3-N concentrations rapidly decreased to <1–2 mg/L. Stream NO_3-N concentrations were similar to the tile-fed oxbows and were lower than the tiles (Figure 7).

FIGURE 6 Sanders oxbow: left: May 2020 (high water), middle: July 2020 and right: October 2020 (low water).

TABLE 2 Summary of water quality analyses at oxbow sites (mean ± standard deviation).

Oxbow	Sample	*n*	NO_3-N (mg/L)	Cl (mg/L)	DRP (mg/L)	pH	SC (µS/m)	DO (mg/L)
Hefty (non-tiled)	H Oxbow	23	0.67 ± 1.7	8.3 ± 4.2	0.12 ± 0.08	8.0 ± 1.1	453 ± 105	10.6 ± 3.0
	H Stream	24	3.52 ± 3.4	17.7 ± 2.6	0.11 ± 0.07	7.8 ± 1.4	619 ± 125	11.0 ± 2.7
	H1 well	24	0.49 ± 0.3	4.8 ± 5.9	0.13 ± 0.09	7.1 ± 0.9	377 ± 61	3.5 ± 0.5
	H2 well	23	0.19 ± 0.1	13.1 ± 3.4	0.08 ± 0.02	7.2 ± 0.9	584 ± 30	3.3 ± 0.6
	HP piez	22	0.17 ± 0.0	3.4 ± 1.2	0.08 ± 0.02	7.4 ± 0.8	388 ± 69	3.7 ± 1.0
McClellan (tiled)	M Stream	21	2.93 ± 2.8	17.8 ± 4.4	0.08 ± 0.02	8.0 ± 0.8	639 ± 155	10.9 ± 2.5
	M Tile	14	9.64 ± 1.7	14.0 ± 1.8	0.11 ± 0.07	7.1 ± 0.9	655 ± 36	9.1 ± 1.4
	M Oxbow	23	3.14 ± 3.5	16.5 ± 4.2	0.11 ± 0.06	8.4 ± 1.1	449 ± 114	14.9 ± 3.8
	MP piez	21	0.35 ± 0.3	17.2 ± 2.8	0.08 ± 0.00	7.0 ± 0.8	611 ± 143	3.5 ± 0.6
	M1 well	20	0.69 ± 0.6	15.3 ± 3.4	0.08 ± 0.02	6.9 ± 0.9	661 ± 87	4.3 ± 0.8
	M2 well	20	0.20 ± 0.1	13.2 ± 3.4	0.08 ± 0.00	6.8 ± 0.8	601 ± 95	3.9 ± 0.5
	M3 well	21	1.48 ± 1.2	6.2 ± 1.5	0.13 ± 0.09	6.8 ± 0.9	390 ± 87	3.1 ± 0.4
	M4 well	23	1.94 ± 1.9	8.8 ± 4.4	0.17 ± 0.11	6.9 ± 0.9	479 ± 178	4.1 ± 1.2
Sanders (tiled)	S Stream	22	3.10 ± 3.4	30.7 ± 12.3	0.09 ± 0.04	8.2 ± 0.8	637 ± 166	10.6 ± 2.3
	S Tile	13	7.66 ± 1.6	14.6 ± 5.0	0.10 ± 0.06	7.4 ± 0.7	687 ± 27	8.5 ± 1.5
	S Oxbow	22	1.42 ± 1.9	15.9 ± 5.6	0.09 ± 0.03	7.5 ± 1.0	594 ± 187	9.1 ± 5.1
	SP piez	23	0.18 ± 0.1	12.2 ± 3.3	0.08 ± 0.00	7.0 ± 0.7	1069 ± 137	3.5 ± 0.8
	S1 well	23	2.40 ± 3.2	7.5 ± 4.5	0.09 ± 0.04	7.2 ± 0.8	838 ± 65	3.3 ± 1.4
	S2 well	23	0.25 ± 0.2	4.8 ± 2.5	0.08 ± 0.00	7.1 ± 0.6	864 ± 182	3.1 ± 0.7
	S3 well	22	0.20 ± 0.1	5.0 ± 2.7	0.08 ± 0.00	7.1 ± 0.7	839 ± 38	3.2 ± 0.5
Van Diest (non-tiled)	V Stream	19	6.18 ± 5.5	17.9 ± 5.1	0.17 ± 0.10	8.0 ± 0.8	682 ± 80	10.2 ± 2.0
	V Oxbow	21	1.23 ± 3.0	16.1 ± 4.2	0.10 ± 0.06	8.2 ± 1.0	470 ± 182	12.1 ± 3.7
	VP piez	23	0.16 ± 0.0	8.0 ± 2.1	0.08 ± 0.00	7.5 ± 0.8	578 ± 111	3.9 ± 1.0
	V1 well	23	0.57 ± 0.9	3.4 ± 1.3	0.08 ± 0.00	7.2 ± 0.8	679 ± 31	3.4 ± 0.9
	V2 well	22	0.44 ± 0.4	2.5 ± 0.6	0.09 ± 0.03	7.2 ± 0.7	698 ± 34	3.2 ± 0.4
	V3 well	23	0.22 ± 0.3	9.8 ± 1.3	0.08 ± 0.00	7.1 ± 0.8	726 ± 97	4.4 ± 1.1
	V4 well	23	0.20 ± 0.1	10.2 ± 1.7	0.08 ± 0.00	7.0 ± 0.8	753 ± 193	4.02 ± 1.2

In contrast to NO_3-N, DRP concentrations were not particularly different among the sites (Table 2) and water sources (Figure 7). Mean DRP ranged between 0.08 to 0.17 mg/L among all sample sites and were typically higher (when detected) in groundwater samples. The majority of DRP concentration measurements were at or near the method detection limit of 0.08 mg/L. The receiving streams had a maximum DRP concentration of 0.39 mg/L and averaged 0.1 mg/L among all four sites.

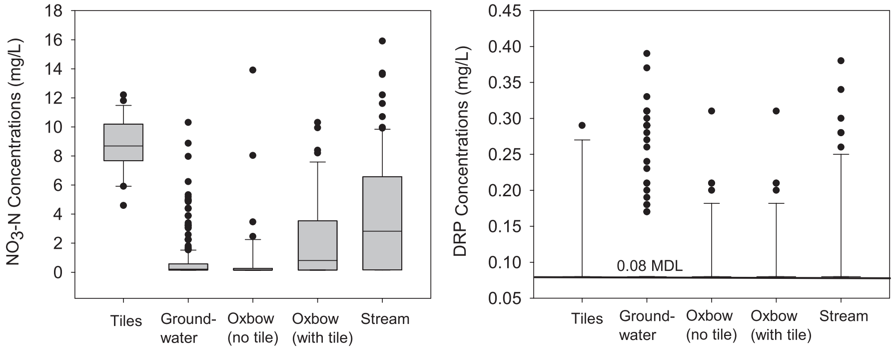

FIGURE 7 Box plot of NO_3-N and dissolved reactive phosphorus (DRP) concentrations measured in tiles, groundwater, oxbows and receiving stream during the 2-year study period.

Mean chloride concentrations were higher in the streams (17–30 mg/L) compared to the oxbow (8–16 mg/L) and groundwater (2–15 mg/L) but concentrations tended to variably fluctuate among the different water sources (Table 2). As would be expected, dissolved oxygen was higher in surface water (>10 mg/L in oxbows and streams) and much lower in floodplain groundwater (<4 mg/L) whereas specific conductance tended to be higher in wells and lower in oxbows and streams (Table 2).

3.4 | Nutrient loads and NO_3-N retention

NO_3-N loads into the tile-fed Sanders and McClellan oxbows were substantially larger than input loads into the non-tiled oxbows with annual input loads into the tile-fed oxbows ranging from 4.4–154 kg compared to <1 kg at the non-tile oxbow (Table 3). Over the 2-year project term, tile-fed oxbows received input NO_3-N loads of 54 kg (Sanders) and 225 kg (McClellan) whereas the non-tile fed oxbows received 0.5 to 1.5 kg. The months of April to June dominated the tile NO_3-N inputs to the oxbows (Table 3).

At the tile-fed Sanders and McClellan sites, daily NO_3-N retention efficiency varied throughout 2020 and 2021 (Figure 8). Daily retention at both sites was low in June 2020 but increased in July and August and remained above 90% for the McClellan site for the duration of 2020. Daily NO_3-N retention at the Sanders oxbow fluctuated in the fall of 2020, but this was largely an artifact of utilizing low input and oxbow NO_3-N concentrations in the calculations of N:Cl ratios at this time. In 2021, a similar annual pattern of daily NO_3-N retention efficiency was observed at the tile-fed sites. Retention increased in April and May, and then decreased in June 2021 when tile flows increased, followed by consistently high NO_3-N retention efficiencies in the mid-summer to fall period (>90%; Figure 8). For the two tile-fed oxbows, the 2-year NO_3-N retention efficiencies were very similar (0.76–0.77; Table 3). Multiplying the annual NO_3-N retention efficiency of the two tile-fed oxbows to their inflow loads suggests that the Sanders oxbow retained 3.05 and 40.71 kg of NO_3-N in 2020 and 2021 respectively, whereas the McClellan oxbow retained 115.77 and 54.82 kg, respectively, over 152 day (2020) and 213 day (2021) monitoring periods, Based on the average surface areas of the oxbows (Table 1), the annual retention rates for the Sanders oxbow ranged from 0.06 to 0.64 g NO_3-N/m^2/day compared to 1.2 to 0.41 g NO_3-N/m^2/day for the McClellan oxbow. Overall, an average annual retention rate for the two tile-fed oxbows was 0.58 g NO_3-N/m^2/day. In contrast to the tile-fed oxbow sites, the non-tiled sites did not receive much NO_3-N load to retain (Table 3). Their calculated retention efficiencies were lower but the values are not particularly meaningful since both the input and oxbow NO_3-N concentrations were often very low (near detection limits) and calculations of N:Cl ratios at these low concentrations are subject to large fluctuations with insignificantly small variations in concentration. Overall, calculation of NO_3-N retention applies best to the tile-fed sites where input concentrations of NO_3-N from tile drainage provides sufficient N mass to follow.

Annual input DRP loads into the four oxbow sites were very low, ranging from 0.1 to 1.8 kg among the sites (Table 3). Greatest monthly input DRP load was observed at the tile-fed McClellan site in June 2020 when the oxbow received nearly 1.2 kg of DRP. The May–June 2020 time period was also associated with the largest monthly NO_3-N inputs at this site. For most of the other months at the other sites, input DRP loads to the oxbows were less than 0.1 kg, and for many months the input load was approximately 0.01 kg. DRP retention could not be estimated because DRP concentrations were very low in the tiles and oxbows and many concentrations were at or below the method detection limit. Overall, while the impact of the oxbows on DRP retention could not be quantified, monitoring results showed that the four oxbows received relatively little DRP mass to retain compared to the NO_3-N inputs to the tile-fed oxbows. In oxbows fed primarily by groundwater seepage, nutrient inputs were too low to calculate meaningful retention rates for both NO_3-N and DRP.

TABLE 3 Summary of Inflow NO_3-N and DRP loads to the oxbows and fraction of input N loads retained.

	Sanders (tiled)			McClellan (tiled)			Van Diest (no tile)			Hefty (no tile)		
Month	Total input NO_3-N load (kg)	Fraction of input NO_3-N retained	Total input DRP load (kg)	Total input NO_3-N load (kg)	Fraction of input NO_3-N retained	Total input DRP load (kg)	Total input NO_3-N load (kg)	Fraction of input NO_3-N retained	Total input DRP load (kg)	Total input NO_3-N load (kg)	Fraction of input NO_3-N retained	Total input DRP load (kg)
June 2020	2.55	0.56	0.029	79.50	0.20	0.622	0.03	0.91	0.001	0.25	0.80	0.011
July 2020	0.77	0.94	0.017	74.39	0.47	1.197	0.02	0.87	0.001	0.11	0.74	0.016
Aug 2020	0.91	0.99	0.035	0.42	0.92	0.011	0.01	0.81	0.002	0.07	0.79	0.016
Sept 2020	0.07	0.75	0.017	0.03	0.96	0.010	0.02	0.46	0.002	0.03	0.65	0.016
Oct 2020	0.07	0.43	0.017	0.02	0.97	0.011	0.01	0.17	0.001	0.03	0.29	0.016
2020 Sum/ mean	4.36 (sum)	0.70 (mean)	0.116 (sum)	154.36 (sum)	0.75 (mean)	1.852 (sum)	0.10 (sum)	0.63 (mean)	0.008 (sum)	0.50 (sum)	0.61 (mean)	0.075 (sum)
April 2021	18.43	0.75	0.164	21.49	0.47	0.222	0.03	0.435	0.001	0.05	0.34	0.016
May 2021	11.12	0.71	0.111	34.45	0.67	0.297	0.01	0.45	0.001	0.24	0.68	0.008
Jun 2021	8.24	0.57	0.109	9.49	0.64	0.091	0.01	0.69	0.001	0.11	0.65	0.003
July 2021	7.75	0.90	0.017	0.03	0.96	0.004	0.01	0.52	0.001	0.12	0.72	0.001
Aug 2021	3.88	0.97	0.017	0.10	0.93	0.004	0.01	0.13	0.001	0.20	0.82	0.010
Sept 2021	0.18	0.97	0.017	4.69	0.91	0.138	0.03	0.40	0.001	0.11	0.63	0.016
Oct 2021	0.05	0.90	0.017	0.03	0.93	0.003	0.03	0.74	0.001	0.12	−0.73	0.016
2021 Sum/ mean	49.65 (sum)	0.82 (mean)	0.453 (sum)	70.29 (sum)	0.78 (mean)	0.759 (sum)	0.13 (sum)	0.46 (mean)	0.007 (sum)	0.96 (sum)	0.56 (mean)	0.009 (sum)
Total 2-year Sum/mean	54.02 (sum)	0.77 (mean)	0.569 (sum)	224.65 (sum)	0.76 (mean)	2.611 (sum)	0.23 (sum)	0.54 (mean)	0.015 (sum)	1.46 (sum)	0.60 (mean)	0.077 (sum)

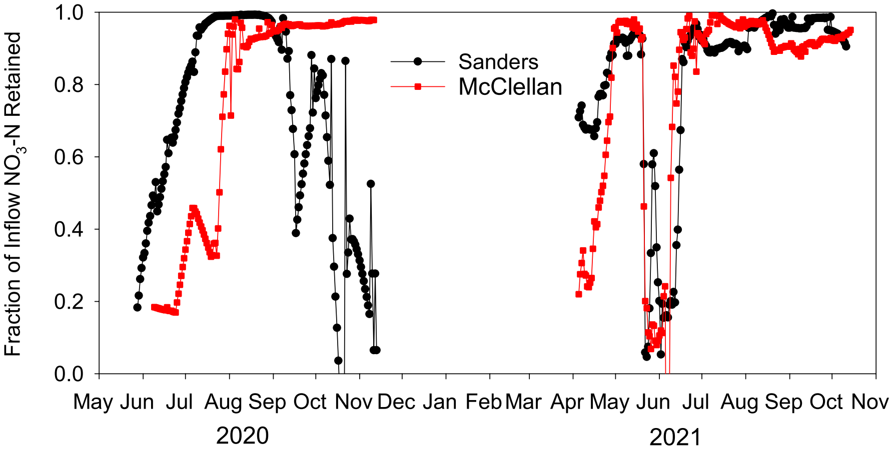

FIGURE 8 Daily NO_3-N retention efficiency at the Sanders and McClellen oxbows in 2020 and 2021.

4 | DISCUSSION

Study results confirm that reconstructed oxbows are an effective edge-of-field, tile drainage NO_3-N reduction practice equivalent to other agricultural BMPs such as bioreactors (Shipper et al., 2010), wetlands (Tomer et al., 2013) and saturated buffers (Jaynes & Isenhart, 2014). Schilling, Wilke, et al. (2019) proposed the term "multipurpose oxbow" to describe oxbows restored for both NO_3-N export reduction and creation of habitat for conservation, and previous work on the water quality benefits of multipurpose oxbows was largely focused on quantifying NO_3-N retention over multiple years at a single site in north-central Iowa (Schilling et al., 2017; Schilling, Kult, et al., 2018). With results presented herein, the number of oxbow sites where nutrient reduction benefits have been quantified increased by two additional sites and four site-years of monitoring, which now includes a paired comparison to non-tile fed oxbows.

The mean annual NO_3-N retention efficiency of the tile-fed Sanders and McClellan sites (0.70–0.82) was substantially higher than previously reported for 3 years of monitoring at the Frye oxbow site in north-central Iowa (0.35–0.45; Schilling, Wilke, et al., 2019). However, hydrologic conditions in 2020–2021 were considerably drier compared to previous years. Annual precipitation during previous monitoring at the Frye site (~1000 mm) was more than double that measured at the Sanders and McClellan sites. Oxbow volumes decreased considerably during the monitoring period (Figure 5) and the Sanders oxbow nearly went dry (Figure 6). Less water availability means less tile flow and N loads into the oxbows. At the Frye site, the oxbow was fed by two 8-inch tiles that discharged into the oxbow split into two 0.08 ha cells (Schilling et al., 2017). In contrast, the two tile-fed oxbows in this study were fed by a single 8-inch tile discharging to the upgradient end of the oxbow. Tile flows into the Frye site were much larger that flows into the Sanders and McClellan sites. Mean annual tile inflow to the Frye oxbow ranged from 149–176 m^3/day and peaked at 3600 m^3/day on a single day compared to 17.3 m^3/day (max of 224 m^3/day) and 67.1 m^3/day (max of 855 m^3/day) for the Sanders and McClellan sites, respectively. Consequently, annual input NO_3-N loading to the oxbows was much greater at the Frye site (200–400 kg) compared to the current sites (4–154 kg). Combining the results from the current study with previous monitoring at the Frye oxbow site suggest that NO_3-N retention in multipurpose oxbows is related, in part, to inflow NO_3-N loading (Figure 9). More tile flow into the oxbow means there is greater NO_3-N mass delivered into the oxbow and more opportunity for NO_3-N reductions to occur. However, there is a tradeoff in that there is higher percent NO_3-N reduction when input loads are lower.

The relation between N retention efficiency of the oxbows to input loading is similar with the concept of hydraulic loading rates (HLRs) developed to describe N removal efficiencies in tile drainage wetlands (Crumpton et al., 2008; Drake et al., 2018). N removal efficiency in wetlands typically decreases as the HLR increases, because water residence times decrease with more water flux into the wetland. For the multipurpose oxbows, less N retention efficiency was provided when input tile drainage flows and N loads were higher. However, it is important to note that the oxbows would be able to process a greater mass of N load from tile drainage because of much greater input N delivered. The input of NO_3-N mass to the tile-fed and non-tiled oxbows in this study provides a stark contrast in loading rates. Non-tiled oxbows only received input NO_3-N from groundwater seepage and rainfall that totaled <1.5 kg over the 2 years whereas the tile-fed oxbows had NO_3-N inputs of 50–225 kg. An annual NO_3-N tile input to the Frye oxbow exceeded 400 kg on one occasion. The annual tile NO_3-N loading into the oxbows was similar to tile loads draining into other edge-of-field remediation practices including saturated buffers reported by Jaynes and Isenhart (2019) (13–179 kg N) and Streeter and Schilling (2021) (75–136 kg N). Our study confirms that reconstructed oxbows should only be considered an agricultural BMP if they are configured to receive tile drainage inputs.

The range of annual NO_3-N retention measured in the north-central Iowa oxbows are similar to other oxbow sites where oxbows have been engineered to receive surface water N. For example, Fink and Mitsch (2007) used an engineered "created" oxbow system to report annual NO_3-N mass reductions of 48%. Harrison et al. (2014) monitored two relict oxbow lakes near an urban environment and reported that the

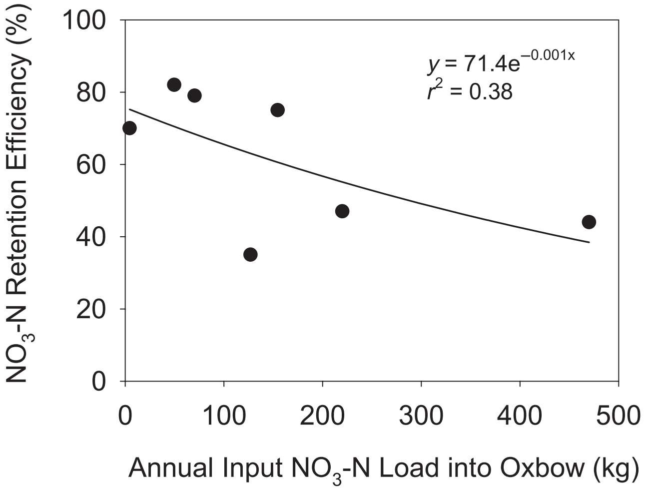

FIGURE 9 Relation of NO_3-N retention efficiency to input NO_3-N loads into the oxbow from tile drainage. Data includes three site-years from tile fed oxbows reported in Schilling et al. (2017) and Schilling, Kult, et al. (2018).

oxbows retained 23% to 87% of NO_3-N load that entered the oxbow during four storm events. Garcia-Garcia et al. (2009) estimated it to be 72% for a wetland-stream system dominated by high inflow NO_3-N concentrations (above 20 mg/L). Jones et al. (2015) compared mean NO_3-N concentrations in three oxbows to inlet tile water and found a 45% to 61% reduction in concentration. At an eastern Iowa restoration where the oxbow was configured to receive inputs from groundwater seepage and overbank flooding NO_3-N loading into the oxbow was dominated by flood pulses (Schilling, Kult, et al., 2018). Following a spring flood event, retention efficiency was estimated to be 74.2%.

The annual NO_3-N retention rate for the two tile-fed oxbows averaged 0.58 g NO_3-N/m^2/day over the 2-year monitoring period (range from 0.06 to 1.2 g NO_3-N/m^2/day). The average rate is slightly higher than the retention rate measured in another central Iowa reconstructed oxbow that was configured to receive tile drainage (0.21 g NO_3-N/m^2/day: Schilling, Kult, et al., 2018). The average rate was similar to rates measured in an eastern Iowa oxbow (0.30; Schilling, Haines, et al., 2018), relict oxbows in Maryland (0.2 to 2.7 g NO_3-N/m^2/day, Harrison et al., 2014) and floodplain diversion wetlands in Illinois (0.01 to 0.55 g NO_3-N/m^2/day, Kadlec, 2010; 0.71 g NO_3-N/m^2/day, Fink & Mitsch, 2007). Although we did not measure NO_3-N retention processes, denitrification and assimilation are considered by others to be the dominant mechanisms for the NO_3-N retention in oxbows. Harrison et al. (2012) conducted ^{15}N additions during the spring and summer at two oxbows and found that the relative contributions of denitrification and assimilation varied by season. Denitrification accounted for 38%–57% of ^{15}N transformation in the summer when vegetative assimilation was active and 86%–97% in the early spring when assimilation was less important (Harrison et al., 2012). Similarly, Kreiling et al. (2011) reported that the majority of nitrate lost in an upper Mississippi backwater lake during a summer period was due to denitrification (82%) whereas Hansen et al. (2015) estimated that 61% of the nitrate loss was from denitrification and 38% was associated with assimilation in an Iowa reservoir. The seasonal pattern of NO_3-N retention at the Sanders and McClellan sites suggests that these processes are active in the oxbows. During the late spring, NO_3-N retention was less than 20% but retention increased to >90% in mid-summer through fall when water temperatures increase. The mid-summer-early fall time period often coincides with greater nitrate removal in Midwestern streams when warm-water and low-flow conditions lead to greater nutrient removal (Royer et al., 2004). NO_3-N removal efficiency in oxbows tends to increase in the summer months when hydrologic conditions are optimized to favor biological uptake and denitrification (Garcia-Garcia et al., 2009).

The term "multipurpose oxbows" implies that a second purpose for reconstructing oxbows is their ecosystem benefits. While not a part of our study, biologists at Iowa State University monitored paired tile-fed and non-tiled reconstructed oxbows to assess whether there are differences in fish populations between the two oxbow types. Previous studies have determined that oxbows are critical habitat for the federally-endangered Topeka Shiner (Bakevich et al., 2013; Simpson et al., 2019). Leberg (2021) sampled 12 restored oxbows in 2019 and 2020 including six that received water from subsurface tile drainage systems (multipurpose oxbows) and six wetlands that had no direct connection to tile. The oxbow population of Leberg (2021) included the four oxbows sampled in this study. While water temperature was somewhat lower in multipurpose oxbow sites (mean = 23.6°C, range = 20.3–26.5) than in non-tiled oxbows (mean = 26.3, range = 24.1–30.0), the difference was not statistically significant ($p = 0.06$). Other measured habitat features, macrophyte composition and invertebrate assemblages were not significantly different between oxbow types. Most importantly, no significant compositional differences in fish assemblage were measured. Over two field seasons Leberg (2021) found 2682 Topeka shiners in three non-tiled and four multipurpose oxbows but there were no statistically significant differences in population abundances between tile-fed and non-tiled oxbows. Leberg (2021) cautioned that since the tile inputs were relatively small compared to oxbow size, this should not be considered evidence that large tile flows would not alter wetland habitat. However, study findings of Leberg (2021) provided promising evidence that tile drainage has minimal impacts on oxbow ecology compared to other oxbows in central Iowa. As research continues to establish the efficacy of restoring oxbows for the conservation of Topeka shiners (Osterhaus et al., 2022; Pierce et al., 2019; Simpson et al., 2019), restoration should be focused on locations where tile drainage can be diverted into them for maximum ecosystem benefits.

A second objective of this study was evaluating possible reduction in DRP in the reconstructed oxbows but on this topic study results were inconclusive since DRP concentrations and loads into the tile-fed oxbows were too low to allow for meaningful estimates. DRP concentrations were slightly higher in floodplain groundwater than in the tiles and oxbows but many values were at or near the method detection limit. Despite higher concentrations, groundwater discharge into the oxbows was very low which limits overall loading rates. Other researchers have reported mixed effects of constructed wetlands for tile drain DRP load reductions. Kynkäänniemi et al. (2013) reported that a newly constructed wetland reduced DRP loads by 9% but the reductions were much less than for particulate phosphorus. On the other hand, Tanner and Sukias (2011) reported that constructed wetlands receiving DRP in tile drain water were a net source of phosphorus. Overall, groundwater DRP concentrations in the oxbow settings were similar to concentrations measured in a variety of landscapes across Iowa (Schilling, Jacobson, et al., 2020). Based on a meta-analysis of 210 water table monitoring well locations across Iowa, median DRP concentrations in Iowa shallow groundwater were 0.1 mg/L with a 95% confidence interval of 0.08 to 0.11 mg/L. Nearly all the DRP concentrations measured at the four oxbow sites were within this median interval. Hence, in the absence of unusually higher DRP concentrations in source water inputs, tracking changes attributable to the oxbow will be subject to considerable uncertainty against a background of relatively high DRP values.

Overall, our study adds data to better quantify NO_3-N reduction benefits at tile-fed multipurpose oxbow sites. In 2019, the multipurpose oxbow was listed as an approved conservation practice for the Iowa Nutrient Reduction Strategy (INRS) with a NO_3-N retention of 42 ± 6% based on 3 years of monitoring at a single site (Schilling et al., 2017; Schilling, Kult, et al., 2018). The practice joined other tile drainage BMPs listed in the Strategy that included bioreactors (43 ± 21%), drainage water management (33 ± 32%), wetlands (52%) and saturated buffers (50 ± 13%) (INRS, 2013). Results from this current study suggest that the retention rate could be considered higher if four site years of monitoring from the Sanders and McClellan sites are added to the population. In this case, the new multipurpose oxbow NO_3-N retention should be considered 62 ± 19%. As noted by Schilling et al. (2017), oxbows achieve similar NO_3-N retention efficiency to bioreactors and saturated buffers that are installed below-ground to treat tile drainage water (e.g., Jaynes & Isenhart, 2014; Jones & Kult, 2016). The cost of reconstructing oxbows will vary based on the volume of sediment removed and transportation costs to haul the excavated material off site ($8000–$28,000; Schilling, Gassman, et al., 2019) but, in general, costs are considered similar to woodchip bioreactors (~$10,000; Jones & Kult, 2016). With an ecosystem-friendly oxbow, landowners are able to provide habitat for fishes, including the endangered Topeka shiner (*Notropis topeka*) (Bakevich et al., 2013), and for waterfowl (LaGrange & Dinsmore, 1989) while simultaneously treating tile drainage on marginal land areas often unsuited for production.

5 | CONCLUSIONS

In this study, we monitored four reconstructed oxbow sites (two tile-fed, two non-tile) over a 2 year period in north-central Iowa and assessed their capacity for NO_3-N and DRP retention. Water flow and quality monitoring of tiles, shallow groundwater, oxbow, and receiving streams documented that the tile-fed oxbows were dominated by tile drainage inputs. NO_3-N concentrations were highest in the drainage tiles flowing into the tile-fed oxbows (mean 8–10 mg/L) and were much lower in floodplain groundwater at all sites (<1–2 mg/L). Hence, annual NO_3-N loads into the tile-fed oxbows were substantially larger (4.4–154 kg) than input loads into the non-tiled oxbows (<1 kg). For the two tile-fed oxbows, the 2-year NO_3-N retention efficiencies were very similar (0.76–0.77) and on a monthly basis, greater retention efficiencies were measured in summer and fall. Low input NO_3-N concentrations hampered quantification of retention at the non-tile sites but were estimated to be near 100%. DRP concentrations and loads into the oxbows at all sites were too low to allow for meaningful estimates of DRP retention. Adding results from the present study to previous work on tile-fed reconstructed oxbows indicates that NO_3-N retention in "multipurpose oxbows" (i.e., those oxbows constructed for multiple ecosystem benefits including fish habitat) could now be considered 62 ± 19% if four additional site-years of data were included with previous assessments. Overall, given ecosystem benefits of oxbows and similar costs compared to other tile drainage edge-of-field practices, reconstructing oxbows to receive tile drainage water should be considered a recommended BMP for tile drainage treatment in floodplain agricultural areas.

AUTHOR CONTRIBUTIONS

Sophie Pierce: Data curation; formal analysis; investigation; methodology; writing – review and editing. **Keith E. Schilling:** Conceptualization; formal analysis; funding acquisition; methodology; supervision; writing – original draft; writing – review and editing.

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CONFLICTS OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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