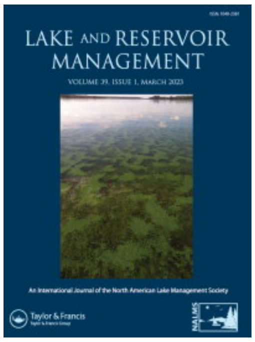

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Nitrate pollution and expansion of free-floating plants in 3 lower Wisconsin River oxbow lakes

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ABSTRACT

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The Lower Wisconsin State Riverway (LWSR) in southwest Wisconsin is one of the highest quality large river floodplain ecosystems in the Midwest and is designated a Ramsar Wetland of International Importance. Oxbow lakes are important features of this floodplain ecosystem but many had become highly eutrophic by about 2011. Free-floating plants (FFP), comprised of duckweeds and filamentous algae, expanded in many groundwater-fed oxbow lakes along the LWSR. Beginning in 2013, we investigated possible causes of eutrophication. Our water pollution investigation indicated the primary oxbow water source is groundwater that flows beneath the cropland intensive Pleistocene sand terrace. The sand terrace aquifer delivers large amounts of NO_3-N with concentrations that exceeded the federal and state Drinking Water Enforcement Standard (10 mg/L). Aquifer total phosphorus concentrations were orders of magnitude lower. NO_3-N:total phosphorus (TP) ratios in terrace groundwater often exceeded 500:1. Estimated NO_3-N loading rates were variable and ranged from 2989 kg/yr discharged to a 5.5 ha oxbow lake up to 33,091 kg/yr discharged to a 35 ha floodplain flowage. The results suggest coordinated groundwater and surface water quality protections are needed, and potentially Clean Water Act enforcement. Strategies designed to protect domestic water supplies beneath the sand terrace can reduce NO_3-N pollution in the oxbow lakes. Addressing this issue could begin with adopting recommended surface water nitrogen criteria and developing FFP impairment criteria for LWSR oxbow lakes.

KEYWORDS
Floodplain lakes; free-floating plants; nitrate nitrogen; oxbow lakes

The Lower Wisconsin River is a braided channel river system that bisects the unglaciated Driftless Area to the confluence with the Mississippi River. Unlike the many aggraded floodplain rivers in southern Wisconsin (Knox 2006), the Lower Wisconsin River remains well connected to its natural floodplain and supports high biodiversity, including 98 native fish species (Lyons 2005). Special designations were established to protect its rich biodiversity, including the 32,000 ha Lower Wisconsin State Riverway (LWSR), Clean Water Act Exceptional Resource Water (ERW), and Ramsar Convention Wetland of International Importance. The Ramsar Convention is an international treaty established in 1971 to protect critically important wetlands.

Prior to the implementation of the federal Clean Water Act, from about the mid 20th century to the late 1970s, the Wisconsin River was severely polluted from the pulp and papermill industry (Ball and Marshall 1978). The LWSR oxbows were likely refugia during worst periods of industrial water pollution. Oxbow lake ecological services include habitat for lateral fish migrations, fish reproduction, and refugia from riverine environmental stressors (Bayley 1995, Killgore and Baker 1996, Amoros 2001, Slipke et al. 2005, Roach et al. 2009). Oxbow lakes near the Pleistocene sand terrace are greatly influenced by upland aquifer discharges (Pfeiffer et al. 2006). Some of the oxbows are spring lakes by definition since their water budgets are strongly influenced by groundwater discharges, with perennial outlets to the river but no inlets.

The network of LWSR oxbow lakes had been described as a "fish safe haven," with a natural

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character resembling pre-European settlement (Marshall and Lyons 2008). By 2011, water quality decline had become evident in many oxbows that lie adjacent to the Pleistocene sand terrace (Wisconsin Department of Natural Resources [WDNR] unpublished data). Dense free-floating plants (FFP) mats covered the surface of many oxbows that were previously open and clear. A water pollution investigation began in 2013 to identify potential causes for the unquantified reported and photographed environmental changes (Fig. 1).

Study area

More than 100 oxbow lakes lie within the 148 km LWSR floodplain. We focused on 4 of the lakes located in Sauk County, where previous groundwater modeling (Gotkowitz et al. 2005, Pfeiffer et al. 2006) enhanced our understanding of oxbow hydrology. Jones Slough is a 3 ha spring lake that discharges to Norton Slough. Norton Slough is a 5.5 ha drainage lake and is also influenced by upgradient groundwater discharge. Bakkens Flowage was a spring lake, expanded into 35 ha impoundment for waterfowl management. It is located within a State Natural Area. Long Lake is a 13.3 ha drainage lake downstream of Bakkens Flowage. Long Lake did not shift to FFP dominance as occurred in the other 3 study oxbow lakes. All 4 oxbow lakes lie downgradient from Pleistocene sand terrace croplands (Fig. 2). All of the oxbow lakes are shallow with maximum depths of about 2.5 m.

Methods and materials

The water pollution study was designed to investigate sand terrace aquifer concentrations and loading rates of nitrate nitrogen (NO_3-N) and total phosphorus (TP). Other potential nutrient sources were investigated, including the Lower Wisconsin River and alluvial (floodplain) aquifer. The study was not designed to evaluate limiting nutrients or FFP biomass as quantitative measures of eutrophication and impairment.

Water sampling

We used a YSI Pro Plus meter to measure groundwater and surface water NO_3-N and ammonia (NH_3-N) concentrations, calibrated daily using 1 mg/L and 100 mg/L standards. Twenty-seven State Laboratory of Hygiene (SLOH) water samples were paired with field NO_3-N measurements ($P < 0.01$, $R^2 = 0.97$) for additional quality assurance. SLOH testing also included TP and to a lesser extent ammonia (NH_3-N). We measured dissolved oxygen (DO) and temperature in oxbows and wells with a YSI ODO DO meter calibrated according to manufacturer specifications. A YSI Model 63 meter was used to measure both pH and specific conductance using recommended calibrations.

Figure 1. The photograph on the left shows Norton Slough on 31 Aug 2007. The photograph on the right show Norton Slough on 26 Aug 2011. Norton Slough was one of many terrace border oxbows that shifted from floating leaf *Nymphaea*, *Nuphar*, and *Potamogeton* to FFP. Photos by David W. Marshall.

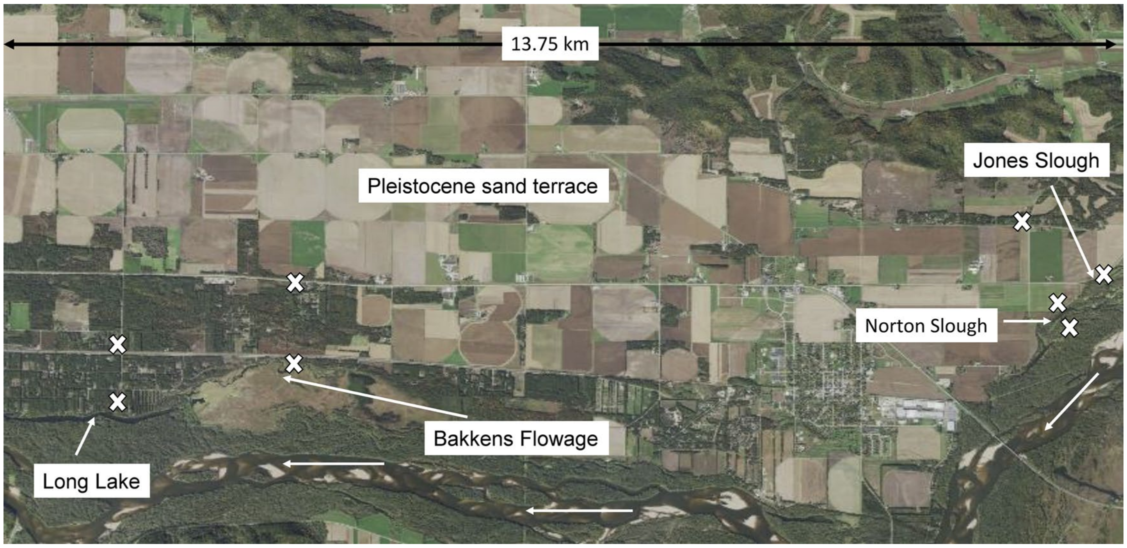

Figure 2. Map of the study area. The dominant land use across the sand terrace is irrigated cropland. X's indicate drilled monitoring well nests. The Lower Wisconsin River flows from the east.

Groundwater monitoring and modeling approach

An environmental contractor operated a geoprobe track mounted drill to install thirty-four 5.1 cm water table wells and piezometers across the sand terrace, with depths ranging from 2.3 to 24.9 m below ground surface. All terrace well nests were installed in nonagricultural areas. Most of the wells were constructed in clusters of 3 or 4, with screen lengths varying from 3 m for water table wells to 0.6 m for piezometers. Drill core soil samples at each well cluster location confirmed the presence of medium well sorted sand, including some fine sand, coarse sand, and gravel, consistent with previous Pleistocene terrace drill core analysis (Pfeiffer et al. 2006). Clay and organic material were scarce and we found no evidence of redoximorphic conditions such as staining, odor, or mottling in the core samples. Five additional wells were manually driven into the floodplain. Two of the floodplain wells were downgradient of Norton Slough. The floodplain deposits contained sand but also finer organic soils that exhibited redoximorphic features including mottling and iron depletion. Pfeiffer et al. (2006) identified LWSR floodplain reducing conditions that had contributed to nitrate attenuation.

A groundwater flow model was developed from our data using United States Geological Survey (USGS) MODFLOW 2000 (Schlaudt 2017). This model encompassed a 3-dimensional steady state solution with 9 model layers. The model boundary fluxes were imported from the regional analytic element model and used as model boundary conditions. The model output indicated significant recharge across the cropland terrace. The model was used to estimate oxbow water budgets and upgradient nutrient loading rates.

We monitored 48 wells across the terrace and floodplain: the 34 we installed, along with private water supply and municipal owned wells. Onset pressure sensors tracked groundwater and surface water level changes. Wells were sampled with a submersible pump and flushed for a least 5 min prior to sample collection. The distribution of the monitoring wells across the Pleistocene sand terrace and adjacent to the oxbow lakes was designed to assess NO_3-N and TP concentrations within conceptualized groundwater flow paths. Previous groundwater modeling of Sauk County indicated the hydraulic conductivity of the outwash and alluvial deposits was 49.4 m/d with a recharge of 25.9 cm/yr (Gotkowitz et al. 2005). The underlying sandstone bedrock and adjacent upland area has a hydraulic conductivity of 2.4 m/d and a recharge rate of 13.2 cm/yr (Gotkowitz et al. 2005). Three floodplain wells were installed to measure groundwater level changes associated with Wisconsin River levels. The 2 floodplain wells downgradient of Norton Slough were monitored to assess potential impacts of higher river stages when alluvial groundwater moves toward the oxbow lakes, described by Amoros and Bornette (2002). Upgradient clustered monitoring wells were sampled monthly during the open water seasons from 2014 through 2017 (Fig. 2).

Potential land use changes were assessed using Natural Resources Conservation Agency (NRCS) aerial photos dating back to 1937. We measured and compared terrace groundwater flow distances beneath agricultural and natural vegetation recharge areas using the WDNR Surface Water Dataviewer. Overall, natural buffer areas were much smaller than agricultural recharge areas. The most significant nonagricultural buffer area is the 530 ha Sauk County School Forest, located upgradient from Long Lake.

Oxbow lake sampling and assessment

The 4 oxbows were sampled monthly during the growing season, from June through September. Watercraft access to the oxbows was limited and sampling often involved wading from shore. A small jonboat was occasionally hauled down the steep terrace banks to measure vertical profiles of temperature, DO, pH, and specific conductivity. Percent FFP surface cover was estimated at terrace vantage points 4 to 5 m above the oxbows. Two observers independently estimated percent FFP without discussion to avoid potential bias anchoring.

In 2013 staff gauge water levels and DO concentrations in Norton Slough were recorded twice daily (morning and late afternoon) from 1 June to 4 July to determine the frequency when high river flows cause groundwater flow reversal and can affect water quality. The twice daily water level and DO measurements were averaged to reduce effects of photosynthesis and respiration. The z-score normalized water level (cm) and DO (mg/L) data were tested for potential relationships using the Pearson correlation coefficient. We could not determine the precise river flows or stages adjacent to Norton Slough but we relied on river flow and stage data collected at a USGS gauging station location 22 km downstream of the study area to determine when groundwater reverses flow.

We also attempted to collect piston core sediment samples from Norton Slough and Jones Slough to assess long-term water quality trends (paleolimnology) and potential source of stored nutrients.

To address concerns that the oxbow water quality declines were affected by river water quality, we reviewed long-term TP and total nitrogen (TN) trends data from 2 long-term Wisconsin River monitoring sites above and below the study area (2003–2017) to determine potential effects of the river on our oxbow lakes. The river, as a potential pollution source, was eliminated from further analysis since mean and median TN concentrations were below 2 mg/L at both stations.

Results

Groundwater sources of N and P

The groundwater elevations demonstrated that the study oxbow lakes, which border the outwash sand terrace, received groundwater discharge from the north. Cross sections for Jones Slough and Long Lake illustrate the elevation differences between oxbow lakes and river (Fig. 3). Aerial photos demonstrated that most of the terrace recharge area was irrigated croplands. Site-specific nutrient application data on private lands were not available. The hydraulic gradients and seepage velocities were calculated for each lake area (Table 1). The groundwater travel times were the shortest at Jones Slough (1.2 years) at the east end of the study area and longest downstream at Long Lake (15.6 years). The relatively brief 1.2 yr groundwater travel time may explain why Jones Slough water quality declined several years before Norton Slough and Bakkens Flowage.

Groundwater discharges to 3 of the lakes contained NO_3-N concentrations exceeding the enforcement standard (10 mg/L) at most well depths. Shallow wells were influenced by nonagricultural recharge areas and had lower NO_3-N concentrations. Deeper wells contained the highest nitrate concentrations due to longer groundwater pathways from agricultural recharge areas north of the floodplain. Unfavorable denitrification conditions were found across the sand terrace due to the scarcity of organic soils and the moderate DO concentrations in the groundwater

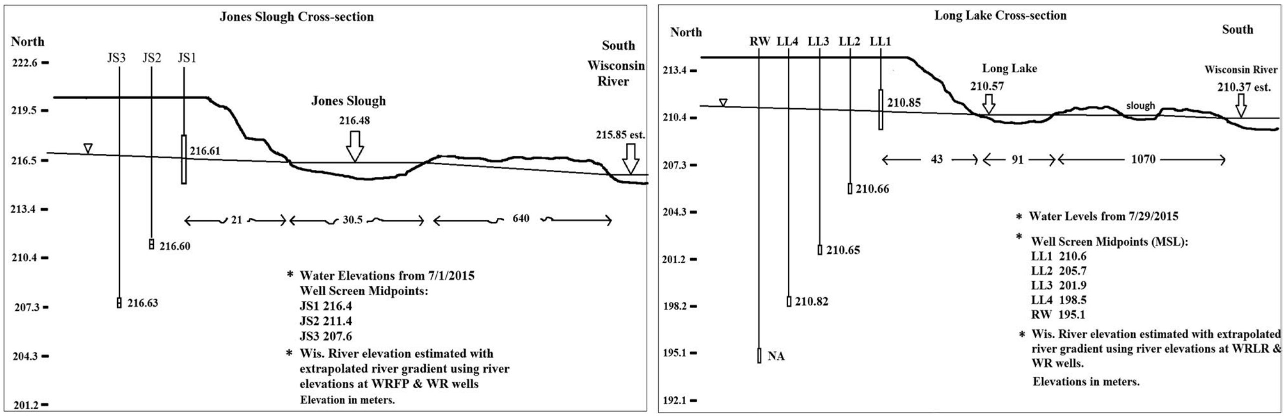

Figure 3. Cross sections of Jones Slough (above left) and Long Lake (above right). Jones Slough, Norton Slough, and Bakkens Pond are about 0.6 m higher than the river. Long Lake is about 0.3 m higher.

Table 1. Agricultural nutrient travel times.

Lake	Distance from agricultural use area (m)	Lake distance to Wis. R. (m)	V_S* terrace (m/d)	V_S* floodplain (m/d)	Travel time to lake (yr)	Travel time to Wis. R. (yr) **	N-S width of agricultural usearea (m)
Jones Slough	107	671	0.25	0.20	1.2	10.5	488
Norton Slough	366	610	0.24	0.30	4.1	9.1	1288
Bakkens Flowage	211	1133	0.59	0.14	6.2	33	2591
Long Lake	2256	1128	0.40	0.04	15.6	94	3871

*Seepage velocities (V_S) calculated with $K = 49.4$ m/d and porosity (ϕ) = 0.25.
**Travel time to Wisconsin River (Wis. R.) includes both terrace and floodplain travel times.

Table 2. DO concentrations in terrace wells adjacent to the 4 oxbows indicated oxic conditions unfavorable for denitrification.

	Jones Slough wells	Norton Slough wells	Floodplain wells	Bakkens Flowage wells	Long Lake wells
DO (mg/L)	7.8	5.0	0.7	4.8	5.8
SD	1.5	2.2	0.65	2.4	1.5

Low DO in the floodplain is likely more favorable for denitrification.

(Table 2). More favorable denitrification conditions were found in the floodplain groundwater where DO and NO_3-N were lower and NH_3-N was higher (Table 3).

Continuous sand terrace groundwater discharge to Jones Slough sustained very cold summer water temperatures in the shallow lake (Fig. 4). During most winter months, the terrace groundwater discharge maintained open water areas in the oxbow (Fig. 5). High nitrate concentrations in the groundwater were accompanied by relatively low TP levels (NO_3-N:TP = 639:1). Springs were evident along the north terrace bank of Jones Slough. NO_3-N concentrations in both the wells and springs averaged 14.7 mg/L (SD = 4.5).

Groundwater discharge was detected at the bottom of Norton Slough near the north terrace bank. Lakebed piezometer samples confirmed NO_3-N concentrations of 11.1 mg/L. Warmer summer water temperatures and observed longer ice cover indicated less groundwater discharge to Norton Slough compared to Jones Slough. The mean NO_3-N concentration in the Norton Slough wells was 11.7 mg/L (SD = 3.12) and the NO_3-N:TP ratio was 557:1.

Groundwater discharges were continuous and we observed sustained open water throughout the winter months at the Bakkens Flowage monitoring site. The wells adjacent to Bakkens Flowage had the highest mean NO_3-N concentration of 23.3 mg/L (SD = 4.1) and lowest TP concentrations among the 4 oxbows (Table 4). The Bakkens Flowage wells also had the highest groundwater NO_3-N:TP ratio at 1792:1. Groundwater discharges contributed to continuous (ungauged) water flow toward the earthen dam. An artesian spring is located close to the Bakkens Flowage monitoring site and had NO_3-N concentrations averaging 19.1 mg/L (SD = 4.78). NO_3-N concentrations in Bakkens Flowage wells exceeded 10 mg/L in 83% of the samples.

Long Lake wells had the lowest terrace groundwater NO_3-N concentrations. Springs were not detected in or around the oxbow,

Table 3. Mean concentrations of NO_3-N, NH_3-N, TP, and DO in Norton Slough terrace and floodplain wells.

Norton Slough wells	NO_3-N (mg/L)	SD	NH_3-N (mg/L)	SD	TP (mg/L)	SD	DO (mg/L)	SD
Sand terrace	11.7	3.12	0.37	0.17	0.021	5.72	5.0	2.2
Floodplain	0.45	0.31	2.2	1.28	0.296	0.29	0.7	0.65

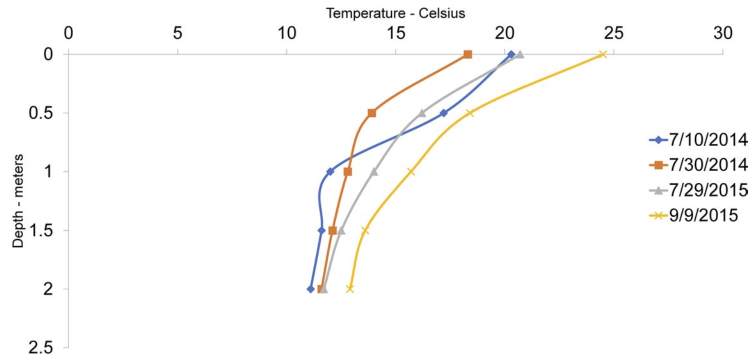

Figure 4. Cold summer water temperatures are sustained in shallow Jones Slough, a characteristic of a high groundwater discharge spring lake.

Figure 5. Significant groundwater discharge from the sand terrace maintains open water during the winter in Jones Slough and other oxbows. Photo by Robert Bertera.

based on both shoreline temperature measurements and observations. Long Lake had warmer water column temperatures and we observed longer periods of ice cover than for either Jones Slough or Bakkens Flowage. Long Lake was the only site where the combined top 3 well depths had NO_3-N concentrations lower than the Drinking Water Enforcement Standard of 10 mg/L (Table 4). The NO_3-N:TP ratio was the lowest among the 4 oxbow lakes at 235:1. Higher NO_3-N concentrations were found in deeper well depths (≥14.1 m), with the model predicting groundwater flow beneath the oxbows and toward the river.

MODFLOW 2000 demonstrated that groundwater flow from the sand terrace dominated oxbow water budgets, with variable flushing rates ranging from 3.7 to 31.7 times per year (Table 5). NO_3-N loading rates from the upgradient aquifer were very high and variable, ranging from 33,091 kg/yr at Bakkens Flowage to 2989 kg/yr at Norton Slough.

NO_3-N concentrations generally increased at deeper groundwater depths. NO_3-N remained high in all 14.1 m, 20.2 m, and 24.9 m deep wells

Table 4. Mean water column and groundwater NO_3-N and TP concentrations.

Lake	Lake TP (mg/L)	SD	Groundwater TP (mg/L)	SD	Lake NO_3-N (mg/L)	SD	Groundwater NO_3-N (mg/L)	SD
Jones Slough	0.203	0.38	0.023	5.99	2.36	1.24	14.7	4.69
Norton Slough	0.046	0.02	0.021	5.72	2.41	1.85	11.7	3.12
Bakkens Flowage	0.036	0.01	0.012	1.29	10.1	3.2	23.3	4.06
Long Lake	0.044	0.02	0.020	10.01	4.15	1.43	4.7	1.27

Table 5. Estimated groundwater NO_3-N and TP loading rates to the oxbows.

Lake	Volume (L)	Groundwater discharge (L/yr)	Flushing rate/yr	TP (mg/L)	TP(kg/yr)	NO_3-N (mg/L)	NO_3-N (kg/y)r
Jones Slough	23,033,479	433,255,000	18.81	0.023	10	14.7	6369
Norton Slough	69,504,843	255,500,000	3.68	0.021	5.4	11.7	2989
Bakkens Flowage	320,954,400	1,420,215,000	4.42	0.013	18.5	23.3	33,091
Long Lake	121,615,200	3,860,605,000	31.74	0.020	77.2	4.7	18,145

Table 6. NO_3-N concentrations in deeper wells 14 to 24.9 m.

Well	Norton Slough	Long Slough	Bakkens Flowage	Bakkens Flowage	Bakkens Flowage
Depth (m)	14.1	14.1	14.1	20.2	24.9
Mean NO_3-N (mg/L)	15.6	10.8	31.8	32.5	27.6
SD	4.73	3.47	7.1	4.78	1.26
n	21	18	16	5	5

Deepest Jones Slough well was 10.2 m.

(Table 6). None of the monitoring wells was deep enough to detect NO_3-N declines below 10 mg/L. Deeper groundwater flow paths, below the monitoring wells, were not accounted for. As a result, the estimated NO_3-N loading to the oxbows reflected only a portion of the nitrogen discharge to the Lower Wisconsin State Riverway and Mississippi River.

River

We found reduced conditions in floodplain wells downgradient from Norton Slough based on visible iron staining and low DO. Compared to the upgradient terrace groundwater, NO_3-N and DO concentrations were in the floodplain aquifer were lower while NH_3-N and TP concentrations were higher (refer back to Table 3). High TP concentrations in floodplain wells indicated that anoxic alluvial groundwater can be a source of TP in Norton Slough.

Based on long-term USGS Wisconsin River flow data, the alluvial aquifer reverses flow away from the river and moves into Norton Slough at about 570 m^3 per second (cms). In the spring of 2013, Norton Slough DO levels declined in 3 separate episodes when the river flow reached 570 cms (Fig. 6). The Pearson correlation coefficient indicated a moderate negative correlation ($r = -0.7473$) for water levels and DO. River flow records indicated that reverse groundwater flow occurred infrequently, about 6% of the time during the growing seasons. The infrequent groundwater flow reversal validates the steady state assumption used in the MODFLOW 2000 model simulations and indicates that groundwater flow from the terrace dominates oxbow hydrology. The Long Lake elevation is 0.3 m closer to the river elevation than to the elevation of the other 3 oxbows. As a result, reverse groundwater flow may have greater influence on Long Lake hydrology and water chemistry.

In 2013, we attempted to collect sediment cores from Norton Slough and Jones Slough to assess water quality histories. However, the substrate was predominately sand with a modest layer of dead organic matter and algae. When river flow rates exceeded about 1130 cms (39,900 cubic feet per second) at the Muscoda gauging station, we observed the river expand and flow into our study lakes on several occasions. Fast river currents briefly returned to the long narrow lakes. Organic sediment scouring and nutrient export is possible under these conditions, for a total of 13 times from 2000 to 2018 based on the USGS Muscoda flow data (Fig. 7).

Estimated FFP densities in oxbow lakes and potential influencing factors

NO_3-N concentrations in Jones Slough and Norton Slough were far lower than in adjacent wells, likely indicating plant uptake and

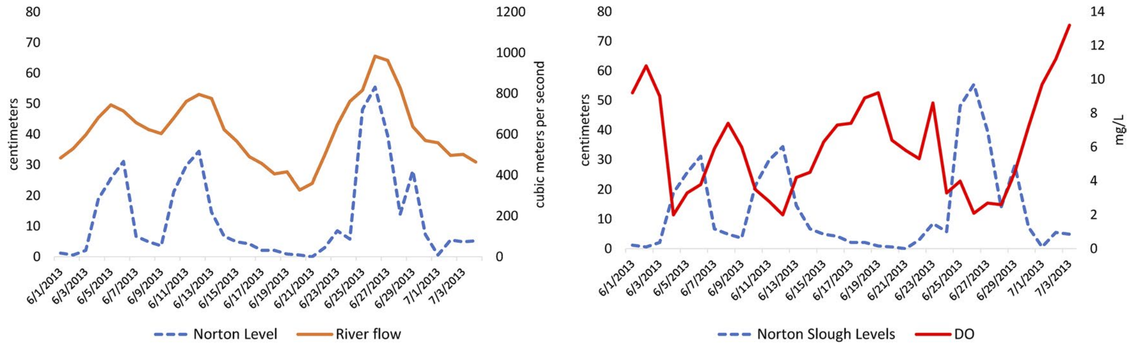

Figure 6. Norton Slough water level changes (zero = minimum level during the study) coincided with river flow 22 km downstream (left). When Wisconsin River flow reached 570 cms, alluvial groundwater reversed flow. Dissolved oxygen levels in Norton Slough declined following groundwater flow reversal (right). The Pearson correlation coefficient applied to the *z*-score normalized data indicated a moderate negative relationship ($R = -0.7473$, $P \leq 0.00001$).

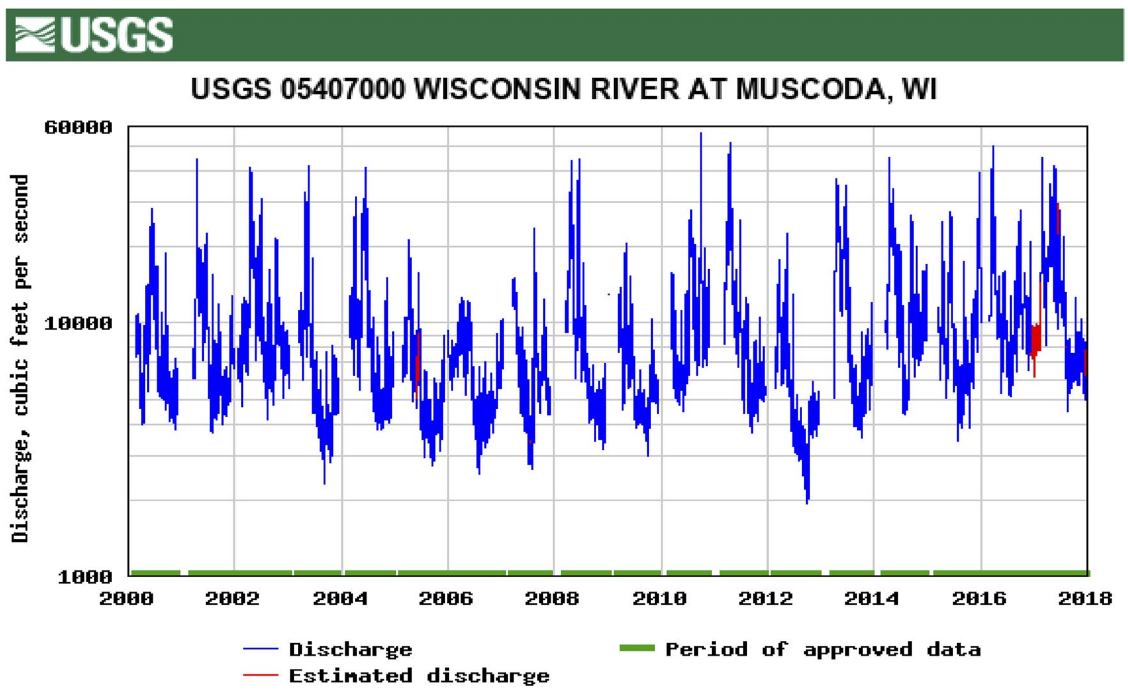

Figure 7. USGS hydrograph for Muscoda, Wisconsin, demonstrates frequency of flow rates reaching 1130 cubic meters per second or 39,906 cubic feet per second 13 times from 2000 to 2018. This is the flow rate when the river reaches the study oxbow lakes.

denitrification. NO_3-N concentrations in Jones Slough and Norton Slough exceeded recommended NO_3-N (Camargo et al. 2005) and TN (Robertson et al. 2006) criteria in most of the samples (Fig. 8). All of the NO_3-N concentrations in Bakkens Flowage and Long Lake exceeded recommended surface water criteria (Fig. 9).

The highest estimated FFP densities occurred in Jones Slough, with extended periods of nearly 100% cover each summer. FFP densities were generally lower in Norton Slough but surface mats remained prominent throughout the growing seasons. Lake TP concentrations were greater than groundwater concentrations in all 4 lakes and may have indicated internal P loading within the waterbodies and periodic alluvial groundwater inputs. Anoxia occurred frequently in Jones Slough beneath heavy FFP mats (Fig. 10). TP concentrations exceeded 1000 µg/L on 2 occasions when the entire water column was anoxic. The highest surface water NO_3-N concentrations were found in Bakkens Flowage but the estimated FFP cover was lower than in Jones Slough.

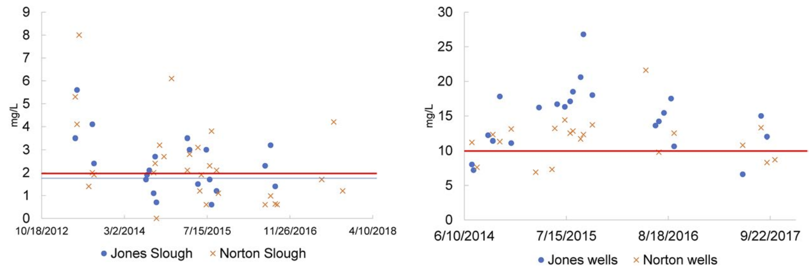

Figure 8. NO_3-N concentrations in Jones Slough and Norton Slough. In left graph, red line indicates recommended NO_3-N criteria (Camargo et al. 2005) and blue line indicates recommended TN criteria (Robertson et al. 2006). In right graph, NO_3-N concentrations in upgradient wells often exceeded the 10 mg/L Drinking Water Enforcement Standard (red line).

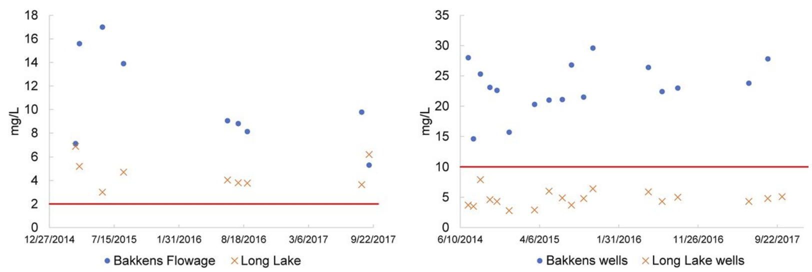

Figure 9. NO_3-N concentrations in Bakkens Flowage and Long Lake (left). All water samples exceeded recommended surface water criteria for both NO_3-N (Camargo and Alonso 2006) and TN (Robertson et al. 2006). NO_3-N concentrations in Long Lake wells, surrounded by the Sauk County Forest, were much lower than for nearby Bakkens Flowage wells (right). All Bakkens Pond wells exceeded the Drinking Water Enforcement Standard of 10 mg/L NO_3-N.

Figure 10. Anoxia often followed annual summer FFP cover in Jones Slough, previously described as "pristine" in the early 2000s (WDNR, unpubl. data). The photograph demonstrates what our estimated 100% FFP cover looked like. Photo by Dave Marshall.

Continuous spring flow moved FFP downstream into the larger impoundment.

The estimated FFP cover in Long Lake provided a stark contrast to nearby Bakkens Flowage and the other 2 oxbows (Table 7). Low FFP densities in Long Lake were observed only in nearshore areas throughout the entire study, and consistent with previous baseline surveys. Despite the low FFP growth in Long Lake, recommended NO_3-N and TN criteria (2 mg/L) and TP WisCALM threshold for shallow lakes (≥ 0.040 mg/L) were often exceeded. WisCALM is the Wisconsin Consolidated Assessment and Listing Methodology under Sections 303d and 305b under the Clean Water Act (WDNR 2022).

As mentioned, the groundwater at Long Lake had the lowest NO_3-N concentrations among the 4 oxbows. The lower groundwater NO_3-N discharge to Long Lake may have been influenced by the county forest recharge area, extending at least 2 km downgradient from terrace croplands. Ratios of agricultural to nonagricultural recharge flow paths roughly coincided with observed FFP levels in the 4 oxbow lakes: 21:1 (96%), 6:1 (67%), 24:1 (79%), and 3:1 (5%) for Jones Slough, Norton Slough, Bakkens Flowage, and Long Lake, respectively.

TP concentrations exceeded the WDNR WisCALM criteria for aquatic life and recreation (≥0.040 mg/L) in 50% of the samples collected from Norton Slough and Long Lake, 75% of the samples collected from Jones Slough, and 36% of the samples from Bakkens Flowage (Fig. 11). TP concentrations in the terrace wells adjacent to the oxbows did not exceed 32 µg/L. The mean TP concentration in the floodplain wells near Norton Slough was 0.296 mg/L (SD = 0.285).

Discussion

The water pollution investigation was not designed to assess N and P as limiting nutrients or to propose nitrogen and phosphorus thresholds for FFP. Instead, the water pollution investigation study determined that the upgradient Pleistocene sand terrace aquifer remains the strongest influence on the oxbow water budgets and water quality. Strong terrace groundwater gradients, combined with very high NO_3-N concentrations, revealed a massive nitrogen loading to the oxbow lakes and LWSR floodplain. Strong groundwater gradient flow originates in the bluffs north of the terrace, with ultimate discharge to the floodplain (Pfeiffer et al. 2006). Consistent with our study, Pfeiffer et al. (2006) described periodic for reverse groundwater flow during high river stages.

A USGS water quality assessment report (Dubrovsky et al. 2010) indicated that groundwater nutrient concentrations in agricultural basins, such as on the Wisconsin River glacial outwash terrace, are substantially greater than naturally occurring or "background" levels. Land uses across the Pleistocene sand terrace in the 21st century had shifted to irrigated (both center pivot and linear systems) croplands that require high nutrient applications.

While baseline water chemistry data are lacking for the study oxbows, and evidence of degradation is primarily narrative, a few reference lakes remain within the LWSR. A pristine 8 ha floodplain lake lies approximately 24 km upstream of our study area in Dane County, Wisconsin. Groundwater NO_3-N concentrations upgradient from the lake do not exceed 1.8 mg/L (UW Stevens Point Center for Watershed Science and Education 2022), a concentration at least one order of magnitude lower than the concentrations in the Spring Green terrace aquifer. The lake is devoid of FFP and displays conditions of our study lakes during the early 2000s and

Table 7. Visually estimated percent FFP cover in the study oxbow lakes.

Date	Jones Slough	Norton Slough	Bakkens Flowage	Long Lake
29/7/2013	100	100	100	5
20/8/2013	100	100	100	5
30/8/2013	100	80	100	5
10/7/2014	90	40	95	5
30/7/2014	95	50	90	5
25/8/2014	90	30	50	5
30/9/2014	95	50	60	5
29/7/2015	100	80	60	5
9/9/2015	100	65	90	5
29/6/2016	95	75	50	5
1/6/2016	95	70	50	5
16/6/2016	90	60	95	5
17/8/2017	100	70	90	5
9/9/2017	100	70	70	5
Mean	96.4	67.1	78.6	5
SD	4.1	20.3	20.6	0

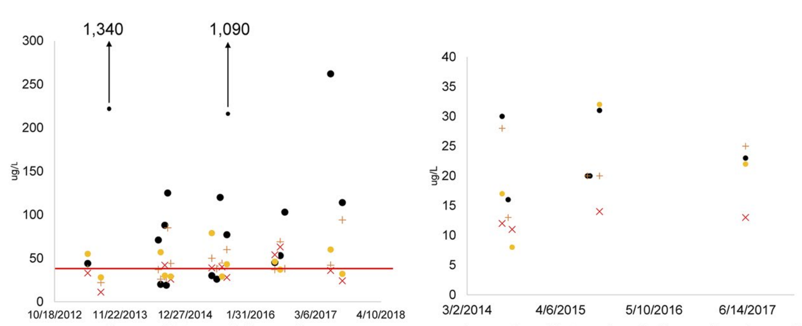

Figure 11. TP concentrations in the 4 oxbows, with the red line indicating WDNR WisCALM criteria (>40 µg/L for shallow lakes—left). TP values in Jones Slough frequently coincided with anoxia. Well TP concentrations were all below 40 µg/L (right).

before. The land surrounding the reference lake is mostly woodlands and hayfields.

The FFP problem along the LWSR is not uncommon. FFP dominance has become a stable state condition in lakes, ponds, and ditches across both temperate and tropical regions (Scheffer et al. 2003). FFP impacts include reduced DO, suppression of phytoplankton, and anoxia-driven sediment nutrient release (Houser et al. 2013, Giblin et al. 2014). Dense FFP mats can also reduce zooplankton populations (Fontanarrosa et al. 2010).

In the Mississippi River backwaters, the roles of N and P as limiting nutrients for FFP growth change during the course of the growing season (Houser et al. 2013). Mississippi River backwaters remain permanently flooded due to regulated flow, an environmental influence not found along the LWSR. It remains untested how FFP in the groundwater-fed LWSR oxbow lakes respond to the relative importance of N and P. Further investigation is required of this matter since this project focused on water pollution and not lake responses.

Giblin et al. (2014) demonstrated that backwaters with limited surface water connections to the Mississippi River supported greater FFP biomass. Houser et al. (2013) found FFP abundance was negatively correlated with DO. Among our 4 study lakes, Jones Slough had the highest FFP densities, lowest DO concentrations, and lowest surface water connectivity with the river. Jones Slough also has the smallest surface area of the 4 lakes, possibly a factor limiting both FFP wind dispersal and periods of open water. The river connectivity of Jones Slough, Norton Slough, and Bakkens Flowage, where FFP growth remains high, is mostly groundwater and surface water discharges to the river. The lower elevation Long Lake has somewhat greater river connectivity but remains terrace groundwater dominated. Given the physical differences between the flooded Mississippi River floodplain lakes and groundwater fed Lower Wisconsin River oxbow lakes, uncertainly remains on whether the Giblin et al. (2014) N and P thresholds can apply to the study of oxbow lakes. N exceeded the Mississippi River floodplain lake threshold in all 4 Lower Wisconsin River oxbow lakes for N (>0.808 mg/L) and the P threshold in Jones Slough (>0.167 mg/L). The estimated Giblin et al. (2014) P threshold for Mississippi River backwaters is also much higher than the WisCALM criteria for shallow lakes (≥0.04 mg/L P).

Private water supply NO_3-N concentrations were generally consistent with our monitoring well data. Mean NO_3-N concentrations in private wells upgradient of Norton Slough, Bakkens Flowage, and Long Lake were 15.2 mg/L, 17.9 mg/L, and 3.7 mg/L, respectively (UW Stevens Point Center for Watershed Science and Education 2022). The database also indicates that NO_3-N concentrations in terrace public water supply systems are increasing.

Limitations of the water pollution investigation included lack of quantified pre-impairment lake and groundwater quality data. Baseline surveys were completed from 2002 to 2008, before FFP became widespread. Information on the off-channel fish assemblage, rare fish species distribution, dominant macrophyte species, basic water quality, and habitat descriptions was gathered during the baseline surveys. FFP was generally a minor lake feature before 2011 in most of the study and other oxbow lakes besides Jones Slough that became degraded by 2008, likely due to its relative short groundwater flow path.

Aerial photos dating back to 1937 demonstrated that agriculture had been the dominant land use across the Pleistocene sand terrace for many decades. Beginning in 1992, linear and center pivot irrigation systems began to appear across the terrace and rapidly expanded into the 21st century (Schlaudt 2017). The linear irrigation system (Fig. 5) was installed in 2018. The irrigation systems require high-capacity wells, which are permitted and tracked by the state (Smail 2015). Increased numbers of high-capacity well permits were issued across the sand terrace and are consistent with expanded irrigation. High yield corn is typically produced on irrigated droughty soils that require higher nitrogen inputs due to rapid NO_3-N leaching into the groundwater (Matson 2017). While data were not available for individual farms, cropland nitrogen applications across Wisconsin increased roughly 35% from 2004 to 2014, in response to higher corn prices (Matson 2017). The vulnerability of the Pleistocene sand terrace to leaching and groundwater contamination had been recognized decades ago (WDNR and Wisconsin Geological and Natural History Survey 1989). The increased groundwater NO_3-N within the last 20 yr could have been predicted. In many parts of the Driftless Area uplands, water quality improvements were associated with long-term conservation programs designed to reduce soil erosion (Marshall et al. 2008). In the flat sand terrace, soil erosion has not been a problem, while agriculture became more industrialized to maximize crop production with irrigation, requiring additional nutrients.

Putting aside the unquantified influence on FFP growth in LWSR oxbow lakes, the nitrogen loading poses other environmental threats to the LWSR oxbow lakes. A maximum of 2 mg/L NO_3-N is recommended to protect environmentally sensitive fish, amphibians, and invertebrates (Camargo et al. 2005). High NO_3-N concentrations in many of the oxbow springs exceeded 3 mg/L, a level indicating "N hypersaturation" (Stanley and Maxted 2008). The recommended TN criterion in Wisconsin's Driftless Area is 1.88 mg/L (Robertson et al. 2006). To avoid eutrophication, the recommended TN concentration should not exceed 1 mg/L (Camargo and Alonso 2006).

The groundwater nitrogen measurements coupled with the aquifer flow modeling indicated nitrogen applications across the Sauk County sand terrace contributed an estimated 60,500 kg/yr NO_3-N to the 4 study oxbows during our study. The total NO_3-N loading along the 26 km long terrace is likely far greater and affects other oxbow lakes, wetlands, and the braided channel river. Similar sand terrace croplands are evident in 4 other LWSR counties. The 148 km Lower Wisconsin River is bordered by 101 km of groundwater-vulnerable sand terraces accompanied by numerous downgradient oxbow lakes, some of which became degraded over the past decade (WDNR, unpubl. data).

Even though more work is required to understand the complex LWSR oxbow lake responses, the massive NO_3-N loading across the sand terrace is clearly polluting the oxbows. On 23 April 2020 the US Supreme Court ruled in *City of Maui v. Hawaii Wildlife Fund* that the Clean Water Act can regulate groundwater pollutant discharges to surface waters. It remains uncertain whether the Supreme Court decision could apply to the LWSR oxbow lakes. Alternatively, actions seeking to protect groundwater based on the Drinking Water Enforcement Standard may improve oxbow water quality. Managing the oxbow lakes could include adopting recommended surface water nitrogen criteria and establishing FFP impairment criteria under WDNR WisCALM. WisCALM encompasses approved WDNR methodologies for reporting water quality data in relation to water quality standards and impairment listings under the Clean Water Act. Assuming that groundwater nutrient sources could ultimately be controlled, oxbow lake responses would take from 1.8 to 15.3 yr based on groundwater travel times. Periodic river inundation and flow scour of the relatively long and narrow former channel oxbow lakes appear to provide conditions favorable for the restoration.

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