The effect of removing hydrologic pulsing on a river-diversion riparian wetland

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Introduction

Hydrologic pulses are key to wetland function. The most productive ecosystems are generally those that receive energy sources (e.g., tides, river floods, pulses of runoff, upwelling) in addition to solar energy (W.E. Odum et al., 1995). Often these extra sources are seasonal or regular "pulses" that not only enhance productivity but also contribute to the stability of the ecosystem. At the same time, they make the system more "open" to exchange of elements with adjacent systems. This concept of stability of ecosystems in the face of continued pulses was termed *pulse-stability* by E.P. Odum (2000).

Day et al. (1977; 1995), Mitsch and Ewel (1979), Mitsch et al. (1979), Mitsch and Rust (1984), Megonigal et al. (1997), McDougal et al. (1997), Galat et al. (1998), Hein et al. (1999), Day et al. (2000), Reyes et al. (2004), Lane et al. (2004) and Mitsch et al. (2005c) describe riverine hydrologic pulses as having both positive and negative effects on overall biotic function of wetland ecosystems. But the overall effects of pulses on biogeochemical processes in these riparian river diversion wetland ecosystems are not clear, nor have they been clearly demonstrated in ecosystem studies (Mitsch and Day, 2006). The role of pulsing in river ecology has evolved from the River Continuum Concept (Vannote et al., 1980) to the Flood Pulse Concept described by Junk (1999) and Tockner et al. (2000) which emphasizes the exchange between a floodplain and a river and its floodplain as the primary factor affecting the function of the both systems.

Excessive nutrients have led to significant eutrophication and subsequent hypoxic conditions in coastal waters throughout the developed world. One of the most notable of these conditions is the 20,000 km^2 hypoxic zone in the Gulf of Mexico caused by excessive nitrates in the Mississippi River Basin (Rabalais et al., 1999; 2002; Turner et al., 2005). The retention of nutrients, especially nitrogen, in Midwestern USA wetlands could be of key importance as an economic solution to the Gulf of Mexico problem. The creation or restoration of 20,000 km^2 of wetlands and riparian ecosystems in the Mississippi River Basin has been recommended as a means to remove nitrogen from the Basin to alleviate the Gulf hypoxic zone (Mitsch et al., 1999, 2001, 2005b). It is necessary to assess the role of these potential wetlands as nutrient sinks and the importance of hydrologic pulses in this function. Nutrient fluxes come as seasonal pulses related to river and runoff discharge, not as fluxes at constant concentrations. If floods flowing into wetlands are synchronized with high concentrations of nitrate, for example, higher nitrogen retention may result (Nixon et al. 1996, Lane et al., 1999). But if hydrologic pulses occur during periods of low nitrate, lower N retention in the wetland may result (Spieles and Mitsch, 2000).

Goals and Objectives

This project examines the effects of removing pulse fluxes of nutrient-laden river waters into created riparian diversion wetlands on a fourth-order river in central Ohio, USA and replacing these fluxes with steady-flow conditions. The river water has sufficient concentrations of nitrate-nitrogen and total phosphorus to illustrate patterns of non-point source pollution from agricultural fields. Wetland function under both pulsing and steady flow conditions was determined through measurements of macrophyte productivity and fluvial inflow and outflow of nutrients.

The goal of this study is to investigate the importance of seasonal pulses on wetlands receiving river diversion water in the Upper Mississippi River Basin. Pursuant to this goal we have the following objectives:

1. Investigate the effect of removing hydrologic pulsing through a riparian wetland on the wetland's ability to retain nutrients;
2. Determine if the wetland will have decreased macrophyte productivity when the hydrologic pulsing of river water is replaced by a steady flow of river water.

A whole-ecosystem approach

While there is no optimal scale for ecosystem experimentation, many studies that attempt to link wetland function with structure are often done at inappropriate spatial and temporal scales. It is not always sound to apply conclusions from small-scale, short-term studies to real-world, full-scale conditions (Ahn and Mitsch, 2002; Mitsch and Day, 2004; Mitsch et al., 2005a). Whole ecosystems are often criticized because the size, cost, and logistics do not allow for much, if any, replication. These weaknesses, however, are compensated for by whole-ecosystem studies being more homeostatic, having a lower variance, and by being more likely to reveal ecosystem properties that are not apparent in smaller scale experiments (Odum, 1990; Carpenter, 1998; Kemp et al., 2001). Even though biotic community structure is often taken as a surrogate for ecosystem function (Kentula et al., 1992), the presence of physical or biological structure may not indicate functional replacement (Campbell et al., 2002). Until our understanding of ecological indicators improves, it is necessary to do in depth whole ecosystem studies to determine what is the true functionality of created ecosystems. Such studies are not often done (Rienartz and Warne, 1993) and there is still much need for improvement in the building of wetlands (Mitsch and Wilson, 1996).

Methods

Site Description

The wetland in this study is a created river diversion wetland located at the Wilma H. Schiermeier Olentangy River Wetland Research Park at The Ohio State University in Columbus, Ohio, USA (latitude 40.021°N, longitude 83.017°E) (Fig. 1). A river diversion wetland is a wetland on the adjacent floodplain or behind artificial levees that receive water by pumping or flood flows from the main channel of a river (Mitsch et al., 2006). From its creation in 1996 until 2004, the 3-ha created riparian wetland (referred to here as a created oxbow) received, on average, 7 to 8 natural flood pulses per year from the Olentangy River. Inflow from 1998-2004 averaged 20 ± 4 m yr^{-1}. The Olentangy River provides frequent short (5-6 days of inflow) flood pulses into the created oxbow which typically result in 9-12 days of outflow from the wetland. Water flows into the northern tip of the wetland through a Red Field Tideflex™ check valve when the river elevation is higher than the wetland; the valve closes when the river elevation is lower than the wetland water level and water then flows back to the Olentangy River though an outflow control weir (Fig. 2; Fink and Mitsch, in press).

Hydrology

The 3-ha created oxbow was subjected to one year of pulsing—2004—and one year with steady-flow conditions—2005(Fig. 3). Pulsing conditions during the first year (April 2004 to March 2005) were created entirely by natural flooding of the river itself. Steady-flow condtions during the second year (April 2005 – March 2006) were created

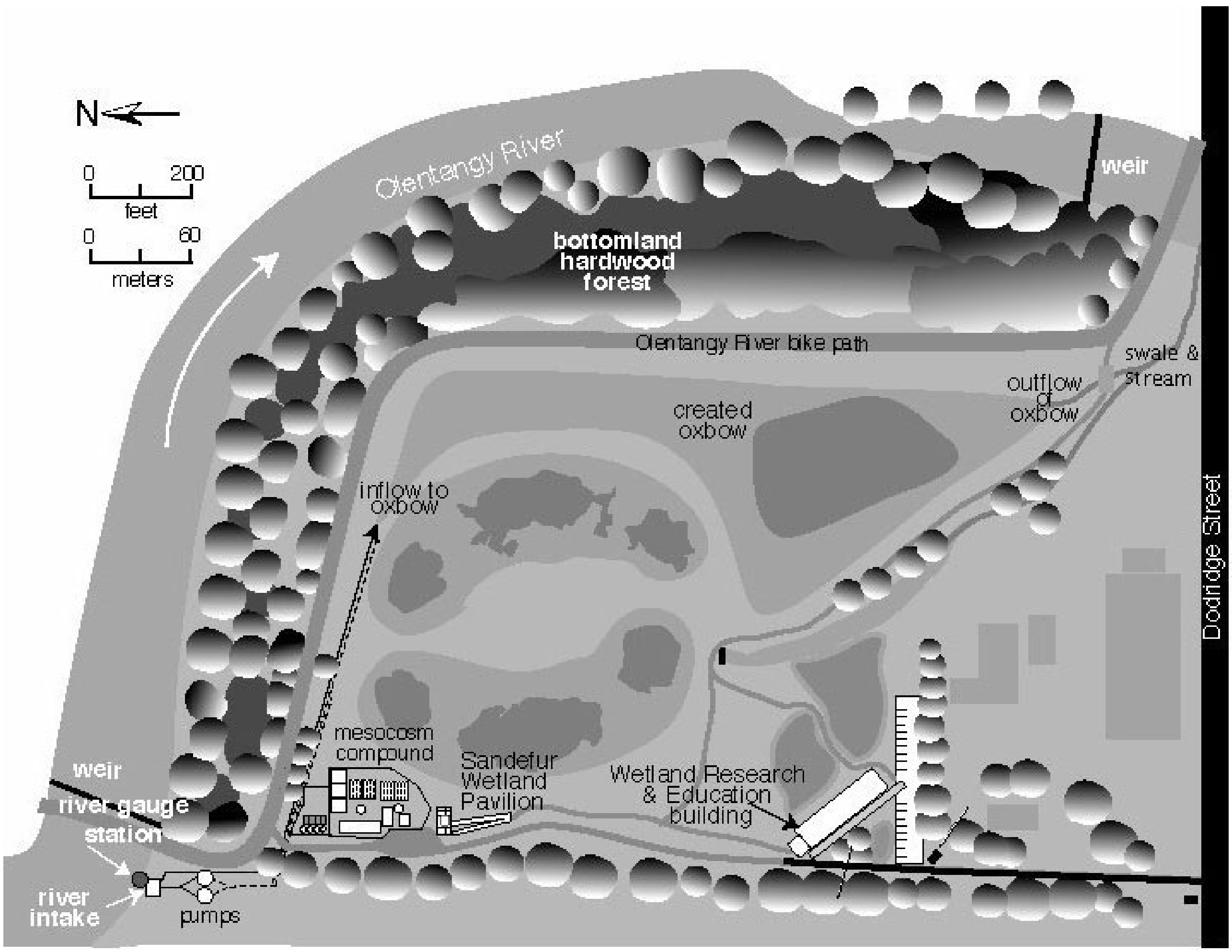

Figure 1a. Site map of the Wilma H. Schiermeier Olentangy River Wetland Research Park. The 2.8 ha created oxbow wetland is located between the experimental wetlands and the bottomland hardwood forest.

Figure 2. Inflow and outflow control structures in the created oxbow wetland. The Red Field TideflexTM check valve, left, opens via water pressure when the river elevation is higher than the wetland and then recloses when the river elevation is lower than the wetland water level, and water pressure is removed. Water then flows back to the Olentangy River though an outflow control weir, right.

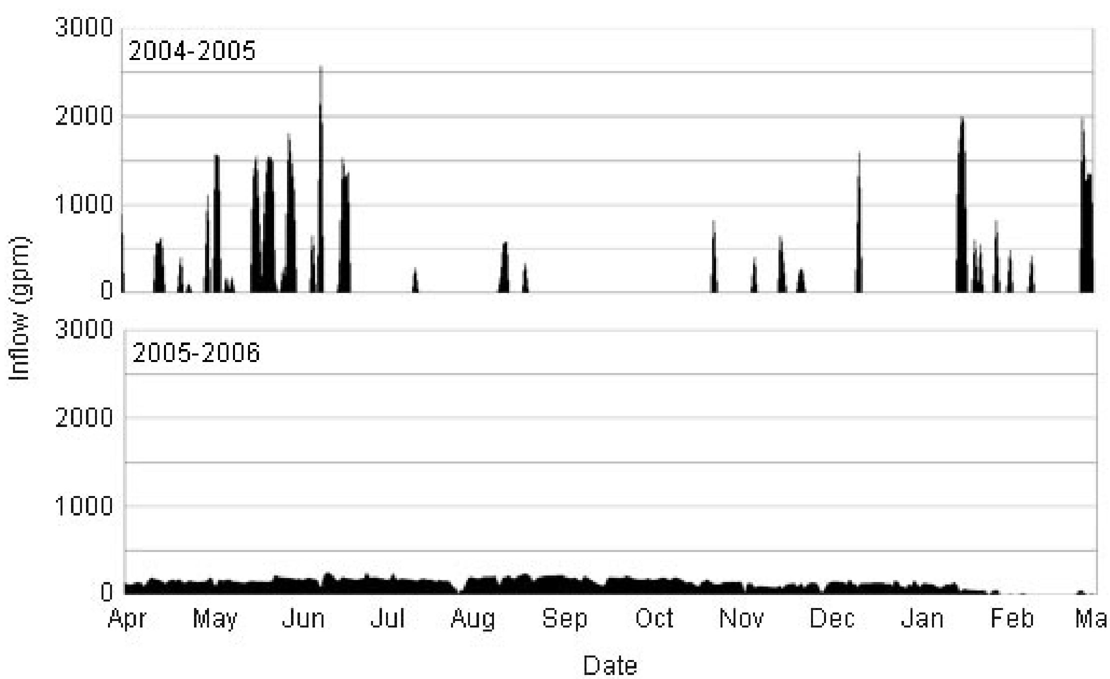

Figure 3. Hydrologic inflow rate for the created oxbow wetland, April 2003 through March 2006.

and controlled by a large submersed bypass-pump on the river intake that "filtered out" floods and created artificial steady-flow conditions. We attempted to provide a similar volume of water to the wetlands in the non-pulsing year with the pump as was provided naturally by the river during the pulsing years.

Flows into and out of the wetland were measured using a Swofer 2100 current meter for water velocity and an ISCO 730 bubbler module to estimate stage and cross-sectional area. A simple mathematical model was developed to describe the inflow based up upon the relative elevation of the river and the oxbow water surface. Outflow was estimated from the stage of water within the wetland and the shape of the outflow weir (USBR, 1997). A daily hydrologic budget was then developed from daily readings of river elevation and wetland stage.

To verify that the steady flow pumping did indeed deliver a significantly different water regime than the natural river pulsing, the Richardson-Baker Flashiness Index for Streams was applied to the wetland (Baker et al., 2004).

$$R-B\ Index = \frac{\sum_{i=1}^{n}|q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i} \qquad (1)$$

Where q is the daily inflow rate. The index measures oscillations in flow relative to total flow, and as such, provides a useful characterization of hydrologic inputs. This index was calculated on a monthly time step to allow a statistical comparison of flow stability between the pulsing and non-pulsing years.

Macrophyte productivity and diversity

The wetland has two significant vegetative zones. The northern (closest to the inflow) half is an emergent marsh and the southern half (closest to the outflow) is an open water basin. The lack of vegetation in the southern half is primarily due to high water conditions during spring, which prevents the germination of emergent aquatic plants except for littoral zones. Vegetation surveys and peak biomass surveys were conducted in August 2004 and 2005. Meandering transects were conducted throughout the entire wetland basin, covering wetted, transitional, and near upland zones. For each species observed, its relative abundance was estimated as present (0-5%), common (5-50%), or abundant (50-100%). Indicator status was determined using the Region I (Northeast) National Wetland Indicator List (Reed, 1998). Species not found on this list were recorded as non-listed (NL). Net aboveground primary productivity (NAPP) was estimated by determining peak biomass on 6 transects across the wetland that pass through different zones of the wetland. Three separate one-meter square plots were selected at random within the areas supporting vegetation along each transect. In each plot the above ground biomass was harvested, keyed to species, and weighed. Subsamples were dried at 105°C to calculate a wet-dry ratio. Aerial photographs were taken by the Ohio Department of Transportation, ground-truthed, and used to estimate the extent of the different macrophyte communities in the wetland. Total net primary productivity was estimated as the product of plot biomass estimates and the areal extent of macrophyte communities.

Spatial community diversity was quantified by calculating a macrophyte community diversity index (CDI). The index is expressed as:

$$CDI = \Sigma\ (C_i \ln(C_i)) \qquad (2)$$

Where C_i is the present cover of community "i" and N is the number of macrophyte communities (Mitsch et al., 2005a). This index includes evenness of plant cover as well as the number of plant communities.

Water Quality

Dawn and dusk inflow and outflow grab samples were taken between April 2004 and March 2006 on days when there was flow into or out of the created oxbow wetland. During the pulsing year of 2004, when the Olentangy River was at a high stage (above 220.9 m MSL), overflow occurred into the diversion wetland from the river. More detailed automatic sampling was conducted during some storm events using ISCO 6874 autosamplers at the inflow and outflow points of the created oxbow. The autosamplers were set to hourly frequencies during high flow periods. Grab samples were also taken at 11 locations around the wetland to determine the spatial distribution of nutrients and suspended sediments. During the pulsing year, these spatial samples were taken every 4 days during flow events; during the steady-flow year, spatial samples were taken twice per month. The inflow, outflow, and spatial grab samples (n = 700 over the two water years) were analyzed for nitrate + nitrite (NO_3^-), total Kjeldahl nitrogen (TKN), soluble reactive phosphorus (SRP), total phosphorus (TP), and total suspended solids (TSS).

Chemical Analysis

Nitrate + nitrite, soluble reactive phosphorous (SRP), total Kjeldahl nitrogen (TKN), and total phosphorus (TP) were analyzed using Lachet (2000) modifications of standard methods (USEPA 1983, APHA 1998) with a Lachet QuickChem flow-injection analyzer (FIA+ 8000). Manual and auto-sampler samples were split into filtered (0.45 µm) and unfiltered subsamples within 48 hours of sampling, and analyzed for appropriate chemistries. TP and SRP were analyzed with an ascorbic acid and molybdate color reagent method. TP samples were digested in a block digester using 0.5 mL of a digestion solution made up of H_2SO_4, K_2SO_4 and mercuric sulfate and heated for 1 hour at 160°C and 1.5 hours at 380°C. TKN was determined using the salicylate and hypochlorite method. Nitrate+nitrite was determined by the sulfanilamide method after reduction in a cadmium column. Throughout this paper references to nitrate or nitrate-N should be interpreted as references to nitrate+nitrite. Total nitrogen (TN) was estimated to be the sum of TKN and nitrate+nitrite-N. Total suspended solids were determined using an empirical correlation with turbidity developed for the Olentangy River Wetlands (Harter and

Mitsch, 2003). Turbidity was measured in the laboratory using a Hach turbidimeter.

Avian use

Avian use of the created oxbow was compared in the hydrologic pulsing (2004) and steady-flow (2005) years twice-per-month during spatial sampling trips. During months in 2004 where there were no spatial sets taken due to a lack of water flow, a meandering transect around the perimeter of the wetland was conducted and avian observations were recorded. For consistency, the durations of these meandering transects were similar in time to the water sampling trips. Birds were recorded only when they were observed visually.

Results

Hydrology

In 2004 there were 8 discrete river pulses into the created wetland for a hydraulic loading rate of 27±3 m yr^{-1}. From April 2005-March 2006 the inflow was a steady of 20±1 m yr^{-1} (Table 1). The steady state hydrologic year (April 2005-March 2006) had 338 days of inflow due to 4 power outages and general pump failure in the March 2006. The total inflow into the oxbow wetland was 25% less in the steady flow year than in the pulsing year. The experimental design called for the same amount of water in both years. Most of the "missing" inflow water occurred due to a loss of pumping ability in March 2006. If this month is disregarded, then the difference in inflow between the two water years is only 15%. The important difference between years was not the amount of water, but rather the timing of the water delivery (Fig 2). This is apparent in the differences in the average monthly Richardson-Baker flashiness index between the pulsing and steady-flow years. The index during the pulsing year was significantly greater than the index during the steady-flow year, 0.96±0.06 and 0.21±0.02 respectively, indicating that the wetland hydrology was indeed much "flashier" during the pulsing conditions (Table 1). During pulsing hydrologic conditions 95 % of the total number of days of flow occurred during the wet season compared to 62% during non-pulsing conditions. The pulsing flow in 2004-2005 is typical of how this wetland has historically functioned (Fink and Mitsch, in press).

Table 1. Hydrology (ave ± std error) of the oxbow wetland in April 2004 – March 2006. Hydraulic retention time (HRT) was not calculated for days when there was not any inflow or outflow. The Richardson-Baker flashiness index (R-B index) for the created oxbow wetland was calculated on a monthly basis for pulsing and steady-flow hydrologic conditions. Wet season is defined as November through May; dry season is defined as June through October.

		Pulsing 2004-2005	Steady-flow 2005-2006
Wet Season	Days of flow	165	148
	Inflow Rate m yr^{-1}	36±5	19±1
	Outflow Rate m yr^{-1}	35±6	19±1
	HRT d	4±0	9±0
Dry Season	Days of flow	7	90
	Inflow Rate m yr^{-1}	1±2	22±1
	Outflow Rate m yr^{-1}	2±2	22±1
	HRT d	3±0	5±0
Annual	Number of Pulses	8	0
	Total Days of flow	172	338
	Inflow Rate m yr^{-1}	27±3	20±1
	Outflow Rate m yr^{-1}	26±4	20±1
	HRT d	4±0	8±0
	R-B index	0.96±0.06	0.21±0.02

Table 2. Net above ground primary productivity (NAPP), total biomass, and percent coverage of the five most abundant macrophyte communities in the created oxbow wetland during 2004 (pulsing hydrology) and 2005 (steady-flow hydrology). The community diversity index ($CDI = \Sigma C_i \ln(C_i)$ where C_i is the percent cover of an individual species) is also given. The species that comprise the mixed littoral wetland plant category are primarily: *Eleocharis* sp., *Scirpus americanus*, *Juncus effusus*, *Leersia oryzoides*, *Sagittaria* sp., *Verbesnia alterniflora*, *Cyperus strigosis*, and *Juncus canadensis*..

	Percent Cover		NAPP g m^{-2} yr^{-1}		Total Biomass kg yr^{-1}	
Macrophyte community	2004	2005	2004	2005	2004	2005
Typha sp.	14.6%	11.9%	1140	1455	4652	4849
Sparganium eurycarpum	2.6%	0.3%	640	646	466	54
Pontederia cordata	0.2%	0.4%	368	260	21	29
Phragmites australis	0.8%	1.2%	549	797	123	268
Mixed littoral wetland plants	12.8%	9.2%	393	442	1408	1140
Total assemblage	31%	23%	769	984	6670	6340
CDI	1.61	1.46				

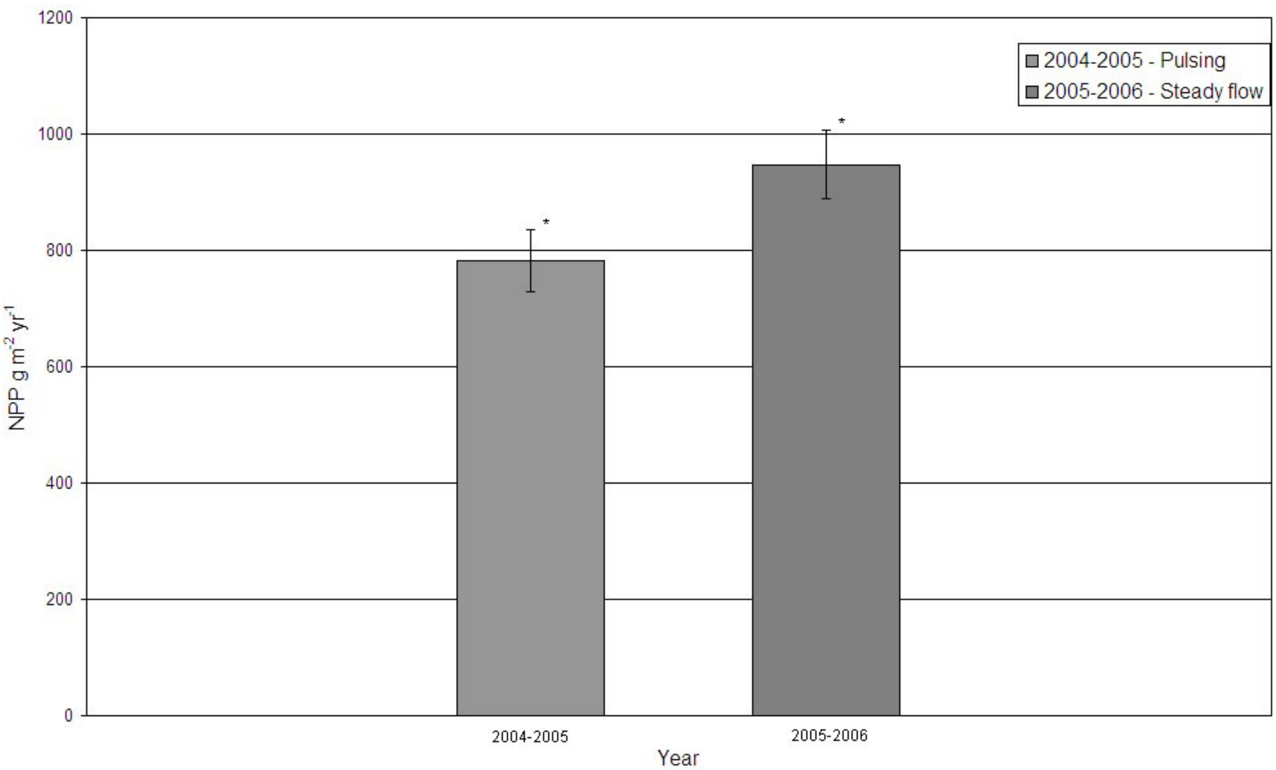

Figure 4. Net above ground primary macrophyte productivity (NAPP) in the created oxbow wetland in during pulsing (2004 - 05) and steady-flow (2005 - 06) conditions in the created oxbow wetland during peak biomass. An asterisk indicates significant difference at the $p < 0.05$ level.

Macrophyte productivity

After hydrologic pulses were removed, the net aboveground primary productivity (NAPP) was 984 g m^{-2} yr^{-1}, significantly higher than the 769 g m^{-2} yr^{-1} measured in the preceding pulsing year (Table 2; Fig. 4). There were 6 different vegetation communities identified from aerial photography in each year of the study, 5 of which were herbaceous wetland macrophytes (Fig. 5). *Typha* sp., *Pontederia cordata*, and *Phragmites australis* (invasive phenotype) were the only macrophyte communities with an increase in total biomass during steady-flow conditions. *Phragmites austalis* also increased in NAPP and areal coverage, with most of the patch expansion occurring along the intermittently to rarely flooded eastern shore of the wetland, with only a very small expansion within the inundated zone. The total productivity of *Typha* sp. did not change significantly as a reduction in areal cover offset an increase in NAPP. This is in contrast to *Pontederia cordata*, which experienced a decrease in NAPP, but still had an increase in total biomass as a result of greater areal coverage. The other wetland macrophyte species that grew as a mixed community along the littoral zone of the southern basin of the created oxbow also had a decrease in areal coverage, but had a slight increase in NAPP. The total macrophyte productivity for these wetland plants, however, was significantly decreased.

Overall, while NAPP increased following the removal of hydrologic pulses, there was less total areal macrophyte coverage within the wetland, which led to less total macrophyte productivity in the wetland during steady-flow conditions (Table 2). This decreased coverage was likely driven by a lack of drawdown conditions coupled with persistent deepwater conditions inhibiting macrphyte germination. The two macrophyte communities that experienced the greatest reduction in areal extent (*Sparganium eurycarpum* and the mixed wetland macrophyte community) both typically colonized along the fluctuating edge between the open water and the upland adjacent to the created oxbow. The removal of the hydrologic pulses made this edge static and appears to have narrowed the width of the niche previously exploited by these two macrophyte communities. This reduction in available niches is also suggested by a reduction in community diversity. The macrophyte community diversity index (CDI) for the created oxbow was higher, 1.61, during the pulsing hydrology and lower, 1.46, during the steady-flow year after the pulses were removed (Table 2).

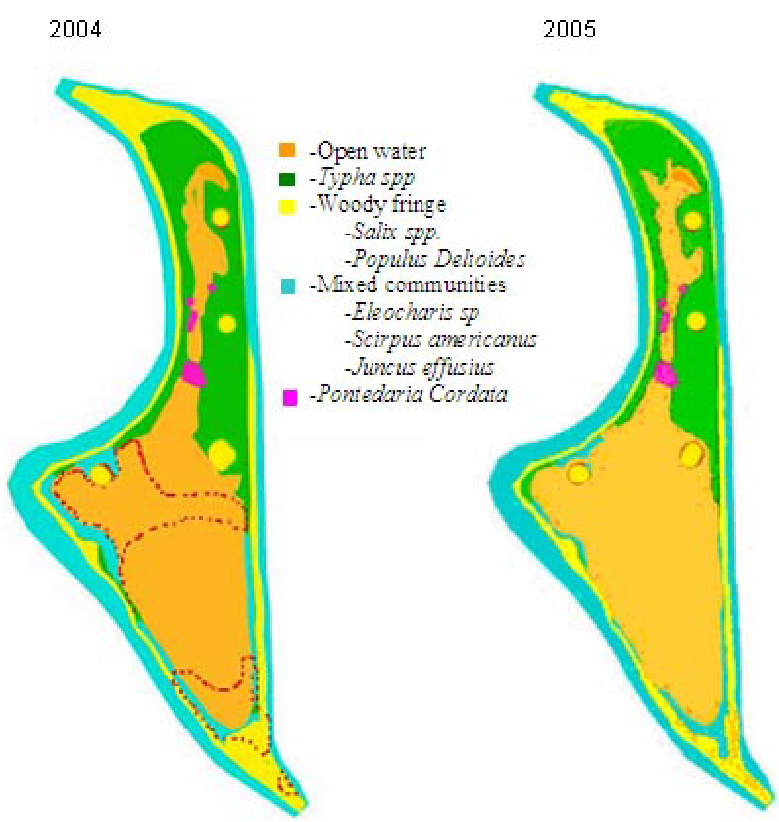

Figure 5. Macrophyte communities in the created oxbow wetland during peak biomass in 2004 and 2005. The area in the 2004 map marked with the dotted lines shows the extent of the spread of *Xanthium strumarium* following a prolonged drawdown that occurred after the biomass surveys were completed.

Table 3. Annual mean loading and retention of nitrate-nitrite (NO_3^--N), total nitrogen (TN), soluble reactive phosphorus (SRP), and total phosphorus (TP) during pulsing (2004) and non-pulsing (2005) years in the river diversion oxbow (ave ± std. error). Rates are in g-N m^{-2} yr^{-1} or g-P m^{-2} yr^{-1} as is appropriate. Rates and the mass retention during the pulsing year are calculated according to the number of actual days of flow; note that the duration of the inflow and outflow are different.

	NO_3^--N		TN		SRP		TP	
	2004	2005	2004	2005	2004	2005	2004	2005
Yearly Mean								
Loading Rate g-X m^{-2} yr^{-1}	32.2±0.2	10.3±0.1	64.5±0.4	17.2±0.1	0.48±0.00	0.14±0.01	6.10±0.04	3.96±0.01
Export Rate g-X m^{-2} yr^{-1}	16.8±0.2	2.3±0.1	32.2±0.3	6.2±0.1	0.43±0.01	0.06±0.01	1.62±0.01	1.09±0.01
Retention								
Rate g-X m^{-2} yr^{-1}	15.4±0.2	8.0±0.2	32.3±0.2	11.0±0.2	0.05±0.01	0.07±0.2	4.48±0.03	2.87±0.02
Percent (by mass)	48±3	77±6	50±4	64±6	10±1.0	57±5	73±8.0	13±7

Unit 'X' is N or P, as appropriate

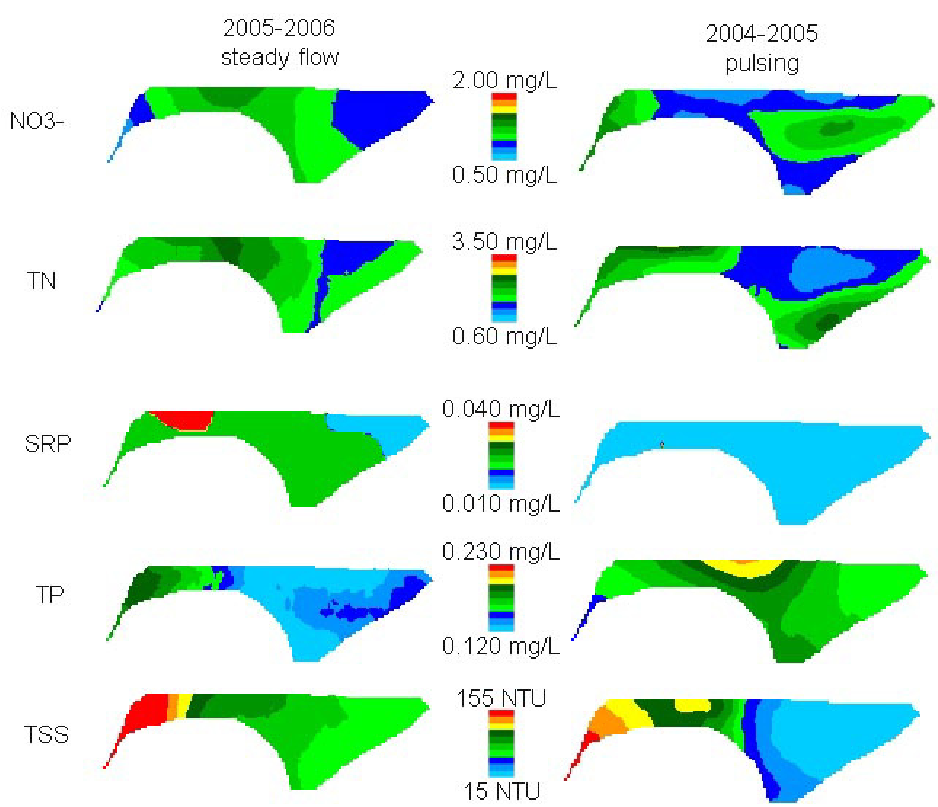

Figure 6. Kriging diagrams of nitrate + nitrate as N (NO3-), total nitrogen (TN), soluble reactive phosphorus (SRP), total phosphorus (TP), and total suspended solids (TSS) in the created oxbow wetland during wet season in 2004 and 2005.

Nutrient loading and retention rates

The loading rate for nitrate-nitrogen was three times higher during the 2004 pulsing year (32.2 ± 0.2 g-N m^{-2} yr^{-1}) than in the 2005 steady-flow year (10.3 ± 0.1 g-N m^{-2} yr^{-1}; Table 3). The loading rate was also higher during the pulsing year for total nitrogen (64.5 compared to 17.2 g-N m^{-2} yr^{-1}) and total phosphorus (6.1 compared to 3.96 g-P m^{-2} yr^{-1}). The retention rate was lower for these three parameters after pulsing was removed. Retention rates were 15.4 ± 0.2 g-N m^{-2} yr^{-1}, 32.3 ± 0.2 g-N m^{-2} yr^{-1}, and 4.48 ± 0.03 g-P m^{-2} yr^{-1} for NO_3^--N, TN, and TP respectively during the pulsing year and were 8.0 ± 0.2 g-N m^{-2} yr^{-1}, 11.0 ± 0.2 g-N m^{-2} yr^{-1}, and 2.87 ± 0.02 g-P m^{-2} yr^{-1} for NO_3^-, TN, and TP respectively during the steady flow year. The only nutrient species that did not have a difference in retention rate was soluble reactive phosphorus. The loading rates were 0.48 ± 0.00 g-P m^{-2} yr^{-1} in the pulsing year and 0.14 ± 0.01 g-P m^{-2} yr^{-1} in the steady flow year with retention rates of 0.05 ± 0.01 g-P m^{-2} yr^{-1} and 0.07 ± 0.2 g-P m^{-2} yr^{-1} respectively.

Seasonal and spatial nutrient dynamics

There were differences between the spatial dynamics of different nutrient species in pulsing and non-pulsing years (Table 4) and between the wet and dry seasons (Figs. 6 and 7). During the pulsing year, there was a slight increase in nitrate concentration in the open water basin during the wet season. This did not occur during the steady flow conditions. During the dry season in the steady flow year there was no difference in nitrate concentration spatially throughout the wetland. Under pulsing conditions nitrate in the dry season was initially reduced and then slightly increased in the shallow swale that exists between the open water basin and the outflow of the wetland. Although there were significant differences in the concentrations of TN during the different flow conditions and in the different seasons, there was not a significant difference in the pattern of the TN dynamics. In all cases TN increased through the emergent marsh and then decreased across the open water basin with a higher concentration band along the more vegetated western shore of the wetland close to the outflow. The increase in TN,

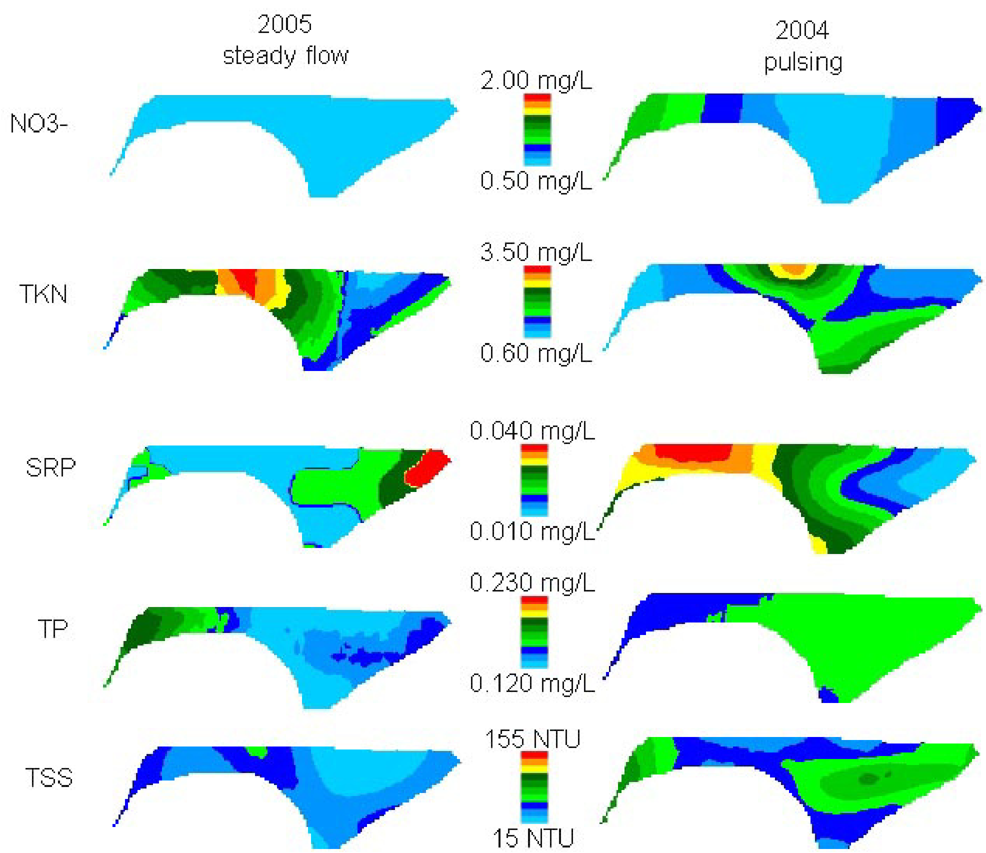

Figure 7. Kriging diagrams of nitrate + nitrate as N (NO3-), total nitrogen (TN), soluble reactive phosphorus (SRP), total phosphorus (TP), and total suspended solids (TSS) in the created oxbow wetland during dry season in 2004 and 2005.

Table 4. Nutrient and suspended sediment concentrations (ave ± std error (# samples). [SRP = soluble reactive phosphorus, TP = total phosphorus, $NO_3^- + NO_2^-$ = nitrate and nitrite, TN = total nitrogen, and TSS = total suspended solids] in the oxbow wetland created at the Olentangy River Wetland Research Park during pulsing (April 2003 – March 2005) and non-pulsing (April 2005 – March 2006) conditions when flooded river water is flowing through the wetland.

Parameter	Inflow		Mid-point		Outflow		% Removal	
	Pulsing	Steady flow	Pulsing	Steady flow	Pulsing	Steady flow	Pulse	Steady flow
SRP (µg-P L^{-1})	46.5±4 (141)[b]	29.0±1 (33)[b]	22±9 (22)[c]	15±1 (24)[c]	23.2±1.3 (184)[c]	18±1 (31)[c]	50.1[b]	39.2[b]
TP (µg-P L^{-1})	92±16 (81)	170±3 (36)	110±16 (14)[c]	126±3 (24)[c]	145±3 (108)[b]	139±5 (32)[b]	24.5	18.3
$NO_3^- + NO_2^-$ (mg-N L^{-1})	2.87±0.10 (141)[b]	2.13±0.07 (21)	1.76±0.21 (21)[bc]	0.97±0.06 (21)[bc]	1.52±0.03 (199)[b]	0.76±0.03 (20)[b]	47.0[b]	64.2[b]
TN (mg-N L^{-1})	3.04±0.05 (77)[b]	3.39±0.09 (21)[b]	3.17±0.35 (7)[c]	2.53±0.11 (20)[bc]	2.31±0.02 (102)[c]	1.94±0.08 (20)[c]	24.0[b]	42.7[b]
TSS (mg L^{-1})	17.3±2.0 (166)[b]	18.2 ±1.8 (36)[b]	14.3±1.3 (23)[b]	9.8±0.3 (23)[bc]	13.2±0.8 (227)[bc]	8.7±0.2 (35)[b]	23.7	52.1

[b]Significant difference between pulsing and steady flow ($p = 0.05$)
[c]Significant difference from upstream location ($p = 0.05$)

Table 5. Bird species observed utilizing the created oxbow wetland during pulsing hydrologic conditions, April 2004 – March 2005, and during non-pulsing hydrologic conditions, April 2005 – March 2006.

Bird species		Pulsing April 2004 -March 2005	Non-pulsing April 2005 -March 2006
Heronlike birds			
Great egret	*Ardea alba*	X	X
Great blue heron	*Ardea herodias*	X	X
American bittern	*Botaurus lentiginosis*	X	X
Green heron	*Butorides virescens*	X	X
Geese and Ducks			
Wood duck	*Aix sponsa*	X	X
Northern shoveler	*Anus clypeata*	X	
Blue wing teal	*Anus discors*	X	X
Mallard	*Anus platyrhynchos*	X	X
Canada goose	*Branta canadensis*	X	X
Ruddy duck	*Oxyura jamaicensis*	X	
Shorebirds			
Least sandpiper	*Calidris minutilla*	X	
Killdeer	*Charadrius vociferus*	X	X
Solitary sandpiper	*Tringa solitaria*	X	
Greater yellowlegs	*Tringa melanoleuca*	X	
Swallows and Kingfishers			
Kingfisher	*Ceryle alcyron*	X	X
Barn swallow	*Hirundo rustica*	X	X
Tree swallow	*Tachycinetea bicolor*	X	X
Songbirds			
American goldfinch	*Carduelis tristis*	X	X
Sedge wren	*Cistothorus platensis*	X	
Song sparrow	*Melospiza melodia*	X	X
Louisiana waterthrush	*Seiurus motacilla*	X	
Total species observed		23	15

seen in all seasons and all flow conditions, is driven by an increase in TKN. Since measured ammonia concentrations have always been negligible, this increase in TKN can be interpreted as an increase in the organic-N fraction. This increase in organic-N corresponds with the extent of the emergent marsh section of the wetland as does the decrease in organic-N with the open water section of the wetland. During the wet season there was a general decrease in SRP under steady flow conditions. Under pulsing conditions no spatial differences in concentration were detected. In the dry season, however, SRP concentration increased across the open water basin during the steady flow conditions whereas it was observed to decrease across that same basin during the pulsing conditions. Total phosphorus increased in concentration through the emergent marsh portion of the wetland during the wet season under pulsing conditions, but decreased through this portion of the wetland under all other conditions. The concentration of TP decreased in the open water basin under all conditions except for during pulsing conditions in the dry season. The pattern of TSS was very similar to the pattern for TP, with a general decrease in TSS during all conditions except for in the open water basin during pulsing conditions in the dry season.

Avian use

From April 2004 to March 2005 (pulsing year), a total of 23 birds species were observed utilizing the wetland while from April 2005 to March 2006, 15 bird species were observed (Table 5). An observation-area curve shows more avian use of the created oxbow wetland during the pulsing than steady flow conditions (Fig. 8). The guild of bird species with the greatest difference in presence between the pulsing and steady-flow conditions was shorebirds. During steady-flow conditions there was not any development of exposed mudflat during the late spring and summer months. Without this habitat, "peep" type shorebirds did not utilize the wetland.

Discussion

The Effect of Pulsing

Pulses can be both a subsidy and a stress for an ecosystem. The springtime hydrologic pulses bring in nutrients (N-P-K), propagules, colonizing animals, and fresh sediments but the high water can also cause oxygen deprivation in the substrate, impede macrophyte germination, and flood out bird nests. It is evident from this study and from other studies on pulsing and other types of disturbances within ecosystems that some intermediate amount of pulsing maximizes ecosystem function (e.g., Odum, 1995; Connell, 1978; Townsend, 1996). This theory suggests that a wetland ecosystem with an intermediate degree of pulsing supports more ecosystem functions than a wetland without pulsing (Fig. 9).

The reason for the difference in the loading rates between the pulsing and non-pulsing condition is the difference in the timing of water delivery. This causes a difference in loading rates because there are differences in the concentrations of nitrogen and phosphorus in the river during the different seasons (Figs. 6 and 7). The concentration of nitrate and total phosphorus are typically greater in the spring, following farm field fertilization (Randell et al., 1997, Fink and Mitsch, 2004). If the maximum delivery of water to the wetland is not timed with the maximum concentration of nutrients in the influent water, then the efficacy of the wetland to treat the nutrient pollution will not be maximized.

In a whole ecosystem comparison of pulsing and steady flow conditions in created riparian wetlands adjacent to the one described here, Mitsch et al. (2005) observed significantly more reduction in SRP during non-pulsing conditions but no differences for NO_3^- or TP reduction. This contrasts the pattern observed in this study where there was no difference in the percent reduction of TP (by concentration) but more reduction of SRP, NO_3^-, and TN (by concentration) during pulsing conditions (Table 4). This difference may be attributable to the differences in experimental design. In the study by Mitsch *et al*. (2005), flood pulses were provided artificially by pumping river water into the wetland during the first week of the month during the wet season regardless of river flow. Hydrologic pulses were therefore not necessarily synchronized with nutrient pulses in the river. This is in contrast to the present study where hydrologic pulses were naturally occurring and therefore likely to be in sync with elevated nutrient levels in the river.

The differences in hydrology also explain the observed differences in the primary productivity measured in this study. Soil exposure, which occurs during pulse drawdowns, has been shown to be positively correlated with species richness and species composition (Atkinson et al., 2005). In the steady-flow year the water remained too deep in many areas for emergent macrophytes to easily germinate. The areal coverage of water in the wetland was also static. Steady flow meant that there was no exposed mudflat during the dry season, which is an area of the wetland that colonized with macrophytes between floods during the pulsing year.

There was also a shift in the proportion of the biomass comprised of *Typha* sp. The percent biomass comprised of *Typha* sp. increased significantly from 2004 to 2005. This is likely also due to the static water levels along the edge of the open water portion of the wetland remaining too deep to provide suitable habitat for macrophyte germination (Keddy and Reznicek, 1986; Squires and van der Valk, 1992). This is the section of the wetland that had the greatest amount of non-*Typha* sp. during the pulsing conditions. The increase in *Typha* productivity following pulse removal may have been a result of the shallower than typical water depths in the spring and early summer allowing for greater *Typha* spread.

This increase in productivity during non-pulsing conditions in the created oxbow is consistent with what was observed by Mitsch et al. (2005c) who observed 46% and 81% decreases in net primary productivty in the two pumped wetlands with the onset of pulsing. Therefore it is not surprising that the productivity was higher during the steady-flow year than the pulsing year. Mesocosm studies by Anderson and Mitsch (2005) did not find a difference in productivity between pulsing and steady-flow conditions. Further research on this topic is necessary.

Management implications

Total cover requirements in compensatory mitigation projects are often set at 75% or 85% for the first two years (Campbell et al., 2002). As such, the created oxbow in this study could have easily been viewed as a failed project (33-40% plant cover) despite its high level of ecosystem function (Fink and Mitsch, in press). The wetland did have a greater areal extent of macrophyte vegetation cover during the pulsing years than the steady flow year. A pulsing hydrology may enable mitigation wetlands to reach target macrophyte coverage goals more easily.

Conclusions

Nutrient uptake is related to nutrient loadings. There was an increased nitrogen uptake during pulsing conditions compared to steady flows. The wetland had higher overall biomass productivity during pulsing conditions than when the wetland received a steady flow of water. While the percent of the total phosphorus removed by the wetland increased during steady flow conditions, the wetland had a greater phosphorus retention rate during pulsing hydrology compared to the steady-flow hydrology. Pulsing hydrology also had a positive effect on avian wildlife by creating greater temporal variability in available habitat for birds to use. Overall the wetland was a more highly functional and powerful ecosystem when subsidized by river pulses.

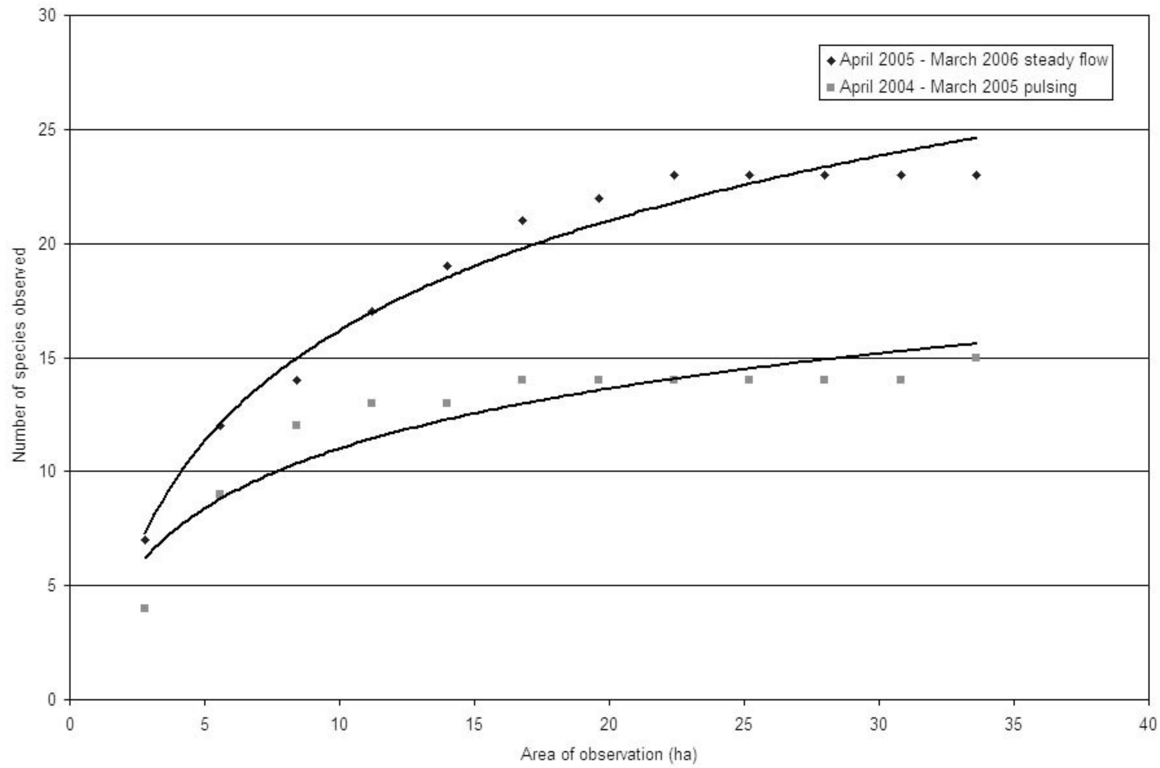

Figure 8. Species-area curve comparing the number of bird species in the created oxbow wetland during pulsing (2004) and steady-flow (2005) conditions.

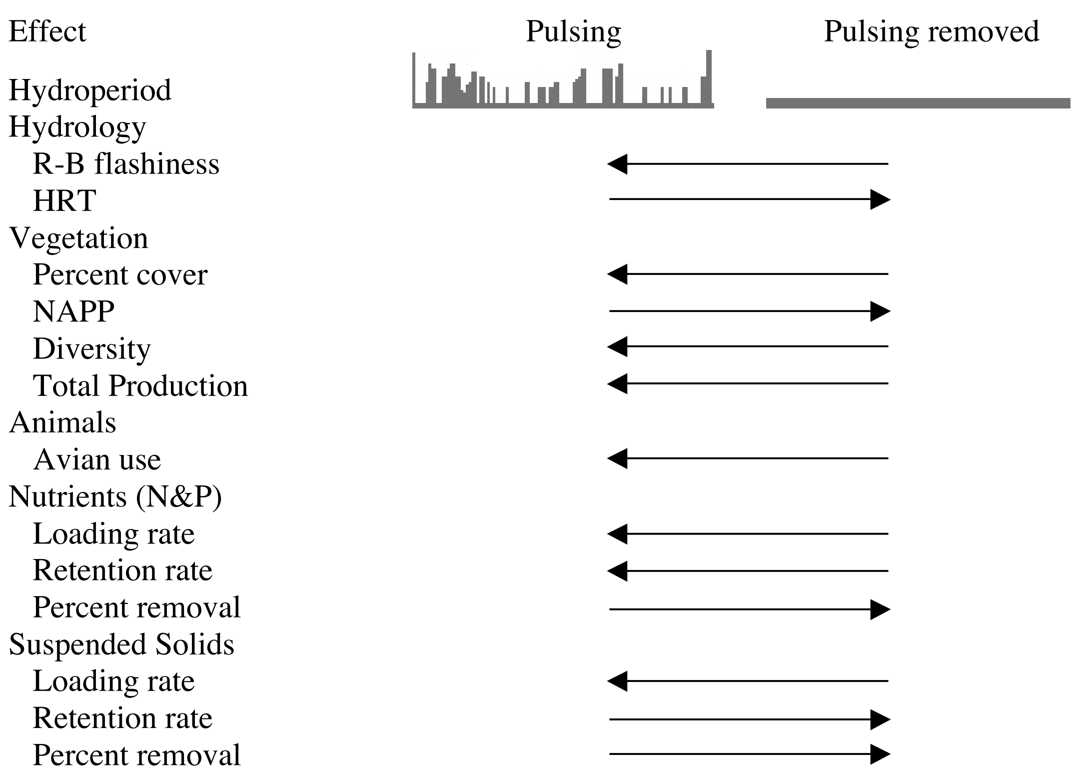

Figure 9. Effect of removing pulsing on wetland ecosystem function. Arrows indicate the direction of increasing value for the indicated wetland ecosystem function.

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