Biogeochemical and nutrient removal patterns of created riparian wetlands: Fifth-year results

William J. Mitsch, Naiming Wang, Virginie Bouchard, Melanie Ford, and Kevin Mohler

School of Natural Resources
The Ohio State University

Introduction

As part of a long-term, large-scale experiment on self-design, two wetland basins at The Olentangy River Wetland Research Park were set up as planting experiment, i.e., one basin was planted with 2400 individuals of macrophytes representing 12 species in 1994 while a second wetland basin remained unplanted (Mitsch et al., 1998). In the 5 years of wetland development since that planting, the basins have gone through 5 growing seasons that have been characterized as follows:

- Year 1 (1994) - Wetland 1 was planted in May with Wetland 2 as unplanted control. Essentially both basins were algal ponds with few macrophytes.
- Year 2 (1995) - Wetland 1 plants developed, particularly around the perimeter to about 13% macrophyte cover in August, compared to essentially no macrophyte cover in Wetland 2. Floods in late June and early August brought in large carp with waters remaining turbid through much of the rest of the year.
- Year 3 (1996) - Wetland 1 continued to develop in vegetation cover with about 39% cover. Unplanted Wetland 2, particularly after spring drawdown in both wetlands to install sedimentation markers, developed to about 35% macrophyte cover by August, essentially catching up with the planted wetland within 3 growing seasons.
- Year 4 (1997) - Macrophyte growth continued to increase in both wetlands with about 54% cover in Wetland 1 and 58% cover in Wetland 2.
- Year 5 (1998) - Macrophyte cover is similar in the two basins but Wetland 2 is beginning to be dominated by highly productive *Typha* spp. while Wetland 1 still has a wider diversity of cover and is not dominated by *Typha* spp. (Bouchard and Mitsch, 1999a.b). In other words, Wetland 1 plant cover is now more diverse.

This study reports water quality results for the fifth year (1998). Other studies of the water quality of these wetlands are reported for Year 1 (Mitsch et al., 1995); Year 2 (Wehr and Mitsch, 1996; Mitsch and Nairn, 1996; Nairn and Mitsch, 1997); Year 3 (Mortensen et al., 1997; Mitsch and Carmichael, 1997; Nairn and Mitsch, 1997; Vorwerk and Mitsch, 1998); and Year 4 (Mitsch and Montgomery, 1998; Spieles and Mitsch, 1998). Two undergraduate honors theses (Wehr, 1995; Vorwerk, 1997), two Master's theses from Europe (Mortensen and Lanzky, 1996; Kang, 1999) and two dissertations (Nairn, 1996; Spieles, 1998) have also

Table 1. Water quality sampling at Olentangy River Wetland site in 1998.

Sample frequency	# sampling stations	Period in 1998	Equipment	Parameters measured
30 minute	4 (two middles; two near outflows)	Jan - Dec	YSI 6000UPG sondes	temperature dissolved oxygen pH redox conductivity turbidity
twice daily	3 (inflow-W1; two outflows)	Jan-Dec	Hydrolab H20G probe YSI probe	temperature dissolved oxygen pH redox conductivity
			Hach turbidimeter	turbidity
weekly	7 river; 1 inflow-W1; 2 middles; 2 outflows; swale)	Jan-Dec	Hydrolab H20G probe YSI probe	temperature dissolved oxygen pH conductivity
			Hach turbidimeter LACHAT QuikChem IV	turbidity total phosphorus soluble reactive P NO_3 + NO_2

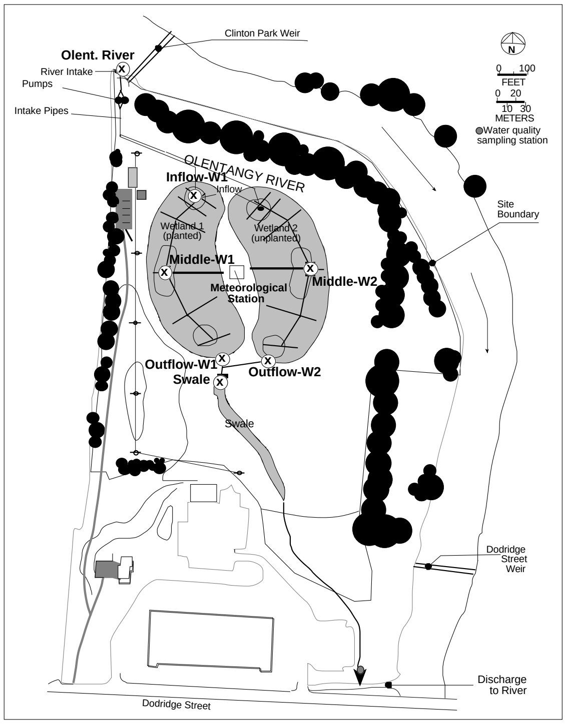

Figure 1. Location of water sampling sampling stations used in 1998 for the experimental wetlands.

investigated water quality at the site. Four journal articles (Mitsch et al., 1998; Kang et al., 1998; Nairn and Mitsch, 2000; Spieles and Mitsch, 2000) have been or soon will be published on water quality changes through these experimental wetlands.

Methods

A summary of the water quality monitoring protocol for the two experimental wetlands in 1998 is shown in Table 1. Locations of the various sampling stations are shown in Figure 1.

Weekly sampling

Weekly water sampling, instituted in late April 1994 continued through 1998. Samples were taken at 7 stations in 1998 as in 1997. One 1000 ml sample was collected at each of the 7 sites. Water samples were taken to the Ecosystem Analytical Laboratory at Ohio State where subsamples were filtered and frozen for later measurement of soluble reactive phosphorus. Unfiltered samples were preserved with concentrated H_2SO_4 (2 ml/liter sample) and frozen for later analysis of total phosphorus and nitrate+nitrite (NO_3+NO_2). A raw sample was also stored for any new or additional analyses to be added. Sample preparation and preservation was completed within 48 hours of original collection.

Daily sampling

Two-per-day water sampling, also initiated in 1994, continued through 1998 by the staff and students of the Wetlands Program at Ohio State. Inflow of Wetland 1 (assumed after several studies to represent the inflow to both basins) and the outflows of Wetland 1 and Wetland 2 were monitored for temperature, dissolved oxygen, pH, conductivity, and redox by the Hydrolab H20G probe and then after June 22, with the YSI probe. Instruments were calibrated and checked for battery power frequently. A 100-ml Nalgene bottle was used to take a sample for turbidity at each time and at each of the three stations.

Sample analysis

For all laboratory analyses in 1998, Standard Methods for the Examination of Water and Wastewater, 17th Edition (APHA, 1989) and EPA Methods for Chemical Analysis of Water and Wastes (U.S. EPA, 1983) were followed. Total Phosphorus, Soluble Reactive Phosphorus, and Nitrate+ Nitrite) were analyzed on a quarterly or more frequent basis on a Lachat QuikChem IV automated system and Lachat methods (U.S. EPA, 1983). Both total phosphorus and soluble reactive phosphorus methods employed the ascorbic acid and a molybdate color reagent method. For soluble reactive phosphorus and total phosphorus, Total phosphorus samples were first digested by adding 0.5 ml of 5.6N H_2SO_4 and 0.2 g NH_3SO_4 to 25 ml of sample and exposing the samples to a heated and pressurized environment for 30 minutes in an autoclave. Nitrate+nitrate, run on the Lachat QuikChem IV automated system, used the cadmium reduction method.

Results

Water quality results for 1998 weekly and two-per-day sampling are summarized in Table 2 while percent change through the wetlands and statistical significance are summarized in Table 3. Seasonal patterns of nutrients are shown in Figure 2. Each of the parameters is discussed separately below.

Nitrate-nitrogen

Nitrate+nitrite patterns in the inflow and outflows of the experimental wetlands for 1998 are shown in Figure 2a. Two significant pulses of nitrate-nitrogen are shown. In late February, a high river flow was experienced and nitrate-nitrogen concentrations in the inflow pulsed to 7 mg-N/L. Interestingly, wetland 2 outflow was 10 mg-N/L then as we pump higher amounts of water when the river flow increases. Again, in late June, river concentrations were 11 mg-N/L of nitrate and wetland outflows were almost the same. Thus nitrate nitrogen reduction mostly occurs when there are lower flows through the wetlands, especially in April, May, and July.

Nitrate decreased overall in 1998 by 33 % in Wetland 1 and 39% in Wetland 2. Differences between wetlands were not significant (α=0.05). The retention of nitrate-nitrogen doubled from 1997 when only 18% was retained in Wetland

Table 2. Summary of water quality measurements at Olentangy River experimental wetlands, 1996 through 1998. Two -per-day sampling refers to dawn-dusk sampling done almost every day that water is flowing. Numbers are average ± std. error (# of samples).

Parameter	Year	Olent. River	Inflow	Middle-W1	Middle-W2	Outflow-W1	Outflow-W2	Swale
Total P, µg-P/L	1996	185±15 (40)	191±18 (30)	85±11 (33)	77±9 (34)	68±8 (34)	64±9 (35)	62±9 (33)
	1997	149±16 (46)	146±17 (45)	99±7(39)	113±13 (38)	125±20 (41)	120±12 (43)	94±7 (44)
	1998	244±28 (47)	186±16 (46)	129±15 (47)	133±14 (47)	98±10 (47)	98±11 (47)	31±7 (47)
SRP, µg-P/L	1996	58±8 (38)	70±11(29)	19±4 (33)	16±4 (33)	8±1 (33)	9±2 (33)	9±2 (32)
	1997	50±6 (48)	67±12 (47)	23±3 (40)	25±3 (39)	26±3 (37)	23±3 (40)	37±13 (39)
	1998	89±11 (47)	82±10 (46)	45±9 (47)	45±9 (47)	27±6 (47)	31±7 (47)	31±7(47)
NO_3 + NO_2, mg-N/L	1996	4.60±0.41 (38)	4.42±0.42 (29)	3.08±0.38(34)	2.89±0.32(34)	2.97±0.40(34)	3.30±0.38(34)	3.19±0.47(31)
	1997	4.89±0.97 (48)	4.23±0.75 (47)	2.92±0.62 (39)	3.02±0.69 (39)	3.51±0.71 (42)	3.55±0.71 (42)	3.45±0.71 (44)
	1998	2.79±0.39 (47)	2.72±36 (46)	2.06 ±0.35 (47)	2.02 ±0.33 (47)	1.83±0.32 (47)	1.67±0.34 (47)	1.82±0.33 (45)
Turbidity, NTU [1]	1996		35±3 (319)			21±2 (404)	20±2 (407)	
	1997		28±2 (453)			26±2 (426)	27±2 (447)	
	1998		25±2 (446)			16±1 (459)	16±1 (462)	
D.O., mg/L [1]	1996		9.69±0.19 (278)			10.55±0.21(336)	10.48±0.18(338)	
	1997		9.90±0.2 (454)			11.38±0.28 (412)	11.32±0.29 (430)	
	1998		9.40±0.14 (430)			11.98±0.26 (433)	11.66±0.25 (436)	
Temp, °C [1]	1996		14.9±0.5 (302)			15.5±0.4 (373)	15.7±0.4 (373)	
	1997		13.2 ±0.4 (476)			13.7±0.4 (443)	13.7±0.4 (464)	
	1998		14.6±0.4 (456)			15.0±0.4 (471)	15.1±0.4 (475)	
Cond., µS/cm [1]	1996		535±6(282)			452±5(349)	454±5(350)	
	1997		621±7 (401)			576±7 (364)	593±7 (385)	
	1998		539±6 (450)			487±5 (462)	502±6 (467)	
pH [1]	1996		7.91±0.02(300)			8.17±0.03(367)	8.19±0.03(368)	
	1997		7.94±0.03 (443)			8.24±0.04 (412)	8.20±0.04 (431)	
	1998		8.18±0.04 (365)			8.47±0.04 (374)	8.38±0.04 (375)	
Redox, mv [1]	1996		394±4(213)			387±3(263)	384±3(265)	
	1997		433±3 (338)			433±3 (352)	430±4 (377)	
	1998		333±6 (440)			309±6 (450)	307±6 (456)	

[1] two-per-day sampling

1 and 17% in Wetland 2. There were 33 and 25% decreases respectively for the two wetlands in 1996. Nitrate-nitrogen decreased in a very similar and almost linear pattern through the two wetlands (Fig. 3a).

Soluble Reactive Phosphorus

Figure 2b illustrates the concentrations of soluble reactive phosphorus (SRP) for 1998. Seasonal pulses in the river did not seem to dramatically affect soluble reactive phosphorus in the river except in early October when there was a 3.75 cm rain event. Otherwise, there is a consistent pattern of separation of inflow and outflow concentrations, particularly in the growing season.

For the third year in a row, a seasonal pattern was observed with well-defined decreases in SRP from inflow to outflow during the summer months and less obvious patterns in spring and winter. On average, SRP decreased by 67% in Wetland 1 and 63% in Wetland 2 in 1998. In 1997, SRP decreased by 61% in Wetland 1 and 66% in Wetland 2. In 1996, the respective decreases were 89 and 87%.

Table 3. Water quality changes (+ indicates increase through wetland) and statistical significance at Olentangy River experimental wetlands, 1998. W1 = planted wetland; W2 = unplanted wetland; In = inflow; Out = outflow.

Parameter	% change		Paired t-test, p-value		
	W1	W2	In v. Out W1	In v. Out W2	Out W1 v. Out W2
	+ = increase; - = decrease				
Temp	3.1	3.5	0.0000	0.0000	nd [1]
Turbidity	-35.6	-37.5	0.0000	0.0000	nd
D.O.	27.5	24.1	0.0000	0.0000	nd
pH	3.8	2.4	0.0000	0.0000	0.001
Conductivity	-9.6	-6.9	0.0000	0.0000	0.00000
Redox	-4.3	-4.8	0.0000	0.0000	nd
Total P	-48	-47	0.00000	0.00000	nd
SRP	-67	-63	0.00000	0.00000	nd
NO_3 + NO_2	-33	-39	0.00001	0.00004	nd

[1] nd = no significant difference at $\alpha = 0.05$

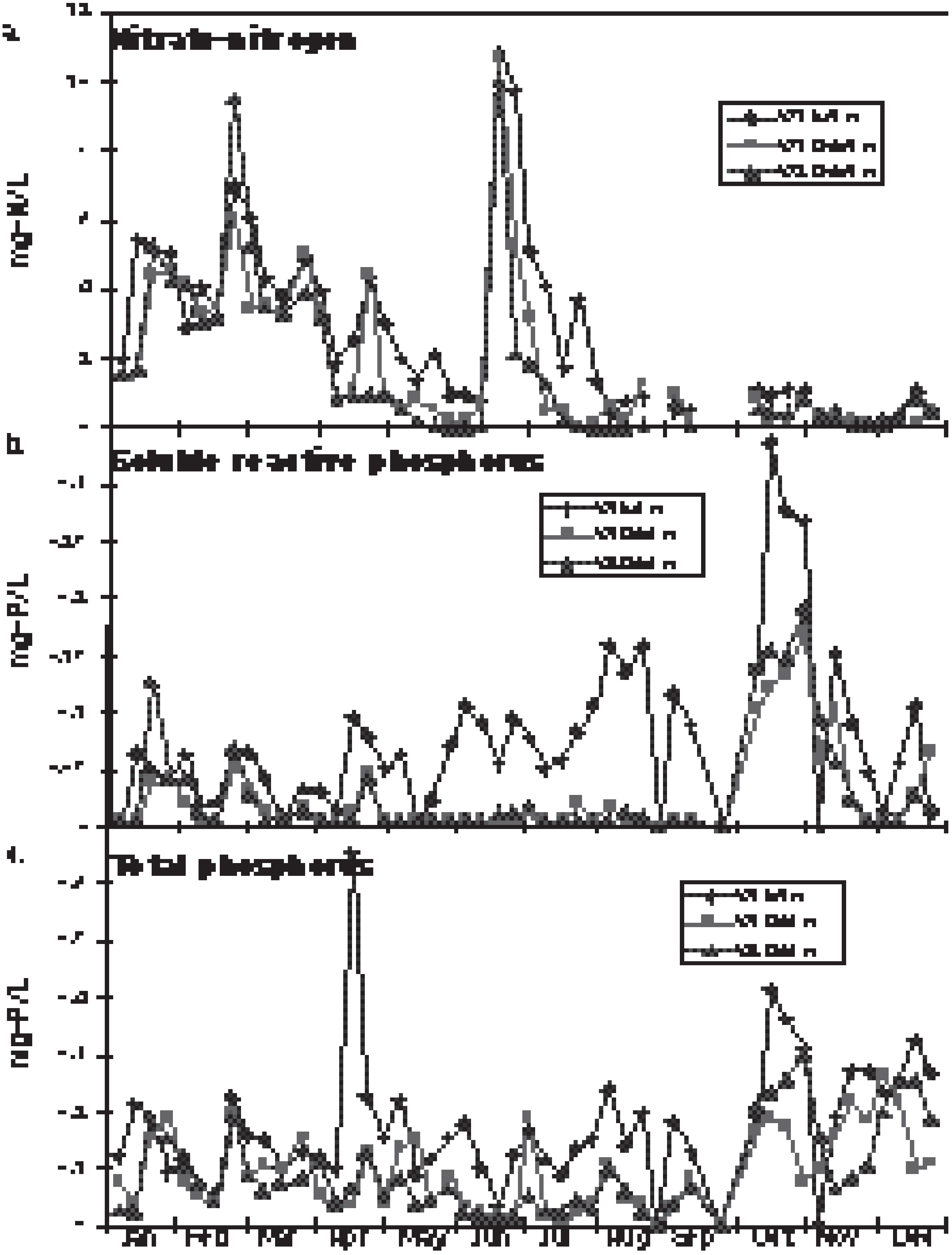

Figure 2. Nitrate-nitrogen, soluble reactive phosphorus, and total phosphorus in inflow and two wetland outflows in 1998.

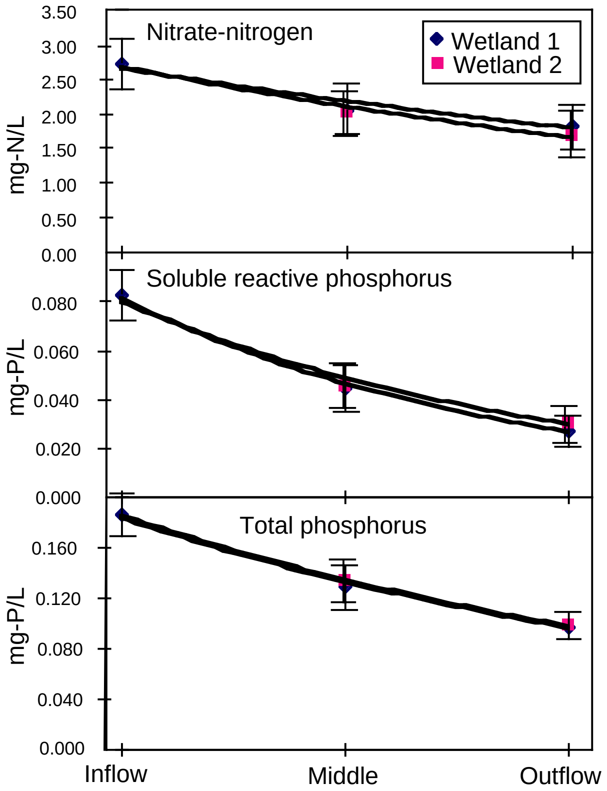

Figure 3. Decay of nitrate-nitrogen, soluble reactive phosphorus, and total phosphorus from inflow to outflow in experimental wetlands for 1998. Bars indicate standard error.

Outflow concentrations of SRP averaged 27-31 µg-P/L in 1998, only slightly more that the 23-26 µg-P/L seen in 1997 but over three times higher than the 8-9 µg-P/L in 1996. The decrease in SRP was almost linear from inflow to outflow in 1998 (Fig. 3b).

Total Phosphorus

There were two noticeable peaks in total phosphorus (TP) coming from the river in 1998 (Fig. 2c). On April 16, a rain event of 6 cm caused a total phosphorus inflow concentration of about 0.65 mg-P/L. Another lower peak occurred in October with a concentration of about 0.4 mg-P/L. In both cases, outflow concentrations generally were much lower.

Total phosphorus (TP) concentrations decreased by 48 and 47% respectively for Wetland 1 and Wetland 2 in 1998 (Table 3; Fig. 2c). The decreases were significant (α=0.05) but the two basins were not significantly different in phosphorus retention. TP decreased by 14% in Wetland 1 and 18% in Wetland 2 in 1997, but neither of these decreased was significant (α = 0.05).

Outflow concentrations were 98 µg-P/L in both wetlands in 1998. The outflow was 125 µg-P/L in Wetland 1 and 120 µg-P/L in Wetland 2 in 1997 and 68 and 64 µg-P/L respectively in 1996.

In 1996, there was a clear pattern of decreasing concentrations of phosphorus from inflow to outflow but that pattern failed to develop in 1997. The pattern returned in 1998, with almost identical exponential decreases for both wetlands for total phosphorus (Fig. 3c).

Turbidity

Turbidity was much less erratic in 1998 than in 1997 and overall decreases from inflow to outflow were more consistent (Tables 2 and 3). Inflow turbidity averaged 25 NTU while the two outflows were 16 NTU. Turbidity decreased 36% in Wetland 1 and 37% in Wetland 2 (Table 3).

Dissolved Oxygen

Dissolved oxygen continued to display significant diurnal patterns coupled to primary productivity and respiration (see previous annual reports). Overall, dissolved oxygen increased from 9.4 mg/L in the inflow to 12.0 and 11.7 mg/L respectively for Wetlands 1 and 2. Outflows were 11.4 and 11.3 mg/L respectively for Wetlands 1 and 2 outflows in 1997.

Temperature

Temperature changes through the wetlands showed seasonal patterns with increases in the summer and decreases in the winter. Overall, there was an annual average increase of 3.1% in Wetland 1 and 3.5% in Wetland 2; these differences were not statistically significant (α=0.05).

Conductivity

Conductivity decreased from an average of 539 µS/cm in the inflow to 487 and 502 µS/cm in the outflows of Wetlands 1 and 2 respectively in 1998 (Table 2). The decreases of 9.6% in Wetland 1 and 6.9% in Wetland 2 were significant and also were significantly different from one another (α=0.05). There was an average of 5 to 7% decrease in dissolved materials in 1997 and a 15% decrease in 1996. While some of the decrease could be due to dilution from rainwater, particularly in wet springs, we continue to believe that the decrease in dissolved ion concentrations from inflow to outflow, particularly in the growing season, is due to precipitation of calcium carbonate and other minerals caused by high pH that, in turn, is caused by the high water column productivity.

pH

pH of the inflow waters from the Olentangy River averaged 8.18 in 1998, 7.94 in 1997, and 7.91 in 1996. Outflows of Wetlands 1 and 2 were slightly higher than the inflow (3.8 and 2.4% higher respectively) in 1998. Wetland 1 pH increase was significantly higher than that in Wetland 2 (α=0.05).

Redox

Redox potential continues to show little difference between the wetlands. Inflow averaged 333 mv while outflows of Wetlands 1 and 2 are 309 and 307 mv respectively (Table 2). Care should be taken in comparing the absolute values from 1998 with previous years as different probes (YSI replacing Hydrolab) give different readings for redox potential.

Discussion

Differences between wetland basins in 5 years

Water quality data have now been collected at the Olentangy River Wetland experimental wetlands for five years. Of the nine water quality parameters consistently measured over that period, seven parameters showed no significant difference between the two wetland basin outflows in 1998, down from 8 parameters in 1997 (Table 3). Mitsch et al. (1998) demonstrated that there were five similar indicators in the first year (1994), followed by a divergence in water quality when only 2 parameters were similar (1995), followed by convergence in 1996 when 6 parameters were similar. The fifth year results (1998) reported here suggest that some divergence may again be occurring due to *Typha* monocultures in Wetland 2 and a more diverse plant community in Wetland 1.

Changes over 5 years

Data have now been collected for five years on water quality changes through the two wetlands. Over the first three-years, there was an average retention of 63% total phosphorus in both wetlands. The biggest differences between the two wetlands occurred in 1995 when Wetland 1 retained 8% more phosphorus than did Wetland 2. By the third year (1996), total phosphorus retention by the two basins was essentially the same and has remained so through 1998. Phosphorus retention in 1998 (47-48%) recovered from poor retention in 1997 (14-18%) due to lower flow rates in 1998.

Soluble reactive phosphorus retention has been consistently high, with 63 to 67% retention in 1998, similar to the 61 to 66% retention in 1997. This remained the only parameter that has consistently shown greater than 50% retention in the wetland basins.

Nitrate-nitrogen retention has consistently been less than 50% and in fact, decreased from 47.5% retention in 1994 to 17.5% in 1997. The retention recovered to 33-39% in 1998. There has been no dramatic difference in nitrate retention between the two wetlands over the 5 years.

Suspended materials, as measured by turbidity, decreased through the wetlands by 36-37% in 1998, much better than the 4 to 6% retention rates in 1997. As expected, total phosphorus and suspended materials show similar patterns from year to year.

Dissolved material retention, as measured by conductivity reduction, was again greater in Wetland 1 than in Wetland 2 in 1998. Overall, dissolved materials decreased 7 to 9 % in 1998 compared to 5 to 7% in the wetlands in 1997. The more significant decrease in conductivity and pH in Wetland 1 compared to Wetland 2 is an enigma. We hypothesize that greater macrophyte productivity (see Bouchard and Mitsch, 1999b) in Wetland 2 causes more shading in that wetland, allowing more water column productivity in Wetland 1. That higher productivity leads to both higher pH and subsequently more calcium carbonate precipitation in Wetland 1. The greater precipitation decreases the conductivity more in Wetland 1.

Conditions recovered in 1998

Water quality improvements were better in 1998 than in the previous year. The generally poor performance of the wetlands in 1997 in retaining both dissolved and suspended materials is puzzling. The overall turnover time of the wetlands in 1998 averaged 1.9 days, the same as the 1.9 day retention time in 1997. Retention time was 5.3-5.8 days in 1996.

Since macrophyte cover in the two wetlands began to diverge in spatial diversity in 1998, water quality may have begun to follow suite. In 1995 when one wetland had considerably greater macrophyte cover than the other, we concluded that the effects of macrophytes on the water quality function of the wetlands was important (Mitsch et al. 1998). The basins may now be diverging not only in macrophyte diversity and productivity but also in biogeochemistry.

References

American Public Health Association. 1989. Standard Methods for the Analysis of Wastewater, 17 ed., APHA, Washington, DC.

Bouchard, V., and W.J. Mitsch. 1999a. Plant richness and community establishment after five growing seasons in the two experimental basins. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1998. Columbus, OH, pp. 43-60.

Bouchard, V., and W.J. Mitsch. 1999b. Net primary productivity of macrophytes after five growing seasons in experimental planted and unplanted marshes. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1998. Columbus, OH. pp. 61-66.

Kang, H. 1999. The significance of enzyme activities in wetland biogeochemistry. Ph.D. thesis, University of Wales, Bangor, UK.

Kang, H., C. Freeman, D. Lee, and W.J. Mitsch. 1998. Enzyme activities in constructed wetlands: Implication for water quality amelioration. Hydrobiologia 368: 231-235.

Mitsch, W.J., R.W. Nairn, X. Wu, and A. Wehr. 1995. Water quality changes in Olentangy River water caused by the experimental wetlands at the Olentangy River Wetlands Research Park—first year results. In: Mitsch, W.J. and X. Wu (eds.) Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1994, Columbus, OH. pp. 51-61.

Mitsch, W.J. and R.W. Nairn. 1996. Nitrogen and phosphorus retention by the Olentangy River experimental wetlands, 1994-95. In: Mitsch, W.J.(ed.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1995, Columbus, OH. pp. 91-102.

Mitsch, W.J. and L. M. Carmichael. 1997. Water quality and nutrient removal patterns of created riparian wetlands: Third year results and a 3-year summary. In: Mitsch, W.J. (ed.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1996, Columbus, OH. pp. 127-138.

Mitsch, W.J. and H. Montgomery, 1998. Water quality and nutrient removal patterns of created riparian wetlands: Fourth year results. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1997. Columbus, OH, pp. 89-95.

Mitsch, W.J., X. Wu, R.W. Nairn, P.E. Weihe, N. Wang, R. Deal, C.E. Boucher. 1998. Creating and restoring wetlands: A whole-ecosystem experiment in self-design. BioScience 48: 1019-1030.

Mortensen, P. and P. Lanzky. 1996. Water quality improvement in a constructed wetland, Thesis, Royal Danish School of Pharmacy, Copenhagen, Denmark.

Mortensen, P., P. Lanzky, and S.E. Jørgensen, 1997. Nitrogen removal by the Olentangy River experimental wetlands two years after construction. In: Mitsch, W.J.(ed.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1996, Columbus, OH. pp. 113-117.

Nairn, R.W. 1996. Biogeochemistry of newly created riparian wetlands: Evaluation of water quality changes and soil development. Ph.D. dissertation, Environmental Science Graduate Program, The Ohio State University, Columbus, OH.

Nairn, R.W. and W.J. Mitsch. 1997. Water quality changes in newly constructed riparian wetland, 1994-95. In: Mitsch, W.J., (ed.) Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1996, Columbus, OH. pp. 139-150.

Nairn, R.W. and W.J. Mitsch. 2000. Phosphorus removal in created wetland ponds receiving river overflow. Ecological Engineering 14: 107-126.

Spieles, D. J. 1998. Nutrient retention and macroinvertebrate community structure in constructed wetlands receiving wastewater and river water. Ph.D. dissertation, Environmental Science Graduate Program, The Ohio State University, Columbus, OH.

Spieles, D.J. and W.J. Mitsch, 1998. The effects of season and hydrologic and chemical loading on nitrate retention in constructed wetlands: A comparison of low and high nutrient riverine systems, In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1997. Columbus, OH, pp. 105-117.

Spieles, D.J. and W.J. Mitsch. 2000. The effects of season and hydrologic and chemical loading on nitrate retention in constructed wetlands: A comparison of low and high nutrient riverine systems. Ecological Engineering 14: 77-91.

U.S. Environmental Protection Agency. 1979. Methods for chemical analysis of water and wastes. 600/4-79-020, U.S. Environmental Protection Agency, Cincinnati, OH.

U.S. Environmental Protection Agency. 1983. Methods for chemical analysis of water and wastes. 600/4-79-020, U.S. Environmental Protection Agency, Cincinnati, OH.

Vorwerk, N. 1997. Comparison of three years of pH values between planted and unplanted wetlands. Honors thesis, School of Natural Resources, The Ohio State University.

Vorwerk, N. and W.J. Mitsch. 1998. Comparison of three years of pH values between planted and unplanted wetlands. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1997, Columbus, OH. pp. 97-104.

Wehr, A. 1995. Early water quality of created wetlands at the Olentangy River Wetland Research Park. Honors thesis, School of Natural Resources, The Ohio State University.

Wehr, A. and W.J. Mitsch. 1996. Early water quality of created wetlands at the Olentangy River Wetland Research Park. In: Mitsch, W.J.(ed.) Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1995, Columbus, OH. pp. 83-90.

YSI Incorporated, 1996. 6000UPG Multi-parameter Water Quality Monitor—Instruction Manual. YSI Incorporated, Yellow Springs, OH.