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Constructed Wetlands for Treatment of Channel Catfish Pond Effluents

MICHAEL F. SCHWARTZ AND CLAUDE E. BOYD[1]

Department of Fisheries and Allied Aquacultures
Auburn University, Alabama 36849, USA

Abstract.—Water from a production pond for channel catfish (*Ictalurus punctatus*) in Hale County, Alabama, was passed through a constructed wetland consisting of two cells, one planted with California bulrush (*Scirpus californicus*) and giant cutgrass (*Zizaniopsis miliacea*) and one planted with Halifax maidencane (*Panicum hemitomon*). The removal of potential pollutants from water flowing through the wetland was determined for 1-, 2-, 3-, and 4-d hydraulic residence times (HRTs), with hydraulic loading rates of 77–91 L/m^2 of wetland per day. Concentrations of potential pollutants were much lower in effluent from the wetland than in influent from the channel catfish ponds. The following reductions in concentrations were recorded: total ammonia nitrogen, 1–81%; nitrite-nitrogen, 43–98%; nitrate-nitrogen, 51–75%; total Kjeldahl nitrogen, 45–61%; total phosphorus, 59–84%; biochemical oxygen demand, 37–67%; suspended solids, 75–87%; volatile suspended solids, 68–91%; and settleable solids, 57–100%. Overall performance of the wetland was best when operated with a 4-d HRT in the vegetative season, but good removal of potential pollutants was achieved for shorter HRTs and when vegetation was dormant.

Regulatory agencies in some states are beginning to require wastewater discharge permits for effluents from aquaculture ponds. Research has been initiated on best management procedures for minimizing the pollution potential of pond effluents. Efforts involve investigations of better feeds and feeding practices to lower nutrient and organic matter inputs, water reuse schemes to reduce effluent volumes, and pond management systems that enhance the rate of organic matter and nutrient assimilation within ponds.

Wetlands act as biological filters to remove pollutants from water (Mitsch and Gosselink 1993), and natural and constructed wetlands sometimes are used for treatment of agricultural, municipal, and industrial wastewaters (Nichols 1983; Hammer 1989; Reed and Brown 1992; Moshiri 1993). There are several advantages to wetland wastewater treatment. Wetlands are inexpensive to build and operate; chemical treatment of wastewater is eliminated; wetlands contribute stability to local hydrologic processes; and plant communities in wetlands provide excellent wildlife habitat. However, there is concern about the feasibility of wetlands for treating aquaculture effluents because of the large areas of land that may be required. In the following study, a free water surface wetland was constructed adjacent to a commercial fish pond used to raise channel catfish (*Ictalurus punctatus*), and its efficiency in removing potential pollutants from pond water was evaluated.

Methods

Wetland.—The constructed wetland used in this study was adjacent to a 6.9-ha channel catfish pro-

[1] To whom correspondence should be addressed.

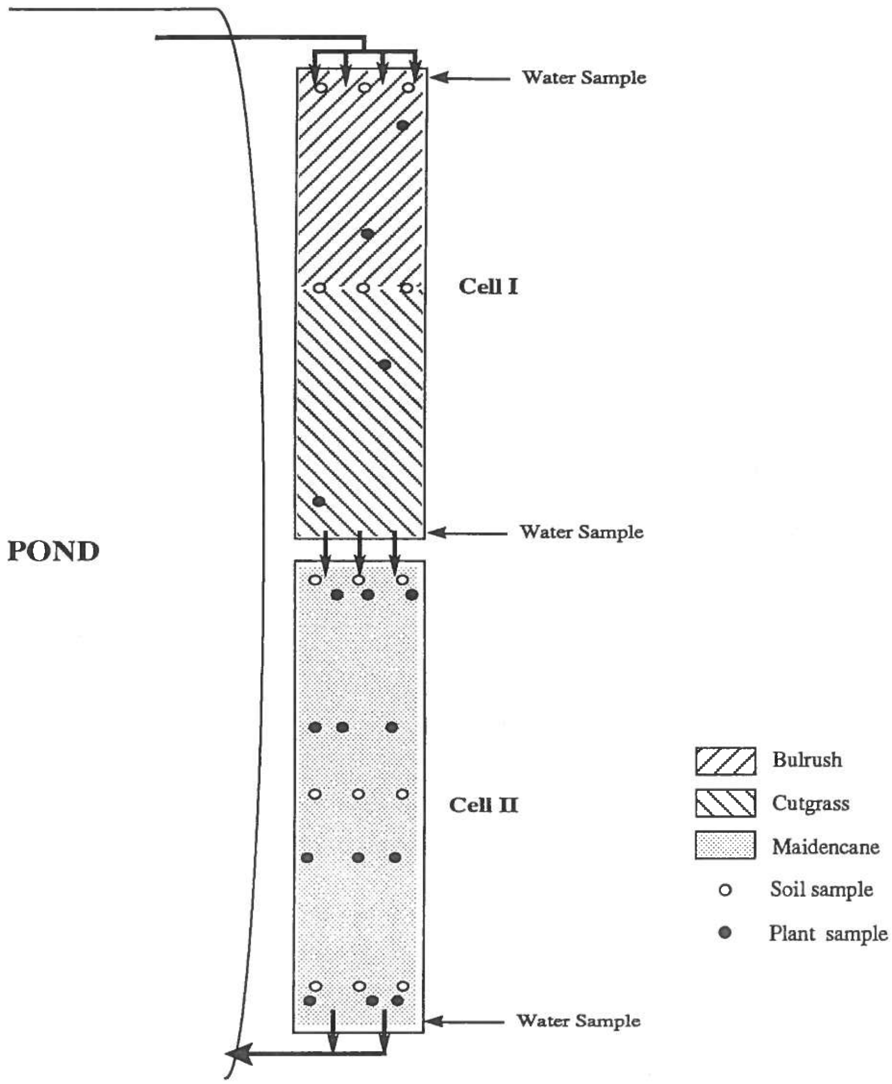

FIGURE 1.—Diagram showing location of the constructed wetland in relation to pond, water delivery scheme, and location of plant and soil sample collection sites. Water was pumped from a 6.9-ha channel catfish pond into cell 1 (I) which contained *Scirpus californicus* and *Zizaniopsis miliacea,* and allowed to flow by gravity into cell 2 (II), which contained primarily *Panicum hemitomon,* and then exited cell 2 to drain back into the pond. Both cells measured 84 × 14 m.

duction pond near Greensboro in Hale County, Alabama. Two cells, each 84 m long × 14 m wide were built in series (Figure 1). The bottoms of cells were sloped 0.05% from inlets to outlets, but no cross slope was provided. Perimeter levees were 3 m wide at the tops and had 2:1 (horizontal : vertical) side slopes. Vertical distance from cell bottoms to levee tops was 0.61 m at the middle of the long axes. Cell bottoms and levees were constructed of heavy clay soil.

A 5-cm-diameter intake pipe of an electric pump extended 10 m horizontally from the pond bank (Figure 1). The end of the horizontal pipe was mounted on a float and an elbow was attached to extend the inlet 45 cm below the water surface. The depth of the pond at this point was approximately 130 cm. The 5-cm-diameter discharge pipe extended from the pump to the head of cell 1, where it discharged into a manifold perpendicular to the long axis of the cell. Elbow pipe fittings inserted in the manifold discharged water at four equidistant points across the cell. The elbows could be turned to slightly alter elevation of discharge points and equalize inflows at all points. Three 10-cm-diameter drain pipes were installed between the end of cell 1 and the head of cell 2. Elbows placed on the end of the drain pipes in cell 1 allowed insertion of stand pipes to regulate the water level. Two 10-cm-diameter drain pipes with elbows for attaching stand pipes were installed through the levee at the end of cell 2 and were connected to another 10-cm-diameter drain pipe to return outflow from cell 2 to the pond.

Rootstocks of California bulrush (*Scirpus californicus*), giant cutgrass (*Zizaniopsis miliacea*), and Halifax maidencane (*Panicum hemitomon*) were provided by the Alabama State Office of the U.S. Department of Agriculture, Soil Conservation Service. Cells were planted during the last week of May 1992. Holes were made in the dry pond bottom with a tool for transplanting pine tree seedlings. Rootstocks were placed in the holes which were closed around the rootstocks by tamping. The upper half of cell 1 was planted with California bulrush on 90-cm centers, and the lower half of the cell was planted with giant cutgrass on 180-cm centers. Cell 2 was planted with Halifax maidencane on 90-cm centers. Two months after planting, a single application of fertilizer (10 g/m^2; 8% N, 8% P_2O_5, 8% K_2O) was applied over cell 2 because the Halifax maidencane was not growing well. The pump was operated continuously, and water depth was maintained at 5 cm while plants became established.

Hydraulic residence time.—The hydraulic residence time (HRT, days) for water in the two cells was computed with the following equation:

$$\mathrm{HRT} = \frac{(A)(D)(1 - P)}{Q};$$

A = area, m^2;
D = depth, m;
Q = (inflow + outflow)/2, m^3/d; and
P = proportion of water volume occupied by plants, dimensionless.

Because there were several different species of plants in the wetland whose stem morphology varied inter- and intraspecifically and because the volume of detritus in the water column was not taken into account, we felt that it would be extremely difficult to precisely calculate the volume of void space in this particular wetland, and we could not find satisfactory estimates of void volumes in the literature. Rough estimates made in the plant stands suggested that the void volume was less than 0.9 and more than 0.75. Therefore, HRTs were computed for P = 0.1, 0.15, and 0.25 and listed in Table 1. In the discussion we will use our target HRTs, but as can be seen from Table 1, target values were probably only slightly different from the actual HRTs. Because the plants were still in the process of spreading through the wetland during the study, the area of plants in each cell was entered into the HRT equation in order to give a more precise HRT value. Four HRT regimes (1, 2, 3, and 4 d) were used in the study. To establish an HRT, the necessary depth was computed with the HRT equation, and stand pipes were installed with their tops at the required elevation. The depth necessary to provide a given HRT was fixed at the geometric centers of the cells. Outflow was determined for each HRT.

TABLE 1.—Computed hydraulic residence times (HRTs) for three proportions of water volume occupied by plants (P).

Target HRT (d)	Computed HRT (d) for plant proportions of:		
	0.10	0.15	0.25
1	1.0	0.9	0.8
2	1.8	1.7	1.5
3	3.0	2.8	2.5
4	4.2	3.9	3.5

The efficiency of the wetland in reducing concentrations of selected water quality variables at each HRT was determined over 6-week periods. The 3-d HRT was conducted from 13 October to 24 November 1992 during the nongrowing season. The 2-d HRT was tested between 11 May and 15 June 1993; the 1-d HRT was tested from 6 July to 10 August 1993; the 4-d HRT was tested from 24 August to 29 September 1993. Water flow through the wetland was maintained between HRT trials by operating the pump continuously.

Sampling and analyses.—During each HRT trial, water samples were collected weekly from the inflow pipe, the drain of cell 1, and the drain of cell 2. Water temperatures were not monitored, but average daily air temperatures were obtained from a nearby weather station at the Black Belt Substation of the Alabama Agricultural Experiment Station, Marion Junction, Alabama. Samples were analyzed for 5-d biochemical oxygen demand (BOD_5), total ammonia nitrogen (TAN), nitrite-nitrogen (NO_2-N), nitrate-nitrogen (NO_3-N), total Kjeldahl nitrogen (TKN), total phosphorus (TP), suspended solids (SS), volatile suspended solids (VSS), and settleable solids (APHA et al. 1992). The pH was determined in samples taken at the outfall of cell 2. Concentrations of dissolved oxygen (DO) were occasionally measured in the wetland discharge with a polarographic DO meter (YSI model 51, Yellow Springs Instrument Co., Yellow Springs, Ohio).

Samples of the original pond bottom soil were obtained from the bottom of the cells immediately after construction, and in early October 1993, five soil samples were collected at evenly spaced intervals from the head of cell 1 to the end of cell 2 (Figure 1). At each soil-sampling site, three 5-cm-deep × 5-cm-diameter cores were taken along a transect across the cell. Plant samples were collected at four evenly spaced intervals along each cell at the same time (Figure 1). In cell 1, where plants were uniform and dense, one 0.25-m^2 quadrant was collected from a single random position along a transect across the cell. In cell 2, three 0.25-m^2 quadrants were taken along each of the four transects. Plant shoots were cut at the soil surface, and roots were removed to a depth of 15 cm. All root material was removed from soil samples, and the soil was dried at 80°C. Fresh weights of plant samples were determined with a spring balance, and subsamples were removed and dried at 60°C for determination of dry matter. Dry soil and plant samples were pulverized with a hammer mill. Weight losses from soil samples upon ignition were determined by ashing them for 8 h in a muffle furnace at 350°C (Jackson 1958). Soil carbon concentrations were estimated as weight loss upon ignition multiplied by 0.58 (Nelson and Sommers 1982). Carbon analyses of plant samples were made with a Leco EC12 carbon determinator. Plant samples were ashed at 550°C for 8 h, and the ash was dissolved in 1 N HNO_3 for phosphorus analysis. Phosphorus was extracted from soil samples with a solution of 0.05 N HCl plus 0.025 N H_2SO_4 (Hue and Evans 1986). Phosphorus concentrations were measured with an inductively coupled agron plasma (ICAP) spectrophotometer (Jarrel-Ash ICAP 9000). Nitrogen concentrations in plants and soil were determined by the macro-Kjeldahl technique.

Results and Discussion

Plants grew slowly, and by the end of September 1992, only California bulrush had grown enough to provide a full canopy over the area in which it was planted. By summer 1993, after a growing period of 280 d, the giant cutgrass had formed a full canopy over the area where it was planted. The Halifax maidencane continued to spread, but even by the end of the study, it had not produced a full canopy. Sampling to estimate the quantity of vegetation and composition of soil in the cells was not conducted during the study to avoid destruction and disturbance of the plants.

TABLE 2.—Shoot height and standing crops of three wetland plants (California bulrush, giant cutgrass, and Halifax maidencane) in a constructed wetland. Water from an aquaculture pond entered at the head of cell 1, flowed through cell 1, entered the head of cell 2, and flowed through cell 2.

Distance from head of cell (m)	Plant	Height (cm)	Standing crop (dry weight, g/m^2)		
			Shoots	Roots	Total
		Cell 1			
5	Bulrush	206	1,520	2,320	3,840
30	Bulrush	193	1,200	1,830	3,030
55	Cutgrass	185	4,300	7,100	11,400
80	Cutgrass	185	890	1,590	2,480
		Cell 2			
5	Maidencane	112	2,610	2,170	4,780
30	Maidencane	86	1,030	1,520	2,550
55	Maidencane	86	1,040	1,700	2,740
80	Maidencane	86	420	1,450	1,870

Standing crops of plant biomass and average shoot heights at the end of the study are provided in Table 2. Although vegetation consisted primarily of the species planted, there was some invasion of cattail (*Typha latifolia*) along the shallow edges of the cells, and mats of filamentous algae were present. Standing crops of California bulrush in cell 1 were slightly higher near the inlet than 25 m away. Standing crops of California bulrush and Halifax maidencane tended to decrease with distance from the point of inflow, suggesting that nutrient concentrations declined as water flowed through the two cells.

Shoot standing crops were similar to those commonly reported for natural stands of herbaceous wetland plants. Polisini and Boyd (1972) reported shoot standing crops for *Panicum hemitomon, Scirpus validus,* and *Typha domingensis* of 1,075, 1,381, and 1,483 g/m^2, respectively. Shoot standing crops of *T. latifolia* ranged from 428–2,252 g/m^2 (mean, 951 g/m^2) for 30 stands in the southern United States (Boyd and Hess 1970). Shoot standing crops for some species of emergent aquatic plants growing in swamps exceed 2,500 g/m^2 (Westlake 1963; Boyd 1971), but most stands have standing crops between 750 and 1,500 g/m^2. Root standing crops were greater than standing crops of shoots (Table 2). Natural stands of wetland plants

TABLE 3.—Concentrations of water quality variables and removal percentages from a constructed wetland with dormant vegetation (13 October–24 November 1992) at a 3-d hydraulic residence time.

Variable	Influent	Cell 1 midpoint	Cell 1 effluent	Cell 2 effluent	Total
Total ammonia nitrogen, mg/L (TAN)	0.337	0.195	0.141	0.097	
Removal		42.1%	16.0%	13.1%	71.2%
Nitrite-nitrogen, mg/L (NO_2-N)	0.041	0.038	0.035	0.023	
Removal		7.3%	7.3%	29.3%	43.9%
Nitrate-nitrogen, mg/L (NO_3-N)	0.543	0.383	0.339	0.257	
Removal		29.5%	8.1%	15.1%	52.7%
Total Kjeldahl nitrogen, mg/L (TKN)	1.61	1.13	1.04	0.88	
Removal		29.8%	5.6%	9.9%	45.3%
Total phosphorus, mg/L (TP)	0.162	0.081	0.067	0.051	
Removal		50.0%	8.6%	9.9%	68.5%
Five-day biochemical oxygen demand, mg/L (BOD_5)	5.61	4.03	3.75	3.54	
Removal		28.2%	5.0%	3.7%	36.9%
Suspended solids, mg/L (SS)	34.5	8.1	8.5	8.5	
Removal		76.5%	−1.2%	0.0%	75.3%
Volatile suspended solids, mg/L (VSS)	12.5	4.1	3.9	3.9	
Removal		67.2%	1.6%	0.0%	68.8%
Settleable solids	0	0	0	0	

often have a high proportion of root material (McNaughton 1966; Boyd and Walley 1972).

Air temperatures averaged 15.0°C during the 3-d HRT trial conducted from 13 October to 24 November 1992. Plants were not growing, and shoots had been killed by frost. The California bulrush had grown enough during the summer to form a dense canopy, but other plants provided less than 25% cover. Thus, in addition to measuring water quality variables in influent and cell effluents, another sample for water quality analysis was taken at the end of the California bulrush stand at the midlength of cell 1. Removal rates of potential pollutants by the wetland ranged from 36.9% for BOD_5 to 75.3% for suspended solids (Table 3). Most of the nitrite-nitrogen was removed in cell 2, but the upper half of cell 1, which contained dense California bulrush, removed the majority of nitrate-nitrogen and at least twice as much of the other substances as the rest of the wetland combined.

It was impossible to maintain the same conditions in the three HRT trials conducted during the growing season in 1993. Average air temperatures varied (1-d HRT, 30.2°C; 2-d HRT, 21.8°C; 4-d HRT, 23.7°C), and feed input to the production pond increased as the fish grew. Concentrations of water quality variables in ponds fluctuate in response to feed inputs, aerator operation, weather, and changes in phytoplankton composition and abundance (Boyd 1990). In addition to variations in temperature and influent water quality, the plants in the wetland continued to expand and filled the spaces among original plantings, and the growth stages of vegetation changed with time.

Influent application to wetlands is often expressed in liters per square meter per day, which is termed the hydraulic loading rate (HLR). In this study, the pump discharge varied because the water level in the pond changed with season and affected the pumping head. Therefore, pump discharge and HLR differed with each trial (Table 4). Although HLR changed over time, HRT was maintained at a constant value for each trial by regulating water depth in the cells (Table 4). The wetland effluent was also expressed as HLR, and the difference in HLR in the influent compared with the effluent represents the excess of seepage and evapotranspiration over rainfall. Water loss from the wetland was 12.5–18.1% of influent volume. Evapotranspiration, calculated by multiplying pan evaporation by 0.8 (Hammer 1992), averaged 5.8% of influent volume during the growing season and 2.8% during the dormant season.

Variations in influent concentrations of TP, BOD_5, SS, and TKN for 1-, 2-, and 4-d HRT trials

TABLE 4.—Hydraulic loading rates (HLRs) and water depth at cell midpoints for different hydraulic residence times (HRTs) for effluent from a channel catfish pond applied to a constructed wetland.

HRT (d)	HLR (L/m^2 each day)		Water depth (cm)
	In	Out	
1	78.8	64.5	11
2	90.6	79.3	30
3	90.9	79.7	24
4	76.9	63.6	42

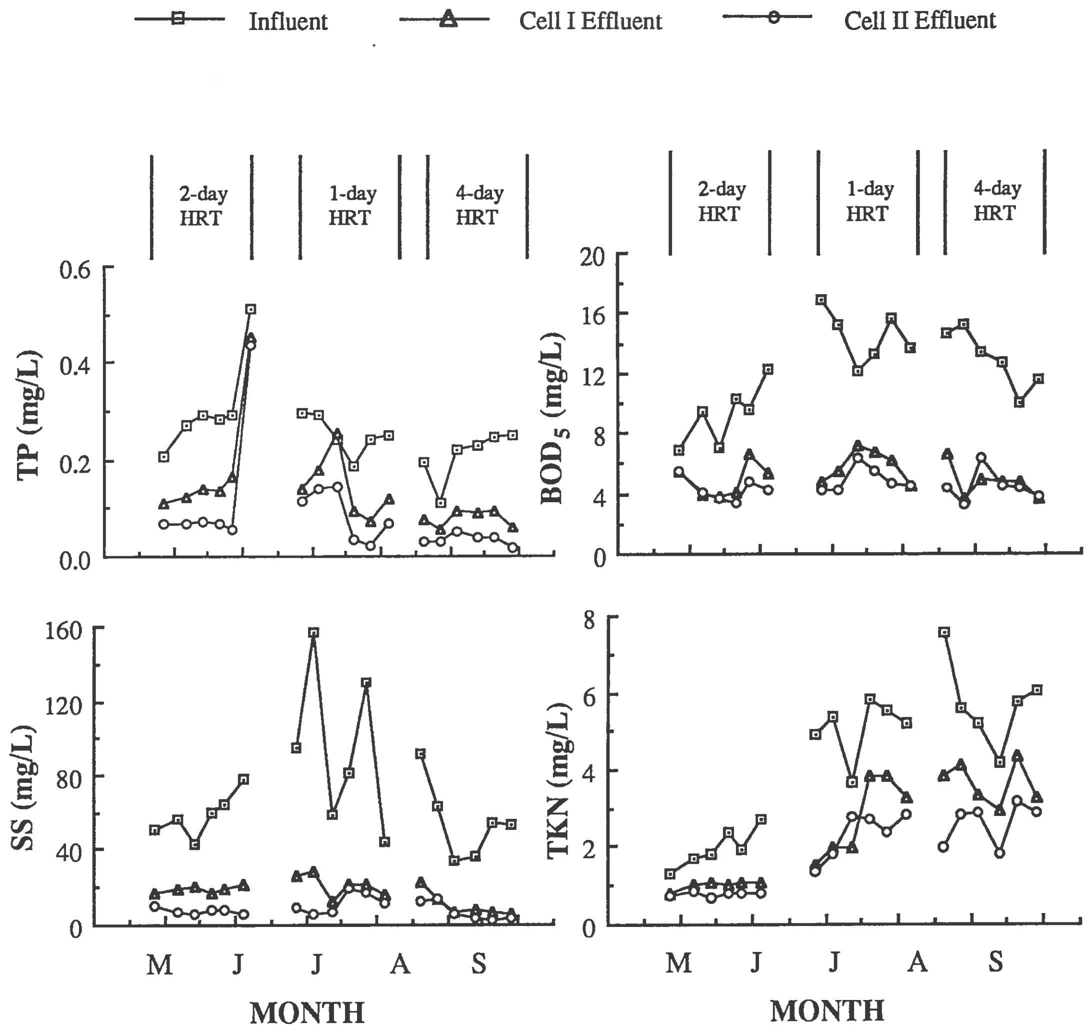

FIGURE 2.—Concentrations of total phosphorus (TP), 5-d biochemical oxygen demand (BOD_5), suspended solids (SS), and total Kjeldahl nitrogen (TKN) in influent, cell 1 (I) effluent, and cell 2 (II) effluent for 1-, 2-, and 4-d hydraulic residence times (HRT) in a constructed wetland. Influent was water from a channel catfish pond.

are illustrated in Figure 2. Concentrations of these substances in effluents tended to follow concentration trends exhibited by influents. Wetland effluents (cell 2 discharge) usually was much lower in concentrations of the four variables than the influents. Differences in concentrations between influents and cell 1 discharges typically were greater than differences between concentrations in discharges of cell 1 and cell 2. Thus, cell 1 was more active in reducing TP, BOD_5, SS, and TKN than cell 2. Concentration of other water quality variables exhibited patterns similar to those shown in Figure 2.

It is difficult to assess the effectiveness of the wetland in removing potential pollutants from influents when only changes in concentrations of water quality variables over time in influent and effluent samples are considered because conditions within the pond and the wetland are continually changing. Therefore, concentrations of water quality variables were averaged for influent and cell effluent samples over each HRT trial (Table 5), and the percentage removal of each variable was computed (Table 6). An even better illustration of wetland performance is provided in Table 7, which shows mass loading and removal rates for organic matter, suspended solids, nitrogen and phosphorus. These data show the absolute amounts added and

TABLE 5.—Average concentrations (mg/L) of water quality variables in the influent and at the outflow of the two cells in a constructed wetland to which water from a channel catfish pond was applied for different hydraulic residence times (HRTs). Abbreviations are defined in Table 3.

Sampling location	TAN	NO_2-N	NO_3-N	TKN	TP	BOD	SS	VSS	Settleable solids
				1-d HRT					
Influent	0.631	0.082	0.407	5.07	0.251	14.48	94.0	49.6	0.14
Cell 1 effluent	1.365	0.004	0.164	2.75	01.42	5.82	20.9	9.6	0.11
Cell 2 effluent	0.625	0.004	0.173	2.30	0.086	4.90	11.5	4.7	0.06
				2-d HRT					
Influent	0.338	0.048	0.310	1.96	0.310	9.25	58.5	27.9	0.09
Cell 1 effluent	0.098	0.007	0.225	1.01	0.188	4.87	19.0	11.1	0.01
Cell 2 effluent	0.064	0.003	0.151	0.77	0.127	4.28	7.5	6.2	0
				4-d HRT					
Influent	1.287	0.132	0.501	5.72	0.208	12.92	45.0	31.3	0.11
Cell 1 effluent	1.072	0.003	0.178	3.63	0.078	4.75	8.1	5.7	0.01
Cell 2 effluent	0.684	0.003	0.125	2.58	0.033	4.45	5.1	3.1	0

removed instead of reduction in concentration. Although some effluent concentrations were higher in the 1-d HRT than in the 4-d HRT, the 1-d HRT removed more BOD, and solids, and an equivalent amount of phosphorus as compared with the 4-d HRT. Average concentrations of water quality variables in the influent tended to be less during the 2-d HRT trial (May–June 1992) than during the other trials. Average influent concentrations of SS and VSS were higher in the 1-d HRT than in the 4-d HRT, but the reverse was true for TAN and NO_2-N. Average concentration of other variables were similar for 1-d and 4-d HRT trials. Cell 1 removed a greater proportion of pollutants from the water than cell 2. This was probably a result of the much denser plant stand in cell 1. Reed and Brown (1992) reported that most of the BOD_5 and solids are removed in the first half of a wetland cell. With the exception of TAN in the 1- and 4-d HRT trials, concentrations of water quality variables were reduced 50% or more by the wetland (Table 6). Removal of NO_2-N, SS, and VSS exceeded 77%, and increasing the HRT beyond 1 d did not appear to enhance the removal of these variables. The greatest removal of TP and NO_3-N, 84% and 75%, respectively, was obtained in the 4-d HRT. The best removal of TAN was ob-

TABLE 6.—Percent reductions in concentrations of potential pollutants in water from a channel catfish pond affected by different hydraulic residence times (HRT) in a created wetland. The wetland had two cells of equal size. Abbreviations are defined in Table 3.

Cell and total	TAN	NO_2-N	NO_3-N	TKN	TP	BOD_5	SS	VSS	Settleable solids
			1-d HRT						
Cell 1	−54	95	60	46	43	59	78	81	21
Cell 2	55	0	−3	9	23	7	10	10	36
Total	1	95	57	55	66	66	88	91	57
			2-d HRT						
Cell 1	71	85	27	48	39	47	68	60	89
Cell 2	10	9	24	13	20	7	19	18	11
Total	81	94	51	61	59	54	87	78	100
			4-d HRT						
Cell 1	17	98	64	37	62	64	81	81	91
Cell 2	30	0	11	18	22	3	7	8	9
Total	47	98	75	55	84	67	88	89	100

TABLE 7.—Mass daily loading and removal rates (kg/ha) for different hydraulic residence times (HRT) for effluent from a channel catfish pond applied to a constructed wetland.

Loads	Organic loading rate	Suspended solids	Nitrogen	Phosphorus
		1-d HRT		
In	11.41	74.07	4.32	0.20
Out	3.16	7.42	1.59	0.60
Removed	8.25	66.65	2.73	0.14
		2-d HRT		
In	8.38	53.00	2.06	0.28
Out	3.39	5.95	0.73	0.10
Removed	4.99	47.05	1.33	0.18
		3-d HRT		
In	5.10	31.40	1.95	0.15
Out	2.82	6.77	0.91	0.04
Removed	2.28	24.63	1.04	0.11
		4-d HRT		
In	9.94	34.61	4.78	0.16
Out	2.83	3.24	1.72	0.02
Removed	7.11	31.37	3.06	0.14

tained in the 2-d HRT, and the lower removal efficiency of TAN in the 4-d HRT cannot be explained. Removal of BOD_5 ranged from 54–67%, and lengthening HRT did not improve BOD_5 removal. Both the 2-d and 4-d HRT trials gave 100% removal of suspended solids.

The removal of substances from water by a wetland involves a number of processes, including sedimentation of suspended particles, filtration of suspended particles by plant materials, uptake of nutrients by plants and bacteria, decomposition of organic matter, denitrification, nitrification, and adsorption of ions by the soil. The wetland removed large amounts of potential nutrients from the water even when vegetation was dormant and temperature was low (Table 3). Much of the observed removal during both dormant and vegetative seasons probably occurred through nonbiological processes of sedimentation, filtration, and soil adsorption. Analyses of soil samples showed that concentrations of phosphorus, nitrogen, and carbon were higher near the head of cell 1 than at other places in the wetland (Figure 3). Concentrations of these elements were slightly elevated throughout the wetland when compared with concentrations in the original bottom soil. Sedimentation of organic matter and adsorption of phosphorus by the soil caused increased concentrations of nitrogen, carbon, and phosphorus in the wetland soil.

Removal efficiencies of BOD_5 and TP are usually found to remain relatively constant throughout the year, while nitrogen removal efficiencies drop by about 40% during winter (Bishop and Eighmy 1989; Conway and Murtha 1989). Bavor et al. (1989) also found that the removal of BOD_5 and solids was not dependent on temperature. The significantly lower BOD_5 removal efficiency in this study during the dormant season must have been caused by the lack of sufficient vegetative cover because BOD_5 removal increased greatly during the next year's growing season after the plant stands became better established. Wolverton et al. (1983) found that the presence of macrophytes enhances ammonia removal, consequently improving the removal of nitrogenous BOD_5. Uptake of nutrients by plants, increased basal area of plants for periphyton colonization, and the influence of higher temperatures on physical and chemical processes probably accounted for the generally better performance of the wetland during the vegetative season. It is generally accepted that the key functions of macrophytes in wetland systems are serving as substrate for periphyton and actively transporting oxygen to the rhizosphere, which serves to facilitate chemical transformations in that portion of the sediment (Hammer 1992; Reed and Brown 1992). Reed and Brown (1992) also state that only 10% of the nitrogen in wetland systems is removed by macrophytes, and Vymazal (1988) found that periphyton can remove up to 80% of ammonia and 70% of phosphorus from water.

Standing crops of the three plant species tended to decline with length of flow in the wetland (Table 2), and concentrations of nitrogen and phosphorus in plant samples clearly decreased with length of flow (Figure 4). These observations suggest that plants in the upper end of the wetland absorbed more nutrients from the water than those in lower reaches and that greater nutrient availability favored their growth. Carbon concentrations and the carbon : nitrogen (C:N) ratio of plants increased along the flow path. This finding is consistent with observations by Polisini and Boyd (1972) that the structural carbohydrate content of plants increases and non-cell wall components, which contain most of the protein and minerals, decrease as nitrogen content declines. The C:N ratio of plants throughout the wetland was high. Decomposition of material with a high C:N ratio is slow, and residues from the species used in this study would be expected to decompose slowly. Plant residue in the wetland would provide surfaces for microbial growth and serve as a biofilter.

Schwartz and Boyd (1994b) averaged effluent concentration limits recommended by the U.S. Environmental Protection Agency and individual states as follows: SS, 30 mg/L; BOD_5, 30 mg/L; TP, 0.17 mg/L; TAN, 1.77 mg/L; NO_2-N, 0.83 mg/L; nitrate-nitrogen, 16.9 mg/L; and settleable solids, 3.3 mg/L. Waters from 25 commercial catfish ponds in Alabama were monitored over a 2-year period, and it was found that 75% of samples exceeded the SS limit, 80% exceeded the TP limit, 25% exceeded the TAN limit, 2% exceeded the BOD_5 limit, and 1% exceeded the NO_2-N limit (Schwartz and Boyd 1994b). When ponds are drained, the last 10–20% of water discharged has higher concentrations of pollutants than normal pond water (Schwartz and Boyd 1994a). Schwartz and Boyd (1994a) found that during pond draining BOD_5 increased from 10 to 104 mg/L, TP increased from 0.18 to 1.35 mg/L, and settleable solids increased from 0.1 to 60.0 mL/L. Most ponds would therefore be expected to exceed recommended EPA discharge limits if they discharged this last 10–20% of water.

Pond water used as influent to the wetland in

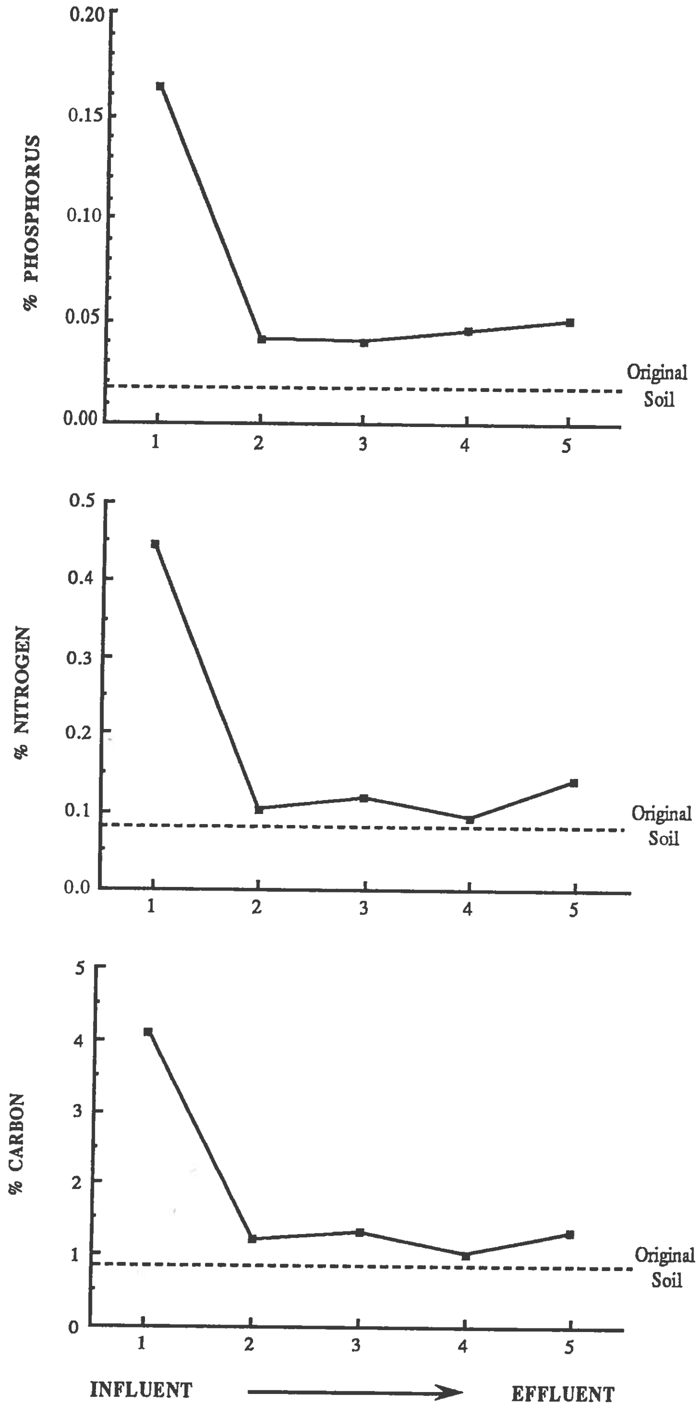

FIGURE 3.—Concentrations of carbon, nitrogen, and phosphorus concentrations in the soil along the length of two cells in a constructed wetland. Numbers on abscissas indicate soil sampling sites (see Figure 1).

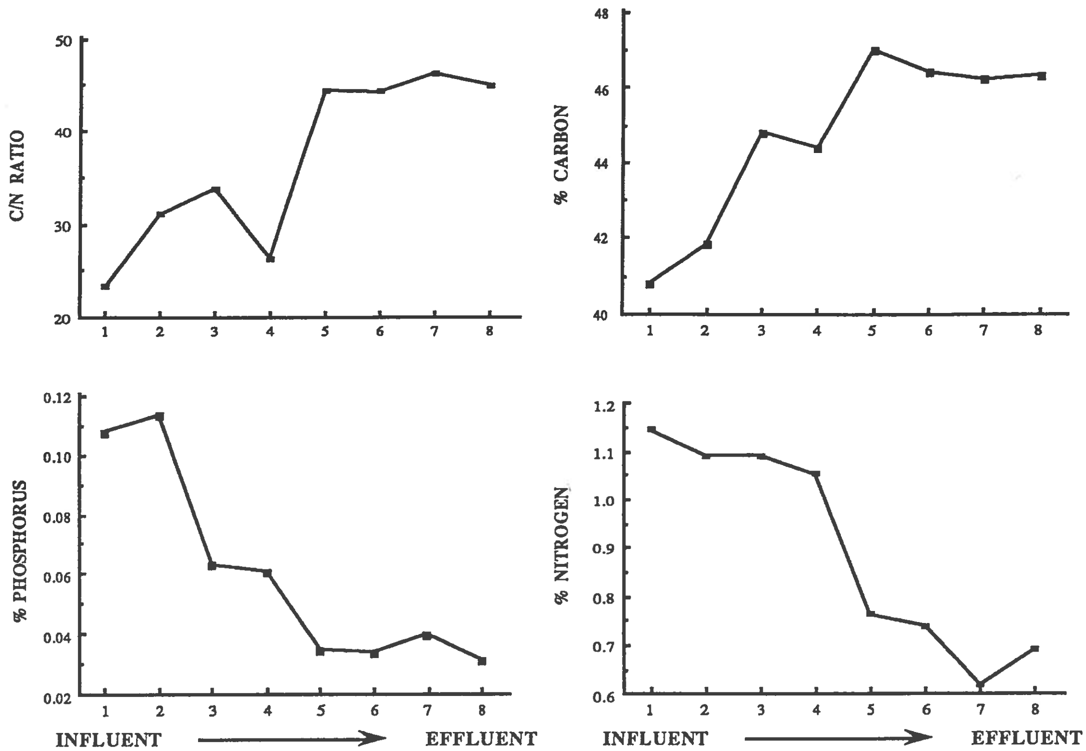

FIGURE 4.—Concentrations of carbon, nitrogen, and phosphorus and carbon : nitrogen (C/N) ratios in plant samples taken along the length of two cells in a constructed wetland. Numbers on abscissas indicate plant sampling sites (see Figure 1).

the present study usually had concentrations of SS and TP higher than recommended effluent concentration limits, and TAN concentrations were sometimes greater than recommended limits. Concentrations of these variables in the outflow from the wetland were always well below the recommended effluent limits, regardless of HRT. However, a 4-d HRT is recommended because it provided the greatest reduction in TP and BOD_5, which are important variables in considerations of the environmental impact of effluents.

Influent to the wetland was similar in composition to the water that overflows from ponds after heavy rains, during water exchange, or during the initial stages of draining, but it was not as concentrated in pollutants as water discharged during the final stages of pond draining (Schwartz and Boyd 1994a). Effluent loads during pond draining were reduced by 95.7% for SS, 73.9% for TKN, 69.1% for TP, and 58.8% for BOD_5 by simply holding the final 10–20% of water in ponds for 2 d after fish removal to allow solids to settle before final discharge (Schwartz and Boyd 1994b).

Passing water through wetlands would be more effective in removing pollutants than simply holding water in ponds. For example, assuming initial BOD_5 and TP concentrations of 104 mg/L and 1.35 mg/L, respectively, holding water for 2 d in the pond would reduce the BOD_5 to 42.6 mg/L and the TP to 0.42 mg/L. Running this effluent through a wetland at a 4-d HRT would further reduce BOD_5 to 14.1 mg/L and TP to 0.07 mg/L. Both of these values fall within the acceptable range of EPA effluent guidelines. If instead, this pond water was passed directly through a wetland, without being held for 2 d, BOD_5 would only be decreased to 34.3 mg/L and TP to 0.22 mg/L. Both of these concentrations exceed recommended discharge limits. Besides acting as sediment basins, wetlands remove pollutants from water by filtration, adsorption on soil, and biological processes.

The disadvantage of wetlands for treating aquaculture pond wastes is the large amount of space necessary to provide an adequate HRT. In the present study, the daily hydraulic loading rates ranged from 77 to 91 L/m^2 of wetland. Hydraulic residence time was altered by varying depth. The system functioned well at the 42-cm depth required for a 4-d HRT. The area of wetland necessary for treating a given volume of water can be calculated as follows:

$$A = \frac{V}{(\mathrm{HLR})(T_d)(10^{-3})};$$

T_d = time of pond draining, d,
V = pond volume, m^3.

Commercial catfish ponds have average depths of 1–2 m, and water usually must be drained in 1 week or less to prevent stress to fish through crowding. If we assume a 1-ha pond of 1.5-m average depth, a draining time of 7 d, and daily HLR of 80 L/m^2, then 2.68 ha of wetland would be required. Even a 1-d HRT would require 0.67 ha of wetland. Wetland areas of 0.7–2.7 times pond area are not feasible for commercial catfish farms.

Integration with other pond effluent management procedures could reduce the area of wetland necessary for treating catfish farm effluents. Hollerman and Boyd (1985) and Seok et al. (1995) showed that water quality deterioration was not a major factor in seine-harvested catfish ponds that were not drained for 3 years. However, after a few years, ponds must be drained to repair levees and adjust fish inventories. When a pond must be drained, about 80% of the water could be pumped into adjacent ponds for reuse, and the remaining 20% of water could be discharged through a wetland. Draining time would not be a critical factor after fish have been removed by seining. If a 15-d draining time is used, a 1-ha × 1.5-m-deep pond would require a 0.25-ha wetland (25% of pond area) to provide a 4-d HRT and a daily HLR of 80 L/m^2. On a large catfish farm, all ponds would not need to be drained each year, and draining could be extended over several weeks or months to further reduce the area of wetland required.

Wetlands also could be used for treating overflow from ponds after rains. Most channel catfish farming is conducted in levee ponds where watersheds consist only of inside slopes and tops of levees. Ponds receive little runoff, and overflow normally does not occur except in winter and early spring following heavy rains (Yoo and Boyd 1993). Boyd and Shelton (1984) reported that the average annual overflow from levee ponds at Auburn, Alabama, was about 1,100 m^3/ha. These ponds had high seepage rates, and 2–4 times more overflow could be expected for ponds with less permeable bottoms and in years with abnormally high rainfall. Most overflow from levee ponds in the southeastern United States occurs during January, February, and March. Average daily overflow rates of 1–5 L/m^2 pond surface can be expected. The wetland area necessary to provide an average HRT of 4 d at a daily HLR of 80 L/m^2 for average daily winter overflow of 5 L/m^2 from a 1-ha catfish pond is 625 m^2 or 6.25% of pond area.

Because watershed ponds are usually located much farther apart than levee ponds, it usually would not be feasible to transfer water between watershed ponds for reuse. Large wetlands would be needed to treat the effluent at pond draining. A smaller wetland could be useful for treating the last 10–20% of highly concentrated effluent from watershed ponds.

The wetland evaluated in this study consisted of two cells and three plant species. However, a single cell would have been just as effective. California bulrush and giant cutgrass provided much thicker stands than Halifax maidencane, and bulrush grew faster initially than the cutgrass. Use of bulrush alone or together with cutgrass would provide for quicker plant establishment and higher standing crops in wetlands than the combination used in this study.

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