Treatment of swine wastewater in marsh-pond-marsh constructed wetlands

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Abstract Swine waste is commonly treated in the USA by flushing into an anaerobic lagoon and subsequently applying to land. This natural system type of application has been part of agricultural practice for many years. However, it is currently under scrutiny by regulators. An alternate natural system technology to treat swine wastewater may be constructed wetland. For this study we used four wetland cells (11 m width × 40 m length) with a marsh-pond-marsh design. The marsh sections were planted to cattail (*Typha latifolia*, L.) and bulrushes (*Scirpus americanus*). Two cells were loaded with 16 kg N ha^{-1} day^{-1} with a detention of 21 days. They removed 51% of the added N. Two additional cells were loaded with 32 kg ha^{-1} day^{-1} with 10.5 days detention. These cells removed only 37% of the added N. However, treatment operations included cold months in which treatment was much less efficient. Removal of N was moderately correlated with the temperature. During the warmer periods removal efficiencies were more consistent with the high removal rates reported for continuous marsh systems – often > than 70%. Phosphorus removal ranged from 30 to 45%. Aquatic macrophytes (plants and floating) assimilated about 320 and 35 kg ha^{-1}, respectively of N and P.

Keywords Constructed wetlands; marsh; pond; swine wastewater

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Introduction

North Carolina ranks second in the US in swine production and annually generates 42 billion pounds of manure per year. Many swine production facilities have flushing systems with fresh or recycled water to flush the liquid manure into an anaerobic lagoon. Excessive wastewater in lagoons is applied on the land with irrigation or spreading equipment, and this requires a large land area. Swine waste management is under scrutiny because of frequent lagoon spills and floods, which have caused surface water contamination of rivers. Therefore, alternate low-cost technologies are required to treat wastewater. Constructed wetlands with vegetation have received considerable interest as a method of wastewater treatment (Hammer, 1989). Constructed wetlands have been used to treat municipal wastewater (Kadlec and Knight, 1996), mine drainage (Kleimann and Girts, 1987), industrial effluents (Polprasert *et al.*, 1996), and animal wastewater (Payne *et al.*, 1992: Hunt *et al.*, 1994). Constructed wetlands are relatively low cost, operation/maintenance, and energy input technology; thus, they have good potential as a technology for treatment of swine wastewater.

Most of the N in the wastewater is in the form of NH_4, and its nitrification is dependent on the O_2 supply. Constructed wetlands with vegetation have aerobic microsites adjacent to the roots and at the water surface where NH_4 can be nitrified to NO_3 and subsequently denitrified in anoxic conditions (Brix, 1994; Hammer and Knight, 1994). On the other hand, P removal in constructed wetlands occurs through chemical precipitation, substrate adsorption, plant and algal uptake, and immobilization into organic matter (Swindell and Jackson, 1990; Moshiri, 1993; Reddy and Reddy, 1993).

Several authors have shown the efficiency of constructed wetlands in removing N, P, COD, and TSS (Reddy and Debusk, 1985; Payne *et al.*, 1992; Hunt *et al.*, 1995). Animal wastewater contains high concentrations of nutrients and ammonia. High ammonia levels can kill aquatic plants in wetlands. Therefore, studies are required to determine the maximum or acceptable wastewater loading rates in constructed wetlands. Also, there is limited data for animal wastewater treatment in constructed wetlands. The purpose of this study was to 1) evaluate the high N loading rates for nutrient removal, 2) compare the performance of marsh-pond-marsh with the continuous marsh system, and 3) determine the temperature effect on N removal.

Methods

Site and wetland cells description

Six wetland cells (11 m wide × 40 m long) were constructed at the swine unit (130–250 sows) on the North Carolina A&T State University farm in 1995. Each cell has a 20 m middle pond section and 10 m section with marshes at the influent and effluent ends. Shallow sections with marshes at the influent and effluent ends and the deep section in the pond had an operating depth of 15 cm and 75 cm, respectively. The marsh sections were planted with cattails (*Typha latifolia, L.*) and bulrushes (*Scirpus americanus*) in March 1996. However, cattails have become dominant in the marsh areas. Plants grew from March through September.

Wastewater flow system

The waste from the swine house was flushed with recycled water into a two stage anaerobic lagoon [primary lagoon (L1) and secondary lagoon (L2)]. Flow from L2 was pumped by a submersible pump to an 8000 L storage tank. The wastewater from the storage tank was discharged by gravity into the wetland cells. Only four wetland cells were used for this study. The effluents from the cells were discharged into a holding pond for recycling into the swine house or application on land. The cells were operated in cold weather, and insulated covers were installed to prevent freezing of the inflow tipping buckets and the associated piping.

Nutrient loading

The wetland cells were operated with 5–6 kg N ha^{-1} day^{-1} in 1997 to establish the wetland ecosystem. From May 15, 1999 two cells received 16 kg N ha^{-1} day^{-1} with 6.06 m^3/day hydraulic load and 21 days theoretical retention and others received 32 kg N ha^{-1} day^{-1} with 12.13 m^3/day hydraulic load and 10.5 days theoretical retention. The experiment was conducted from June, 1999 to January, 2000.

Monitoring equipment

One tipping bucket wired to an electronic totalizer (volume counter) was installed at the inflow and outflow points of each wetland cell. Four ISCO 2700 (ISCO, Lincoln, NE) auto samplers were installed. The water sampler combined daily samples into weekly composites. Two mL concentrated HCl was added to each sampling bottle to lower the pH below 2.5. The samples were transfered to the laboratory and stored at 4°C.

Wastewater analysis

Weekly samples were carried to the laboratory and used for the following analysis. Ammonium (NH_4-N), nitrate-N (NO_3-N), total Kjeldahl-N (TKN), Ortho phosphate (o-PO_4), total phosphorus (TP), total solids (TS) were analyzed in accordance with the USEPA methodology by using TRAACS 800 Auto Analyzer (Kopp and McKee, 1983). Electrical conductivity, temperature, Eh and pH readings were recorded by electronic methods. Chemical oxygen demand (COD) was analyzed by use of the Hatch method (Gibbs, 1979).

Plant tissue analysis

Cattails/bulrushes and duckweed were sampled in the second week of September in marshes (0.25 m^2 area) and in the pond area (0.04 m^2), respectively. The samples were dried at 60°C for 24 hours, and dry weights (biomass) were recorded. Total N was determined by using C-N-H-S analyzers (Perkin-Elmer model 2400), and total-P was analyzed with the perchloric acid digestion method and measured by using TRAACS 800 Auto Analyzer.

Results and discussion

Mean pH values ranged from 6.8 to 7.9. No seasonal changes of pH were observed (Table 1). The average temperature in the water ranged from 6.45 in winter to 21.9°C in the summer. The inflow water temperature was 1°C less than the outflow water temperature in late fall and winter months. The concentration of total Kjeldahl N (TKN), ammonium (NH_4), and total phosphorus (TP) were higher in the winter than in either the fall or summer for both the inflow and outflow wastewater. Redox ranges in inflow marsh, pond, and outflow marsh were –114 to –326, –15 to +150, and –194 to –320 –Eh (mV), respectively. The total rainfall was 683 mm and more than 25% of the total rainfall occurred during the three storms in September.

Treatment efficiency

The annual mean mass reductions of TKN, NH_4, TP, PO_4, COD, TSS during the experimental period are shown in Table 2.

Nitrogen removal. The TKN removal rate was 51 and 37% at 16 and 32 kg ha^{-1} day^{-1} loading rates, respectively. The TKN mass inflow and outflow ratio was approximately 2.1 for 16 kg and 3.9 for 32 kg N loading rate. When N loading rate was reduced from 32 to 16 kg ha^{-1} day^{-1}, the wastewater detention time was increased from 10.5 to 21 days. The decrease in loading rate with an increase in detention time improved the treatment efficiency of the wetland cell. Others (Nichols, 1983; Knight *et al.*, 1985; Hammer and Knight, 1994) have reported that an average mass reduction of TKN was in the range of 46–72%. Similar results were also found in our previous study (Phillips *et al.*, 1999).

Ammonium removal. Mass reduction of NH_4 was 60 and 43% at the low and high N loading rates, respectively. Most of the N removal occurred in warmer months. The reasonably high NH_4 in the outflow suggests that nitrification is limited in this system. This is consistent with the report of Hunt *et al.*, (1999) that the continuous marsh wetlands were oxygen limited for nitrification. Additionally, the high loading rates without dilution of the wastewater

Table 1 Wastewater characteristics

Average Inflow Concentration (mg L^{-1})			–Eh (mV) range	pH range
TKN	144.55	marsh inflow	–114 to –326	6.8 to 7.9
NH_4	80.53	pond	–15 to 150	
TP	74.81	marsh outflow	–194 to –302	
PO_4	61.87			
TSS	521.80			
COD	820.52			
NO_3	1.59			

Table 2 Performance of marsh-pond-marsh constructed wetlands

Loading rates ($kg\ ha^{-1}\ day^{-1}$)		TKN	NH_4	NO_3 ($g\ m^{-2}\ day^{-1}$)	TP	PO_4	TSS	COD
16	Inflow	1.52	0.67	0.01	0.66	0.53	4.03	6.74
	Outflow	0.74	0.27	0.01	0.37	0.33	1.27	3.14
	% Reduction	51.26	59.53		44.37	39.00	68.55	53.38
32	Inflow	3.10	1.47	0.02	1.35	1.21	10.72	15.47
	Outflow	1.97	0.84	0.03	0.94	0.78	3.60	8.88
	% Reduction	36.53	43.05		30.56	35.30	66.41	42.61

may have caused the high oxygen demand and slowed down the nitrification process. The N removal in the marsh-pond-marsh system coincided moderately well with the continuous marsh system operation in Duplin County, North Carolina, when cells were loaded with 15 kg N ha^{-1} day^{-1}, particularly during the warmer months. However, the results do not indicate that a significant oxidative benefit was obtained from the pond section even though it had higher Eh values than the marsh sections.

Temperature effect on TKN removal. Since the significant seasonal differences were observed in N removal, the correlation was made between the weekly mean temperature and N removal. A linear relationship was observed between N reduction and water temperature for both N loading rates (Figure 1). The relation between the temperature and N removal was highly significant (R^2 = 0.65 for 16 kg and R^2 = 0.46 for 32 kg). The increased N removal in warmer months is directly related to the biological processes involving N-transformations. Similar results were also reported by Hunt *et al.* (1999).

Phosphorus removal. The total P and soluble-P (PO_4) removals were 44 and 39% at 16 kg N loading rate and 31 and 35% at 32 kg N loading rate, respectively. Phosphorus in wastewater is removed in wetlands by several physical, chemical, and biological mechanisms such as sorption, precipitation, and biological immobilization. These mechanisms may occur simultaneously in the wetland cells. In our study the P removal may be due to the sorption process and assimilation by the macrophytes.

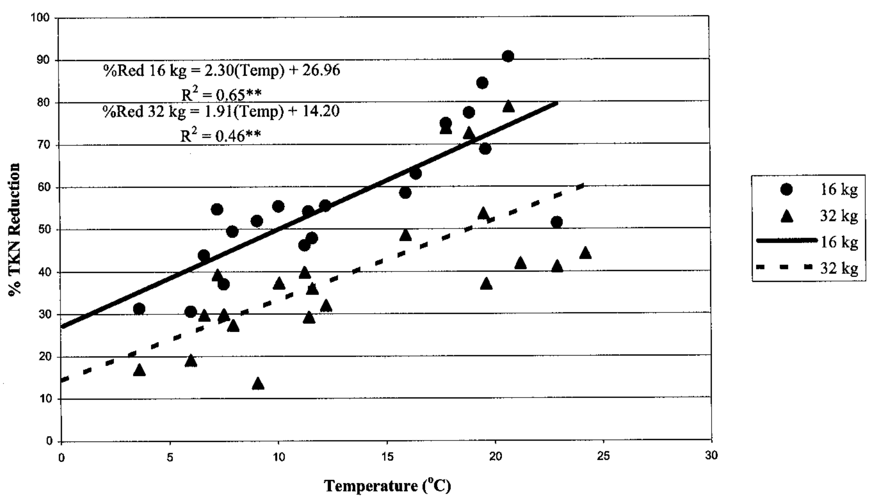

Figure 1 Temperature influence on TKN removal

Table 3 Aquatic macrophyte biomass, N and P uptake

Macrophytes	Biomass		N-uptake		P-uptake	
	N-Loading Rates (kg N ha^{-1} day^{-1})					
	16	32	16	32	16	32
	kg (dry wt.) m^{-2}			g m^{-2}		
Cattails and Bulrushes						
Inflow Marsh	1.62	2.51	30.00	33.00	3.30	3.70
Outflow Marsh	2.34	2.30	34.10	33.80	3.30	3.20
Duckweed (Pond Area)	0.19	0.08	9.45	3.70	0.60	0.20

Nitrogen and P removal by macrophytes. The nutrients (N and P) accumulation in macrophytes in autumn is shown in Table 3. Approximately 32 g N m^{-2} was assimilated by the plants grown in the marshes (Table 3). These results are in agreement with Szogi *et al.* (1999). Whereas, 9.3 g N m^{-2} and 3.3 g N m^{-2} was assimilated by duckweed in the pond area of the wetland cells loaded with 16 kg N and 32 kg N ha^{-1} day^{-1}. The plant biomass was 415 g m^{-2} higher in 32 kg N ha^{-1} day^{-1} than in the low N loading rate. The amount of N assimilated by duckweed in the wetland cell was directly related to the biomass. High N loading rate had a negative influence on duckweed growth. Aquatic macrophytes assimilated 3.3 to 3.9 g P m^{-2} in marsh areas. Duckweed assimilated 0.59 g P m^{-2} and 0.19 g P m^{-2} in pond area at 16 and 32 kg N ha^{-1} day^{-1} loading rates, respectively. The differences in P assimilation were related to the biomass.

Total suspended solids (TSS) removal. Total suspended solids were reduced by over 66 to 69%. However, no difference was observed in TSS removal based on N loading rate. Mass removal rates for TSS did not show a relationship to mass loading. The removal of TSS is primarily due to the physical processes such as sedimentation and filtration. Gearheart (1992) observed that approximately 75% of the TSS removal occurs in the first day of the retention.

Chemical oxygen demand (COD) removal. The removal of COD ranged from 43 to 53% across the N loading rates. The COD reduction followed the same pattern as TSS. This trend can be expected due to the association of organics with the solids.

Conclusion

The results indicate that constructed wetlands have a potential for nutrient removal and treatment of animal wastewater. The annual mean of TKN, NH_4, TP, and PO_4 at 16 and 32 kg N ha^{-1} day^{-1} loading rates were 51, 60, 44, and 39% and 37, 43, 31, and 35%, respectively. Similar results were shown in the N-data from the 17 constructed surface flow (SF) wetlands in the North American Database (Knight *et al.*, 1992). The average N efficiency of the SF wetlands was 49.9% for TKN and 33.9% for NH_4. Also Knight *et al.* (1985) reported a decline of total-N mass removal efficiency at higher loading rates (30 kg/ha/day). These low removal rates are due to the combined data of warmer and cooler months. However, high removal rates were observed in warmer months (June to August). Hydraulic loading was twice as high in 32 kg N with half of the retention days (10.5 days) as compared to 16 kg N loading rate. The high concentrations and mass of NH_4 in the outflow revealed that nitrification was a limiting factor. A significant reduction of TSS and COD occurred in wetlands. Temperature had a significant influence on TKN reduction. The outflow wastewater does not meet the discharging permit standards, however the large reduction in mass means that the wastewater can be applied on a smaller land area.

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