



Marsh-pond-marsh constructed wetland design analysis for swine lagoon wastewater treatment

K.C. Stone^{a,*}, M.E. Poach^a, P.G. Hunt^a, G.B. Reddy^b

^a USDA-ARS, 2611 West Lucas Street, Florence, SC 29501, USA

^b North Carolina A&T State University, Greensboro, NC, USA.

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Abstract

Constructed wetlands have been identified as a potentially important component of animal wastewater treatment systems. Continuous marsh constructed wetlands have been shown to be effective in treating swine lagoon effluent and reducing the land needed for terminal application. Constructed wetlands have also been used widely in polishing wastewater from municipal systems. Constructed wetland design for animal wastewater treatment has largely been based on that of municipal systems. The objective of this research was to determine if a marsh-pond-marsh wetland system could be described using existing design approaches used for constructed wetland design. The marsh-pond-marsh wetlands investigated in this study were constructed in 1995 at the North Carolina A&T University research farm near Greensboro, NC. There were six wetland systems (11 m × 40 m). The first 10-m was a marsh followed by a 20-m pond section followed by a 10-m marsh planted with bulrushes and cattails. The wetlands were effective in treating nitrogen with mean total nitrogen and ammonia-N concentration reductions of approximately 30%; however, they were not as effective in the treatment of phosphorus (8%). Outflow concentrations were reasonably correlated ($r^2 \geq 0.86$ and $r^2 \geq 0.83$, respectively) to inflow concentrations and hydraulic loading rates for both total N and ammonia-N. The calculated first-order plug-flow kinetics model rate constants (K_{20}) for total N and ammonia-N (3.7–4.5 m/day and 4.2–4.5 m/day, respectively) were considerably lower than those reported in the limited literature and currently recommended for use in constructed wetland design for animal wastewater treatment.

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1. Introduction

Animal production has expanded rapidly during the early 1990's in the eastern US. In North Carolina, the

number of swine has increased from approximately 2.8 million in 1990 to more than 9 million by 1996 (USDA-NASS, 2004). This rapid expansion of high population animal production has resulted in greater amounts of concentrated animal waste to be utilized or disposed of in an efficient and environmentally friendly manner. This rapid animal production expansion has exceeded the pace at which new innovative treatment

* Corresponding author. Tel.: +1 843 669 5203x1111;
fax: +1 843 669 6970.

E-mail address: stone@florence.ars.usda.gov (K.C. Stone).

systems have been developed, and has resulted in the animal production industry investigating the adaptation of some municipal wastewater treatment technologies. In this study, we evaluated the effectiveness of a marsh-pond-marsh constructed wetland that has been used to treat swine wastewater since 1995. Design parameters from these wetlands were calculated to compare their effectiveness to other wetland systems and aid in the design of future constructed wetland systems.

Constructed wetlands have been used for many years in municipal wastewater treatment. Since 1989, many constructed wetlands have been installed to investigate their effectiveness in treating animal waste (Payne and Knight, 1997). The technical requirements for these wetlands treating animal waste were based mainly on municipal systems and limited data on animal waste systems. Although, constructed wetlands treating animal wastewater were originally thought to be able to produce an effluent that could be discharged, concern for the environment and discharge regulations has mostly precluded this approach. Constructed wetlands treating animal waste are typically used to reduce wastewater spray field nutrient loading. This is an important concern where land for application is limited (Barker and Zublena, 1995).

Preliminary constructed wetland design guidelines for animal waste treatment proposed by the USDA Natural Resources Conservation Service (1991) were based on BOD₅ loading to the wetlands (presumptive method). These guidelines were based on minimum levels of BOD₅ and ammonia-N exiting in the wetland and a recommended residence time of at least 12 days. Updated design guidelines for constructed wetlands based on research findings and a physically based approach were released by USDA Natural Resources Conservation Service (2002). They proposed two methods: a modified presumptive method and a new field-test method. The new field-test method was based on a physical approach by Kadlec and Knight (1996).

Kadlec and Knight (1996) and Reed et al. (1995) presented physically based constructed wetland design approaches based on municipal wastewater treatment wetlands. Both models are based on a first-order kinetics area-based uptake model. Reed et al. (1995) incorporated flow rate, wetland depth, wetland porosity, a temperature-based rate constant, and inflow and outflow concentrations. The rate constant used in this ap-

proach is a function of depth and porosity of the wetlands.

Kadlec and Knight (1996) refer to their model as the $k-C^*$ model. The model incorporates the hydraulic loading rate, concentrations into and out of the wetlands, and a temperature-based rate constant. They also include a background concentration parameter (C^*). Their rate constant differs from Reed et al. (1995) in that depth and porosity are not included in the calculation.

Payne and Knight (1997) compared both the Reed et al. (1995) and Kadlec and Knight (1996) design methods. They found that the Kadlec and Knight (1996) method typically required a greater surface area for the constructed wetland than the Reed et al. (1995) method. The main difference was based on the design depth of the wetland in the Reed et al. (1995) model. Payne and Knight (1997) suggested that if the Reed et al. (1995) model were to be used, an initial minimum depth should be used in order to maximize the surface area of the wetland.

The wetlands discussed in this paper were constructed to treat swine lagoon effluent in 1995. Aspects of their performance have been discussed by Reddy et al. (2001) and Poach et al. (2004a, 2004b). The objective of this paper was to determine if the marsh-pond-marsh wetland system could be described using existing design approaches used for constructed wetlands.

2. Methods

2.1. Site description and operation

In 1995, six wetland systems to treat swine lagoon wastewater were constructed at the North Carolina A&T State University farm near Greensboro, North Carolina. The wetland systems were configured into a marsh section, a central pond section, and another marsh section (marsh-pond-marsh). The marsh sections were approximately 10 m × 10 m and the pond section was 10 m × 20 m. The marsh sections were planted with *Typha latifolia* L. (broadleaf cattail) and *Schoenoplectus americanus* (Pers.) Volkart ex Schinz & R. Keller (American bulrush) in March 1996. Additional details on construction, initial wetland operation and initial data analysis were reported by Reddy et al. (2001). In September 2000, the wetlands were

reconfigured to allow each wetland system to be loaded with a specific total-N (TN) loading rate from 10 to 50 kg/(ha day) (5, 14, 23, 32, 41, and 50 kg/(ha day)). For approximately 1 year, the wetland hydraulic loading rates were held approximately equal, with only the TN loading rate varying. The operating depths of the constructed wetlands were 15 cm for marsh sections and 75 cm for pond sections.

2.2. Statistical analyses

Statistical analyses on the constructed wetland data were performed using the Statistical Analysis System software (SAS, 1990). Nutrient concentration reductions were calculated as:

$$C_{\text{reduction}} = C_{\text{in}} - C_{\text{out}} \quad (1)$$

where C_{out} is the outflow concentration (mg/L) and C_{in} is the inflow concentration (mg/L).

Percentage nutrient concentration reductions were calculated as:

$$\% C_{\text{reduction}} = \frac{C_{\text{in}} - C_{\text{out}}}{C_{\text{in}}} \times 100 \quad (2)$$

2.3. Regression analysis

A regression analysis was performed to determine if significant relationships existed between inflow and outflow concentrations to the wetlands. The regression equation was modeled to predict outflow concentration as a function of inflow concentration and hydraulic loading rate and took the form of:

$$C_{\text{out}} = aC_{\text{in}}^b q^c \quad (3)$$

where q is the hydraulic loading rate (m/day) and a , b , c are the regression coefficients.

Eq. (3) was transformed in order to perform the regression in the SAS system with the Proc Reg procedure and was analyzed as:

$$\ln C_{\text{out}} = \ln a + b \ln C_{\text{in}} + c \ln q \quad (4)$$

The regression models provide information on the overall performance of the wetlands, but they are typically considered valid only for the range of data used to model them. To determine how our regression analysis relates to other wetlands treating animal wastewater, we compared our results to those regression models

published by Knight et al. (2000). Their study included summary data from various constructed wetlands treating dairy, cattle, swine, poultry, catfish pond water, and runoff from cattle feeding operations. Their data, although extremely important and on a wide-ranging variety of systems, did not provide an extensive study nor quantification of wetlands performance and operation that are provided in this study. This comparison was useful because it combined the strength of both scales of study.

2.4. Wetland design analysis

Design of surface flow wetlands for animal waste treatment was originally derived from municipal treatment wetlands (Kadlec and Knight, 1996). Surface flow treatment wetlands typically have nutrient concentration profiles that decrease exponentially with distance from the inlet (Knight et al., 2000). This exponential decrease in nutrient concentration through the wetland is generally modeled as a simple first-order reaction. The first-order reaction model is typically integrated with a plug-flow assumption (Kadlec and Knight, 1996; Reed et al., 1995). Although the flow in constructed wetlands is generally intermediate between plug-flow and completely mixed, the first-order model with plug-flow assumptions provides a conservative design estimate (Knight et al., 2000). Kadlec and Knight (1996) presented the area-based first-order plug-flow design model as:

$$\ln \left[\frac{C_{\text{out}} - C^*}{C_{\text{in}} - C^*} \right] = -\frac{K_T}{q} \quad (5)$$

where C^* is the background concentration (mg/L) and K_T is the rate constant adjusted for temperature (m/day).

$$K_T = K_{20}\theta^{(T-200)} \quad (6)$$

K_{20} is the rate constant at 20 °C (m/day), θ is dimensionless temperature coefficient, and T is temperature (°C).

The hydraulic loading rate (q) is defined as

$$q = \frac{Q_{\text{in}}}{A} \quad (7)$$

where Q_{in} is the inflow (m³/day) and A is the wetland surface area (m²).

We rearranged Eq. (5) to solve for the temperature-related rate constant for TN, ammonia-N ($\text{NH}_4\text{-N}$), and total phosphorus (TP) from the wetland data as:

$$K_T = \frac{Q}{A} \ln \left[\frac{C_{\text{in}} - C^*}{C_{\text{out}} - C^*} \right] \quad (8)$$

Eq. (6) was then rearranged in order to calculate the K_{20} rate constant at 20 °C and the dimensionless temperature coefficient.

$$\ln K_T = \ln K_{20} + (T - 20) \ln \theta \quad (9)$$

where the $\ln K_T$ would be regressed against the temperature term ($T - 20$).

In addition to solving for rate constants (K_{20} , θ , and C^*) using regression analysis in SAS, we used the Solver spreadsheet function in Microsoft Excel 2000 (Microsoft Corporation, Redmond, WA) to simultaneously solve Eqs. (5) and (6) for K_{20} , θ , and C^* . This required an Excel spreadsheet to be constructed with columns of C_{in} , C_{out} , q , mean monthly temperature, initial estimates of K_{20} , C^* , θ , estimated C_{out} , and the sum square error (SSE) term for the difference between observed and estimated C_{out} . The Solver routine then minimized the total SSE term by changing the estimated K_{20} , C^* , and θ values. This simultaneous solution method minimizes the sum of squares between the measured and predicted outflow nutrient concentrations (Kadlec, 2000, personal communication). We used this Excel spreadsheet procedure for TN, $\text{NH}_4\text{-N}$, and TP. Additionally, we calculated K_{20} and θ using $C^* = 0$ to compare with our SAS regression results, and using C^* values estimated from Knight et al. (2000) to compare with their results.

3. Results

During the study period from September 2000 to September 2001, the marsh-pond-marsh wetlands had a mean residence time of approximately 16 days with a hydraulic loading rate of ~ 0.02 m/day (Table 1). The overall mean TN loading rate was 23 kg/(ha day) and the individual wetland systems ranged from 7 to 39 kg/(ha day). The actual TN loading rates varied from target rates due to rainfall and occasional equipment malfunctions. Mean inflow TN concentration was 116 mg/L and ranged from 42 to 173 mg/L for the indi-

Table 1
Means of flow, residence time, and hydraulic loading rate for the constructed wetland systems

Flow (m^3/day)		Nominal residence time (day)		Hydraulic loading rate (m/day)	
Mean	S.D.	Mean	S.D.	Mean	S.D.
6.38	1.83	16.40	12.70	0.02	0.01

vidual wetland systems (Table 2). Corresponding outflow TN concentration was 70 mg/L and varied from ~ 20 to ~ 112 mg/L across the wetland systems. Overall concentration reduction was 35% and ranged from 28 to 43%.

The mean $\text{NH}_4\text{-N}$ loading rate was 17 kg/(ha day) and ranged from 3 to 30 kg/(ha day) for the individual wetland systems. Mean inflow $\text{NH}_4\text{-N}$ concentration was 86 mg/L and ranged from 18 at the lower loading rate to 140 mg/L at the higher loading rates. Outflow $\text{NH}_4\text{-N}$ concentration was 53 mg/L and ranged from 10 to 94 mg/L. The overall $\text{NH}_4\text{-N}$ concentration reduction was 25%. Ammonia volatilization from the wetlands was identified to be a potential significant removal pathway at higher loading rates (Poach et al., 2002, 2004a, 2004b) particularly in the pond section of the marsh-pond-marsh wetlands.

The mean TP loading rate was 12 kg/(ha day) and ranged from ~ 8 to ~ 15 kg/(ha day) at the higher TN loading rates. The mean TP concentration entering the wetlands was 56 mg/L and ranged from ~ 40 at the lower loading rate to ~ 68 mg/L at the higher loading rates. Mean outlet TP concentration (48 mg/L) was close to the inlet concentration for most wetland systems ranging from 34 to 62 mg/L with concentration reductions ranging from -1 to 16% with a mean reduction of 8%. To accomplish more efficient P removal in the wetland systems, pre- and/or post-treatment will likely be required.

Table 2
Means of inflow, outflow, removal, and percent removal for the constructed wetland systems

	Inflow (mg/L)		Outflow (mg/L)		Percent reduction (mg/L) Mean
	Mean	S.D.	Mean	S.D.	
TN	116	63	70	40	35
$\text{NH}_4\text{-N}$	86	56	53	37	25
TP	56	28	48	15	8

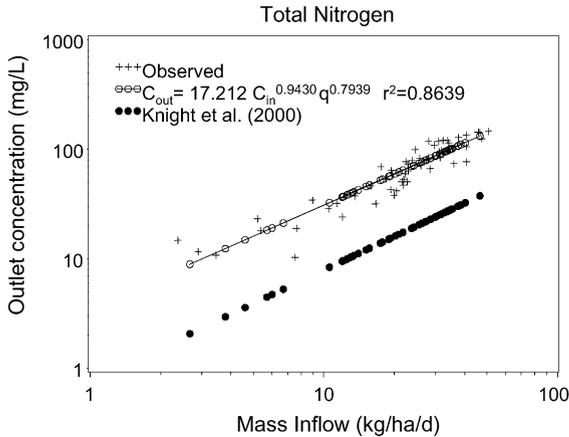


Fig. 1. Relationship between total nitrogen mass loading and outlet concentration. Equations plotted with mean loading rate of $q = 0.02$ m/day for comparison.

3.1. Regression analysis

The coefficient of determination (r^2) for the regression of TN outlet concentration as a function of inlet concentration and flow was 0.86 for the marsh-pond-marsh wetland systems. (Fig. 1). For comparison, we plotted our calculated regression equation with the mean hydraulic loading rate of 0.02 m/day along with those from Knight et al. (2000) (Fig. 1). Our regression results predicted less treatment over the range of loading rates than those of Knight et al. (2000).

The regression for $\text{NH}_4\text{-N}$ had r^2 values was 0.83 (Fig. 2). Our $\text{NH}_4\text{-N}$ regression results were very similar to those from TN, which was expected since most of the TN is in the $\text{NH}_4\text{-N}$ form. Our wetlands predicted lower $\text{NH}_4\text{-N}$ treatment than Knight et al. (2000). Slopes of both the TN and $\text{NH}_4\text{-N}$ regression lines were similar to those of Knight et al. (2000) indicating similar treatment characteristics, however at a lower treatment efficiency.

The TP regression analysis for the inlet concentration and hydraulic loading rate versus the outlet TP concentration had r^2 values of approximately 0.64 (Fig. 3). For TP, our regression equation predicted less treatment than Knight et al. (2000), particularly at lower loading rates.

3.2. Wetland design analysis

The wetland data for the entire study period were analyzed to calculate the rate constants of TN, $\text{NH}_4\text{-N}$,

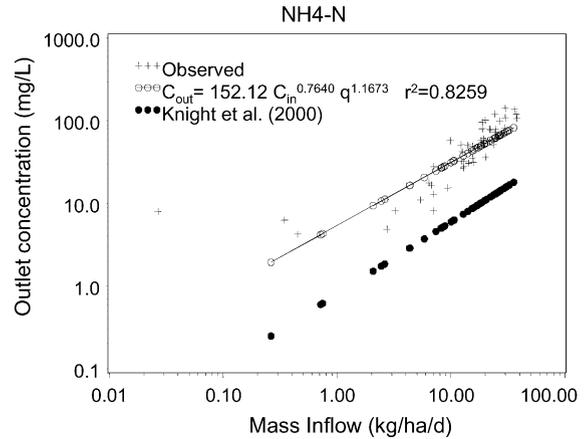


Fig. 2. Relationship between ammonia-N mass loading and outlet concentration. Equations plotted with mean loading rate of $q = 0.02$ m/day for comparison.

and TP for the six marsh-pond-marsh wetland systems. The temperature-based rate constants were calculated using Eq. (8) and then regressed against the temperature to determine the K_{20} rate constant and θ from Eq. (9) and using Excel solver. In Tables 3 and 4, K_{20} and θ are shown, for TN and $\text{NH}_4\text{-N}$ for the wetland systems studied. These results are lower than those from continuous marsh systems reported by Reed et al. (1995), Kadlec and Knight (1996) and Knight et al. (2000). The NRCS field-test method (Payne and

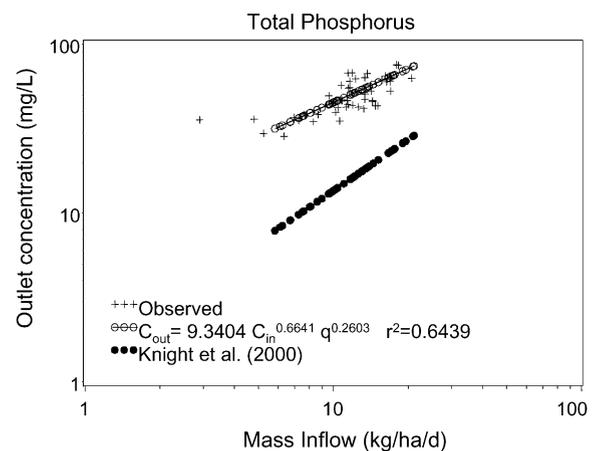


Fig. 3. Relationship between total phosphorus mass loading and outlet concentration. Equations plotted with mean loading rate of $q = 0.02$ m/day for comparison.

Table 3
Regression parameters for the calculation of rate constants for the first-order area-based treatment design model

	Intercept	K_{20} (m/year)	Slope	θ	r^2
TN	1.308	3.69	0.024	1.02	0.138
NH ₄ -N	1.486	4.20	0.056	1.05	0.349
TP	0.084	1.09	-0.003	0.99	0.001

Knight, 1997) suggests using a K_{20} of 14 m/year for TN and 10 m/year for NH₄-N. We calculated TN K_{20} values of 3.7–4.5 m/year and NH₄-N K_{20} values of 4.2–4.5 m/year. The TN and NH₄-N K_{20} values are similar for our system because most of the TN in our system was in the NH₄-N form. Our lower values for the rate constants compared with the NRCS field-test method were calculated assuming both $C^* = 0$ and C^* equal to those suggested in the literature (USDA Natural Resources Conservation Service, 2002; Knight et al., 2000). The calculated lower K_{20} values would result in a more conservative prediction for treatment in the wetland systems and would result in a larger wetland area. In our regression analysis, we had very low coefficients of determination, which suggest that the rate constants in our systems were not strongly related to temperature. However, these r^2 values were higher than those calculated for a continuous marsh wetland system located in the coastal plain of North Carolina (Stone et al., 2002). Mean weekly air temperatures ranged from -3 to 21 °C during the 1-year study.

The rate constants (K_{20}) for TP ranged from 1.1 to 1.7 m/year for the marsh-pond-marsh wetland system studied (Tables 3 and 4). These rate constant values were much lower than those reported in Kadlec and

Table 4
Rate constant (K_{20}) and dimensionless temperature coefficient (θ) calculated simultaneously using the excel solver routine to minimize sum of squares between observed and predicted outflow concentrations

	C^* assumed ^a			$C^* = 0$	
	K_{20} (m/year)	θ	C^* (mg/L)	K_{20} (m/year)	θ
TN	4.45	1.04	10	4.02	1.04
NH ₄ -N	4.53	1.06	3	4.35	1.06
TP	1.67	1.03	2	1.61	1.03

^a C^* assumed from Knight et al. (2000).

Knight (1996) and Reed et al. (1995). Their values from the analyzed databases ranged from 2 to 24 m/year with a mean of 12 m/year, and Reed et al. (1995) suggested a value of 10 m/year. Our data were on the lower end of their range of values. The data from this project had a much higher loading rate of TP than many of those reported in the references. Stone et al. (2002) calculated similar rate constants for a continuous marsh wetland in the NC coastal plain with similar high TP loading rates. This suggests that an alternative method of phosphorus removal should be investigated.

The marsh-pond-marsh constructed wetlands were less efficient in treating swine lagoon wastewater than continuous marsh wetlands (Hunt et al., 2002). Poach et al. (2004a) measured ammonia volatilization from both the marsh and pond sections of these wetlands. They found that the marsh sections had relatively low volatilization while at higher loading rates the pond sections had high rates of ammonia volatilization. The original intent of the pond section was to enhance nitrification (Hammer, 1994; Reaves, 1996). Subsequent research on marsh-pond-marsh wetlands has found that marsh-pond-marsh wetlands did not improve N removal compared to continuous marsh wetlands (Poach et al., 2004b).

4. Conclusions

Marsh-pond-marsh constructed wetlands at the North Carolina A&T University swine farm near Greensboro, North Carolina were evaluated for treatment of swine lagoon effluent. Overall, these constructed wetlands were effective in treating nitrogen from swine lagoon wastewater. Mean TN and NH₄-N concentration reductions were 35 and 25%, respectively.

The constructed wetlands were not very effective in treating phosphorus. Overall TP concentration reduction was 8%. To accomplish more efficient removal of P in the wetland systems, additional treatment would be required either pre- or post-wetland.

The calculated regression equations to predict outflow concentration from inflow concentration and hydraulic loading rate were lower than those in the literature. They predict less treatment in the marsh-pond-marsh wetlands than those from the literature database.

Rate constants for the first-order rate equation ($k-C^*$ model) developed by Kadlec and Knight (1996) were determined for nutrient treatment (TN, $\text{NH}_4\text{-N}$, and TP) in the marsh-pond-marsh constructed wetlands treating swine lagoon effluent in eastern North Carolina. The calculated rate constants were generally much lower than those reported in the limited literature. Use of our calculated rate constants and parameters would result in a more conservative design and require a larger wetland area.

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