Paper No. 00-4148
An ASAE Meeting Presentation

CONSTRUCTED WETLAND DESIGN AND PERFORMANCE FOR SWINE LAGOON WASTE WATER TREATMENT

by

K. C. Stone, P. G. Hunt, A. A. Szogi

USDA-ARS
Coastal Plains Soil, Water, and Plant Research Center
Florence, SC

and

F. J. Humenik, and J. M. Rice

North Carolina State University
Raleigh, NC

Written for Presentation at the
2000 ASAE Annual International Meeting
Sponsored by ASAE

Midwest Express Center
Milwaukee, Wisconsin
July 9-12, 2000

Summary:
Constructed wetlands are being considered as components of alternative technologies for animal wastewater treatment. An investigation was initiated to determine the effectiveness of using constructed wetlands to treat swine wastewater and to provide recommendations for their design. The constructed wetlands were effective in treating Total Nitrogen and Ammonia-N with treatment efficiencies >75%. They were not as effective in treatment of Total Phosphorus. Design parameters were calculated based on first-order area-based uptake equations. First-order area-based rate constants were calculated and found to be in close agreement with those in the literature.

Keywords: Constructed Wetlands, Total Nitrogen, Ammonia, Phosphorus

Constructed Wetland Design and Performance for Swine Lagoon Wastewater Treatment

K. C. Stone, P. G. Hunt, A. A. Szogi, F. J. Humenik, and J. M. Rice

INTRODUCTION

Constructed wetlands have been identified as a potentially important component for treatment of animal wastewater. They have been used for many years in municipal wastewater treatment. In the late 1980's, interest began to increase for using constructed wetlands for animal wastewater treatment. The technical requirements were based mainly on municipal systems and limited data on animal waste systems. The majority of constructed wetlands for treatment of animal waste have been installed since 1989 (Payne Engineering, 1997). Constructed wetlands were originally thought to be able to produce a dischargeable effluent. However, concern for the environment and discharge regulations have precluded this approach. Constructed wetlands are used to reduce the nutrient loading of wastewater water spray fields. This is an important concern where land for application is limited or nutrient production exceeds the plant requirements for that geographical area (Barker and Zublena, 1995).

The USDA-Natural Resources Conservation Service (1991) constructed wetland design guidelines for animal waste treatment were mainly based on BOD_5 loading to the wetlands (Presumptive Method). Guidelines stated minimum levels of BOD_5 and ammonia-N exiting the wetland. The NRCS method also recommended a residence time of at least 12 days. NRCS cautioned that their design guidelines were preliminary and they would be modified as more information on using constructed wetlands for animal waste became available.

A more physically based approach was presented by both Reed et al. (1995) and Kadlec and Knight (1996). Both design 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. Their rate constant 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 it is not dependent on the depth or porosity of the wetlands.

Payne (1997) compared both the Reed et al. (1995) and Kadlec and Knight (1996) design methods. He 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 (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. They were installed in 1992 as part of a Water Quality Demonstration Project (WQDP) in the Cape Fear River Basin, Duplin County, NC (Stone et al., 1995). Aspects of their performance has been discussed by Hunt et al. (1994), Szogi et al. (1995), Hunt et al. (1999), and Szogi et al. (2000). The objective of this paper was to examine the various design approaches in relation to their performance to these wetlands.

METHODS

The wetland system consisted of six 3.5- x 33.5-m wetlands, constructed in Duplin County, NC, in 1992. The systems were designed by the Natural Resources Conservation Service (NRCS) and were constructed by the NRCS and Murphy Farms, Inc. as part of the USDA Water Quality Demonstration Project. The cells were excavated and the bottoms and sidewalls were lined with 0.3-m clay and covered with 0.25 m of loamy sand topsoil. The cells were arranged into three parallel sets of two end-to-end connected cells. The lengthwise slope of the wetland cells was approximately 0.2% and a water level of 0.15 m was maintained at the outlet of the cell. Four wetland cells were planted with natural vegetation in 1992. The wetland cells 1 and 2 contained rush and bulrushes. The wetland cells 3 and 4 contained bur-reed and cattails. Cells 5 and 6 were designed to experiment with agronomic crops and was discussed in Szogi et. al. (2000) (data not discussed in this paper).

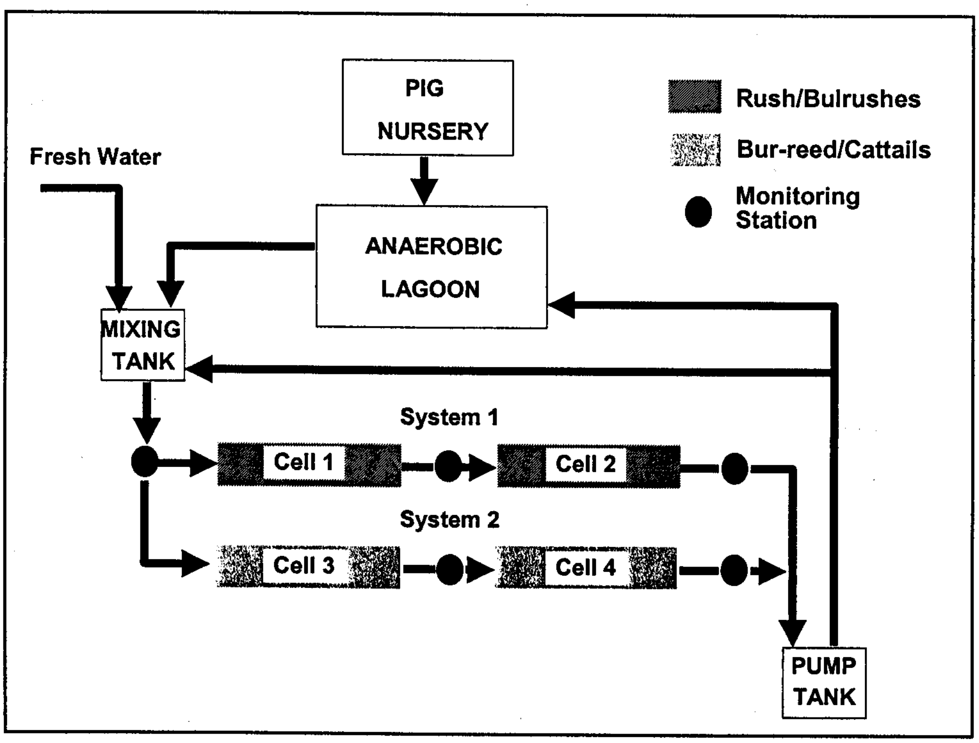

Figure 1. Schematic of constructed wetlands configuration and layout.

Initially, to prevent possible damage to the wetland plants, the lagoon effluent was diluted 10-fold to provide a target nitrogen loading rate of 3 kg/ha/day. Later, after determining the plants in the system could receive effluent with greater ammonia concentrations, the wetlands were loaded at higher nitrogen loading rates ranging from 8 to 25 kg/ha/day. The wetland cells were loaded using an automated system with float control valves in the dilution mixing tank.

Flow into and out of the wetland cells was measured using V-notch weirs and six PDS-350 ultrasonic open-channel flow meters (Control Electronics, Morgantown, PA). Later, tipping bucket samplers were placed in the wetland cells as a check and backup flow measurement method. An automated wastewater sampler was installed to measure wastewater inflow, and six samplers were installed to measure wastewater at the outlets of each cell. The automated samplers initially combined hourly samples into a 3.5-day composite. Later, the automated samplers were programmed to collect a 7-day composite.

Wastewater samples were analyzed for Total Nitrogen (TN), Total Keldahl Nitrogen(TKN), Ammonia-Nitrogen (NH_4-N), Nitrate-Nitrogen (NO_3-N), Total Phosphorus (TP), and Ortho-Phosphorus (PO_4-P). The samples were analyzed according to USEPA recommended methodology using a TRAACS 800 auto analyzer.

Statistical Analyses

Statistical analyses on the constructed wetland data were performed using the SAS system (SAS, 1990). A regression analysis was performed to determine if any significant relationships existed between inflow and outflow concentrations to the wetlands.

Wetland Design Analysis

Design of wetlands for animal waste treatment was originally derived from municipal treatment wetlands (Kadlec and Knight, 1996). Constructed wetland design has typically been approached as a first-order rate equation based on plug flow assumptions. The most popular approach in design has been presented by Kadlec and Knight (1996) as

$$\left[\frac{C_{out} - C_{\bullet}}{C_{in} - C_{\bullet}}\right] = \exp(-\frac{K_T}{q}) \qquad (1)$$

where C_{out} = the outflow concentration,
C_{in} = the inflow concentration,
$C_{\bullet}$ = the background concentration,
q = the hydraulic loading rate,
K_T = the rate constant adjusted for temperature.

$$K_T = K_{20}\theta^{(T-20)} \qquad (2)$$

K_{20}= the rate constant at 20° C,
θ = dimensionless temperature coefficient,
T = the temperature.

The hydraulic loading rate is defined as

$$q = \frac{Q_{ave}}{A}$$

where

$$Q_{ave} = \frac{Q_{in} + Q_{out}}{2}$$

The temperature-related rate constant for TN and NH_4-N from the wetland data was calculated rearranging equation (1) as

$$K_T = \frac{Q}{A}\log\left[\frac{C_{in} - C_*}{C_{out} - C_*}\right] \qquad (5)$$

Equation (2) was then rearranged in order to calculate the K_{20} rate constant at 20°C and the dimensionless temperature coefficient

$$\log(K_T) = \log(K_{20}) + \log(\theta)(T - 20) \qquad (6)$$

Total Phosphorus rate constant was calculated based on equation (5). The TP rate constant is not considered a function of temperature.

RESULTS

The constructed wetlands in Duplin County, NC, have been in operation since 1993. During this time, target TN loading rates have been increased from an initial loading rate of 3 kg/ha/day to a high target rate of 25 kg/ha/day (Rice et al., 1999). The mean loading rate over the entire evaluation period was ~13 kg/ha/day with the yearly loading rates ranging from ~5 kg/ha/day to ~50 kg/ha/day. The actual loading rates varied from target rates due to rainfall and occasional malfunctions in the pumping system delivering lagoon effluent to the wetland cells. Inflow TN concentrations increased from a mean initial year concentration of ~35 mg/L to ~250 mg/L for the greater loading rates. Corresponding outflow TN concentrations varied from ~2 mg/L to ~74 mg/L. Concentration reduction efficiencies ranged from 92% at the lower TN loading rate to 70% at the greater loading rates. The overall concentration reduction efficiency for the entire 1993-1999 operation of the wetlands was from 78 to 81%. Figure 2 shows that the TN concentration reductions for the wetland system 1 were consistently between 75 and 100%.

Much of the TN inflow into the wetlands consisted of Ammonia-N (NH_4-N). The NH_4-N loading rate ranged from 3.8 to 44 kg/ha/day. Inflow NH_4-N concentrations were initially ~30 mg/L and increased with the increased loading rate to ~ 220 mg/L. Outflow NH_4-N concentrations were initially ~2 mg/L and increased to ~55 mg/L at the higher loading rates. The overall concentration reduction for the entire study was ~81%. At the lower loading rates, the concentration reduction efficiencies were ~92-95%. Concentration reduction efficiencies at the higher loading rates were ~74%.

Total Phosphorus (TP) loading of the wetlands ranged from ~1 kg/ha/day initially to ~11 kg/ha/day at the higher TN loading rates. The TP concentration entering the wetlands at the lower loading rate was ~7 mg/L and ~57 mg/L at the higher loading rates. Initially, the wetlands were very effective at removing the TP. Initial TP outflow concentrations were from 1 to 2 mg/L. This provided an initial concentration reduction efficiency of 88%. At the higher loading rates, the outflow concentration increased to ~40 mg/L with concentration reduction efficiencies ranging from 6 to 35%. This is illustrated in figure 3. Initially, at lower loading rates, the concentration reduction was high, but as the input concentrations increased, the concentration reduction declined. It appears that the wetland system is not as effective in removal of TP as it is with nitrogen. To accomplish more efficient removal of P in the wetland systems, pre/post treatment may be required.

Regression Analysis

The wetland data were log transformed for the analysis of regression of inflow and outflow concentrations (figures 4-6). The regressions of the wetland inflow and outflow were similar to those reported by Kadlec and Knight (1996). The regression coefficients (r^2)were <0.6 in most cases, indicating that other factors are influencing the results. Regressions adding the hydraulic loading rate to the inflow and outflow concentrations did not significantly increase the regression coefficients (>0.02). The hydraulic loading rates calculated were from 9 to 20 mm/day.

Rate Constants

The wetland data were analyzed to calculate the rate constants of TN, NH_4-N, and TP for the two wetland systems. The temperature-based rate constants were calculated using equation (5). The rate constants were calculated and then regressed against the temperature to determine the K_{20} rate constant and θ from equation (6). In table 1, K_{20} and θ are shown for TN and NH4-N for the two wetland systems studied. There was little difference among the individual constitutes across the two wetland systems. These results compare favorably with those from Kadlec and Knight (1996) and Reed et al. (1995). The NRCS field test method suggests using a K_{20} of 14 m/yr for TN and 10 m/yr for NH_4-N. We calculated TN K_{20} values of 11-13 m/yr and NH_4-N K_{20} values of 10-12 m/yr. In our analysis, we assumed that minimal ammonia volatilization occurred based on the pH of the effluent. Current research is underway to quantify the ammonia volatilization from these constructed wetlands. If volatilization is shown to be a major component, the rate constants would have to be re-assessed. Pre-treatment of lagoon effluent at higher loading rates would be required.

Table 1. Regression parameters for the calculation of rate constants for the first-order area-based uptake design model.

	n	intercept	K_{20} (m/d)	K_{20} (m/yr)	slope	θ	r^2
TN System 1	369	-3.481	0.031	11	0.016	1.016	0.015
TN System 2	376	-3.339	0.035	13	0.021	1.021	0.024
NH_4-N System 1	360	-3.590	0.028	10	0.017	1.017	0.017
NH_4-N System 2	360	-3.457	0.032	12	0.020	1.020	0.021

The rate constants for TP were calculated based on equation (5). The K_T values for TP ranged from 42 to 44 m/yr for the two wetland systems studied. These rate constant values were higher than those from Kadlec and Knight (1996) and Reed et al. (1995). Their values from the analyzed data bases ranged from 2 to 24 m/yr with a mean of 12 m/yr, and Reed et al. (1995) suggested a value of 10 m/yr. The data from this project had a much higher loading rate of TP than those reported in the references. Also, after the first year, the efficiency of the wetlands for phosphorus treatment declined dramatically. This would suggest that an alternative method of phosphorus removal should be investigated.

CONCLUSIONS

Constructed wetlands were evaluated for treatment of swine lagoon effluent. The constructed wetlands were effective in treating Nitrogen. Total Nitrogen concentration reduction efficiencies ranged from 92% at the lower loading rates to 70% at the greater loading rates. The NH_4-N concentration reduction efficiencies were ~92-95% initially to ~74% at greater loading rates.

The constructed wetlands were not effective for treating Phosphorus. At low loading rates, initial TP concentration reduction efficiency was ~88%. However, at the higher loading rates, concentration reduction efficiencies decreased to 6-35%. To accomplish more efficient removal of P in the wetland systems, pre/post treatment may be required.

Parameters for the major design models were estimated from the constructed wetlands data, and were in close agreement with those from the literature for TN and NH_4-N. Design parameters for TP were calculated, but they were higher than those reported in the literature.

REFERENCES

Barker, J. C., and J. P. Zublena. 1995. Livestock manure nutrient assessment in North Carolina. p. 98-106. *In* Proceedings of the Seventh International Symposium on Agricultural Wastes. Chicago, IL. June 18-20, 1995. ASAE Pub. 7-95, St. Joseph, MI.

Hunt, P. G., A. A. Szogi, F. J. Humenik, J. M. Rice, and K. C. Stone. 1994. Swine wastewater treatment by constructed wetlands in the southeastern United States. *In* DuBowy, P. J., and R. P. Reaves (eds.) Proceedings of Constructed Wetlands for Animal Waste Management Workshop, Purdue University, Lafayette, IN, pp. 144-154.

Hunt, P.G., A.A. Szogi, F.J. Humenik, J.M. and Rice. 1999. Treatment of animal wastewater in constructed wetlands. pp. 305-313. In Proc. of the poster presentations of the 8th Int'l. Conf. on the FAO ESCORENA Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture. 26-29 May 1998, Rennes, France.

Kadlec, R. H., and R. L. Knight. 1996. Treatment Wetlands. Lewis Publishers, Boca Raton, FL. 893 p.

Payne Engineering and CH2M Hill. 1997. Constructed wetlands for animal waste treatment. Report prepared for the EPA's Gulf of Mexico Program; pub. Alabama Soil and Water Conservation Committee, Montgomery, AL.

Reed, S. C., R. W. Crites, and E. J. Middlebrooks. 1995. Natural Systems for Waste Management and Treatment. Second edition. McGraw-Hill, NY.

Rice, J. M., A. A. Szogi, F. J. Humenik, and P. G. Hunt. 1999. Long term data for constructed wetlands for swine wastewater. Third National Workshop on Constructed Wetlands/BMPs for Nutrient Reduction and Coastal Water Protection. June 9-12, 1999, New Orleans, LA. Waste Management Program Office, NC State University, Raleigh, NC.

SAS. 1990. SAS version 6.07. SAS Institute, Cary, NC.

Stone, K. C., P. G. Hunt, S. W. Coffey, and T. A. Matheny. 1995. Water quality status of a USDA water quality demonstration project in the eastern Coastal Plain. J. Soil and Water Cons. 50(5):567-571.

Szogi, A.A., P. G. Hunt, F.J. Humenik, K. C. Stone, and J. M. Rice. 1995. Constructed wetlands for swine wastewater treatment in the eastern Coastal Plain, USA. p. 675-682. *In* K. L. Campbell (ed.) Versatility of Wetlands in the Agricultural Landscape, September 17-20, Tampa, FL. ASAE, St. Joseph, MI.

Szogi, A.A., P. G. Hunt, and F. J. Humenik. 2000. Treatment of Swine Wastewater using a saturated-soil-culture soybean and flooded rice system. Trans. of ASAE 43(2):327-335.

USDA Natural Resources Conservation Service. 1991. Constructed wetlands for agricultural wastewater treatment, technical requirements. Washington, DC.

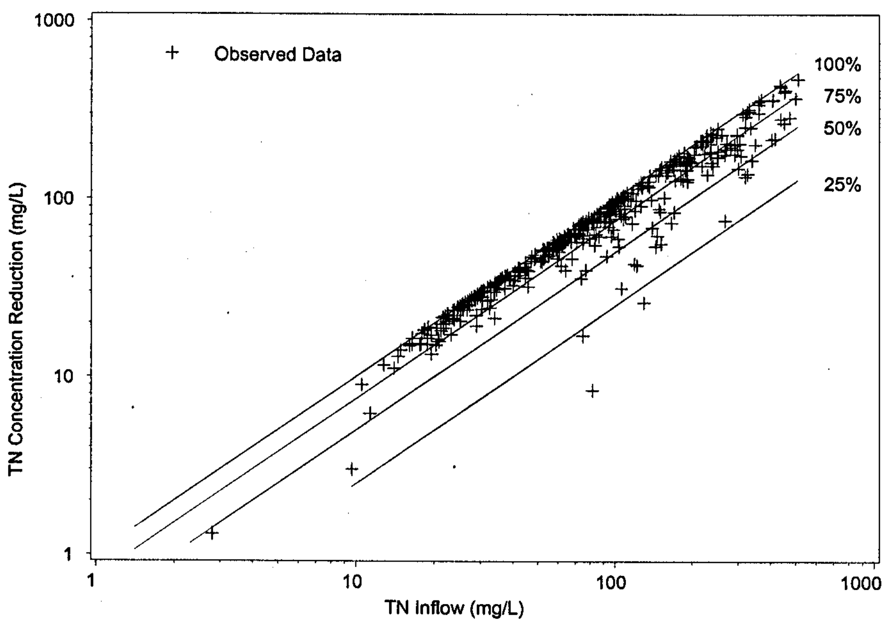

Figure 2. Total nitrogen concentration reduction.

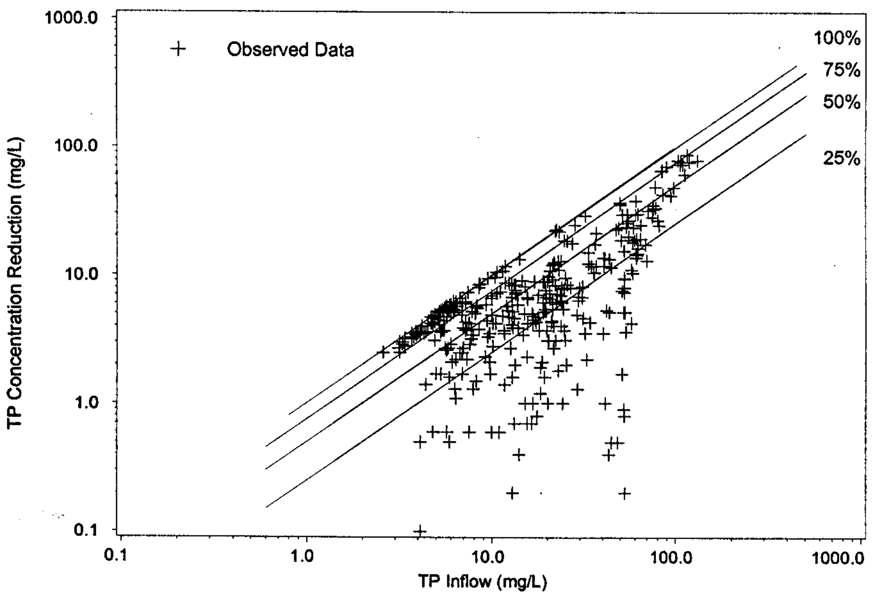

Figure 3. Total phosphorus concentration reduction.

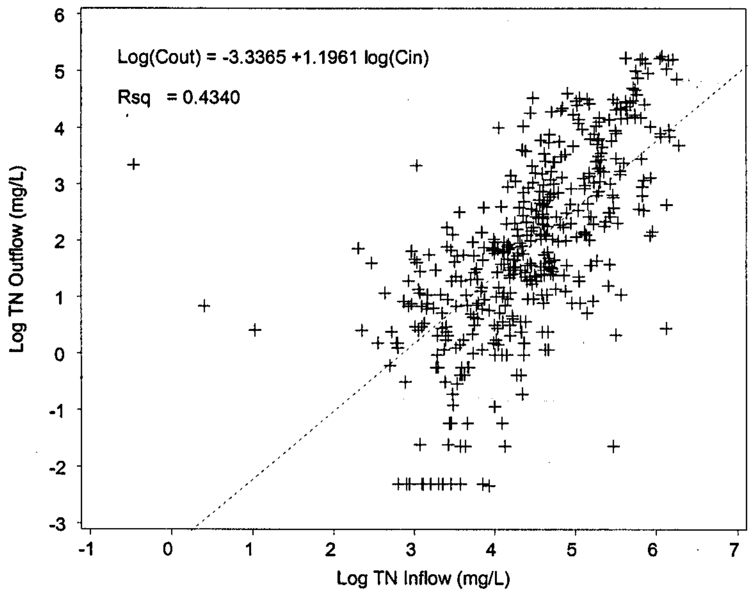

Figure 4. Regression of total nitrogen inflow and outflow.

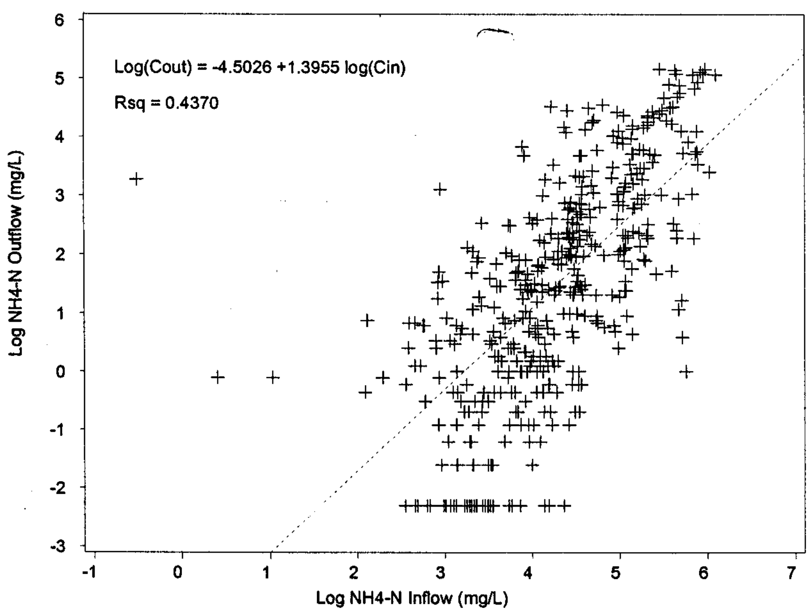

Figure 5. Regression of ammonia-N inflow and outflow concentrations.

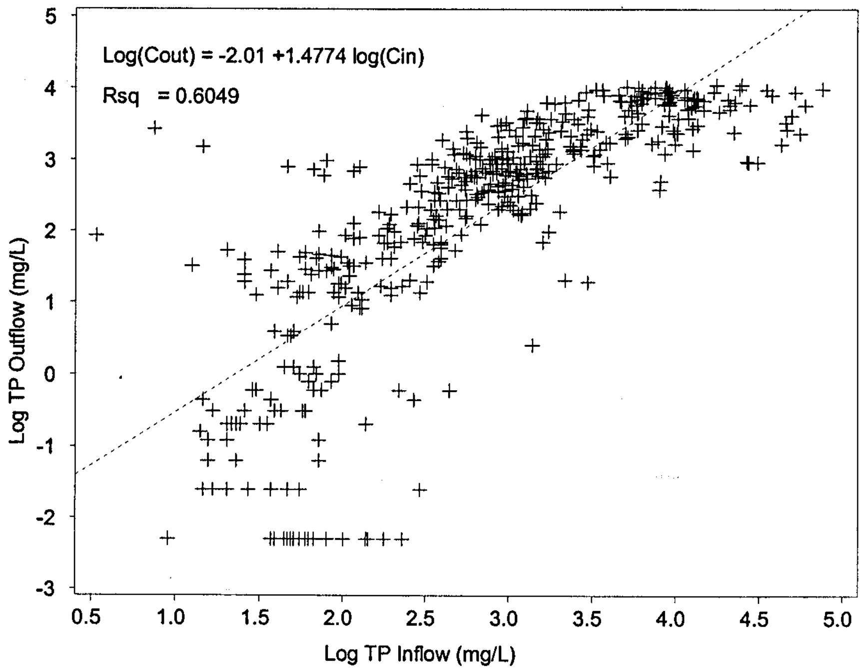

Figure 6. Regression of total phosphorus inflow and outflow concentrations.