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Development of Design Criteria for Denitrifying Treatment Wetlands

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DEVELOPMENT OF DESIGN CRITERIA FOR DENITRIFYING TREATMENT WETLANDS

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1.0 Introduction

Subsurface wetlands are well suited for on-site applications because they provide odor and vector control and they mitigate public access issues (U.S. EPA, 1993). Artificial subsurface wetlands are typically designed with an inert rock medium, can be either planted or unplanted, and are designed so that the water flows below the surface of the wetlands through the porous medium. The medium provides a surface area for the growth of bacterial films but inhibits the carbon cycling from plant debris because the packing material prevents the plant debris from reaching the water. As a result, subsurface wetlands are only marginally successful at removing nitrogen from wastewater. The nitrogen removal that does occur is the result of plant assimilation and microbial denitrification that utilizes any remaining carbon source in the influent and from plant decay (Kadlec and Knight, 1996). To increase the denitrification performance, an alternative carbon source is required. Gersberg et al. (1983) demonstrated that the addition of carbon, in the form of methanol, stimulated bacterial denitrification and increased nitrate removal efficiencies to 95%.

Based on previous research, it has been found that a variety of organic solids can be used simultaneously as media and as a carbon source to support the denitrification process. These include plant biomass (Gersberg et al., 1983), cotton burr and mulch compost (Su and Puls, 2007), wheat straw (Aslan and Turkman, 2003), sawdust (Robertson and Cherry, 1995; Schipper et al., 1998), and woodchips (Healy et al., 2005; Robertson et al., 2009). Schipper et al. (1998) demonstrated that porous groundwater treatment walls amended with sawdust were successful in removing nitrate from contaminated groundwater. Robertson et al. (2005) demonstrated that the proprietary Nitrex filters, which utilize a nitrate reactive material, produced septic tank effluent nitrate removal rates of up to 96%, remaining effective for at least five years, but removal rates were diminished during the winter months. The temperature of the water in a wetland system can significantly affect the rate of denitrification (Kadlec and Knight, 1996). The use of a readily available organic medium in a constructed subsurface wetland as a method for denitrification of nitrified septic tank effluent has not been investigated.

2.0 Methodology

The pilot facility used in this study consisted of a septic tank, a fixed media nitrification system, and various experimental subsurface flow wetlands. Wastewater used in the study was diverted from the influent to the University of California Davis Wastewater Treatment Plant (UCD WWTP). The septic tank was a conventional design with a nominal volume of 7.5 m^3. The fixed media nitrification system consisted of three parallel single pass units that utilized a synthetic textile media (Orenco Systems, Inc.) and employed natural ventilation for oxygen transfer. The nitrified effluent was collected in a pump tank and evenly distributed to six subsurface wetlands using water meters and throttling gate valves.

Six different subsurface wetlands were constructed to study the effect that media type, time of operation, and aquatic plants (typha spp.) have on the removal of nitrate. The subsurface wetlands were rectangular fiberglass tanks (3 m long, 1 m high and 0.6 m wide). The inlet structure for the wetlands was designed to allow the nitrified wastewater to be distributed evenly along the height of the tank, as presented in Figure 1. To investigate the effect of medium type, four of the wetlands were filled with readily obtained recycled pallet woodchips (Waste Management, Inc.) with particle lengths ranging from 1.3 to 15.2 cm, with an average thickness of 0.63 cm. The other two wetlands were filled with gravel classified as 1.9 cm clean crushed rock. To investigate the effect of time of operation, two of the woodchip filled wetlands were placed in operation in July 2007 (but not monitored) and the other four wetlands were put into operation in June 2008. To investigate the effect of the presence of aquatic plants, three of the wetlands (a woodchip wetland placed into operation in 2007, a woodchip wetland placed into operation in 2008, and a gravel wetland) were planted with cattails at the time of startup and the remaining three wetlands were left unplanted. The configurations of the wetlands are shown in Figure 2. A summary of the design information is presented in Table 1. Each wetland received 0.6 m^3/day of nitrified effluent, which resulted in a theoretical hydraulic detention time (HDT) of 0.9 days and 2.1 days for the gravel and woodchip wetlands, respectively.

Influent and effluent grab samples were collected from each of the wetlands and were analyzed for temperature, nitrate, and nitrite. The temperature was measured in the field using a Myron L handheld meter. The latter parameters were measured using Ion Chromatography [DIONEX LC20 Chromatography Enclosure, DIONEX ION Pac AS14A 4X250 mm Analytical (ANION)]. Periodically, ammonium ion and total kjehldahl nitrogen were measured in accordance with Standard Methods to ensure that the wetland influent was completely nitrified. BOD_5 was measured in accordance with Standard Methods to evaluate effluent water quality.

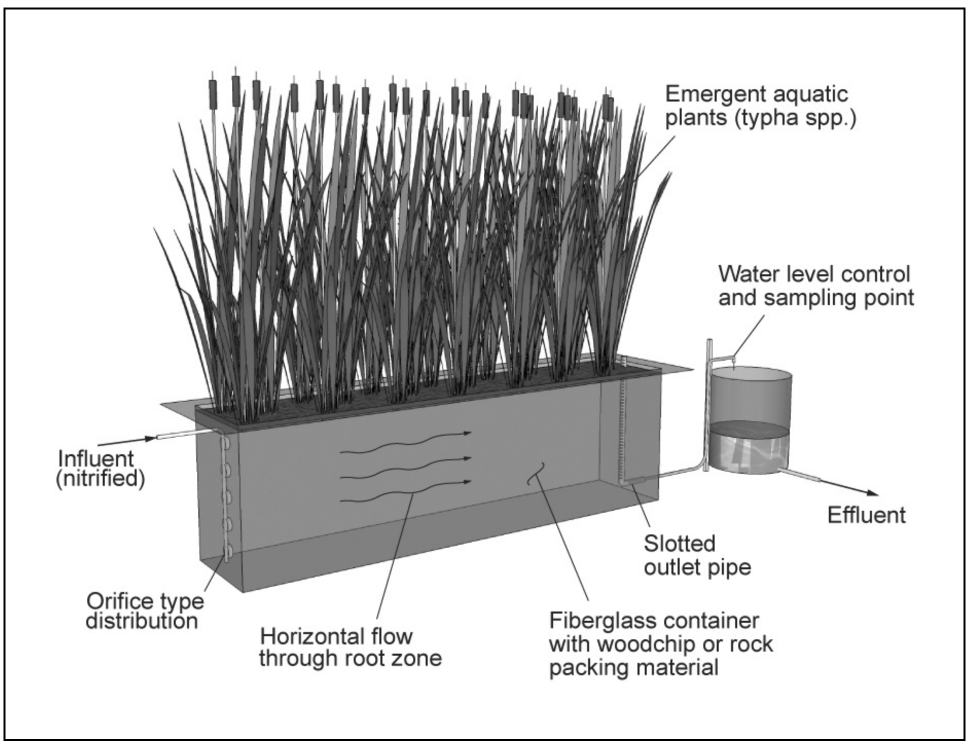

Figure 1. Schematic of Experimental Constructed Wetland.

During the first three months of operation, influent and effluent grab samples were collected twice a week from each wetland. After this period, each wetland was typically sampled at least once a week. Grab samples were also collected periodically along the length of each wetland to determine nitrate removal profiles. Intermediate samples were obtained using tree watering stakes (PVC pipe sections with perforated ends) inserted in the media with the perforated section at mid-depth, and samples were withdrawn using a hand pump.

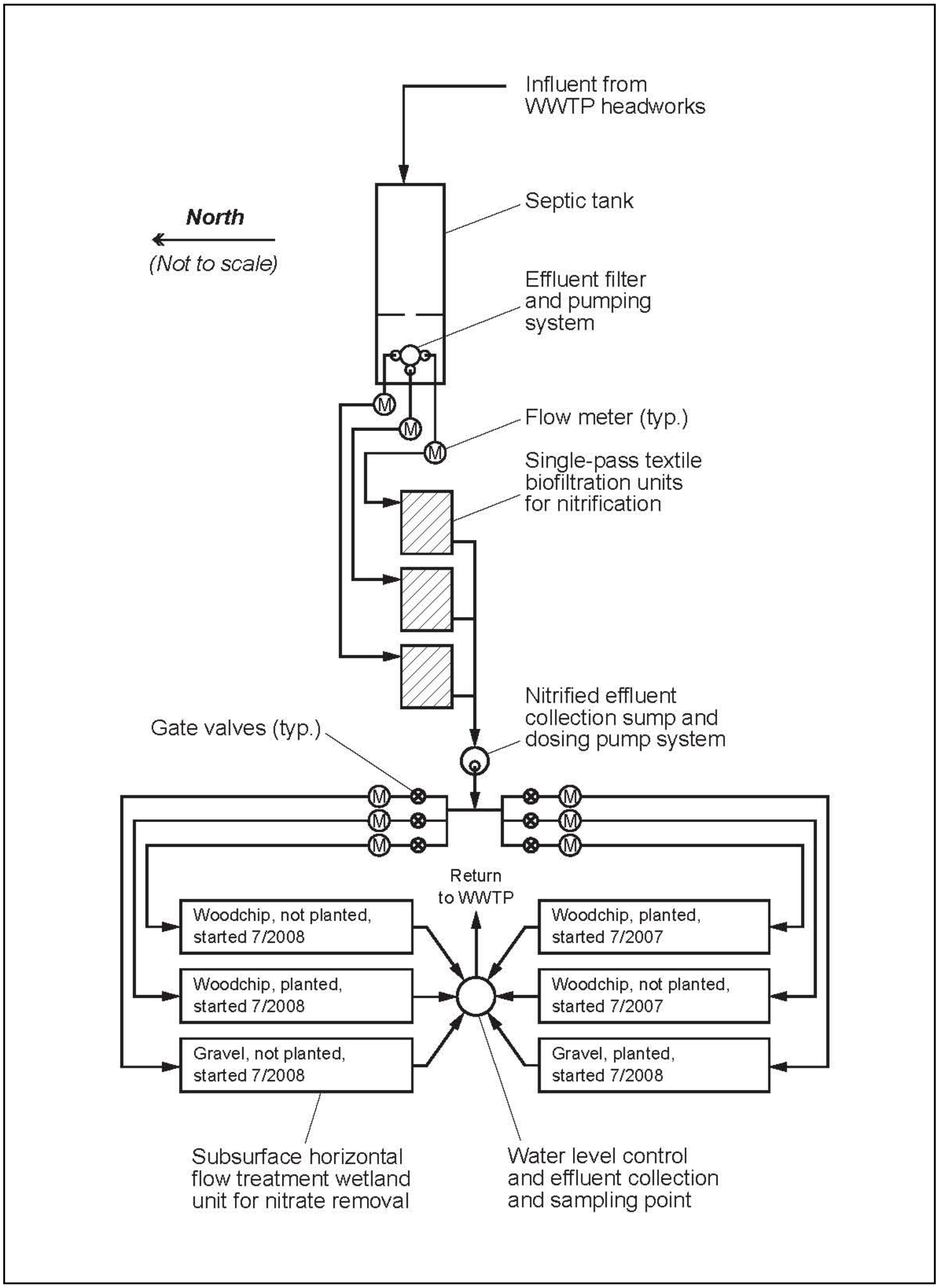

Figure 2. Schematic of Pilot System.

Table 1. Summary of Wetland Design Information.

Wetland	Date Initiated	Planted	Media Type	Abbreviation
1	7/2008	Yes	Gravel	G, P, 08
2	7/2008	No	Gravel	G, UP, 08
3	7/2007	Yes	Woodchip	W, P, 07
4	7/2007	No	Woodchip	W, UP, 07
5	7/2008	Yes	Woodchip	W, P, 08
6	7/2008	No	Woodchip	W, UP, 08

3.0 Results and Discussion

A summary of the primary research findings are presented below.

Performance of Nitrifying Filters. During the fall and winter, effluent grab samples from the septic tank and nitrifying filters were analyzed for TKN and ammonium ion. In the fall, the average TKN and ammonium ion concentrations in the septic tank effluent were 18 and 1 mg/L, respectively. The fall nitrifying filter effluent average TKN and ammonium ion concentrations were 1 and 0.19 mg/L, respectively. In the winter, the average TKN and ammonium ion concentrations in the septic tank effluent were 30 and 24 mg/L, respectively. The winter nitrifying filter effluent average TKN and ammonium ion concentrations were 2.6 and 1.4 mg/L, respectively. The nitrifying filter effluent nitrite concentrations were non-detectable throughout the study. Based on the TKN, ammonium ion and nitrite data, near complete nitrification was occurring throughout the study.

Nitrate Removal Performance. The influent temperature profile, shown in Figure 3A, varied from 22 to 30^{o}C (degrees Celsius) during the first four months of operation. In November, the influent temperature began to decrease reaching a low of 11^{o}C. The wetland effluent temperatures were typically 3 to 5^{o}C below the influent temperature.

The influent concentration of nitrate to the constructed wetlands is shown in Figure 3B. For the first four months of operation, the influent concentrations averaged 53 mg/L, after which the influent concentration increased to an average of 82 mg/L when the student population increased at the start of the academic year.

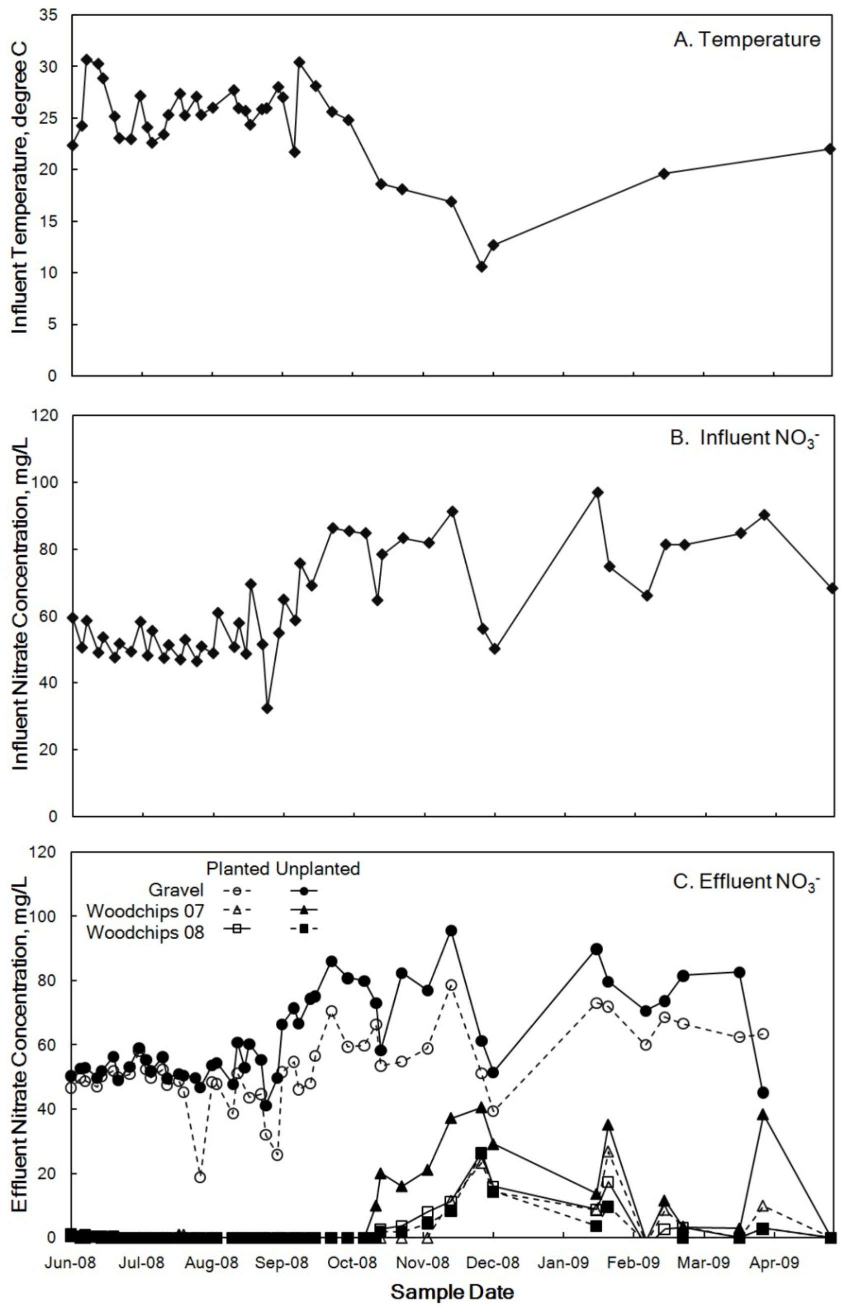

Figure 3. Influent Temperature and Influent and Effluent Nitrate Concentrations for Each Subsurface Wetland.

The effluent concentration of nitrate from each wetland is presented in Figure 3C. Nitrate removal in the unplanted gravel wetland (G, UP, 08) was negligible, approximately 5 to 10 mg/L (as nitrate), throughout the study. Removal in the planted gravel (G, P, 08) wetland for the first two months was 6%. However, as the study progressed, nitrate removal in the planted gravel wetland (G, P, 08) increased to approximately 20%. The observed nitrate reduction is likely associated with plant assimilation, which increased as the plants became established and covered the surface of the wetland after several months of operation.

Nitrate removal in all of the woodchip wetlands was high throughout the study, ranging from 80 to 100%. For the first five months of operation, the woodchip wetlands removed an average of 99.7% of the influent nitrate. When the influent nitrate concentration increased in October, the nitrate loading increased by approximately 150% and the woodchip wetlands continued to remove all nitrate. However, beginning in November, the removal rates began to decrease and the effluent nitrate concentration from the wetlands began to rise. This decrease in performance coincided with a decrease in the influent water temperature and may be attributed to decreased microbial activity at lower temperatures. Throughout the study, the nitrate removal performance of the woodchip wetlands resulted in effluent concentrations which were consistently below the U.S. EPA drinking water standard (10 mg/L NO_3^- as N or 44.2 mg/L NO_3^-).

As shown in Figure 3C, there was no significant difference in the effluent nitrate concentrations between the 2008 planted and unplanted woodchip wetlands (W, P, 08 and W, UP, 08), which indicates that the availability of carbon from the woodchips was not rate limiting in these wetlands. Similarly, for the first four months of operation there was no significant difference in the effluent concentrations between the planted and unplanted woodchip wetlands constructed in 2007 (W, P, 07 and W, UP, 07). However, in November when the temperatures began to decline, the unplanted woodchip wetland constructed in 2007 (W, UP, 07) exhibited higher effluent nitrate concentrations than the planted woodchip wetland constructed in 2007 (W, P, 07). This difference is attributed to a decrease in the amount of available carbon in the older wetlands combined with the beneficial compensating effects of plant assimilation in the planted wetland.

Nitrate Profiles. Nitrate profile data collected at varying influent nitrate concentrations and temperatures are presented in Figure 4. In each profile data set, the nitrate concentrations in the unplanted gravel wetland (G, UP, 08) reflect the absence of nitrate removal. Planting the gravel wetland (G, P, 08) consistently improved nitrate removal, but only slightly. This observation is consistent with the low overall nitrate removal for the planted and unplanted gravel wetlands (G, P, 08 and G, UP, 08) as shown in Figure 3.

The effect of influent nitrate concentration is evident when the profiles in 4A and 4B are compared. Both of these data sets represent similar high temperature conditions (25 and 29^{o}C, respectively) but different influent nitrate concentrations (52 and 69 mg/L, respectively). The data presented in 4B represent a higher removal rate than that presented in 4A, which is consistent with what would be expected at a slightly higher temperature. However, the increase in the mass loading associated with the data in 4B required a larger media volume (longer length) to achieve the same effluent quality.

The effect of temperature variation is evident when the profiles presented in 4B, 4C, and 4D are compared. These data sets were collected under similar influent concentrations (69, 66, and 72 mg/L, respectively) but at significantly different temperatures (29, 19, and 11^{o}C, respectively). The profile data reflects a decline in the nitrate removal rate with declining temperature. This temperature dependent removal relationship is consistent with lower microbial activity that would be associated with lower temperatures.

Nitrate Removal Rates. The nitrate profile data for the woodchip wetlands were analyzed to assess nitrate removal kinetics. The profile data presented in Figure 4 can be described with a first-order removal rate model ($r_A = -k\,[A]$, where k is the reaction rate constant and A is the concentration). The first-order removal constants are summarized in Table 2. As the temperature increased, the nitrate removal rate constant increased from a low of 0.33 d^{-1} for the unplanted 2007 wetland (W, UP, 07) at 11°C to a high of 4.10 d^{-1} for the planted 2008 wetland (W, UP, 08) profile data collected at 25-29°C. This temperature effect corresponds to a temperature coefficient of 1.14 to 1.21, respectively, as defined by $k_2 = k_1\theta^{T_2-T_1}$ (where k_1 and k_2 are the respective removal rate constants at temperatures T_1 and T_2 and θ is the temperature coefficient). Nitrate removal rate constants and the temperature coefficients were lower for the woodchip wetlands constructed in 2007.

Table 2. Summary of First-Order Reaction Rate and Temperature Coefficients for Woodchip Wetlands.

Wetland	k_{20} (d^{-1}) [a]	θ
W, P, 07	1.41	1.10
W, UP, 07	1.30	1.17
W, P, 08	2.61	1.10
W, UP, 08	2.28	1.17

[a]Assumed to be valid from 5 to 20°C

Biochemical Oxygen Demand. Influent and effluent concentrations of biochemical oxygen demand (BOD_5) for each wetland are shown in Figure 5. The influent BOD_5 concentrations were consistently less than 2 mg/L. The effluent BOD_5 concentrations of the planted and unplanted gravel wetlands (G, P, 08 and G, UP, 08) remained below 2 mg/L. For the woodchip wetlands constructed in 2008, the effluent BOD_5 concentrations were quite high (e.g., 120 mg/L) during the first month of operation, reflecting a significant release of readily available carbon from the new woodchips. The elevated effluent BOD_5 concentrations associated with the release of readily available carbon was also observed by Robertson et al., (2005) for the Nitrex system. Following the first month of operation, the effluent BOD_5 concentration decreased to less than 20 mg/L. The effluent BOD_5 concentrations in both the planted and unplanted woodchip wetlands constructed in 2007 (W, P, 07 and W, UP, 07) increased from the influent concentration of 2 mg/L to effluent values ranging from 10 to 20 mg/L. The increased BOD_5 concentrations observed in the effluent of the woodchip wetlands reflect the impact of unutilized carbon released from the woodchips.

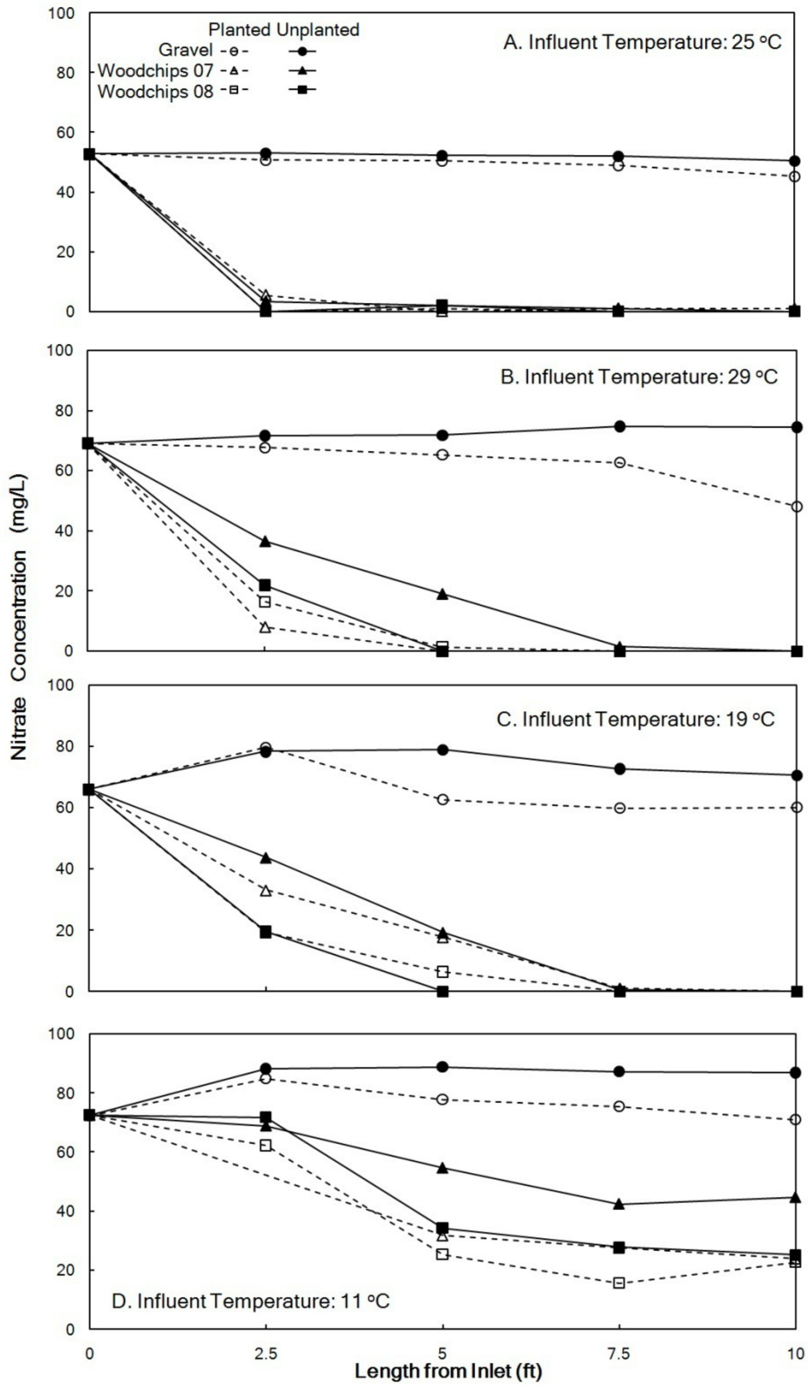

Figure 4. Nitrate (NO_3^-) Profile Along the Length of the Wetland on (A) 8/13/08, (B) 10/6/08, (C) 2/26/09, and (D) 12/12/08.

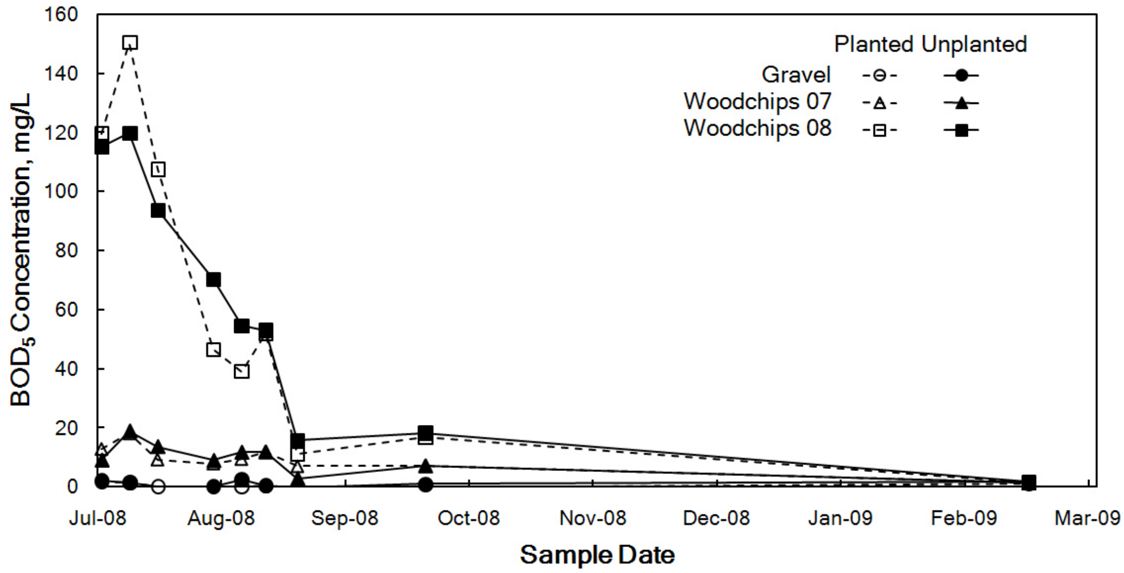

Figure 5. Effluent BOD_5 Concentration for Each of the Wetlands (influent BOD_5 was consistently less than 2 mg/L).

4.0 Conclusions

The purpose of this research was to evaluate the use of subsurface wetlands constructed with a readily obtained organic medium for the denitrification of domestic wastewater. Nitrate removal performance and the effects of concentration, temperature, length of operation, and aquatic plants were assessed. The following conclusions were drawn:

- Readily available woodchips were an effective source of the carbon for denitrification of nitrified septic tank effluent.
- In subsurface wetlands constructed with woodchips, high rates of nitrate removal were observed. Nitrate concentrations as high as 97 mg/L as NO_3^- (22 mg/L as N) were reduced to effluent concentrations below the U.S. EPA drinking water standard of 10 mg/L as N.
- The observed nitrate removal performance in submerged wetlands constructed with woodchips can be described with first-order reaction rate kinetics with rate constants (k_{20}) that varied from 1.30 to 1.41 d^{-1} and temperature coefficients that varied from 1.17 to 1.10 for unplanted and planted woodchip-media SSF wetlands, respectively, after two years in operation.
- Removal performance was independent of influent concentration because the nitrate removal reaction can be effectively described by a first-order kinetic model.
- Longer operation times for the woodchip wetlands resulted in lower first-order removal rate coefficients and temperature coefficients.

- Nitrate removal by plant uptake varied from 5 to 10 mg/L during the study, with increased removal occurring as plants became established in the wetlands.

5.0 Acknowledgments

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