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Performance of a Constructed Wetland for On-Site Wastewater Treatment

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ABSTRACT

A subsurface flow (SSF) constructed wetland system was operated in Lexington, Kentucky, to treat wastewaters from a single household. The system was monitored monthly for a period of 1 year for temperature, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD_5), total suspended solids (TSS), nitrate nitrogen (NO_3-N), ammonia nitrogen (NH_4-N), orthophosphate (PO_4 ion), and fecal coliform (FC) bacteria. It provided satisfactory reductions in concentrations of TSS, NH_4-N, and BOD_5. NH_4-N level in the septic tank was 86.67 mg/liter then dropped to 34.63 over the first 7 m of the bed and reached 10.76 mg/liter at the discharge end of the system (21.3 m). Over the same bed distance (21.3 m), counts of fecal bacteria were reduced about 99.93% but still averaged 811 colonies/100 ml, which exceeds the concentration of 200 colonies/100 ml of wastewater (reference level established by EPA) at the discharge end of the wetland system. Dissolved oxygen increased from 0.22 mg/liter in the septic tank to 1.91 mg/liter at the beginning of the wetland system, then fluctuated through the system to reach 1.32 mg/liter in the effluent discharge. There was no significant difference between the various regions of the bed for NO_3-N removal. The wetland system shows promise for a novel treatment process for removal of BOD, TSS, and pathogenic bacteria (FC) that can provide a sustainable solution for treatment of septic tank effluent. Further research work may lead to improvements in the system design to increase efficiency for removal of NO_3, NH_4 and PO_4.

INTRODUCTION

Steiner and Combs (1993) indicated the need for alternative wastewater treatment systems in Kentucky due to the vulnerability of Kentucky's groundwater to pollution. At least half of Kentucky's aquifer systems occur in karst regions, which make these aquifers highly susceptible to contamination from the surface (Anonymous 1994). The treatment of domestic sewage is a problem confronting small communities throughout the U.S. (Wolverton 1987a). A promising solution to this problem is an emerging technology using subsurface flow (SSF) wetland systems with plants for wastewater treatment.

SSF wetland systems have the capacity to remove a large percentage of the total nitrogen and other pollutants in wastewater (Gersberg, Elkins, and Goldman 1983) and to satisfy regulatory effluent criteria (EPA 1993). They can be installed in any suitable location proximal to the home, taking advantage of the land elevations. In SSF wetland systems, a major part of the treatment process for degradation of pollutants is attributed to the microorganisms living in a symbiotic relationship on and around root systems of the plants (Wolverton 1987b). During microbial degradation of pollutants, metabolites are produced which the plants absorb and utilize along with nitrogen, phosphorus, and other minerals as a food source. Microorganisms also use some or all metabolites released through plant roots as a food source. Recent advances in SSF wetland systems take advantage of high surface support media (such as rock-based filter beds) and their support of certain wetland plants with associated microbiota. The synergistic effect of this type of technology removes many of the substances contributing to BOD (e.g., NO_3, NO_2, NH_4, and PO_4 ions) from domestic sewage wastewaters. When plants such as cattail (*Typha latifolia*) are planted in the rock filter, their roots penetrate into the wastewa-

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ter, adding oxygen and producing an aerobic rhizosphere around the roots, thereby increasing biological activity.

An understanding of the effectiveness of the constructed SSF wetland treatment systems is the long-range goal of the present study, which provides an overview of preliminary characteristics important in considering treatment efficiency. Characteristics of the wastewater to be treated include BOD_5, TSS, nitrogen and phosphorus compounds, heavy metals, and microbial load (Wieder, Tchobanoglous, and Tuttle 1989). Currently, however, quality performance standards are based on BOD_5, TSS, and FC bacteria. Well-designed SSF wetland treatment systems typically can produce effluent water with BOD_5 values of 10 mg/liter and suspended solids concentrations below 10 mg/liter (Tchobanoglous 1987). A BOD_5 level of <20 mg/liter and TSS level of <20 mg/liter meet regulatory effluent criteria, according to current EPA regulations (EPA 1993).

The main objectives of the present study were to provide information on the treatment efficiency of an SSF constructed wetland used for single-home wastewater treatment. These monitoring data can be used to define the fate of wastewater constituents including their removal, retardation, transformation, and movement within the wetland system so that management decisions may be made regarding suitability of these systems for area installations and approval by the Health Department in Kentucky.

MATERIALS AND METHODS

A single-family dwelling (three-bedroom house of three people) in Lexington, Fayette County, Kentucky was studied as a model system. The wetland was a plastic-lined trench 21.34 m long, 1.22 m wide, and 0.46 m in depth. This type of SSF, commonly called a rock-plant filter, was developed by National Aeronautic and Space Administration (NASA) at the National Space Technologies Laboratory in Mississippi (Wolverton 1987b). The trench was partially filled with size 2 rock (crushed limestone) to a depth of ca. 0.36 m; the water level was maintained at 0.36 m; the trench was then covered with size 5 and 6 rock to a depth of 0.46 m. The inlet of the system was fed wastewater from the septic tank (Figure 1). Cattail (*Typha latifolia*) was planted. The estimated wastewater flow throughout the system was 1.36 m^3/day (360 gallon/day). Retention time in the SSF system was 4.39 days calculated on the basis of 360 gallons of wastewater flow throughout the system per day. Cattail rhizomes were planted in 1990, allowed to mature for several seasons, and were set out with one plant per each 0.37 m^2 of bed surface (70 plants were used for the system) for optimum efficiency (Gersberg, Elkins, and Goldman 1983).

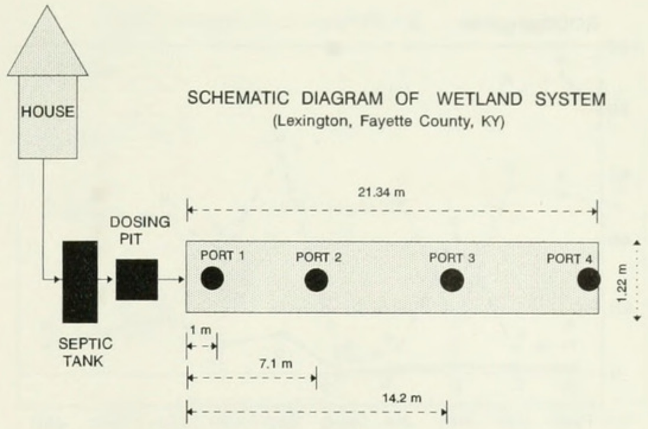

Figure 1. Schematic diagram of a subsurface flow (SSF) constructed wetland system for a three-bedroom house (Lexington, Fayette County, KY 1991). Note that sampling ports are 1 meter (port 1), 7.1 meter (port 2), 14.2 meter (port 3), and 21.3 meter (port 4) from the edge of the system.

The system was sampled three times over the course of a single day once a month from February 1991 to January 1992 (for technical reasons samples of April and June 1991 were not available for analysis). The samplings occurred in the morning, mid-day, and evening from fixed sampling ports throughout the system: the septic tank (ST), inlet port (port 1), two middle ports (ports 2 and 3, which represent 1/3 [7.1 m] and 2/3 [14.2 m] the system length, respectively), and the discharge end port (port 4).

The system was monitored monthly for temperature, pH, and dissolved oxygen (DO) in the field and analysed for biochemical oxygen demand (BOD_5) in the 5-day test, total suspended solids (TSS), nitrate nitrogen (NO_3-N), ammonia nitrogen (NH_4-N), orthophosphate (PO_4 ion), and FC bacteria. The water quality parameters of the collected samples were analysed at the Water Quality and En-

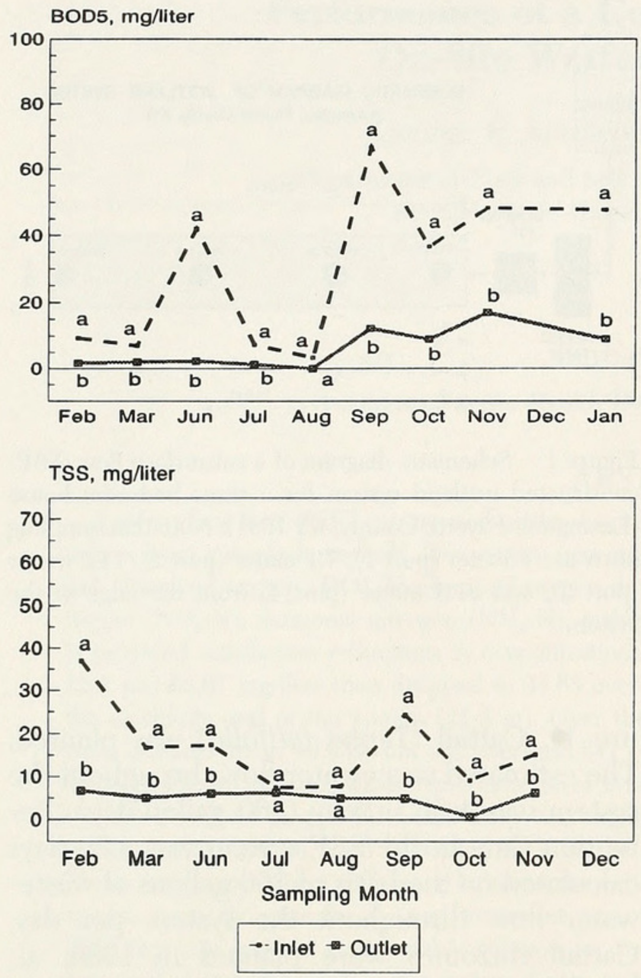

Figure 2. Mean concentration (n=30) of BOD_5 and TSS in influent and effluent wastewater from constructed wetland system for a three-bedroom house (Lexington, Fayette County, KY 1991) versus sampling month. Inlet and outlet concentrations having different letters are significantly different ($P<0.05$).

vironmental Toxicology laboratory at Kentucky State University using standard methods (APHA 1992). Ammonia (NH_4-N) was determined by the selective ion electrode method 4500-F; BOD_5, by method 5210-B; nitrate (NO_3-N), by method 4500-NO_3-E; orthophosphate, by method 4500-P-E; pH was determined by the electrometric method (method 4500-H); and total suspended solids, by method 2540-D.

FC bacterial analysis was carried out in the Lexington-Fayette Health Department Laboratory using the membrane filter standard method no. 9222 (APHA 1992). All samples were collected 13 cm above the bottom of system from each sampling port to avoid disturbing any sediment and were analysed within 6 hours.

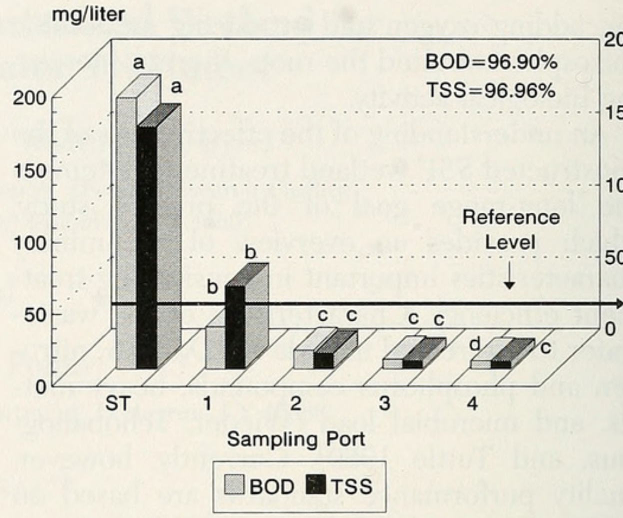

Figure 3. Concentration of BOD_5 and TSS (n=30) in wastewater from constructed wetland system for a three-bedroom house (Lexington, Fayette County, KY 1991) versus sampling port and septic tank (ST). Bars having different letters are significantly different ($P<0.05$).

Data were analysed for each parameter by port distance with respect to the septic tank and by sampling months using analysis of variance (ANOVA) procedure (SAS Institute 1991). Means (n=30) were compared using Fisher's protected LSD test (Snedecor and Cochran 1967).

RESULTS AND DISCUSSION

BOD_5 and TSS effluent values for the studied system during all sampling months were below the 20 mg/liter reference level, which is a common permit requirement (EPA 1993) (Figure 2). Overall BOD_5 average value dropped significantly ($P<0.05$) from 187.8 mg/liter in the septic tank (ST) to 5.7 mg/liter at the discharge of the system (port 4), which indicated an overall removal of 96.9% (Figure 3). TSS also dropped from 168.0 mg/liter (ST) to 5.10 mg/liter (discharge of the system), which indicated 96.9% removal (Figure 3).

Oxygen plays an important role for many changes in wastewater composition. One oxygen source in these wetland beds is roots of the cattails. Therefore, it is essential to bring the wastewater into direct contact with the root zone. Brix and Schierup (1990) indicated that oxygen may also be supplied as a result of air movement into the bed as the feedwater level falls during the flow-off period of an intermittent flow regime, and possibly as a result

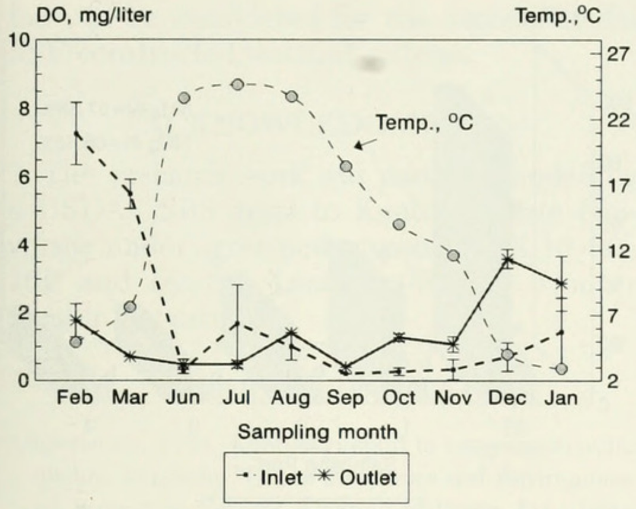

Figure 4. Dissolved oxygen (DO) concentrations in influent and effluent and temperature levels in wastewater from constructed wetland system for a three-bedroom house (Lexington, Fayette County, KY 1991). Vertical bars indicate ± standard error.

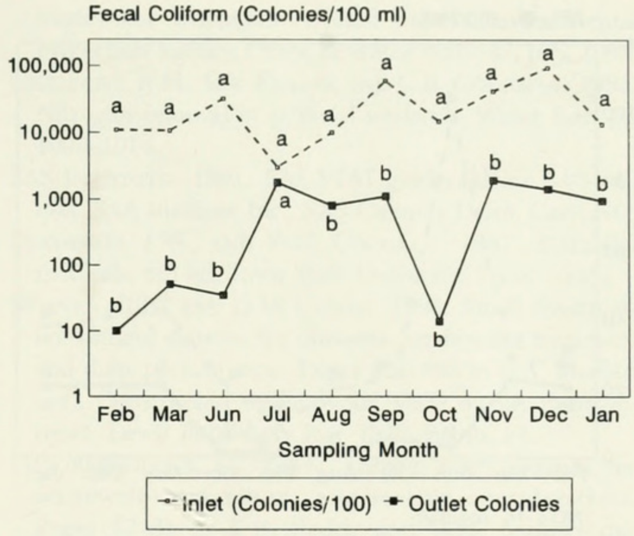

Figure 5. Mean counts of fecal coliform colonies (n=30) in influent and effluent wastewater from constructed wetland system for a three-bedroom house (Lexington, Fayette County, KY 1991) versus sampling month. Inlet and outlet counts having different letters are significantly different ($P<0.05$).

of flow around the gravel particles and through air-filled pores.

Average DO, pH, and temperature in the septic tank were 0.22 mg/liter, 7.96, and 10° C, respectively. These values showed significant variation throughout the system. The DO concentration in this system averaged 0.22 mg/liter in samples collected from septic tank and 1.32 mg/liter in port 4. The relationship between DO and temperature by sampling month is illustrated in Figure 4. DO level increased significantly ($P<0.05$) when temperature decreased (winter months).

Removal of FC bacteria is a concern of health officials (Wolverton 1987a). The system under study cannot satisfy the discharge requirements of FC removal, which often specifies <200 colonies/100 ml of wastewater (EPA 1993). Table 1 shows that the overall average counts of FC dropped from 1.2×10^6/100 ml wastewater in the septic tank to 0.8×10^3/100 ml at the end of the system (99.9% removal); but these remaining levels are still over the discharge requirements. FC counts in wastewater sampled from inlet and outlet versus sampling month (Figure 5) indicated significant differences.

Wetlands have the capacity to remove large percentages of total nitrogen in wastewater. Chemoautotrophic nitrifying bacteria, mainly *Nitrobacter* and *Nitrosomonas*, oxidize ammonia (NH_4) to nitrite (NO_2) and nitrate (NO_3), respectively. NO_3 and NO_2 are reduced by facultative bacteria to nitrous oxide (N_2O) and nitrogen gas (N_2) in the anaerobic denitrification process (Davido and Conway 1991). Oxygen consumption in this process is due to the direct microbial oxidation of organic mat-

Table 1. Impact of a constructed subsurface flow wetland system for three-bedroom house on some wastewater parameters[1] (Fayette County, Lexington, KY 1991).

Sampling port	Colonies/100 ml of water	Dissolved O_2 (mg/liter)	PO_4 (mg/liter)	pH	Temperature °C
Septic tank	1,200,000 ± 505,000a	0.22 ± 0.02c	—	7.96 ± 0.3a	10.0 ± 0.0d
Port 1	29,000 ± 21,200b	1.91 ± 1.46a	1.76 ± 0.70a	7.51 ± 0.2b	14.5 ± 8.5a
Port 2	12,000 ± 11,070b	1.40 ± 1.07b	1.77 ± 0.72a	7.46 ± 0.2b	13.9 ± 9.1b
Port 3	900 ± 811b	1.85 ± 1.18a	1.46 ± 0.91b	7.30 ± 0.1c	13.4 ± 9.3bc
Port 4	800 ± 717b	1.32 ± 0.94b	1.20 ± 1.10c	7.22 ± 0.2c	13.2 ± 8.7c

[1] Each value in the table is an average ±SE of 10 months analysis. Values within a column having different letters are significantly different from each other, using Fisher's protected LSD ($P<0.05$). Note that sampling ports are 1 meter (port 1), 7.1 meter (port 2), 14.2 meter (port 3), and 21.3 meter (port 4) from the edge of the system.

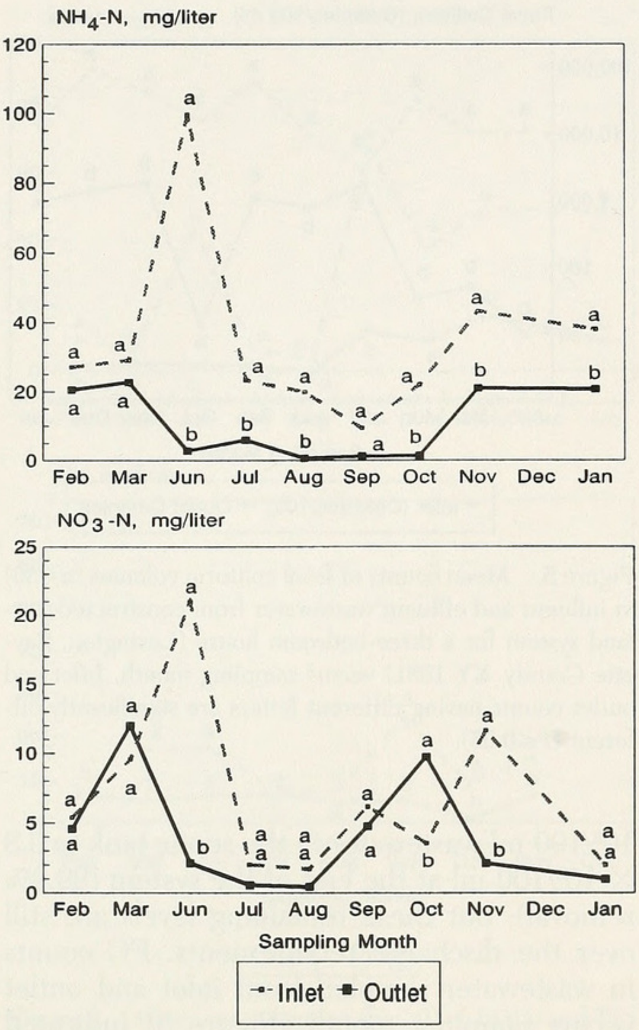

Figure 6. Mean concentration (n=30) of NH_4-N and NO_3-N in influent and effluent wastewater from constructed wetland system for a three-bedroom house (Lexington, Fayette County, KY 1991) versus sampling month. Inlet and outlet concentrations having different letters are significantly different ($P<0.05$).

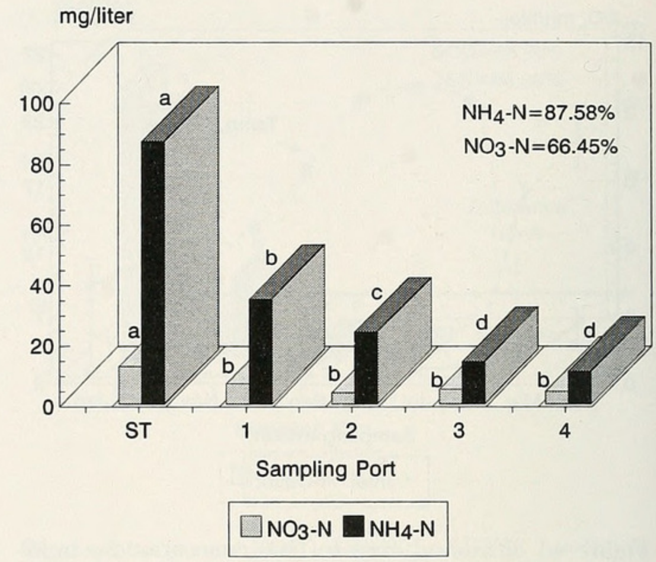

Figure 7. Levels of NH_4-N and NO_3-N (n=30) versus sampling port and septic tank (ST). Bars having the same letters are not significantly different ($P>0.05$).

ter and oxidation of reduced substances. Systems with good aeration will likely have most of the nitrogen in the nitrate form. Generally, levels of NH_4-N were significantly lower in wastewater effluent than in influent, as indicated in Figure 6. This decrease in NH_4-N level should be accompanied by an increase in NO_3-N level during the same sampling period if nitrification process is taking place properly in the system. But what is clear in Figure 6 is that NO_3-N level in effluent wastewater was equal to the level in the influent from January to March (2 to 7.5° C) and also from July to September (18 to 24.5° C). These findings indicated that the system was not effective in reducing nitrate.

Figure 7 shows that NH_4-N concentrations decreased from 86.7 mg/liter (septic tank) to all depths across the wetland system and reached 10.8 mg/liter at the discharge end of the system. This corresponds to 87.6% ammonia removal. On the other hand, the decrease in NH_4-N concentration should correspond with an overall NO_2-N and NO_3-N increase (Davido and Conway 1991) at all depths in the marsh. One may consider that the decrease in NH_4-N is due mainly to nitrification during aeration and that the decrease in NO_3-N is probably due to denitrification and absorption by wetland plants. Figure 7 indicates that NO_3-N was 12.4 mg/liter in the septic tank and then showed little variation throughout the system ranging from 6.7 mg/liter at the beginning of the system to 4.1 mg/liter at the system end with no significant differences.

Data obtained from the present study are start-up data; the system may not respond the same after several years of use. Generally, operation and maintenance of onsite systems are left to the homeowner. Maintenance of septic systems consists primarily of periodic pumping of the tank to remove the build-up of sludge in the tank. Many homeowners are not aware that septic tanks are designed to accommodate a particular daily water usage and that systems can malfunction from overload. Therefore, with increasing use of onsite systems, homeowner education and personal responsibility have to be considered for the success of the SSF constructed wetland systems.

ACKNOWLEDGMENTS

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