Available online at www.sciencedirect.com
SCIENCE @ DIRECT®
Ecological Engineering 20 (2003) 157–169
ECOLOGICAL ENGINEERING
www.elsevier.com/locate/ecoleng

Vegetation effects on fecal bacteria, BOD, and suspended solid removal in constructed wetlands treating domestic wastewater

A.D. Karathanasis *, C.L. Potter, M.S. Coyne

Agronomy Department, University of Kentucky, N-122K Ag. Science North, Lexington, KY 40546-0091, USA

Received 20 September 2002; received in revised form 18 February 2003; accepted 3 March 2003

Abstract

Constructed wetlands have emerged as a viable alternative for secondary treatment of domestic wastewater in areas with landscape limitations, poor soil conditions, and high water tables, which limit installation of full-scale adsorption fields. Existing information on the effects of macrophytes on treatment performance is contradictory and mostly derived from greenhouse mesocosm experiments. This study investigated the removal efficiency of fecal bacteria, biological oxygen demand (BOD), and total suspended solids (TSS) in 12 constructed wetlands treating secondary effluent from single household domestic wastewater in Kentucky. The wetlands were monoculture systems planted to cattails (*Typha latifolia* L.) or fescue (*Festuca arundinacea* Schreb.), polyculture systems planted with a variety of flowering plants, and unplanted systems. Influent and effluent samples were taken on a monthly basis over a period of 1 year and analyzed for fecal coliforms (FC), fecal streptococci (FS), BOD and TSS. The findings suggested no significant differences ($P < 0.05$) in the average yearly removal of fecal bacteria (> 93%) between systems, with the vegetated systems performing best during warmer months and the unplanted systems performing best during the winter. The vegetated systems showed significantly greater ($P < 0.05$) removal efficiencies for BOD (> 75%) and TSS (> 88%) than the unplanted systems (63 and 46%, respectively) throughout the year. Overall, the polyculture systems seemed to provide the best and most consistent treatment for all wastewater parameters, while being least susceptible to seasonal variations. The performance of the cattail systems may improve by harvesting the plants at the end of the growing season, thus reducing additional BOD and TSS inputs from decaying biomass litter. The fescue systems were generally inferior to the polyculture and cattail systems because of their shallow rooting zone and limited biofilm surface area, while the unplanted systems were completely inefficient for BOD and TSS removal and should not be recommended.

Keywords: Wastewater treatment; Monoculture wetlands; Polyculture wetlands; Unplanted wetlands; Fecal coliforms; Fecal streptococci; Seasonal performance

1. Introduction

In areas with landscape limitations, poor soil conditions, and high water tables, which forbid the use of soil adsorption fields, public health officials are experimenting with alternative systems for

* Corresponding author. Tel.: +1-859-257-5925; fax: +1-859-257-2185.
E-mail address: akaratha@uky.edu (A.D. Karathanasis).

0925-8574/03/$ - see front matter
doi:10.1016/S0925-8574(03)00011-9

domestic wastewater treatment, including constructed wetlands. Their low cost, low maintenance and generally good performance in improving water quality have appealed to many individual homeowners and small communities. Although considerable progress has been made in our understanding of the physical, chemical and biological processes that facilitate treatment, inconsistent results suggest that further research is needed to optimize system functioning. One aspect that has been controversial is the role of vegetation and the effects of different plant species as mono- or polycultures in promoting treatment. Although some studies (Neralla et al., 2000; Soto et al., 1999; Vymazal, 1999; Merlin et al., 2002) have documented that macrophytes can improve BOD and bacterial removal from wastewaters through sedimentation, mechanical filtration, nutrient assimilation, oxygenation, and microbial attachment mechanisms, others did not detect any significant difference between planted and unplanted systems (Tanner et al., 1995; Baldizon et al., 2002). Comparisons of different studies are difficult because they utilize diverse substrates, different water flow designs and rates, and variable hydraulic and mass loadings. For example, the role of the substrate and the rhizosphere in surface flow systems is quite negligible compared with the subsurface flow systems, where long residence times allow extensive interaction with the wastewater. While resilient, slow growing species with low seasonal biomass turnover, and high root-zone aeration capacity may be suitable for surface flow systems, high productivity species, tolerant to high levels of pollutants and hypertrophic waterlogged conditions may be functionally superior in subsurface flow systems (Tanner et al., 1995). Furthermore, some polyculture species may form floristical and structural vegetation patterns with enhanced ecological, functional and aesthetic values, while others may be more efficient in monoculture stands.

Fecal bacteria removal efficiency in constructed wetlands is generally excellent, usually exceeding 95%, but varies with hydraulic residence time, wetland design, hydraulic and mass loading rate, substrate, and temperature (Gersberg et al., 1987; Haberl et al., 1995; Potter and Karathanasis, 2001). Subsurface flow wetlands have also proved to be effective in treating total suspended solids (TSS) and biological oxygen demand (BOD), with primary removal mechanisms being sedimentation, adsorption, and microbial metabolism (Green et al., 1997; Leonard, 2000). However, their performance is contingent upon microbial activity, hydraulic retention time, hydraulic loading rate, temperature, and vegetation type (Gearheart, 1992). Seasonal variations in BOD removal efficiency by constructed wetlands in the presence of various macrophytes have been reported by several investigators, with consistent treatment deterioration being observed in late winter months (Kuehn and Moore, 1995; Leonard, 2000). It is uncertain, however, whether the poor winter performances are due to cold temperatures alone or the combined effect with increased hydraulic loadings, because several other studies have not shown significant treatment effects between winter and summer (Watson et al., 1987; Brown and Reed, 1994; Neralla et al., 2000). Therefore, further investigations are needed to clarify optimal operational design options for these parameters in the treatment process. The primary objective of this study was to compare the efficiency of non-vegetated and vegetated monoculture and polyculture wetland systems for fecal bacteria, BOD, and suspended solids removal. A secondary objective was to analyze the effects of seasonal variations, system maturity, and size on the treatment process.

2. Materials and methods

Twelve subsurface flow wetlands treating domestic wastewater from single family houses in Jessamine, Fayette, Woodford, and Boyle Counties in the Inner Bluegrass region of Kentucky were evaluated in this study (Fig. 1). These systems serve two to five family members and consist of one or two septic tanks for primary treatment and a single lined wetland cell of varying size and age. The treatment cells are 41–46 cm deep with a substrate of limestone gravel ranging from 2.5 to 6 cm in diameter. Three of the wetland cells were planted to cattails (*Typha latifolia* L.), three to

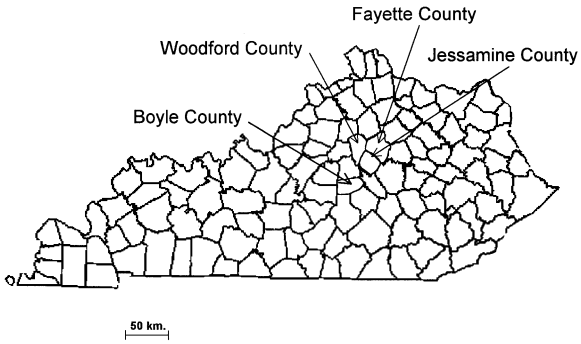

Fig. 1. Location of the constructed wetland systems used in the study.

fescue (*Festuca arundinacea* Schreb.), three to a variety of plants (polyculture), consisting mainly of yellow flag iris (*Iris pseudacorus* L.), canna lilies (*Canna x. generalis* L.H. Bail.), day lilies (*Hemerocallis fulva* L.), hibiscus (*Hibiscus moscheutos* L.), soft-stem bulrush (*Scirpus validus* Vahl.), and mint (*Mentha spicata* L.), and three remained unplanted. All systems had soil leach fields of 46–74 m, providing additional treatment to the wetland discharge. General characteristics of the systems studied are listed in Table 1.

Monitoring for fecal coliforms (FC) and TSS started in July 1999 and was completed in June 2000. Biochemical oxygen demand was monitored from October 1999 to September 2000. Samples were collected on a monthly basis at the influent and effluent ends of each wetland system from sample collection ports made of 1-inch PVC pipe. Samples were pumped from each collection port using a ‘‘Guzzler’’ hand-operated pump that gave a representative sample. Samples were pumped into clean 1000-ml containers that had been disinfected with bleach (sodium-hypochlorite) to insure that no fecal bacteria were present and transported to the University of Kentucky on ice to minimize population changes in the wastewater.

Fecal bacteria were analyzed by the membrane filtration technique (APHA, 1992), using sterile and gridded 0.2-μm pore-size Millipore filters. Three sample volumes of 0.1, 1.0, and 3.0 ml were used to increase the probability of obtaining counts within acceptable ranges. Filtered samples were incubated on M-FC agar (DIFCO, Detroit, MI) for 22 h at 44.5 °C to enumerate FC colonies and incubated on K-FS agar (DIFCO) for 48 h at 35 °C to assess fecal streptococci (FS).

Table 1
Description and features of the 12 wetland systems studied

Identification	Location (KY)	Size (m^2)	Age (years)	# of residents	Total		
					Septic tank volume (l)	Substrate[a] (cm)	Estimated flow (m^3/day)
Cattail 1	Woodford Co.	56	6	5	5670	LGR 5–6	1.42
Cattail 2	Woodford Co.	56	4	2	3780	LGR 5–6	0.57
Cattail 3	Fayette Co.	45	8	3	3780	LGR 5–6	0.85
	Average	52.3	6.0	3.3	4410		0.95
Polyculture 1	Fayette Co.	36	6	5	3780	LGR 5–6	1.42
Polyculture 2	Boyle Co.	45	3	2	3780	LGR 5–6	0.57
Polyculture 3	Boyle Co.	56	2	2	5725	LGR 5–6	0.57
	Average	45.7	3.7	3.0	4428		0.85
Fescue 1	Boyle Co.	34	6	2	3780	LGR 5–6+SC	0.47
Fescue 2	Boyle Co.	44	1	3	3780	LGR 5–6+SC	0.85
Fescue 3	Boyle Co.	60	8	4	8505	LGR 5–6+SC	1.14
	Average	46.0	5.0	3.0	5355		0.85
Unplanted 1	Jessamine Co.	44	2	2	8505	LGR 2.5–5	0.57
Unplanted 2	Jessamine Co.	44	4	4	5670	LGR 2.5–5	1.14
Unplanted 3	Jessamine Co.	44	5	3	5670	LGR 2.5–5	0.85
	Average	44.0	3.7	3.0	6615		0.85

[a] LGR, limestone gravel; SC, soil cover 15–20 cm.

The standard 5-day BOD (BOD_5) test was used to assess reduction in biochemical oxygen demand. Samples were stored at $< 4\,^{\circ}C$ for approximately 24 h. Sample volumes ranging from 15 to 30 ml were brought to room temperature, placed in standard 300 ml BOD bottles and filled with water buffered with a 1.0 ml/l phosphate buffer solution containing $MgSO_4$, $CaCl_2$, and $FeCl_3$ (APHA, 1992). The pH was adjusted to between 6.5 and 7.5 before analysis if necessary. Samples were incubated at $20\,^{\circ}C$ in a BOD incubator. The dissolved oxygen content was determined at inoculation and after 5 days of incubation. TSS were determined gravimetrically following filtration through glass-fiber membrane filters and drying (APHA, 1992).

The least significance difference (LSD) procedure in PC-SAS at the 0.05 probability level ($P < 0.05$) was used to test statistical differences between and within treatments in terms of percentage (%) removal, loading rate, and removal rate efficiency. The LSD procedure was also used to test seasonal differences. Correlation and regression analyses ($P < 0.05$) were also used to develop relationships between wetland design and performance parameters.

3. Results and discussion

3.1. Fecal coliforms

FC concentrations in the influent were highly variable between systems and sampling periods. They ranged from as high as 251.3×10^3 CFU/100 ml in the non-planted systems to as low as 5.7×10^3 CFU/100 ml in the fescue systems with no consistent seasonal trends. Total average concentrations were highest overall in the cattail systems (90.4×10^3 CFU/100 ml) and lowest in the fescue systems (32.9×10^3 CFU/100 ml) (Table 2). The polyculture and unplanted systems showed intermediate concentrations (36.4×10^3 CFU/100 ml and 48.0×10^3 CFU/100 ml, respectively), but greater variability between samplings (Table 2). Average effluent concentrations were also variable (0.1×10^3–11.0×10^3 CFU/100 ml), being usually highest in the cattail and the unplanted systems.

Table 2
Mean influent and effluent concentrations, and % removal efficiencies (RE) in the wetlands studied during the sampling period[a] (standard deviations are shown in parentheses)

Wetlands	FC (CFU/100 ml × 10^3)			FS (CFU/100 ml × 10^3)			BOD (mg/l)			TSS (mg/l)		
	Influent	Effluent	% RE	Influent	Effluent	% RE	Influent	Effluent	% RE	Influent	Effluent	% RE
Cattail	90.4	4.6	95	52.8	3.6	93	392	81	79	1310	136	90
	(64.3)	(3.7)	(4)	(33.3)	(3.6)	(6)	(96)	(43)	(5)	(1376)	(114)	(7)
Polyculture	36.4	1.1	97	72.1	1.3	98	271	69	75	2102	202	90
	(43.2)	(1.1)	(3)	(83.2)	(1.3)	(2)	(96)	(35)	(3)	(1788)	(178)	(6)
Fescue	32.9	1.0	97	14.7	0.9	94	230	58	75	814	97	88
	(27.7)	(0.9)	(3)	(11.1)	(1.1)	(5)	(125)	(28)	(4)	(908)	(92)	(7)
Unplanted	48.0	2.7	94	75.3	3.2	94	274	102	63	418	226	46
	(58.4)	(2.5)	(5)	(73.9)	(4.2)	(5)	(157)	(30)	(5)	(284)	(162)	(10)

[a] n = 12 monthly samplings from July 1999 through June 2000 for fecal bacteria and TSS and from October 1999 through September of 2000 for BOD.

The polyculture and fescue systems had average FC concentrations near the EPA recommended levels of 1×10^3 CFU/100 ml and met the criteria 7 out of 12 months. In contrast, effluents from cattail and unplanted systems were nearly 3–5 fold higher than the required levels and in compliance only 3–4 months of the monitoring year.

In spite of the substantial variability in influent and effluent FC concentrations, percent removal efficiencies were very similar between systems, ranging from 94% in unplanted systems to 97% in the polyculture and fescue systems (Table 2, Fig. 2). However, there were significant ($P < 0.05$) seasonal differences in FC removal between and within systems. Overall, all vegetated systems showed significantly better performance during the warmer months of the year (May–September), while the unplanted systems performed best during the winter and early spring (December–April) (Fig. 2). Seasonal removal for the cattail and fescue systems ranged from a high of 97% in the spring to lows of 82 and 78% in the winter, respectively. The polyculture systems performed more consistently than any other system during the warm months of the year, showing the best treatment in the fall (98%) and the worst during the winter (82%). The lower removal of FC during the winter in the vegetated systems can be attributed to the lower metabolic activity and significant reductions in the populations of predator microbes resulting from prolonged periods of < 3 °C temperatures (Fig. 3) (Merlin et al., 2002). Alternatively, a substantial reduction in root biomass during the winter season may limit microbial attachment surface area and filtering capacity of the substrate. The increased rainfall during the winter months may have accentuated these trends by increasing hydraulic loading and decreasing residence time (Fig. 3). In contrast, the unplanted systems showed the highest removal efficiency during the winter (93%) and the lowest in the fall (75%). This trend may be attributed to reductions in FC populations due to low temperatures, or to greater overall total septic tank volume (Table 1) used in these systems for primary treatment, which may partially compensate for the lack of vegetation during the winter months. Further, the smaller size gravel used in the substrate of these systems may provide considerable filtering capacity, especially following substantial biofilm development (Coleman et al., 2001).

There were significant differences in the average FC loading rate, ranging from 9.8×10^6 CFU/m^2 day in the fescue systems to 23.4×10^6 CFU/m^2 day in the cattail systems (Table 3). The removal rate increased with loading rate in all systems, but the 0.94–0.98 removal-rate efficiency ratio (removal rate/loading rate) observed in the polyculture, fescue and unplanted systems dropped to 0.77 in the high loading rate cattail systems. Still, because of the high seasonal variability in the loading rate of the systems, these differences were not statistically significant ($P < 0.05$). Cattail and unplanted systems showed a significant positive relationship between system age and FC removal efficiency ($R^2 = 0.75$ and 0.86, respectively), but there was no clear maturity effect on system performance when considering all systems.

In spite of better overall treatment of FC provided by the vegetated systems, especially during the warmer months of the year, the yearly performance differences from the unplanted systems were rather small and not statistically significant. These results are in agreement with those reported by Green et al. (1997), but contradict other findings in which the presence of vegetation drastically improved FC removal (Rivera et al., 1995; Soto et al., 1999). Rooted biofilms are supposed to provide a more effective substrate than gravel for bacterial removal through mechanical filtration, sedimentation, adsorption, die-off, predation, and antibiotic excretion (Soto et al., 1999). One of the reasons that this effect did not materialize in this study may be the existing inherent variability between and within treatment systems not only in vegetation type, but in other critical design parameters as well (size, age, number of residents, primary treatment, substrate, hydraulic and mass loading). Since several of these parameters may not be proportional or compensational to each other, their effects may overshadow the influence of plant species or lack thereof on treatment performance. This is one of the disadvantages of working with field systems rather than uniform experimental mesocosms, however, the

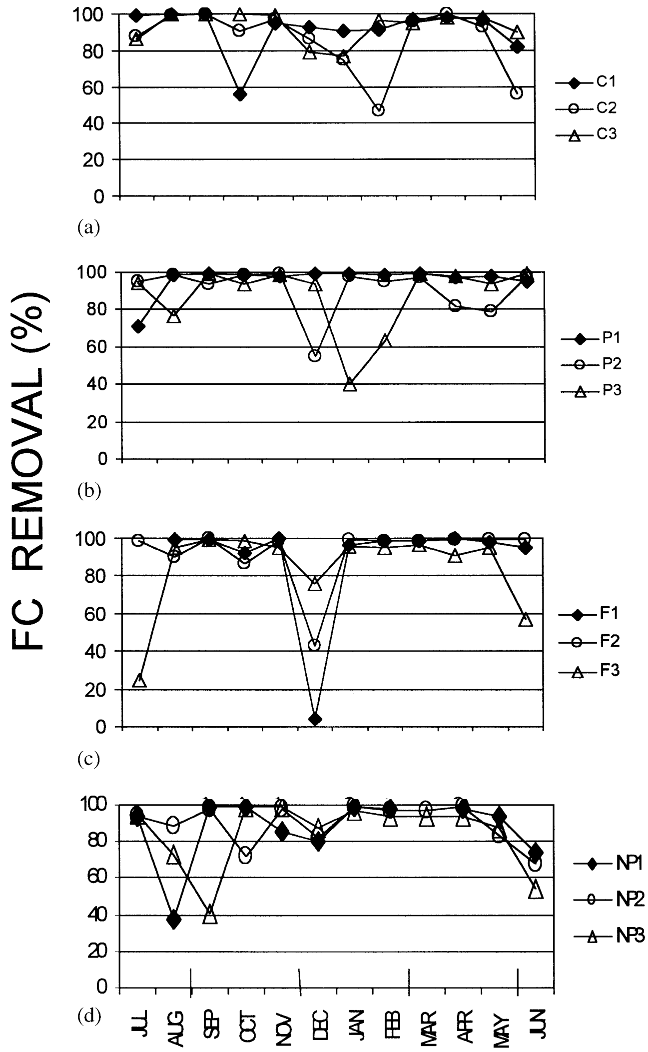

Fig. 2. Monthly average % removal of FC by cattail (a), polyculture (b), fescue (c), and unplanted (d) wetland systems from July 1999 through June 2000.

results are needed not only for comparison but because they represent current design field systems (Srinivasan et al., 2000). Among vegetated systems, the polyculture wetlands appeared to provide the most consistent FC removal throughout the year, while the fescue systems showed the greater seasonal fluctuations, being particularly unstable during the summer and the winter. It has been suggested that diverse species may provide more effective spatial and temporal partitioning of the rooting zone, thus exceeding the treatment ability of monoculture systems (Karpiscak et al., 1996; Coleman et al., 2001). The weak performance shown by the fescue systems is likely the result of the shallow roots of the plant, and the limited biofilm available for bacterial adsorption and predator microbial proliferation.

3.2. Fecal streptococci

Mean influent FS concentrations were highest and most variable in unplanted and polyculture

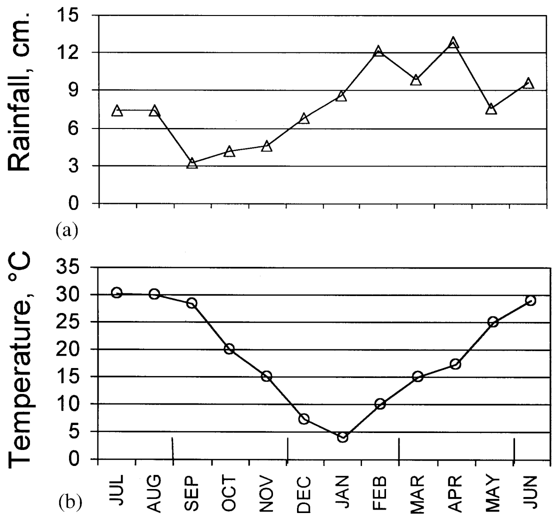

Fig. 3. Monthly average rainfall and temperature distribution during the sampling period.

systems ($> 70.0 \times 10^3$ CFU/100 ml) and lowest in fescue systems (14.7×10^3 CFU/100 ml) (Table 2). Values as high as 370.0×10^3 CFU/100 ml were observed in late summer and early fall and as low as 2.0×10^3 CFU/ml in early spring in the unplanted systems. Mean effluent concentrations in cattail and unplanted systems were > 3-fold higher than the EPA recommended levels of 1.0×10^3 CFU/100 ml, while the polyculture and fescue levels were just above or below the criteria at 1.3 and 0.9×10^3 CFU/100 ml, respectively. The corresponding monthly compliance numbers for cattail, polyculture, unplanted, and fescue systems were 1, 4, 5, and 8, respectively.

Average percent removal efficiencies ranged from 93% in the cattail systems to 98% in the polyculture systems, but the differences were not statistically significant ($P < 0.05$). Significant differences in FS percent removal were evident, however, during the winter between the unplanted (98%) and fescue (86%) systems and during the spring between the polyculture (96%) and unplanted (84%) systems (Fig. 4). The polyculture systems provided the best and most consistent treatment during the warm months of the year,

Table 3
Seasonal mean loading and removal rates in the wetlands studied during the sampling period

Wetland	Season	FC (CFU × 10^6/m^2 day)		FS (CFU × 10^6/m^2 day)		BOD (g/m^2 day)		TSS (g/m^2 day)	
		Loading	Removal	Loading	Removal	Loading	Removal	Loading	Removal
Cattail	Summer	30.4±20.1	22.3±13.4	9.9±6.9	8.9±6.6	14.8±14.4	12.6±13.3	47.5±39.4	41.2±45.0
	Fall	23.7±4.2	15.7±4.2	30.2±4.3	29.4±4.5	11.6±6.6	10.2±6.1	48.4±16.5	45.4±16.5
	Winter	16.2±6.7	15.4±4.9	12.0±3.6	11.6±4.5	6.4±2.4	4.2±1.8	25.0±13.3	23.2±12.5
	Spring	23.4±9.4	17.6±10.1	3.1±0.7	2.8±0.7	8.6±3.8	6.1±3.4	14.4±8.4	12.9±8.4
	Mean	23.4±11.3	18.0±8.4	13.8±11.2	13.3±11.5	10.2±7.8	8.1±7.4	33.9±24.7	30.7±25.5
Poly-culture	Summer	10.4±6.0	10.1±6.2	12.3±6.8	11.9±6.8	13.8±1.2	10.8±10.0	36.4±6.9	31.0±5.7
	Fall	18.4±13.5	18.1±13.4	47.5±54.0	47.2±53.7	10.3±10.6	8.2±8.5	111.1±52.8	99.6±49.1
	Winter	7.4±4.2	7.2±4.2	11.3±14.7	10.8±14.5	2.9±0.9	1.8±0.6	33.7±7.2	29.2±4.9
	Spring	7.4±5.5	7.2±5.4	10.3±3.5	9.9±3.3	5.6±0.7	4.1±0.7	51.0±34.9	48.2±33.9
	Mean	10.9±8.4	10.7±8.3	20.4±29.1	20.0±29.1	8.0±7.6	6.0±6.5	58.1±42.6	52.0±39.3
Fescue	Summer	7.5±5.1	6.9±4.8	10.5±7.6	1.3±0.7	12.2±8.4	9.8±7.9	28.2±14.2	24.7±14.8
	Fall	13.6±5.4	13.4±5.3	31.0±23.6	9.1±0.6	7.4±6.6	5.5±5.2	15.1±2.9	13.0±3.1
	Winter	8.3±6.5	7.9±6.7	13.2±8.8	2.6±1.5	2.2±0.8	1.2±0.6	18.9±11.0	17.4±11.1
	Spring	10.0±6.8	9.9±6.7	6.3±2.4	3.6±3.5	5.9±2.6	4.5±2.7	42.9±44.5	38.3±41.3
	Mean	9.8±5.7	9.5±5.7	15.3±14.6	4.1±3.6	6.9±5.9	5.2±5.3	26.3±23.4	23.4±21.8
Unplanted	Summer	10.2±9.8	8.8±9.7	8.3±6.8	7.7±6.3	25.1±13.7	21.2±13.6	14.7±4.1	12.1±10.2
	Fall	35.7±38.6	35.0±38.2	26.5±1.5	25.4±1.9	10.7±3.3	7.4±2.6	10.9±2.1	3.8±1.1
	Winter	10.9±8.8	10.0±7.6	15.1±14.8	14.8±14.4	7.6±2.8	4.9±3.0	16.9±12.0	10.0±6.6
	Spring	3.1±2.3	2.7±1.8	3.5±4.0	2.7±3.0	6.4±1.8	3.5±1.7	5.0±1.4	1.9±0.2
	Mean	15.0±21.7	14.1±21.5	14.3±11.6	13.5±11.3	13.1±10.8	9.8±10.3	11.9±7.2	7.4±7.0

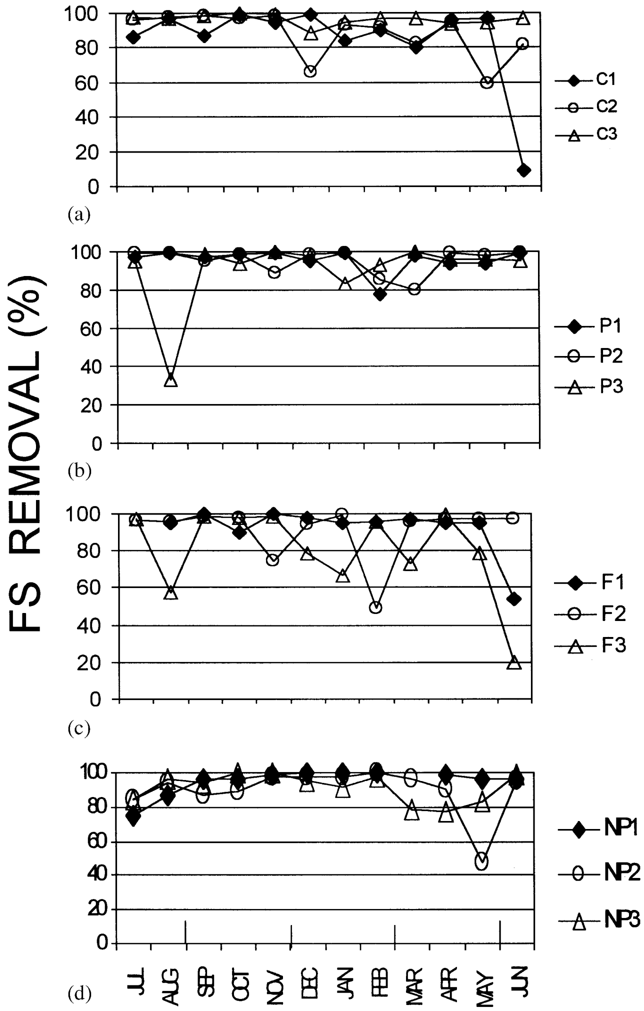

Fig. 4. Monthly average % removal of FS by cattail (a), polyculture (b), fescue (c), and unplanted (d) wetland systems from July 1999 through June 2000.

while the fescue systems had the poorest performance in every season (80–86%) except for the spring (95%). As it was the case for FC removal, the unplanted systems performed the best during the winter months.

Loading rates for FS were significantly higher in polyculture systems (20.4×10^6 CFU/m^2 day compared with other systems (Table 3). Removal rates of FS increased with loading rates in all systems, with a high removal rate efficiency ratio (0.94–0.98) being maintained even at the highest loading rates in all but the fescue systems. Fescue systems exhibited significantly lower removal rates (4.1×10^6 CFU/m^2 day) with an average removal efficiency ratio of only 0.27, which dropped even lower during the summer and winter months (Table 3). As was the case for FC, there was a significant positive correlation ($R^2 = 0.90$) between system maturity and removal rate of FS in cattail systems, suggesting improved treatment with increasing root biomass production. A significant positive relationship ($R^2 = 0.87$) was also found between system size and FS removal rate in the polyculture systems. These relationships, however, were not significant across all systems.

Even though the FS loading rate patterns were different from those for FC, removal rates were similar between systems. As was the case for FC, the polyculture systems showed consistently better performance throughout the year, but the average FS removal rate efficiencies between systems were not statistically significant ($P < 0.05$). This is probably due to the inherent variability between and within systems referred to under the FC section and the fact that the mechanisms for fecal bacteria removal are very similar. Nevertheless, some seasonal effects were evident, especially during the hottest and coldest months of the year, when FS removal efficiencies declined considerably as a result of intense evapotranspiration or reduced metabolic activity of predator microbes, particularly in fescue and cattail systems (Merlin et al., 2002). Overall, no clear evidence was shown in this study supporting the superiority of vegetated over unplanted systems in FS removal as was reported by other investigators (Soto et al., 1999).

3.3. Biological oxygen demand

Influent BOD levels varied greatly between treatment systems and were generally on the high end of the range reported in the literature for domestic wastewater. The highest mean concentrations were observed in cattail systems (392 mg/l) and the lowest in the fescue systems (230 mg/l) (Table 2), although maximum levels reached as high as ∼1200 mg/l in cattail and unplanted systems in late summer months. Mean effluent BOD concentrations were at least 2-fold higher in all systems than the EPA recommended level of 30 mg/l. They were generally higher in unplanted and cattail systems (102 and 81 mg/l, respectively) and somewhat lower in polyculture and fescue systems (69 and 58 mg/l, respectively). Except for one sampling in the fescue systems (January), no other system met the total maximum daily BOD load criteria recommended by EPA during the entire monitoring period. However, all of the wetland systems in this study discharge into a leaching field, which provides tertiary treatment to the domestic wastewater.

The average BOD percent removal efficiency (Table 2) was significantly lower ($P < 0.05$) in unplanted systems (63%) than in other systems (75–79%). In spite of the high influent BOD concentrations, these removal efficiencies are within the range of those reported in the literature (Thomas et al., 1995; Steer et al., 2002). Since sedimentation, adsorption and microbial metabolism are considered to be the primary mechanisms for BOD removal, it is likely that the plant roots and falling residues provide a more effective settling medium than gravel alone, while at the same time increasing attachment surface area and food sources for the microbial populations. Seasonal effects on BOD removal efficiencies were also evident, with the best and most consistent overall performance occurring during the summer and the worst during the winter months (Fig. 5) (Henneck et al., 2001). The decline in BOD

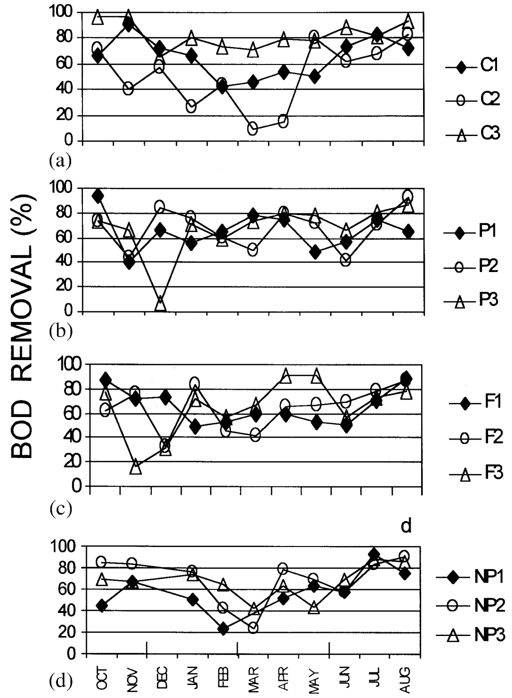

Fig. 5. Monthly average % removal of BOD by cattail (a), polyculture (b), fescue (c), and unplanted (d) wetland systems from October 1999 through September 2000.

removal efficiency observed in cattail systems in the spring, when their average BOD removal dipped below 55%, is probably due to the larger overall aboveground biomass that was returned to the wetland during the previous season, which upon decay contributes additional BOD to the wastewater (Thomas et al., 1995). The result is more evident in the spring because of the increased hydraulic loading during this period from high rainfall (Fig. 3), which mobilizes organic particles within the wetland and reduces retention time. A similar decline in BOD removal efficiency during the spring in unplanted systems is also the result of reduced residence time, while sporadic low removals in variety systems during the summer are attributed to increased concentration due to greater evapotranspiration.

Average BOD loading rates varied from 6.9 g/m^2 day in fescue systems to 13.1 g/m^2 day in unplanted systems (Table 3). The BOD removal rates increased linearly with loading rates at ratios of 0.75–0.79, with no evidence of declining treatment efficiency at higher loading rates (Table 3). The unplanted and cattail systems showed slightly higher overall BOD removal rates (>10.0 g/m^2 day) than the polyculture and fescue systems ($<$ 8.0 g/m^2 day). Other than their high loading rate during the summer, the relatively high BOD removal rate of the unplanted systems may also be related to the lack of vegetation cover, which may have resulted in extra aeration and oxidation of the organic load (Thomas et al., 1995). In contrast, the low BOD removal rates of the fescue systems are likely due to the shallow and relatively small root biomass, which renders this type of vegetation system somewhat inefficient, in spite of the low loading rates. This was especially evident during the winter months when the BOD removal rate in the fescue systems dropped to 1.2 g/m^2 day (Table 3). There was a positive statistically significant relationship ($R^2 = 0.95$) between BOD removal rate efficiency and system maturity in the cattail systems and system size in polyculture ($R^2 = 0.94$) and fescue ($R^2 = 0.83$) systems.

The high overall BOD removal efficiency shown by the cattail and variety systems during the warmer months of the year suggests that these types of vegetation can enhance substrate attenuation capacity through dense rooting and large surface area biomass conducive to increased microbial metabolic activity, and by transporting extra oxygen to the substrate through their aerenhyma tissue (Tanner et al., 1995). The performance of the cattail systems may be enhanced even further if most of the above ground biomass is harvested at the end of the season rather than allowed to return and decay within the wetland, thus increasing the organic load. The benefits of the polyculture systems, on the other hand, stem from their greater diversity, which allows for more types of microbial populations to proliferate within the substrate, their controlled growth and harvest resulting in lower overall biomass production, and their higher aesthetic quality, which makes them more socially attractive systems (Coleman et al., 2001).

3.4. Total suspended solids

Mean influent concentrations for TSS ranged from 418 mg/l in unplanted systems to 2102 mg/l in the polyculture systems (Table 2). However, monthly levels were highly variable, exceeding 3000 mg/l at least once in all but the unplanted systems, in which the maximum concentration was never >1000 mg/l. These levels are some of the highest reported in the literature (Hiley, 1995). Considering all the BOD as a fraction of the TSS load, the organic load made up only 13% of the TSS in the polyculture systems, while the respective values for the fescue, cattail, and unplanted systems were 28, 30, and 65%. Mean effluent concentrations were lowest in the fescue systems (97 mg/l) and highest in the unplanted systems (226 mg/l). Monthly TSS levels met the EPA recommended TMDL criteria of 30 mg/l only once in the cattail, polyculture, and fescue systems and never in the unplanted systems.

Average % removal of TSS was significantly higher ($P < 0.05$) in vegetated systems (88–90%) than in unplanted systems (46%), contradicting the results of Thomas et al. (1995) and Tanner et al. (1995), which reported similar removal efficiencies between systems with and without plants (Table 2). The differences in TSS treatment between vegetated and unvegetated systems in this study persisted in all seasons of the year, with the polyculture and fescue wetlands providing the most consistent performance even during the winter season (Fig. 6). This confirms that TSS removal is mostly a physical settling and filtration process and generally independent of microbial metabolic activity, except possibly if a large portion of the TSS load is organic. Such was the case with the unplanted systems, in which nearly 2/3 of the TSS load was organic. Even though these systems had the lowest overall TSS load, the lack of extensive surface area for microbial attachment in their substrate deprives them from an additional removal mechanism, which is so effective in vegetated systems. Sporadic drops in TSS removal efficiencies of some cattail systems in the winter and spring are probably the result of increased hydraulic loadings, which reduced retention times and mobilized decayed plant residue within the wetland. Similar cases with some fescue systems are likely the result of temporary clogging. The declined efficiency in early fall of some polyculture systems is probably due to drought conditions, which increased TSS concentrations.

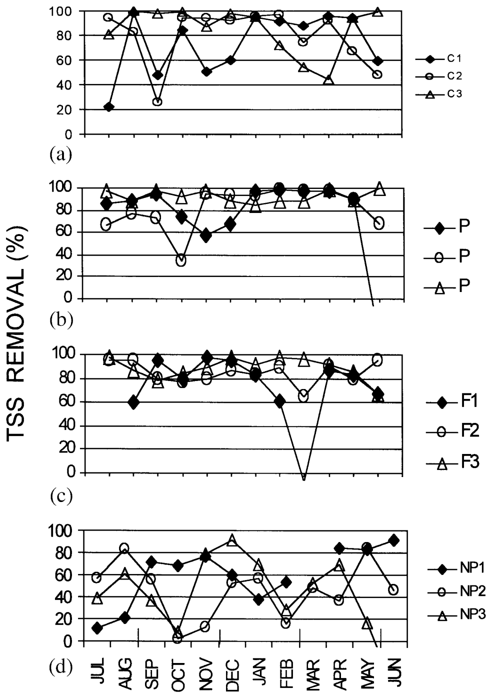

Fig. 6. Monthly average % removal of TSS by cattail (a), polyculture (b), fescue (c), and unplanted (d) wetland systems from July 1999 through June 2000.

The polyculture systems had the highest average loading rate of 58.1 g/m^2 day compared with 33.9, 26.3, and 11.9 g/m^2 day for the cattail, fescue and unplanted systems, respectively (Table 3). Average removal rates increased linearly with loading rates, at ratios of 0.89–0.91 in the vegetated systems, but dropped drastically ($P < 0.05$) to < 0.62 in the unplanted systems, particularly in the fall and the winter months. There was a statistically significant positive relationship between TSS removal and system maturity in the cattail ($R^2 = 0.92$) and unplanted ($R^2 = 0.61$) systems as well as system size ($R^2 = 0.95$) in the polyculture systems, indicating improved performance over time and in larger size systems.

These results clearly indicate that the rooting biomass of the vegetated systems provided more effective filtration of the TSS load and contributed complimentary treatment of the organic portion of the TSS load through microbial decomposition processes. In spite of the higher TSS influent load, the vegetated systems exhibited nearly twice as high a removal efficiency as the unplanted systems. In the case of the fescue systems the lack of deep and extensive root biomass may have been compensated by the extra filtration of suspended particles provided by the 10–15 cm soil cover present on top of the limestone gravel substrate.

4. Conclusions

In conclusion, the constructed wetland systems involved in this study showed considerable potential for removing fecal bacteria, BOD, and TSS from single house domestic wastewater effluents following primary treatment. Yearly average removal efficiencies ranged from 93–98% for FC and FS, 63–78% for BOD, and 46–90% for TSS. Considerable variation in loading rates, as well as size and age differences between and within wetland systems, caused the annual differences in fecal bacteria removal efficiency between vegetated and unplanted systems to be statistically similar ($P <$ 0.05). However, significant seasonal differences were evident, with the vegetated systems showing a much better performance during the warmer months of the year (especially the polyculture systems) and the unplanted systems performing best during the winter months. In spite of unusually high loading rates, the vegetated systems also showed a statistically greater ($P < 0.05$) annual removal in BOD and TSS than the unplanted systems, with a slight decline during the winter. Apparently, the plant roots and falling residues in vegetated cells provided a more effective filtration medium than gravel alone, while increasing attachment surface area and food sources for microbial populations.

Overall, the polyculture systems seemed to provide the best and most consistent treatment for all wastewater parameters, while being least susceptible to seasonal variations. The presence of diverse species may have provided a more effective distribution of the rooting biomass and a habitat for more diverse microbial populations than the monoculture systems. The performance of cattail systems may improve by harvesting the plants at the end of the growing season, thus avoiding extra BOD and TSS loads being added to the wetland cells from descending biomass litter in late fall and early spring. These two systems should be preferred over the fescue systems because the shallow rooting zone of fescue provides limited biofilm surface area and predator microbial proliferation. Finally, the unplanted systems, while showing good removal efficiencies for fecal bacteria, were substantially inferior to vegetated systems in treating BOD and TSS, and should not be recommended.

Acknowledgements

The authors would like to express their sincere gratitude to Yvonne Thompson, Abigail Villalba and Jim Crutchfield for their help with sampling and analysis, and Virginia Fernandez-Canigia for helping with the statistical analysis. The authors would also like to express sincere thanks to Rudy Gabhart, Larry Halcomb, Daniel Troutman, Kenneth Spach, and Tim Wright of the Kentucky Health Department for helping with the site selection, and the homeowners for allowing sampling of their systems.

References

APHA, 1992. Standard Methods for the Examination of Water and Wastewater, 18th ed. American Public Health Association, Washington, DC.

Baldizon, M.E., Dolmus, R., Quintana, J., Navarro, Y., Donze, M., 2002. Comparison of conventional and macrophyte-based systems for the treatment of domestic wastewater. Water Sci. Technol. 45, 111–116.

Brown, D.S., Reed, S.C., 1994. Inventory of constructed wetlands in the United States. Water Sci. Technol. 29, 309–318.

Coleman, J., Hench, K., Garbutt, K., Sexstone, A., Bissonnette, G., Skousen, J., 2001. Treatment of domestic wastewater by three plant species in constructed wetlands. Water Air Soil Pollut. 128, 283–295.

Gearheart, R.A., 1992. Use of constructed wetlands to treat domestic wastewater, City of Arcata, California. Water Sci. Technol. 26, 1625–1635.

Gersberg, R.M., Brenner, R., Lyon, S.R., Elkins, B.V., 1987. Survival of bacteria and viruses in municipal wastewater applied to artificial wetlands. In: Reddy, K.R., Smith, W.H. (Eds.), Aquatic Plants for Water Treatment and Resource Recovery. Magnolia Publishing, Orlando, FL, pp. 237–245.

Green, M.B., Griffin, P., Seabridge, J.K., Dhobie, D., 1997. Removal of bacteria in subsurface flow wetlands. Water Sci. Technol. 35, 109–116.

Haberl, R., Perfler, R., Mayer, H., 1995. Constructed wetlands in Europe. Water Sci. Technol. 32, 305–315.

Henneck, J., Axler, R., McCarthy, B., Geerts., S.M., 2001. Onsite treatment of septic tank effluent in Minnesota using SSF constructed wetlands: performance, costs and maintenance. Proceedings of Ninth National Symposium on Individual and Small Community Sewage Systems, ASAE, Fort Worth, TX, March, 2001, pp. 650–662.

Hiley, P.D., 1995. The reality of sewage treatment using wetlands. Water Sci. Technol. 32, 329–338.

Karpiscak, M.M., Gerba, C.P., Watt, P.M., Foster, K.E., Falabi, J.A., 1996. Multi-species plant systems for wastewater quality improvement and habitat enhancement. Water Sci. Tecnol. 33, 231–236.

Kuehn, E., Moore, J.A., 1995. Variability of treatment performance in constructed wetlands. Water Sci. Technol. 32, 241–250.

Leonard, K.M., 2000. Analysis of residential subsurface flow constructed wetlands performance in Northern Alabama. Small Flows Quart. 2, 34–39.

Merlin, G., Pajean, J.L., Lissolo, T., 2002. Performances of constructed wetlands for municipal wastewater treatment in rural mountainous areas. Hydrobiologia 469, 87–98.

Neralla, S., Weaver, R.W., Lesikar, B.J., Persyn, R.A., 2000. Improvement of domestic wastewater quality by subsurface flow constructed wetlands. Bioresource Technol. 75, 19–25.

Potter, C.L., Karathanasis, A.D., 2001. Vegetation effects on the performance of constructed wetlands treating domestic wastewater. Proceedings of Ninth National Symposium on Individual and Small Community Sewage Systems, ASAE, Fort Worth, TX, March 2001, pp. 663–673.

Rivera, F., Warren, A., Ramirez, E., Decamp, O., Bonilla, P., Gallogos, E., Calderon, A., Sanchez, J.T., 1995. Removal of pathogens from wastewaters by the root zone method (RZM). Water Sci. Technol. 32, 211–218.

Soto, F., Garcia, M., de Luis, E., Becares, E., 1999. Role of *Scirpus lacustris* in bacterial and nutrient removal from wastewater. Water Sci. Technol. 40, 241–247.

Srinivasan, N., Weaver, R.W., Lesikar, B.J., Persyn, R.A., 2000. Improvement of domestic wastewater quality by subsurface flow constructed wetlands. Bioresour. Technol. 75, 19–25.

Steer, D., Fraser, D.L., Boddy, J., Seibert, B., 2002. Efficiency of small constructed wetlands for subsurface treatment of single-family domestic effluent. Ecol. Eng. 18, 429–440.

Tanner, C.C., Clayton, J.S., Upsdell, M.P., 1995. Effect of loading rate and planting on treatment of dairy farm wastewaters in constructed wetlands: removal of oxygen demand, suspended solids and fecal coliforms. Water Res. 29, 17–26.

Thomas, P.R., Glover, P., Kalaroopan, T., 1995. An evaluation of pollutant removal from secondary treated sewage effluent using a constructed wetland system. Water Sci. Technol. 32, 87–93.

Vymazal, J., 1999. Removal of BOD in constructed wetlands with horizontal subsurface flow: Czech experience. Water Sci. Technol. 40, 133–138.

Watson, J.T., Diodato, F.D., Lauch, M., 1987. Design and performance of artificial wetlands wastewater treatment plant at Iselin, Pennsylvania. In: Reddy, K.R., Smith, W.H. (Eds.), Aquatic Plants for Water Treatment and Resource Recovery. Magnolia Publishing, Orlando, FL, pp. 263–270.