IMPACT OF EFFLUENT QUALITY AND SOIL DEPTH ON RENOVATION OF DOMESTIC WASTEWATER

C.S. Duncan, R.B. Reneau, Jr., and C. Hagedorn*

ABSTRACT

Many soils are marginally suited for installation of on-site wastewater disposal systems. With soil limitations, additional wastewater treatment prior to soil application may allow for a reduction in soil depth. Undisturbed 20-cm-diameter soil columns (fine loamy, mixed, mesic Typic Hapludult), in a factorial arrangement between depth of soil (15, 30, and 45 cm) and type of effluent (septic tank, constructed wetlands, and recirculating sand filter), were used in this study. Effluent (670 cm^3/d) was applied 6 times daily. Additional treatment of septic tank effluent by a constructed wetland and a recirculating sand filter resulted in 30 and 70% higher average soil infiltration rates, 92 and 96% reduction in fecal coliforms, 34 and 44% reduction in total nitrogen, and a 60 and 94% reduction in BOD_5, respectively. Fecal coliforms were present only in soil leachate from the 15 and 30 cm soil depths receiving septic tank effluent and the 15 cm depth that received constructed wetland effluent. Average soil leachate NO_3^--N concentrations were 19, 10 and 14 mg/L from soil columns receiving septic tank, constructed wetland, and recirculating sand filter effluents, respectively. Soil leachate contained <5 mg/L TKN and 1.8 mg/L NH_4^+-N. Total nitrogen losses were 55, 73, and 66 for the septic tank, constructed wetland, and recirculating sand filter treatments, respectively. BOD_5 averaged less than 4 mg/L in the soil column leachate, despite a 10 fold difference among influent types. In comparing the 1993 and 1994 growing seasons, average plant tissue dry weight, percent N, and percent P were greater during the 1994 growing season. The results from this study indicate that additional treatment of septic tank effluent can be substituted for soil depth.

KEYWORDS: Constructed wetland, Onsite wastewater treatment, Sand filters, Septic tank effluent, Wastewater renovation

INTRODUCTION

Approximately one quarter of all residences in the United States are not connected to public sewer systems (Bureau of the Census, 1990). In these areas, people have traditionally relied upon on-site wastewater treatment and disposal systems (OSWTDS) to adequately renovate waste before reaching ground or surface waters. The State of Virginia relies heavily on OSWTDS, with 58% of the localities in Virginia having 60% or more households served by OSWTDS (Stolt and Reneau, 1991). In 1980, 34% of Virginia residences relied on OSWTDS; this percentage is increasing, with approximately 40,000 new OSWTDS applications received by the Virginia Department of Health each year (Ijzerman et al., 1992). Traditionally, the conventional septic tank-soil absorption system (drainage field) has been the OSWTDS of choice.

Since the majority of these residences also rely on well water for their drinking water supply, adequate performance of the OSWTDS is crucial. Unfortunately, septic systems are the most frequently reported source of groundwater contamination (Hagedorn et al., 1981; Sandhu et al., 1981; Sevebeck and Kroehler, 1992; Yates, 1985). Installation in "poor" soils and increased septic tank density are cited as the primary reasons for groundwater contamination by septic systems (Ijzerman et al., 1992; Yates, 1985).

When groundwater contamination became an environmental issue in the early 1980's, the regulations concerning septic drainfields became much stricter. In 1981, the State of Virginia revised the Sewage Handling and Disposal Regulations such that certain depths of suitable soil must exist beneath a septic drainfield (Virginia Department of Health, 1982). Necessary soil depth between the bottom of the drainfield trench and rock, restricting soil horizon, or water table was dependent upon the soil texture group. Separation distance from trench bottom to a seasonal water table ranged from 5 cm for a sandy soil (texture group I) to 50 cm for a clay soil (texture group IV) (Virginia Department of Health, 1982). In 1994, the Sewage Handling and Disposal Regulations are being revised with respect to soil depth. The proposed Regulations will require a soil depth of 60 cm (24 inches) of texture group I soils and 45 cm (18 inches) of texture group II, III, and IV soils between the drainfield and restricting soil horizon or water table (Virginia Department of Health, 1994).

Many soils are poorly or marginally suited for installation of traditional OSWTDS because of insufficient depth to rock, restricting soil horizons, or a water table. Less than 35% of the total land area in the United States has soils suitable for conventional septic tank-soil absorption systems (Wenk, 1971). Based on regulations that existed in the 1970's, Goode (1974) estimated that 50% of the State of Virginia land area did not have soils suitable for conventional septic tank-soil absorption systems. With the 1994 proposed Regulations, land area in Virginia with suitable soils for conventional drainfields will be greatly lessened.

Additional treatment of septic tank effluent (STE), by either constructed wetlands (CW) or recirculating sand filters (RSF), prior to discharge to a drainfield may improve effluent quality such that less soil depth is required below the drainfield trench for wastewater renovation, but still prevent ground or surface water contamination. The objective of this study was to evaluate the impact of effluent quality and soil depth on renovation of domestic wastewater.

MATERIALS AND METHODS

Undisturbed 20–cm–diameter soil columns were extracted with a Giddings hydraulic soil probe to study the relationship between influent type and depth of soil on wastewater renovation. The soil column was designed to simulate a septic drainfield (Figure 1). The column influent distribution system was located 30 cm below the soil surface within a 15 cm layer of 5.0 to 7.4 cm diameter gravel. Influent was applied to the soil columns 6 times daily at a total application rate of 670 cm^3/day. A gas collection system was placed within the gravel distribution layer to facilitate denitrification measurements. Redox electrodes were placed 5 cm below the undisturbed soil surface and 2.5 cm above the bottom of the soil column. A tensiometer and thermocouple were placed in the center of the undisturbed soil core to monitor the energy status of water and temperature, respectively. Fescue (*Festuca arundinacea*) was planted in the soil columns.

This study was conducted under field conditions in a facility constructed at the Whitethorne Agriculture Research Farm in Montgomery County, Virginia. Columns were placed in a completely randomized factorial design replicated three times in the field facility. Soil depths studied were 15, 30, and 45 cm. Column influent types were septic tank effluent (STE), constructed wetland effluent (CWE), and recirculating sand filter effluent (RSFE).

Septic tank effluent was obtained from a single family residence located on the research site. Constructed wetland effluent was obtained from 16 prototype subsurface vegetated bed wetlands located on the research site as described by Huang et al. (1994). Each prototype wetland consisted of two lined cells measuring 41 cm depth x 51 cm width x 61 cm length. The 16 wetlands encompassed four treatments consisting of three influent (STE) detention times (3.4, 5.12, and 7.73 days), two recirculation ratios (0 and 50%), and two plant species [cattail (*Typha latifolia*) and woolgrass (*Scirpus cyperinus*)] (Huang et al., 1994). Effluent from each of the 16 prototype SVB wetlands was collected and mixed in a septic tank prior to introduction into the soil columns.

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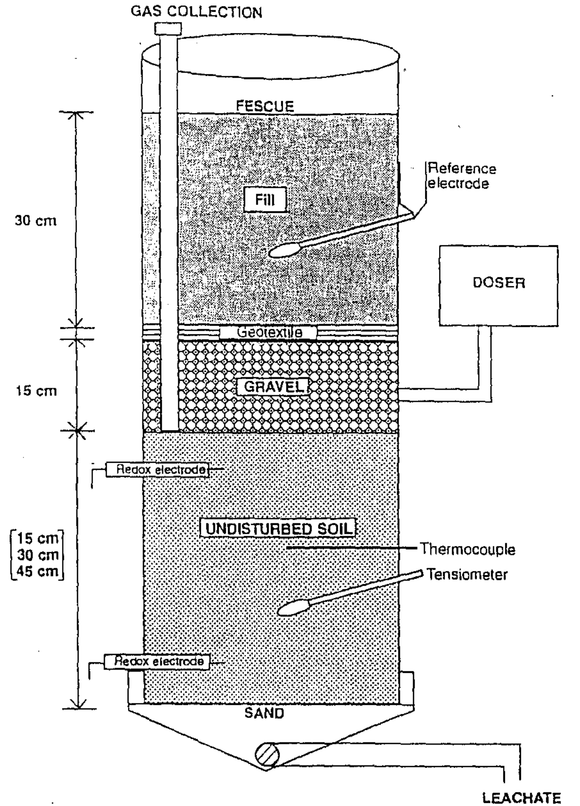


Figure 1: Schematic of the Soil Column Used in the Study.

A recirculating sand filter (Figure 2) was constructed at the field facility in a 20 cm diameter PVC pipe which was 1.5 m in height. The RSF design was based upon the OSWTDS Design Manual (USEPA, 1980), with an imposed water table modification based on work by Mote et al. (1991). The design characteristics are summarized in Table 1. The STE hydraulic loading was 0.20 m/day, applied in six incremental doses of 1100 cm^3. A recirculation ratio of 5 parts recirculate to 1 part STE was employed (USEPA, 1980). Therefore, before each dose to the sand filter, 5500 cm^3 of recirculate was pumped to a reservoir above the RSF and mixed with the 1100 cm^3 of STE, and gravity fed to the sand surface by a solenoid valve on a timer. The sand's effective size and uniformity coefficient (Table 1) were determined by sieve analysis.

Soil column dosing was initiated on May 27, 1993. Sampling began on June 7, 1993 and was bi-weekly during the summer and became monthly throughout the fall, winter, and spring. Samples were collected through May of 1994. Due to mechanical problems at the research site, samples were not collected from October 1993 through January 1994.

Influent sources (STE, CWE, and RSFE) and leachate from the soil columns were analyzed for biochemical oxygen demand (BOD_5), fecal coliforms, total dissolved solids (TDS), electrical conductivity (EC), pH, total organic carbon (TOC), Total Kjeldahl Nitrogen (TKN), six anions (Cl^-, F^-, NO_2^--N, NO_3^--N, PO_4^{3-}-P, SO_4^{2-}), and five cations (Ca^{2+}, K^+, Mg^{2+}, NH_4^+-N, Na^+) (APHA, 1992). Soil temperature, soil water potentials, redox potentials, infiltration rates, and denitrification rates were also measured. Plant tissue was sampled every three weeks throughout the 1993 growing season and every two weeks in the spring of 1994. Plant tissue was analyzed for dry weight, Ca, K, Mg, Mn, Na, total P, and TKN. Plant tissue elements were analyzed by an Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES) system.

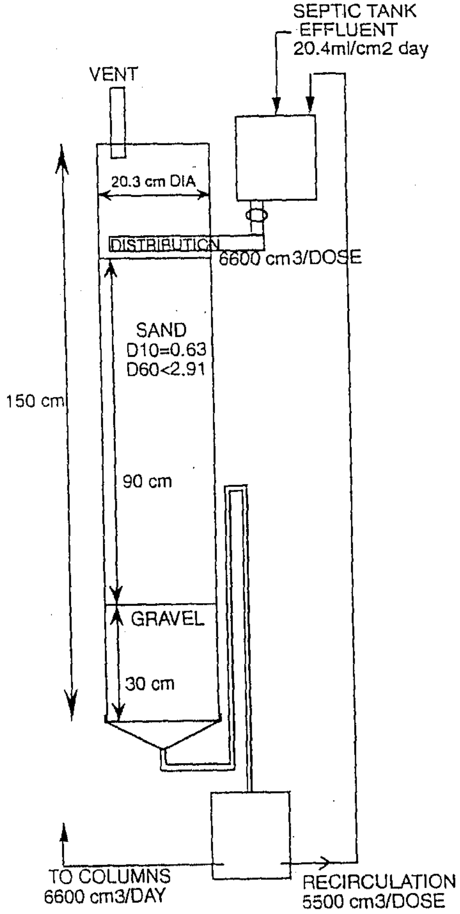
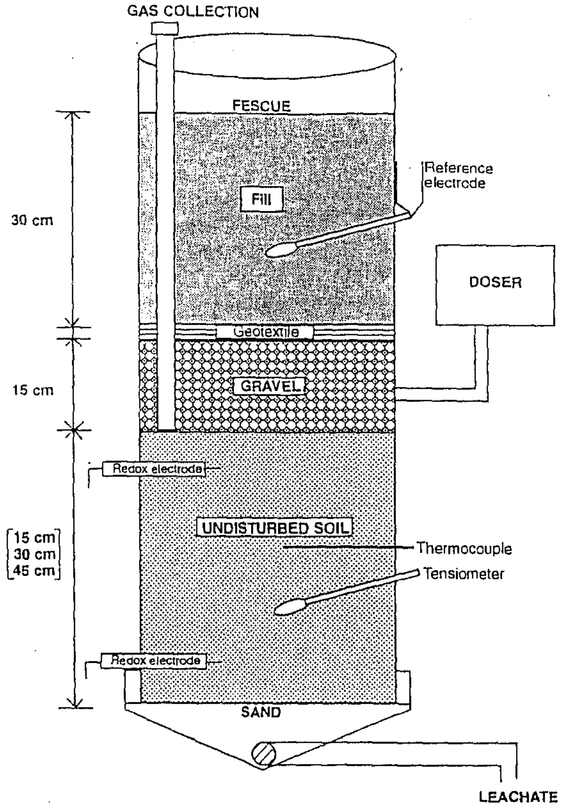


Figure 2: Schematic of the Recirculating Sand Filter Used in the Study.

Table 1: Design Characteristics for Recirculating Sand Filter

Raw hydraulic loading	0.20 m/d
Recirculation rate	5:1
Raw loading/dose	1100 cm^3
Recirculate loading/dose	5500 cm^3
Filter sand depth	90 cm
Depth to imposed water table	60 cm
Sand effective size (D_{10})	0.63 mm
Sand uniformity coefficient (D_{60})	< 2.91 mm
Number of doses/day	6

D_{10} = size for which 10% of the sand grains are smaller by weight
D_{60} = size for which 60% of the sand grains are smaller by weight



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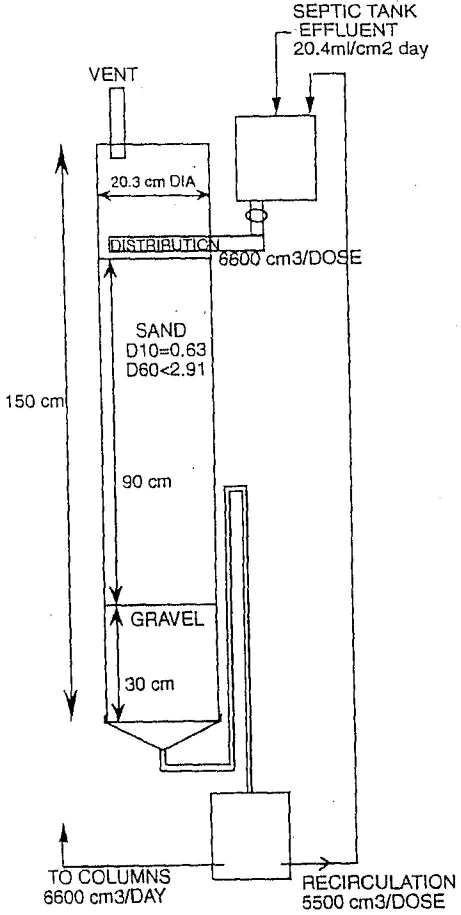

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Table 1: Design Characteristics for Recirculating Sand Filter

Raw hydraulic loading	0.20 m/d
Recirculation rate	5:1
Raw loading/dose	1100 cm^3
Recirculate loading/dose	5500 cm^3
Filter sand depth	90 cm
Depth to imposed water table	60 cm
Sand effective size (D$_{10}$)	0.63 mm
Sand uniformity coefficient (D$_{60}$)	< 2.91 mm
Number of doses/day	6

D_{10} = size for which 10% of the sand grains are smaller by weight
D_{60} = size for which 60% of the sand grains are smaller by weight

RESULTS AND DISCUSSION

Fecal coliform counts (Table 2) were reduced by 92% when the STE received additional treatment by the CW, and by 96% by the RSF. Fecal coliform counts in the column leachate were impacted by both the type of influent applied to the column and soil depth in the column (Table 2). Where STE was applied to the soil column, organisms were reduced to 910, 70, and no detectable counts/100 mL, for the 15, 30, and 45 cm soil depths, respectively. This corresponds to a 1.5, 2.9, and 4.5 log reduction, for the 15, 30, and 45 cm soil depths, respectively (Figure 3). Where either CWE or RSFE was applied as column influent, no organisms were present in the column leachate with the exception of the 15 cm soil column that received CWE and then the count averaged 40/100 mL. This data suggests that additional treatment of STE may be an effective substitute for soil depth and thus decrease the potential for fecal coliform transport to ground and surface waters where soils have limited treatment capacity.

Analysis of the three influents for selected chemical constituents indicate good renovation of the wastewater with additional STE treatment (Table 3). BOD_5 was reduced 60% by the CW and 94% by the RSF. Total N decreased 34% in the CW. This reduction was primarily attributed to ammonia volatilization within the CW (Huang et al., 1994). NH_4^+–N concentration decreased 82% with the RSF. This reduction was primarily attributed to nitrification within the sand filter. As indicated by the elevated NO_3^-–N and SO_4^{2-}–S levels, the RSF was aerobic and nitrification was occurring within the filter (Table 3). Nitrification is an essential step if denitrification is to be an effective medium for N loss. Denitrification of the oxidized N is a process that can significantly reduce the total N in the STE within the RSF. Based on mass balance of N, the RSF treatment resulted in a total N reduction of 44%. This reduction was attributed to denitrification within the RSF. EC and TDS increased in the CW while these parameters were decreased by the RSF (Table 3). This increase in TDS and EC through the CW was due to evapotranspiration causing concentration of these parameters. PO_4^{3-}–P concentration decreased 32% in the CW (Table 3). This was attributed primarily to P uptake by the vegetation within the CW (Huang et al., 1994).

Table 2: The Effect of Influent Type and Soil Depth on Fecal Coliforms in Column Leachate.

Influent type	Soil depth (cm)	Fecal Coliforms (counts/100 mL)
	Column influent	
STE	--	35800
CWE	--	3200
RSFE	--	170
	Column leachate	
STE	15	910 a*
STE	30	70 b
STE	45	0 b
CWE	15	40 b
CWE	30	0 b
CWE	45	0 b
RSFE	15	0 b
RSFE	30	0 b
RSFE	45	0 b

* means followed by the same letter are not significantly different ($p<0.05$) as determined by Duncan's Multiple Range Test
STE - septic tank effluent
CWE - constructed wetland effluent
RSFE- recirculating sand filter effluent

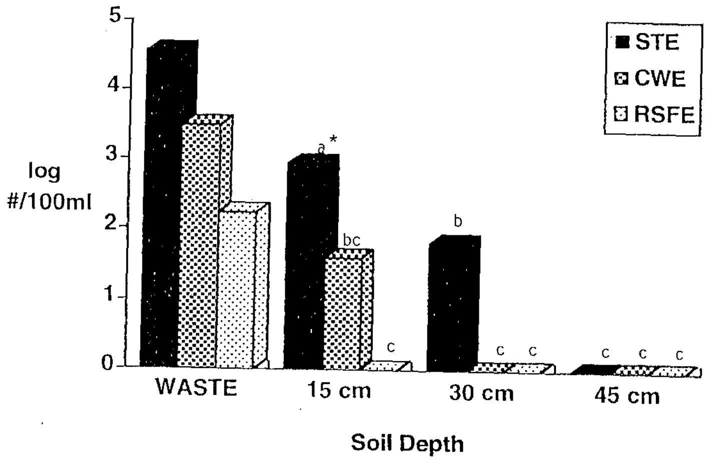

Figure 3: Lognormalized Fecal Coliform Differences with Soil Depth and Influent Type.
* means followed by the same letter are not significantly different ($p<0.05$) as determined by Duncan's Multiple Range Test
STE - Septic Tank Effluent
CWE - Constructed Wetland Effluent
RSFE- Recirculating Sand Filter Effluent

For all soil depths and influent types, the soil column leachate showed reductions in BOD_5, EC, TDS, PO_4^{3-}–P, and NH_4^+–N, and increases in NO_2^-–N, NO_3^-–N, and SO_4^{2-}–S (Table 3). BOD_5, EC, and TDS decreased with an increase in soil depth for all influent types (Table 3). All soil column treatments resulted in leachate with less than 4 mg/L BOD_5 (Table 3). Phosphate was not detectable in leachate from any of the soil columns (Table 3). Even though the three influents TKN varied by a factor of five, the soil leachate TKN was reduced to less than 5.0 mg/L for all treatments (Figure 4). All soil column treatments resulted in leachate with less than 1.8 mg/L NH_4^+–N (Table 3). The NH_4^+–N concentration decreased with soil depth for all soil columns (Table 3). NO_3^-–N concentration was unaffected by the soil depth treatment (Table 3). However, there were differences in soil leachate NO_3^--N concentration with influent type (Table 3). Average NO_3^--N concentration was lower in the soil column leachate where CWE and RSFE were added to the soil column (Figure 5). Average leachate NO_3^--N concentration from columns receiving STE was 19.2 mg/L, while from soil columns receiving CWE and RSFE were 10.3 and 14.4 mg/L, respectively (Table 3). The lower NO_3^--N concentrations in CWE soil column leachate may be a result of repressed nitrification in these columns due to by-products of the anaerobic decomposition occurring within the CW. Nitrogen loss (based on mass balance of total N from septic tank to soil column leachate) resulted in 55%, 73%, and 66% reduction in total N for the STE, CWE, and RSFE treatments, respectively. The elevated N loss from the CWE treatment was due to the extensive ammonia volatilization and denitrification within the CW.

Soil infiltration rate after one year of effluent applications varied with both the column influent type and soil depth. When the STE received additional treatment by the CW, soil infiltration rates were 30% higher in soil columns receiving CWE in comparison to the soil columns receiving STE. Additional treatment of STE with a RSF resulted in a 70% higher average soil infiltration rate. One consequence of this higher average infiltration rate is the possibility of drainfield size reduction. Laak (1974) concluded that additional treatment of STE can lead to an approximate 50% reduction in required trench length because of the higher effluent acceptance rate. Although no direct research has been completed to determine the environmental impact of applying RSFE to a reduced size drainfield.

Table 3: The Effect of Soil Depth and Influent Type on Selected Constituents in Column Leachate.

Influent type	Soil depth (cm)	BOD_5 mg/L	EC uS/mL	TDS	SO_4	NO_2	NO_3 mg/L	NH_4	PO_4
Column influent									
STE	—	116	1070	575	5.68	0.02	0.32	38.0	3.36
CWE	—	46	1120	600	12.6	0.01	0.30	27.7	2.29
RSFE	—	6.6	895	500	22.2	0.05	20.9	6.87	3.43
Column leachate									
STE	15	2.32 a*	861 a	475 ab	33.5 cd	0.51 a	17.0 abc	1.68 a	<DL
STE	30	1.38 a	776 c	434 c	39.2 cd	0.30 ab	19.1 ab	0.34 b	<DL
STE	45	1.09 a	716 de	401 d	58.7 a	0.32 ab	21.3 a	0.21 b	<DL
CWE	15	3.87 a	870 a	490 a	28.4 d	0.06 b	6.64 e	1.68 a	<DL
CWE	30	1.27 a	817 b	458 b	32.9 cd	0.08 b	13.1 cd	0.25 b	<DL
CWE	45	1.19 a	739 de	407 d	55.7 a	0.17 b	11.0 de	0.20 b	<DL
RSFE	15	1.53 a	788 bc	437 c	42.3 bc	0.01 b	13.9 bcd	0.53 b	<DL
RSFE	30	1.21 a	724 d	400 d	51.2 ab	0.11 b	13.9 bcd	0.20 b	<DL
RSFE	45	1.11 a	683 e	380 e	61.0 a	0.01 b	15.4 abcd	0.23 b	<DL

* means followed by the same letter are not significantly different ($p<0.05$) as determined by Duncan's Multiple Range Test

STE - septic tank effluent
CWE - constructed wetland effluent
RSFE- recirculating sand filter effluent
<DL - below instrument detection limit

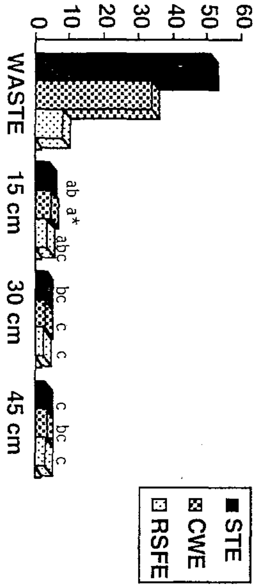

Figure 4: Influent Wastewater and Soil Column Leachate TKN as Influenced by Column Influent and Soil Depth.

* means followed by the same letter are not significantly different ($p<0.05$) as determined by Duncan's Multiple Range Test
STE - Septic Tank Effluent
CWE - Constructed Wetland Effluent
RSFE- Recirculating Sand Filter Effluent

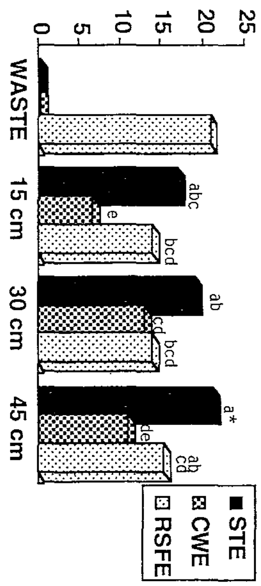

Figure 5: Influent Wastewater and Soil Column Leachate NO_3-N as Influenced by Column Influent and Soil Depth.

* means followed by the same letter are not significantly different ($p<0.05$) as determined by Duncan's Multiple Range Test
STE - Septic Tank Effluent
CWE - Constructed Wetland Effluent
RSFE- Recirculating Sand Filter Effluent

Analysis of plant tissue harvested from the soil columns in 1993 showed no differences between type of influent and dry weight, TKN, Total P, K, Ca, Mg, Mn, Na. For 1993, average percent N, P, and K were 3.0, 0.25, and 3.4, respectively. In comparing the 1993 and 1994 growing seasons, average weekly plant tissue dry weight was greater during the 1994 growing season. In addition, there were elemental concentration differences in the plant tissue with type of influent introduced to the soil columns in 1994. For 1994, average percent N, P, and K were 4.2, 0.33, and 3.4, respectively.

CONCLUSIONS

The results from this study indicate that additional treatment of septic tank effluent improved effluent quality. Additional treatment of septic tank effluent by a constructed wetland and a recirculating sand filter resulted in 30 and 70% higher average soil infiltration rates, 92 and 96% reduction in fecal coliforms, 34 and 44% reduction in total nitrogen, and a 60 and 94% reduction in BOD$_5$, respectively.

Results indicate differences in domestic wastewater renovation for biological contaminants and NO_3^--N with effluent quality and soil depth for fine textured soils. Adequate wastewater renovation with respect to fecal coliforms, BOD$_5$, and total N was achieved with less soil depth when septic tank effluent was additionally treated by constructed wetlands or recirculating sand filters prior to subsurface soil disposal. Fecal coliforms were present only in the 15 cm soil depths that received septic tank and constructed wetland effluents, and the 30 cm depth in soil columns that received septic tank effluent. BOD$_5$ averaged less than 4 mg/L in the soil column leachate, despite a 10 fold difference among influent types. For all influent types and soil depths, the soil column leachate showed reductions in TKN and NH_4^+-N, and increases in NO_3^--N and NO_2^--N, in comparison to the applied influent. Soil leachate contained less than 5 mg/L TKN and 1.8 mg/L NH_4^+-N. NO_3^--N concentrations were lower in treatments receiving constructed wetland effluent for all depths (average of 10 mg/L). In comparison, average NO_3^--N concentrations from columns receiving septic tank effluent were almost twice as high (19 mg/L). Gaseous N loss (based on mass balance of total N from septic tank to soil column leachate) resulted in 55, 73, and 66% reductions in total N for the septic tank, constructed wetland, and recirculating sand filter effluent treatments, respectively.

In conclusion, if a site is limited by marginal soils, constructed wetlands or recirculating sand filters appear to be viable methods for additional treatment of domestic wastewater so that a shallower separation distance between effluent introduction and a water table or restricting soil horizon can be utilized. Additional treatment can safely be a substitute for soil depth. The choice of which additional treatment mechanism to utilize will have to be site specific.

ACKNOWLEDGMENT

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