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IN-SITU LYSIMETER INVESTIGATION OF POLLUTANT ATTENUATION IN THE VADOSE ZONE OF A FINE SAND

D.L. Anderson, R.J. Otis, J.I. McNeillie, R.A. Apfel*

ABSTRACT

A unique *in-situ* field lysimeter research facility was constructed to monitor the fate of septic tank effluent (STE) pollutants in the vadose zone of fine sand soils in Florida. The lysimeter facility was designed to evaluate the treatment capability of the soil over time, under controlled conditions in the field. Controlled variables were the thickness of unsaturated soil (vadose zone) below the wastewater infiltration area and the hydraulic loading rate of STE to the infiltration system. The vadose zone thicknesses investigated were 0.6 and 1.2 meters (2 and 4 ft) for each experimental condition. The hydraulic loading rates investigated were 3.1 and 6.1 cm/d (0.75 and 1.5 gpd/ft^2). In addition, several control cells were operated with a tap water feed to evaluate affects of the natural soil.

Results of the lysimeter facility monitoring after 9 months of operation indicated substantial attenuation of key STE pollutants in the vadose zone of fine sand soils. Biochemical oxygen demand (BOD_5) reductions were in excess of 98 percent, total organic carbon (TOC) reductions were over 90 percent, and surfactant reductions, as measured by the MBAS test, were reduced by over 99 percent. Total Kjeldahl nitrogen (TKN) reductions were in excess of 97 percent. Nitrate-nitrogen (NO_3-N) generated from nitrification was transported to both the 0.6 and 1.2 meters (2 and 4 ft) depths, but at lower concentrations than the total nitrogen applied to the soil, indicating some reduction of total nitrogen concentrations within the soil system. Phosphorus attenuation was variable, but averaged over a 90 percent reduction during the first 9 months of operation. No positive sample results were obtained for fecal coliform or fecal streptococcus bacteria below the infiltration systems at any of the variable levels, indicating that significant attenuation of these fecal indicators also occurred in the sandy soil.
KEYWORDS: Septic tank effluent, Infiltration, Attenuation, Lysimeters, Onsite wastewater treatment.

INTRODUCTION

Concerns over the potential adverse impacts from onsite wastewater treatment system (OWTS) use on Florida's groundwater resources led to initiation of the Florida OWTS Research Project in 1986. Since the project began, a series of studies and field investigations have been conducted to evaluate the impact of high density OWTS use on groundwater and surface water quality, and to determine the capability of Florida soils to accept and treat septic tank effluent under various conditions (Sherman et. al., 1987; Anderson et. al., 1987; Sherman and Anderson, 1991; Anderson, et. al., 1991). As part of this continuing research effort, an *in-situ* field lysimeter facility was constructed to evaluate the fate and transport of septic tank effluent (STE) pollutants in the vadose zone of fine sandy soils. Details of the design, construction, and operation of this facility can be found elsewhere (Ayres Associates, 1993b). This paper presents a brief summary of the preliminary results of this research effort.

* D.L. Anderson, Regional Vice President, Ayres Associates, Tampa, FL
R.J. Otis, Vice President, Ayres Associates, Madison, WI
J.I. McNeillie, Senior Hydrogeologist, Ayres Associates, Tampa, FL
R.A. Apfel, Senior Soil Scientist, Ayres Associates, Madison, WI

The lysimeter facility was designed to evaluate the treatment capability of undisturbed natural soil over time, under controlled conditions in the field. Controlled conditions are necessary because determination of OWTS treatment capabilities and impacts to groundwater is difficult from field studies of existing systems due to variable flows, differing wastewater characteristics, and fluctuating groundwater elevations. Most of the previous controlled experimental work has been done with laboratory soil columns, but field conditions cannot be duplicated in the laboratory, limiting the validity and extrapolation of results. Laboratory simulation of field conditions is particularly difficult for Florida's climate where heavy thunderstorms may be affecting treatment performance within the very porous, sandy soils of the state. For these reasons, a field study on undisturbed natural soils with control over selected variables important to the evaluation of treatment capability was desired. The field lysimeter research facility was designed and constructed to accomplish this.

MATERIALS AND METHODS

Experimental Design

The experimental design consisted of evaluating the effect of vadose zone (unsaturated soil) thickness and wastewater hydraulic loading rate on the capability of fine sandy soil to attenuate septic tank effluent pollutants. To conduct this research, a unique field lysimeter research facility was designed, constructed, and operated under controlled conditions. Multiple *in-situ* soil infiltration cells, or lysimeters, were designed so that experiments at two STE hydraulic loading rates and two vadose zone thicknesses could be conducted simultaneously with the same wastewater on the same soil. In addition, numerous soil physical/chemical parameters and meteorological conditions were monitored to aid in interpretation of the results. Table 1 summarizes the selected variables which were controlled and studied.

Table 1. Summary of Lysimeter Facility Study Variables

Controlled Variables	Values of Variables Studied
Soil Type	fine sand (Quartzipsamment)
Unsaturated Zone Thickness	0.6 m (2 ft) below infiltrative surface 1.2 m (4 ft) below infiltrative surface
Hydraulic Loading Rate of STE	0.31 cm/d (0.75 gpd/ft^2) 0.61 cm/d (1.50 gpd/ft^2)

Triplicate STE infiltration cells were operated for each experimental condition. In addition, one infiltration cell at each condition was operated with a tap water feed instead of STE to act as controls to evaluate any affects of the natural soil. Also, four natural soil infiltration cells without any loading were monitored to evaluate natural soil conditions and impacts of rainfall.

The main response variable measured was the quality of soil water below the infiltrative surface. Parameters measured included biochemical oxygen demand (BOD_5), total organic carbon (TOC), total Kjeldahl nitrogen (TKN), nitrate nitrogen (NO_3-N), total phosphorus (TP), chloride (Cl), surfactants, as methylene blue active substances (MBAS), fecal coliform (FC) bacteria, fecal streptococcus (FS) bacteria, and several conventional water quality indicators.

In addition, soil moisture content, oxidation-reduction potential (ORP), and temperature were measured to evaluate soil characteristics. Climatic conditions, such as temperature and rainfall were also monitored to better evaluate treatment efficiency of the soil.

Lysimeter Facility Design and Construction

The research lysimeter facility was constructed on the University of South Florida (USF) Campus in Tampa. Figures 1 and 2 show plan and sectional views, respectively, of the facility. Septic tank effluent was obtained from a campus ministry building, which houses three to four students and is currently served by an existing OWTS. Soil at the research station site is Candler fine sand, an excessively drained, uniform, fine sand commonly found on the uplands of central Florida. Groundwater at the site was greater than 6 meters (20 ft) below ground surface.

To evaluate the effect of unsaturated thickness on treatment, a subsurface sampling gallery was constructed to a depth of approximately 2.4 meters (8 ft) below grade (see Fig. 2). To preserve undisturbed, native soil conditions next to the gallery for wastewater infiltration areas, rows of sheet-piling were vibrated into place isolating a 1.2 meters wide by 21.3 meters long (4 ft wide by 70 ft) soil area on each side of the proposed gallery structure. The gallery was constructed between the sheet-piled areas. Outside of each sheet-piled area, artificial water tables were constructed to simulate the soil moisture conditions for the two unsaturated thicknesses selected (See Fig. 2). The artificial water tables were constructed with the water surface at a depth of approximately 0.6 meters (2 ft) below the proposed infiltrative surface elevation on one side of the gallery and 1.2 meters (4 ft) below on the other side. These were constructed by excavating to the desired depth and lining the excavation with 10 mil plastic. A 10 cm (4 in) layer of pea gravel was placed on the liner, and 2.5 cm (1 in) PVC water distribution line placed on the gravel. These areas were backfilled with native soil to original grade. Saturation was maintained for 15 to 30 cm (6 to 12 in) above the liner to simulate the effects of a water table and to increase the soil moisture content around the boundary of the infiltration cells.

Once construction of the gallery and water tables was completed, the sheet-pilings were removed, leaving undisturbed soil next to the gallery walls. Sixty centimeter (2 ft) wide, gravel-filled, wastewater infiltration trenches were constructed on either side of the gallery, approximately 46 cm (18 in) from the gallery walls. Each trench was divided into eight individual infiltration cells, separated by a divider wall which prevents liquid short circuiting from one cell to another, and two end cells. Divider walls were placed to a depth of 5 cm (2 in) below the infiltrative surface and extended 5 cm (2 in) above the top of the 30 cm (12 in) thick gravel layer. Except for the cells at the end of the trenches, each cell has a separate distribution system to which loading can be controlled. Thus, 16 separate infiltration systems can be operated simultaneously, eight subject to a 1.2 meter (4 ft) water table and eight subject to a 0.6 meter (2 ft) water table. The four end cells were established to examine the quality of water naturally percolating through the soil and consist only of a column of natural soil, and do not contain gravel or distribution piping.

Lysimeter Monitoring Equipment

To obtain soil water samples from the two unsaturated depths, stainless steel sampling pans were fabricated and pushed from within the gallery, with a hydraulic jack, into the unsaturated soil below the infiltration trenches. The pans were inserted below each individual infiltration cell, at 0.6 or 1.2 meters (2 or 4 ft) below the infiltrative surfaces. The pans have a slight descending gradient toward the gallery for collection of samples. The intent of the pans was to intercept septic tank effluent percolating through the unsaturated soil. Soil water, which saturates at the pan surface, flows through a sampling tube into the gallery for collection in sample bottles. The pans extend to within approximately 30 cm (12 in) of the artificial water tables. Horizontal and vertical separation prevents the water tables from flowing onto the pans, which would cause sample dilution. The purpose of the water tables was to maintain adequate moisture content in the soil to minimize lateral movement of percolating soil water. Without the artificial water tables, dry soil next to the lysimeter pans would likely pull much of the percolating STE away

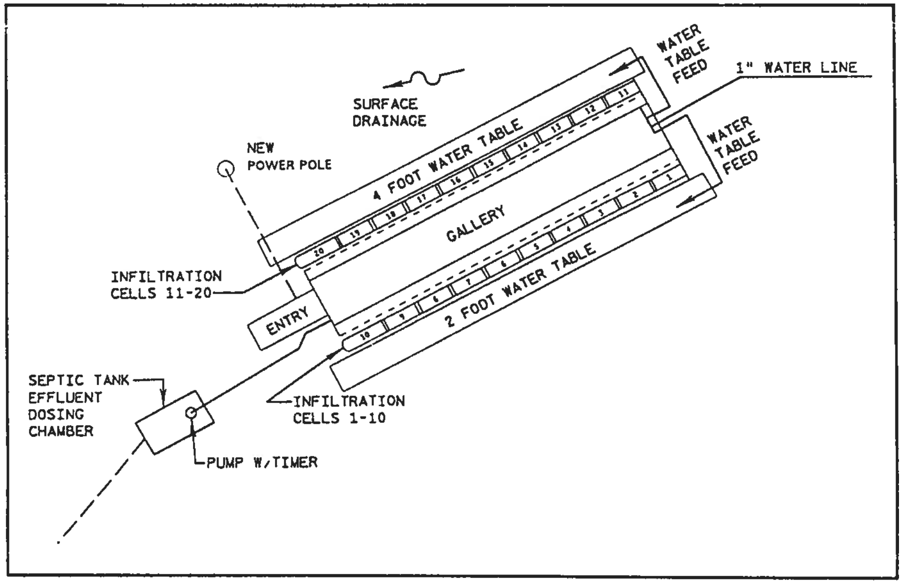

Figure 1. Plan View of the Lysimeter Station Facility

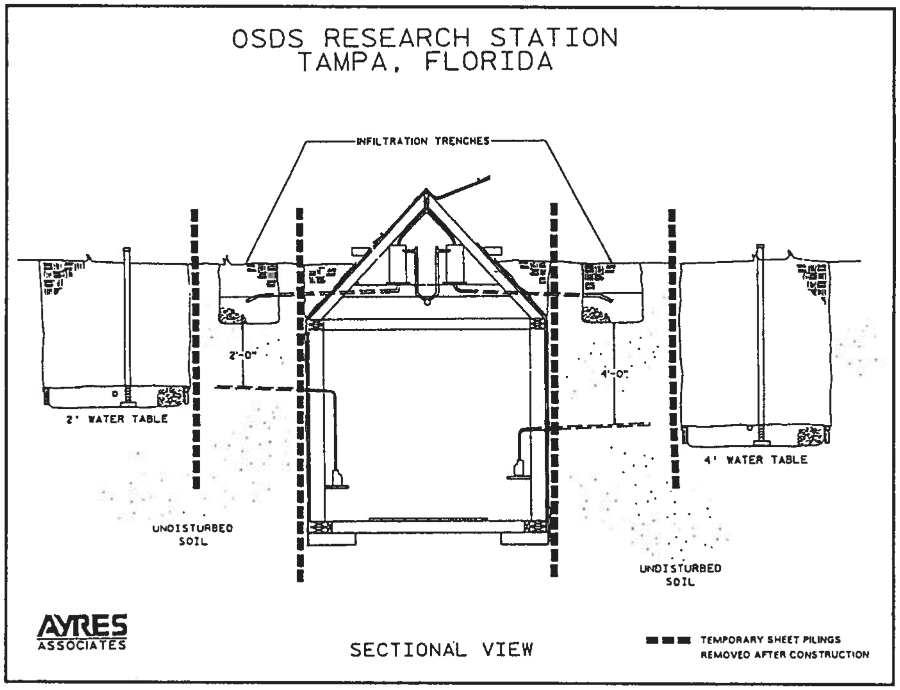

Figure 2. Sectional View of the Lysimeter Station Facility

from the pans preventing sample collection. The resulting effect of the water table-lysimeter pan complex was to simulate the physical soil conditions above 0.6 and 1.2 meter (2 and 4 ft) water tables.

In addition to the stainless pans, porous ceramic suction lysimeters were placed in the soil at selected locations. The suction lysimeters were placed in the soil immediately over, and at 30 cm (1 ft) intervals, above the pans in several cells. This allowed sample collection from a desired depth in the absence of complete saturation of the soil above the pans. Soil moisture tensiometers, soil thermometers, and oxidation-reduction probes were also placed in the unsaturated zone at selected locations.

Lysimeter Operation

Wastewater was dosed to the infiltration cells by pumping into dose pots, which were calibrated based on a desired cell loading rate. Wastewater was distributed to the cells six times per day on a schedule designed to approximate the loading from a single family home. Doses were applied at 6:00, 7:00, and 8:00 a.m., noon, and 6:00 and 7:00 p.m. each day. On each side of the gallery, three cells received 0.31 cm/d (0.75 gpd/ft^2) of STE and three cells received 0.61 cm/d (1.5 gpd/ft^2) of STE. The remaining two cells received tap water, one at each loading rate, on the same loading schedule as the cells that received STE. Tap water cells were used as additional controls to examine effects which were not related to wastewater loading. The experimental conditions are summarized in Table 2.

Table 2. Summary of Lysimeter Station Experimental Condition

Number of Infiltration Cells	Unsaturated Thickness (ft)	Loading Rate (gpd/ft^2)	Loading Type
3	2	0.75	STE
3	2	1.50	STE
1	2	0.75	Water
1	2	1.50	Water
2	2	0.00	None
3	4	0.75	STE
3	4	1.50	STE
1	4	0.75	Water
1	4	1.50	Water
2	4	0.00	None

Operation of the lysimeter facility was started in June 1992, with tap water to correct any operational problems. In August 1992, wastewater dosing was initiated with STE from the campus ministry. Monitoring of STE quality began after several days and soil water sample collection after two weeks.

It was realized during the initial operation with tap water that soil water samples may be difficult to obtain by gravity from the lysimeter pans. Apparently soil saturation at the pan surface did not occur under the loading rates and soil conditions of the experiment. The facility design was based on the premise that a steady state moisture condition would develop below the infiltrative surfaces resulting in saturation on the pan surfaces. This did not occur because of the pore size distribution of the soil. Figure 3 presents soil moisture retention curves of cores collected from the site. Four curves are shown for sample depths of 0.3 to 1.2 meters (1 to 4 ft) below the infiltrative surface. This data shows the uniformity of the soils with depth. They also show the abrupt drop in volumetric water content that occurs as soil moisture tension rises. This is typical of a sand with very uniform grain and pore sizes, as all pores tend to drain at the same tension. Soil moisture tension immediately above the pans under operating conditions of the 0.6 meter (2 ft) unsaturated zone was observed to be 35 to 40 millibars (mb), and 40 to 45 mb below the 1.2 meter (4 ft) unsaturated zone. Although near saturation, these soil moisture tensions were enough to retain water in the soil pores. Higher soil moisture tension beyond the pans probably created a gradient away from the gallery and was the likely cause for failure to achieve zero potential at the soil-pan surface interface. Distribution of greater volumes of water to the artificial water tables may sufficiently modify these conditions and allow saturated flow on the pan surface.

Because the pans did not yield samples by gravity, the ceramic suction lysimeters were used for soil water sample collection during the first five sampling events. By applying a vacuum to the porous ceramic cups, soil suction was overcome and soil water pulled into the sampler. The ceramic suction lysimeters were of limited use, however, as they cannot be used to sample for bacteria because of attenuation by the porous ceramic. To allow sampling from the pans, a very low vacuum ($\leq$50 mb) was applied to the sampling tubes of the pan lysimeters. This method was successful in releasing soil water for sample collection. Initial samples contained small quantities of soil particles and were turbid, but samples progressively cleared with each sample event. Subsequent samples were collected from the pans by this method.

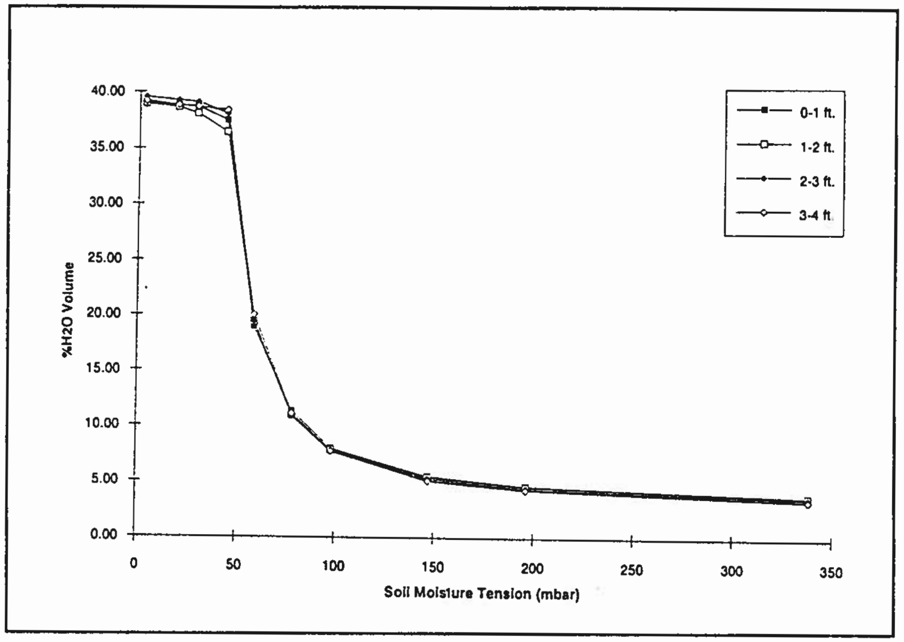

Figure 3. Soil Moisture Retention Curves

RESULTS AND DISCUSSION

<u>Soil Water Quality</u>

Table 3 shows preliminary results for several key parameters of this research effort based on sample analyses through the first nine months of facility operation. Statistical comparisons of data from the ceramic suction samplers and stainless steel pan samplers indicated no significant differences, so the data was combined on this table. Differences among treatment replicates were not observed so values from all similar cells were combined for this analysis. Septic tank effluent sample analysis results are also presented in Table 3.

Results of monitoring soil water below the tap water control cells indicated that the only parameter contributed was TOC. Tap water increased in TOC concentrations by approximately 2 to 4 mg/L as it percolated through the native soil at the site, regardless of loading rate or unsaturated zone thickness. All other parameters appeared to remain relatively unchanged.

The average soil water quality results are interesting when compared to the average quality of the applied STE. These results show significant attenuation of BOD, TOC, MBAS, TP, and TKN in both the 0.6 and 1.2 meter (2 and 4 ft) cells. In fact, little difference in attenuation of these parameters was observed between results of the two unsaturated zones. BOD_5 was reduced by over 98 percent to values below the detection limit of 1 mg/L. TOC reductions were over 90 percent when adjusted for the control cell TOC. MBAS was reduced by over 99 percent. TKN reductions were in excess of 97 percent, most likely due to nitrification of STE nitrogen.

Total phosphorus concentrations in the soil water were variable, but were reduced by an average of over 96 percent for all conditions except the high loading of the 0.6 meter (2 ft) cells. Since capacity of the soil to retain phosphorus is limited, it may eventually "break through" and enter the saturated zone. Continued sampling of the cells should allow measurement of the time to phosphorus breakthrough thereby giving an estimate of the phosphorus capacity of the fine sand soil.

The reductions in pollutant concentrations apparently are due in part to dilution of the effluent with natural soil moisture. Using chloride as a conservative parameter, it appears that a 40 to 45 percent reduction in chloride concentration occurred in the STE cells due to dilution. It should be noted that the reduction in chloride in the lower loaded, 1.2 meter (4 ft) cells is unusually high and was not included in determination of this estimate. In the tapwater cells, however, only a 2 to 8 percent reduction in chloride concentration was observed. The reason for the disparity between the STE cells and tapwater cells is unclear. In addition, there was little evidence of dilution effects in the TDS data. The actual dilution due to natural soil moisture was, therefore, difficult to estimate.

Nitrification of STE nitrogen resulted in NO_3 nitrogen concentrations of approximately 20 mg/L at both the 0.6 and 1.2 meter (2 and 4 ft) depths. Although this suggests a significant reduction in total nitrogen from STE concentrations, some of this reduction is due to dilution with natural soil moisture as previously indicated.

No detection of fecal coliform or fecal streptococcus has occurred after nine months of sampling. It appears that these fecal indicator bacteria are effectively attenuated in the unsaturated, fine sand soil below the infiltration trenches.

Table 3. Summary of STE and Soil Water Quality[a]

Parameter (units)	Statistics	STE Quality	Soil Water Quality 0.6 m[b] 3.1 cm/d[c]	0.6 m 6.1 cm/d	1.2m 3.1 cm/d	1.2m 6.1 cm/d
BOD_5 (mg/L)	Mean	93.5	<1[d]	<1	<1	<1
	Range	46 - 156	<1	<1	<1	<1
	n	11	6	6	6	6
TOC (mg/L)	Mean	47.4	7.8	8.1	8.0	8.7
	Range	31 - 68	3.7 - 17.0	3.6 - 18.0	3.1 - 25.0	5.0 - 18.0
	n	11	34	37	33	35
MBAS (mg/L)	Mean	9.1	0.05[d]	0.05	0.05	0.05
	Range	4.5 - 17.0	0.05 - 0.08	0.05 - 0.08	0.05 - 0.08	0.05 - 0.09
	n	11	33	35	31	35
TKN (mg/L)	Mean	44.2	0.77	0.88	0.77	1.10
	Range	19 - 53	0.40 - 1.40	0.33 - 1.60	0.25 - 2.10	0.56 - 3.50
	n	11	35	39	33	35
NO_3-N (mg/L)	Mean	0.04	21.6	19.9	13.0	20.9
	Range	0.01 - 0.16	1.7 - 39.0	0.0 - 38.0	2.0 - 29.0	9.1 - 35.0
	n	11	35	38	32	35
TP (mg/L)	Mean	8.6	0.40	1.24	0.18	0.53
	Range	7.2 - 17.0	0.01 - 3.80	0.02 - 8.80	0.02 - 1.80	0.02 - 2.70
	n	11	35	40	33	35
TDS (mg/L)	Mean	497	448	445	355	480
	Range	354 - 610	184 - 620	172 - 654	200 - 592	270 - 656
	n	11	34	37	32	35
Cl^- (mg/L)	Mean	70	41	41	29	42
	Range	37 - 110	9 - 65	14 - 65	9 - 49	22 - 58
	n	11	34	35	31	35
F. Coli. (log#/100 ml)	Mean	4.57	nd[e]	nd	nd	nd
	Range	3.6 - 5.4	<1	<1 - <10	<1	<1
	n	11	24	25	21	21
F. Strep. (log #/100 ml)	Mean	3.60	nd	nd	nd	nd
	Range	1.9 - 5.3	<1	<1 - <2	<1	<1
	n	11	23	24	20	20

[a] Results based on samples taken over first 9 months of lysimeter facility operation.
[b] Unsaturated soil thickness between infiltrative surface and pan lysimeter
[c] STE hydraulic loading rate
[d] value equals the method detection limit
[e] nd = none detected

CONCLUSIONS

The preliminary results at the lysimeter facility showed excellent treatment of STE by unsaturated, fine sand soil below typical OWTS infiltration systems.Effective removal of BOD, TOC, MBAS, TP, TKN, and fecal indicator bacteria was observed at both the 0.6 and 1.2 meter (2 and 4 ft) depths. Little difference was noted due to the hydraulic loading variation. Nitrate-nitrogen, as expected, was generated from nitrification of STE nitrogen and was transported to both the 0.6 and 1.2 meter (2 and 4 ft) depths at relatively high concentrations but was substantially reduced from the total nitrogen concentrations of the STE. It is apparent that 0.6 meters (2 ft) of unsaturated, fine sand provides treatment levels well above typical secondary wastewater treatment limits.

As discussed, saturated conditions did not form at the pan samplers. This indicates that soil below the infiltration trenches may be slightly drier than would be the case if an actual water table were present. Measurements of soil moisture near the pan surface indicated very wet, but not quite saturated conditions. Based on the soil moisture retention data collected, it appears that present lysimeter conditions more closely simulated 0.6 and 1.2 meter (2 and 4 ft) distances to a capillary fringe, rather than a true water table. Thus, the observed reductions of some pollutants may be somewhat higher than would occur with the existence of a true water table condition within 0.6 meters (2 ft) of the infiltration system. It is felt that such a condition can be simulated at the lysimeter station with minor modifications and this would help to provide more data with which to evaluate the treatment capability of these systems.

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