WASTEWATER APPLICATION TO SOILS: HYDRAULIC AND NITROGEN CONSIDERATIONS

by

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(ABSTRACT)

Land application of domestic and industrial wastewaters provides an effective means of recycling water and its components into the ecosystem. Successful treatment by soil requires that wastewater is applied in quantities that both maintain infiltrative capacity of the soil and do not exceed the capacity of the soil-plant system to assimilate biological and chemical contaminants. Application of N-rich wastewaters requires that consideration be given to both the ability of the soil to transmit the hydraulic load and remove sufficient N to maintain groundwater quality standards. A textile wastewater containing high concentrations of organic N was spray-irrigated to tall fescue *(Festuca arunindinacea)* to determine optimum N application levels. Nitrogen balances were determined at each N level and and the potential for predicting the leaching component of the excess N applied was investigated. Historically on-site wastewater disposal systems (OSWDS) for treating septic tank effluent (STE) have been designed on a hydraulic loading basis with N pollution potential essentially ignored. Many soils have been deemed unsuitable for application of STE because of textural, water table, or landscape restrictions. The relations between soil properties, hydraulic performance of OSWDS, and N distribution around OSWDS are evaluated.

Wastewater from a nylon processing plant was applied to 'Ky 31' tall fescue at total Kjeldahl nitrogen (TKN) levels of approximately 250, 430, and 1900 kg ha^{-1} during 1982 and 1983. Fescue yield and N removal was comparable to agricultural yields at similar N application levels. Nitrogen balances indicate that plant uptake efficiency decreased with increasing organic N levels above the 250 kg ha^{-1} level and that maximum uptake occurred at the 450 kg ha^{-1} level. Most of the N not recovered in plant tissue mineralized rapidly to the nitrate NO_3^- form and leaching was noted during the winter and spring. This data is evaluated with quasi-transient analytical solution of the

convection-dispersion equation. The movement of the solute center of mass is predicted on the basis of assumptions of piston flow as well as alternative assumptions of mixing via plate layer theory. Prediction of the location of the center of solute mass (α) provides a moving lagrangian coordinate solution around which dispersion of solute is calculated. The assumptions made about the sequence of evaporation and infiltration events significantly influence the prediction of α and hence the agreement between predicted and measured solute distribution. Both approaches give results which are within experimental error and provide a rational basis for predicting leaching losses and carry-over NO_3^- available to future crops.

Prototype OSWDS with low pressure distribution installed in three clayey limestone-derived soils were dosed with STE at flux densities ranging from 0.4 to 3.6 cm d^{-1} on a trench bottom area basis. Ponding was noted in OSWDS at all sites dosed at the 3.6 cm d^{-1} flux due to both underlying hydraulic restrictions and resultant anaerobic conditions. It is concluded that clayey B horizons low in swelling clays but moderately well structured can be dosed at flux densities up to 2 cm d^{-1} if low pressure distribution of STE is used. Nitrification was found to be quite limited in soils where effluent was ponded above a restrictive layer but occurred readily within 30 cm below trenches which were freely drained or had matric potentials of at least 40 cm of water. Ratios of NO_3^- to Cl^- indicate that only limited denitrification can be expected and that substantial NO_3^- does leach from below OSWDS in the direction of water flow.

DEDICATION

To   and

In giving their lives in simple service to others
they have given definition to love

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First I acknowledge the power of God's love, without which I could not have overcome my own limitations and completed this work. When the obstacles seemed insurmountable, His love gave me the peace and courage to go on. Acknowledgement goes to my parents, my wife,   and to my brothers and sisters, all of whose love and support have helped mold me into the person I am and to   whom have taught me to play.

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and many others are acknowledged for their camaraderie and shared path.

Fabric of Life

An accomplishment such as a degree is not the work of one man or woman
It is rather a part of the fabric of life
A fabric begun long ago
As a man and woman wove their lives together in a song of love

The core of this fabric draws on the early threads of life
Threads which give unique texture, flavor, resiliency
As the fabric grows larger the weaver draws on threads of other's lives
Mixing and interweaving of lives gives color, strength

Tighten does the garment with adulthood
Stretching must occur - new sources of thread, of wool, are found
Stitches may be torn, may fray
Yet patches only tear

Healing is the art of interweaving the new with the old
New wool to strengthen, give texture, yet not replace
Only enhance
Give resilience

Arise young weaver arise!
Weave now in unison with those around
Share your thread, give depth to the garment of life
Wool uncolored by yourself, rather interwoven by those around you has indeed given beauty

Share it!
Share the fabric
Do not admire it - warm the heart covered by a sparse fabric
Interweave its threads of love in the fabric of life

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John J. Simon
March 18, 1986

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1.0 CHAPTER I.

INTRODUCTION

Renovation of wastewater is a combination of biochemical and mechanical processes which break down complex organic materials in the wastewater and remove them as the water flows through the treatment plant, stream, or soil system. The complex communities of microflora in the soil system and its porous nature provide an environment quite suitable for renovation of many types of wastewaters. Soils are commonly used to renovate industrial and municipal wastewaters as well as septic tank effluent. In addition, a variety of animal manures and municipal sludges are recycled back into the environment via land application.

Design of a soil treatment system for wastewater application requires consideration of both the ability of the soil to transmit the hydraulic load and to assimilate, recycle, or dilute any contaminants to safe levels prior to movement into ground and surface water supplies. Domestic wastewaters disposed of on-site are typically nitrogen (N) rich relative to the amount of carbon (C) present. Likewise, N may be the limiting factor for many municipal and industrial wastewaters. Depending on the N levels present, loading rates may either be determined on a hydraulic basis or on the basis of potential for removal of N by the soil plant system. Historically, most on-site wastewater disposal systems have been designed on the former basis with little consideration for the latter. In contrast, municipal and industrial application of wastewater is often limited by levels of N anticipated to be in renovated water moving to ground and surface water bodies.

This dissertation is a summary studies related to wastewater application to soils. Each of these studies are written as individual research papers in a format suitable for scientific publication. Each paper is presented as an independent chapter which stands alone. A summary of the objectives and content of each chapter follows:

1.1 Chapter 2 is entitled "Irrigation of fescue with textile wastewater: I.Nitrogen Balances."

The first topic addressed is the fate of N present in a textile wastewater surface applied to

tall fescue (*Festuca arunindinacea*). The objective of this study was to determine N balances for wastewater- irrigated fescue at different N application rates. The response of tall fescue to varying rates of N application over a two year period of time is determined. Nitrogen removal by fescue is discussed as well as the movement of soil inorganic N and unaccounted for losses assumed to represent denitrification and leaching.

1.2 Chapter 3 is entitled "Irrigation of Fescue with Textile Wastewater: II. Prediction of NO_3^- Leaching." Nitrate leaching following the nitrification of the organic N in the wastewater is predicted and compared to observed leaching rates. The objectives of the study are (1) to determine whether mean solute penetration depth is best described by equations based on piston flow (Model 1) or plate layer theory (Model 2), and (2) to compare NO_3^--N distribution predicted by two transient models (Models 1 and 2) and one equivalent steady state model (Model 3) with field measured NO_3^--N distribution. Water additions and losses are averaged by week and input separately in transient form in Models 1 and 2. In Model 3, the cumulative water losses are subtracted from the cumulative additions and the mean velocity is determined by assuming that it is equivalent to steady state conditions. Model 3 is also used in an inversion mode to determine the changes in the dispersion coefficient and apparent velocity with time.

1.3 Chapter 4 is entitled "Septic Tank Subsurface Absorption Systems in Clayey Limestone-Derived Soils: I.Performance." In this chapter the suitability of clayey limestone-derived soils for application of septic tank effluent (STE) is discussed. The objectives of this study were (1) to test the hypothesis that clayey, well drained soils are suitable for ST-SAS if LPD of effluent is used and (2) determine appropriate loading rates for different soil structures and depths to restrictive layers. Soils with a range of structures and depths to bedrock or restrictive layers were dosed at different flux densities with septic tank effluent for a three year period of time. The relations between soil morphological properties, hydraulic loading rates, ponding, and observed clogging are discussed. Optimum hydraulic

loading rates are suggested for clayey soils with different grades and sizes of soil structures and depths to a restrictive layer.

1.4 Chapter 5 is entitled "Septic Tank Subsurface Absorption Systems in Clayey Limestone-Derived Soils: II. Relations between Ponding, Pressure Heads, and Nitrification." Potential for nitrification relative to the hydraulic status of the soils surrounding an OSWDS is discussed in this chapter. The objective is to determine the extent of nitrification in clayey limestone derived soils below ST-SAS which are (1) ponded and (2) not ponded with STE. This research indicates that substantial nitrification below OSWDS in well drained soils is to be expected if oxygen can diffuse to the zone into which ammonium (NH_4^+) is being transported.

1.6 Chapter 6 summarizes this work and lists the major conclusions of the four studies.

1.7 Appendix A contains the FORTRAN program for Model 1 which predicts the movement of the solute peak based on piston flow assumptions (see Chapter 3.). Dispersion of solute around the center of mass is subsequently calculated by the model.

1.8 Appendix B contains the FORTRAN program for Model 2 which predicts the movement of the solute peak using plate-layer theory (see Chapter 3.). Dispersion of solute is calculated as in Model 1.

2.0 CHAPTER II

IRRIGATION OF FESCUE WITH TEXTILE WASTEWATER: I. NITROGEN BALANCES

2.1 ABSTRACT

Numerous studies have indicated that application of municipal, industrial, and food processing wastewaters at N levels near or below those required for maximum yield have resulted in minimal N leaching. This study evaluates the N balance for irrigation of a nylon processing wastewater containing capralactam at TKN concentrations of about 2000 mg L^{-1}. Wastewater was applied to 'Ky 31' tall fescue *(Festuca arunindinacea)* growing on a Pamunkey sandy loam (fine loamy, thermic, mixed Ultic Hapludult) soil at total Kjeldahl nitrogen (TKN) levels of approximately 250, 430, and 1900 kg ha^{-1} in 1983 and at slightly lower TKN levels in 1982. Fescue yields and N uptake were comparable to those reported in the literature for similar levels of N fertilization. The organic N mineralized and nitrified rapidly during summer and fall months. Nitrate not removed by plant growth moved steadily through the soil profile during winter months in response to surplus rainfall. Fescue growth during the summer of 1983, but prior to irrigation, depleted subsoil NO_3^- remaining from wastewater applied in 1982. While some losses due to denitrification may occur, wastewaters with readily mineralizable, but high TKN concentrations should be applied at N levels expected to result in maximum uptake efficiency prior to periods of anticipated maximum plant growth. Wastewater should not be applied late in the fall if the grass is not anticipated to remove most N or unless winter rainfall will not result in substantial leaching.

Additional key words: spray irrigation, nitrate leaching, ammonium, volatilization, mineralization, denitrification, land treatment

2.2 INTRODUCTION

Economical recycling of wastewater and nutrients back into the environment is often best accomplished by irrigation of agronomic crops. When applying effluents with relatively high concentrations of N, groundwater discharge standards of 10 mg L^{-1} typically control application levels rather than maximum infiltration rates. Irrigation of crops with food processing and municipal wastewaters which have relatively high mineralizable N concentrations has led to the conclusion that wastewater N uptake rates by plants are closely approximated by plant response to similar levels of N addition from inorganic fertilizer sources (Smith and Hayden, 1984; Olson et al., 1982; Adriano et al., 1975; Feigin and Kipnis, 1980; Broadbent and Carlton, 1978). In treatment systems where plant removal of N is the wastewater load limiting factor, maximum removal of N can normally be obtained by growing a long season grass (Smith and Peterson, 1982). Irrigation with low C to N ratio wastewaters at levels of mineralizable N exceeding potential crop assimilation results in accumulation in the root zone and leaching to ground or surface water. The continuation of high flux densities, excessive N loading rates, and anoxic periods has resulted in large losses (Burton and Hook, 1979; Smith, 1976; Smith and Peterson, 1982). Even with substantial denitrification, groundwater N levels below the root zone may exceed maximum standards (Burton and Hook, 1980; Adriano et al., 1975). Likewise timing of wastewater application may be critical, especially for crops grown on sandy soils or with shallow root systems. Feigin and Kipnis (1980) reported maximum yield and minimum N losses for a tropical grass which was irrigated twice weekly instead of once per week. They concluded that single weekly irrigations of wastewater carried N beyond the relatively shallow root zone. With more deeply rooted crops, removal of carry-over N in subsequent years has been reported by authors using direct (Broadbent and Carlton, 1978) and indirect (Smith and Hayden, 1984) measurements.

In this study a nylon processing wastewater containing approximately 2000 mg L^{-1} organic N as capralactam, a readily mineralizable compound with a C to N ratio of approximately 4, was applied to 'Ky 31' tall fescue (*Festuca arunindinacea*). The objective of this study was to determine the optimum N application level while minimizing carry-over N available for leaching. Plots were

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irrigated at TKN levels of approximately 0, 250, 430, and 1900 kg ha^{-1} in 1983 and at slightly lower TKN levels in 1982. Due to late season application in 1982, large quantities of inorganic carry-over N were measured in the soil profile during winter and spring of 1983. Much of this N was removed by fescue grown before onset of the 1983 irrigation. Optimal loading levels are discussed and N balances presented in this paper.

2.3 MATERIALS AND METHODS

A Pamunkey sandy loam (fine-loamy, thermic, mixed Ultic Hapludult) was seeded with 'Ky 31' tall fescue in the spring of 1982 and reseeded in the spring of 1983 to improve the ground cover. A small amount of fertilizer N (included in the N balance) was applied at each seeding to enhance fescue establishment. Plots (duplicate) were circular and consisted of an irrigation riser that wetted an area 8.2 m in diameter. Soil and grass samples were collected from a 0.8 X 1.8 m area centered at the midpoint of the radius of each plot (see Fig. 1). Wastewater fluxes applied to each treatment are listed in Table 1. Wastewater was applied from September 28 to October 27 in 1982 and from July 8 to November 2, 1983. Fescue was harvested October 28, 1982 and June 16, August 10, and November 9, 1983 and dry weight determined after drying at 70° C for 24 h.

Soil samples were collected on October 27, 1982, January 5, and April 6, 1983 with a hand-held soil sampling tube to a minimum depth of 1.2 m. A Giddings soil coring machine was used to collect samples to a minimum depth of 1.5 m on November 9, 1983. Samples were taken from at least two points in each plot on each sampling date.

2.3.1 Chemical Analysis

Plant tissue samples were ground to pass a 40 mesh screen and TKN determined using a procedure similar to that of Nelson and Sommers (1972). Soil samples were placed on dry ice and frozen immediately after collection. Soil NO_3^- and NH_4^+ was extracted from a 5 g subsample with 50 ml of 1N KCl solution. The nitrite (NO_2^-) + NO_3^- concentrations were determined colorimetrically at 540μm as NO_2^--N using the Cu coated Cd reduction technique and an autoanalyzer (U.S. Environmental Protection Agency, 1974). Ammonium-N was determined using the indophenol-blue technique on an autoanalyzer (U.S. Environmental Protection Agency, 1974).
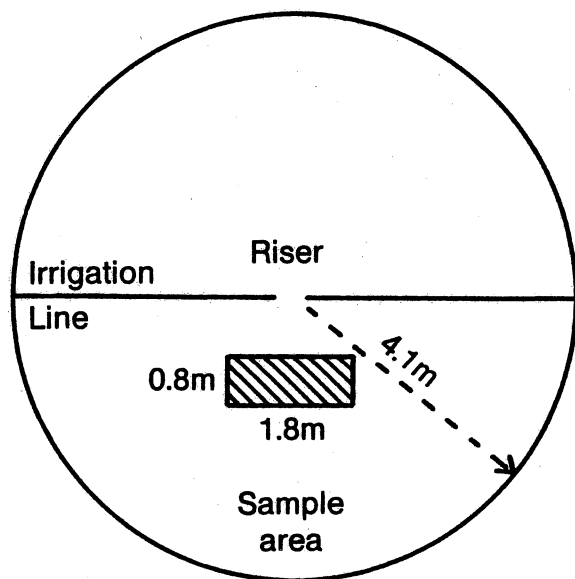
Figure 1. Experimental design for wastewater irrigation plots.

Table 1. Wastewater and nitrogen applied to fescue.

Treatment	Spray times/wk	Wastewater total cm	Nitrogen(TKN) $(kg\ ha^{-1})$
		1982	
Control	0.0	0.3[1]	68
Low	0.5	0.9	231
Mid	1.0	1.5	316
High	5.0	5.1	1245
		1983	
Control	0.0	----	----
Low	0.5	1.8	267
Mid	1.0	2.8	429
High	5.0	12.3	1889

[1]Wastewater applied only on initiation of experiment

2.3.2 Determination of N Balance Components

Removal of N by the tall fescue (Table 2) was determined from the yield and tissue N concentration data for each sampling event summed for each year. Background N levels present in tissue harvested from the control plots were subtracted from the tissue N levels in the treatment plots. The mass of inorganic N present in the soil was calculated from the sum of the NO_3^- concentration in the soil profile less the amount in the control profile. Ammonium-N was not included except as noted because NH_4^+-N concentrations were at background levels.

Nitrification rates were determined in a green house study with 15 cm diameter by 40 cm long soil microcosms containing fescue. The microcosms were collected by pressing 40 cm lengths of plastic pipe 15 cm diameter in the soil in an unused fescue plot adjacent to the study area. The conversion of organic N was described by the equation

$$[NO_3^-] = N_{organic} (1 - e^{-0.10t}), \quad (r^2 = 0.90) \tag{1}$$

where t is the time in days since application of the wastewater pulse and $N_{organic}$ is the TKN present in the wastewater (Slike, 1986). This equation predicts that mineralization should be at least 95% complete within one month after the last application of wastewater to a system that has an acclimated microbial population.

Ammonia volatilization was measured following irrigation with wastewater on a one time basis using a procedure similar to that of Kissel et al. (1977). Volatilization losses due to denitrification were not determined but are included in the unaccounted-for N. Other sources of unaccounted-for N include variability in wastewater application and immobilized N.

Table 2. Yields and total nitrogen (TN) present in the fescue under various wastewater treatments.

Treatment	1982		1983	
	Yield	TN	Yield	TN
	kg ha^{-1}			
Control[1]	----	--	7,480	153
Low	1,530	36	10,110	153
Mid	2,120	63	13,540	356
High	1,610	45	13,200	348

[1]Sprayed by mistake in 1982. Data was not used.

2.4 RESULTS AND DISCUSSION

2.4.1 Plant Uptake

Fescue yield and N uptake during the 1983 growing season (Table 2) were comparable to yields and N uptake reported by Smith (1975). The maximum yield occurred at the mid N application rate. Yield and hence total N removal were reduced at the highest wastewater flux because the wastewater was phytotoxic at the highest N loading rate as evidenced by leaf tip burn. A similar yield response trend but with lower yields and percentage N recoveries was reported by Hallock et al. (1966) for fescue grown on sandier soil -- a trend that would be expected on sandy soils with lower water holding capacities. Yield and uptake data for 1982 (Table 2) are low because wastewater was only applied from September 28 to October 27 in 1982.

Nitrogen levels in plant tissue increased throughout the season in 1983 and increased as a function of N application level (Table 3). Tissue N concentrations at each fertilization level are in close agreement with those reported by Hallock et al. (1966). The increased N concentration in the tissue as the season progressed, particularly at higher levels of wastewater application, was probably due to slower growth rates later in the season and the presence of more available N. Nitrate may have accumulated in plant tissue with $> 3\%$ total N. Donohue et al. (1981) reported accumulations of NO_3^- in orchardgrass (*Dactylis glomesata*), another cool season grass, with total N concentrations $> 3.25\%$.

2.4.2 Ammonia Volatilization

Measured NH_3 volatilization following irrigation indicated losses of approximately 1% of the applied N. The low volatilization rate was anticipated since most of the N present in the wastewater was in an organic form. Subsequent to infiltration of wastewater into the soil, NH_3 produced by microbial mineralization of organic N would freely convert to NH_4^+ and be adsorbed onto the cation exchange complex or be nitrified.

Table 3. The nitrogen concentration in fescue harvested in 1983.

Treatment	Date		
	June 16	August 10	November 9
	% N		
Control	1.96	1.90	2.20
Low	2.22	2.52	3.33
Mid	2.28	2.43	3.30
High	2.46	3.20	3.55

2.4.3 Soil Inorganic Nitrogen

In contrast to many municipal and food processing wastewaters, this wastewater was high in TKN with concentrations ranging from 1500 to 2500 mg L^{-1} over the course of the study. Relatively small quantities of water were applied to the soil during periods of the year when rainfall was also limited. This environment favored nitrification of NH_4^+ as is indicated in Figure 2a,b,c,d. Only during the fall of 1982 were NH_4^+-N concentrations in the upper layer of the mid and high treatments above background levels. This was expected since the wastewater was applied over a one month period of time in four irrigations; the last irrigation was one week before sampling. By the following January, NH_4^+-N concentrations were at background levels for all treatments and remained very close to background at each subsequent sampling (Fig. 2b,c,d).

Greater NO_3^- recovery (Table 4) in January 1983 than October 1982 indicates that substantial mineralization and nitrification of N occurred during late fall or early winter of 1982. Complete mineralization and nitrification of applied N is suggested by the low concentrations of NH_4^+ and the relatively high concentrations of NO_3^--N in the soil by January (Fig. 2).

Substantial winter leaching is reflected in the sequence of curves in Figure 3a to 3c. The solute peaks appeared to move at similar velocities and disperse at similar rates. Although both the mid and high N rates show net decreases in recovered N on April 6, 1983 compared with January 5, 1983, a slight increase is noted in the concentrations in Figure 3c and recovered N (Table 3) at the lowest N level. This slight increase may be either do to spatial variability or more likely due to release of NO_3^- by decaying roots. Slight decreases in recovered N at the mid and high rates may be due to early season plant uptake, denitrification, or leaching. In spite of these slight changes in the mass balance, the most important factor to be considered is the net downward movement of the NO_3^- peak during the winter months when there is a surplus of precipitation.

By November 9, 1983 only a limited portion of the 1982 peak remained in the lower portion of the soil profile of the low and mid N treatments (Fig. 4). In the high N treatment, the 1982 and 1983 peaks overlapped enough to mask the relative portion of each peak present. The sharp decrease in concentrations lower in the profile are suggested to be due to both leaching and substantial
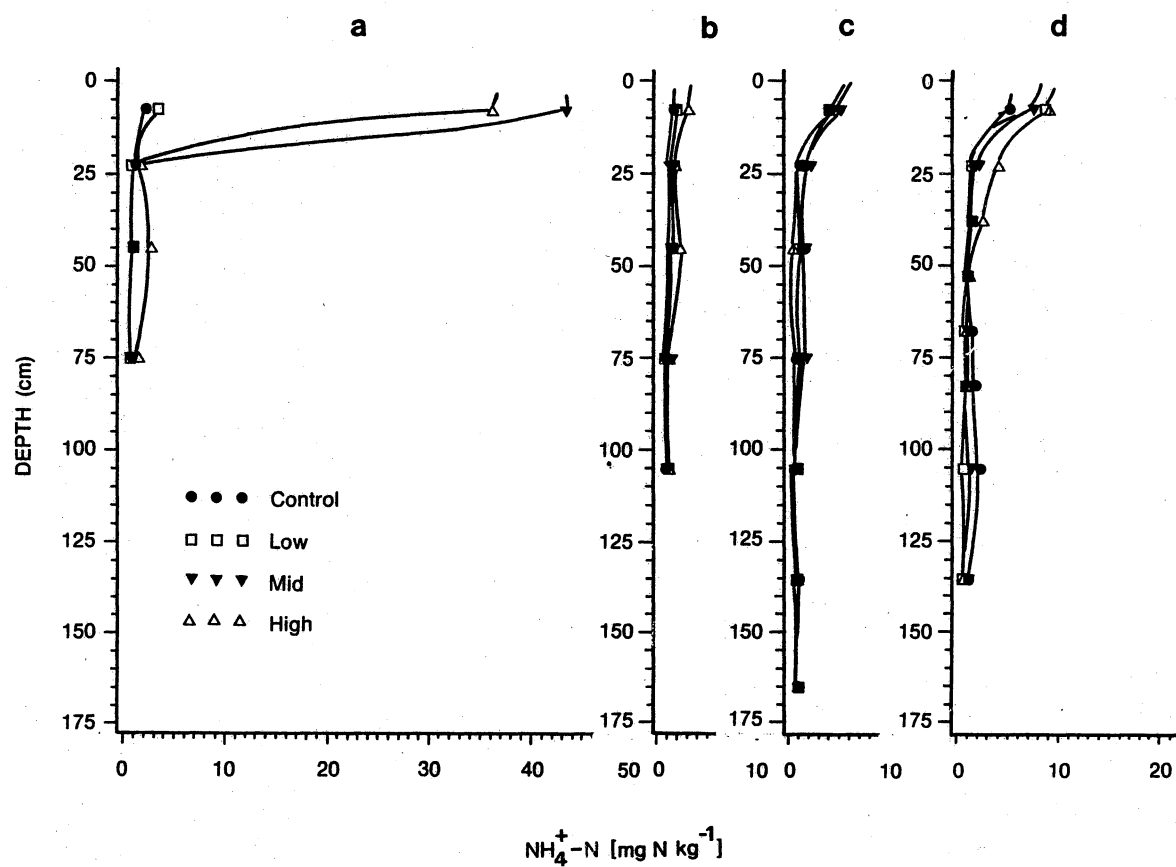
Figure 2. Soil NH$^+_4$-N for the control, low, mid, and high N level treatments: samples were collected on October 31, 1982 (a); January 5 (b), April 6 (c), and November 9, 1983 (d).
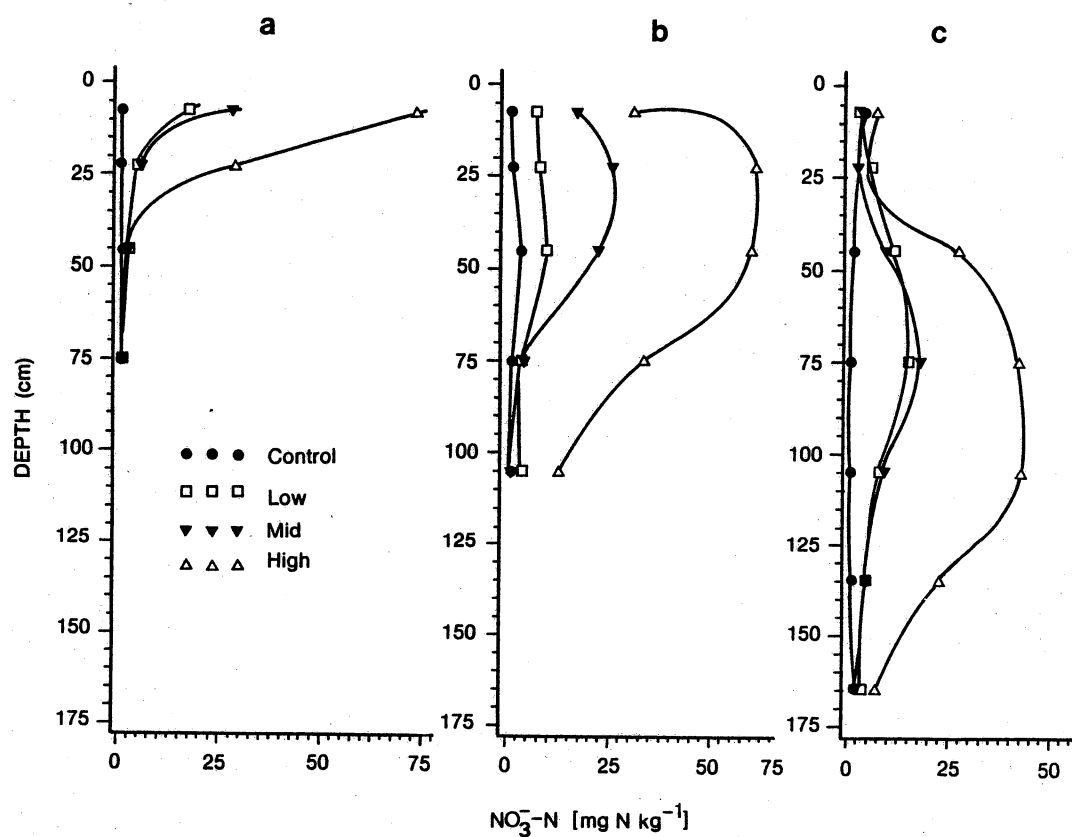
Figure 3. Soil NO_3^--N concentration for the control, low, mid, and high N treatments: Samples were collected on October 31, 1982 (a); January 5 (b), and April 6, 1983 (c).
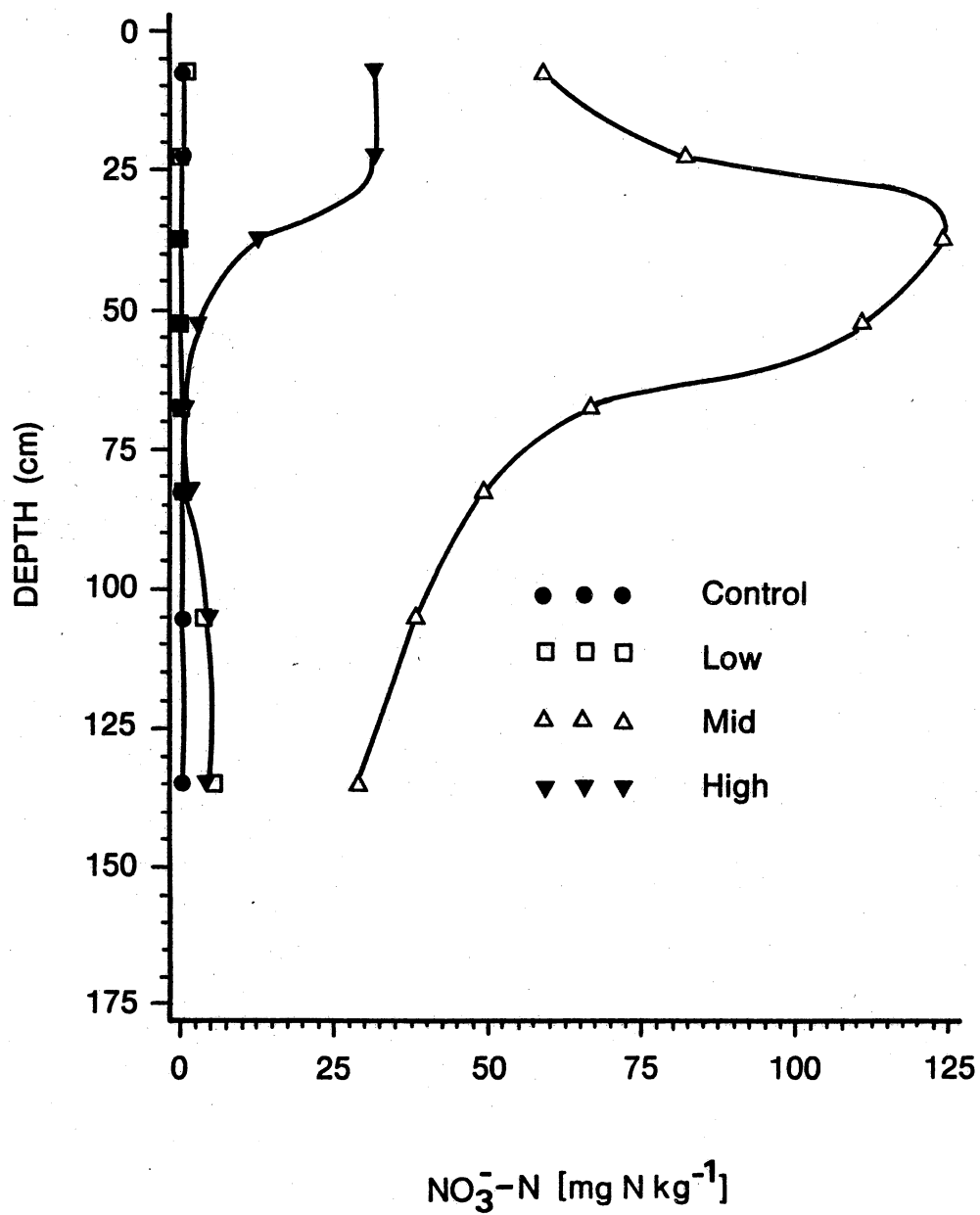
Figure 4. Soil NO_3^--N concentration for N treatments sampled on November 9, 1983.

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Table 4. Nitrogen mass recovered as NO_3^--N from the soil.

Sampling date	Sampling depth (cm)	low	medium N kg ha^{-1}	high
October 9, 1982[1]	90	34	55	216
January 5, 1983	120	84	198	680
April 6, 1983	150	166	168	621
November 9, 1983	150	45	226	1473

[1]Mineralization and nitrification of organic N apparently was not complete on this date. The adjusted sum of NO_3^- + NH_4^+ recovered for each treatment was 37, 151, and 295 kg ha^{-1}, respectively.

removal of N from the 1982 peak. Approximately half of the 1983 fescue yield was harvested prior to commencement of wastewater irrigation in July, 1983. Removal of N from lower in the profile is also supported by recovery of 108% of N applied in 1983 in the mid N treatment (Table 5). It is also anticipated that the lower part of the NO_3^- distribution curve for the high N treatment may be due to partial overlapping of the 1983 and the 1982 NO_3^- peaks. While this is inconclusive, it is supported by leaching predictions over a similar period of time (Chapter II; Simon et al., 1985).

2.4.4 Nitrogen Balance

Late season application of the wastewater in 1982 resulted in only small fractions of the wastewater N being removed by crop uptake (Table 5). Large percentages of the TKN applied were present as carry-over N in the NO_3^- form. In addition, relatively large percentages were un-accounted for, possibly lost to denitrification. Rainfall events in the fall and early winter could have resulted in some denitrification even if the soil was not completely saturated due to the presence of anaerobic microsites (Patrick, 1982).

The fraction of N applied in 1983 which was recovered by November 9, 1983 was higher in all plots. The recovery of 108% of N applied in 1983 at the mid N treatment suggests that much of the crop N removed in 1983 is from the 1982 peak, a phenomena expected and reported else-where in the literature (i. e. Broadbent and Carlton, 1978; Smith and Hayden, 1984). Considering that much of the crop N recovered has to be attributed to the 1982 peak, and that NH_4^+ levels are at or near background, losses probably due to denitrification may be of similar magnitude to those in 1982. Substantial N carry-over remained available for losses due to leaching from the root zone or plant intake in 1984. With continued N application and similar rainfall and plant intake levels, data in Figure 3a-c indicate that substantial leaching of N from the mid and high N treatments would be expected in subsequent years.

Evaluation of the balance of total N applied in 1982 and 1983 (lower part of Table 5) indicates that N recovery by the fescue is lower than might be expected due to limited uptake during 1982, hence this section of Table 5 does not reflect the anticipated long term trend for N recovery. The

Table 5. Nitrogen balances for wastewater irrigated fescue crop. All crop and soil N have been normalized by subtracting the values for a control plot.

	Treatment					
	Low kg N ha^{-1}	%	Mid kg N ha^{-1}	%	High kg N ha^{-1}	%
1982						
N applied						
wastewater	231		316		1245	
N recovered						
crop	36	16	62	20	45	4
$NO_3{}^-$-N in soil[1]	84	36	198	63	680	55
volatilized as NH_3	2	1	3	1	13	1
Total recovered	122	53	263	84	738	60
Unaccounted	109	47	53	16	507	40
1983						
N applied						
wastewater	267		429		1879	
fertilizer	34		34		34	
Total applied	301		463		1913	
N recovered						
crop	198	66	269	58	251	13
$NO_3{}^-$-N in soil[2]	45	15	226	49	1473	77
volatilized as NH_3	3	1	5	1	21	1
Total recovered	246	82	500	108	1745	91
Unaccounted	55	18	-37	-8	168	9
Total for 1982 and 1983						
Total N applied	532		779		3158	
N recovered						
crop	234	44	331	42	296	9
$NO_3{}^-$-N in soil[2]	45	8	226	29	1473	47
volatilized as NH_3	5	1	8	1	34	1
Total recovered	284	53	565	72	1803	57
Unaccounted	250	47	218	28	1358	43

[1]Includes all $NO_3{}^-$-N in the upper 120cm of the profile less control on January 5, 1983.

[2]Includes all $NO_3{}^-$-N in the upper 150cm of the profile less control on November 9, 1983.

total unaccounted-for N for the two years combined ranged from 28 to 47%, and probably included substantial losses to both leaching and denitrification, especially at the mid and high N treatments. Data from 1983 (center of Table 5) is representative of yields and losses expected for subsequent years. As illustrated by Fig. 5, maximum uptake of N while maintaining maintaining carry-over N at minimum levels should occur at about 300 kg ha^{-1}. Timing of irrigations, mineralization rates, climatic conditions, and soil properties must be considered in extrapolating to other sites.
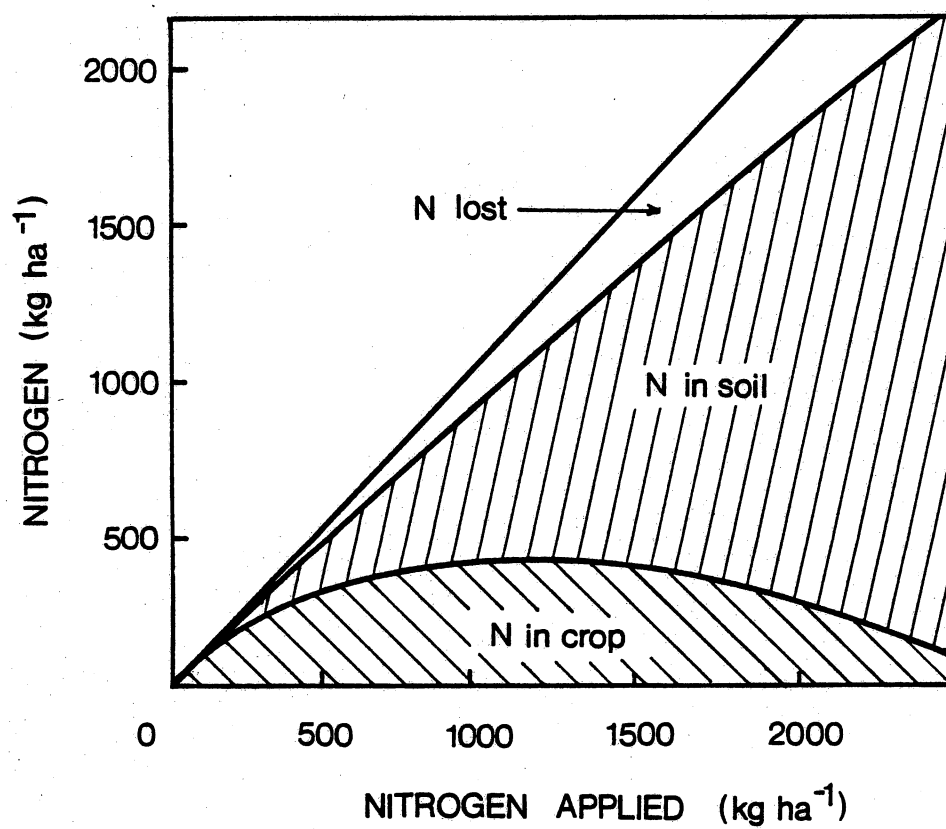
Figure 5.   Nitrogen balance for wastewater irrigation study in 1983.

2.5 CONCLUSIONS

Irrigation of a nylon processing wastewater with relatively high concentrations of organic N resulted in accumulation of inorganic N, primarily in the NO_3^- form, at N application rates above the crop requirement. However, the importance of scheduling of irrigation prior to maximum herbage growth to minimize carry-over of N in the soil inorganic fraction is illustrated by limited uptake of N applied late in the 1982 growing season. Substantial leaching of NO_3^- is evident but does not appear to account for all losses. It is hypothesized that denitrification associated with irrigation and rainfall events may partially explain unaccounted-for losses. Spray irrigation of wastewater with high TKN concentrations was an effective means of treatment and environmentally sound with respect to N pollution if application levels were low enough to maximize crop uptake efficiency. For this crop and site application of wastewater at an annual TKN level below 300 kg ha^{-1} should minimize leaching losses while maximizing application rates.

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3.0 CHAPTER III

IRRIGATION OF FESCUE WITH TEXTILE WASTEWATER:
II. PREDICTION OF NITRATE LEACHING

3.1 ABSTRACT

Leaching of NO_3^- through soils used for both agronomic and/or waste treatment purposes is of concern because of the mobility of NO_3^- and the potential for contamination of ground and surface waters. A textile wastewater with a low C to N ratio was spray irrigated on tall fescue (*Festuca arunindinacea*) during two growing seasons. The magnitude and rate of NO_3^- leaching through a Pamunkey sandy loam (fine-loamy, mixed, thermic Ultic Hapludalf) soil was determined. This data is evaluated with three simple analytical solute transport models. An equivalent steady state convection - dispersion (C-D) model is used in both the inverse and prediction mode after a simple theory for linearization of the net surface flux is derived. In addition, a transient analytical solution of the C-D equation is evaluated which predicts movement of the center of solute mass based on the assumption of piston flow. The location of the center of mass, α , provides a moving Lagrangian coordinate system around which dispersion of solute is calculated by assuming that α values derived from transient data can be considered as equivalent steady state values. Some evidence in the literature suggests that piston flow assumptions overpredict α and that an equation describing α based on plate layer theory better describes field data. Theory is developed to predict α based on this approach for input into the transient model described above. Analyses of data suggest that while the plate layer model appears to most adequately describe data when infiltration (I) is assumed to occur before evaporation (E), use of the contrasting E before I assumption results in adequate description of the velocity of the center of mass using piston flow theory. These results suggest that the inadequate description of the relationships between timing of precipitation, infiltration, and evaporation within the soil-plant-atmosphere system may bias conclusions regarding

which conceptual approach to solute flow is most applicable. However for management purposes either of the transient approaches give results which are within experimental error and provide a rational basis for predicting leaching losses and carry-over NO_3^- available for use by future crops.

Additional Keywords: piston flow, plate layer, solute leaching, groundwater contamination, dispersion, convection

3.2 INTRODUCTION

Successful management of NO_3^- leaching from soils used for land application of wastewater and for strictly agronomic purposes is receiving increased attention as groundwater NO_3^- concentrations continue to increase in both rural and more urban areas (Keeney, 1982; Miller, 1975; Quam et al., 1974). Except for limited amounts of adsorbed NH_4^+, most N applied to well drained soils suitable for crop growth nitrifies rapidly at temperatures above freezing and is susceptible to leaching in soils with low anion exchange capacity which includes most temperate region soils. Leaching of NO_3^- is reduced if N application is timed to correspond to periods of intense crop growth with low net throughflow of water (Keeney, 1982). Likewise, substantial N may be present for subsequent crops if winter rainfall does not result in extensive leaching.

Numerous models and equations for predicting solute flow through soils have been presented which have had varying degrees of success (Wagenet, 1983). Numerical models conceptually can better describe transient water flow conditions but require more detailed data inputs such as hydraulic conductivity and moisture retention functions, which may be prohibitively expensive for management purposes. Simple analytical models have been presented for estimating solute fluxes but require steady state assumptions. Wierenga (1977) and DeSmedt and Wierenga (1978a) demonstrated that solute transport during nonuniform water flow through laboratory columns was satisfactorily modelled by assuming an equivalent uniform water flux and water content. Similarly DeSmedt and Wierenga (1978b) and Selim et al. (1977) have shown that the assumption of uniform average values for the volumetric water content (θ), Darcian flux (q), and dispersion coefficient (D) allowed sufficiently accurate modelling of breakthrough curves for profiles with non-uniform water contents. Rose et al. (1982a) presented a framework for calculating the movement of the solute peak depth (α) through the soil in the presence of transient evapotranspiration (ET) and precipitation conditions. Rose et al. (1982b) used α as a moving Lagrangian coordinate system to apply a semi-infinite steady-flow solution of the convection-dispersion equation to overlay dispersion symmetrically about the moving peak. While Rose et al. (1982b) and Barry et al. (1985) concluded that this approach adequately described field data, Cameroon and Wild (1982) suggested further

testing of the model in field soils to be necessary. Cameroon and Wild evaluated the leaching models of Rose et al. (1982a,b) Burns (1975) and Addiscott (1977). The latter two authors both assumed that leaching can be predicted using modified chromatography theory. Leaching of NO_3^- and Cl^- predicted by the Rose model was highly correlated on all sampling dates with field measured concentrations of NO_3^- and Cl^- . Much poorer correlations were reported for the other two models except after substantial winter rainfall (Cameron and Wild, 1982).

Burns (1975) justified using his model by noting that measured mean solute penetration depths for some data sets were more closely approximated by his theory than by the piston flow assumption. The mean solute peak penetration depth predicted by the Burns model (α_B) is defined by the equation

$$\alpha_B = \log\left(\frac{P}{P + \theta_{fc}}\right) \tag{1}$$

while for the piston flow model it is defined by

$$\alpha = \frac{P}{\theta_{fc}}. \tag{2}$$

where P is the net cumulative surface flux and θ_{fc} is the volumetric water content at "field capacity". Although neither equation definitively described the movement of the solute pulse under transient field conditions, Smith et al. (1984) concluded that the Burns equation was in better agreement with field data. Jury et al. (1982) reported good agreement between a calibrated leaching transfer function model and field data. Their model predicted solute distribution by determining the probability that solute had penetrated to a particular depth at each time interval.

In this study we compare measured resident soil NO_3^--N concentrations under spray-irrigated fescue with those predicted by three approximate models: (1) the model of Rose et al. (1982a,b), (2) model 1 with α computed using the Burns equation, and (3) an analytic approximate steady state model in the vein of Jury et al. (1982).

3.3 THEORY

Both the Rose model (Rose et al., 1982a) and a modification presented here assume that a mean solute peak penetration depth (α), calculated from transient climatalogical data and easily estimated soil data, can be considered to represent an equivalent steady state condition. The concentration c_0 of an initial solute pulse is defined

$$c_0 = \frac{\text{mass } NO_3^-}{\Delta F \ \theta_{fc} \ \text{area}}.$$ [3]

where ΔF is the depth that the initial solute peak penetrates into the soil. The change in relative concentration $\frac{c}{c_0}$ of the initial pulse after a step change in concentration has occurred is defined

$$\frac{c}{c_0} = \frac{1}{2} \left\{ \text{erfc} \left(\frac{z - \alpha}{2(D_0 t + \varepsilon\alpha)^{0.5}} \right) - \text{erfc} \left(\frac{z - \beta}{2(D_0 t + \varepsilon\beta)^{0.5}} \right) \right\}$$ [4]

where c is the concentration at depth z from the infiltration surface, time t (days from step-change in concentration); β is defined as $\alpha - \Delta F$; D_0 is molecular diffusion coefficient appropriate for NO_3^-; and ε is the dispersivity (Rose et al., 1982b).

While the value of ε can be varied by up to 50% with little effect (Rose et al., 1982b; Cameron and Wild, 1982; Barry et al., 1985) the model is quite sensitive to variation of the value of α. Two similar approaches will be described here for calculating $\alpha(t)$. Both models use equation 4 to predict dispersion around α.

3.3.1 Model 1

This model is more rigorously derived by Rose et al. (1982a) and is a discontinuous form of theory suitable for practical calculation of displacement ($\Delta\alpha$) of the mean solute penetration depth. Infiltration results in a change in α only if $\theta = \theta_{fc}$ for $z \leq \alpha$. Furthermore, at the end of an ET period θ is assumed constant within the maximum depth of root penetration (D_R) and only a function of time. Drainage to θ_{fc} is assumed to be complete following any infiltration during each

time interval Δt. Following redistribution of an infiltration event the water content distribution is treated as a delta function of θ (Rose et al., 1982a). As only the displacement of α with time is of concern for management questions, $\Delta\alpha$ can be defined

$$\Delta\alpha_n = \frac{\Delta W_{z_n}}{\theta_{fc}} \qquad [5]$$

where

$$\alpha_n = \alpha_{n-1} + \Delta\alpha_n. \qquad [6]$$

The quantity W_{z_n} is defined as the equivalent ponded depth of water which has passed the depth z_{n-1} of the solute peak prior to the infiltration event n and is stated in equation form as

$$\Delta W_{z_n} = I_n \Delta t - \alpha_{n-1}(\theta_{fc} - \theta_{n-1}), \quad (\alpha_{n-1} < Z_n^{\times}, D_R). \qquad [7]$$

where I_n is the mean rate of water application during Δt and D_R is the rooting depth. The position of the wetting front $Z_n^{\times}$ is defined

$$Z_n^{\times} = \frac{I_n \Delta t}{\theta_{fc} - \theta_{n-1}}, \quad (\theta_{fc} > \theta_{n-1}, \ Z_n^{\times} < D_R). \qquad [8]$$

However if $\alpha_{n-1} > D_R$ and $Z_n^{\times} > D_R$ then

$$\Delta W_{z_n} = I_n \Delta t - D_R(\theta_{fc} - \theta_{n-1}) \qquad [9]$$

because by definition $\theta = \theta_{fc}$ for $Z_n^{\times} > D_R$.

It is assumed that the roots serve as a homogenous sink throughout the whole depth D_R and thus that evaporation and nutrient uptake occur evenly throughout the root zone. During evaporation events for which no drainage occurs

$$\frac{\partial\theta}{\partial t} = \frac{I - E}{D_R}, \quad (\theta \leq \theta_{fc}). \qquad [10]$$

Therefore at the end of time interval (n-1) the water content θ_{n-1} is defined

$$\theta_{n-1} = \theta_{n-2} + \frac{(I_{n-1} - E_{n-1})\Delta t}{D_R}, \quad (\theta_{n-1} \leq \theta_{fc}) \tag{11}$$

and if calculated $\theta_{n-1} > \theta_{fc}$ then

$$\theta_{n-1} = \theta_{fc}. \tag{12}$$

The above equations assume that all infiltration events are complete before evaporation occurs. If the extreme that all ET occurs before infiltration is considered, then Eq. 7 becomes

$$\Delta W_{z_n} = (I_n - E_n)\Delta t \quad - \quad \alpha_{n-1}(\theta_{fc} - \theta_{n-1}), \quad (\alpha_{n-1} < Z_n^{\times}, D_R). \tag{13}$$

and Eq. 9 would be similarly altered. Rose et al. (1982a, 1983) concluded that the assumption of infiltration before evaporation better described lysimeter data for leaching of preplant N from soil growing corn (*Zea mays* L.) under natural rainfall conditions. Barry et al. (1985) determined that there was little difference in calculated α values when the extreme assumptions of I before E and E before I were used in describing leaching of NO_3^- below an irrigated potato crop grown on ly-simeters. However, all authors conclude that reality lies somewhere between the extremes (Rose et al., 1982a; 1983; Barry et al., 1985).

3.3.2 Model 2

Model 2 uses Eq. 1 as the basis for predicting α instead of Eq. 2. Smith et al., (1984) presented Eq. 1 derived from the theory of Burns (1975). In this theory water is assumed to move through the soil and mix in 'plates' or layers. The net effect is that Eq. 1 predicts α values approximately 30% smaller than those predicted with Eq. 2. These predictions have been in better agreement with some data sets (Burns, 1975; Smith et al., 1984).

In Eq. 1, P represents the net cumulative surface flux of water. To consider changes in α using this model we define

$$\alpha_B = \log_{10}\left(\frac{Q_n}{Q_n + \theta_{fc}}\right) \qquad [14]$$

where the subscript B refers to the Burns equation. We further define Q_n as

$$Q_n = \sum_{i=1}^{n} W_{z_n} \qquad [15]$$

where W_{z_n} is defined as in Eqs. 7, 9, and 13. Likewise the conditions defined in Eqs. 10 to 13 are assumed to apply.

3.3.3 Model 3

We employ the convection dispersion equation linearized over time interval 0 to t_m and depth 0 to z_m. and written as

$$\frac{\partial C}{\partial \tau} = D\frac{\partial^2 C}{\partial Z^2} - V\frac{\partial C}{\partial Z} \qquad [16]$$

where τ is transformed time, C is the same as $\frac{c}{c_o}$ previously defined, and V is the apparent velocity. The solution of Eq. 16 is case B6 of van Genuchten and Alves (1982). The mean surface flux density $\bar{q}$ is defined

$$\bar{q} = \frac{1}{t_m} \int_0^{t_m} q(z,t)_{z=0}\, dt \qquad [17]$$

where the average moisture content in the profile is defined as

$$\bar{\theta} = \frac{1}{t_m x_m} \int_0^{t_m} \int_0^{x_m} \theta(x,t)\, dx\, dt \qquad [18]$$

yielding an apparent velocity V defined

$$V = \frac{\bar{q}}{\bar{\theta}}. \qquad [19]$$

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Defining Q(t) as $\int_0^t q(0,t)\,dt$, then transformed time (τ) is defined

$$\tau(t) = \frac{Q(t)}{\bar{q}}\ .$$ [20]

This transformation requires an evaluation over a time when net infiltration at the surface occurs at a relatively uniform rate. In climates with alternating deficit and surplus moisture conditions, the change in the slope of the cumulative surface flux curve may alternate between negative and positive values. Figure 6 illustrates this problem. Evaluation of data therefore requires a further restriction. In this case we can define times (t_{max_1} and t_{max_2}) where the slope of Q(t) changes from positive to negative occur and times (t_{min_1} and t_{min_2}) where the slope of Q(t) changes from negative to positive. If we evaluate the $\bar{q}$ when $\dfrac{dQ(t)}{dt} > 0$ then

$$\bar{q} = \frac{1}{(t_{max_1} - t_{min_1}) + (t_{max_2} - t_{min_2})}\left(\int_{t_{min_1}}^{t_{max_1}} q(0,t)\,dt + \int_{t_{min_2}}^{t_{max_2}} q(0,t)\,dt\right).$$ [21]

This approach assumes that the change in mass of solute as a function of depth is 0 when $\dfrac{dQ(t)}{dt} \leq 0$ and will allow estimation of leaching with intervening deficit periods.
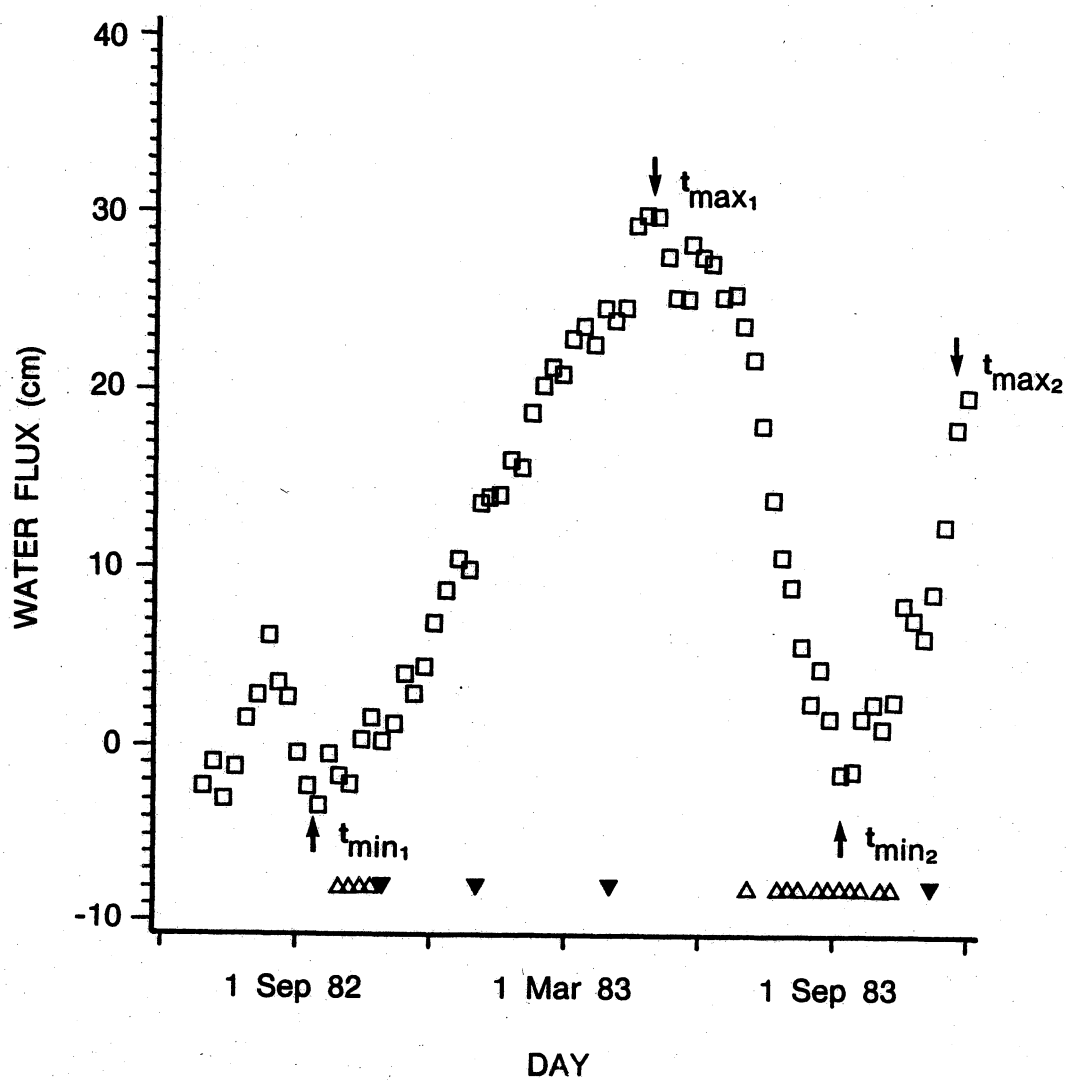
Figure 6. Calculated cumulative surface flux (Q): Open and inverted solid triangles represent waste-water irrigation events and dates of soil sampling, respectively. Subscripted time symbols note range over which average flux was determined for model 3.

3.4 MATERIALS AND METHODS

An industrial wastewater containing a readily mineralizable organic N component with a low C to N ratio was applied to a Pamunkey sandy loam (fine-loamy, mixed, thermic Ultic Hapludalf) soil by spray irrigation during the summer and fall of 1982 and 1983. Plots (duplicate) were circular (8.2 m) with a irrigation riser at the center (see Chapter II for details). The irrigation line split the plots into halves each containing 'Tiff' bermuda grass *(Cynodon dactylon)* and 'Ky 31' fescue *(Festuca arunindinacea)* respectively as well as a mixture of other species but primarily field paspalum *(Paspalum laeve)* due to the difficulty of establishing a good grass cover quickly. Although wastewater was applied at multiple flux densities, data from the fescue treatment which received approximately 450 kg N per year is chosen for evaluation here because the residual NO_3^- peaks were detectable.

Open and solid inverted triangles in Figure 6 represent dates of wastewater application and soil sampling respectively. Wastewater was applied in larger irrigations over a much shorter period of time in late summer and early fall in 1982 compared with 1983 due to difficulties in establishing the experiment. Rainfall and irrigation quantities were measured at the site. Evapotranspiration was determined for the months of April to October from the nearest weather station with a class A pan. A correction coefficient of 0.80 (Jensen, 1973) was used to estimate ET at the site. Winter ET was estimated from weighing lysimeter data from two sites in the eastern part of the United States (Coshocton, OH and Seabrook, NJ as reported by Jensen, 1973). Estimates of θ_{fc} were determined from volumetric water contents of soil cores sampled during winter months. In addition the bulk density and desorption soil moisture characteristics of 40 soil cores, 5 cm in diameter and 4 cm long were determined over a pressure range of 10-1000 cm water. Field measured θ was in close agreement with lab-measured θ in the pressure range of 100-300 cm of water. Soil N analyses were determined as described in Chapter 2.

3.4.1 Model Inputs

3.4.1.1 Models 1 and 2

A θ_{fc} value of 0.38 m³ m⁻³ was determined from the average θ of soil cores collected on 5 winter sampling dates after several days had passed since the previous rainfall but the soil was not frozen. An ε value of 6.4 cm² d⁻¹ was determined from an inverse solution of Eq. (16) determined with Model 3. The value of ε was calculated from the equation (DeSmedt and Weirenga, 1978a)

$$D = D_0 + \varepsilon V \qquad [22]$$

where D_0 was taken to be 1 cm² d⁻¹. The 3 parameter version of Model 3 (solving for V, D, and t_0) was used to fit the upper 75 cm of the NO_3^- profile on November 9, 1983 because this data had the smallest sampling increments, hence the best resolution. The rooting depth D_R was chosen as 150 cm (Wilkinson and Mays, 1979). The pulse width ΔF was determined by calculating α when 95% of the organic N was anticipated to be mineralized as discussed in the following section. Solute was assumed to be evenly distributed throughout the pulse thickness at the time of the step change.

3.4.1.2 Model 3

The slope of the curve in Figure 6 was assumed to be linear over time intervals t_{min_1} to t_{max_1} and t_{min_2} to t_{max_2} and $\bar{q}$ determined. The former interval had an average surface flux density of 0.155 cm d⁻¹ while the later value was 0.150 cm d⁻¹. For modelling purposes $\bar{q}$ was chosen at 0.155 cm d⁻¹ and t chosen to reflect the appropriate Q for the week of interest. Values of V, t_0, and D were determined by nonlinear regression with Model 3 (Parker and van Genuchten, 1984) using measured concentration data from each sampling date. Values for apparent θ and ε were calculated using Eq. [19] and [22], respectively. The solute pulse duration (t_0) was calculated in the following manner. Using the prediction equation

$$[NO_3^-] = [N_0] (1 - e^{-0.10t}), \quad (r^2 = 0.90) \qquad [23]$$

determined from wastewater nitrification studies conducted with soil microcosms (Slike, 1986), the time (t) at which 95% of all wastewater N applied (N_0) could be expected to be nitrified was determined. (This point corresponded to a sharp slope change in the calculated cumulative nitrification curve). The $\bar{q}$ value over this time period was used to determine t_0 such that

$$Q(t) = \bar{q} \, t_0 \; . \qquad [24]$$

Model 3 was also used in a prediction mode. Values determined for V and D from the 1983 pulse and the independently calculated t_0 values were used to predict the movement of the 1982 and 1983 pulses. To predict NO_3^- distribution on November 9, 1983, the technique of superposition (Wierenga, 1977) is used to sum the effects of multiple pulses. Barry et al., (1985) concluded that the technique described the multiple applications of a fertilizer N adequately. Here wastewater application is assumed to occur in two pulses - one in each of the two time periods illustrated in Figure 6 when $\dfrac{dq}{dt} > 0$. Distribution of NO_3^- from each of the solute pulses was predicted with each model and the predicted concentrations added together to obtain the curves in Figure 7c.

3.4.2 Corrections for Plant Uptake - All Models

Rose et al., (1982b) and Barry et al., (1985) have shown that the concentration effects of plant removal of N can adequately be described by multiplying the values of $\dfrac{c}{c_o}$ by an uptake factor (f) defined as

$$f = \frac{c_o - u_t}{c_o} \qquad [25]$$

where u_t is the sum of plant uptake at any time t. This approach is deemed more valid in this case than approximating uptake as a first order decay function (Smith et al., 1984) due to the dormancy of plant growth during winter months and the lack of knowledge about rates of uptake. Measured

N removed when plant tissue was harvested was used to estimate the value of f at each soil sampling date. N removal was assumed to have occurred evenly over the entire rooting zone. Nitrogen unaccounted for by subtraction of soil inorganic N and plant uptake in the fall of 1982 and 1983 (approximately 15%) was also subtracted out and assumed to represent denitrification.

3.5 RESULTS AND DISCUSSION

3.5.1 Comparison of predicted solute distribution profiles

Solute distribution profiles predicted by models 1, 2 , and 3 are compared with measured solute distribution in Fig. 7a,b,c. In Figure 7a, Model 3 most closely approximates the measured solute distribution as would be expected since its parameters were fit to the 1983 peak with a similar solute distribution. However the large values of apparent volumetric water content ($\bar{\theta} = \frac{\bar{q}}{\bar{V}}$) (Table 6) suggest that $\bar{V}$ as determined in the regression process for both the January 1983 and November 1983 sampling dates does not have a physical basis.

Values for V, D, ε , and θ determined when t_0 was independently calculated are also reported in Table 6. It is notable that t_0 values determined with the three parameter inverse solution using Model 3 agree well with values of t_o calculated with Eq. 23 and 24. The agreement between the nitrification rate studies and fitted values of t_o support the conclusions that nitrification of the organic wastewater N applied in the field was relatively rapid (Chapter 2).

3.5.2 Prediction of Peak Penetration Depth

Substantial differences in predicted $\alpha(t)$ are noted between the assumptions of I before E and E before I with both models (Fig. 8). When either I before E or E before I is assumed for both models, the relative difference in the α values predicted by each model is of similar magnitude. It is notable that values of α predicted by Model 2 using the assumption I before E are almost identical to predictions by Model 1 using the the assumption E before I. Inspection of Figure 7a, b, and c indicates that α predicted by the latter two approaches is in good agreement with measured data although the E before I assumption using Model 2 seems to underestimate α as much as the former two appear to overestimate α . While the field solute distribution data presented here do not allow conclusive determination of the most appropriate choice of equations, the trends do suggest important considerations for evaluating effects of precipitation and ET distribution. Rose
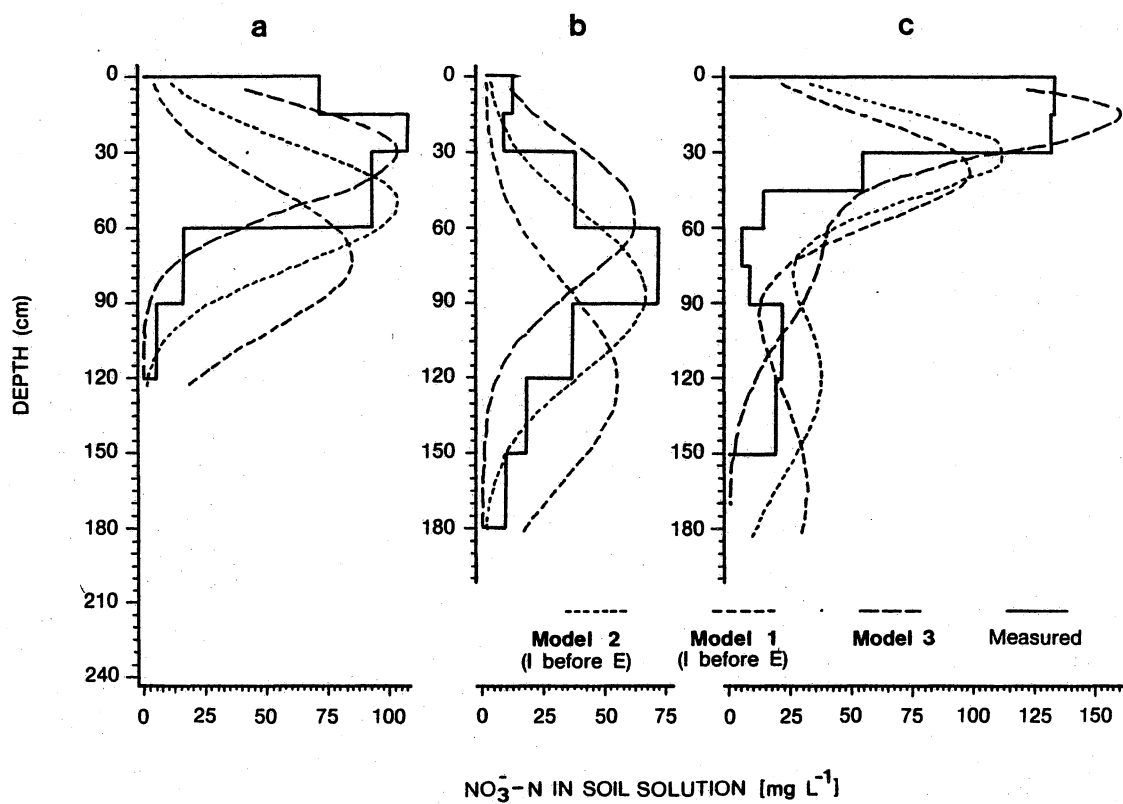
Figure 7. Measured and predicted NO_3^--N distribution on January 5 (a), April 6 (b), and November 9, 1983 (c), respectively: Note that the rectangular form of the measured curves reflects the profile sampling increments.
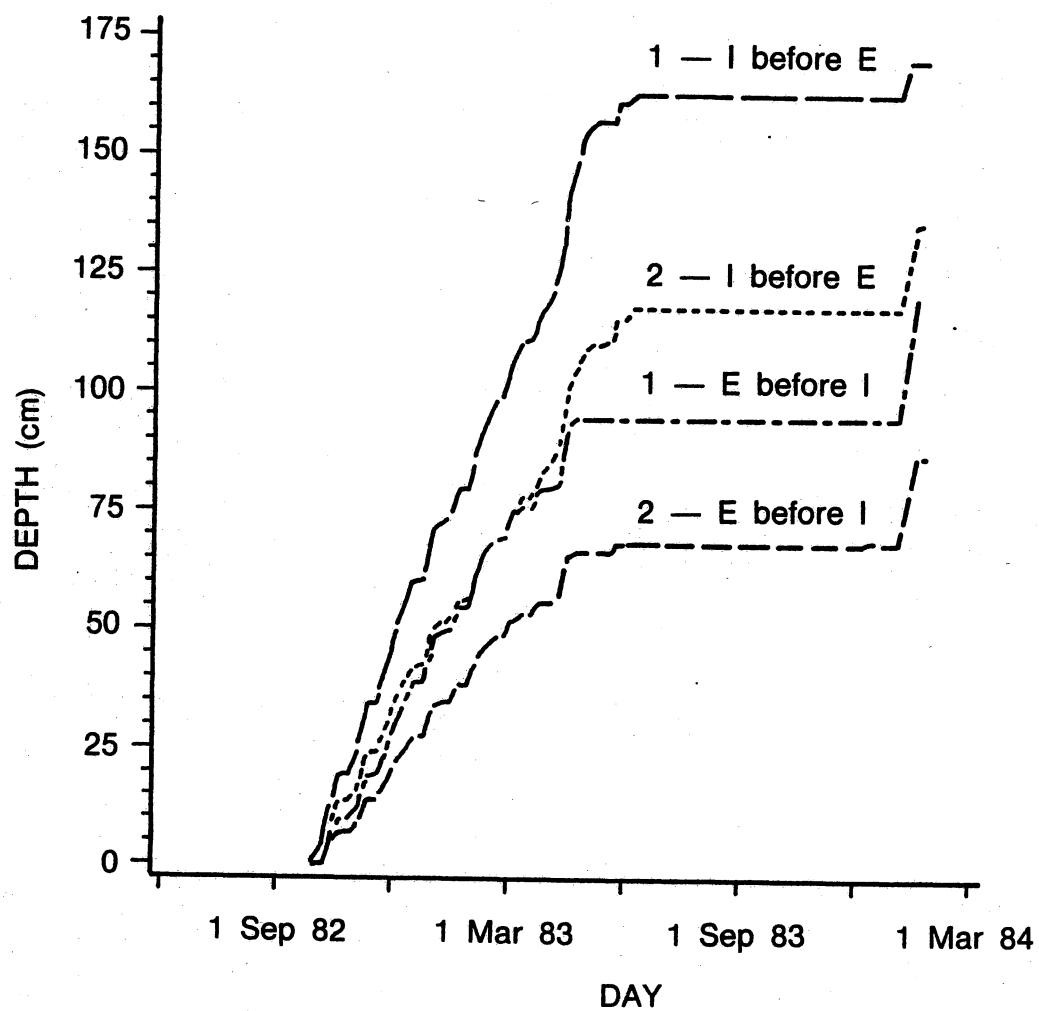
Figure 8. Predicted α(t) using Model 1 (Rose) and Model 2 (Burns): Models are both presented with contrasting I before E and E before I assumptions.

et al. (1982a, 1983) concluded that the assumption of I before E was in much better agreement with measured data than E before I. The latter assumption predicted a peak emergence from the lysimeters studied months later than both the measured and I-before-E-predicted peak emergence. In contrast Barry et al. (1985) reported essentially the same predicted dates of peak emergence below an irrigated potato crop grown in lysimeters. However frequent irrigation maintained θ near a constant value - a condition not expected to occur with either the conditions of this study or the lysimeters with corn studied by Rose et al. (1982a). While these results may be inconclusive, they do illustrate that unspecified choice of assumptions made by Smith et al. (1984) and Burns (1975) in evaluating the flux of water across the soil surface could significantly bias either approach. The assumption of uniform water uptake over D_R , also made elsewhere (Rose et al., 1982a; Cameron and Wild, 1982; Barry et al., 1985) does not consider any effects of uneven root distribution on water uptake but is expected to provide acceptable error for management level decisions.

The dispersivity value calculated from V and D values for the 1983 pulse data (Table 6) appears to adequately describe the dispersion process associated with the convection of solute through the soil profile. The differences in dispersion between curves for Model 1 and 2 are simply due to the greater predicted value of α at time t. As shown by Eq. 3, dispersion predicted by both models is a function of α, ε, and D_0. While D_0 is included in Eq. 3, hydrodynamic dispersion is of primary importance (Barry et al., 1985).

3.5.3 Superposition of Multiple Solute Pulses

Absence of data with depth prevents testing of the suitability of the superpostion process here but some general trends can be noted. As indicated in Figure 7c, Model 2 (with I before E) appears to be in best agreement with location of both peaks. Mass balance is obviously not completely met possibly due to a slightly sandier texture with depth or uneven plant uptake of N. However the trend is in reasonable agreement. Lack of sampling below 150 cm makes it impossible to discern which model is the better predictor of the 1982 peak by this point in time. However, considering the relative location of predicted α and apparent α in Figure 7a and b, it is anticipated that

Model 1 (with I before E) would continue to substantially overpredict α. Assuming continued wastewater irrigation, by the following growing season this question would be anticipated to be irrelevant when the amount of N remaining from the 1983 peak and anticipated rainfall is considered.

Prediction of NO_3^- distribution on November 9, 1983 using the superposition process and Model 3 is in obvious error (Fig. 7c). The predicted location of the 1982 peak based on V fitted in fall of 1983 underestimates α, already apparent in Figure 7b. An additional error may be caused by assumptions made in Eq. 21, however, this does not detract from the usefulness of this model for evaluating a single peak where assumptions of linear flux density are adequately met.

3.5.4   Maintenance of Mass Balance

Curves in Figure 7a, b, and c have been adjusted for losses due to plant uptake and NH_3 volatilization and additional unaccounted-for losses assumed to be due to denitrification. As previously noted some discrepancy may occur if plant uptake does not occur uniformly from the solute profile, an assumption which would be expected to result in slight error. From a management approach, the use of a depletion factor f does appear to provide a readily acceptable estimate as long as the potential for error is acknowledged. This use of a depletion factor is useful when it is more convenient to consider N losses in lump sums or when losses can not be estimated by a decay function.

3.5.5   Estimation of C-D parameters

Model 3 was used in a regression mode to provide estimates of V, D, and t_0 presented in Table 6. Fitted velocities for the January 5, 1983 sampling of the 1982 peak and the November 9, 1983 sampling of the 1983 peak are comparable, but a substantially higher velocity was suggested by the location of the 1982 peak on April 6, 1983. This trend probably reflects an increase in both convection and dispersion when the moisture content throughout the soil profile is near field capacity. However the decrease in the fitted t_0 value between January 1983 and April 1983 suggests that plant

Table 6. Values of convection-dispersion equation coefficients determined with Model 3 from measured resident NO_3^- concentrations. The January and April 1983 coefficients are for the wastewater applied in 1982. The November 1983 coefficients correspond to the solute distribution profile attributable to wastewater applied in 1983.

Date cm d^{-1} cm^2 d$^-$&sup1 d cm d^{-1}	V	D	t_0	ϵ[1]	θ[1]	r^2
			Three Parameter Model			
January 5, 1983	0.323	4.29	27.9	10.1	0.50	0.996
April 6, 1983	0.479	3.31	17.7	4.8	0.32	0.920
November 9, 1983	0.340	3.19	41.7	6.4	0.46	0.999
			Two Parameter Model			
January 5, 1983	0.352	2.89	[22][2]	5.4	0.44	0.919
April 6, 1983	0.458	4.84	[22][2]	8.4	0.34	0.840
November 9, 1983	0.329	3.80	[45][2]	8.5	0.47	0.996

[1]Values for θ and ϵ were calculated from Eq. [19] and [22], respectively.

[2]Values independently calculated from Eq. [23] and [24].

uptake of NO_3^- or denitrification occurring unevenly in the upper part of the profile could also contribute to a higher fitted value for V. The relative agreement between plant uptake and changes in recovered soil inorganic N with time (data not reported here) suggest, though inconclusively, that beyond an initial amount of unaccounted-for N, further losses are probably due to plant uptake (Chapter 2). A longer t_0 value would be anticipated for the 1983 peak due to the application of solute over a longer time period involving a greater calculated net flux of water into the profile.

3.6 CONCLUSIONS

The temporal differences in C-D parameter in Table 6 indicate either a real change in the relative magnitudes of the convection and dispersion processes as the climatic pattern shifts from summer deficits to fall-winter-spring surpluses of precipitation or the inability to adequately model the system with Model 3 and the relaxed assumptions made in this paper. Use of the model as an investigative tool is suggested, however as it lends insight into processes needing further consideration and provides an approximate way to estimate D and hence ε .

Prediction of α for use in Eq. 3 is quite sensitive to how the relation between the timing of infiltration and evaporation is defined. Careful study will be required to determine whether Eqs. 1 or 2 are more realistic for estimating depth of peak penetration or rather if greater consideration needs to be placed on defining evaporation losses. For management purposes it does appear that Model 2 based on Burns equation or Model 1 with the assumption of E before I best describes observed data. Model 2 with the I before E assumption is recommended because it appears to agree best with measured data and is intermediate between Model 1 when contrasting assumptions are used. The modeling approaches presented are useful for data interpretations and predictions — especially for less sensitive management decisions but further research should address the relations between the timing of infiltration and evaporation events. The use of an adjustment factor, f, to account for losses of NO_3^- to sinks was satisfactory.

Where similar studies of NO_3^- are planned, especially when using resident concentrations in soil cores, it is important to sample with small depth increments to increase the resolution of data available for interpretation. Changes in volumetric water content during the growing season (which were not available for this study) would be quite beneficial for further interpretation of observed phenomena.

In spite of the limitations discussed, use of appropriate simplified models of solute leaching does provide a rational basis for management decisions regarding the potential for leaching of NO_3^- and other non-reactive ions from soils used for treatment of waste products and or agronomic and silvicultural practices.

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4.0 CHAPTER IV

SEPTIC TANK SUBSURFACE ABSORPTION SYSTEMS IN CLAYEY

LIMESTONE-DERIVED SOILS:

I. PERFORMANCE

4.1 ABSTRACT

Decreasing federal support for construction of sewage collection and treatment facilities and continued growth in suburban and rural areas is resulting in increased numbers of residences relying on some type of on-site sewage treatment and disposal system (OSWDS). Soils developed in limestone residuum which have clayey B horizons comprise significant portions of the United States but research directly addressing their suitability for septic tank subsurface absorption systems (ST-SAS) has been minimal. These soils are characterized by strongly structured B horizons with potentially high saturated conductivities but sharp decreases in conductivity with desaturation. Previous research has indicated that clogging processes associated with conventional ST-SAS result in decreased infiltration rates in sandy soils, however use of ST-SAS with low pressure distribution (LPD) has been suggested as an alternative to improve long term infiltration rates and treatment of septic tank effluent (STE). The objective of this research is to determine the acceptable effluent loading rates in clayey limestone-derived soils for ST-SAS with LPD. Soils studied represent a range of soil structures and depths to bedrock. A total of 23 prototype ST-SAS with simulated LPD were installed on four different soils developed in limestone residuum in the Appalachian Valley. Prototype ST-SAS were dosed at flux densities (trench bottom area basis) ranging from 0.4 cm d^{-1} to 3.6 cm d^{-1}. Ponding of 15 to 50 cm of effluent was noted in ST-SAS dosed at 1.8 and 3.6 cm d^{-1} underlain by a C horizon with massive structure and occasional cracks but no pore clogging was noted below ST-SAS dosed at 0.4 cm d^{-1}. Effluent ponded to depths which allowed horizontal transmission of effluent through the well structured B horizon but organic materials

appeared to be accumulating in the interpedal voids. ST-SAS installed in soils without restrictive horizons within 75 cm of the trench bottom did not pond at 1.8 cm d^{-1} but ponding was noted at the 3.6 cm d^{-1} in soils with bedrock or weathered shale within 1 m of the trench bottom. Results indicate that ST-SAS with LPD can be dosed at flux densities up to 2 cm d^{-1} in clayey, well structured soils with at least 30 cm of depth above a restrictive layer. Where a restrictive layer is closer to the trench bottom, flux densities of 0.4 to 1 cm d^{-1} may be suitable if soil colors indicate that soils are moderately well drained.

4.2 INTRODUCTION

Decreasing federal support for construction of sewage collection and treatment facilities and continued growth in both suburban and rural areas is resulting in increased numbers of residences relying on some type of on-site wastewater disposal and treatment system (OSWDS). Sewage from 20.9 million residences (24.1% of the U. S. total) was treated via OSWDS using septic tank sub-surface absorption systems (ST-SAS) or cesspools as of 1980 (Bureau of Census, 1983b). This re-presents a 26% increase during the last decade in the number of residences occupied year-round which are served by OSWDS (Bureau of Census, 1972; 1983b). Assuming that 170 L of wastewater per capita per day (U.S. Environmental Protection Agency, 1980) is generated by 8.25×10^7 people (Bureau of Census, 1983a, b), then 14×10^9 L of wastewater are applied daily via OSWDS to USA soils.

New regulations were promulgated by the Virginia State Board of Health during 1980 and 1981 (Virginia Department of Health, 1982) which provided estimated loading rates for ST-SAS similar to those suggested elsewhere (U.S. Environmental Protection Agency, 1977). Of particular interest is a section of the code providing for up to a 50% reduction in trench bottom area required for fine textured soils with estimated percolation rates of 25 to 50 min cm^{-1} when ST-SAS with low pressure distribution (LPD) are used. Soils developed in limestone and shale residuum with clayey Bt horizons comprise much of the Appalachian Valley, Kentucky, Tennessee, Arkansas, Missouri, and other parts of the U. S. A research project was undertaken in 1982 to evaluate performance of prototype ST-SAS dosed with LPD over a spectrum of effluent flux densities which ranged from 0.4 to 3.6 cm d^{-1} (trench bottom area basis).

4.2.1   Processes Limiting Effluent Infiltration

Adequate performance of a properly designed and constructed OSWDS depends on the ability of soil or soil material to transmit and renovate wastewater. Both of these processes are directly related to soil hydraulic conductivity characteristics which are largely determined by soil pore ge-

ometry (U.S. Environmental Protection Agency, 1977). In addition, the velocity of water trans-mission is a function of the hydraulic gradient or driving force of the system. The primary components of hydraulic gradient of interest in soils around OSWDS are the pressure potential (ψ_p) and the gravity potential (ψ_g).

Effluent infiltration can not be maintained at flux densities (q) predicted by the Darcy equation for 1 dimensional flow

$$q = -K_{sat}\frac{dH}{dZ} \qquad [1]$$

where K_{sat} is the saturated conductivity and $\frac{dH}{dZ}$ is the hydraulic gradient over extended periods of time (Bouma et al., 1972; Jones and Taylor, 1964; Magdoff et al., 1974). Temporal reductions in infiltration rates have been attributed to formation of a biological mat or crust. While some authors suggest that accumulation of solids filtered from the effluent (Winneberger et al., 1960; De Vries, 1972) is important in the clogging processes, lower anaerobic respiration rates of bacteria, slimes, and polysaccharides produced by bacteria may be more important (Jones and Talyor, 1964; Mitchell and Nevo, 1964; Kristiansen, 1981a). Kristiansen (1981a) concluded that quantitatively poly-saccharides were not the dominant form of organic matter accumulated in a OSWDS crust, but that they may serve to bind or cement other cellular material together resulting in a layer resistant to flow.

Infiltration (q_c) through a crust of resistance (R_c), where R_c is the inverse of crust saturated conductivity, can be approximated by the equation

$$q_c = R_c^{-1}\frac{(H_o + \psi_{sc} + Z_c)}{Z_c} \qquad [2]$$

where H_o is the depth of ponded water, ψ_{sc} is the subcrustal pressure potential, and Z_c is the crust thickness (Magdoff and Bouma, 1974). Unless values are known for R_c this relationship is not useful for predictive purposes but it does illustrate the relative effects of both increasing H_o or de-creasing ψ_{sc}. The resulting infiltration rate is an equilibrium between q_c and the subcrustal flux determined by the $\frac{dH}{dZ}$ and unsaturated conductivity function of the underlying soil.

In fine textured, well structured soils, most of the saturated flow occurs through the interpedal voids and cracks. Tracer experiments have confirmed that under initial conditions of both saturation and unsaturation, that water applied moves quickly through the interpedal voids resulting in high dispersion values (Anderson and Bouma, 1977a, b). Although concern was expressed regarding the potential for contamination of groundwater where pedal soils overlie creviced bedrock or high water tables, Anderson and Bouma (1977b) concluded that daily doses of 1 cm d^{-1} or less resulted in substantial reduction of apparent dispersion. When crusts were applied to the top of columns, the dispersion was reduced to similar values for both saturated and unsaturated columns. Bouma (1975) summarized much of the data from earlier work at Wisconsin and concluded that soils of conductivity type IV which include clays and some silty clay loams could be dosed at a maximum loading rate of 1 cm d^{-1} on a trench bottom area basis. These soils are considered to lack many large pores and have low K_{sat} values. Soils of conductivity type III which include silt loams and some silty clay loams can be loaded to a maximum of 5 cm d^{-1}. In both cases Bouma (1975) suggests that dosing and equal distribution is desirable but perhaps not crucial. Although the silty clay loam and clay textures are associated primarily with the type IV conductivity curves, K_{sat} values may be relatively high in well structured residual soils.

The objectives of this study were (1) to test the hypothesis that clayey, well drained soils are suitable for ST-SAS if LPD of effluent is used; and (2) to determine approximate loading rates for soils with different grade, size, and type of structure, and depths to restrictive layers. This paper summarizes performance of 23 prototype ST-SAS installed on four soil types located in three different geographical locations in the Appalachian Valley of Virginia. A spectrum of soil and soil horizons of silty clay loam and clay textures with structure ranging from moderate fine subangular blocky to massive were chosen for evaluation of effluent dosing rates. Two related hypotheses are tested. The first is that ST-SAS with LPD installed in clayey subsoils with poor structure but colors indicating good drainage may be dosed at flux densities (trench bottom area basis) of 0.4 to 0.8 cm d^{-1} without effluent ponding and formation of a biological clogging zone. The second hypothesis is that where a horizon with 30 cm or more of clayey subsoil with moderate to strong subangular blocky structure underlies the ST-SAS, a dosing rate approaching 2 cm d^{-1} will not result in

ponding or mat formation. Both of these hypotheses assume that distribution does not vary by more than 10% over the entire ST-SAS.

4.3 MATERIALS AND METHODS

Three sites were located for installation of prototype LPD systems which included a range of soil textures, structures, and depths to restrictive layers. Each site contains some restrictive soil characteristics under at least some of the prototype ST-SAS.

4.3.1   Research Site Descriptions

4.3.1.1   Site 1

Site 1, installed in the summer of 1982, was located in High Meadows subdivision near Bristol, Virginia. At least 75% of the ST-SAS installed in this subdivision had failed in the 15 years since construction (Carter, 1982). Many of the repair systems which consisted of trenches 90 cm wide and 60 to 120 cm deep with gravity distribution were also failing at least seasonally. The ST-SAS at the site chosen for study, which had been enlarged in November, 1981 by adding trenches with gravity distribution, had effluent surfacing from the system located on a 15% slope. The soil at Site 1, a variant of the Frederick silt loam (clayey, mixed, mesic, Typic Paleudult) described in Table 7, was truncated over part of the site by grading during subdivision construction. All of the A and some of the B horizon had been removed from most of the site.

4.3.1.2   Site 2

Site 2, installed in the summer of 1982, was located on the south side of Rt. 600 1 km west of Rt. 643 in Pulaski County, Virginia on the nose and side slope of a gently sloping interfluve. The soil, a variant of the Lowell series (fine, mixed, mesic Typic Hapludalf) is described in Tables 8 and 9. Unit 1 (Table 8) consists of a soil developed in a thin alluvial cap over residuum from interbedded shale and limestone. Unit 2 (Table 9) lacks the alluvial cap. The site is surrounded

Table 7. Profile description for Site 1, Frederick silt loam, located near Bristol, Va.

Ap	0-13 cm. Mixed clayey fill. Strong brown (7.5YR 5/6) clay; moderate fine granular; friable (moist); abrupt smooth boundry.
A2	13-26 cm. Dark yellowish brown (10YR 4/6) clay loam. Moderate fine granular structure; friable (moist); clear smooth boundary.
Bt1	26-44 cm. Strong brown (7.5YR 5/6 and 5/8) clay; 20 percent yellowish brown (10YR 5/4 to 10YR 5/8) mottles; moderate to strong, fine subangular blocky structure; friable (moist); gradual smooth boundary.
Bt2	44-70 cm. Strong brown (7.5YR 5/6) clay; 30 percent yellowish brown (10YR 5/6 to 5/8) mottles; moderate medium subangular blocky structure; firm (moist); abundant coarse, medium, and fine roots from nearby white pine trees; clear smooth boundary.
BC	70-95 cm. Yellowish red (5YR 5/6) clay; 40 percent yellowish brown (10YR 5/8) mottles; coarse to very coarse blocky structure; massive on ped interiors; very firm (moist); gradual smooth boundary.
C	95-200+ cm. Yellowish red (5YR 5/6) clay; 20 to 30 percent brown (10YR 5/3) and yellowish brown (10YR 5/4 to 5/8) mottles; massive structure; occasional horizontal sand lenses (3 to 10 cm thick) and cracks (1 to 3 cm thick) filled with loose friable silty material.

NOTE: Soil cores taken through the bottom of trench 2 indicated that effluent was ponded above an almost impermeable horizon beginning at 95 cm. Ped faces in the 70 to 95 cm zone had some light gray (10YR 5/1) mottles although the ped interiors appeared to be unchanged. Several horizontal and vertical cracks filled with very pale brown loose silty material contained streaks of very dark gray organic material and appear to be carrying the effluent away from the bottom and sides of the trench through the massive layer. Tree roots were noted in these cracks as well as in the trench gravel.

Table 8. Profile description for Lowell silt loam (variant), Site 2, Unit 1, located on a gently sloping shoulder position of an interfluve near Fairlawn, VA.

Ap   0-25 cm. Brown (10YR 4/3) silt loam; moderate fine granular structure; very friable (moist); clear smooth boundary.

B1   25-60 cm. Pale brown (10YR 6/3) to very pale brown (10YR 7/4) silt loam; many strong brown (7.5YR 5/6) mottles; weak to moderate fine subangular blocky structure; friable (moist); 10 to 20 percent small pebbles including several very rounded cobbles identified as being from the Chilhowee group of cambrian age; clear wavy boundary.

II Bt1   60-80 cm. Light yellowish brown (10YR 6/4) silty clay loam; 40 percent strong brown (7.5YR 5/6) mottles; moderate fine to medium structure; some oriented weathered shale fragments; friable (moist); clear wavy boundary.

II Bt2   80-120 cm. Yellowish brown (10YR 5/8) silty clay to clay; many yellowish red and few very pale brown (10YR 7/3) mottles; moderate medium subangular blocky structure; horizon is developed in weathered shale layer which is up to 40 percent of soil volume; many manganese deposits on shale faces; gradual wavy boundary.

II BC   120-150 cm. Strong brown (7.5YR 5/6) silty clay matrix; yellowish brown (10YR 5/4) weathered shale; 30 to 40 percent by volume; coarse subangular blocky structure imparted by weathered shale.

NOTE: This unit is characterized by the thin capping of New River Sediment over a B horizon formed in weathered shale. Both the coarse fragment and clay content of this underlying shale layer are somewhat variable as the bedding plains of the parent material are inclined 15 to 30 percent, resulting in a substantial spatial variability.

Table 9. Profile descriptin for Lowell silt loam (variant), Site 2, Unit 2, located on gently sloping nose position of an interfluve near Fairlawn, VA.

Ap	0-25 cm. Brown (10YR 4/3) silt loam; moderate fine granular structure; friable (moist); clear, smooth boundary.
Bt1	25-56 cm. Brownish yellow (10YR 6/6) silty clay loam; many reddish yellow (7.5YR 6/8) and strong brown (7.5YR 5/8) mottles; strong fine subangular blocky structure; very friable (moist); moderately thick clay films; gradual smooth boundary.
Bt2	56-90 cm. Brownish yellow (10YR 6/6) and strong brown (7.5YR 5/8) clay; color patterns are arranged more in layers than as mottles; strong medium subangular blocky structure; friable (moist); 10 to 60 percent weathered shale in lower part of horizon; thick clay films noted on both ped and shale faces; gradual wavy boundary.
BC	90-130 cm. Brownish yellow (10YR 6/6) silt loam to silty clay loam with strong brown (7.5YR 5/8) layers of weathered shale which makes up 30 to 60 percent of horizon; friable (moist); some clay films evident on shale faces; clear wavy boundary.
C	130-150+ cm. Yellow (10YR 7/8) silt loam with strong brown (7.5YR 5/8) layers common; moderate medium to coarse structure, probably of parent material origin; 10 to 20 percent shale fragment in parts of the horizon.

NOTE: This unit is developed in limestone interbedded with shale. The abundance of clay films on both peds and shale faces in both the B and BC horizons, indicates that water moves freely through the profile. At the edge of the site, limestone outcrops at the surface.

by karst topography and was chosen because it contained soils developed in limestone residuum considered to be suitable for an ST-SAS.

4.3.1.3   Site 3

Site 3, installed in the summer of 1983, was located at the Giles County Eastern Elementary School on U.S. Rt. 460, 3 km east of Pembroke, Virginia. The school is served by a mass drainfield installed in a Frederick loam. The research site was installed in a variant of the Carbo (very fine, mixed, mesic Typic Hapludalf) series (Table 10) developed in limestone residuum with less than 2 m depth to bedrock which lies adjacent to the Frederick soil on 10% slopes. Pinnacles of limestone extend up into the bottoms of trenches 1 and 2 and are within 1 m of the bottoms of all the trenches. The soil is characterized by a series of clayey Bt horizons with strong subangular blocky structure (Table 10).

4.3.2   Soil Physical and Chemical Properties

The chemical and physical properties of the soils are reported in Table 11. Cations were extracted with the ammonium acetate technique (Chapman, 1965) and exchangable acidity determined with the $BaCl_2$ tri-ethanol amine technique (Peech, 1965). The pipette technique (Day, 1965) was used to conduct particle size distribution analyses. The double tube permeameter technique (Bouwer and Jackson, 1974) was used to determine K_{sat} values at the 40 and 75 cm depths at a minimum of 6 locations at each site (Table 12). Percolation tests were also run and soil moisture retention characteristics determined (data not reported here).

Table 10. Profile description for Carbo loam (variant), Site 3, located on a sideslope at Eastern the Elementary School, Giles County, VA.

A1	0-18 cm. Dark brown (10YR 3/3) silt loam; moderate medium granular structure; friable (moist); clear smooth boundary.
Bt1	18-39 cm. Yellowish brown (10YR 5/8) silty clay loam; medium moderate subangular blocky structure; friable (moist); 10 percent chert fragments; clear smooth boundary.
Bt2	39-63 cm. Strong brown (7.5Y 4/6) silty clay with few medium prominent dark brown Mn mottles on ped faces; moderate medium subangular blocky structure; friable (moist), clear smooth boundary.
Bt3	63-92 cm. Strong brown (7.5YR 5/6) clay; common medium prominent yellowish brown (10YR 5/8) mottles, moderate medium subangular blocky; friable (moist); 40 percent chert fragments; clear smooth boundary.
Bt4	92-112 cm. Red (2.5 YR 4/6) clay; common medium very dark grayish brown (10YR 3/2) Mn films on ped faces and common medium yellowish brown (10YR 5/8) mottles; medium moderate subangular blocky structure; friable (moist); 5 percent chert fragments; clear smooth boundary.
BC	112-130+ cm. Red (2.5 YR 4/6) clay; few fine brownish yellow (10YR 5/8) mottles; many medium very dark grayish brown Mn films on ped faces; strong coarse to very coarse structure approaching massive near limestone contact; firm to very firm (moist); abrupt irregular boundary.
R	limestone.

NOTE: This site lies in the Rome geologic formation, a faulted limestone formation characterized by karst topography (sink holes were located within 100 m in four directions) and somewhat variable soils. Within the experimental area the surface layer of relatively silty varied in thickness between 18 and 80 cm and averaged about 40 cm. A B horizon with moderate medium structure extended to about 80 cm and was underlain by a B with moderate coarse structure that approached massive near the limestone contact which varied between a minimun of 75 and a maximum of more than 225 cm but averaged about 180 cm. Water appears to locally pond above the limestone layer.

Table 11. Representative chemical and physical properties of soils studied.

Horizon	Depth (cm)	pH (H$_2$O)	CEC cmol(+)kg^{-1}	base sat	sand	silt	clay
					---------------percent---------------		

Site 1 - Trench 2

Horizon	Depth (cm)	pH (H$_2$O)	CEC cmol(+)kg^{-1}	base sat	sand	silt	clay
A1	0-13	6.0	4.0	60	24	25	51
A2	13-26	5.5	7.2	56	30	42	28
Bt1	26-44	4.4	12.3	24	22	26	52
Bt2	44-70	4.4	8.2	8	24	21	55
BC	90-95	4.5	6.2	8	47	17	36
C	95-150+	4.4	10.3	7	24	18	58

Site 1 - Trench 3 (truncated profile)

Horizon	Depth (cm)	pH (H$_2$O)	CEC cmol(+)kg^{-1}	base sat	sand	silt	clay
Bt1	0-18	4.3	14.3	39			
Bt2	18-44	4.5	12.3	8			
BC	44-59	4.5	12.6	7	13	17	70
C	59-80	4.5	11.8	7			
	80-100	4.4	7.9	7			
	100-150	4.3	9.2	4	41	9	50

Site 2 - Unit 1 (alluvial cap)

Horizon	Depth (cm)	pH (H$_2$O)	CEC cmol(+)kg^{-1}	base sat	sand	silt	clay
Ap	0-20	5.7	11.9	57	18	63	19
Bt1	20-42	5.5	7.7	56	22	52	25
B2	42-68	5.1	6.2	43	14	63	23
Bt3	68-88	4.9	7.0	38	12	58	29
BC	88-108	4.9	6.5	30	13	61	26
C	140-171	5.2	7.6	43	9	56	35

Site 2 - Unit 2 (limestone residuum only)

Horizon	Depth (cm)	pH (H$_2$O)	CEC cmol(+)kg^{-1}	base sat	sand	silt	clay
Ap	0-23	5.6	13.0	51.0	14	60	26
Bt1	23-51	6.2	8.9	53.7	9	54	37
Bt2	63-86	6.1	14.9	56.3	10	40	50
BC	86-105	6.0	15.4	74.4	21	38	41
C	105-124	6.2	8.8	70.8	16	58	26

Site 3 - Trench 6

Horizon	Depth (cm)	pH (H$_2$O)	CEC cmol(+)kg^{-1}	base sat	sand	silt	clay
A1	0-18	5.6	12.8	59	23	63	14
Bt1	18-39	4.9	10.4	57	19	51	30
Bt2	39-63	4.5	19.3	49	12	40	48
Bt3	63-92	4.8	18.8	58	19	27	54
Bt4	92-112	5.0	19.0	62	18	23	59
BC	112-155	4.8	16.0	60	18	34	48

Table 12. Saturated conductivity values for soils determined at two depths with the double tube permeameter technique. Arithmetic means ($\bar{x}$) standard deviations (S.D.), and sample number (n) are reported. In addition log-normalized means ($\bar{x}_{ln}$) were calculated from the equation $\bar{x}_{ln} = e^{(\bar{x}_{ln(k)} + 0.5 s^2_{ln(k)})}$ where $\bar{x}_{ln}(k)$ and $s_{ln}(k)^2$ are the sample mean and variance of natural logs of the K sat values.

	Depth = 40cm				Depth = 75cm			
	$\bar{x}$	SD	$\bar{x}_{ln}$	n	$\bar{x}$	SD	$\bar{x}_{ln}$	n
	------ cm hr^{-1} ------				------ cm hr^{-1} ------			
Site 1	5.60	8.80	9.40	6	1.00	1.20	1.20	6
Site 2								
Unit 1	0.34	0.28	0.36	5	0.56	0.38	0.62	4
Unit 2	15.00	--	--	1	1.30	1.40	1.60	4
Site 3	0.22	0.27	0.41	6	0.61	0.95	2.20	6

4.3.3 Effluent Characteristics

Effluent samples were collected regularly while the prototype ST-SAS were being dosed. Effluent characteristics reported in Table 13 were analyzed by routine procedures (U.S. Environmental Protection Agency, 1979). Even though limited variability in the mean values is noted between sites, the effluents at each site have very similar characteristics. The low nonfilterable residue concentrations of < 0.04 mg L^{-1} indicate that effluent contains less suspended solids than normally found in other effluents (U.S. Environmental Protection Agency, 1980). This is further supported by the fact that 90% of the N in the wastewater from each site is present as NH_4^+ in contrast to the 80% reported elsewhere (Brown et al., 1984; Kristiansen, 1981b; Walker et al., 1973). The COD values for each site are approximately half of the average presented in U.S. Environmental Protection Agency (1980) while phosphate and total P concentrations fall within the range reported. The additional treatment may be the result of increased retention time afforded by the pumping chamber.

4.3.4 Design of Prototype ST-SAS Trenches

Trenches 4.5 m long by 0.6 m wide were dug to a 0.75 to 0.8 m depth at each site. Trench dividers made of 1 mm thick steel were driven into the trench bottom 1.5 m from each end to maintain good distribution. If effluent ponded above the divider height (50 cm Sites 1 and 2, 15 cm at Site 3) then it could redistribute to other parts of the trench. Neutron access tubes, tensiometers, observation ports, soil sampling tubes and water level recorders were installed in and around the trenches. A 0.6 m envelope of crushed limestone rock 1.2 to 1.8 cm in diameter was placed in each trench and covered with a 1 μm woven filtration cloth to prevent migration of silt and clay from the topsoil cover into the gravel envelope. Each section of trench was dosed independently to optimize the distribution. Exceptions to this were trenches which were installed without dividers and were dosed 12 times d^{-1} instead of 1 time d^{-1} to simulate the trickling nature

Table 13. Arithmetic means ($\bar{x}$), standard deviations (SD), and sample sizes (n) of selected effluent characteristics for research sites.

	Site 1			Site 2			Site 3		
	$\bar{x}$	SD	n	$\bar{x}$	SD	n	$\bar{x}$	SD	n
pH	7.3	0.3	19	7.3	0.3	18	7.1	0.4	16
electrolytic conductivity (S m^{-1})	79.8	9.9	15	87.0	20.0	15	92.7	19.6	12
Cl$^-$ (mg L^{-1})	43.2	13.1	14	49.8	20.4	15	60.3	34.9	13
TKN (mg L^{-1})	42.8	15.7	26	62.3	19.3	25	53.6	22.2	13
NH$_4^+$-N (mg L^{-1})	38.6	12.3	26	55.0	17.9	25	49.8	18.0	13
NO$_3^-$-N (mg L^{-1})	0.39	1.1	26	0.16	0.20	25	0.13	0.10	13
nonfiltered residue (mg L^{-1})	0.02	0.02	7	0.03	0.02	9	0.04	0.04	9
COD (mg L^{-1})	31.8	123	16	407	166	16	378	180	14
orthophosphate-P (mg L^{-1})	21.6	7.6	8	17.1	9.3	9	15.1	4.8	8
Total P (mg L^{-1})	22.8	8.4	9	18.5	8.6	10	18.2	4.8	9

of gravity distribution. These trenches will not be considered separately, as performance was similar to the LPD simulations.

Figures 9, 10, and 11 contain the relative location of the prototype ST-SAS trenches and their identification by number. The loading rates for the prototype ST-SAS are reported in Table 14. Prototype ST-SAS which were dosed 12 times d^{-1} are also noted in Table 14. To obtain effluent for the prototype ST-SAS, a pumping chamber was installed at Sites 1 and 2 between the distribution box and septic tank, but an existing pumping chamber was used at Site 3. A timer driven effluent pump filled tanks constructed from epoxy-painted plywood one time d^{-1}. After the tank was full but before the pump turned off, effluent overflowed back to the pumping chamber thus a constant daily volume could be obtained. Tank volumes were varied to obtain different loading rates. Following pump shut down, 1 cm solenoid valves (110v dishwasher dump valves) were energized by solid state timer and the tanks drained. Each tank also contained a 40 watt light bulb on a separate circuit which could be turned on for timed increments during winter months to prevent the valves from freezing. Warm temperatures in the tank did not affect the effluent quality since effluent resided in the tank for less than 10 minutes. The entire tank was insulated with boxes constructed from 5 cm thick sheets of expanded polystyrene.

During dosing, effluent flowed via a separate solenoid valve to each section of the trench and exited from a 3.8 cm plastic pipe simulating LPD. The effect was the same as flow from an orifice except that the quantity of effluent could be accurately controlled. Even though the solenoid valves worked well, an interval timer had to be installed in the circuit which prevented them from being turned on by mistake for more than 5 minutes lest they burn up.

Ponding depths were determined by installing model 5 FW-1 Belfort stage recorders with a 5:12 gear ratio in wells that extended to the bottom of the drainfield. One recorder was installed in each trench in which ponding was observed to occur. Ponding depths reported in this paper are the time-averaged median depth during the last year of ST-SAS dosing. The ST-SAS appeared to be in equilibrium during this time interval. Photographs of trench cross sections at Site 1 and soil cores at Site 3 were taken during the fall of 1985. Other photographs were taken during site installation and characterization.
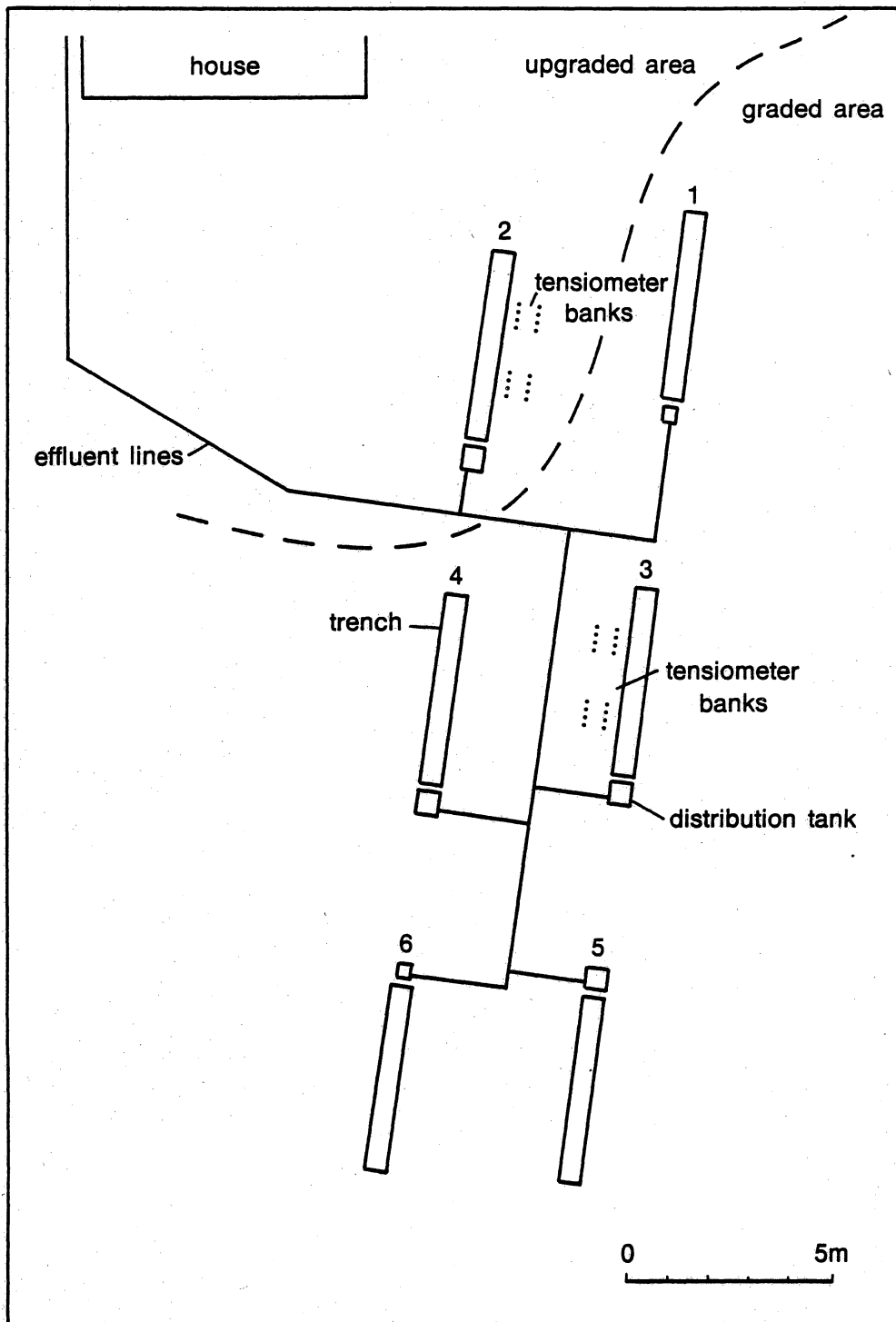
Figure 9. Layout of Site 1: The dots represent tensiometers placed outside of the trench.
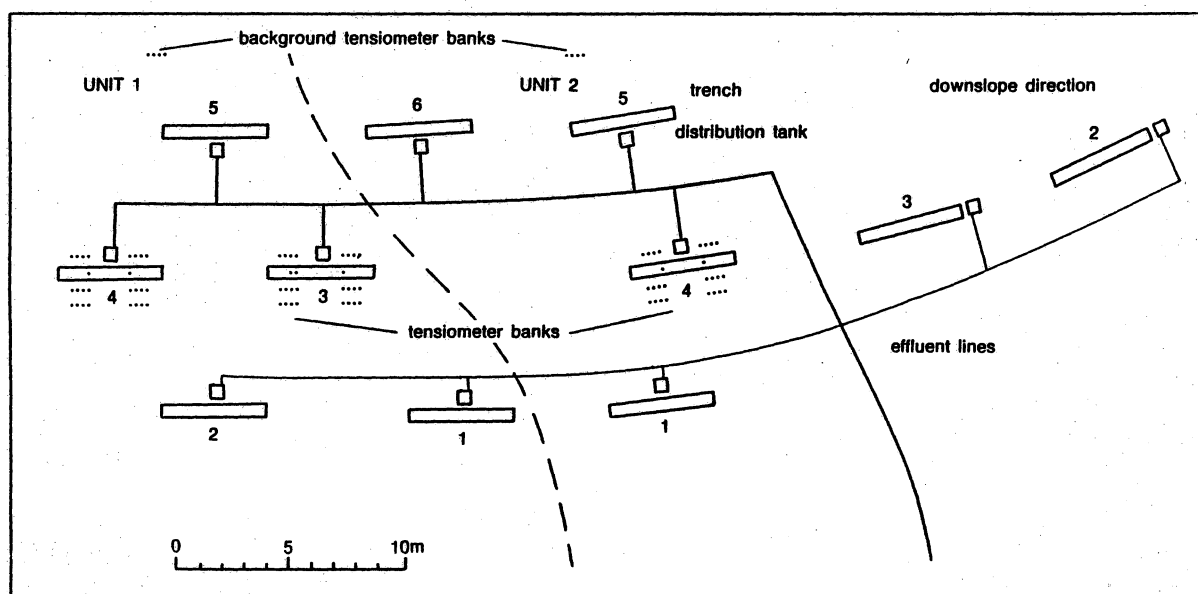
Figure 10. Layout of Site 2: Note the dashed line separates Unit 1 from Unit 2. Dots represent tensiometers.
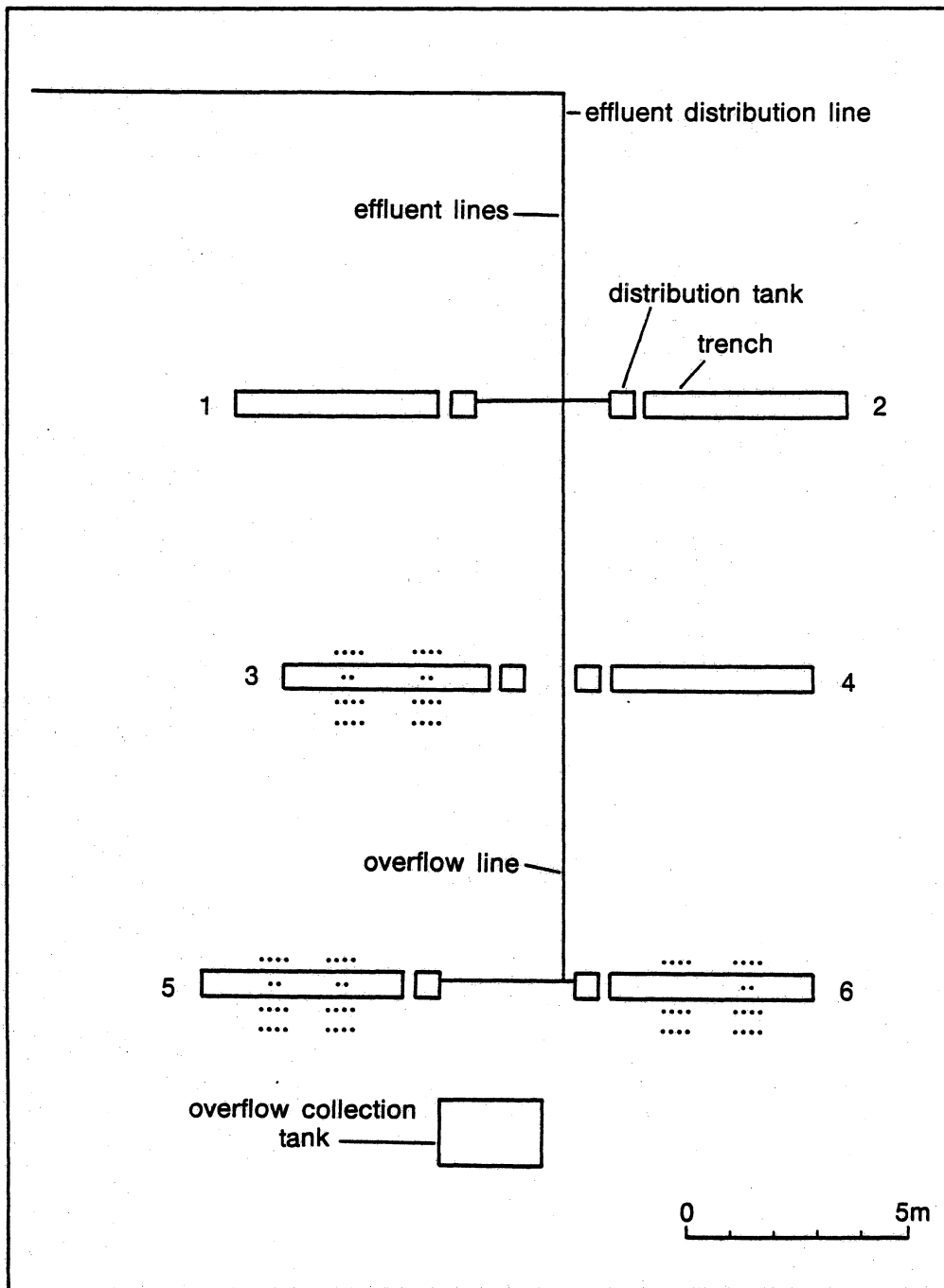
Figure 11. Layout of Site 3: The dots represent tensiometers outside of the trench.

Table 14. Effluent flux densities and ponding levels in trenches at each site.

	Trench[1]					
	1	2	3	4	5	6
			Site 1			
q^2 (cm day^{-1})	0.4[4]	1.8	1.8	1.8[3]	3.6	0.4
ponding depth (cm)	0	0-15	40-50	10-20	40-60	0-15
			Site 2 - Unit 1			
q (cm day^{-1})	3.6[4]	0.8[4]	0.8	3.6	3.6	
ponding depth (cm)	30-40	0-1	0	30-40	20-30	
			Site 2 - Unit 2			
q (cm day^{-1})	3.6[3]	3.6[4]	0.8[4]	3.6	3.6	0.8
ponding depth (cm)	0	0	0	0	0	0
			Site 3			
q (cm day^{-1})	3.6[3]	0.8[3]	0.8	1.8	1.8	3.6
ponding depth (cm)	15-20	0	0	0	0	15-20

[1] See Fig. 1, 2, and 3 for relative locations

[2] Flux density defined on a trench bottom area basis

[3] These trenches contain a 10cm layer of medium sand below the gravel envelope.

[4] Thus flux density was split into 12 small doses d^{-1}.

4.4 RESULTS

4.4.1 Relationships between Soil Properties and Effluent Ponding

4.4.1.1 <u>Site 1</u>

During initial site evaluation, the subtleties of horizon depth differences caused by grading and the strength of the structure in the B horizon near the surface on most of the site were not fully appreciated. Trenches were designed with the 60 cm gravel envelope to maximize the sidewall area available for infiltration as well as to provide some reserve volume for anticipated ponding. During site installation and subsequent intensive sampling for determination of N distribution, the extent of grading and horizon truncation at the site became apparent. The depth to the Bt-BC contact was approximately 50 cm in all of the trenches except for trench 2 where the contact zone was approximately 90 to 95 cm and trench 4 where it was approximately 60 cm. These two trenches were at the edge of a shoulder which became part of a flat summit after 30 to 50 cm of the summit was graded off to fill gullies during subdivision construction. The net effect of the horizon distribution was that it provided an excellent mechanism for comparing the effects of soil structure on performance of ST-SAS without actually varying depths of installation.

As indicated in Table 14 continuous ponding occurred in two of the trenches dosed at 1.8 cm d^{-1} as well as in the trench dosed at 3.6 cm d^{-1}. Trench 2 ponded at about 15 cm during periods of excess rainfall but drained out during dry summer and fall months. Trench 1 did not have a stage recorder but was only noted to be ponded during one site visit after several cm of rainfall. Trench 6 commonly ponded following major rainfall events or during wet winter and spring months but dried out during summer and fall months. On several occasions ponding levels in trenches 2 to 5 increased as much as 20 cm over a 24 to 48 h period of time following a rainfall event of several cm. Because effluent dosing rates were constant, it was ascertained that the rapid changes in ponding depth were due to redistribution of water temporarily perched above the BC horizon.

Consideration of the order of magnitude differences in conductivity values between the Bt vs the BC horizons (Table 12), the above phenomena are not unexpected. Likewise evaluation of Plates 1, 2, and 3 indicate that the Bt horizon was dissipating much of the effluent load for the trenches dosed at 1.8 and 3.6 cm d^{-1}. It is evident in Plate 1 that much of the effluent from this trench is flowing horizontally and vertically through cracks or old root channels in the BC and C horizons. In addition, the lower ponding levels during summer and fall months may have been due in part to water uptake by a nearby silver maple (*Acer saccharinum*) and white pine (*Pinus strobus*) trees. Their roots were observed to proliferate in the cracks and gravel envelope and the Bt horizon near the trench.

Plate 2 is a core from the 10 to 70 cm section of the profile sampled 30 cm from trench 3. The top of the gray zone at 30 to 33 cm below the surface corresponds with the level at which effluent was ponded in the trench throughout most of the year. Accumulation of organic matter in the interpedal voids (Plates 2 and 3) not only defines the coarse blocky structure of the lower Bt horizon and the weak very coarse blocky structure of the BC horizon but also suggests that continued accumulation of organic matter could eventually lead to reductions in the sidewall infiltrative capacity. It also became apparent that limited depth to a restrictive layer may be the reason for failure of many of the ST-SAS installed on sideslopes in this subdivision.

While no difference in performance could be attributed to placement of the sand layer in the bottom of the trench, Plate 4 does illustrate that a substantial amount of biological material has accumulated in the sand. It is impossible to determine whether the sand had a beneficial effect at the 1.8 cm d^{-1} flux density. Flow along cracks in the BC and C horizons also contributed to transmission of the effluent load away from this system.

Plate 5, a cross section of trench 6 dosed at 0.4 cm d^{-1} indicates that even though ponding occurred in response to temporary perched water tables, the low effluent flux densities did not result in any pore clogging or mat formation. Processes which minimize pore clogging associated with anaerobic conditions should be maximized to lengthen the life of systems placed in similarly restricted soils. These include lower flux densities and shallow placement of ST-SAS.
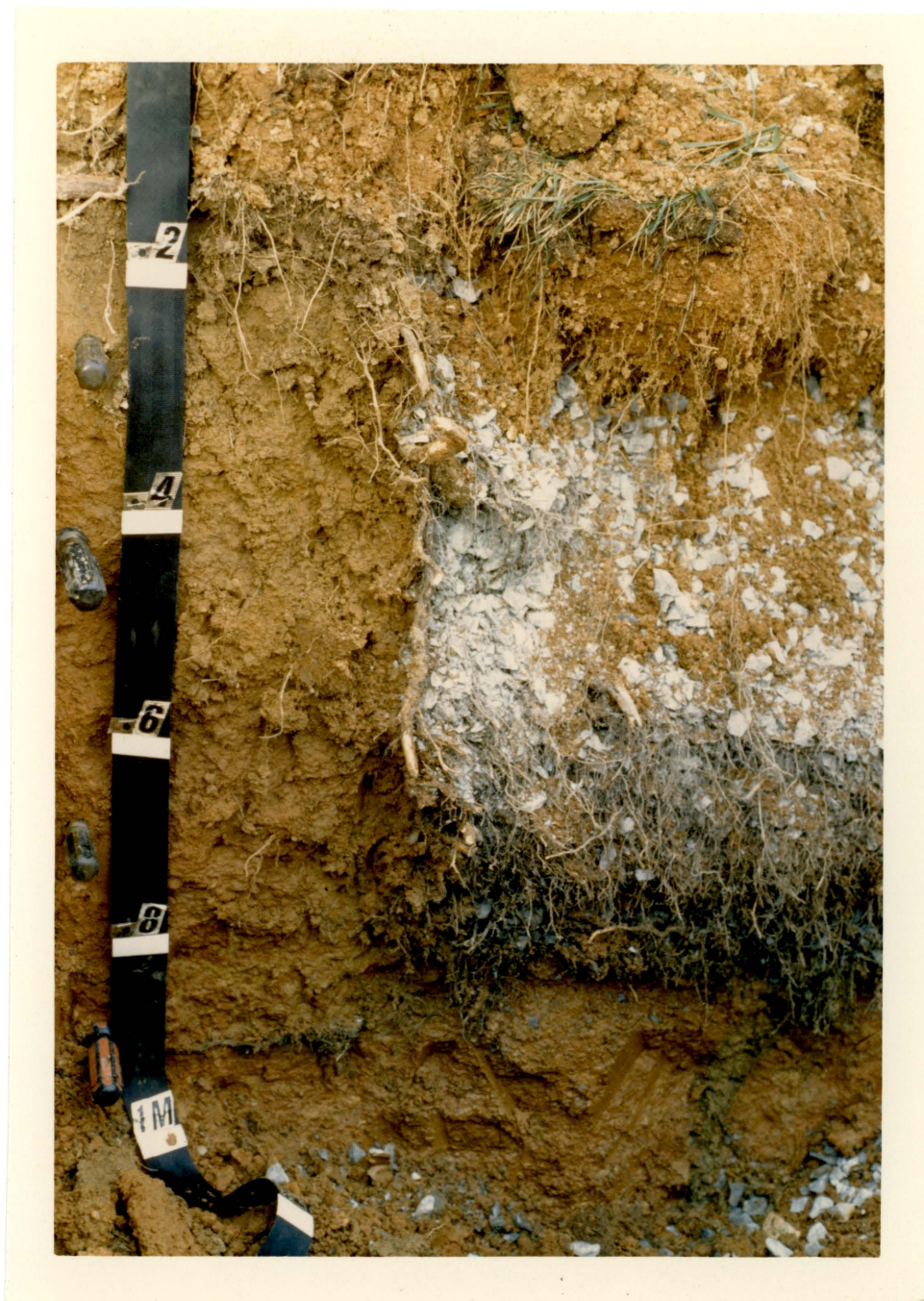
Plate 1. Cross section of trench 2 at Site 1 illustrating horizonation described in Table 2 of the variant of a Frederick (clayey, mixed, mesic, Typic Paleudult) soil. Note the accumulation of organic matter on the lower 15 cm of the gravel envelope and the abundance of roots. Wastewater appears to be flowing primarily through both horizontal and vertical cracks through the BC and C horizons.

Plate 2. Section of soil core sampled 30 cm from trench 2 at Site 1. Note the definition of the coarse blocky structure in the Bt2 by the accumulation of organic matter. The much coarser, weaker structure of the underlying BC is defined by the more yellow lines with streaks of gray. The bottom of the photo is about 10 cm above the trench bottom while the top is 10 cm below the soil surface. The scale on the left is in cm while the scale of the right is in inches.

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Plate 3. Close up of Plate 2. Visible scale represents depth (cm) from the surface. Comparison of this plate with date in Table 8 indicates that the zone of discoloration corresponds to the top 10 cm of the effluent ponding level (80 cm trench depth - 30 cm from surface = 50 cm of effluent).

Plate 4. Cross section of trench 4 with soil profile similar to trench 3. Note the accumulation of organic matter in the 10 cm sand layer. Although effluent has discolored a 1 to 5 cm zone around the gravel-trench interface, most movement appears to be through cracks and overlying more structured horizons.

Plate 5. Cross section of trench 6, Site 1. The pen knife marks the contact between the Bt2 and BC horizons. Note that in spite of seasonal ponding due to perching of a water table above the C horizon, no evidence of formation of a biological mat is apparent.

4.4.1.2 Site 2

As indicated in Figure 10 and Tables 8 and 9 the prototype systems at this site are located in two different but similar soils. Unit 1 consists of a soil developed in an alluvial cap and underlying weathered shale. While the shale is fractured and interbedded with structured silty material, it apparently does not contain enough pore space to adequately transmit the 3.6 cm d^{-1} load. This effect of the weathered shale fragments on reducing the cross sectional area of pore space available for effluent infiltration is illustrated in Plate 6. This 20 cm diameter horizontal cross section was removed from the same depth in Unit 1 as which the trench bottoms are located. Similar distributions of shale were noted near the bottoms in all of the trenches in Unit 1 during construction. The systems dosed at 0.8 cm d^{-1} all performed without significant ponding in both units suggesting the suitability of this flux density in this and similar soils.

The profile in Plate 7 is typical of Unit 2. Weathered shale fragments were also encountered at about 90 cm but the strong medium blocky structure of the silty clay loam Bt transmits the 3.6 cm effluent dose away from the soil gravel interface in < 30 min. Several percolation tests had rates faster than 1 min cm^{-1} in this unit even though the conductivity values in Table 12 are slower. There were not enough K_{sat} tests run in Unit 2 at the 40 cm depth to determine if the 15 cm hr^{-1} is representative of the true mean. The rate at which effluent moves through this soil following dosing does suggest that a system with poor distribution and potential saturated flow, such as conventional gravity flow systems (U.S. Environmental Protection Agency, 1977), could pose a pollution hazard with respect to groundwater contamination in this karst topography. A 20 cm diameter channel was intersected at 75 cm depth when the K_{sat} tests were being run which did not appear to be of floral or faunal origin but rather a relic solution channel. When the bottom of the test hole collapsed, 40 L of water flowed down the channel in a few seconds indicating the importance of good distribution and unsaturated flow in these soils.

Plate 6. Close up of horizontal soil layer removed from 75 cm depth with the hole cleaner for a double tube conductivity test. Note the shale layer with fingers of structured residuum between. This photo was from a conductivity test hole in Unit 1.

Plate 7. Soil profile of Unit 2, a variant of the Lowell (fine, mixed, mesic Typic Hapludalf) series. The pit was centrally located between trenches 1 and 3, of Unit 1 and trenches 1, 4, 5, and 6 of Unit 2. Yellow caps mark major horizons corresponding to the profile description in Table 2.

4.4.1.3 Site 3

This soil, developed in a thin regolith of limestone residuum, is characterized by clayey Bt horizons with moderate to strong subangular blocky structure (Table 10, Plate 8). The presence of at least 20 to 30 cm of well structured material below the soil-gravel interface appears to be adequate for transmission of effluent fluxes of up to 2 cm d^{-1}. Ponding occurred within 6 months at the 3.6 cm d^{-1} flux and was continuous. Tensiometer data (see chapter 4) indicate that maintenance of a pressure potential of slightly negative value is adequate in this soil to prevent development of a crust at the interface. Plates 9 and 10 are photographs of the top 10 cm of cores taken from the bottom of trenches dosed for two years at 1.8 and 3.6 cm d^{-1} respectively. Note the 1 cm thick mat which has developed at the interfacial zone of the trench dosed at 3.6 cm d^{-1} but is absent in the trench dosed at the 1.8 cm flux density. No performance difference has been noted between the trenches with or without sand layers at this site or Sites 1 and 2.

Plate 8. A soil profile at Site 3, a variant of the Carbo (very fine, mixed mesic Typic Hapludalf). This profile was the wall of a soil pit dug for placement of overflow collection tank noted in Figure 3. Note that the profile is shallower than described in Table 3. Horizons marked are A1, 0-18 cm; Bt1 and Bt2, 18-63 cm; Bt3, (corresponds to Bt4 in Table 4), 63-90 cm; BC, 90-105 cm; and R at approximately 105 cm.

Plate 9. Top 10 cm of soil core sampled below trench 5, Site 3. Note that effluent has not ponded in this trench, hence no accumulation of a clogging zone is apparent at the interfacial region.

Plate 10. Top 10 cm of soil core sample below trench 6, Site 3. Note the mat of organic matter which has accumulated at the gravel-soil interface under ponded conditions.

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4.5 DISCUSSION

The importance of having at least 30 cm of moderate to strongly structured B horizon below ST-SAS is illustrated when the overall performance of these prototype systems is considered. Data from Unit 2 at Site 2 and from Site 3 indicate that uniformly applied flux densities of 2 cm d^{-1} may be suitable for ST-SAS underlain by 30 cm or more of a clayey Bt horizon with moderate to strong blocky structure. Systems should be installed as shallow as possible to gain maximum benefit from the potential flow capacity of the structured B horizon. Placement of trenches deeper in the profile with a thicker gravel envelope resulted in adequate performance at all sites via transmission of effluent through bottom and sidewall areas. The organic matter accumulation in interpedal voids and cracks noted in Plates 1 to 4 suggest, however, that design to minimize or eliminate ponding is to be preferred as the mat development was not noted under aerobic conditions in trenches with effluent doses of 0.4 cm d^{-1} at Site 1, 3.6 cm d^{-1} at Site 2 Unit 2, and 1.8 cm d^{-1} at Site 3. While installing a ST-SAS in a soil as limited as the graded portion of Site 1 would be expensive due to sizing requirements, the morphology of the interfacial region of trench 6 at Site 1 after three years of operation is encouraging and suggests that soils which may be somewhat restricted but which have bright chromas can be used for ST-SAS with LPD if dosed at low flux densities.

Table 15 is a summary of loading rates recommended on the basis of this research for clayey soils of varying grade, size, and type of structure and depth to bedrock or other flow restrictive layer. Rather than suggesting that these loading rates may be suitable for similar soils with conventional gravity distribution, the ponding at higher flux densities suggests that clogging can be anticipated if flow is not uniform and does not remain unsaturated at least part of the time. The lateral creep of a surface mat with gravity distribution systems is documented and discussed elsewhere (U.S. Environmental Protection Agency, 1977). While systems with gravity distribution may function adequately, this research suggests better long-term performance of OSWDS with LPD. Although concern has been expressed about macropore transmission of pathogens during dosing events (Anderson and Bouma, 1977a,b) or in uncrusted soils (Rahe et al., 1978; McCoy and Hagedorn, 1980), application of smaller flux densities (i.e, < 1 cm d^{-1}; Anderson and Bouma, 1977b) in

Table 15. Summary of proposed loading rates for limestone-derived soils.

loading rate (cm d^{-1})		
0.5	1.0	2.0 - 3.0
weak coarse sbk[1], abk[2], pr[3], or cr[4] structure	mod[5] to strong sbk, abk, pr, or cr structure 15 to 30 thick layer or > 30 cm but 25 to 50% c.f.	mod to strong sbk, abk, pr, or cr structure no apparent restrictions < 60 cm

[1]subangular blocky
[2]angular blocky
[3]prismatic
[4]columnar
[5]moderate

OSWDS where this is of major concern should minimize these dangers, but further research in this area is warranted.

4.6 CONCLUSIONS

Clayey, well structured B horizons without observed morphological restrictions, including shallow depth to bedrock, high coarse fragment content, or closely underlying horizons with massive structure, adequately transmitted effluent doses of up to 3.6 cm d^{-1} without evidence of ponding or crust formation. Soils with pinnacles of limestone adjacent to the trench bottom, but with strong structure in the underlying B horizon performed satisfactorily without any ponding or mat accumulation at 0.8 and 1.8 cm d^{-1} doses of effluent. Ponding and mat accumulation with substantial ponding was noted in these systems dosed at 3.6 cm d^{-1}.

Presence of large amounts of weathered shale or other coarse fragments in otherwise well structured soils may result in lower effluent acceptance rates. Evidence indicates that rates approaching 1 cm d^{-1} may be suitable in similar soils. Where possible, at least 30 cm of well structured soil should be maintained between trench bottoms and restrictive or poorly structured soil horizons, even if colors with high chromas are observed in the underlying horizons. In fine textured soils where colors indicate good drainage but structure is weak and no other alternative exists, flux densities of 0.4 to 1 cm d^{-1} may be suitable.

Most importantly this research indicates that fine textured soils with good drainage are suitable for OSWDS, but long term reduction in infiltration rates will probably occur at the localized high loading rates typically associated with gravity distribution. Pressure distribution of effluent is recommended for these soils at up to 2 cm d^{-1} in clayey well structured soils with at least 30 cm distance between a trench bottom and a restrictive layer. Where a restrictive layer is closer to the trench bottom or coarse fragment content is > 25%, flux densities of 0.4 to 1 cm d^{-1} may be suitable if soil colors indicate that soils are moderately well drained.

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5.0 CHAPTER V

SEPTIC TANK SUBSURFACE ABSORPTION SYSTEMS IN CLAYEY

LIMESTONE-DERIVED SOILS:

II. RELATIONS BETWEEN PONDING, PRESSURE HEADS, AND NITRIFICATION

5.1 ABSTRACT

Nitrogen is the chemical contaminant in septic tank effluent (STE) with the greatest potential for environmental degradation of ground and surface waters. Increasing NO_3^- levels have been attributed in part to nitrification of STE in well drained soils. While substantial information regarding the relationships between nitrification, effluent ponding, and pressure heads is available for sandy soils with and without shallow water tables, little information is available for soils with clayey Bt horizons developed in limestone residuum. The relations between effluent flux density, ponding, pressure heads, and distribution of inorganic N species and their ratios with respect to Cl^- are evaluated for 8 prototype ST-SAS dosed at flux densities (trench bottom area basis) ranging from 0.8 to 3.6 cm d^{-1}. Minimal nitrification and positive pressure heads were noted below and beside a ponded ST-SAS placed in a very restrictive C horizon and dosed at 1.8 cm d^{-1} as well as below a ST-SAS shallow to limestone dosed at 3.6 cm d^{-1}. Where ST-SAS were not ponded or where average pressure heads close to the effluent source were < -20 cm of water, nitrification did not appear to be limited. Concentrations of NO_3^- in soil solution were highest below ST-SAS with negative pressure heads regardless of flux density. Ratios of NO_3^--N/Cl^- did not suggest denitrification below the ST-SAS. Slightly decreasing ratios adjacent to trenches could not definitely be attributed to denitrification. Substantial dispersive flow in saturated, well structured, clayey soils was evidenced by substantial horizontal and vertical movement of NH_4^+. Nitrification was greatest below ST-SAS which were not ponded. Where nitrification occurs below deeply placed ST-SAS in well drained soils there appears to be limited potential for denitrification thus dilution is the

primary mechanism for meeting USPHS standards of 10 mg L^{-1} of NO_3^--N for groundwater recharge below OSWDS.

Additional keywords: pressure transducer, tensiometer, infiltration rates, biological mat, low pressure distribution, alternative wastewater systems, soil structure

5.2 INTRODUCTION

Nitrogen has been identified as the contaminant in STE with the greatest potential for environmental degradation of ground and surface waters (Brown et al., 1977; Walker et al., 1973b). Leaching of NO_3^- into drinking waters can lead to methemoglobinemia in infants and in some animals. The USPHS standard of 10 mg L^{-1} NO_3^--N suggested by a comprehensive review by Walton (1951) has with stood several critical reviews by the scientific community (Keeney, 1982). Previous studies have implicated OSWDS as being responsible for substantial increases in groundwater NO_3^- levels (Quam et al., 1974; Miller 1975). Substantial nitrification around OSWDS and subsequent movement of NO_3^- has been reported (Walker et al., 1973a,b; Whelan and Barrow, 1984; Reneau, 1977, 1979). Simple models for estimating pollution potential have even been developed (Bauman and Shafer, 1985). A major limitation remains a lack of predictability of N processes in soils surrounding OSWDS. While some information is available for sandy glacial outwash and lacustrine soils (Walker et al., 1973a, b; Bouma et al., 1972) and coastal plain soils (Reneau, 1977, 1979, Stewart and Reneau, 1984; Whelan and Barrow, 1984) limited information is available for clayey soils (Sikora and Corey, 1976). Total N concentrations in STE have been reported to range from 35 to 100 mg L^{-1} (U.S. Environmental Protection Agency, 1980) with approximately 80 percent present as NH_4^+-N but less than 1 mg L^{-1} as NO_3^--N or NO_2^--N (Walker et al., 1973a; Brown et al., 1977; Kristiansen, 1981).

Diffusion of adequate O_2 to zones of nitrification is the factor most likely to limit nitrification in saturated and nearly saturated soils or soil materials surrounding OSWDS (Walker et al., 1973a; Reneau, 1977, 1979; Brown et al., 1977; 1984; Kristiansen, 1981). While nitrification processes may be relatively predictable in soils which are well drained, complex interactions of mineralization, nitrification, denitrification, and leaching processes may occur in flooded or saturated soils (Patrick, 1982). In soils with shallow seasonally fluctuating water tables, Reneau (1977, 1979) reported zones of NH_4^+ absorption directly adjacent to OSWDS and zones of nitrification and subsequent denitrification as effluent moved with ground water flow away from OSWDS to subsurface tile drains. These phenomena were supported by NO_3^--N/Cl^- ratios in the soil solution. Almost complete

nitrification and subsequent leaching of NO_3^- to perched groundwater layers has been reported below OSWDS located in sandy soils even though effluent was ponded above a crusted zone (Walker et al., 1973a; Whelan and Barrow, 1984). Unsaturated subcrustal soils allowed O_2 diffusion to zones of nitrification adjacent to OSWDS. In contrast minimal nitrification of accumulating NH_4^+ was reported below trenches submerged in groundwater (Walker et al., 1973a). Brown et al. (1977; 1984) reported similar accumulations of NH_4^+ by processes of adsorption below OSWDS which were anaerobic, but when lysimeters were allowed to become aerobic, nitrification and subsequent leaching of NO_3^- to underlying groundwater occurred.

Denitrification is expected to be minimal in optimally functioning OSWDS located in well drained soils (Bouma, 1979) thus dilution remains the primary mechanism for meeting groundwater standards in these soils. Walker et al. (1973b) reported that approximately 0.2 ha of downgradient watershed was required to dilute NO_3^- leaching from OSWDS to acceptable levels. In contrast, the work of Reneau (1977, 1979) indicates that in poorly drained soils with high seasonal fluctuating water tables substantial dentrification may occur with conventional ST-SAS using gravity distribution providing that a zone of nitrification is present. Availability of an adequate C source has been cited as the most limiting factor for promoting dentrification (Sikora and Keeney, 1974) especially for OSWDS placed in lower soil horizons. Stewart et al. (1979) conducted laboratory column studies using a mixture of a histic epipedon and sand to evaluate the use of soil organic matter as an energy source. Their results indicate that residual soil organic matter is probably not a satisfactory long-term energy source for denitrification. Similarly, only 32 percent denitrification was reported in laboratory columns simulating sand mounds (Magdoff et al., 1974). In contrast, up to 86 percent of N applied has been denitrified in mounds (Harkin et al., 1979). Summarizing the work of Stewart and Reneau (1984), Reneau et al., (1986) reported 98 percent reduction in NO_3^--N/Cl^- ratios as a winter time rising water table carried NO_3^-, which had accumulated below a shallow-placed ST-SAS with LPD, back up into the lower part of the Ap horizon. In all of these studies (Reneau 1977, 1979; Harkin et al., 1979; Stewart and Reneau, 1984), large scale denitrification was apparent when a water table fluctuated close to the surface at least seasonally.

Firestone (1982) summarizes several studies where denitrification was enhanced in the rhizosphere by presence of root and microbial exudates rich in soluble C. Most likely the presence of grass roots, their exudates, and the accompanying microbial activity is the primary source of C for denitrification associated with mounds and shallow-placed OSWDS. Unfortunately, OSWDS placed in freely drained soils of any texture will probably be characterized by loss of most NO_3^- to groundwater layers too deep to have sufficient soluble C present to allow denitrification.

Temporal and spatial distribution of soil moisture tensions have been used to evaluate the hydraulic performance of ST-SAS and have been related to the nitrification potential (Bouma et al., 1972; Bouma, 1975; Walker et al., 1973a). Sikora and Corey (1976) in summarizing this work concluded that at tensions of -60 to -100 cm of water, sandy loams and loams below OSWDS were aerobic and nitrification occurred. Noting a lack of similar data for finer textured soils, they assumed a general soil moisture characteristic could be described for a silty clay loam. Taking into account an assumed air entry value they estimated that a pressure head of -35 cm could be expected to correspond to an approximate borderline between anaerobic and aerobic conditions. A limitation of such an approach is that it does not consider the effect of varying soil structures on pressure heads at which nitrification may occur.

The objective of htis study was to determine the extent of nitrification in clayey limestone-derived soils below ST-SAS in which effluent was (1) ponded and (2) undponded. The relations between soil morphological properties, effluent ponding, pressure heads, and distribution of NO_3^--N and NH_4^+-N were examined for prototype ST-SAS with simulated LPD of effluent located on four clayey soils developed in limestone residuum.

5.3 MATERIALS AND METHODS

Morphological, chemical, and physical properties of soils, details of the experimental design and a discussion of the performance of prototype ST-SAS were described in chapter 4. Duplicate banks of pencil tensiometers with Hg manometers (Bouma et al., 1972) were installed 5, 10, and 45 cm below the bottom of the trenches during construction of prototype ST-SAS. They were placed through the side of 15 cm diameter plastic pipe buried in auger holes and grouted with a bentonite clay and sand mixture to prevent migration of effluent along the plastic pipe. The tensiometers were 7.5 cm long, 0.6 cm diameter, and installed with a grout of B horizon material in small holes made by hand with a 0.6 cm drill bit. To obtain additional information, duplicate rows of cup tensiometers were installed at Site 1 at distances of 0.3 and 0.9 m from trenches 2 and 3 during August, 1985 (Chapter 4, Fig. 9) and at Sites 2 and 3 in January 1986 and October 1985, respectively (Chapter 4, Fig. 10 and 11, respectively). The cup tensiometers were installed by removing a 4.5 cm soil core with a Giddings soil coring machine to a depth 10 cm above where the ceramic cup was placed. Holes were augered to the depth of cup placement with a 2.5 cm diameter hand auger. Tensiometers were grouted with a slurry of silica flour and relative elevations of cups determined with a level transit. At the recommendation of Wierenga (1985) tensiometers were filled with a mixture of equal parts of water and ethylene glycol (antifreeze solution for automobile engines) during December 1986. This facilitated ongoing measurements of tensions even though the surface soil was frozen. All of the tensiometers installed at Sites 1, 2, and 3 in the summer, fall, and winter of 1985 and 1986 were constructed as described by Marthaler et al. (1983), and monitored with a Tensimeter[TM] (available from Soil Measurement Systems, Las Cruces, NM), a pressure transducer with solid state digital output. In contrast to the relatively labor intensive features of the tensiometers with Hg manometers, excellent performance was obtained from the Tensimeter[TM] after the stock 20 gauge needle with a metal base was replaced with a 25 gauge needle with a plastic base. A 1 mm silicon rubber layer was applied to the top of the septums at the advice of the manufacturer. The meter normally equilibrated within 30 seconds when the smaller needle was used but often took more than 1 minute if a larger needle was used. On occasion, a foreign particle would

get in the loehr lock when the metal base needle was used. If this occurred, the Tensimeter™ would slowly increase (less tension) indicating a loss of vacuum in the tensiometer. This problem was solved with use of the plastic base needles. With this instrument, it was possible to read about 150 tensiometers in approximately 2 h.

Mean pressure heads at Site 1 were determined from eight measurements taken during August 1985 to November 1985. Soil conditions ranged from dry to saturated following a 15 cm rainfall during this time period. Pressure heads at Sites 2 and 3 were monitored eight and five times, respectively, from January to April, 1986 and means determined. During this time pressure heads fluctuated substantially in response to several cm of precipitation during March, 1986.

Soil cores for N and Cl^- analyses were collected with a Giddings soil coring machine. Data for Site 3 was obtained from the cores removed when the tensiometers were installed while data from Site 1 was obtained from separate cores the same distance from the trenches as the tensiometer banks. Samples taken below the drainfield were obtained by sampling through a pipe previously installed through the gravel layer to allow access to the trench bottom. At the time of sampling, the pipe was pressed into the soil and ponded effluent pumped out of the inside of the pipe to prevent sample contamination. Cores were sectioned into increments ranging from 5 to 15 cm long depending on the location of the core relative to the trench and on soil physical and morphologic properties, placed on dry ice, and transported to the laboratory for analysis within one month. While in storage samples were frozen at $-15°$ C. Soil NO_3^--N and NO_2^--N concentrations were determined colorimetrically at 540μm as NO_2^- -N using the Cu coated Cd reduction technique and an autoanalyzer (U.S. Environmental Protection Agency, 1974). Ammonium-N (NH_4^+) was determined using the indophenol-blue technique on an autoanalyzer (U.S. Environmental Protection Agency, 1974). Chloride was extracted by placing a 5 g subsample in 50 ml of 1N NH_4NO_3 solution, shaking for 1 h, and extract concentration determined with a specific Cl^- ion electrode (Selmer-Olsen and Oien, 1973). Comparisons of data determined with an Aminco-Maniclove Cl^- autotitrator indicated close agreement between the two techniques.

5.4 , RESULTS

5.4.1 Relations between Soil Moisture Tensions and ST-SAS Performance

5.4.1.1 Site 1

The depth of ponding illustrated in Figure 12 for trench 2 is representative of the time period when the additional tensiometer banks were monitored (summer and fall of 1985). During most of the year effluent was ponded to approximately 15 cm in this trench. There were, however extended periods during the summer when effluent was not ponded. Average pressure heads were considerably lower during summer and fall of 1985 adjacent to and below trench 2. Pressure heads decreased with depth below the trench indicating horizontal as well as vertical movement of effluent. Substantial variation in pressure heads in response to major rainfall events is reflected by the standard deviations reported in Fig. 12.

Ponding depths in trench 3 ranged from 40 to 50 cm (Fig. 13). Pressure heads decrease below and horizontally from trench 3. Pressure heads as high as 45 cm of water were noted at the 5.05 m elevation 30 cm from the trench 1 to 2 d following a rainfall event of approximately 8 cm.

5.4.1.2 Site 2 Unit 1

Trench 3, dosed at a flux density of 0.8 cm d^{-1}, was not observed to pond although it was located in soil material that included weathered shale. Mean subtrench pressure heads (Fig. 14) during winter and spring of 1986 were slightly negative immediately below the trench and decreased with both depth and horizontal distance.

The ponding depth in trench 4, dosed at 3.6 cm d^{-1} was approximately 45 cm during January to April, 1986 (Fig. 15). Pressure heads were positive below the trench. While pressure heads decreased horizontally between the 30 and 90 cm downslope distances, at each of these distances they increased with increasing depth (Fig. 15). They also increased with increasing depth at the 30 cm
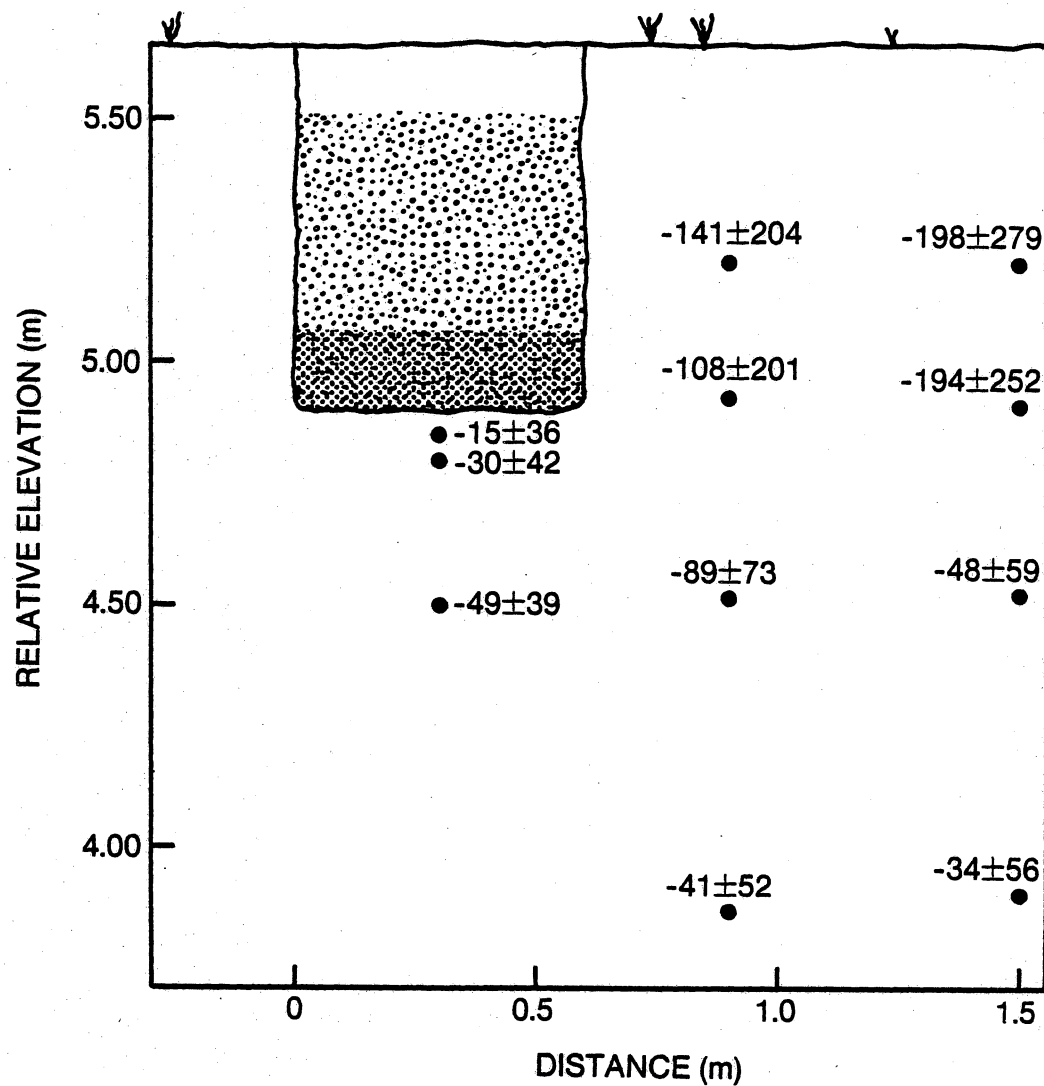
Figure 12. Cross section of trench 2 at Site 1 illustrating means and standard deviations of pressure potentials: points define tensiometer location relative to the trench. The darker shaded area in the gravel envelope corresponds to the depth of ponding. Pressure units are cm of water.
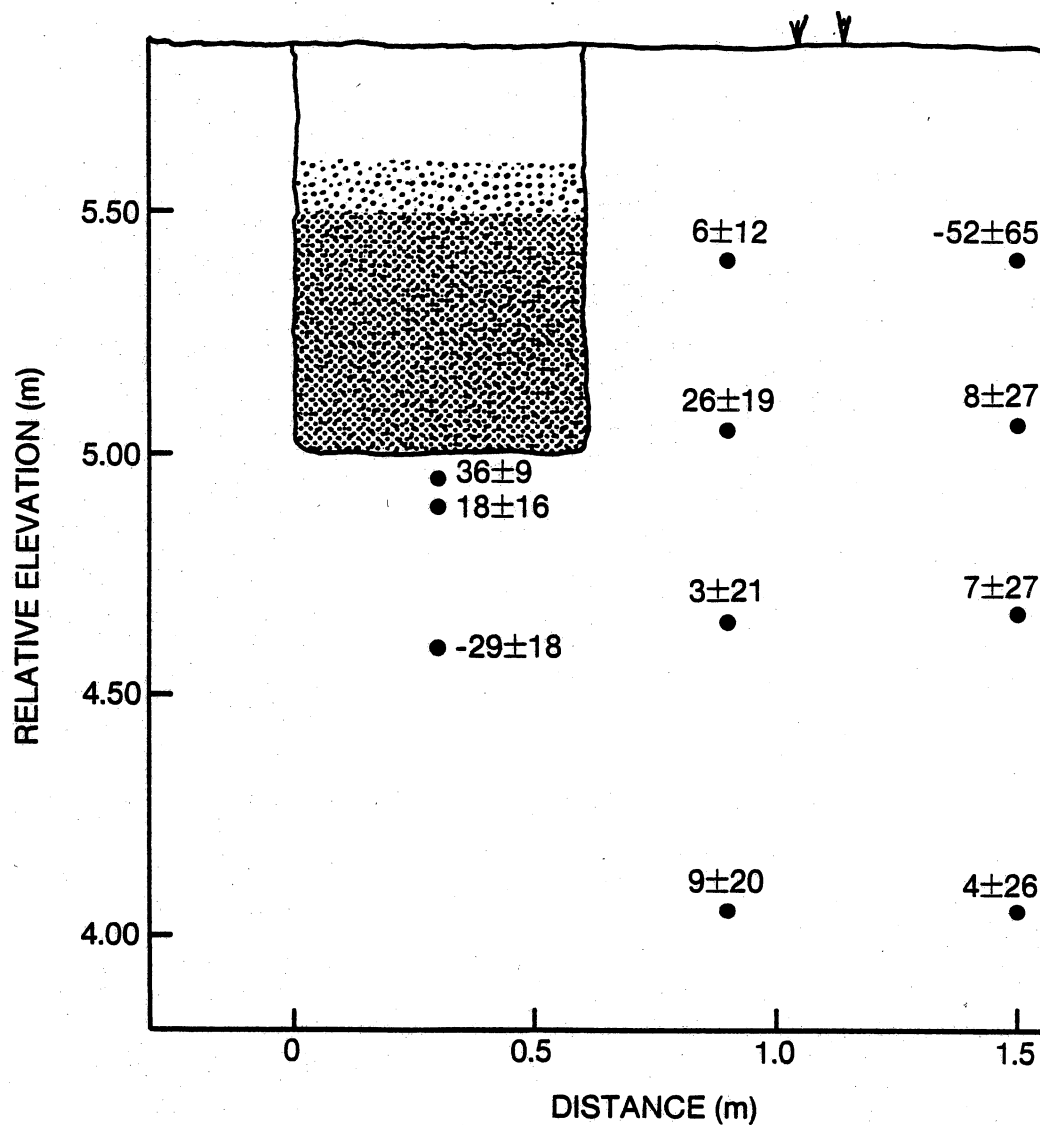
Figure 13. Cross section of trench 3 at Site 1 illustrating means and standard deviations of pressure potentials: points define tensiometer location relative to the trench. The darker shaded area in the gravel envelope corresponds to the depth of ponding. Pressure units are cm of water.
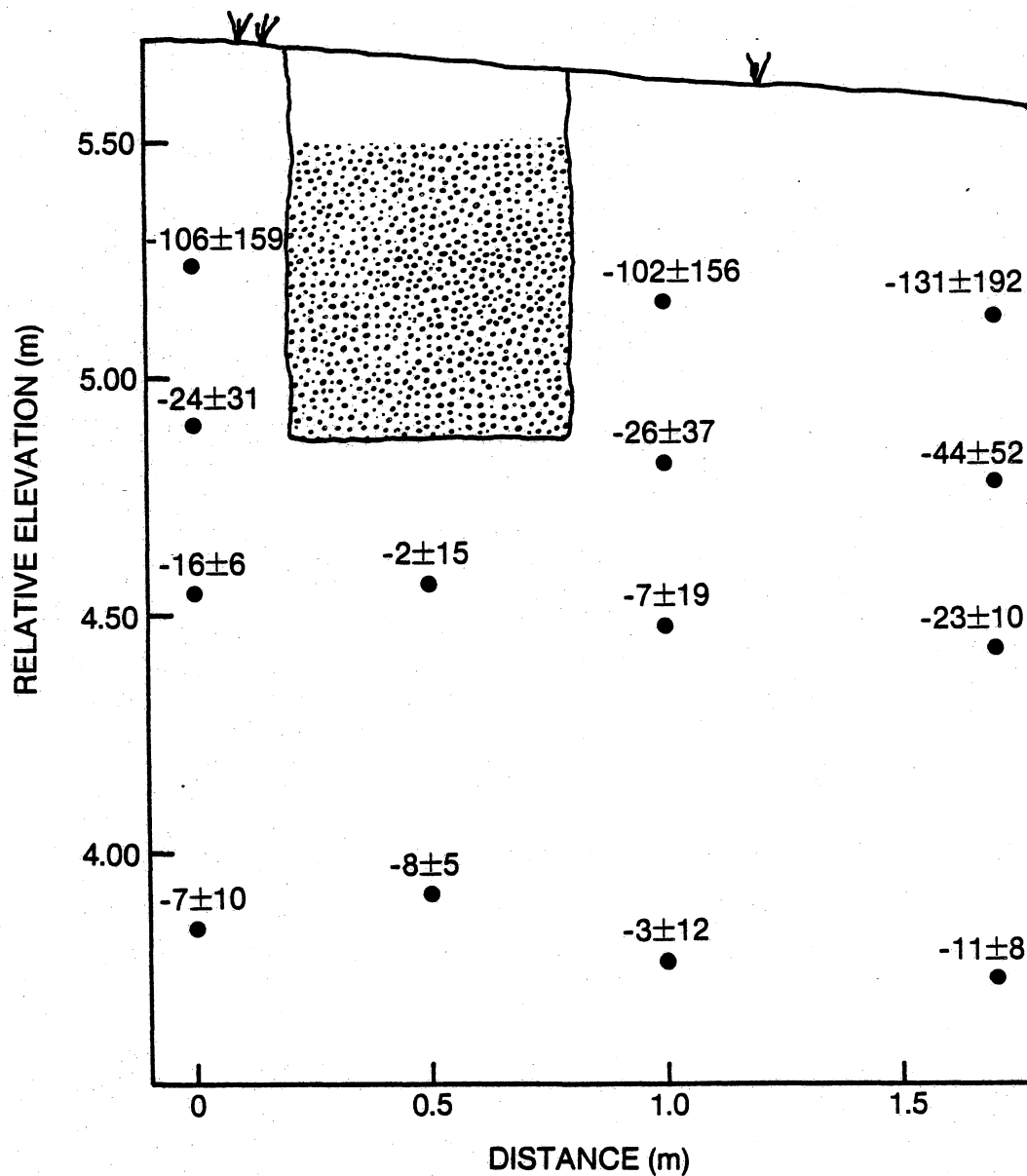
Figure 14. Cross section of trench 3, Unit 1 at Site 2 illustrating means and standard deviations of pressure potentials : points define tensiometer location relative to the trench. The darker shaded area in the gravel envelope corresponds to the depth of ponding. Pressure units are cm of water.
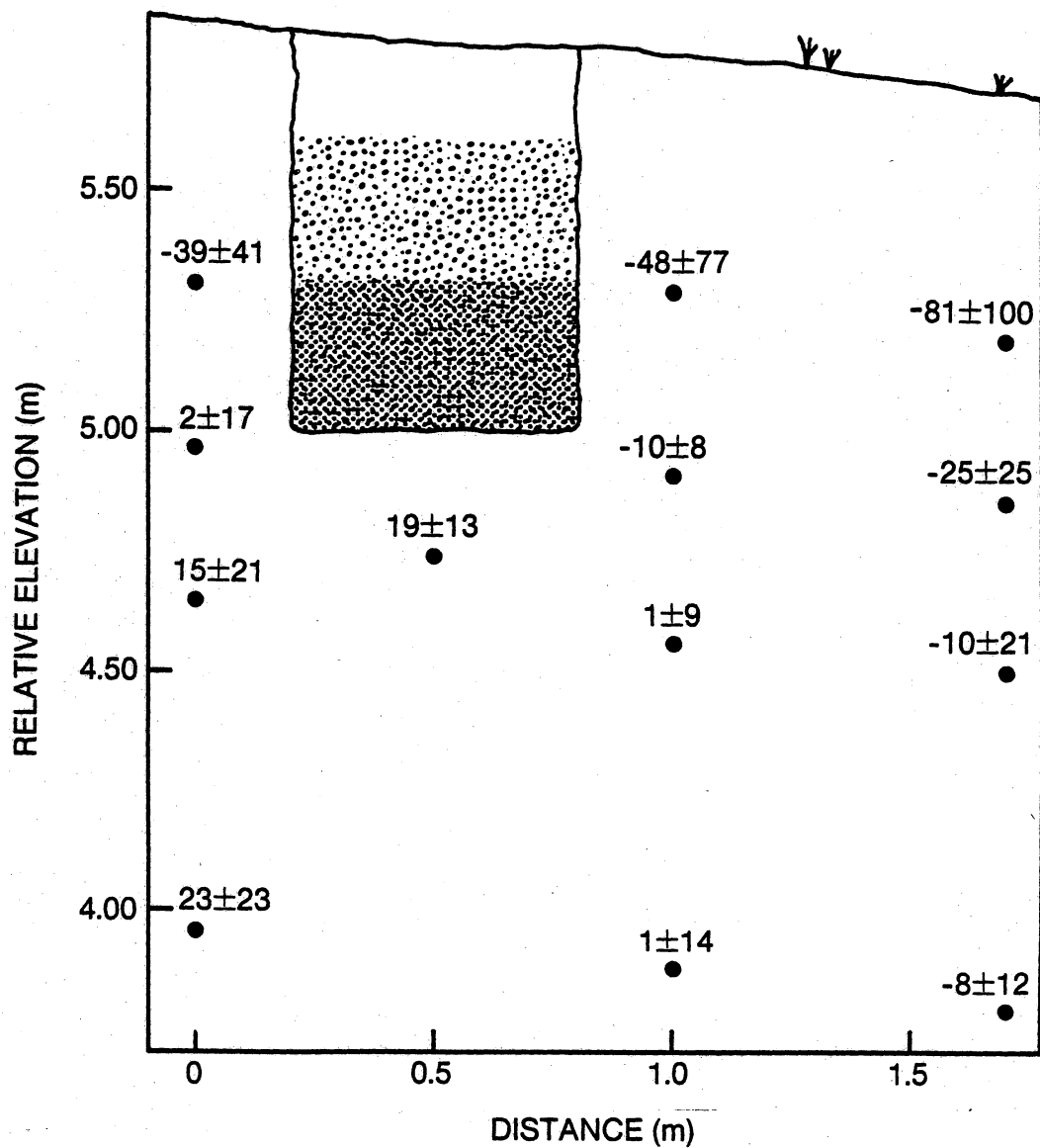
Figure 15. Cross section of trench 4, Unit 1 at Site 2 illustrating means and standard deviations of pressure potentials: points define tesiometer location relative to the trench. The darker shaded area in the gravel envelope corresponds to the depth of ponding. Pressure units are cm of water.

upslope distance. This trench was not dosed for 2 months during January and February of 1985 or during November and December of 1985 due to mechanical failure however ponding levels quickly returned to previous levels following commencement of dosing.

5.4.1.3 Site 2 Unit 2

Ponding was never noted in trench 4. The almost uniform negative pressure heads around trench 4 of Unit 2 (Fig. 16) contrast with the trenches in Unit 1. Values at trench bottom elevations are relatively uniform vertically and horizontally around the trench. The standard deviations are also relatively low below the 5 m elevation. The 3.6 cm d^{-1} dose for trench 4 as well as the other trenches in this unit infiltrated in less than 30 minutes.

5.4.1.4 Site 3

Trench 3, dosed at 0.8 cm d^{-1} did not pond in spite of the presence of pinnacles of limestone within 30 cm of the trench bottom. Mean pressure head values are positive 10 cm below the trench (Fig. 17) and increase with depth, although not on an unit gradient basis. Subtrench pressure head values are negative upslope and downslope from the trench and in general increase with depth to slightly positive values above the limestone bedrock. Note also the decreasing pressure head values with distance downslope. The approximate lithic contact noted in Fig. 17 reflects depths where limestone rock was encountered when tensiometers were installed.

Ponding of effluent in trench 5, dosed at 1.8 cm d^{-1} has not been recorded (Fig 18) except that ponding of 1 cm of effluent on part but not all of the bottom of the central section of the trench was noted on two occasions. Pressure heads are positive below the trench and increase with depth. However the subtrench pressure heads upslope and downslope are all negative just below the trench bottom elevation but increase to positive values with depth except 90 cm downslope from the trench. Infiltration occurred rapidly, usually within 1 to 2 h.
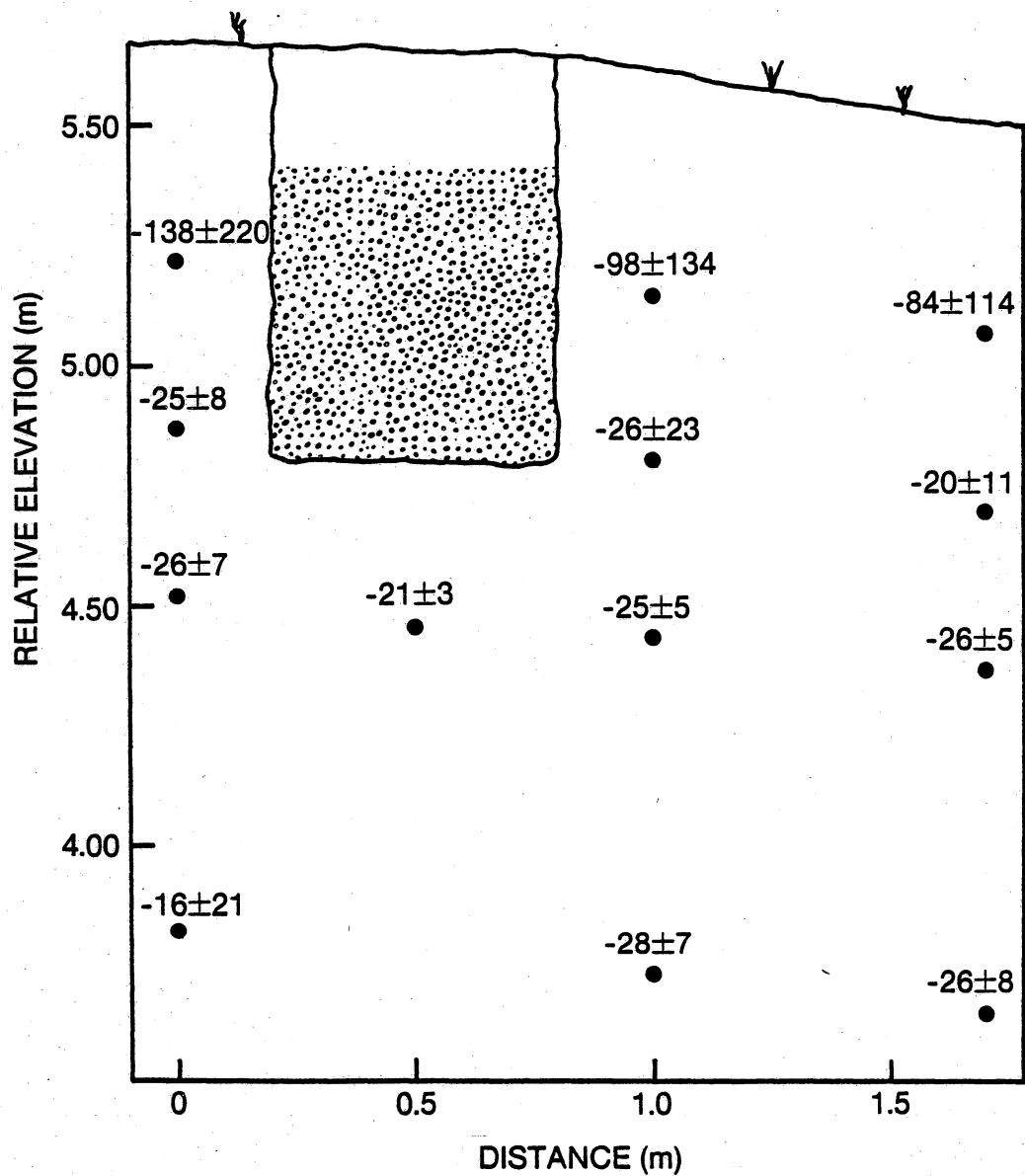
Figure 16. Cross section of trench 4, Unit 2 at Site 2 illustrating means and standard deviations of pressure potentials: points define tensiometer location relative to the trench. No ponding in the gravel envelope has been noted. Pressure units are cm of water.

5.50

5.00

RELATIVE ELEVATION (m)

-75±83

-41±63

-9±30

-16±14

4.50

1±23

16±41

4.00

Approximate lithic contact

3.50

-180±72

-13±9

-9±8

7±2

-214±308

-26±30

-28±59

6±9

0   0.5   1.0   1.5

DISTANCE (m)
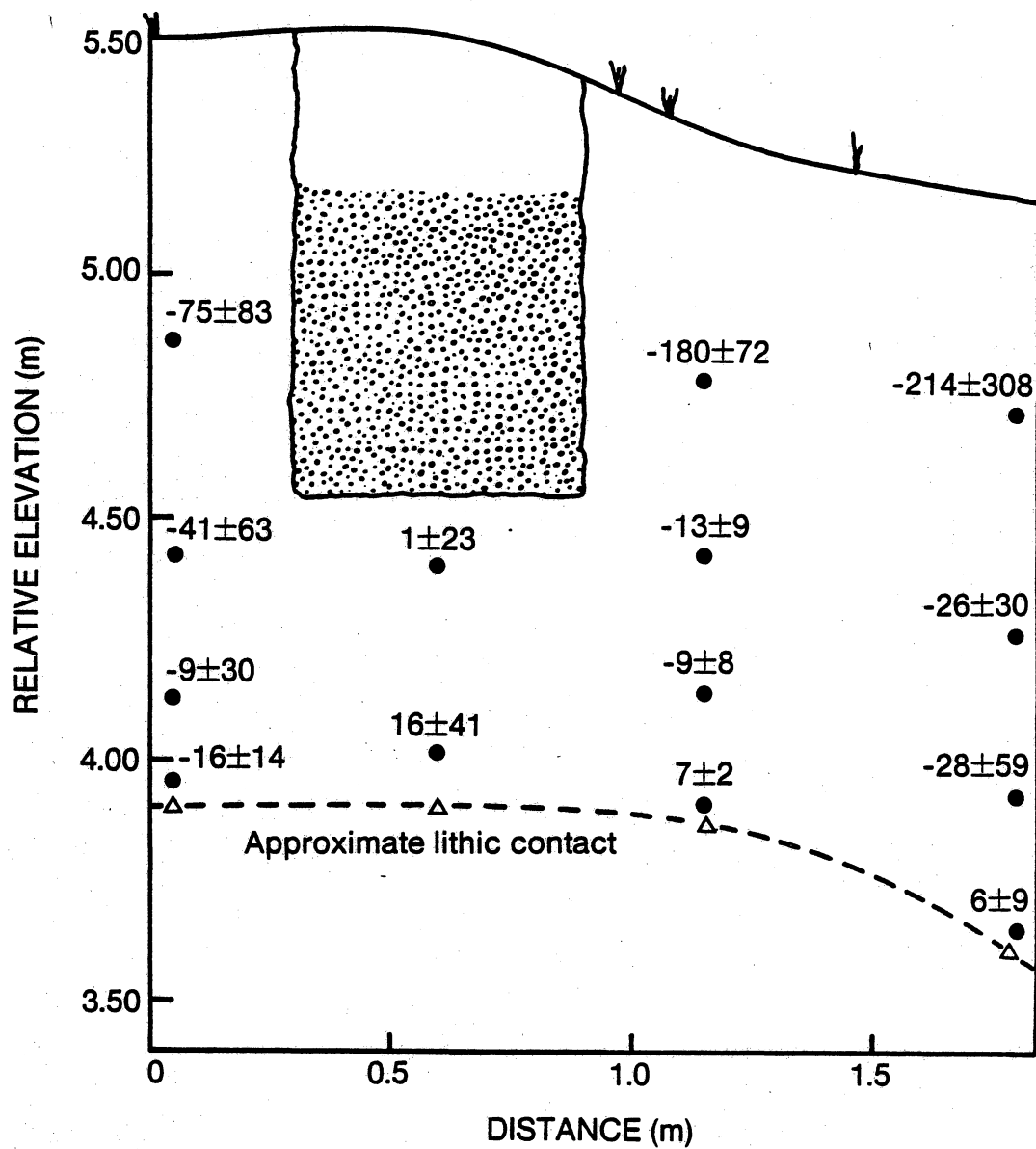
Figure 17. Cross section of trench 3 at Site 3 illustrating means and standard deviations of pressure
potentials: points define tensiometer location relative to the trench. No ponding in the
gravel envelope has been noted. The triangles note points where limestone was encount-
ered when installing the tensiometers. Pinnacles of limestone may be closer to the trench
bottom under parts of the trench. Pressure units are cm of water.
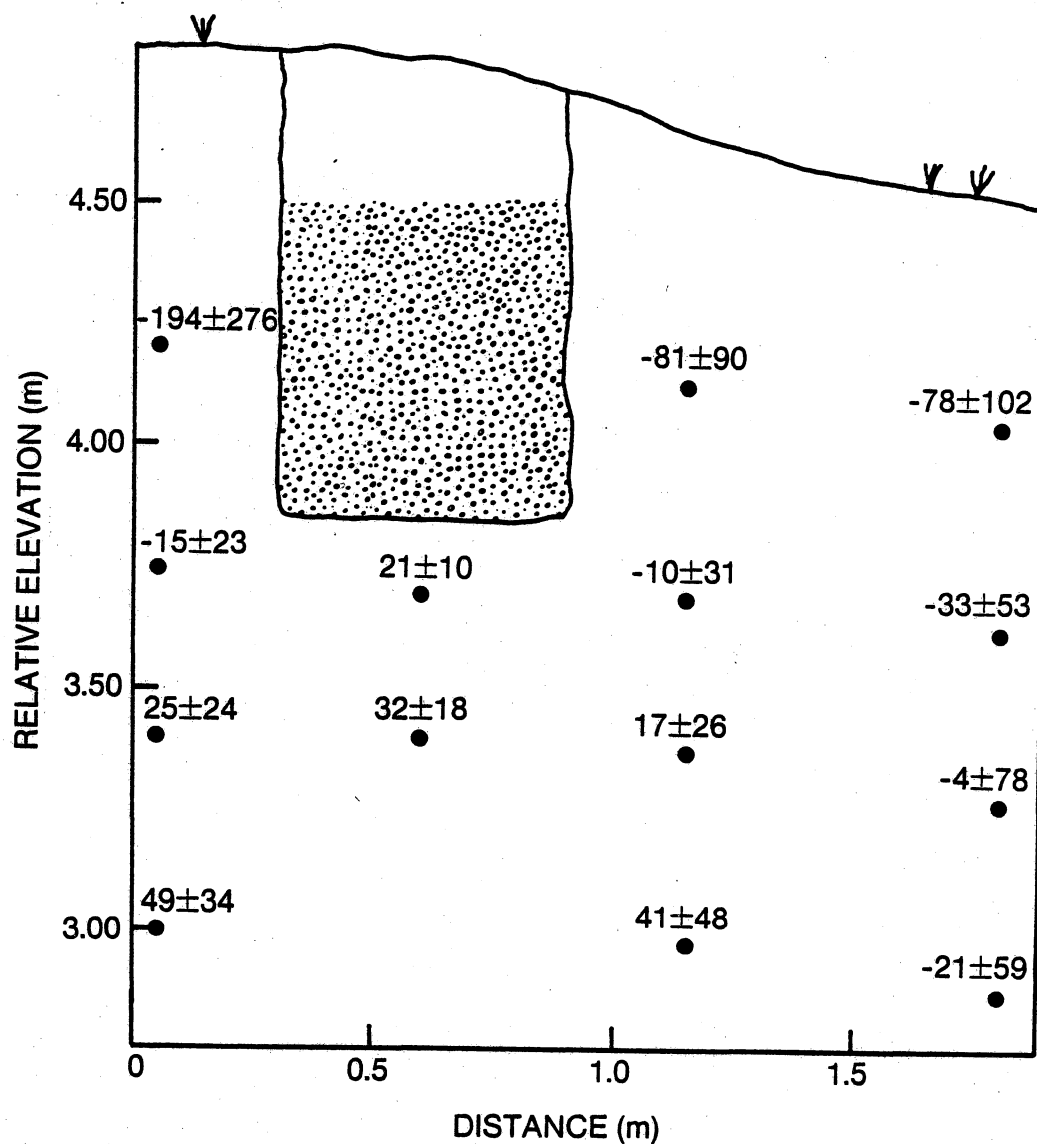
Figure 18. Cross section of trench 5 at Site 3 illustrating means and standard deviations of pressure potentials: points define tensiometer location relative to the trench. No ponding in the gravel envelope across the entire trench bottom has been noted. Pressure units are cm of water.

Trench 6, dosed at 1.8 cm d^{-1} was ponded to about 15 cm (Fig. 19). Positive pressures immediately below the trench increased with depth. The slightly negative values at the 3.8 m depth both 30 cm upslope and downslope from the trench increase to positive values within 40 cm of the trench bottom. Increases are almost unit in gradient. On two different occasions the solenoid valves were turned off for 2 w. On each occasion it took more than 5 d for the trench to drain.

5.4.2   Nitrogen Distribution Below Prototype ST-SAS

5.4.2.1   Site 1

Soil NH_4^+-N concentrations (Fig. 20) decrease with depth below trench 2 and are less than 5 mg kg^{-1} throughout most of the profile below and around the trench. Exceptions are the 0 to 5 cm zone immediately below the trench and the zone 20 to 25 cm below the trench where NH_4^+-N concentrations are 46 and 10 mg kg^{-1} respectively and the zone 0 to 15 cm below the trench bottom at a distance of 0.9 m which had a mean NH_4^+-N concentration of 8 mg kg^{-1}. Though some variability is obvious, solution NO_3^--N concentrations increase with depth below the trench (Fig. 21), both below and at the 30 and 90 cm distances from the trench.

The NH_4^+-N concentrations decrease almost logarithmically with depth below trench 3 (Fig. 22). A maximum concentration of NH_4^+-N is noted in the 5.3 to 5.4 m elevation zone at 30 and 90 cm from the trench which corresponds to the depth of ponding in the trench and zones of positive pressure heads beside the trench (Fig. 13).

The NO_3^--N concentrations (Fig. 23) are low below trench 3 and 30 cm from the trench above the 5 m elevation corresponding to the trench bottom. Higher values are noted at some depth below the trench probably corresponding to pressence of lenses of weathered sandstone. At the 90 cm distance from the trench, NO_3^--N is slightly higher at the 5.5 m elevation corresponding to a zone of lower pressure heads (Fig. 12). Nitrate-N concentrations also increase with depth below the trench at the 90 cm distance.
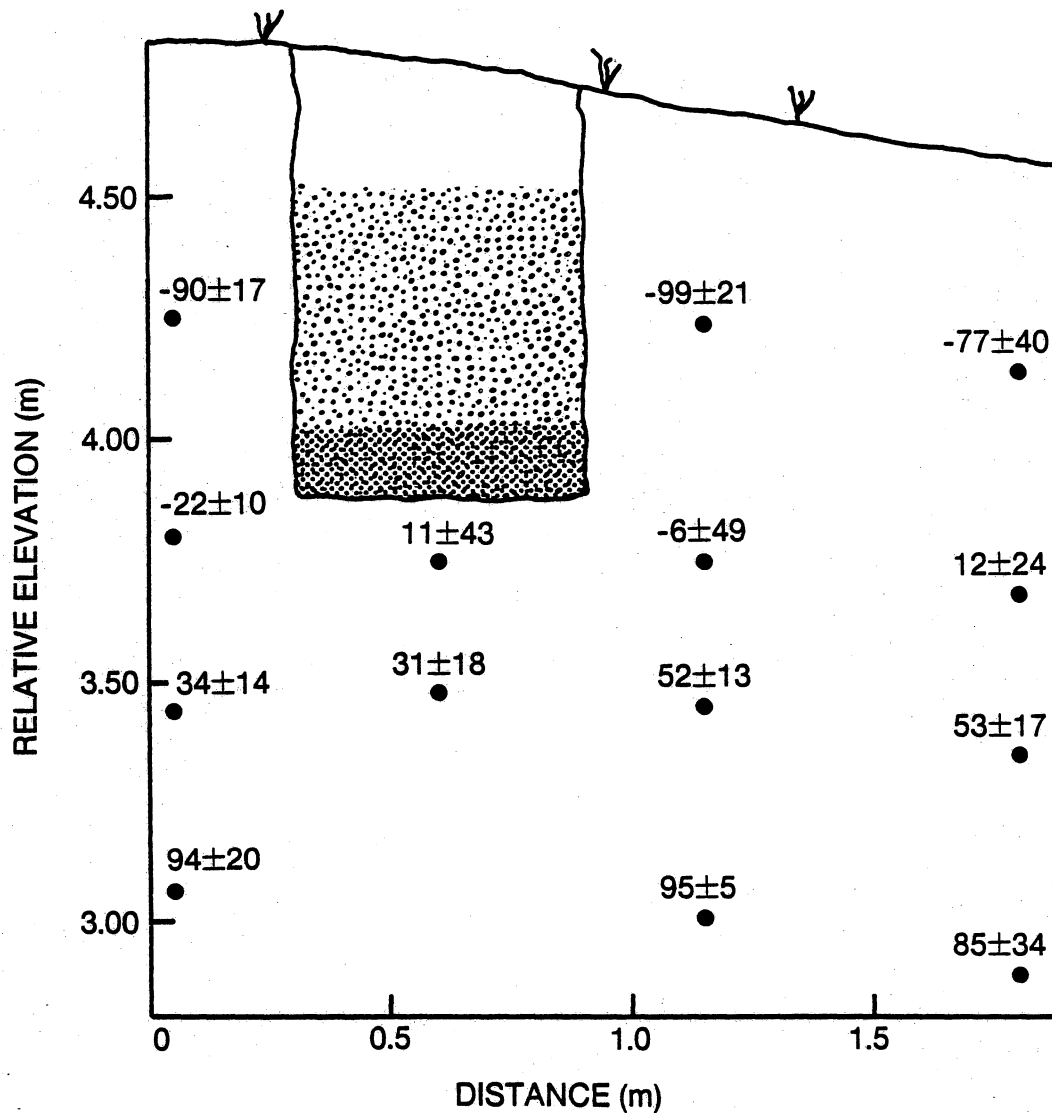
Figure 19. Cross section of trench 6 at Site 3 illustrating means and standard deviations of pressure potentials: points define tensiometer location relative to the trench. The darker shaded area in the gravel envelope corresponds to the depth of ponding. Pressure units are cm of water.

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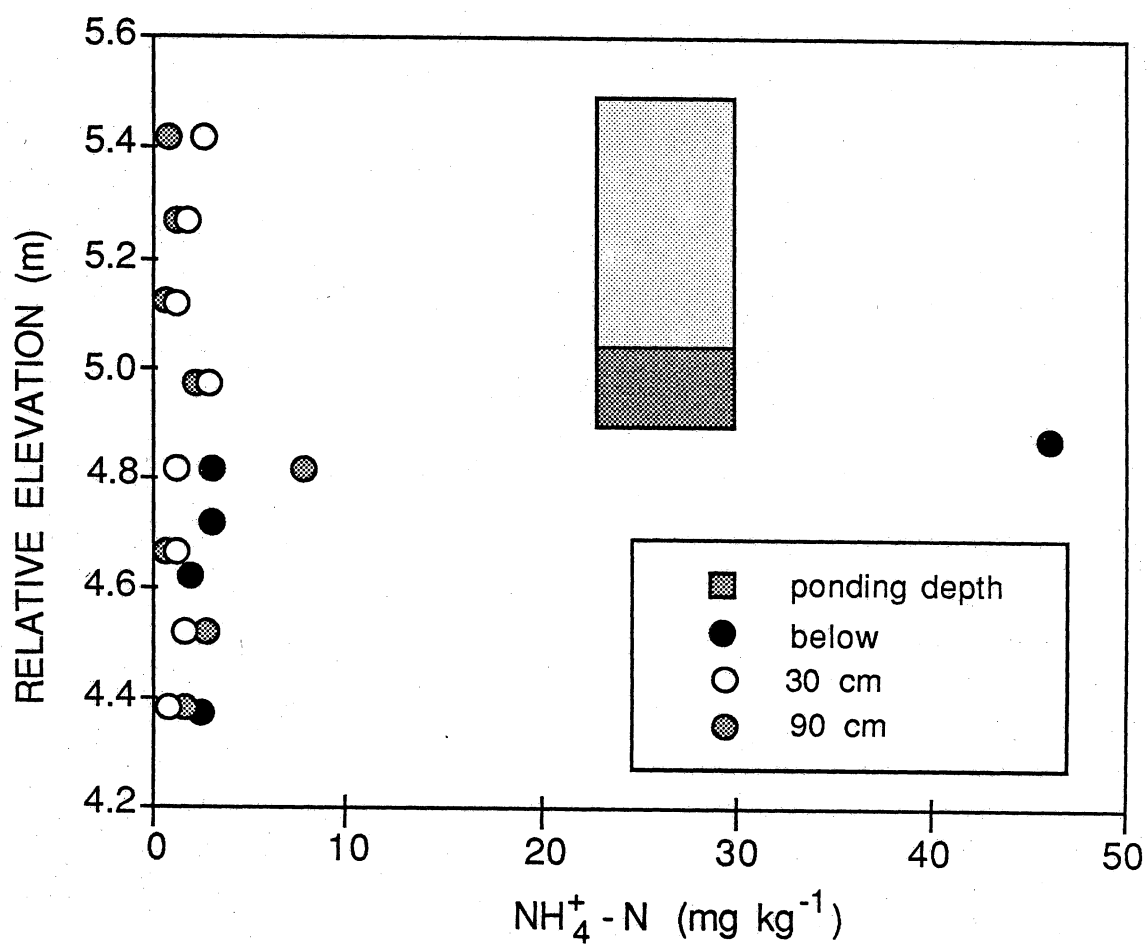
Figure 20. Distribution of NH$^+_4$-N around trench 2 at Site 1 on November 21, 1985: below, 30 cm and 90 cm from the trench. The inset box describes the relative elevation of the trench bottom and ponding of effluent.
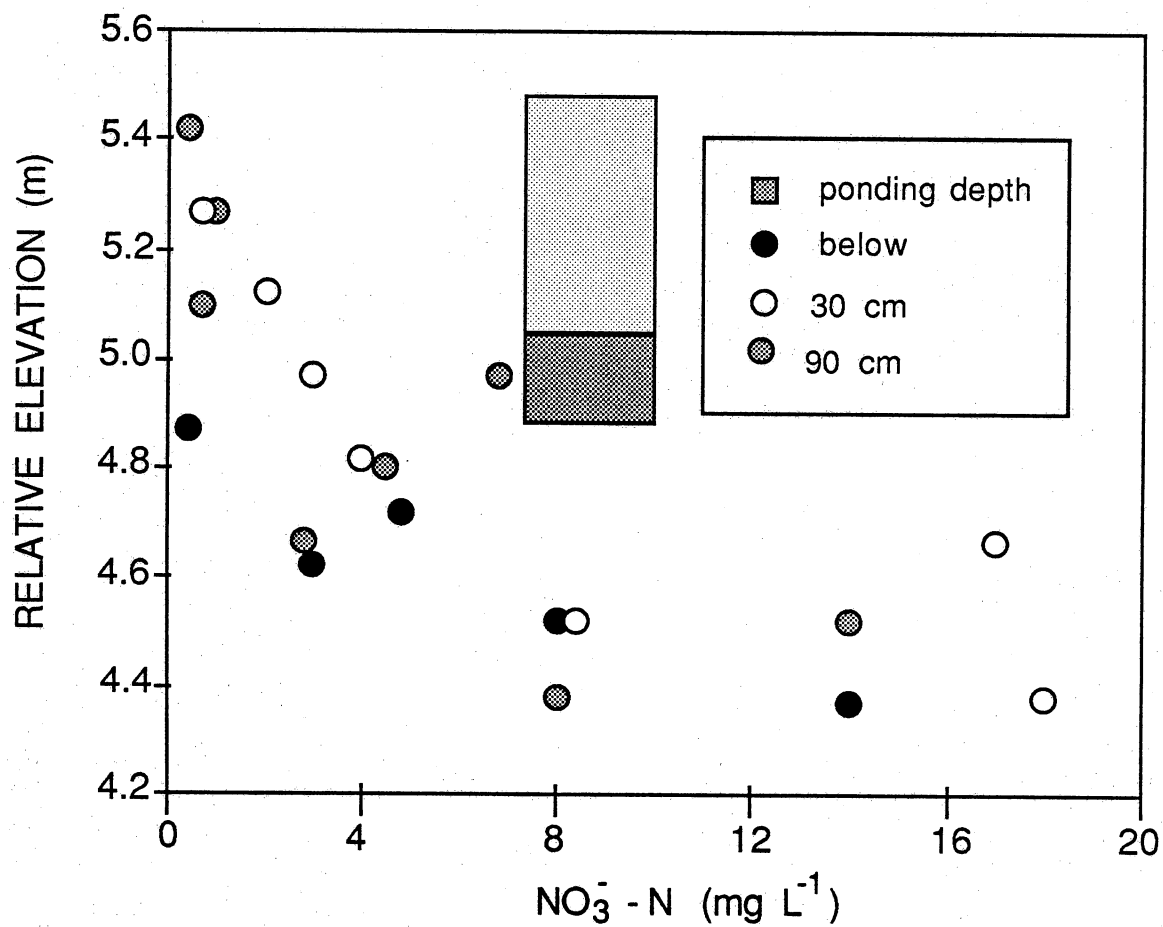
Figure 21. Distribution of NO^-_3-N in soil solution around trench 2 at Site 1 on November 21, 1985: below, 30 cm and 90 cm from the trench. The inset box represents the relative elevation of the trench bottom and the ponding depth.
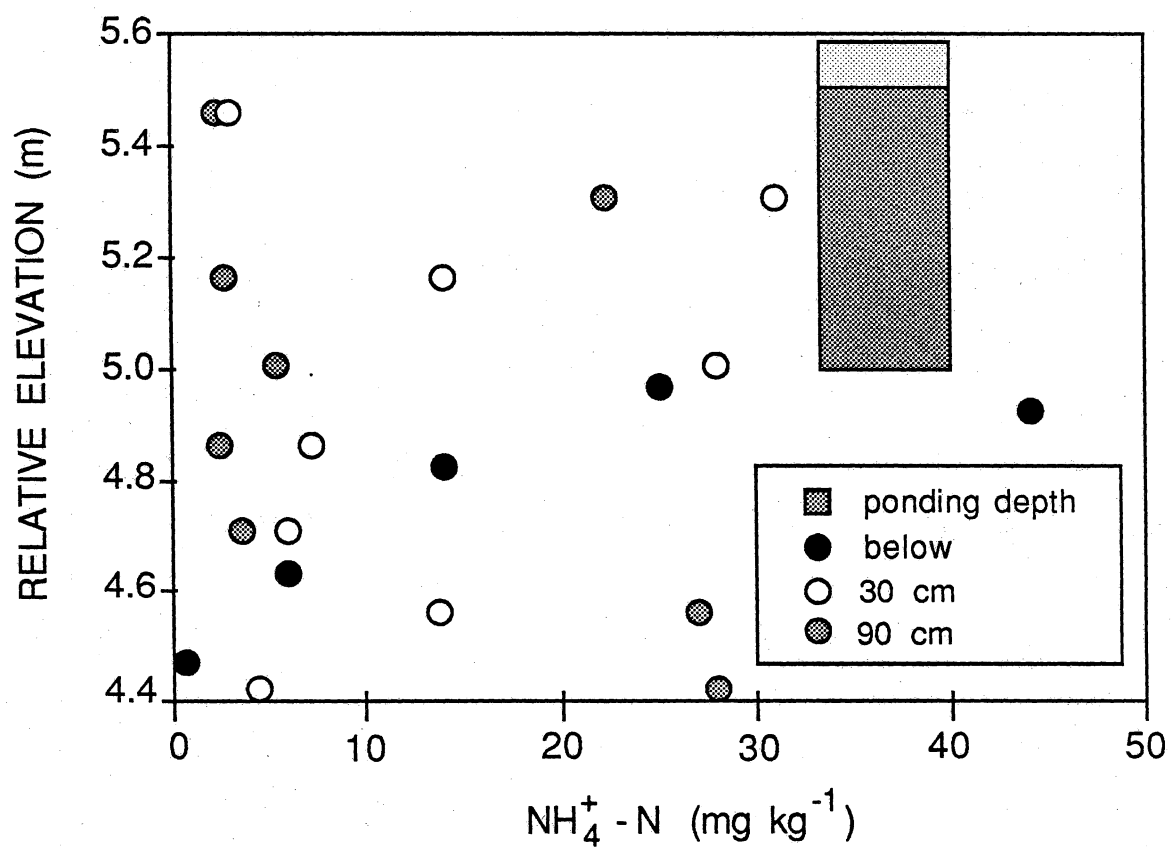
Figure 22. Distribution of NH$^+_4$-N around trench 3 at Site 1 on November 21, 1985: below, 30 cm and 90 cm from the trench. The inset box represents the relative elevation of the trench bottom and ponding depth.
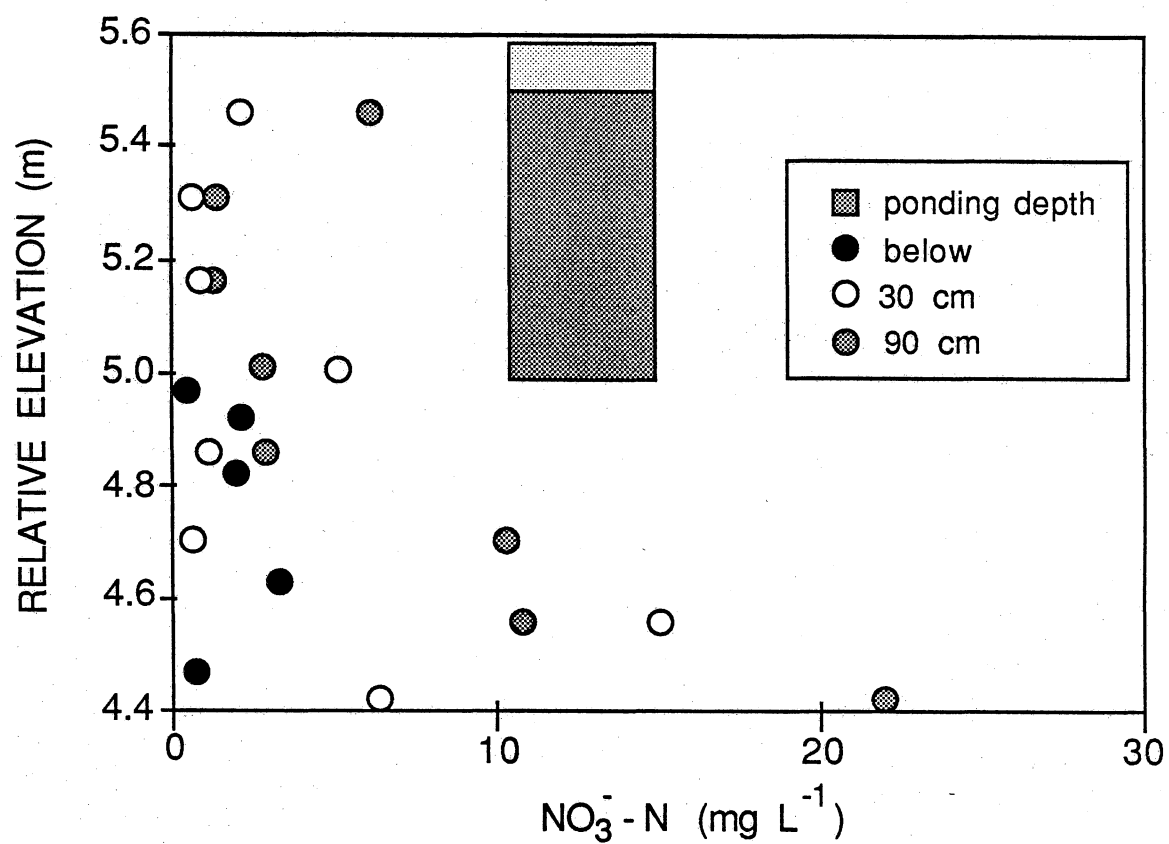
Figure 23. Distribution of NO^-_3-N in soil solution around trench 3 at Site 1 on November 21, 1985: below, 30 cm and 90 cm from the trench. The inset box and shaded areas represent the relative elevation of the trench bottom and ponded effluent.

5.4.2.2 Site 3

Except for the zone 5 cm below trench 5 which had an NH_4^+-N concentration of 20 mg kg^{-1}, NH_4^+-N concentrations were < 2.0 mg L^{-1} below as well as 30 and 90 cm from the trench (data not presented in figure form). Concentrations of NO_3^--N were above 50 mg L^{-1} in most of the meter below the trench, although mean concentrations were as low as 26 mg L^{-1} (Fig 24) were noted at three sampling increments below the trench. Nitrate-N concentrations 30 cm downslope increase with depth beside and immediately below the trench indicating limited horizontal flow of effluent. No increase in NO_3^--N with depth was noted 90 cm downslope from the trench.

High NH_4^+ concentrations immediately below trench 6 decrease logarithmically with depth (Fig. 25). An increase in NH_4^+-N concentration 30 cm downslope at the elevation corresponding to effluent ponding indicates that substantial horizontal transport of NH_4^+ is occurring through the trench sidewalls. The concentration 30 cm downslope decreases logarithmically with depth from a maximum in the 3.88 to 3.98 m zone to concentrations similar those below to trench. No change in NH_4^+-N concentration with depth is distinguishable 90 cm downslope from trench 6.

Nitrate-N concentrations (Fig. 26) 30 cm from trench 6 increase with depth down to the zone of maximum NH_4^+-N accumulation (Fig. 25) but decrease sharply to uniform concentrations at all distances below the 3.9 m elevation corresponding to the trench bottom. Downslope 90 cm, NO_3^--N concentrations are relatively uniform above the 3.8 m elevation but decrease sharply below the trench bottom.
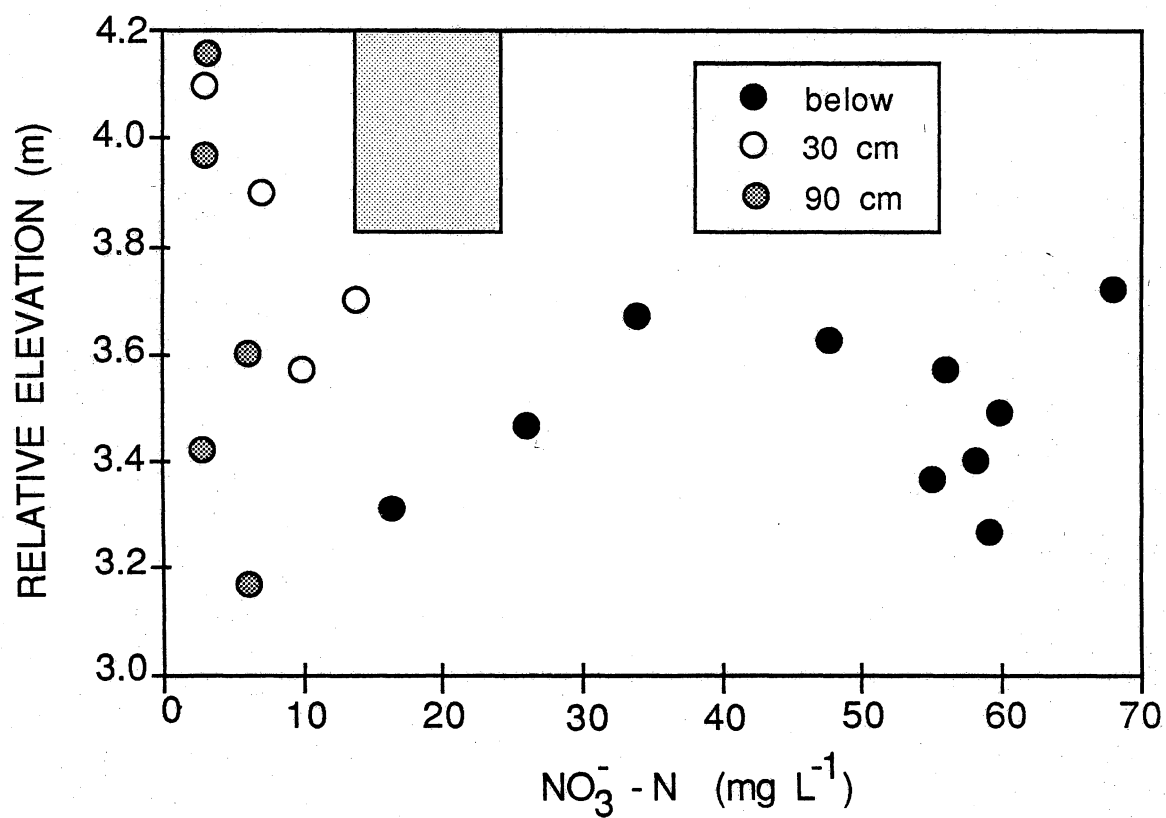
Figure 24. Distribution of NO_3^--N in soil solution around trench 5 at Site 3 on November 1, 1985: below, 30 cm and 90 cm from the trench. The inset box represents the relative elevation of the trench bottom.
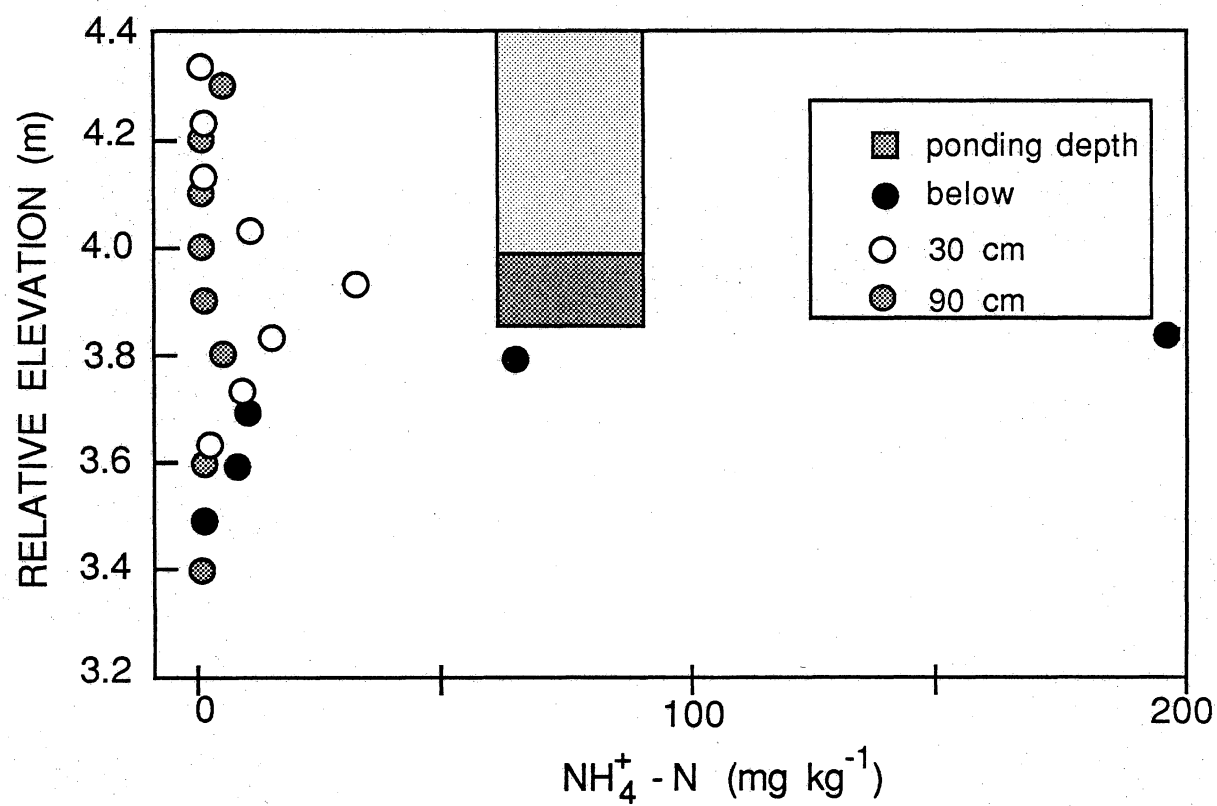
Figure 25. Distribution of NH^+_4-N around trench 6 at Site 3 on November 1, 1985: below, 30 cm and 90 cm from the trench. The inset box represents the relative elevation of the trench bottom and the depth of ponding.

Figure 26. Distribution of NO^-_3-N in soil solution around trench 6 at Site 3 on November 1, 1985: below, 30 cm and 90 cm from the trench. The inset box represents the relative elevation of the trench bottom and the depth of ponding.
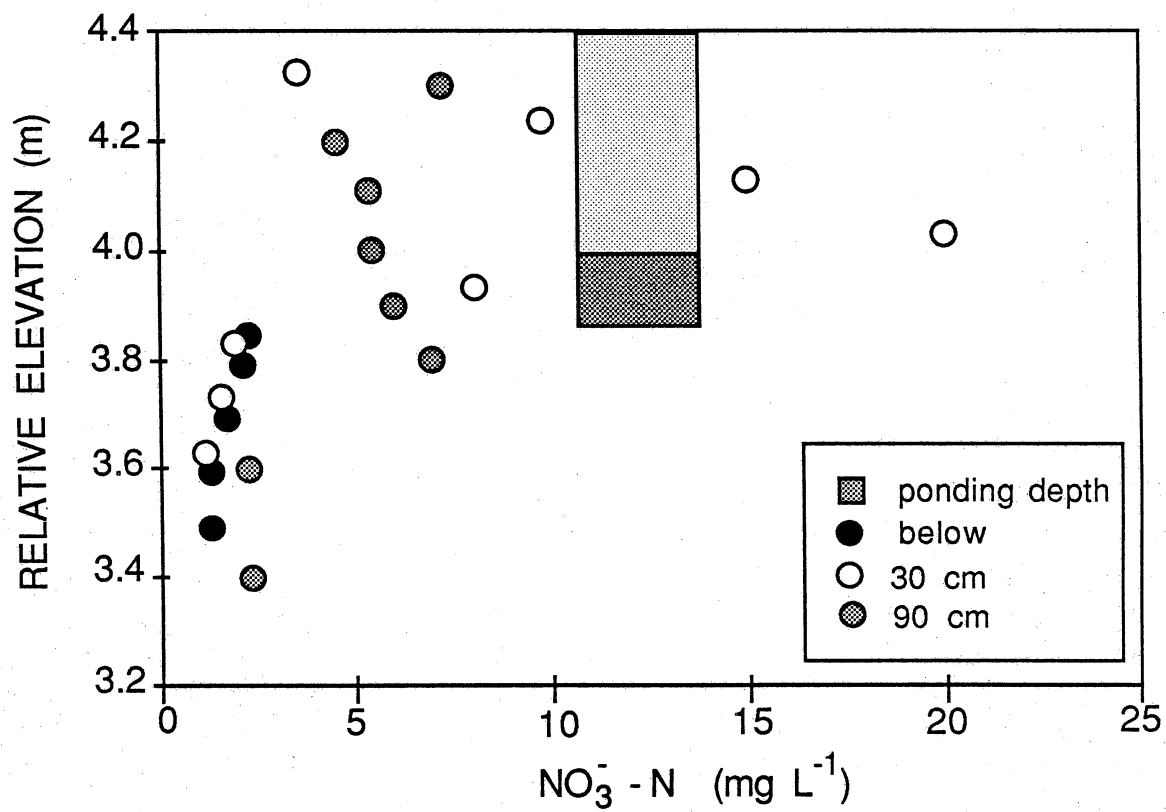
5.5 DISCUSSION

Mean positive pressure heads below prototype ST-SAS ponded with effluent for more than 2 years indicate that although formation of a biological clogging mat was evident, the apparent cause of ponding was the inability of the subsoil to adequately transmit effluent away from the ST-SAS at higher loading rates. Relations between soil structure, distance to restrictive layers, and ponding will be discussed in greater detail below. Nitrogen distribution around ponded and un-ponded ST-SAS will subsequently be related to the ponding and pressure head data.

5.5.1 Relations between Pressure Heads and ST-SAS Performance

5.5.1.1 Site 1

Presence of mean negative pressure heads around trench 2 during the summer and fall of 1985 coupled with continued presence of ponding supports the morphological observation of the formation of a flow restrictive biological clogging layer. However it should be noted that in spite of the ponding to 15 cm, placement of a 60 cm gravel envelope resulted in adequate performance. The high standard deviations in pressure heads reflect the occurrence of positive pressure heads in response to two major rainfall events where > 7 cm of rain fell in 24 h.

Presence of white pine (*Pinus strobus*) and silver maple (*Acer saccharinum*) trees nearby may have resulted in lower mean pressure heads around the trench. An abundance of roots in both the gravel envelope and cracks or old root channels was also evident (Chapter 4, Plate 1).

In contrast, removal of the A and part of the B horizon during subdivision construction and placement of trench 3 the same depth from the surface as trench 2, resulted in bottom of trench 3 being deep into the C horizon. The upper 25 cm of the gravel envelope was in the strongly structured B horizon. Positive pressure heads highest in value immediately below and beside the trench and in general decreasing with distance vertically and horizontally, indicate that the C horizon is restrictive to flow and has resulted in ponding of effluent to a depth which provides sufficient gra-

dient for horizontal and vertical transport of the effluent load. These data support the magnitude of differences in mean saturated conductivity reported in Chapter 4 (Table 12).

On numerous occasions effluent levels in the all of the trenches at Site 1 except trench 1 rose from 5 to 15 cm in response to rainfall events and often remained at these high levels during rainy periods. Tensiometer data (Simon and Reneau, 1985) indicated that most of the year all trenches had positive pressures beneath them or at best had slight tensions. While the drop in positive pressures with distance may in part be due to antecedent soil properties, evidence of accumulation of organic matter (Chapter 4, Plates 1-3) indicates pore clogging could eventually lead to surfacing of STE in trenches dosed at rates of 1.8 cm d^{-1} or higher. ST-SAS should be placed as close to the surface as possible to maximize the use of the well structured soil material. Where the thickness of an underlying well structured horizon is 15 to 30 cm above a restrictive layer, data from trench 2 suggest that effluent dosing rates should be at most 1 cm d^{-1}. Where presence of moderate sub-angular blocky or similar structure is not evident in clayey soils but soil colors suggest good drainage (Chapter 4, Plate 5), effluent dosing rates of 0.4 cm d^{-1} may be appropriate.

5.5.1.2 Site 2 Unit 1

Mean negative pressure heads within 40 cm of the bottom of trench 3 ranged from -2 to -26 cm of water indicating predominance of unsaturated flow. The lack of ponding in trench 3 or any of the trenches in Unit 1 dosed at 0.8 cm d^{-1} and the pressure heads surrounding trench 3 indicate that soils with up to 50% by volume of fractured shale interbedded with fine textured material with subangular blocky structure may be suitable for ST-SAS dosed at 1 cm d^{-1}.

The ponding of trench 4 and mean positive pressure heads below it suggest that flux densities approaching 4 cm d^{-1} are unsuitable in these soils. The effect of the reduction in pore space by presence of coarse fragments must be considered when evaluating similar soils. The results also implicate use of gravity distribution as being marginally suitable because localized loading rates may be very high (U.S. Environmental Protection Agency, 1977) until ponding occurs following development of a clogging mat. Likewise, the quick return to previous ponding levels after this

trench was rested on 2 occasions indicates that seasonally alternating between drainfields may not be justification for allowing substantially greater loading rates.

5.5.1.3 Site 2 Unit 2

The uniform distribution of pressure heads around trench 4 and the almost immediate infiltration of effluent into all of the trenches in this unit suggests that ST-SAS placed in Bt horizons with strong blocky structure, clay films, and bright chromas indicating a freely drained profile with potentially high permeabilities may function adequately if dosed at > 3 cm d^{-1}. However because of potentially highly dispersive flow resulting in greater pathogen transport, effluent dosing rates should be more conservative (Bouma, 1975). Likewise use of gravity distribution in soils similar to Unit 2 should raise concern as saturated flow could result in transport of an effluent plume to groundwater.

5.5.1.4 Site 3

Lack of ponding and the mean pressure heads adjacent to trench 3 as well as the pressure head of 1 cm at 15 cm below trench 3, indicate that although the subsoil is near saturation, the large interpedal voids adequately transmit the effluent load away from the trench. Positive pressure heads at the 4 m elevation (Fig. 17) and noted presence of bedrock pinnacles within 30 cm of the trench bottom (not shown in Fig. 17) suggest that if the ST-SAS trench is underlain by a strongly structured horizon of 30 to 60 cm thickness above limestone, and chromas are bright, performance of systems dosed at 1 cm d^{-1} should be adequate.

Although bedrock was not encountered within the 60 cm below trenches 5 and 6, the positive pressure heads close to the trench bottoms but more negative with distance below trench 5, indicate that some mounding of water is occurring below the trench. The 1.8 cm d^{-1} dosing rate appears to be a maximum for trenches placed at this depth in this soil. Ponding of trench 6 probably oc-

curred initially due to anaerobic conditions accompanying mounding up into the trench bottom. Subsequently, the biological mat has accumulated resulting in further resistance to flow.

In summary, clayey, well structured soils appear to be able to accept up to 2 cm d^{-1} of effluent even with bedrock restrictions within 0.7 m without ponding. Well structured material may accept effluent loads greater than 3.6 cm d^{-1}, however the potential for biological contamination due to macropore flow (Rahe et al., 1978; McCoy and Hagedorn, 1980) dictates that fluxes should probably be held below 2 cm d^{-1} (Anderson and Bouma, 1977b). With presence of unstructured soil layers or bedrock below well structured B horizons and less than 0.7 m below the trench bottom, loading flux densities should be 1 cm d^{-1} and 30 cm or more distance maintained above the slowly permeable or impermeable layer.

5.5.2   Nitrogen Distribution Around Drainfields

5.5.2.1   Site 1

A zone of maximum NH_4^+-N accumulation occurs just below trench 2. Concentration of NH_4^+-N decreased with depth probably due to nitrification as suggested by presence of NO_3^--N to concentrations of 19 mg L^{-1} within 20 to 30 cm of the drainfield. Concentrations of NO_3^--N increased with depth at all distances from the drainfield suggesting that nitrification occurred during periods when pressure heads were < 0 and interpedal voids drained allowing O_2 to diffuse to regions of NH_4^+ adsorption. The closer the zone of aeration extends to the effluent source, or the more dispersive the flow, the more likely will be significant nitrification.

The NH_4^+-N distribution below and adjacent to trench 3 (Fig. 22) corresponds with morphological (Chapter 4, Plates 2 and 3) and tensiometric evidence (Fig. 13) of horizontal flow through the well structured Bt horizon above the almost structureless C horizon. Decreasing NH_4^+-N concentrations with distance is probably due to increased contact with clay surfaces during flow and resultant adsorption of NH_4^+-N. Variability in NH_4^+-N concentration with depth such as the three points noted for the 30 cm distance between the elevations of 4.9 to 5.4 m is probably

due to intersection of interpedal voids or flow zones. Presence of sandy layers were noted in some cores below the 4.8 m relative elevation and may also account for the increased NH_4^+-N concentration 30 and 90 cm from the trench at this depth. Flow through a relatively small fraction of the pore space probably is resulting in substantial dispersion.

Two zones of limited nitrification are apparent around trench 3. One is in the Bt horizon above 5.4 m reflected by samples 90 cm from the trench (Fig. 23). The other occurs below but away from the trench as evidenced by increasing NO_3^--N concentrations with depth 30 and 90 cm from the trench (Fig. 23).

5.5.2.2   Site 3

Low NH_4^+-N concentrations and high solution NO_3^--N concentrations below trench 5 (Fig. 24) indicated rapid nitrification of NH_4^+ present in the effluent. These data indicate that even though mean pressure heads below these trenches indicate that the soil is close to saturation, drainage of interpedal voids between dosing events provided adequate aeration for nitrification to occur. The much lower NO_3^--N concentrations in cores at 0.3 and 0.9 m from the trenches support the conclusions drawn from pressure head data that flow must be predominantly vertical. Dense placement of ST-SAS in well drained fine-textured soils could impact substantially on groundwater quality where nitrification occurs. The high solution NO_3^--N concentrations below both trench 3 (data reported here) and trench 5 approached TKN values in the effluent (Chapter 4, Table 13) suggesting occurrence of large scale nitrification. High NO_3^--N concentrations indicated substantial area may be required for dilution of NO_3^--N to USPHS acceptable concentrations for drinking water of 10 mg L^{-1} (Keeney, 1982).

Little nitrification occurred below trench 6 (Fig. 26) due to the ponded and saturated conditions measured. Soil NH_4^+ concentrations at both 30 and 90 cm downslope suggest dispersive flow under saturated conditions may be occurring. Large structural cracks noted in the lower B horizon would favor dispersion (Anderson and Bouma, 1977a, b). Some nitrification appears to occur along the apparent top of the water table. Decreasing NO_3^--N/Cl^- ratios downslope (data not reported

here) were noted and could be due either to mixing of NO_3^- formed at an aerobic-anaerobic contact with Cl^- rich waters below or could be due to limited denitrification.

In summary, in soils around ST-SAS which always remained saturated, nitrification was minimal and appeared to be limited to parts of the profile some distance from the ST-SAS where interpedal voids might drain allowing limited nitrification. The relatively high CEC of clayey soils could result in adsorption of large quantities of NH_4^+ for long periods of time. However design of ST-SAS to promote conditions limiting nitrification in soils may lead to hydraulic failure (Chapter 4) due to accumulation of a biological mat. In addition a relatively concentrated pulse of NO_3^- could be released to ground water if the ST-SAS were rested and became aerobic.

Where mean pressure heads were slightly negative in well drained, structured fine textured soils, nitrification was indicated by high solution NO_3^--N concentrations and low concentrations of NH_4^+-N adsorbed onto the soil CEC below and adjacent to ST-SAS. Concentration of NO_3^--N in solution below unponded trenches at Site 3 was comparable to TKN concentrations in the STE further suggesting large amounts of nitrification. At Site 1, zones with mean negative pressure heads away from trench 2 had solution NO_3^--N values of approximately 50% of TKN values in the STE (Chapter 4).

5.6 CONCLUSIONS

Tensiometer data supported morphological evidence of restrictive layers but indicated that clayey soils with moderate to strong subangular blocky structure can be expected to transmit effluent horizontally above a restrictive layer. Under very restrictive conditions, flux densities should be maintained with pressure dosing at levels of 0.5 to 1.0 cm d^{-1}.

In well structured soils, nitrification will be limited if positive pressures predominate in the zone of effluent flow. Nitrification in soils with average negative pressure heads but that approached 0 was not limited below unponded trenches. Effluent leaving the immediate trench bottom area in well structured, well drained soils may have solution NO_3^--N concentrations of 70 mg L^{-1} or more. Solution NO_3^--N concentrations below ST-SAS were of a similar magnitude independent of flux density if the effluent was not ponded in the trench and were close to TKN concentrations in the STE.

Movement of NH_4^+-N substantial distances from ponded trenches in well structure soils under positive pressures indicated that a large potential exists for highly dispersive flow in similar soils of moderate to coarse structure when flow is saturated or occurs through large voids. Pressure dosing at fluxes < 2 cm d^{-1} should be used to minimize potential for transport of organisms by such dispersive flow until further research indicates otherwise.

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6.0 CHAPTER VI

SUMMARY AND CONCLUSIONS

Nitrogen rich wastewaters both of domestic and industrial origin may result in excessive leaching of NO_3^- to ground and surface water bodies if N application levels exceed losses to plant uptake and denitrification. In the study of textile wastewater application to tall fescue, maximum yield and plant uptake occurred at the 450 kg N ha^{-1} however USPHS standards for groundwater discharge would be exceeded at the mid and high N levels. Temporal NO_3^- distribution data indicated substantial carryover of soil inorganic N could be expected for 1 year.

Simple convective-dispersive solute leaching models predicted the NO_3^- -N distribution for the mid N level treatment but suggested further research to evaluate the timing of evaporation relative to infiltration under different precipitation or irrigation patterns.

Clayey limestone-derived soils with moderate to strong structure are suitable for ST-SAS at flux densities up to 2 cm d^{-1} (trench bottom area basis). Where the bottom of the ST-SAS was less than 30 cm above a restrictive layer, ponding occurred and a biological clogging mat developed. Rapid nitrification was noted around ST-SAS which drained to mean pressure heads < -20 cm of water. In soils with mean pressure heads > 0, nitrification was limited. Under these conditions, NH_4^+ moved at least 1 m indicating highly dispersive flow conditions. The concentration of NO_3^--N in soil solution below unponded ST-SAS exceeded USPHS standards and approached the TKN values of the effluent. Specific conclusions related to these studies follow below.

1. Irrigation of a nylon processing wastewater with relatively high concentrations of organic N resulted in accumulation of inorganic N in the root zone, primarily in the NO_3^- form, at N application rates above the crop requirement.

2. The importance of scheduling of irrigation prior to maximum herbage growth to minimize carryover of N in the soil inorganic fraction is illustrated by limited uptake of N applied late in the 1982 growing season.

3. Substantial leaching of NO_3^- is evident but does not appear to account for all losses. It is hypothesized that denitrification associated with irrigation and rainfall events may partially explain unaccounted-for losses.

4. Spray irrigation of wastewater with high TKN levels was an effective means of treatment and environmentally sound with respect to N pollution if application levels were low enough to maximize crop uptake efficiency.

5. The temporal differences in fitted convection-dispersion equation parameters indicate either a real change in the relative magnitudes of the convection and dispersion processes as the climatic pattern shifts from summer deficits to fall-winter-spring surpluses of precipitation or the inability to adequately model the system with the restrictive assumptions required to Model 3.

6. Prediction of mean solute peak penetration depth for use in models 1 and 2 is quite sensitive to how the relation between the timing of infiltration and evaporation is defined. Careful study will be required to determine whether models 1 or 2 are more realistic for estimating depth of peak penetration or rather if greater consideration needs to be placed on defining evaporation losses. For management purposes it does appear here that model 2 based on Burns equation with the I before E assumption or model 1 with the assumption of E before I best describes observed data.

7. The modelling approaches presented are useful for further data interpretations and predictions — especially for less sensitive management decisions.

8. Where similar studies of NO_3^- are planned, especially when using resident concentrations in soil cores, it is important to sample with small depth increments to increase the resolution of

data available for interpretation. Changes in volumetric water content during the growing season (which were not available for this study) would be quite beneficial for further interpretation of observed phenomena.

9. In spite of the limitations discussed, use of appropriate simplified models of solute leaching does provide a rational basis for management decisions regarding the potential for leaching of NO_3^- and other non-reactive ions from soils used for treatment of waste products and or agronomic and silvicultural practices.

10. Clayey, well structured B horizons without observed morphological restrictions, including shallow depth to bedrock, high coarse fragment content or closely underlying horizons with massive structure, adequately transmitted effluent doses of up to 3.6 cm d^{-1} without evidence of ponding or crust formation. Soils shallow to limestone bedrock but with strong structure in the underlying B horizon performed without any ponding or mat accumulation with 0.8 and 1.8 cm d^{-1} doses of effluent. Ponding and mat accumulation with substantial ponding was noted in systems dosed at 3.6 cm d^{-1}.

11. Presence of large amounts of weathered shale or other coarse fragments in otherwise well structured soils may result in lower effluent acceptance rates. Evidence indicates that rates approaching 1 cm d^{-1} may be suitable in similar soils. Where possible, at least 30 cm of well structured material should be maintained between trench bottoms and restrictive or poorly structured horizons, even if colors of the underlying horizons have high chromas. In fine textured soils where colors indicate good drainage but structure is weak and no other alternative exists, flux densities of 0.4 to 1 cm d^{-1} may be suitable.

12. Fine textured soils with good drainage are suitable for OSWDS, but optimal long term performance will probably not occur at the localized high loading rates typically associated with gravity distribution. Pressure distribution of effluent is recommended for these soils.

13. Tensiometer data supported morphological evidence of restrictive layers but indicated that clayey soils with moderate to strong subangular blocky structure can be expected to transmit effluent horizontally above a restrictive layer. Under very restrictive conditions, flux densities should be maintained with pressure dosing at levels of 0.5 to 1.0 cm d^{-1}. Where at least 70 cm of well structured material was present, effluent flux densities approaching 4 cm were transmitted successfully without ponding. When an effluent mound develops below the trench bottom, anaerobic conditions can be expected to result in accumulation of a biological mat which may lead to reductions in the infiltration rate. Where this may occur, flux densities should be < 2 cm d^{-1} Systems should be installed with as much well structured soil material below the trench bottom as possible.

14. Even in well structured soils, nitrification will be limited if positive pressures predominate in the zone of effluent flow. However in soils with average pressure heads of negative value but approaching 0, nitrification was not limited below unponded trenches. In well structured, well drained soils, the water leaving the immediate trench bottom area may have solution NO_3^- -N concentrations of 70 mg L^{-1} or more. Solution NO_3^--N concentrations below ST-SAS were of a similar magnitude independent of flux density if the effluent was not ponded in the trench and were close to TKN concentrations in the STE.

15. Movement of NH_4^+ substantial distances from ponded trenches in well structure soils under positive pressures indicated that a large potential exists for highly dispersive flow in similar soils of moderate to coarse structure when flow is saturated or occurs through large voids. Pressure dosing at fluxes < 2 cm d^{-1} should be used to minimize potential for transport of organisms by such dispersive flow until further research indicates otherwise.

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C$JOB         JOHN,PAGES=80                                          SOL00010
      REAL VWTO,ALPHAO,VWFC,RAIN(75),IRR(75),ET(75),INF(75),INET(75),  SOL00020
     XZWF(75),VW(75),DALPHA(75),ALPHA(75),DR,CUNIT(75,50),EPSIL,T,DO,   SOL00030
     XBETA,A,B,E(75),W(75),SW(75)                                       SOL00040
      INTEGER N,DT,WEEK(75),JULIAN(75)                                  SOL00050
C***************************************************************** SOL00060
C******     VARIABLES ARE DEFINED AS FOLLOWS:           ****** SOL00070
C                                                                       SOL00080
C A      DUMMY VARIABLE FOR PASSING INTO ERROR FUNCTION SUBROUTINE   SOL00090
C ALPHA  MEAN SOLUTE PENETRATION DEPTH                               SOL00100
C ALPHAO ALPHA AT BEGINNING OF CALCULATIONS                          SOL00110
C B      DUMMY VARIABLE FOR PASSING INTO ERROR FUNTION SUBROUTINE    SOL00120
C BETA   ALPHA - F                                                   SOL00130
C CC     CORRECTION FACTOR FOR ADJUSTING PAN EVAPORTATION TO ESTIMATED SOL00140
C        EVAPOTRANSPIRATION                                          SOL00150
C CUNIT  UNIT SOLUTION CONCENTRATION DEFINED C./INITIAL C.           SOL00160
C DALPHA THE CALCULATED CHANGE IN ALPHA DURING A PARTICULAR TIME INTERVASOL00170
C DO     DIFFUSION COEFFICIENT FOR NITRATE                           SOL00180
C DR     ROOTING DEPTH                                               SOL00190
C DT     INCREMENTING VARIABLE FOR DETERMINING HOW OFTEN THE CALCULATIONSOL00200
C        ARE MADE BY THE PROGRAM                                     SOL00210
C ET     WEEKLY EVAPORATION FROM THE CLASS A PAN    (CM)             SOL00220
C E      PAN EVAP. CORRECTED TO ESTIMATE EVAPORTRANSPIRATION   (CM)  SOL00230
C EPSIL  THE DISPERSIVITY                                            SOL00240
C INET   INFILTRATION - EVAPOTRANSPIRATION FOR TIME INTERVAL   (CM)  SOL00250
C INF    SUM OF RAINFALL AND IRRIGATION   (CM)                       SOL00260
C IRR    QUANTITY OF WATER ADDED AS IRRIGATION   (CM)                SOL00270
C F      DEPTH OF INITIAL SOLUTE PEAK PENETRATION BEFORE CONCENTRATION CSOL00280
C RAIN   QUANTITY OF WATER ADDED AS PRECIPITATION                    SOL00290
C W      DEPTH OF WATER AVAILABLE TO MOVE ALPHA AFTER PREVIOUS EVAPORATISOL00300
C        BEEN RECHARGED ABOVE PREVIOUS ALPHA                         SOL00310
C T      DAYS SINCE STEP CHANGE IN CONCENTRATION                     SOL00320
C VW     CALCULATED VOLUMETRIC WATER CONTENT OF SOIL                 SOL00330
C VWTO   INITIAL VW                                                  SOL00340
C VWFC   VOLUMETRIC WATER CONTENT AT FIELD CAPACITY                  SOL00350
C VWWP   MINIMUM WATER CONTENT TO ALLOW THE SOIL TO DRY TO (WILTING POINSOL00360
C N      NUMBER OF TIME INTERVALS TO CONSIDER                        SOL00370
C************** DEFINE CONSTANTS************************************** SOL00380
      READ 1000, VWTO,ALPHAO,VWFC,N                                   SOL00390
      EPSIL= 8.                                                       SOL00400
      F=9.2                                                           SOL00410
      C=0                                                             SOL00420
      VWFC=.38                                                        SOL00430
      CC=.80                                                          SOL00440
      DT=1                                                            SOL00450
      M=3                                                             SOL00460
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      DR=150                                                        SOL00470
C***********************************************************************  SOL00480
 1000 FORMAT(F4.2,1X,F4.0,1X,F4.2,1X,I2,1X,I2)                      SOL00490
      WRITE (6,1000) VWTO ,ALPHA0,VWFC,N,DT                         SOL00500
 1020 FORMAT(I4,3X,F5.2,3X,F5.2,4X,5X,4X,F5.2)                      SOL00510
      DO 10 I=1,N                                                   SOL00520
C***********************************************************************  SOL00530
C READ WATER BALANCE DATA                                          SOL00540
C***********************************************************************  SOL00550
         READ 1020,WEEK (I),RAIN(I),ET(I),IRR(I)                   SOL00560
         WRITE(6,1020)WEEK (I),RAIN(I),ET(I),IRR(I)                SOL00570
   10 CONTINUE                                                      SOL00580
      DO 20 I=M,N                                                   SOL00590
      RAIN(I)=RAIN(I)                                               SOL00600
         INF(I)=RAIN(I)+IRR(I)                                      SOL00610
         INET(I)=INF(I)-CC*ET(I)                                    SOL00620
      ZWF(I)=0.                                                     SOL00630
   20 CONTINUE                                                      SOL00640
C***************INITIALIZE**********************************************   SOL00650
         ALPHA(N)=ALPHA0                                            SOL00660
         VW(N)=VWTO                                                 SOL00670
         VWWP=0.12                                                  SOL00680
         SW(N)=0.0                                                  SOL00690
C***********************************************************************  SOL00700
      DO 100 I=M,N                                                  SOL00710
         E(I)=ET(I)*CC                                              SOL00720
         J=I-1                                                      SOL00730
         K=I-M                                                      SOL00740
         IF(K.EQ.0)J=N                                              SOL00750
C***********************************************************************  SOL00760
C CALCULATE DALPHA(J)+INET(I)*DT/DR                                SOL00770
C***********************************************************************  SOL00780
         W(I)=INF(I)*DT-ALPHA(J)*(VWFC-VW(J))                       SOL00790
         IF (ALPHA(J).GT.DR)W(I)=INF(I)*DT-DR*(VWFC-VW(J))          SOL00800
         IF (VW(J).NE.VWFC) GO TO 105                               SOL00810
         ZWF(I)=DR+1                                                SOL00820
         GO TO 106                                                  SOL00830
  105    ZWF(I)=INF(I)*DT/(VWFC-VW(J))                              SOL00840
  106    IF (W(I).LT.0)W(I)=0                                       SOL00850
         SW(I)=W(I)+SW(J)                                           SOL00860
         DALPHA(I)=W(I)/VWFC                                        SOL00870
         IF (ZWF(I).LT.ALPHA(J))DALPHA(I)=0                         SOL00880
         ALPHA(I)=ALPHA(J)+DALPHA(I)                                SOL00890
         VW(I)=VW(J)+(INF(I)-E(J))*DT/DR                            SOL00900
         IF(VW(I).GT.VWFC)VW(I)=VWFC                                SOL00910
         IF(VW(I).LT.VWWP )VW(I)=VWWP                               SOL00920
  100    CONTINUE                                                   SOL00930
      WRITE (6,1105)                                                SOL00940
      WRITE (6,1100) VWTO,VWFC,ALPHA0,N,DT                          SOL00950
      WRITE (6,1125)                                                SOL00960
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      WRITE (6,1126)                                              SOL00970
      DO 180 I=M,N                                                SOL00980
        WRITE (6,1120)RAIN(I),IRR(I),INF(I),ET(I),INET(I),ZWF(I), SOL00990
   X      DALPHA(I),ALPHA(I),VW(I)                                SOL01000
 180 CONTINUE                                                     SOL01010
1105 FORMAT ('1',' VWTO   VWFC  ALPHAO    N    DT')               SOL01020
1100 FORMAT (' ',3X,F5.3,3X,F5.3,3X,F5.2,I3,2X,I3)               SOL01030
1120 FORMAT(' ',3X,F5.2,3X,F5.2,3X,F5.2,3X,F5.2,3X,F5.2,3X,F5.2  SOL01040
   X,3X,F5.2,3X,F5.2,3X,F5.3)                                     SOL01050
1126 FORMAT(' ')                                                  SOL01060
1125 FORMAT('   RAIN    IRR    INF     ET    INET    ZWF          SOL01070
   XDALPHA  ALPHA   VW')                                          SOL01080
C******DEFINE DO AND T AND INITIAL CONCENTRATION OF SOIL SOLUTION (C)  SOL01090
      DO=1.0                                                      SOL01100
      T=7                                                         SOL01110
      ALPHA(N)=ALPHAO                                             SOL01120
      C=0.0                                                       SOL01130
C******************************************************             SOL01140
      WRITE(6,1130)                                               SOL01150
C*************************************************************      SOL01160
C CALCULATE CONCENTRATIONS FOR EACH DEPTH AND TIME INCREMENT       SOL01170
C*************************************************************      SOL01180
      DO  2 I=M,N                                                 SOL01190
        K=I-1                                                     SOL01200
        T=7                                                       SOL01210
        IF (K.EQ.0)K=N                                            SOL01220
        IF(I.GT.21)T=T+7                                          SOL01230
C*************************************************************      SOL01240
C SPECIFY NUMBER OF DEPTH INCREMENTS AND MIDPOINT OF EACH INCREMENT SOL01250
C*************************************************************      SOL01260
          DO 4 J=1,15                                             SOL01270
            Z=J*15.-7.5                                           SOL01280
        IF (I.EQ.16) GO TO 300                                    SOL01290
        IF (I.EQ.29)GO TO 400                                     SOL01300
        IF (I.EQ.60)GO TO 450                                     SOL01310
        IF (I.GT.60) GO TO 500                                    SOL01320
 300    IF (J.GT.2) Z=J*15                                        SOL01330
        GO TO 500                                                 SOL01340
 400    IF (J.GT.2) Z=J*15                                        SOL01350
        GO TO 500                                                 SOL01360
 450    IF (J.GT.6) Z=J*15                                        SOL01370
 500        IF (ALPHA(I).LT.F)GO TO 6                             SOL01380
            A=(Z-ALPHA(I))/(2*(DO*T+EPSIL*ALPHA(I))**.5)          SOL01390
            BETA=ALPHA(I)-F                                       SOL01400
            IF (BETA.LT.0)BETA=0                                  SOL01410
            B=(Z-BETA)/(2*(DO*T+EPSIL*BETA)**.5)                  SOL01420
            CUNIT(I,J)=.5*(EXF(C,A)-EXF(C,B))                     SOL01430
            DUM=EXF(C,A)                                          SOL01440
            EUM=EXF(C,B)                                          SOL01450
            IF (I.EQ.16) GO TO 6                                  SOL01460
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            IF (I.EQ.29) GO TO 6                                        SOL01470
            IF (I.EQ.60) GO TO 6                                        SOL01480
            IF (I.EQ.72) GO TO 6                                        SOL01490
            GO TO 5                                                     SOL01500
C*************************************************************          SOL01510
C OUTPUT TO DISK                                                        SOL01520
C*************************************************************          SOL01530
      6           WRITE(8,1127)I,Z,ALPHA(I),CUNIT(I,J)                  SOL01540
C*************************************************************          SOL01550
C OUTPUT TO READER                                                      SOL01560
C*************************************************************          SOL01570
      5           WRITE(6,1127)I,Z,ALPHA(I),CUNIT(I,J)                  SOL01580
      4         CONTINUE                                                SOL01590
      2 CONTINUE                                                        SOL01600
 1130 FORMAT('1','    WEEK   DEPTH   CUNIT')                            SOL01610
 1127 FORMAT(' ',I3,2X,F5.1,6(2X,F9.3))                                 SOL01620
      STOP                                                              SOL01630
      END                                                               SOL01640
C*************************************************************          SOL01650
C ERROR FUNCTION SUBROUTINE                                             SOL01660
C*************************************************************          SOL01670
      FUNCTION EXF(A,B)                                                 SOL01680
C                                                                       SOL01690
C     PURPOSE:   TO CALCULATE EXP(A) ERFC(B)                            SOL01700
C                                                                       SOL01710
      EXF=0.D00                                                         SOL01720
      IF((ABS(A).GT.100.).AND.(B.LE.0.)) RETURN                         SOL01730
      C=A-B*B                                                           SOL01740
      IF((ABS(C).GT.100.).AND.(B.GE.0.)) RETURN                         SOL01750
      IF(C.LT.-100.) GO TO 3                                            SOL01760
      X=ABS(B)                                                          SOL01770
      IF(X.GT.3.0) GO TO 1                                              SOL01780
      T=1./(1.+.3275911*X)                                              SOL01790
      Y=T*(.2548296-T*(.2844967-T*(1.421414-T*(1.453152-1.061405*T))))  SOL01800
      GO TO 2                                                           SOL01810
    1 Y=.5641896/(X+.5/(X+1./(X+1.5/(X+2./(X+2.5/X+1.)))))             SOL01820
    2 EXF=Y*EXP(C)                                                      SOL01830
    3 IF(B.LT.0.0) EXF=2.*EXP(A)-EXF                                    SOL01840
      RETURN                                                            SOL01850
      END                                                               SOL01860
C**********************INPUT DATA FOLLOWS**********************          SOL01870
C$ENTRY                                                                 SOL01880
0.38     0 0.38 73                                                     SOL01890
   01    1.01    2.59    16SEP                                          SOL01900
   02    4.57    2.15    09SEP                                          SOL01910
   03    0       1.88    30SEP         0.38                             SOL01920
   04    1.01    2.23    07OCT         0.38                             SOL01930
   05    3.05    1.04    14OCT         0.38                             SOL01940
   06    2.29    1.70    21OCT         0.38                             SOL01950
   07    0       1.64    28OCT                                          SOL01960
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08	2.03	1.31	04N6V		SOL01970
09	3.81	1.31	11N6V		SOL01980
10	0	1.31	18N6V		SOL01990
11	2.54	1.31	25N6V		SOL02000
12	3.05	.66			SOL02010
13	2.29	.66	9DEC		SOL02020
14	2.29	.66	16DEC		SOL02030
15	0	.66	23DEC		SOL02040
16	4.06	.46	30DEC		SOL02050
17	.76	.46	61AN		SOL02060
18	0.51	.46	131AN		SOL02070
19	2.29	.46	201AN		SOL02080
20	0.00	.49	271AN		SOL02090
21	3.56	.61	3FEB		SOL02100
22	2.03	.61	10FEB		SOL02110
23	1.52	.61	17FEB		SOL02120
24	0.25	.81	24FEB		SOL02130
25	3.05	1.31	30AR		SOL02140
26	1.78	1.31	100AR		SOL02150
27	0	1.31	170AR		SOL02160
28	3.05	1.31	240AR		SOL02170
29	1.27	2.25	310AR		SOL02180
30	2.54	2.41	7APR		SOL02190
31	6.6	2.41	14APR		SOL02200
32	2.54	2.41	21APR		SOL02210
33	2.03	2.66	28APR		SOL02220
34	0.76	3.75	50AY		SOL02230
35	1.27	4.45	120AY		SOL02240
36	1.02	1.39	190AY		SOL02250
37	6.35	4.11	83143		SOL02260
38	1.02	2.13	83150		SOL02270
39	3.05	4.29	83157		SOL02280
40	1.52	4.24	83164		SOL02290
41	3.05	3.63	83171		SOL02300
42	0.76	3.18	83178		SOL02310
43	1.52	4.37	83185	.07	SOL02320
44	0.00	4.62	83192		SOL02330
45	0.00	5.21	83199		SOL02340
46	0.00	4.39	83206	.27	SOL02350
47	1.27	3.99	83213	.27	SOL02360
48	0.25	4.90	83220	.27	SOL02370
49	0.00	3.94	83227		SOL02380
50	5.08	4.29	83234	.27	SOL02390
51	0.00	3.78	83241	.27	SOL02400
52	0.00	4.24	83248	.27	SOL02410
53	2.03	2.62	83255	.27	SOL02420
54	4.57	2.41	83262	.27	SOL02430
55	2.79	2.34	83269		SOL02440
56	0.00	2.24	83276	.27	SOL02450
57	2.79	1.85	83283	.27	SOL02460

58	6.86	1.88	83290		SOL02470
59	0.76	1.88	83297		SOL02480
60	0.00	1.31	83304		SOL02490
61	3.56	1.31	83311		SOL02500
62	4.83	1.31	83318		SOL02510
63	6.60	1.31	83325		SOL02520
64	2.54	0.93	83332		SOL02530
65	2.03	0.66	83339		SOL02540
66	4.57	0.66	83346		SOL02550
67	1.27	0.66			SOL02560
68	1.52	0.60			SOL02570
69	0.00	0.46			SOL02580
70	5.84	0.46			SOL02590
71	6.35	0.46			SOL02600
72	0.00	0.46			SOL02610
73	0				SOL02620

APPENDIX B. MODEL 2 (BURNS)

```
C$JOB          JOHN,PAGES=80                                          SOL00010
       REAL VWTO,ALPHAO,VWFC,RAIN(75),IRR(75),ET(75),INF(75),INET(75),  SOL00020
      XZWF(75),VW(75),DALPHA(75),ALPHA(75),DR,CUNIT(75,50),EPSIL,T,DO,   SOL00030
      XBETA,A,B,E(75),W(75),SW(75)                                      SOL00040
       INTEGER N,DT,WEEK(75),JULIAN(75)                                 SOL00050
C*************************************************************************SOL00060
C******          VARIABLES ARE DEFINED AS FOLLOWS:              ****** SOL00070
C                                                                      SOL00080
C A      DUMMY VARIABLE FOR PASSING INTO ERROR FUNCTION SUBROUTINE     SOL00090
C ALPHA  MEAN SOLUTE PENETRATION DEPTH                                 SOL00100
C ALPHAO ALPHA AT BEGINNING OF CALCULATIONS                           SOL00110
C B      DUMMY VARIABLE FOR PASSING INTO ERROR FUNTION SUBROUTINE      SOL00120
C BETA   ALPHA - F                                                     SOL00130
C CC     CORRECTION FACTOR FOR ADJUSTING PAN EVAPORTATION TO ESTIMATED SOL00140
C        EVAPOTRANSPIRATION                                            SOL00150
C CUNIT  UNIT SOLUTION CONCENTRATION DEFINED C./INITIAL C.             SOL00160
C DALPHA THE CALCULATED CHANGE IN ALPHA DURING A PARTICULAR TIME INTERVASOL00170
C DO     DIFFUSION COEFFICIENT FOR NITRATE                             SOL00180
C DR     ROOTING DEPTH                                                 SOL00190
C DT     INCREMENTING VARIABLE FOR DETERMINING HOW OFTEN THE CALCULATIONSOL00200
C        ARE MADE BY THE PROGRAM                                       SOL00210
C ET     WEEKLY EVAPORATION FROM THE CLASS A PAN    (CM)               SOL00220
C E      PAN EVAP. CORRECTED TO ESTIMATE EVAPORTRANSPIRATION    (CM)   SOL00230
C EPSIL  THE DISPERSIVITY                                              SOL00240
C INET   INFILTRATION - EVAPOTRANSPIRATION FOR TIME INTERVAL   (CM)    SOL00250
C INF    SUM OF RAINFALL AND IRRIGATION   (CM)                         SOL00260
C IRR    QUANTITY OF WATER ADDED AS IRRIGATION    (CM)                 SOL00270
C F      DEPTH OF INITIAL SOLUTE PEAK PENETRATION BEFORE CONCENTRATION CSOL00280
C RAIN   QUANTITY OF WATER ADDED AS PRECIPITATION                      SOL00290
C W      DEPTH OF WATER AVAILABLE TO MOVE ALPHA AFTER PREVIOUS EVAPORATISOL00300
C        BEEN RECHARGED ABOVE PREVIOUS ALPHA                           SOL00310
C SW     CUMULATIVE NET INFILTRATION (Q)                               SOL00320
C T      DAYS SINCE STEP CHANGE IN CONCENTRATION                       SOL00330
C VW     CALCULATED VOLUMETRIC WATER CONTENT OF SOIL                   SOL00340
C VWTO   INITIAL VW                                                    SOL00350
C VWFC   VOLUMETRIC WATER CONTENT AT FIELD CAPACITY                    SOL00360
C VWWP   MINIMUM WATER CONTENT TO ALLOW THE SOIL TO DRY TO (WILTING POINSOL00370
C N      NUMBER OF TIME INTERVALS TO CONSIDER                          SOL00380
C*************** DEFINE CONSTANTS*************************************** SOL00390
       READ 1000, VWTO,ALPHAO,VWFC,N                                    SOL00400
       EPSIL= 8.0                                                       SOL00410
       F=9.2                                                            SOL00420
       C=0                                                              SOL00430
       VWFC=.38                                                         SOL00440
       CC=.80                                                           SOL00450
       DT=1                                                             SOL00460
       M=3                                                              SOL00470
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          DR=150                                                      SOL00480
C*********************************************************************  SOL00490
 1000 FORMAT(F4.2,1X,F4.0,1X,F4.2,1X,I2,1X,I2)                         SOL00500
      WRITE (6,1000) VWT0 ,ALPHA0,VWFC,N,DT                            SOL00510
 1020 FORMAT(I4,3X,F5.2,3X,F5.2,4X,5X,4X,F5.2)                         SOL00520
      DO 10 I=1,N                                                     SOL00530
C*********************************************************************  SOL00540
C READ WATER BALANCE DATA                                              SOL00550
C*********************************************************************  SOL00560
         READ 1020,WEEK (I),RAIN(I),ET(I),IRR(I)                       SOL00570
         WRITE(6,1020)WEEK (I),RAIN(I),ET(I),IRR(I)                    SOL00580
  10 CONTINUE                                                         SOL00590
     DO 20 I=M,N                                                      SOL00600
     RAIN(I)=RAIN(I)                                                  SOL00610
         INF(I)=RAIN(I)+IRR(I)                                        SOL00620
         INET(I)=INF(I)-CC*ET(I)                                      SOL00630
       ZWF(I)=0.                                                      SOL00640
  20 CONTINUE                                                         SOL00650
C*************INITIALIZE**********************************************   SOL00660
         ALPHA(N)=ALPHA0                                              SOL00670
         VW(N)=VWT0                                                   SOL00680
         VWWP=0.12                                                    SOL00690
         SW(N)=0.0                                                    SOL00700
C*********************************************************************  SOL00710
     DO 100 I=M,N                                                     SOL00720
         E(I)=ET(I)*CC                                                SOL00730
         J=I-1                                                        SOL00740
         K=I-M                                                        SOL00750
         IF(K.EQ.0)J=N                                                SOL00760
C*********************************************************************  SOL00770
C CALCULATE DALPHA(J)+INET(I)*DT/DR                                    SOL00780
C*********************************************************************  SOL00790
         W(I)=INF(I)*DT-ALPHA(J)*(VWFC-VW(J))                         SOL00800
         IF (ALPHA(J).GT.DR)W(I)=INF(I)*DT-DR*(VWFC-VW(J))            SOL00810
         IF (VW(J).NE.VWFC) GO TO 105                                 SOL00820
         ZWF(I)=DR+1                                                  SOL00830
         GO TO 106                                                    SOL00840
  105    ZWF(I)=INF(I)*DT/(VWFC-VW(J))                                SOL00850
  106    IF (W(I).LT.0)W(I)=0                                         SOL00860
         SW(I)=W(I)+SW(J)                                             SOL00870
         ALPHA(I)=-.693/ALOG(SW(I)/(SW(I)+VWFC))                      SOL00880
         IF (ZWF(I).LT.ALPHA(J))ALPHA(I)=ALPHA(J)                     SOL00890
C        IF (I.LT.24)ALPHA(I)=23                                      SOL00900
         VW(I)=VW(J)+(INF(I)-E(I))*DT/DR                              SOL00910
         IF(VW(I).GT.VWFC)VW(I)=VWFC                                  SOL00920
         IF(VW(I).LT.VWWP )VW(I)=VWWP                                 SOL00930
        PRINT,ZWF(I),'ZWF','    DALPHA',DALPHA(I),'W',W(I),'SW',SW(I), SOL00940
     X'ALPHA',ALPHA(I)                                                SOL00950
  100    CONTINUE                                                     SOL00960
     WRITE (6,1105)                                                   SOL00970
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      WRITE (6,1100) VWTO,VWFC,ALPHAO,N,DT                          SOL00980
      WRITE (6,1125)                                                SOL00990
      WRITE (6,1126)                                                SOL01000
      DO 180 I=M,N                                                  SOL01010
          WRITE (6,1120)RAIN(I),IRR(I),INF(I),ET(I),INET(I),ZWF(I), SOL01020
     X    DALPHA(I),ALPHA(I),VW(I)                                  SOL01030
  180 CONTINUE                                                      SOL01040
 1105 FORMAT ('1','   VWTO    VWFC   ALPHAO    N    DT')            SOL01050
 1100 FORMAT (' ',3X,F5.3,3X,F5.3,3X,F5.2,I3,2X,I3)                 SOL01060
 1120 FORMAT(' ',3X,F5.2,3X,F5.2,3X,F5.2,3X,F5.2,3X,F5.2,3X,F5.2    SOL01070
     X,3X,F5.2,3X,F5.2,3X,F5.3)                                     SOL01080
 1126 FORMAT(' ')                                                   SOL01090
 1125 FORMAT('    RAIN     IRR     INF     ET     INET    ZWF       SOL01100
     XDALPHA   ALPHA    VW')                                        SOL01110
      DO=1.0                                                        SOL01120
C*******DEFINE DO AND T AND INITIAL CONCENTRATION OF SOIL SOLUTION (C) SOL01130
      T=7                                                           SOL01140
      ALPHA(N)=ALPHAO                                               SOL01150
      C=0.0                                                         SOL01160
C****************************************************               SOL01170
      WRITE(6,1130)                                                 SOL01180
C************************************************************************ SOL01190
C CALCULATE CONCENTRATIONS FOR EACH DEPTH AND TIME INCREMENT       SOL01200
C************************************************************************ SOL01210
      DO  2 I=M,N                                                   SOL01220
          K=I-1                                                     SOL01230
          T=7                                                       SOL01240
          IF (K.EQ.0)K=N                                            SOL01250
          IF(I.GT.21)T=T+7                                          SOL01260
C************************************************************************ SOL01270
C SPECIFY NUMBER OF DEPTH INCREMENTS AND MIDPOINT OF EACH INCREMENT SOL01280
C************************************************************************ SOL01290
          DO 4 J=1,15                                               SOL01300
              Z=J*15.-7.5                                           SOL01310
          IF (I.EQ.16) GO TO 300                                    SOL01320
          IF (I.EQ.29)GO TO 400                                     SOL01330
          IF (I.EQ.60)GO TO 450                                     SOL01340
          IF (I.GT.60) GO TO 500                                    SOL01350
  300     IF (J.GT.2) Z=J*15                                        SOL01360
          GO TO 500                                                 SOL01370
  400     IF (J.GT.2) Z=J*15                                        SOL01380
          GO TO 500                                                 SOL01390
  450     IF (J.GT.6) Z=J*15                                        SOL01400
  500         IF (ALPHA(I).LT.F)GO TO 6                             SOL01410
              A=(Z-ALPHA(I))/(2*(DO*T+EPSIL*ALPHA(I))**.5)          SOL01420
              BETA=ALPHA(I)-F                                       SOL01430
              IF (BETA.LT.0)BETA=0                                  SOL01440
              B=(Z-BETA)/(2*(DO*T+EPSIL*BETA)**.5)                  SOL01450
              CUNIT(I,J)=.5*(EXF(C,A)-EXF(C,B))                     SOL01460
              DUM=EXF(C,A)                                          SOL01470
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              EUM=EXF(C,B)                                     SOL01480
              IF (I.EQ.16) GO TO 6                             SOL01490
              IF (I.EQ.29) GO TO 6                             SOL01500
              IF (I.EQ.60) GO TO 6                             SOL01510
              IF (I.EQ.72) GO TO 6                             SOL01520
              GO TO 5                                          SOL01530
C********************************************************      SOL01540
C OUTPUT TO DISK                                               SOL01550
C********************************************************      SOL01560
      6         WRITE(8,1127)I,Z,ALPHA(I),CUNIT(I,J)           SOL01570
C********************************************************      SOL01580
C OUTPUT TO READER                                             SOL01590
C********************************************************      SOL01600
      5         WRITE(6,1127)I,Z,ALPHA(I),CUNIT(I,J)           SOL01610
      4       CONTINUE                                         SOL01620
      2 CONTINUE                                               SOL01630
   1130 FORMAT('1','  WEEK  DEPTH   CUNIT')                    SOL01640
   1127 FORMAT(' ',I3,2X,F5.1,6(2X,F9.3))                      SOL01650
        STOP                                                   SOL01660
        END                                                    SOL01670
C                                                              SOL01680
C********************************************************      SOL01690
C ERROR FUNCTION SUBROUTINE                                    SOL01700
C********************************************************      SOL01710
        FUNCTION EXF(A,B)                                      SOL01720
C                                                              SOL01730
C     PURPOSE:  TO CALCULATE EXP(A) ERFC(B)                    SOL01740
C                                                              SOL01750
        EXF=0.D00                                              SOL01760
        IF((ABS(A).GT.100.).AND.(B.LE.0.)) RETURN             SOL01770
        C=A-B*B                                                SOL01780
        IF((ABS(C).GT.100.).AND.(B.GE.0.)) RETURN             SOL01790
        IF(C.LT.-100.) GO TO 3                                 SOL01800
        X=ABS(B)                                               SOL01810
        IF(X.GT.3.0) GO TO 1                                   SOL01820
        T=1./(1.+.3275911*X)                                   SOL01830
        Y=T*(.2548296-T*(.2844967-T*(1.421414-T*(1.453152-1.061405*T))))  SOL01840
        GO TO 2                                                SOL01850
      1 Y=.5641896/(X+.5/(X+1./(X+1.5/(X+2./(X+2.5/X+1.)))))   SOL01860
      2 EXF=Y*EXP(C)                                           SOL01870
      3 IF(B.LT.0.0) EXF=2.*EXP(A)-EXF                         SOL01880
C         READ 1020,WEEK (I),RAIN(I),ET(I),JULIAN(I),IRR(I)    SOL01890
        RETURN                                                 SOL01900
        END                                                    SOL01910
C$ENTRY                                                        SOL01920
0.38    0 0.40 73                                              SOL01930
   01    1.01    2.59    16SEP                                 SOL01940
   02    4.57    2.15    09SEP                                 SOL01950
   03    0       1.88    30SEP       0.38                      SOL01960
   04    1.01    2.23    07OCT       0.38                      SOL01970
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05	3.05	1.04	146CT	0.38	SOL01980
06	2.29	1.70	216CT	0.38	SOL01990
07	0	1.64	286CT		SOL02000
08	2.03	1.31	04N6V		SOL02010
09	3.81	1.31	11N6V		SOL02020
10	0	1.31	18N6V		SOL02030
11	2.54	1.31	25N6V		SOL02040
12	3.05	.66			SOL02050
13	2.29	.66	9DEC		SOL02060
14	2.29	.66	16DEC		SOL02070
15	0	.66	23DEC		SOL02080
16	4.06	.46	30DEC		SOL02090
17	.76	.46	61AN		SOL02100
18	0.51	.46	131AN		SOL02110
19	2.29	.46	201AN		SOL02120
20	0.00	.49	271AN		SOL02130
21	3.56	.61	3FEB		SOL02140
22	2.03	.61	10FEB		SOL02150
23	1.52	.61	17FEB		SOL02160
24	0.25	.81	24FEB		SOL02170
25	3.05	1.31	30AR		SOL02180
26	1.78	1.31	100AR		SOL02190
27	0	1.31	170AR		SOL02200
28	3.05	1.31	240AR		SOL02210
29	1.27	2.25	310AR		SOL02220
30	2.54	2.41	7APR		SOL02230
31	6.6	2.41	14APR		SOL02240
32	2.54	2.41	21APR		SOL02250
33	2.03	2.66	28APR		SOL02260
34	0.76	3.75	50AY		SOL02270
35	1.27	4.45	120AY		SOL02280
36	1.02	1.39	190AY		SOL02290
37	6.35	4.11	83143		SOL02300
38	1.02	2.13	83150		SOL02310
39	3.05	4.29	83157		SOL02320
40	1.52	4.24	83164		SOL02330
41	3.05	3.63	83171		SOL02340
42	0.76	3.18	83178		SOL02350
43	1.52	4.37	83185	.07	SOL02360
44	0.00	4.62	83192		SOL02370
45	0.00	5.21	83199		SOL02380
46	0.00	4.39	83206	.27	SOL02390
47	1.27	3.99	83213	.27	SOL02400
48	0.25	4.90	83220	.27	SOL02410
49	0.00	3.94	83227		SOL02420
50	5.08	4.29	83234	.27	SOL02430
51	0.00	3.78	83241	.27	SOL02440
52	0.00	4.24	83248	.27	SOL02450
53	2.03	2.62	83255	.27	SOL02460
54	4.57	2.41	83262	.27	SOL02470

55	2.79	2.34	83269		SOL02480
56	0.00	2.24	83276	.27	SOL02490
57	2.79	1.85	83283	.27	SOL02500
58	6.86	1.88	83290		SOL02510
59	0.76	1.88	83297		SOL02520
60	0.00	1.31	83304		SOL02530
61	3.56	1.31	83311		SOL02540
62	4.83	1.31	83318		SOL02550
63	6.60	1.31	83325		SOL02560
64	2.54	0.93	83332		SOL02570
65	2.03	0.66	83339		SOL02580
66	4.57	0.66	83346		SOL02590
67	1.27	0.66			SOL02600
68	1.52	0.60			SOL02610
69	0.00	0.46			SOL02620
70	5.84	0.46			SOL02630
71	6.35	0.46			SOL02640
72	0.00	0.46			SOL02650
73	0				SOL02660
					SOL02670