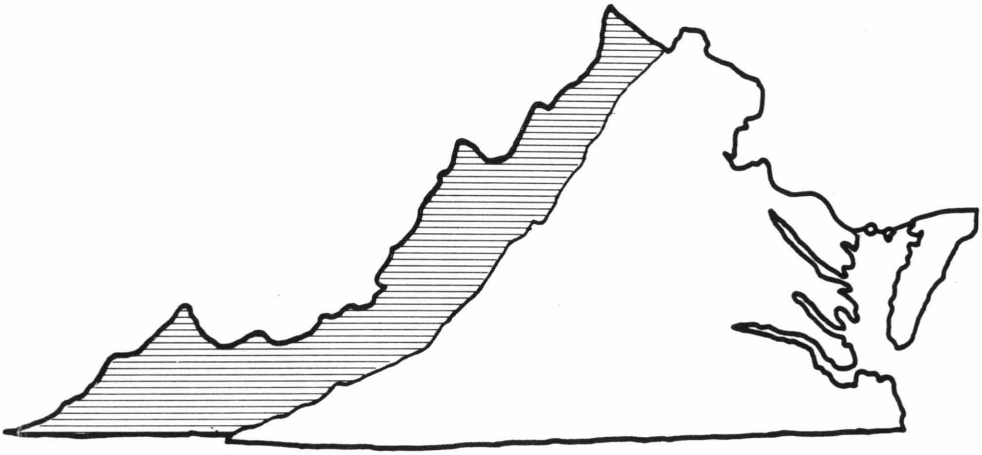
ginia Agricultural Experiment Station
ginia Polytechnic Institute and State University

Bulletin 86-6
ISSN 0096-6088

uitability of mestone-Derived Soils or On-Site Wastewater Disposal

n J. Simon, Raymond B. Reneau, Jr., and Marcia J. Degen



James R. Nichols, Dean and Director
College of Agriculture and Life Sciences
Virginia Agricultural Experiment Station
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

The Virginia Agricultural and Mechanical College came into being in 1872 upon acceptance by the Commonwealth of the provisions of the Morrill Act of 1862 "to promote the liberal and practical education of the industrial classes in the several pursuits and professions of life." Research and investigations were first authorized at Virginia's land-grant college when the Virginia Agricultural Experiment Station was established by the Virginia General Assembly in 1886.

The Virginia Agricultural Experiment Station received its first allotment upon passage of the Hatch Act by the United States Congress in 1887. Other related Acts followed, and all were consolidated in 1955 under the Amended Hatch Act which states "It shall be the object and duty of the State agricultural experiment stations . . . to conduct original and other researches, investigations and experiments bearing directly on and contributing to the establishment and maintenance of a permanent and effective agricultural industry of the United States, including the researches basic to the problems of agriculture and its broadest aspects and such investigations as have for their purpose the development and improvement of the rural home and rural life and the maximum contributions by agriculture to the welfare of the consumer . . . "

In 1962, Congress passed the McIntire-Stennis Cooperative Forestry Research Act to encourage and assist the states in carrying on a program of forestry research, including reforestation, land management, watershed management, rangeland management, wildlife habitat improvement, outdoor recreation, harvesting and marketing of forest products, and "such other studies as may be necessary to obtain the fullest and most effective use of forest resources."

In 1966, the Virginia General Assembly "established within the Virginia Polytechnic Institute a division to be known as the Research Division . . . which shall encompass the now existing Virginia Agricultural Experiment Station . . . "

SUITABILITY OF LIMESTONE-DERIVED SOILS FOR ON-SITE WASTEWATER DISPOSAL

John J. Simon
Raymond B. Reneau, Jr.
Marcia J. Degen

Agronomy Department
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

Virginia Agricultural Experiment Station
Bulletin 86-6
Fall 1986

This study was funded in part by the
Virginia Department of Health.

4/1/87 MCR

1.0 Abstract

Limestone-derived soils comprise large parts of the Great Valley of Virginia as well as other parts of the United States and world. Previous researchers proposed relatively low application rates for septic tank effluent (STE) to clayey subsoils of glacial origin but much higher rates of application have been noted to be suitable in some but not all clayey soils developed in limestone residuum. Additional questions have also been raised about the potential for pollution of groundwaters by nitrate (NO_3^--N) formation from the ammonium (NH_4^+-N) and organic nitrogen present in STE. New regulations promulgated by the Virginia State Board of Health in 1982 provided for effluent loading rates to be determined either by the soil texture or the percolation rate but did not take into account soil structure or the potential for leaching of NO_3^--N to groundwaters. The purpose of this work was to (1) test the hypothesis that clayey, well drained soils are suitable for septic tank subsurface absorption systems (ST-SAS) if low pressure distribution (LPD) of STE is used; (2) determine approximate loading rates for soils with different grade, size, and type of structure, and depths to restrictive layers; (3) determine the extent of nitrification in clayey limestone-derived soils below ST-SAS in which effluent was (a) ponded and (b) not ponded. Results of this study indicate that clayey soils developed in limestone residuum are suitable for disposal of STE. Where the soil structure is weak blocky to massive but soil colors indicate good drainage, flux densities of 0.5 cm d^{-1} may be suitable with LPD. ST-SAS installed in fine textured soils with 15 to 30 cm of soil with moderate to strong blocky structure beneath them may be dosed at 1 cm d^{-1}. Where more than 60 cm of soil with strong structure but no other apparent restrictions underlies a ST-SAS, loading rates of 2 to 3 cm d^{-1} may be suitable. Presence of $>25\%$ coarse fragments in otherwise well structured soils may result in lower effluent acceptance rates, hence a maximum rate of 1 to 2 cm d^{-1} may be suitable in these soils depending on other soil properties. If effluent is continually ponded in ST-SAS, nitrification may be minimal. However, nitrification was predominant below ST-SAS which were not continuously ponded and below trenches which were rested. Concentrations >60 mg L^{-1} of NO_3^- may be present in water leaving the immediate trench bottom area below ST-SAS. The density of ST-SAS placement and loading rate should be determined in part by the area required to dilute NO_3^- concentrations to the U. S. Public Health Service standards of 10 mg L^{-1}.

2.0 Acknowledgments

The Virginia Department of Health provided financial support for this study; Mr. E. D. Simmons deserves special thanks for his insight and support. Mr. and Mrs. Freddie King, Mr. and Mrs. Tom James, and the Giles County School Board provided the research sites. Mr. Lynn Higginbottom and Mr. Jim Wheeler made us welcome at Giles County Eastern Elementary School, and Mr. Alvis Jamison allowed us to install our research site on part of the land he rented.

Lenoor Oosterhuis, Jenny Schwanke, Hubert Walker, Jim Harris, and Jodie Compton are acknowledged for their laboratory assistance. Perry Gayle, Joe Wade, Dr. Kevin Crosby, Dr. Tony Holthuizen, Michael Saluta, Kathy Molten, Danny Hatch, and Rick Joslin all contributed at various times with their field work. Dr. J. C. Baker is acknowledged for providing assistance with soil description and classification.

Mrs. Barbara Robinson provided hours of assistance in formatting this document. Mrs. Mary Holliman edited and prepared the camera ready copy. Special thanks go to both of these individuals.

3.0 Table of Contents

4.0 List of Tables

5.0 List of Plates

6.0 List of Illustrations

7.0 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 subsurface absorption systems (ST-SAS) or cesspools as of 1980 (Bureau of Census, 1983b). This number represents 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 (45 gal) of wastewater per capita per day (U.S. Environmental Protection Agency, 1980) is generated by $8.25X10^7$ people (Bureau of Census, 1983a, b), then $14X10^9$ L ($4X10^9$ gal) of wastewater are applied daily via OSWDS to USA soils.

In 1980, 34% of the 2 million homes in Virginia were not served by public sewer systems with some type of OSWDS representing the most common form of waste treatment and disposal (Bureau of Census, 1983b). Sewage from 10% of the homes in urban areas (121,000) and 75% of rural homes (497,000) was disposed on-site. A rural home was defined as being in a town of <2500 people or in an unincorporated area (Bureau of Census, 1983b).

New regulations, promulgated by the Virginia State Board of Health during 1980 and 1981 (Virginia State Board of Health, 1982), 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} (60 to 120 min $inch^{-1}$) 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 of Virginia as well as other parts of the United States. A research project was undertaken in 1982 to evaluate performance of prototype ST-SAS dosed with LPD over a spectrum of effluent flux densities (trench bottom area basis) which ranged from 0.4 to 3.6 cm d^{-1} (0.1 to 0.9 gal d^{-1}).

7.1 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 geometry (U.S. Environmental Protection Agency, 1977). In addition, the velocity of water transmission is a function of the hydraulic gradient or driving force of the system. The primary components of the 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 one dimensional flow

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

where K_{sat} is the saturated conductivity and 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 and slimes and of polysaccharides produced by bacteria may be more important (Jones and Taylor, 1964; Mitchell and Nevo, 1964; Kristiansen, 1981a). Kristiansen (1981a) concluded that quantitatively, polysaccharides 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 decreasing ψ_{sc}. The resulting infiltration rate is an equilibrium between q_c and the subcrustal flux determined by the dH/dZ and by the unsaturated conductivity function of the underlying soil.

In fine-textured, well-structured soils, most of the saturated flow occurs through interpedal voids and cracks. Under initial conditions of both saturation and unsaturation, tracer experiments have confirmed 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} (0.25 gal 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} (0.25 gal 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} (1.25 gal 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.

7.2 Fate of N in Soils Receiving Septic Tank Effluent

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), resulting in both increased eutrophication of water bodies and potential health hazards. 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 Shaefer, 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, 1981b).

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, 1981b). 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 denitrification 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 denitrification (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 applied N 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 grass roots present in the soil, with their exudates and accompanying microbial activity, are 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 leaching of most of the 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 that nitrification therefore 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.

7.3 Research Objectives

The objectives of this study were to

1. Test the hypothesis that clayey, well-drained soils are suitable for ST-SAS if LPD of effluent is used.

2. Determine approximate loading rates for soils with different grade, size, and type of structure, and depths to restrictive layers.

3. Determine the extent of nitrification in clayey limestone-derived soils below ST-SAS in which effluent was (a) ponded and (b) unponded.

This report 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. The relations between soil morphological properties, effluent ponding, pressure heads, and distribution of NO_3^--N and NH_4^+-N around prototype ST-SAS with simulated LPD of effluent are examined.

8.0 MATERIALS AND METHODS

The three sites chosen (Fig. 1) for installation of prototype LPD systems 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.

8.1 Research Site Descriptions

8.1.1 Site 1

Site 1, installed in the summer of 1982, was located in the 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 that 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, which was 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 1, was truncated over part of the site by grading during subdivision construction.

8.1.2 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. The experimental site was positioned 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 2 and 3. All of the A and some of the B horizon had been removed from most of the site. Unit 1 (Table 2) consists of a soil developed in a thin alluvial cap over residuum from interbedded shale and limestone. Unit 2 (Table 3) lacks the alluvial cap. The site is surrounded by karst to-

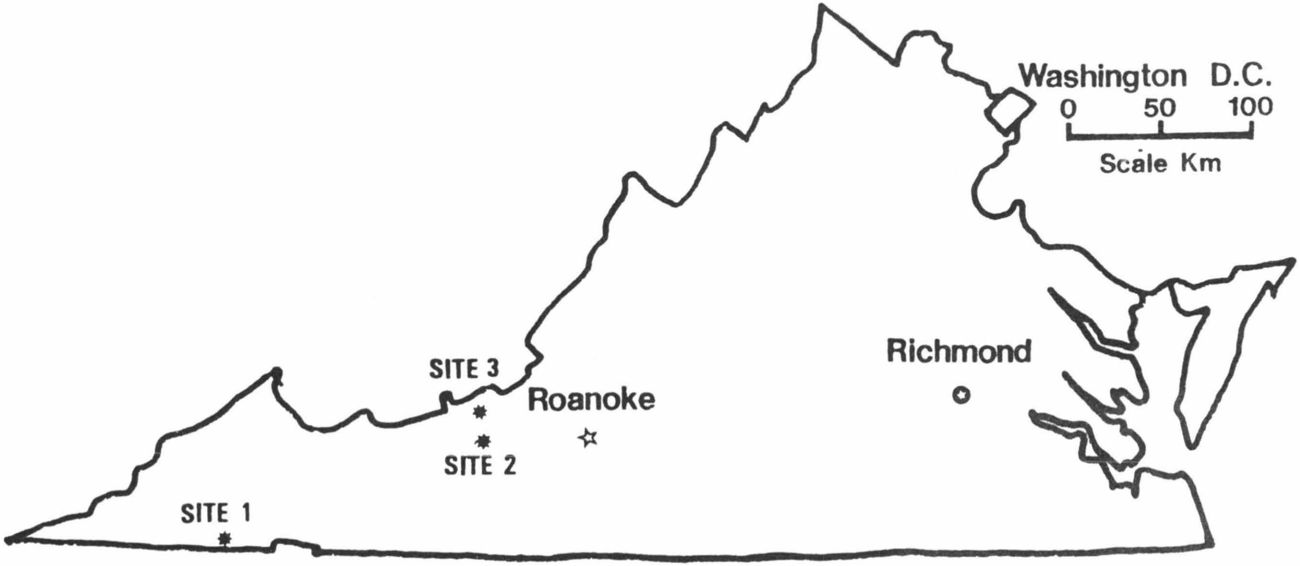


Figure 1. Location of experimental sites in Virginia.

Table 1. 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 boundary.
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 appeared 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.

pography and was chosen because it contains soils developed in limestone residuum considered to be suitable for a ST-SAS.

8.1.3 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, located on a 10% slope, was installed in a variant of the Carbo (very fine, mixed, mesic Typic Hapludalf) series (Table 4) developed in limestone residuum with less than 2 m depth to bedrock. 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 4).

8.2 Soil Physical and Chemical Properties

The chemical and physical properties of the soils are reported in Table 5. Cations were extracted with the ammonium acetate procedure (Chapman, 1965) and exchangable acidity determined with the $BaCl_2$ triethanol amine technique (Peech, 1965). The pipette procedure (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 6). Soil moisture retention characteristics are included in appendices.

8.3 Effluent Characteristics

Effluent samples were collected regularly while the prototype ST-SAS were being dosed. Effluent characteristics (Table 7) 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 lower amount 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., 1973a). 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.

Table 2. Profile description for Lowell silt loam (variant), Site 2, Unit 1.

The unit is 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 3. Profile description for Lowell silt loam (variant), Site 2, Unit 2.

The unit is 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.

8.4 Design of Prototype ST-SAS Trenches

Trenches 4.5 m long by 0.6 m wide were excavated to a 0.75 to 0.8 m depth at each site. Trench dividers made of 1 mm thick steel were driven vertically into the trench bottom 1.5 m from each end to maintain good dis-

Table 4. Profile description for Carbo loam (variant), Site 3.

The site is located on a sideslope at the Eastern 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 relatively silty surface layer 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 5. **Representative chemical and physical properties of soils studied.**

Horizon	Depth	pH	CEC	base sat	sand	silt	clay
	(cm)	(H_2O)	cmol(+)kg^{-1}	percent			
			Site 1 - Trench 2				
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)				
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)				
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)				
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				
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 6. Saturated conductivity values for soils determined at two depths with the double tube permeameter technique.

	Depth = 40cm				Depth = 75cm			
	$\bar{x}$[1]	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

[1] Arithmetic means ($\bar{x}$), standard deviations (SD), and sample number (n) are reported. In addition log-normalized means ($\bar{x}_{ln}$) were calculated from the equation $\bar{x}_{ln} = e^{(\bar{x}_{ln(k)} + 0.5s^2_{ln(k)})}$ where $\bar{x}_{ln}(k)$ and $s_{ln}(k)^2$ are the sample mean and variance of natural logs of the K sat values.

tribution (Figures 2 and 3). If effluent ponded above the divider height (50 cm at 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 (Figure 4).

Each section of trench was dosed independently to optimize distribution, except for 1 to 2 trenches at each site, which were installed with a 10 cm sand layer below the gravel envelope (Figure 4), and trenches without dividers, which were dosed 12 times d^{-1} (Figure 4) instead of 1 time d^{-1} to simulate the trickling nature of gravity distribution. These trenches will not be considered separately, as performance was similar to the LPD simulations. Figures 5, 6, and 7 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 8. Prototype ST-SAS were dosed 12 times d^{-1} (Table 8).

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

Table 7. Arithmetic means (x), standard deviations (SD), and sample sizes (n) of effluent characteristics.

	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

existing pumping chamber was used at Site 3. A timer-driven effluent pump filled tanks constructed from epoxy-painted plywood one time d^{-1} (Figure 8). After the tank was full but before the pump was 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 a solid state timer and the tanks drained. Each tank also contained a 40w 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

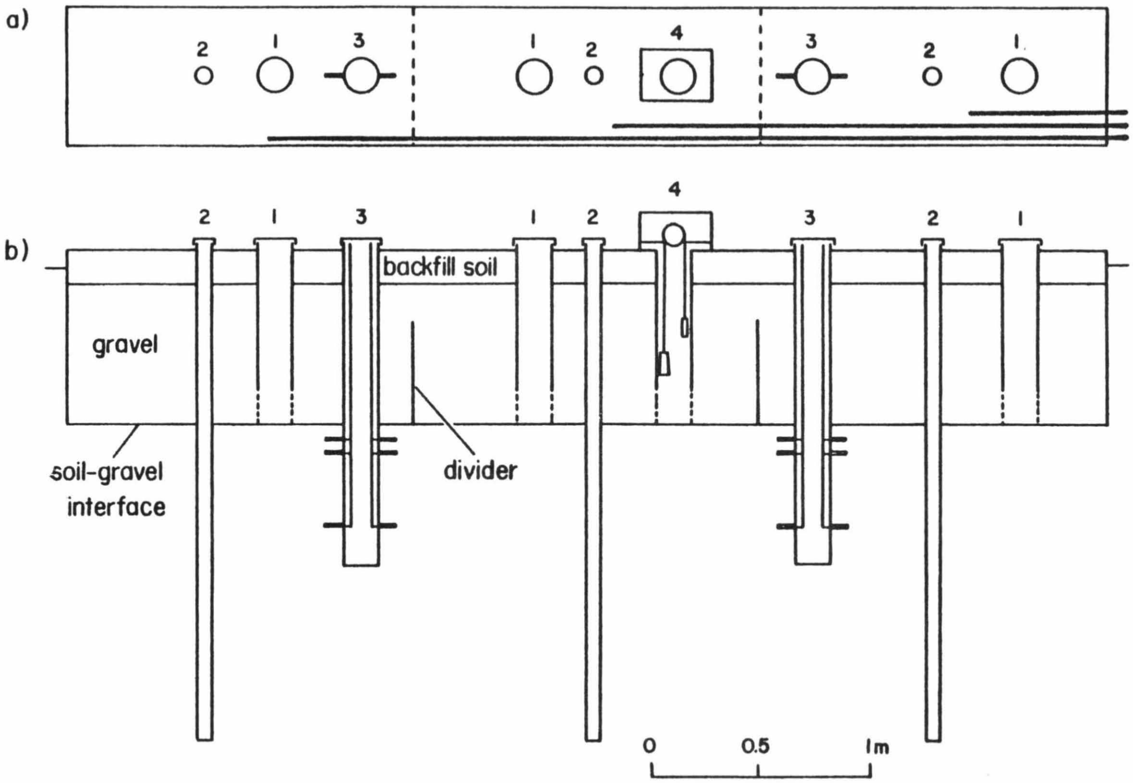


Figure 2. **Top (a) and side (b) views of monitoring equipment for prototype ST-SAS simulating LPD:** Key: 1 - soil sampling access well; 2 - neutron moisture meter access tube; 3 - tensiometer well; 4 - stage recorder.

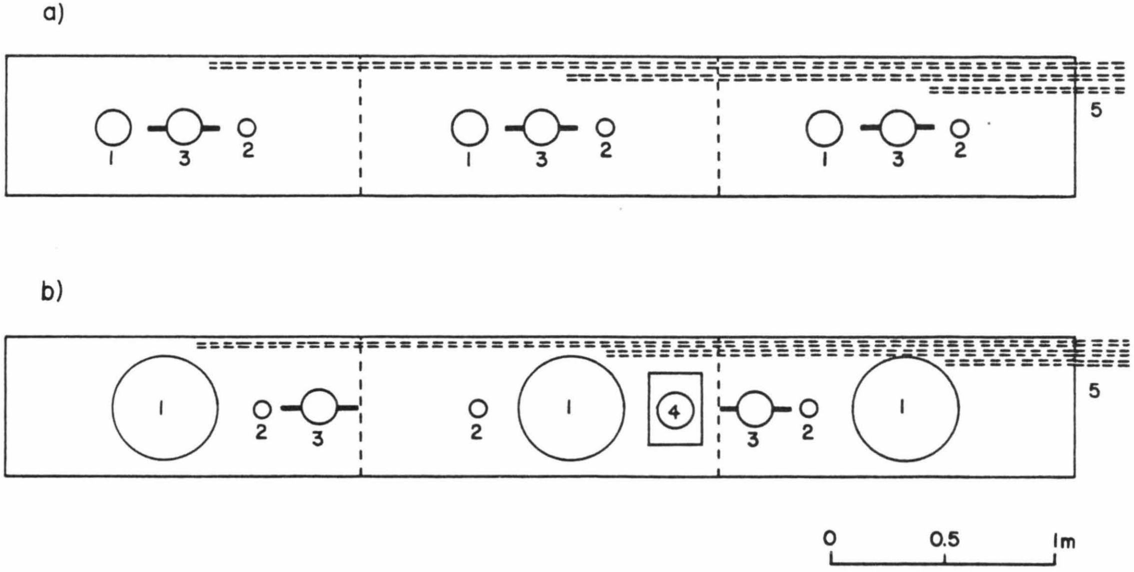


Figure 3. **Top views of prototype ST-SAS simulating LPD at Site 2 (a) and Site 3 (b):** Key: 1 - soil sampling access well; 2 - neutron moisture meter access tube; 3 - tensiometer well; 4 - stage recorder; 5 - effluent distribution line.

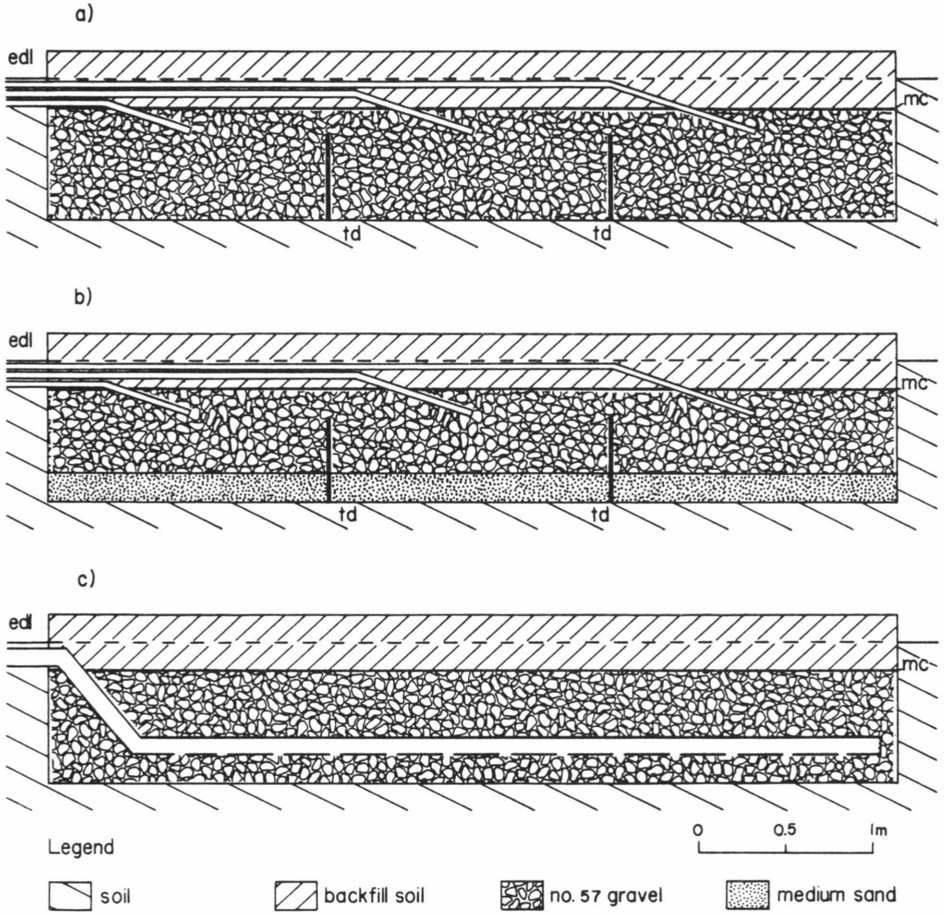


Figure 4. Side view of three designs used for prototype ST-SAS trenches: (a) side view of LPD-SAS with 60 cm gravel fill; (b) side view of LPD-SAS with 10 cm of sand overlain by 50 cm of gravel fill; (c) side view of simulated gravity SAS installed at Sites 1 and 2. Key: edl - effluent distribution line; mc - 1 micron woven filtration cloth to prevent migration of soil fine fraction into gravel envelope; td - trench divider.

Table 8. 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[3]	1.8	1.8	1.8[4]	3.6	0.4
ponding depth (cm)						
minimum	0	0	40	0	35	0
maximum	0	17	50	12	50	15
			Site 2 - Unit 1			
q (cm day^{-1})	3.6[3]	0.8[3]	0.8	3.6	3.6	
ponding depth (cm)						
minimum	28	0	0	25	15	
maximum	40	1	0	35	21	
			Site 2 - Unit 2			
q (cm day^{-1})	3.6[4]	3.6[3]	0.8[3]	3.6	3.6	0.8
ponding depth (cm)						
minimum	0	0	0	0	0	0
maximum	0	0	0	0	0	0
			Site 3			
q (cm day^{-1})	3.6[4]	0.8[4]	0.8	1.8	1.8	3.6
ponding depth (cm)						
minimum	1	0	0	0	0	7
maximum	17	0	0	0	0	18

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

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

[3] The daily effluent dose was split into 12 small doses d^{-1}.

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

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 to prevent 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. Photographs (Plates 1,2,3, and 6) of trench cross sections and soil cores were taken during the fall of 1985. The photographs (Plates 4 and 5) of soil profiles at Sites 2 and 3 were taken during site installation and characterization.

8.5 Soil Moisture Tensions

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 (Figure 9). The tensiometers were 7.5 cm long and 0.6 cm in diameter and were 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, we installed duplicate rows of cup tensiometers at Site 1 at distances of 0.3 and 0.9 m from trenches 2 and 3 during August, 1985 (Figure 5) and at Sites 2 and 3 in January 1986 and October 1985, respectively (Figures 6 and 7, 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, New Mexico), 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

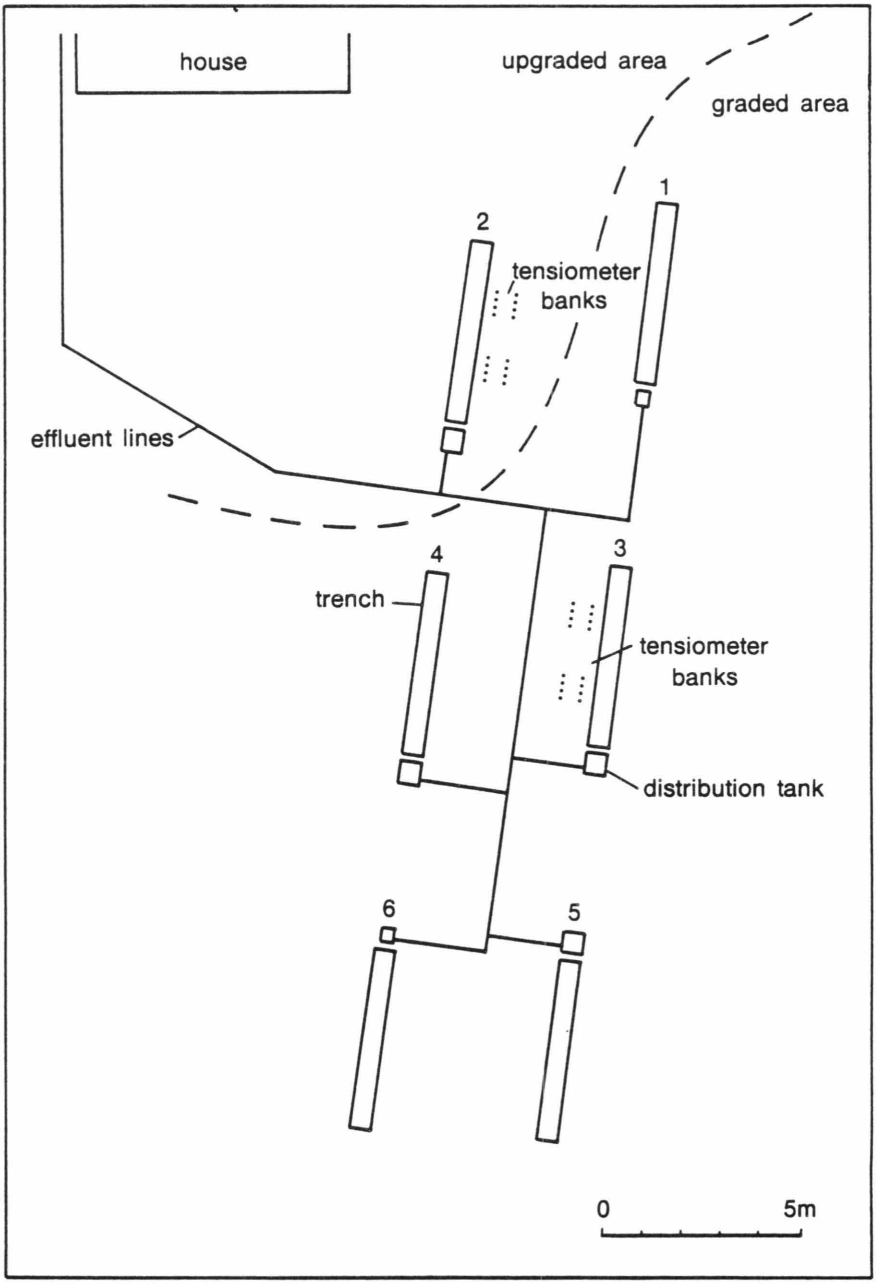


Figure 5. **Layout of Site 1:** The dots represent tensiometers placed outside the trenches.

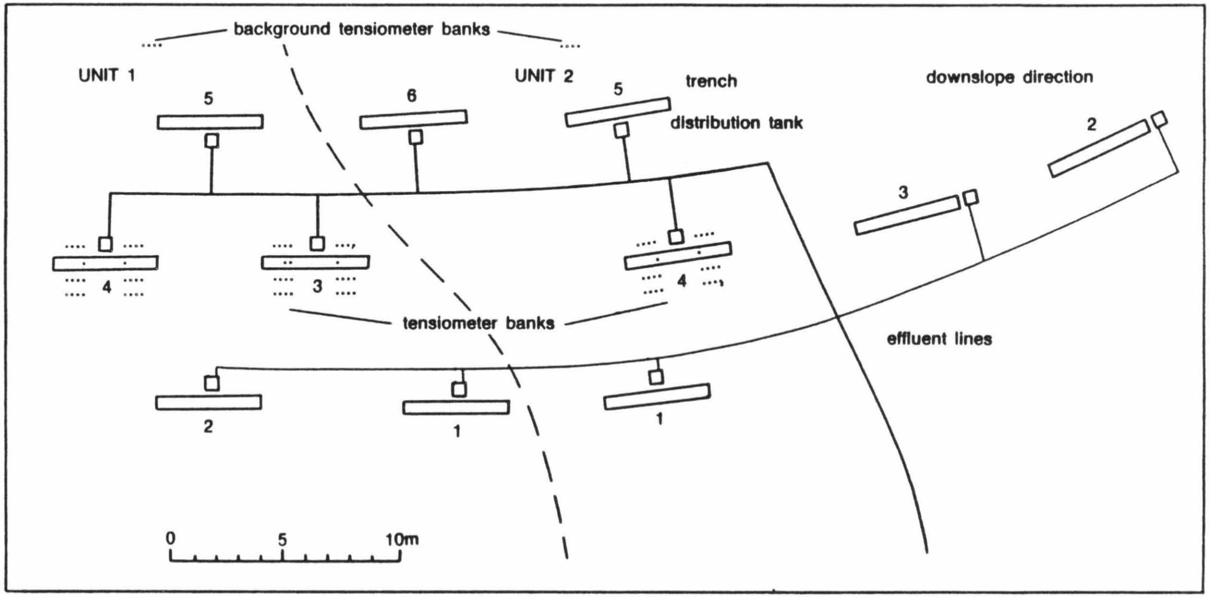


Figure 6. **Layout of Site 2:** Note the dashed line that separates Unit 1 from Unit 2. Dots represent tensiometers.

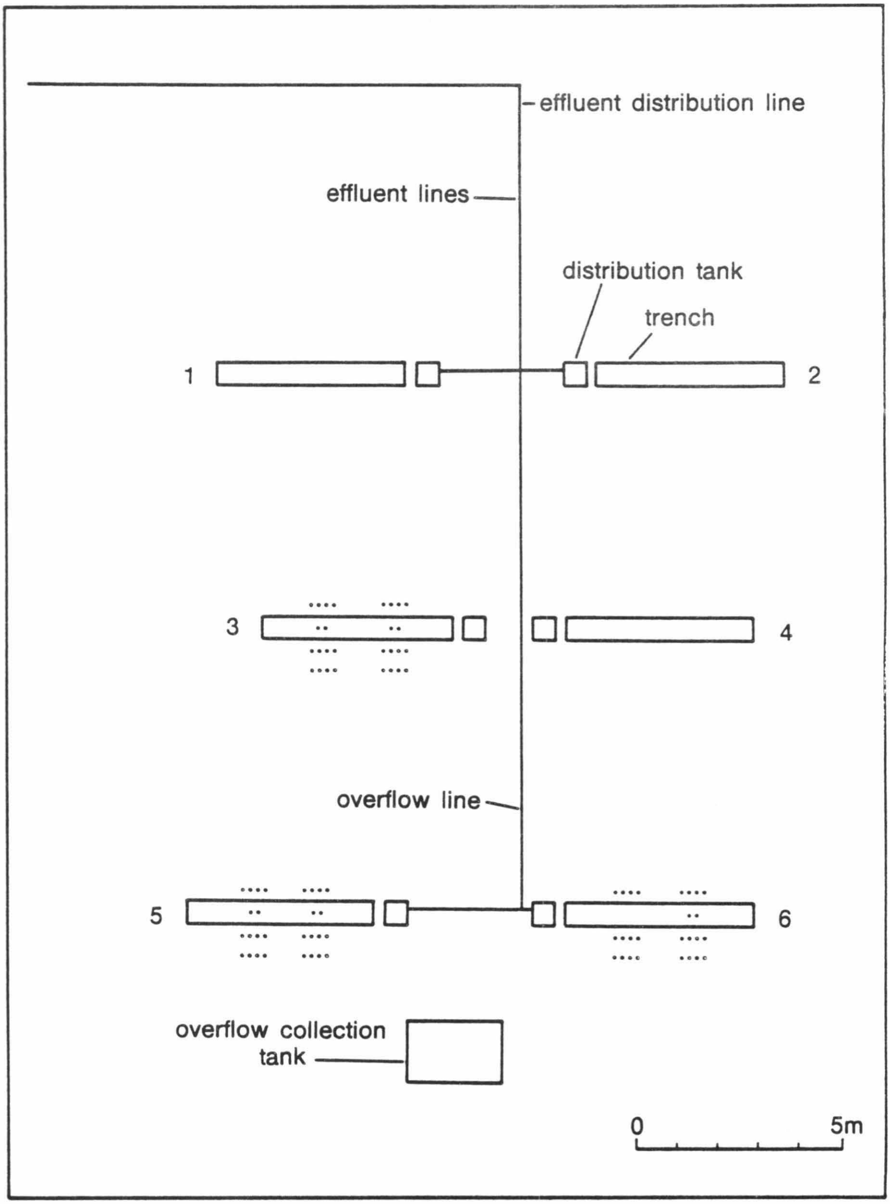


Figure 7. **Layout of Site 3:** The dots represent tensiometers outside the trenches.

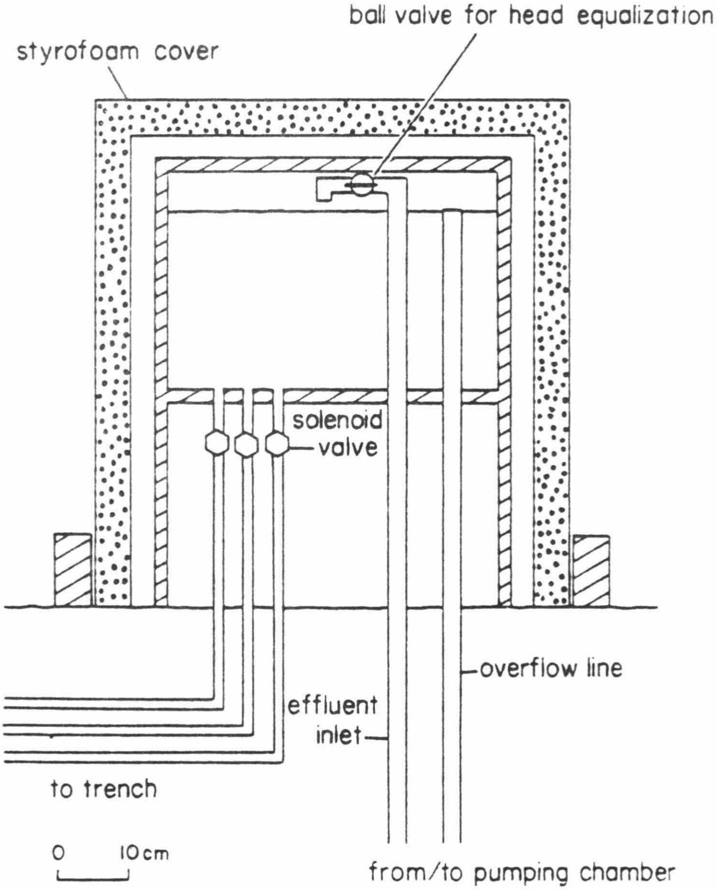


Figure 8. Effluent distribution tank for dosing prototype drainfields.

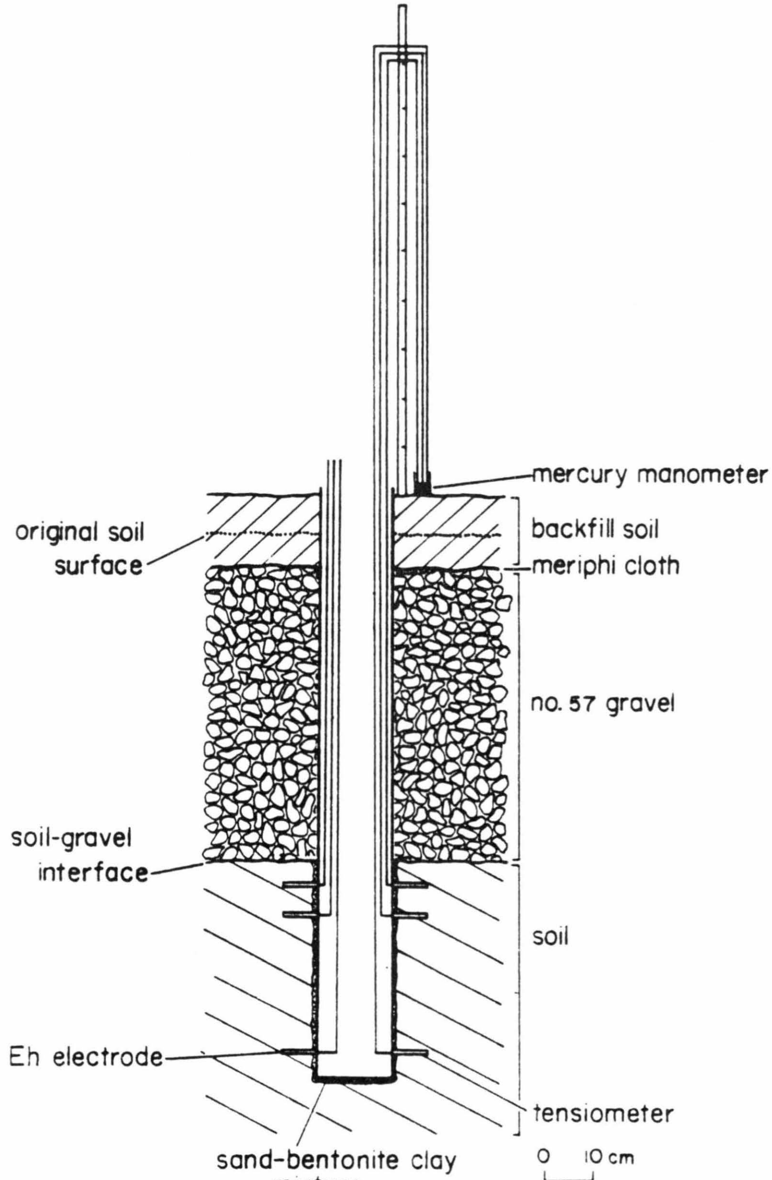


Figure 9. Side view of access well containing pencil tensiometers and Eh electrodes.

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™ reading 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 period. Pressure heads at Sites 2 and 3 were monitored eight and five times, respectively, from January to April, 1986, and means were determined. During this time pressure heads fluctuated substantially in response to several cm of precipitation during March, 1986.

8.6 Nitrogen Distribution

Soil cores for N and Cl^- analyses were collected with a Giddings soil coring machine. Data for Site 3 were obtained from the cores removed when the tensiometers were installed while data from Site 1 were 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 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 540 µm 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 and shaking for 1 h, and extract concentration was determined with a specific Cl^- ion electrode (Selmer-Olsen and Oien, 1973). Comparisons of data determined with an Aminco-Cotlove Cl^- autotitrator indicated close agreement between the two techniques. Data not reported within the main body of the report are included in the appendices.

9.0 RESULTS

9.1 Relationships between Soil Properties and Effluent Ponding

9.1.1 Site 1

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 thick 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 40 cm in all of the trenches except for trenches 2 and 4 where the contact zone was approximately 70 and 60 cm deep, respectively.

The effects of the varying depth to a restrictive layer is reflected in the ponding history of the final year of operation summarized in Table 8. Note that trenches 2, 3, and 4 are all dosed at 1.8 cm d^{-1}. Trenches 2 and 4 were underlain by 10 to 15 cm of weakly structured BC horizon, and the sidewall area was in well structured Bt horizons. These trenches were characterized by ponding when precipitation exceeded evapotranspiration but during the first 2 years of operation did not pond during dry months (Figure 10).

Plate 1, a cross section of trench 2 and an ungraded portion of the soil profile, corresponds to the profile description in Table 1. The screwdrivers mark major horizon boundaries. Note that cracks and root channels in the BC horizon were apparently carrying much of the effluent horizontaly and vertically through the C horizon (Plate 1). These cracks tended to have reduced colors and some indication of organic matter accumulation. Tree roots visible in Plate 1 were from nearby silver maple (*Acer saccharinum*) and white pine (*Pinus strobus*) trees. Roots were prolific in the Bt, cracks in the BC and C horizons, and in the gravel envelop. The bottom of the trench extended about midway through the BC horizon (Plate 1). The ponding history in trench 4 was comparable to trench 3 (Table 8), indicating that the sand had

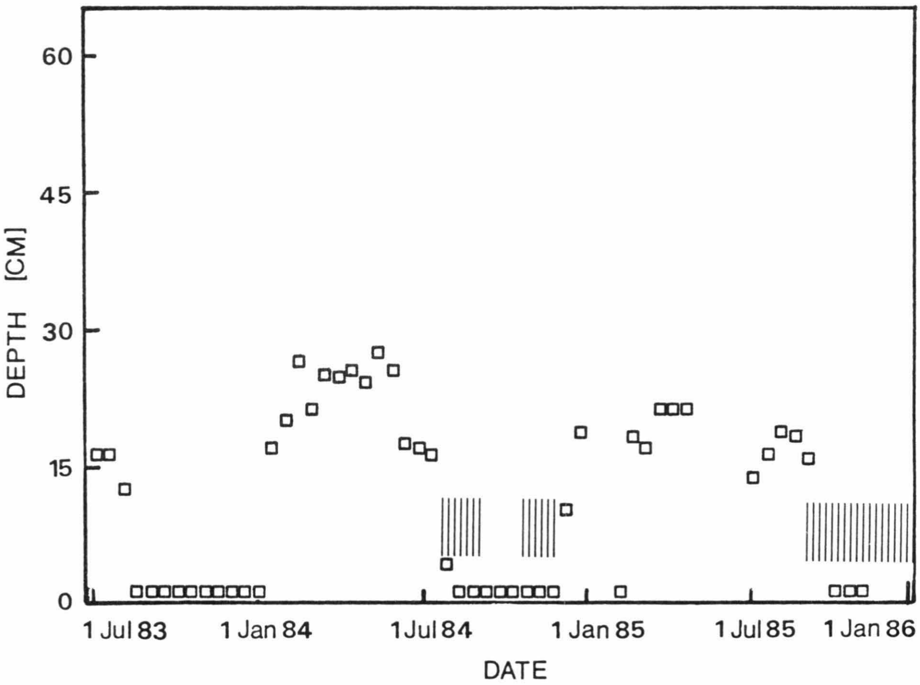


Figure 10. Temporal change in ponding depth following dosing for trench 2 at Site 1: periods when the system did not get dosed with STE are noted by vertical bars just above the horizontal axis.

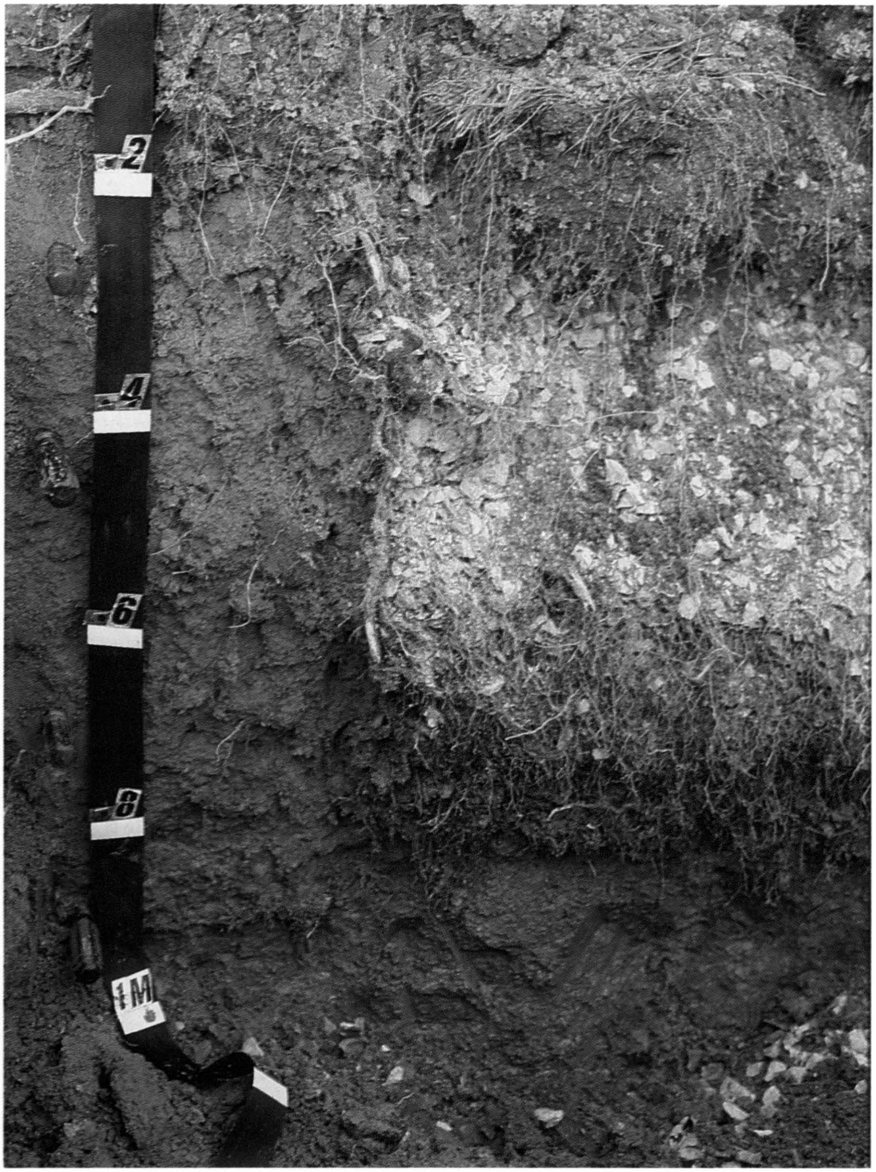


Plate 1. Cross section of trench 2 at Site 1 illustrating horizonation described in Table 2 of the variant of a Frederick (clayey, mixed, mesic, Typic Paleudult) soil. Note the accumulation of organic matter on the lower 15 cm of the gravel envelope and the abundance of roots. Wastewater appears to be flowing primarily through both horizontal and vertical cracks through the BC and C horizons.

no major impact on ponding levels at this loading rate. However much organic matter appeared to have coated the sand to the point that it was black, perhaps due to the much higher specific surface area of the sand layer than the overlying gravel layer.

Contrasting in both morphology and performance was trench 3. Figure 11 indicates a gradually increasing ponding depth with time which did not appear to have been affected by 3 months of resting in the summer and fall of 1984 caused by mechanical failure of solenoid valves. Plate 2 illustrates that accumulation of a biological mat 30 cm (12 inches) horizontally from the trench has defined the soil structure and horizonation. Note that the trench bottom is at approximately 80 cm (32 inches), and thus the greying of interpedal voids corresponds to the depth of ponding in the adjacent trench.

Ponding recorded in trench 6 appeared to be in direct response to major rainfall events and periods of high precipitation (Figure 12). Because the loading rate was low (0.4 cm d^{-1}), this trench essentially represents background conditions. Indeed evaluation of Plate 3 indicates no evidence of iron reduction or formation of a biological mat even though this trench was ponded substantial portions of the year (Figure 12).

9.1.2 Site 2

As indicated in Figure 6 and Tables 2 and 3, 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 limestone residuum that contains a large fraction of weathered shale. While the shale is fractured and interbedded with structured silty and clayey material, it apparently does not contain enough pore space to adequately transmit the 3.6 cm d^{-1} load.

Although trench 4 in Unit 1 ponded in 1983, a stage recorder was not installed until July 1984. Data in Figure 13 on page 35 indicate that resting of the system in the summer and fall of 1984 had some benefit in the short term on the infiltration rate. However, the system ponded back to original levels by mid spring of 1985. Subsequent rests had little impact on the level of ponding. A similar ponding history was reflected for trench 1, Unit 1 except it was operated on a more continuous basis. The ponding depth in both trenches 1 and 5 increased gradually to the values in Table 8. No long term effects were noted following resting in either of these trenches as they both eventually ponded deeper than before any resting period once effluent dosing was resumed. 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 4 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 6 are

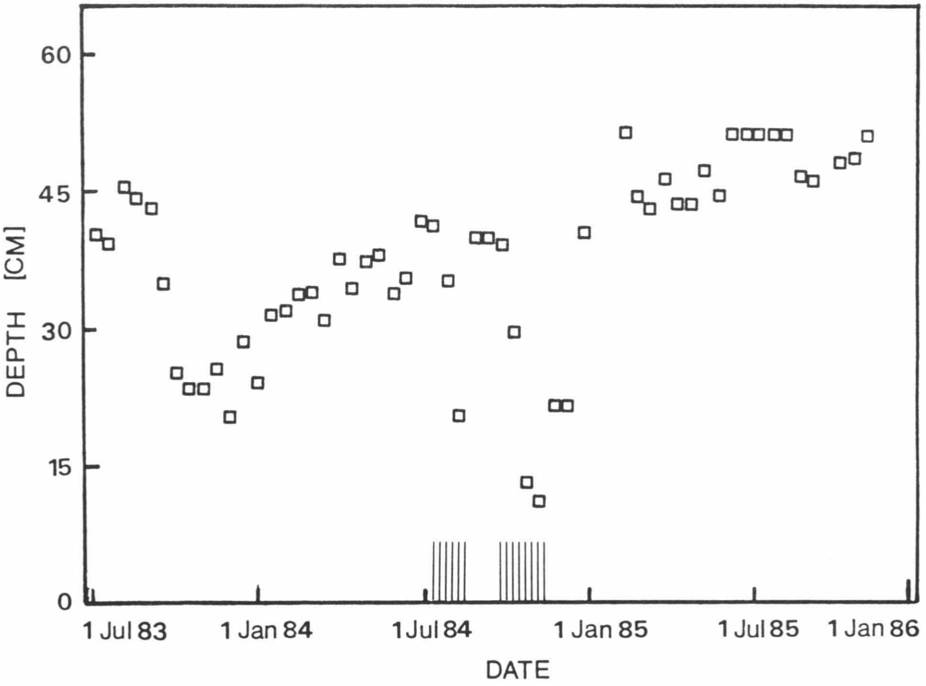


Figure 11. **Temporal changes in ponding depth following dosing** for trench 3 at Site 1: periods when the system did not get dosed with STE are noted by vertical bars just above the horizontal axis.

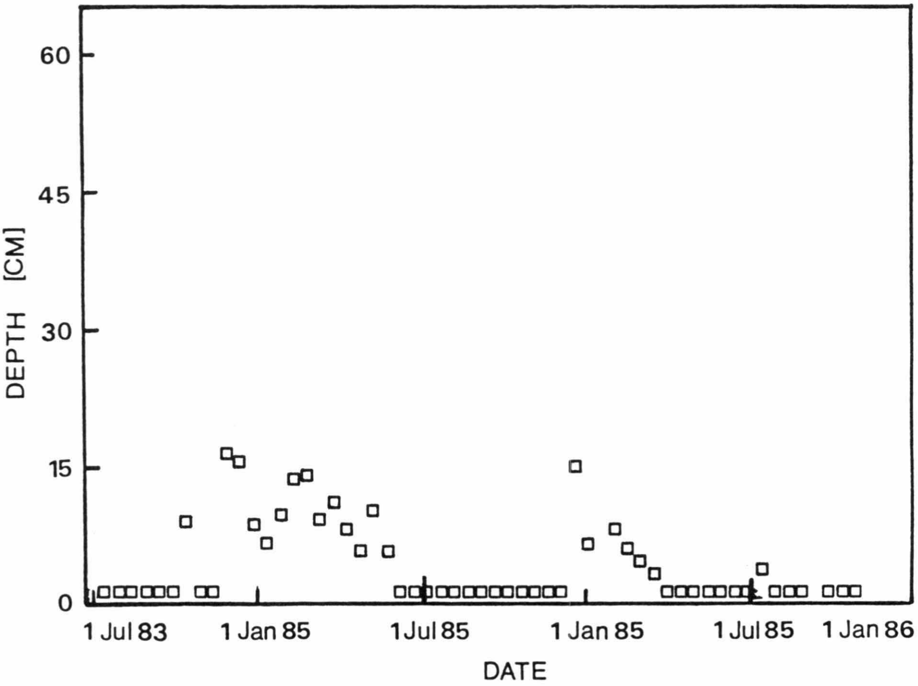


Figure 12. Temporal changes in ponding depth in trench 6 at Site 1.

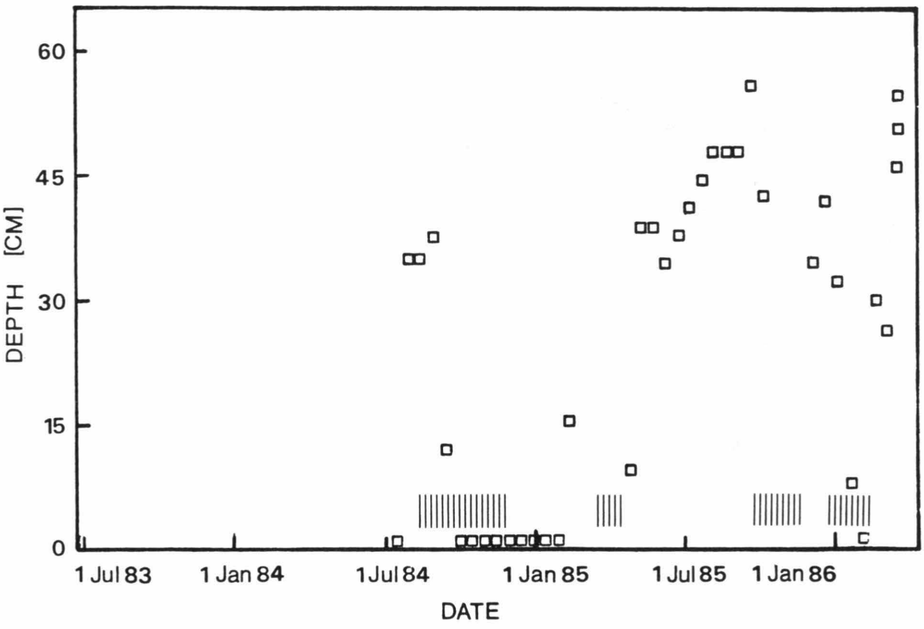


Figure 13. Temporal change in the ponding depth in trench 4, Unit 1, at Site 2: Areas near the horizontal axis shaded with vertical bars indicate time periods when the trench was not dosed with septic tank effluent.

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.

Plate 3. 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.

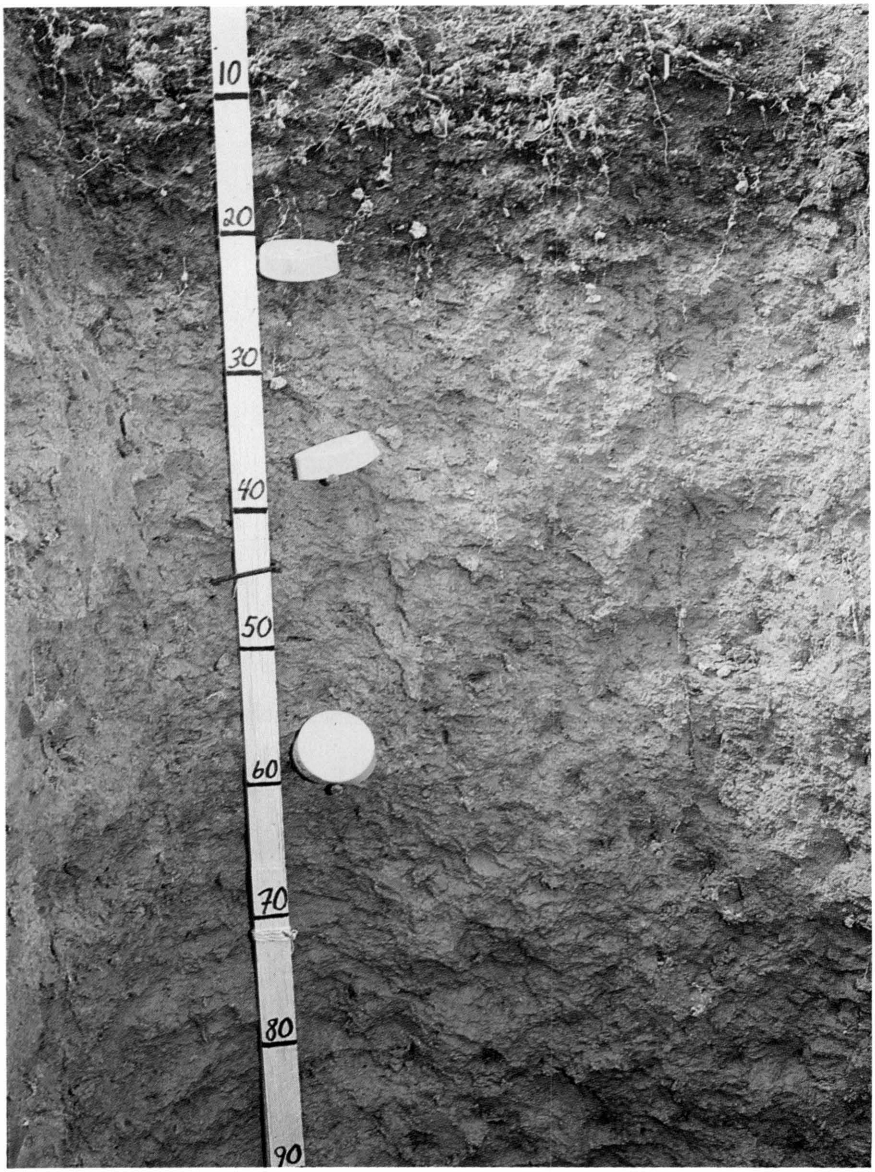


Plate 4. Soil profile of Unit 2, a variant of the Lowell (fine, mixed, mesic Typic Hapludalf) series. The pit was centrally located between trenches 1 and 3 of Unit 1 and trenches 1, 4, 5, and 6 of Unit 2. Yellow caps mark major horizons corresponding to the profile description in Table 2.

slower. There were not enough K_{sat} tests run in Unit 2 at the 40 cm depth to determine if 15 cm hr^{-1} is representative of the true mean. The rate at which effluent moves through this soil following dosing suggests 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. When the K_{sat} tests were being run, a 20 cm diameter channel was intersected at 75 cm depth 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.

9.1.3 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 4, Plate 5). 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 in trenches dosed at the 3.6 cm d^{-1} flux occurred within 1 year and was subsequently continuous (Figure 14). Ponding depths slowly increased with time in trench 6 (Figure 14). Although trench 1 had a 10 cm sand layer in the bottom, there was not a noticeable difference in performance between trenches 1 and 6. None of the trenches dosed at lower rates were continuously ponded during the study. About 1 cm of effluent, on part but not all the bottom of the central section of trench 5, was noted prior to dosing during at least two site visits during the winter of 1986. No ponding was noted in the rest of the trench, however, nor in trench 4; nor was the formation of a biological mat noted in the trenches dosed at < 2 cm d^{-1}. Plate 6 is a photograph of the top 10 cm of a core taken from the bottom of trench 6 after it was dosed for two years and ponded for about 1 year. Note the 1 cm thick mat which has developed at the interfacial zone of the trench (Plate 6) which was absent in the trenches dosed at the two lower rates. No performance difference has been noted between the trenches with or without sand layers at this site or at Sites 1 and 2.

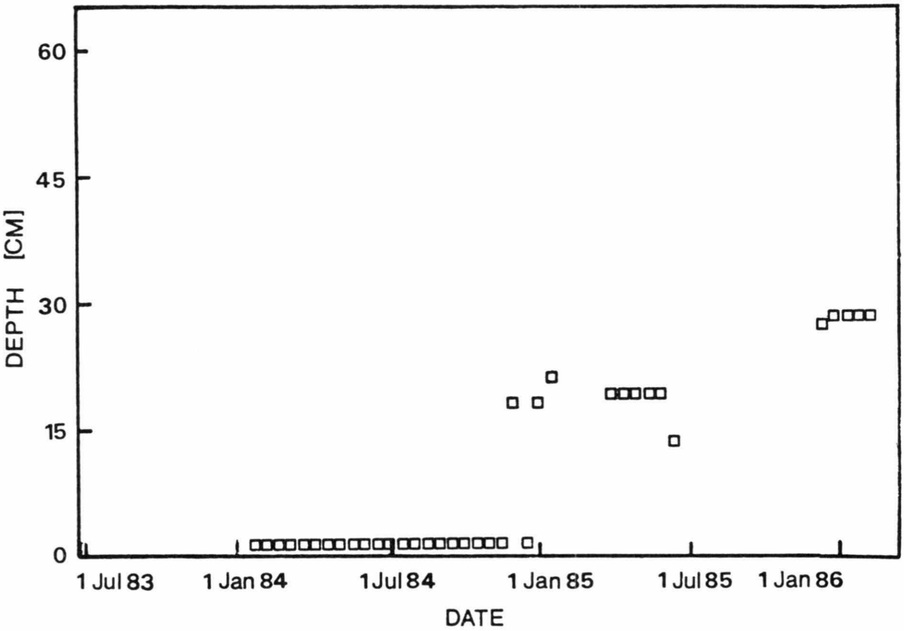


Figure 14. Temporal change in ponding depth in trench 6 at Site 3.

Plate 5. 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 the overflow collection tank noted in Figure 7. Note that the profile is shallower than described in Table 4. 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 6. 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.

9.2 Relations between Soil Moisture Tensions and ST-SAS Performance

9.2.1 Site 1

The depth of ponding illustrated in Figure 15 for trench 2 is representative of the period when the additional tensiometer banks were monitored (summer and fall of 1985) prior to system shutdown. During most of the year effluent was ponded to approximately 15 cm in this trench (Figure 9). 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 (Figure 15), indicating horizontal as well as vertical movement of effluent, but adjacent to the trench pressure heads increased with depth. Substantial variation in pressure heads in response to major rainfall events is reflected by the standard deviations reported in Figure 15.

Ponding depths in trench 3 ranged from 40 to 50 cm (Figure 16). 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. Average pressure heads are positive throughout most of the cross section illustrated in Figure 16.

9.2.2 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 (Figure 17) during winter and spring of 1986 were slightly negative immediately below the trench and decreased with both depth and horizontal distance.

The average ponding depth in trench 4, dosed at 3.6 cm d^{-1}, was approximately 45 cm during January to April, 1986 (Figure 18). 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 (Figure 18). They also increased with increasing depth at the 30 cm upslope distance.

9.2.3 Site 2 Unit 2

Ponding was never noted in trench 4. The almost uniform negative pressure heads around trench 4 of Unit 2 (Figure 19) 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

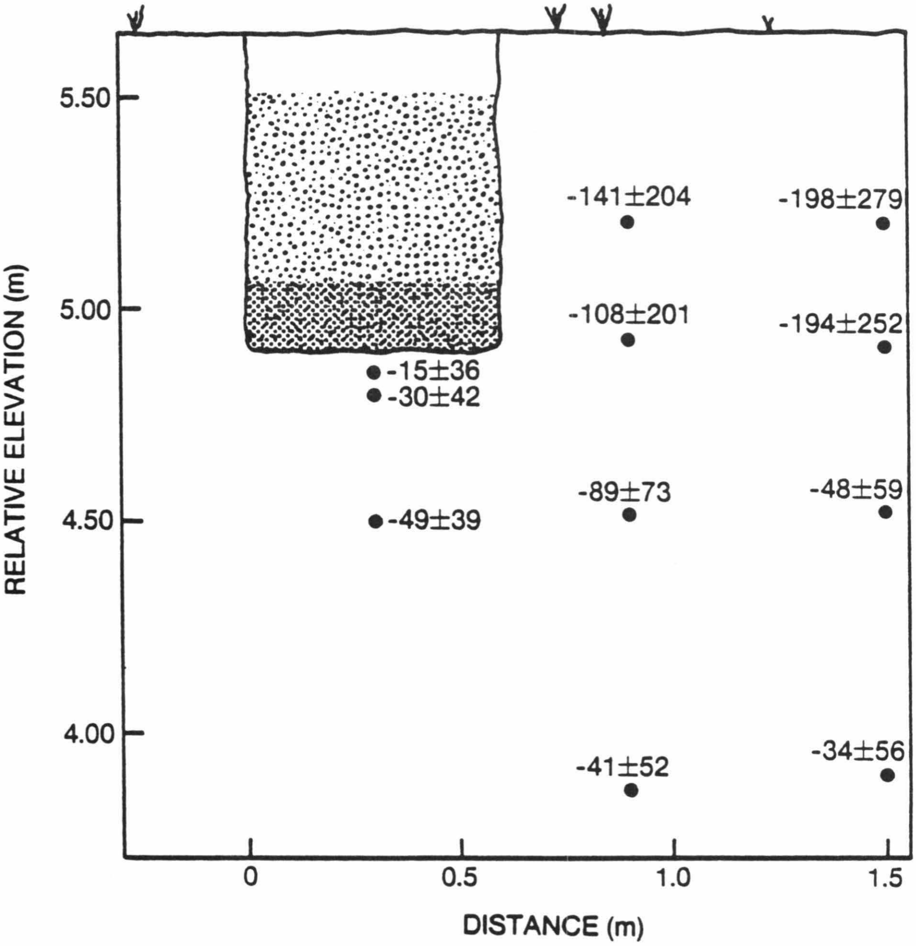


Figure 15. Cross section of trench 2 at Site 1 illustrating means and standard deviations of pressure potentials: points define tensiometer locations relative to the trench. The darker shaded area in the gravel envelope corresponds to the depth of ponding. Pressure units are cm of water.

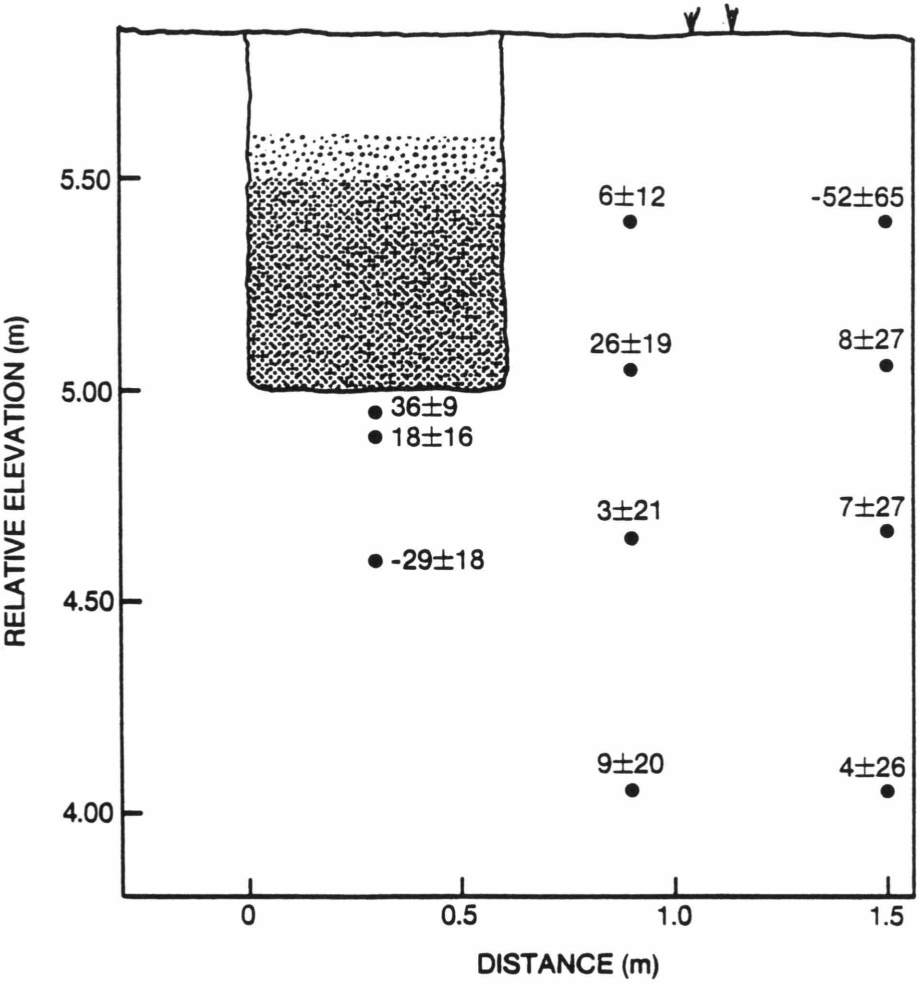


Figure 16. Cross section of trench 3 at Site 1 illustrating means and standard deviations of pressure potentials: points define tensiometer locations relative to the trench. The darker shaded area in the gravel envelope corresponds to the depth of ponding. Pressure units are cm of water.

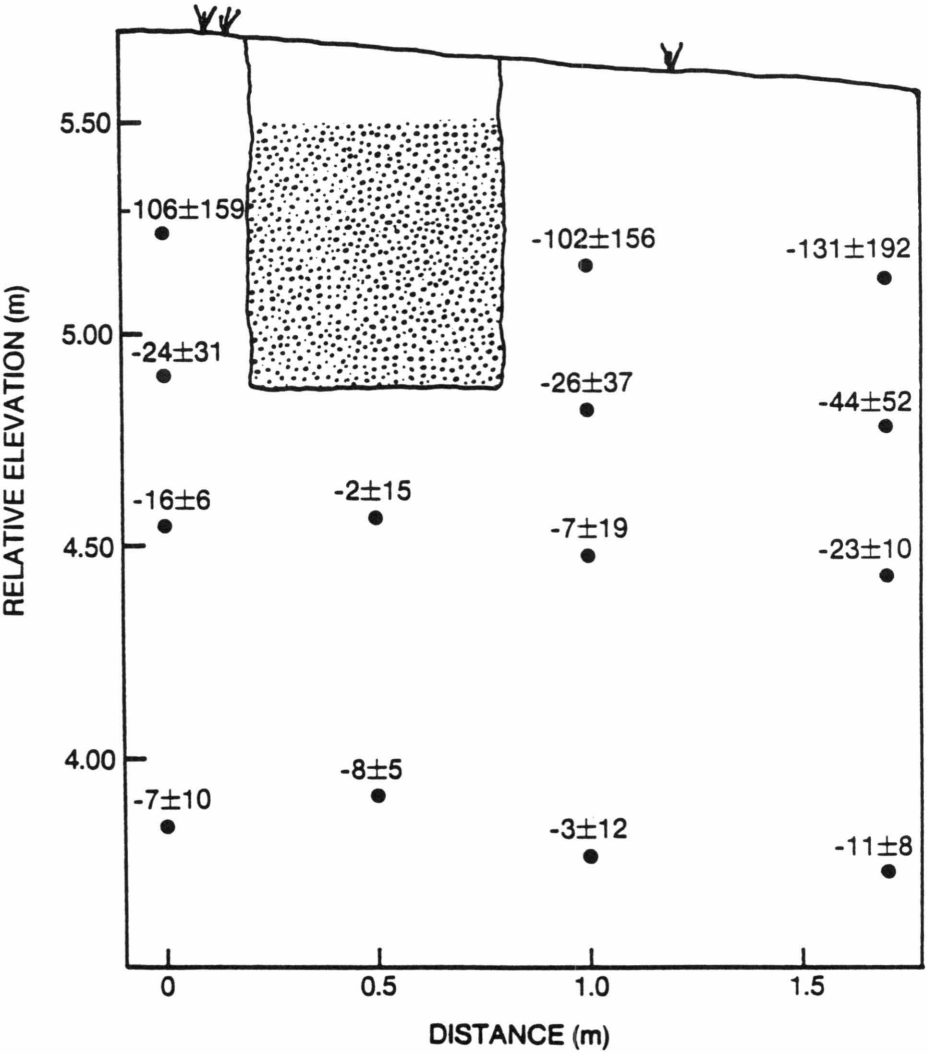


Figure 17. **Cross section of trench 3, Unit 1 at Site 2 illustrating means and standard deviations of pressure potentials:** points define tensiometer locations relative to the trench. The absence of a darker shaded area in the gravel envelope indicates that continuous ponding of effluent did not occur. Pressure units are cm of water.

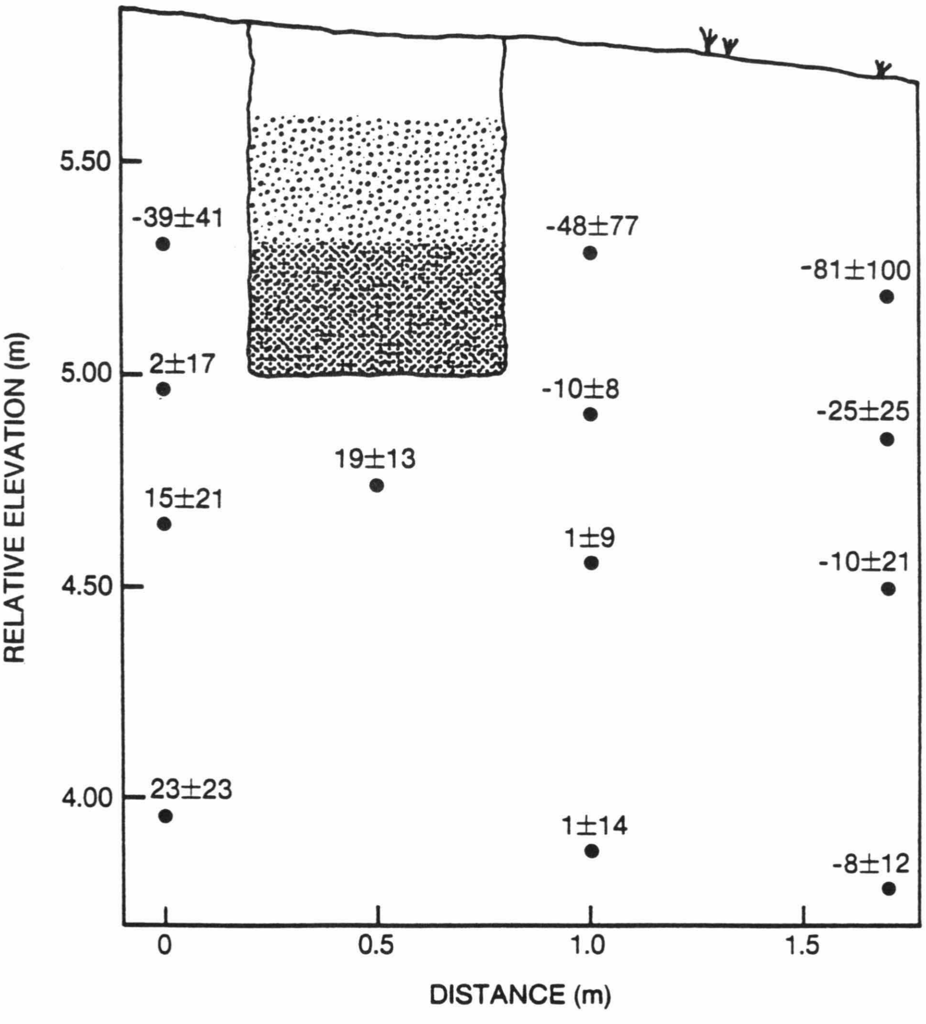


Figure 18. Cross section of trench 4, Unit 1 at Site 2 illustrating means and standard deviations of pressure potentials: points define tensiometer locations relative to the trench. The darker shaded area in the gravel envelope corresponds to the depth of ponding. Pressure units are cm of water.

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.

9.2.4 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 (Figure 20) 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 Figure 20 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 (Figure 21) 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.

Trench 6, dosed at 1.8 cm d^{-1}, was ponded to about 15 cm (Figure 22). 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 in pressure head with depth are almost a unit hydraulic gradient change with depth. 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 further indicating presence of a restrictive layer.

9.3 Nitrogen Distribution Below Prototype ST-SAS

9.3.1 Site 1

Soil NH_4^+-N concentrations (Figure 23) 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

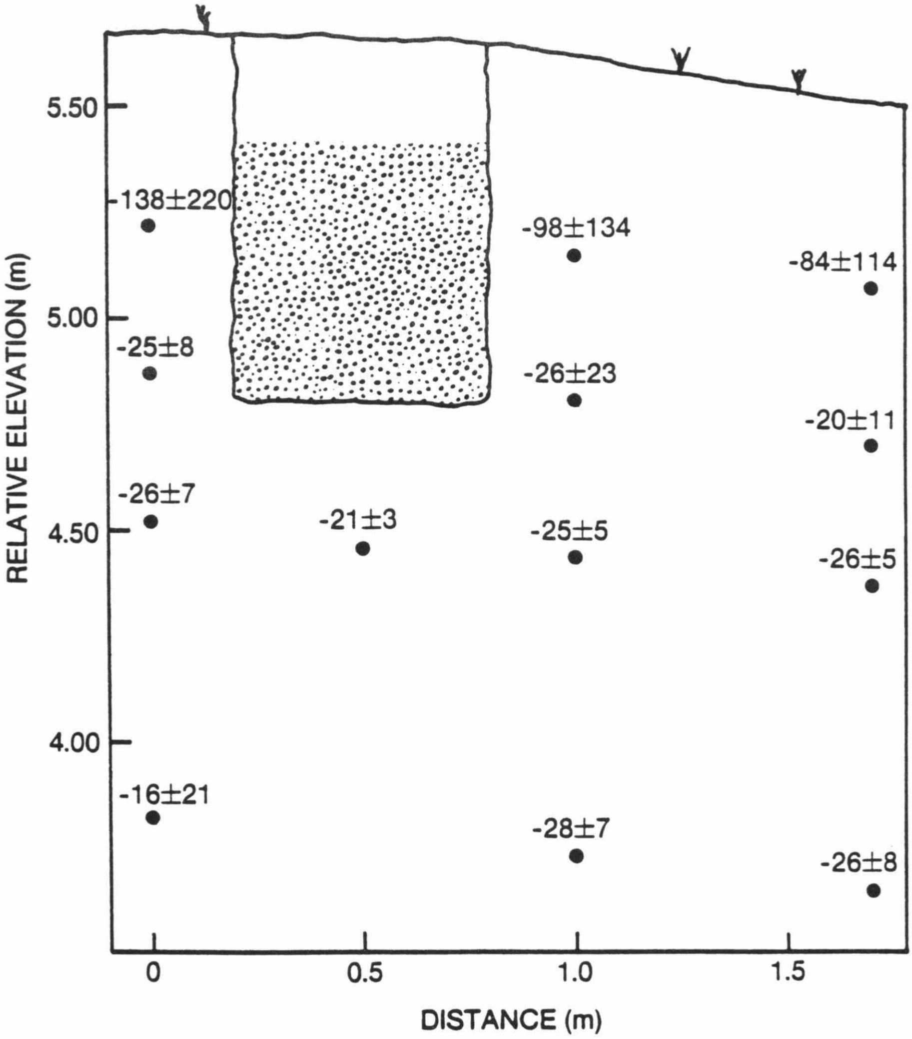


Figure 19. Cross section of trench 4, Unit 2 at Site 2 illustrating means and standard deviations of pressure potentials: points define tensiometer locations relative to the trench. No ponding in the gravel envelope has been noted. Pressure units are cm of water.

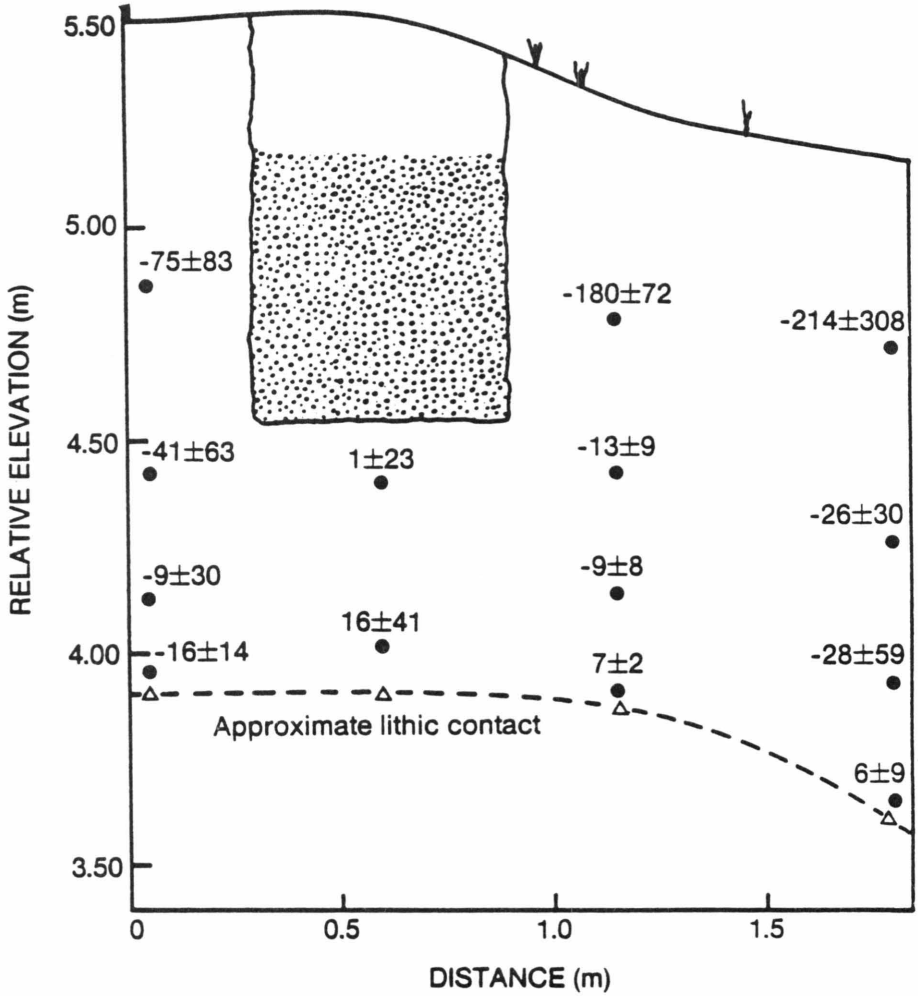


Figure 20. **Cross section of trench 3 at Site 3 illustrating means and standard deviations of pressure potentials:** points define tensiometer locations relative to the trench. No ponding in the gravel envelope has been noted. The triangles note points where limestone was encountered when installing the tensiometers. Pinnacles of limestone may be closer to the trench bottom under parts of the trench. Pressure units are cm of water.

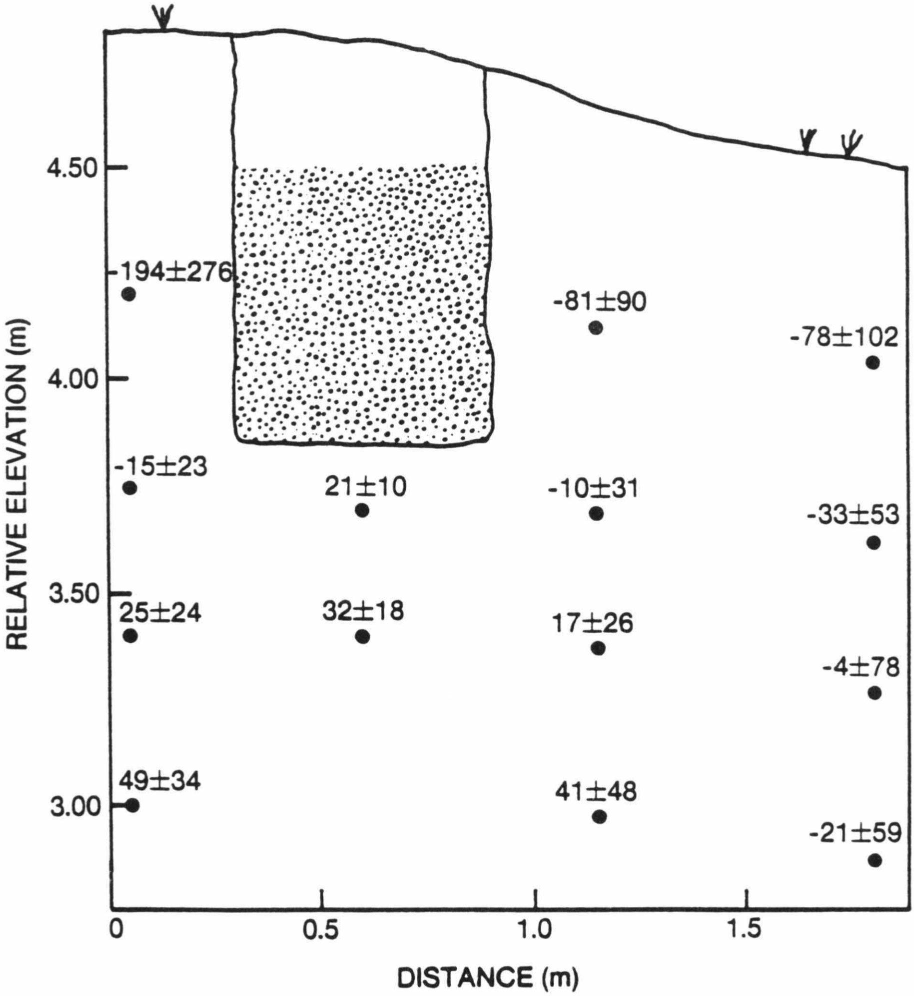


Figure 21. Cross section of trench 5 at Site 3 illustrating means and standard deviations of pressure potentials: points define tensiometer locations relative to the trench. No ponding in the gravel envelope across the entire trench bottom has been noted. Pressure units are cm of water.

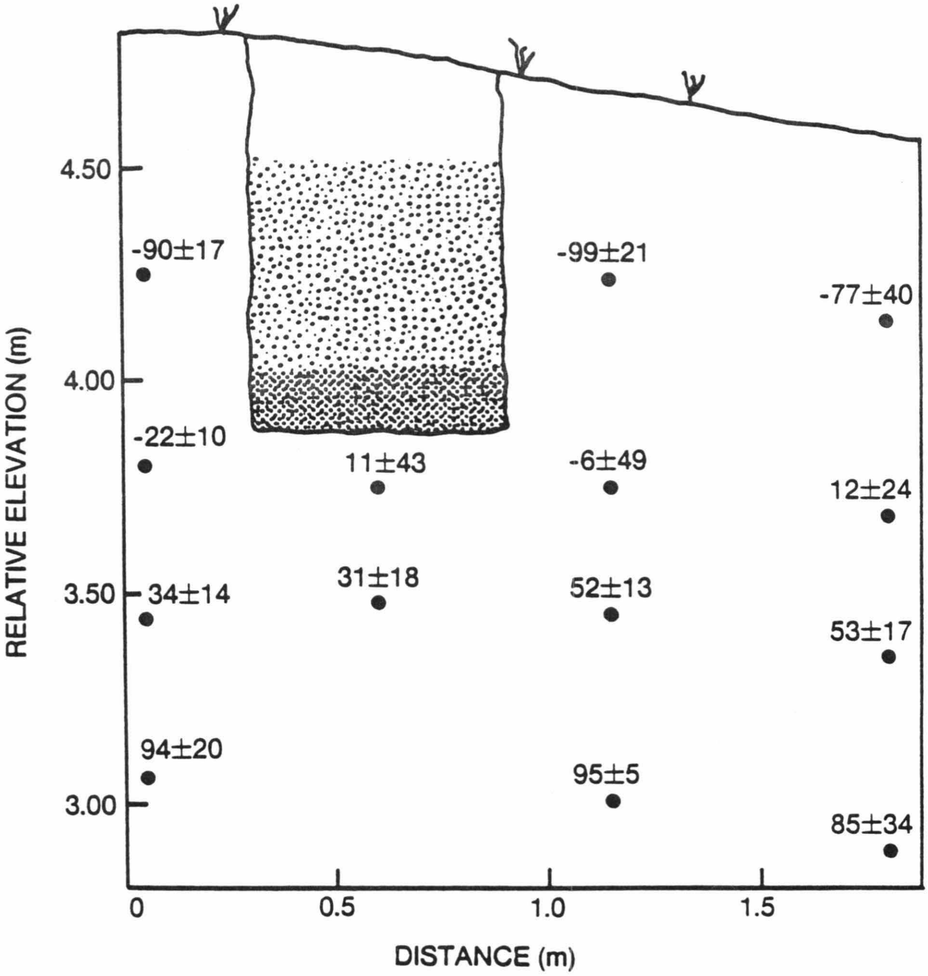


Figure 22. Cross section of trench 6 at Site 3 illustrating means and standard deviations of pressure potentials: points define tensiometer locations relative to the trench. The darker shaded area in the gravel envelope corresponds to the depth of ponding. Pressure units are cm of water.

concentrations increase with depth below the trench (Figure 24) and at the 30 and 90 cm distances from the trench.

The NH_4^+-N concentrations decrease almost logarithmically with depth below trench 3 (Figure 25). 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 to zones of positive pressure heads beside the trench (Figure 13).

The NO_3^--N concentrations (Figure 26) 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 presence 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 (Figure 10). Nitrate-N concentrations also increase with depth below the trench at the 90 cm distance.

9.3.2 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 as low as 26 mg L^{-1} (Figure 27) 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 (Figure 28). 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 to those below the trench. No change in NH_4^+-N concentration with depth is distinguishable 90 cm downslope from trench 6.

Nitrate-N concentrations (Figure 29) 30 cm from trench 6 increase with depth down to the zone of maximum NH_4^+-N accumulation (Figure 28) 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.

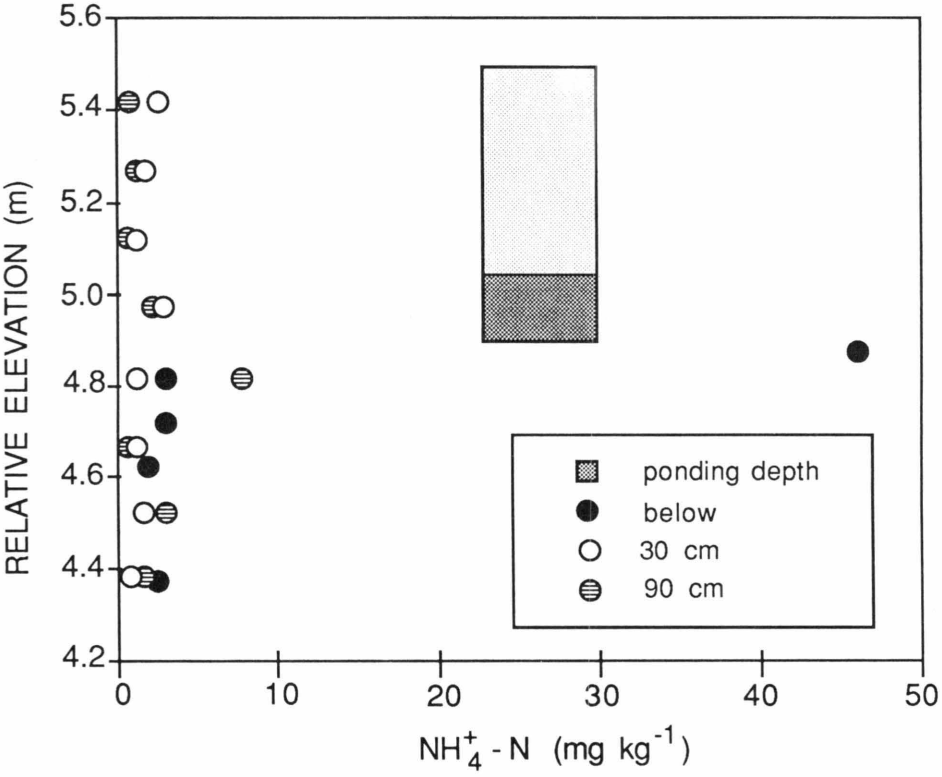


Figure 23. **Distribution of $NH^+{}_4$-N around trench 2 at Site 1 on November 21, 1985:** below, 30 cm and 90 cm from the trench. The inset box describes the relative elevation of the trench bottom and ponding of effluent.

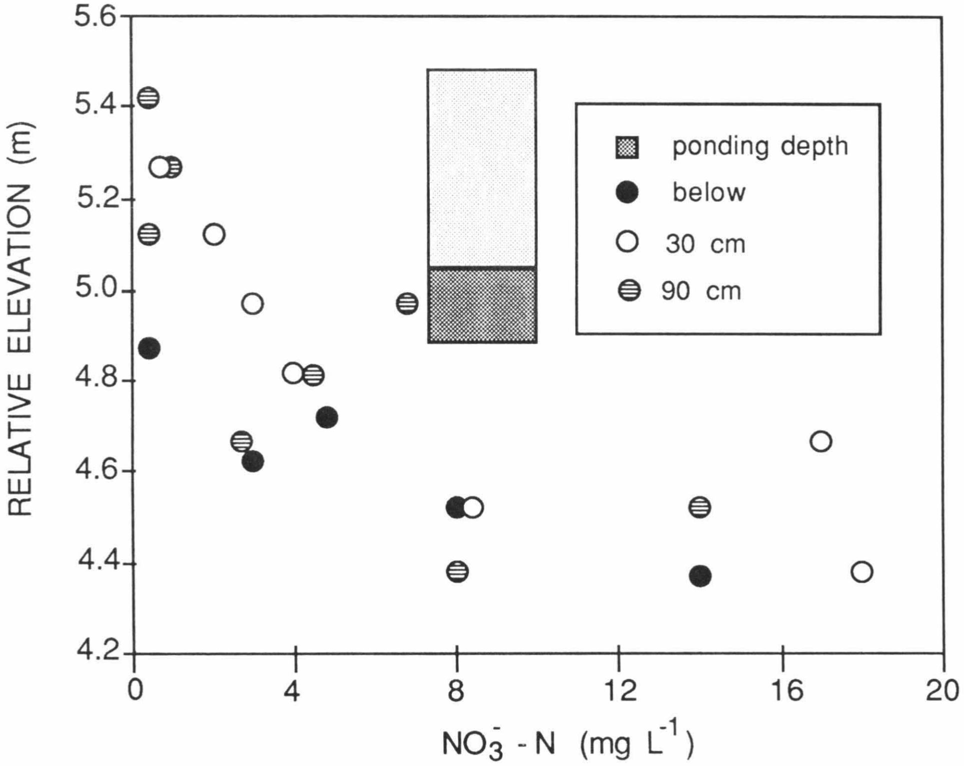


Figure 24. **Distribution of NO^-_3-N in soil solution around trench 2 at Site 1 on November 21, 1985:** below, 30 cm and 90 cm from the trench. The inset box represents the relative elevation of the trench bottom and the ponding depth.

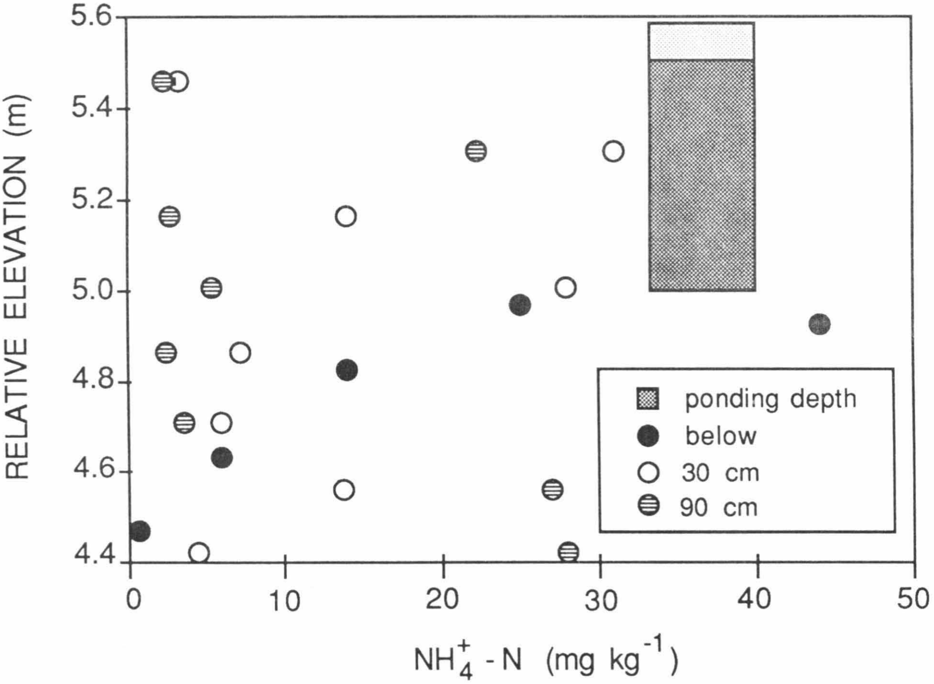


Figure 25. Distribution of NH^+_4-N around trench 3 at Site 1 on November 21, 1985: below, 30 cm and 90 cm from the trench. The inset box represents the relative elevation of the trench bottom and ponding depth.

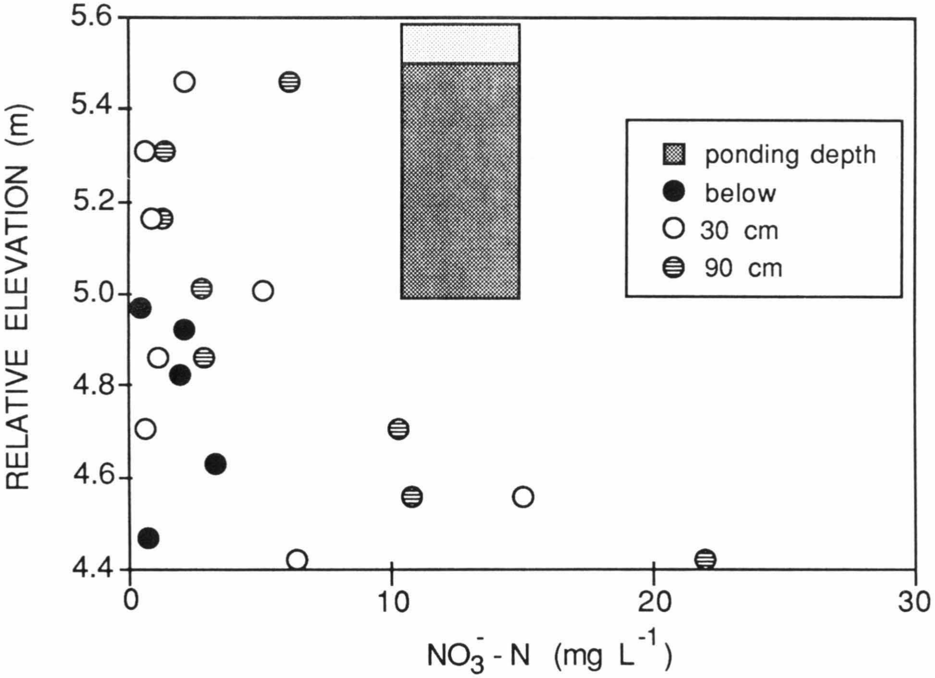


Figure 26. Distribution of NO^-_3-N in soil solution around trench 3 at Site 1 on November 21, 1985: below, 30 cm and 90 cm from the trench. The inset box and shaded areas represent the relative elevation of the trench bottom and ponded effluent.

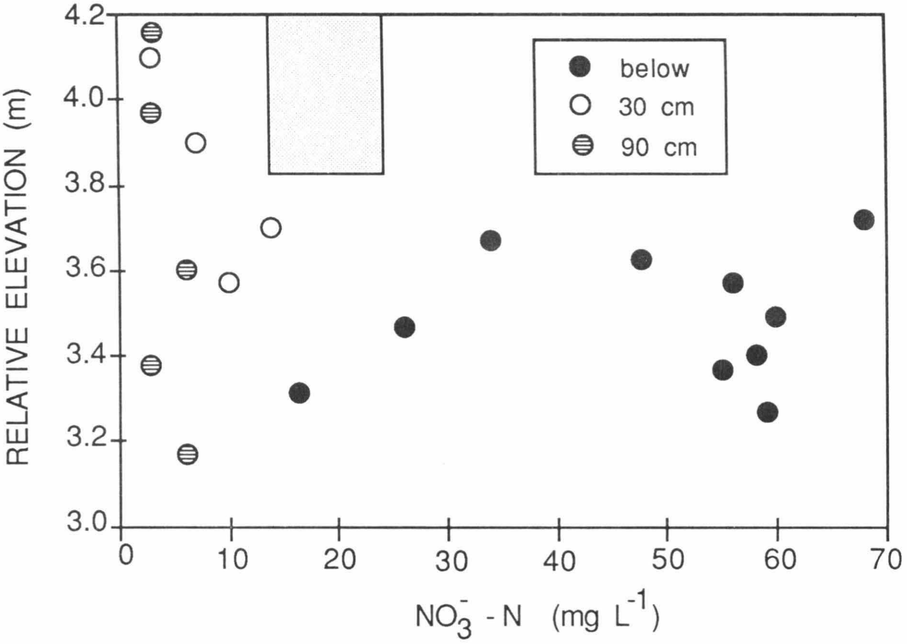


Figure 27. **Distribution of NO^-_3-N in soil solution around trench 5 at Site 3 on November 1, 1985:** below, 30 cm and 90 cm from the trench. The inset box represents the relative elevation of the trench bottom.

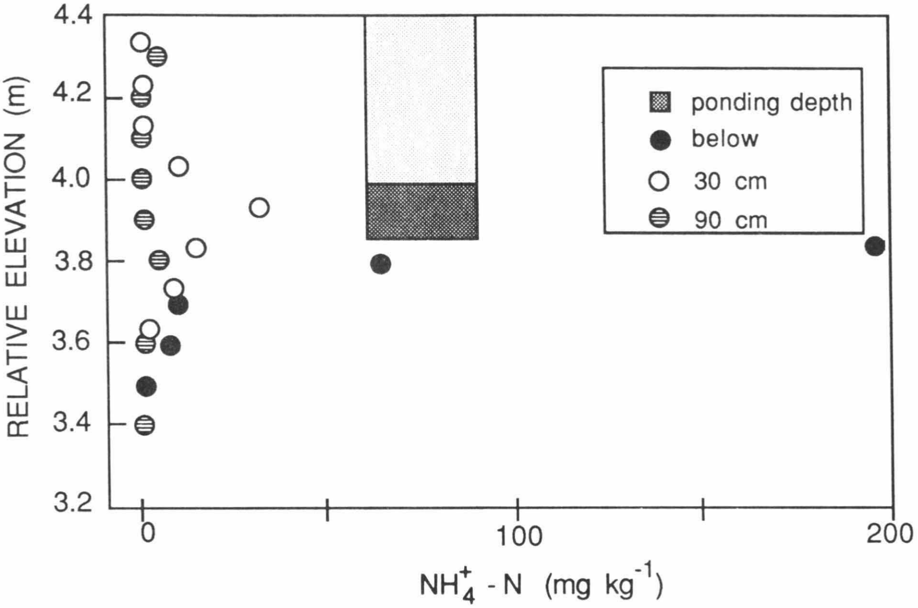


Figure 28. **Distribution of NH$^+{}_4$-N around trench 6 at Site 3 on November 1, 1985:** below, 30 cm and 90 cm from the trench. The inset box represents the relative elevation of the trench bottom and the depth of ponding.

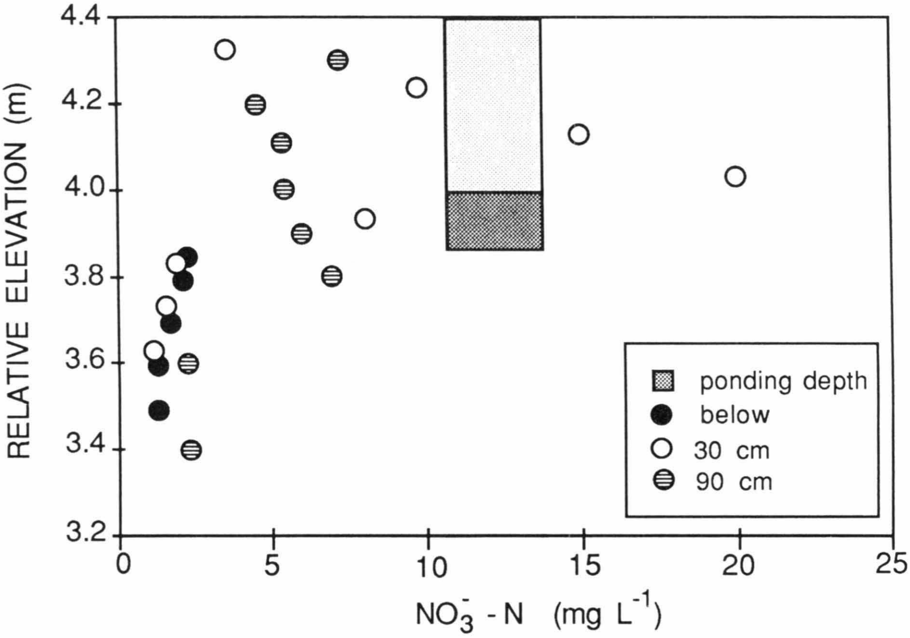


Figure 29. **Distribution of NO^-_3-N in soil solution around trench 6 at Site 3 on November 1, 1985:** below, 30 cm and 90 cm from the trench. The inset box represents the relative elevation of the trench bottom and the depth of ponding.

10.0 DISCUSSION

10.1 Ponding of Effluent in Trenches

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 soil 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 accumulations in interpedal voids and cracks noted in Plates 1, 2, and 6 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.

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.

10.2 Relations between Pressure Heads and ST-SAS Performance

10.2.1 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 ponding of effluent 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 and silver maple 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 (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 the 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 gradient for horizontal and vertical transport of the effluent load. These data support the magnitude of differences in mean saturated conductivity (Table 6).

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 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 subangular blocky or similar structure is not evident in clayey soils but soil colors suggest good drainage (Plate 3), effluent dosing rates of 0.4 cm d^{-1} may be appropriate.

10.2.2 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.

10.2.3 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.

10.2.4 Site 3

Lack of ponding and the mean pressure heads adjacient 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 (Figure 20) and noted presence of bedrock pinnacles within 30 cm of the trench bottom (not shown in Figure 20) 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 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 occurred 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.

Table 9 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 OSWDS where this is of major concern should minimize these dangers. Further research in this area is warranted.

10.3 Recommendations for Alternating Drainfields

Resting of ponded trenches dosed at 1.8 cm d^{-1} for 1 to 2 months (Figures 10 and 11) and of trenches dosed at 3.6 cm for approximately 3 months (Figure 13) did not prevent recurrence of ponding. The delay of ponding in Figures 10 and 13 suggests that some benefit may have occurred due to the resting period. The recurrence in ponding at Site 1 (Figures 10 and 11) may have been due in great part to seasonal water content fluctuations in the subsoil surrounding the ST-SAS.

Alternating drainfields dosed with LPD should provide the greatest longevity of OSWDS. The second best solution appears to be use of LPD because the whole system is dosed at a relatively uniform rate. However, where gravity distribution is used, considering that it is generally accepted that only part of the drainfield lines are normally receiving effluent, benefits may be gained by splitting the drainfield in half and resting each half seasonally. It

Table 9. Summary of proposed loading rates for limestone-derived soils.

loading rate ($cm\ d^{-1}$) 0.5	1.0	2.0 - 3.0
weak coarse subangular blocky, angular blocky, prismatic, or columnar structure	moderate to strong subangular blocky, angular blocky, prismatic or columnar structure underlain by a similar layer 15 to 30 cm thick or > 30 cm but 25 to 50% coarse fragments.	moderate to strong subangular blocky, angular blocky, prismatic or columnar structure with > 60 cm to a restrictive layer

should be noted that many areas for which alternating drainfields might be recommended may not be ponded to the degree noted above; thus the benefits of alternation may be greater. Further evaluation of several full scale systems designed in this manner is suggested to support these conclusions.

10.4 Nitrogen Distribution Around Drainfields

10.4.1 Site 1

A zone of maximum NH_4^+-N accumulation occurred just below trench 2. The NO_3^--N concentrations of 19 mg L^{-1} within 20 to 30 cm below the drainfield and the decrease in NH_4^+ -N with depth indicated that nitrification was occurring. 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 causing interpedal voids to drain, thus allowing 0_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 adjacient to trench 3 (Figure 25) corresponds with morphological (Plate 2) and tensiometric evidence (Figure 16) 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 nitrification are apparent around trench 3. One is in the Bt horizon above 5.4 m reflected by samples 90 cm from the trench (Figure 26). 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 (Figure 26).

10.4.2 Site 3

Low NH_4^+-N concentrations and high solution NO_3^--N concentrations below trench 5 (Figure 27) indicated rapid nitrification of NH_4^+ present in the effluent. Although mean pressure heads below these trenches indicate that the soil was 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 in appendix A) and trench 5 approached TKN values in the effluent (Table 7), suggesting occurrence of large scale nitrification. High NO_3^--N concentrations indicate that a 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 (Figure 29) 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 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, 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, strongly 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 almost complete nitrification. At Site 1, zones around trench 2 with mean negative pressure heads had solution NO_3^--N values of approximately 50% of TKN values in the STE.

10.5 Estimation of Potential for Nitrate Leaching

Using conservative techniques and making several simplifying assumptions, we can estimate some general trends for leaching of NO_3^--N below ST-SAS in well drained soils at varying loading rates. Let us assume (a) that 25% of the drainfield area is comprised of trench bottom and the remaining 75% does not directly receive effluent; (b) that there is a surplus of 50 cm of rainfall at the site each year to dilute the leaching NO_3^-; (c) that soil solution leaves the immediate trench bottom at concentrations of 60 mg L^{-1} (Figure 27); (d) that all of the NO_3^- is equally diluted and mixed with the water from precipitation; and (e) that any N leaving the trench bottom will not be removed by plant uptake. With these assumptions, we would expect the approximate average concentrations reported in Table 10.

Note that even at low application rates, solution NO_3^- concentrations may be above USPHS drinking water standards of 10 mg L^{-1} if further dilution does not occur. During water deficit periods of the year, the solution leaching through the soil profile may be more concentrated than during time periods when throughflow is more abundant. This simple analysis does suggest that drainfields for large flows should be designed with consideration given to N loading rates. Concern should also exist in sandy coastal areas or other areas where soils are loaded at relatively high flux densities on small lots. Obviously, in soils where there is some potential for denitrification or plant uptake, the potential for NO_3^- would be reduced.

Table 10. Estimated average concentrations of NO^{-}_{3}-N in solution leaving the drainfield area.

loading rate (cm d^{-1})			
0.5	1.0	2.0	3.0
NO^{-}_{3}-N (mg L^{-1})			
27	38	47	54

11.0 CONCLUSIONS

1. Clayey, well structured B horizons without 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.

2. 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 those systems dosed at 3.6 cm d^{-1}.

3. In fine textured soils where colors indicate good drainage, but structure is weak and no other alternative exists, flux densities of 0.5 cm d^{-1} may be suitable.

4. 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 of 1 to 2 cm d^{-1} may be suitable in these soils.

5. At least 30 cm of moderately to strongly 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.

6. ST-SAS installed in fine-textured soils with 15 to 30 cm of moderately to strongly structured soil underlying the system may be dosed at 1 cm d^{-1}.

7. ST-SAS installed in moderately to strongly structured soils of fine texture with no apparent restrictions within the 60 cm underlying the system may be dosed at 2 to 3 cm d^{-1}

8. This research indicates that fine textured soils (class IV, Virginia Department of Health, 1982) 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.

9. Seasonally alternating the dosing of drainfields with gravity distribution is recommended if LPD is not chosen. Further research should evaluate the performance of such systems relative to those dosed via LPD.
10. In well structured soils, nitrification will be limited if positive pressures predominate in the zone of effluent flow.
11. Nitrification was not limited below unponded trenches in soils with average negative pressure heads that approached 0.
12. 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.
13. Movement of NH_4^+-N substantial distances from ponded trenches in well structured 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.

12.0 REFERENCES

Anderson, J. L. and J. Bouma. 1977a. Water movement through pedal soils: I. Saturated flow. Soil Sci. Soc. Am. J. 41:413-418.

Anderson, J. L. and J. Bouma. 1977b. Water movement through pedal soils: II. Unsaturated flow. Soil Sci. Soc. Am. J. 41:419-423.

Bauman, R. J. and W. M. Schaefer. 1985. Estimating groundwater quality impacts from on-site sewage treatment systems. Pp. 285-294, *In*, On-site waste water treatment. Proceedings of the Fourth National Symposium on Individual and Small Community Sewage Systems. December 10-11, 1984. American Society of Agricultural Engineers. St. Joseph, Michigan.

Bouma, J. 1975. Unsaturated flow during soil treatment of septic tank effluent. J. Environ. Eng. Div. Am. Soc. Civil Eng. 101:967-983.

Bouma, J. 1979. Subsurface applications of sewage effluent. Pp. 665-703, *In*, M. T. Beatty et al., ed. Planning the uses and management of land. American Society of Agronomy. Madison, Wisconsin.

Bouma, J., W. A. Ziebell, W. G. Walker, P. G. Olcott, E. McCoy, and F. D. Hole. 1972. Soil absorption of septic tank effluent. Inf. Circ. No. 20, Geological and Natural History Service, University Extension, Univ. of Wisconsin. Madison. 235 p.

Bouwer, Herman and R. D. Jackson. 1974. Determining soil properties. *In* Jan Van Schilfgaarde, ed. Drainage for agriculture. Agronomy 17:611-672.

Brown, K. W., J. F. Slowey, and H. W. Wolf. 1977. The movement of salts, nutrients, fecal coliform, and virus below septic leach fields in three soils. Pp. 208-217, *In*, Home sewage treatment. Proceedings of the Second National Home Sewage Treatment Symposium. American Society of Agricultural Engineers, St. Joseph, Michigan.

Brown, K. W., H. W. Wolf, K. C. Donnelly, and J. F. Slowey. 1984. The movement of nitrogen species through three soils below septic fields. J. Environ. Qual. 13:460-465.

Bureau of the Census, 1972. 1970 Census of housing. Volume 1. Housing characteristics for states, cities, and counties. Part 1. United States summary. U. S. Department of Commerce. p. S20-1-9. Washington, D.C.

Bureau of the Census. 1983a. 1980 Census of housing. Volume 1. Characteristics of housing. Chapter A. General housing characteristics. Part 1. United States summary. U. S. Department of Commerce. p. 59. Washington, D.C.

Bureau of the Census. 1983b. 1980 Census of housing. Volume 1. Characteristics of housing. Chapter B. Detailed housing characteristics. Part 1. United States summary. U. S. Department of Commerce. p. 55, 66. Washington, D.C.

Carter, Edward. 1982. Personal communication. Former sanitarian, Department of Health, Bristol, Virginia.

Chapman, H. D. 1965. Cation-exhange capacity. *In* C. A. Black, ed. Methods of analysis. Part 2. Agronomy 9:891-901.

Day, P. R. 1965. Particle fractionation and particle-size analysis. *In* C. A. Black, ed. Methods of analysis. Part 1. Agronomy 9:545-567.

DeVries, J. 1972. Soil filtration of wastewater effluent and the mechanism of pore clogging. J. Water Pollut. Control Fed. 44:565-573.

Firestone, M. D. 1982. Biological denitrification. *In* F. J. Stevenson, ed. Nitrogen in agricultural soils. Agronomy 22:289-326.

Harkin, J. M., C. P. Duffy, and D. G. Kroll. 1979. Evaluation of mound systems for purification of septic tank effluent. Tech. Rep. Wis-WRG79-05. Univ. of Wisconsin Water Resources Center, Madison, Wisconsin.

Keeney, D. R. 1982. Nitrogen management for maximum efficiency and minimum pollution. *In* F. J. Stevenson, ed. Nitrogen in agricultural soils. Agronomy 22:605-649.

Jones, J. H. and G. S. Taylor. 1964. Septic tank effluent percolation through sands under laboratory conditions. Soil Sci. 99:301-309.

Kristiansen, R. 1981a. Sand-filter trenches for purification of septic tank effluent: I. The clogging mechanism and soil physical environment. J. Environ. Qual. 10:353-357.

Kristiansen, R. 1981b. Sand-filter trenches for purification of septic tank effluent: II. The fate of nitrogen. J. Environ. Qual. 10:358-361.

Magdoff, F. R. and J. Bouma. 1974. The development of soil clogging in sands leached with septic tank effluent. Pp. 37-47, *In*, Home sewage disposal. Proceedings of the National Home Sewage Disposal Symposium. American Society of Agricultural Engineers, St. Joseph, Michigan.

Magdoff, F. R., D. R. Keeney, J. Bouma, and W. A. Ziebell. 1974. Columns representing mound-type disposal systems for septic tank effluent: II. Nutrient transformations and bacterial populations. J. Environ. Qual. 3:228-234.

Marthaler, H. P., W. Vogelsanger, F. Richard, and P. J. Wierenga. 1983. A pressure transducer for field tensiometers. Soil Sci. Soc. Am. J. 47:624-627.

McCoy, E. L. and C. Hagedorn. 1980. Transport of resistance-labelled *Escherichia coli* strains through a transition between two soils in a topographic sequence. J. Environ. Qual. 9:686-691.

Miller, J. C. 1975. Nitrate contamination of the water-table aquifer by septic tank systems in the Coastal Plain of Delaware. Pp. 121-133, *In*, W. S. Jewell and R. Swan, ed. Water pollution control in low density areas. Proceedings of the Rural Environmental Engineering Conference. University Press of New England. Hanover, N.H.

Mitchell, R. and Z. Nevo. 1964. Effects of bacterial polysaccharide accumulation on infiltration of water through sand. Appl. Microbiol. 12:219-223.

Patrick, W. H., Jr. 1982. Nitrogen transformations in submerged soils. *In*, F. J. Stevenson, ed. Nitrogen in agricultural soils. Agronomy 22:449-465.

Peech, M. 1965. Exchange acidity. *In*, C. A. Black, ed. Methods of analysis. Part 2. Agronomy 9:905-913.

Quam, E. L., H. R. Swett, and J. R. Illian. 1974. Subsurface sewage disposal and contamination of groundwater in East Portland, Oregon. Groundwater 22:356-367.

Rahe, T. M., C. Hagedorn, E. L. McCoy, and G. F. Kling. 1978. Transport of antibiotic-resistant *Escherichia coli* through western Oregon hillslope soils under conditions of saturated flow. J. Environ. Qual. 7:487-494.

Reneau, R. B., Jr. 1977. Changes in inorganic nitrogenous compounds from septic tank effluent in a soil with fluctuating water table. J. Environ. Qual. 2:173-178.

Reneau, R. B., Jr. 1979. Changes in concentrations of selected chemical pollutants in wet, tile-drained soil systems as influenced by disposal of septic tank effluents. J. Environ. Qual. 8:189-196.

Reneau, R. B., Jr., J. J. Simon, and M. J. Degen. 1986. Treatment by onsite systems. *In* Utilization, treatment, and disposal of waste on land. Soil Science Society of America. Madison, Wisconsin.

Schmidt, E. L. 1982. Nitrification in soil. *In*, F. J. Stevenson, ed. Nitrogen in agricultural soils. Agronomy 22:253-288.

Selmer-Olsen, A. R. and A. Oien. 1973. Determination of chloride in aqueous soil extracts and water samples by means of a chloride-selective electrode. Analyst (London) 98:412-415.

Sikora, L. J. and R. B. Corey. 1976. Fate of nitrogen and phosphorus in soils under septic tank waste disposal fields. Trans. Am. Soc. Agric. Eng. 19:866-870.

Sikora, L. J. and D. R. Keeney. 1974. Laboratory studies on simulation of biological denitrification. Pp. 64-73, *In*, Home sewage disposal. Proceedings of the National Home Sewage Disposal Symposium. American Society of Agricultural Engineers, St. Joseph, Michigan.

Simon, J. J. and R. B. Reneau, Jr. 1985. Hydraulic performance of prototype low pressure distribution systems. Pp. 251-259, *In*, On-site waste water treatment. Proceedings of the Fourth National Symposium on Individual and Small Community Sewage Treatment. American Society of Agricultural Engineers, St. Joseph, Michigan.

Stewart, L. W., B. L. Carlile, and D. K. Cassell. 1979. An evaluation of alternative simulated treatments of septic tank effluent. J. Environ. Qual. 8:397-402.

Stewart, L. W. and R. B. Reneau. 1984. Septic tank effluent disposal experiments using nonconventional systems in selected coastal plain soils. Final report. Submitted to the Virginia Department of Health, June 1984. Agronomy Department, Virginia Polytechnic Institute and State University.

U.S. Environmental Protection Agency. 1974. Nitrate nitrogen. Pp. 215-216, *In*, Methods for chemical analysis of water and wastes. U.S.E.P.A., Washington, D.C.

U.S. Environomental Protection Agency. 1977. Alternatives for small wastewater treatment systems. EPA-625/4-77-011. U.S.E.P.A. Washington, D.C.

U.S. Environmental Protection Agency. 1979. Methods for chemical analysis of water and wastes. Environmental Monitoring Support Laboratory, Cincinnati, Ohio.

U.S. Environmental Protection Agency. 1980. Design manual. Onsite wastewater treatment and disposal systems. EPA 625/1-80-012. U.S.EPA, Washington, D.C.

Virginia State Board of Health. 1982. Sewage handling and disposal regulations. Virginia Department of Health. Richmond, Virginia.

Walker, W. G., J. Bouma, D. R. Keeney, and F. R. Magdoff. 1973a. Nitrogen transformations during subsurface disposal of septic tank effluent in sands: I. Soil transformations. J. Environ. Qual. 2:475-479.

Walker, W. G., J. Bouma, D. R. Keeney, and P. G. Olcott. 1973b. Nitrogen transformation during subsurface disposal of septic tank effluent in sands: II. Groundwater quality. J. Environ. Qual. 2:251- 525.

Walton, G. 1951. Survey of literature relating to infant methemoglobinemia due to nitrate-contaminated water. Am. J. Publ. Health. 41:986-996.

Whelan, B. R. and N. J. Barrow. 1984. The movement of septic tank effluent through sandy soils near Perth. I. Movement of nitrogen. Aust. J. Soil Res. 22:283-292.

Wierenga, P. J. 1985. Personal communication.

Winneberger, J. H., L. Francis, S. A. Klein, and P. H. McCauley, 1960. Biological aspects of failure of septic tank percolation systems. Sanitary Engineering Research, University of California, Berkeley, California.

13.0 APPENDIX A: Nitrogen and Chloride Distribution Data

Table 1. Distributions of NH_4^+, $NH_4^+:Cl$, NO_3^- , and $NO_3^-:Cl$ concentrations and ratios on a gravimetric basis; and NO_3^- in soil solution in soil cores[1] collected from Sites 1 and 2, June 1984.

Relative elevation	NH_4^+ $\bar{x}$	NH_4^+ SD	$NH_4^+:Cl$ $\bar{x}$	$NH_4^+:Cl$ SD	NO_3^- $\bar{x}$	NO_3^- SD	$NO_3^-:Cl$ $\bar{x}$	$NO_3^-:Cl$ SD	NO_3^- $\bar{x}$	NO_3^- SD
m	mg kg^{-1}				mg kg^{-1}				mg L^{-1}	
Site 1, Trench 3 - below trench										
4.92	181.89	30.67	0.96	0.41	0.61	0.36	0.00	0.00	1.68	1.30
4.88	231.82	80.49	1.58	0.15	0.71	0.60	0.00	0.00	1.50	1.14
4.77	80.11	47.84	0.47	0.39	0.69	0.59	0.00	0.00	1.82	1.67
4.63	37.36	4.22	0.20	0.01	0.60	0.29	0.00	0.00	1.48	0.84
4.47	12.03	8.16	0.07	0.06	2.19	1.37	0.01	0.01	5.52	2.63
4.32	20.65	5.99	0.19	0.16	1.64	0.90	0.02	0.02	3.89	2.36
4.13	14.62	12.42	0.22	0.28	1.79	0.58	0.02	0.02	4.65	0.37
3.88	55.91	55.94	0.45	0.04	1.99	1.92	0.04	0.06	5.29	5.30
3.38	44.45	5.92	0.44	0.29	0.68	0.15	0.01	0.01	1.40	0.39
2.88	37.05	24.63	0.83	1.03	2.20	2.81	0.01	0.01	4.71	5.92
Site 1, Trench 3 - 0.03 m from trench										
5.69	4.62	4.95	0.03	0.02	0.65	0.38	0.01	0.01	2.67	1.37
5.31	7.24	10.31	0.04	0.04	2.08	1.52	0.02	0.01	6.93	2.15
5.01	6.67	10.36	0.03	0.05	3.78	1.55	0.02	0.02	10.20	1.64
4.71	6.23	7.75	0.03	0.03	4.95	2.40	0.03	0.03	13.89	4.88
4.42	3.28	4.90	0.02	0.02	4.29	1.77	0.05	0.07	12.85	4.70
3.96	6.70	5.27	0.03	0.01	2.96	0.53	0.03	0.03	8.01	1.96
3.46	4.14	3.49	0.02	0.01	4.83	2.31	0.08	0.11	13.18	5.45
2.96	1.20	0.87	0.01	0.02	6.08	4.03	0.08	0.12	14.24	6.16
Site 2, Unit 1, Trench 4 - below trench										
4.97	57.99	12.83	0.60	0.41	0.82	0.20	0.01	0.00	2.73	0.63
4.88	6.45	3.53	0.10	0.10	8.12	6.47	0.07	0.01	20.93	14.04
4.63	12.77	1.84	0.15	0.13	41.16	24.77	0.48	0.41	112.14	27.64
4.32	33.77	10.83	0.39	0.36	59.34	14.62	0.57	0.29	147.53	0.74
3.88	23.89	30.02	0.47	0.66	26.48	18.26	0.18	0.14	66.32	36.21
3.38	8.24	10.64	0.21	0.30	35.68	19.30	0.35	0.35	80.73	34.06
2.88	14.21	18.72	0.44	0.62	31.42	25.16	0.27	0.23	71.45	53.85
Site 2, Unit 1, Trench 4 - 0.30 m from trench										
5.63	1.67	0.79	0.04	0.04	1.36	0.14	0.03	0.01	10.01	1.06
5.25	1.02	0.10	0.04	0.03	1.10	0.28	0.04	0.03	5.02	2.10
4.95	0.97	0.22	0.03	0.01	2.62	2.26	0.07	0.06	7.71	4.03
4.65	24.52	41.32	0.63	1.06	8.11	6.36	0.19	0.17	22.33	12.29
4.35	3.00	3.53	0.07	0.09	14.79	5.85	0.36	0.20	41.46	9.30
3.90	1.52	0.92	0.03	0.01	28.70	19.21	0.69	0.49	75.08	34.55
3.40	2.16	0.96	0.05	0.01	29.75	24.58	0.86	0.63	71.99	54.88
2.90	1.64	1.36	0.04	0.02	23.31	21.87	0.71	0.49	53.03	43.74

---

[1] Values are means of three cores.

Table 2. Distributions of $NH_4^+ \cdot NH_4^+ : Cl$, NO_3^- , and $NO_3^- : Cl$ concentrations and ratios on a gravimetric basis; and NO_3^- in soil solution in soil cores[1] collected from Site 2, November 1985.

Relative elevation	$NH_4{}^+$		$NH_4^+ : Cl$		NO_3^-		$NO_3^- : Cl$		NO sub 3 sup -	
	$\overline{x}$	SD	$\overline{x}$	SD	$\overline{x}$	SD	$\overline{x}$	SD	$\overline{x}$	SD
m	$mg\ kg^{-1}$				$mg\ kg^{-1}$				$mg\ L^{-1}$	
					Trench 2 - below trench					
4.87	46.27	65.63	2.19	3.11	0.21	0.30	0.01	0.01	0.40	0.56
4.82	3.08	4.78	0.13	0.18	0.52	0.59	0.03	0.04	1.45	1.71
4.77	0.27	0.30	0.01	0.01	0.56	0.72	0.03	0.03	0.98	2.34
4.72	3.17	2.33	0.15	0.12	1.62	1.28	0.07	0.04	4.79	4.39
4.67	10.32	8.09	0.57	0.44	1.36	1.69	0.07	0.08	4.27	5.57
4.62	1.96	4.79	0.12	0.27	0.63	1.49	0.04	0.08	3.03	3.68
4.52	1.75	0.96	0.09	0.05	2.51	1.89	0.13	0.10	8.40	6.90
4.37	2.50	2.37	0.11	0.08	5.44	5.77	0.23	0.21	14.47	12.05
4.22	25.60	28.21	1.17	1.36	1.89	1.44	0.10	0.08	5.57	4.46
4.07	12.73	14.88	0.71	0.80	4.48	5.02	0.24	0.24	17.21	20.04
3.92	17.81	21.06	0.76	0.79	9.68	10.14	0.43	0.44	24.56	23.51
3.77	21.74	33.94	1.26	1.99	9.93	8.53	0.52	0.40	27.98	23.78
3.63	2.79	1.67	0.15	0.08	8.65	5.89	0.47	0.31	20.63	12.14
3.40	8.32	10.60	0.52	0.67	3.70	2.29	0.20	0.12	9.86	5.94
3.10	1.10	1.52	0.05	0.06	1.12	1.21	0.06	0.07	2.39	2.35
2.80	7.11	8.21	0.34	0.34	3.36	3.20	0.21	0.24	7.66	7.63
					Trench 2 - 0.30 m from trench					
5.57	2.19	3.34	0.09	0.13	3.18	2.40	0.26	0.18	17.65	14.51
5.42	2.59	1.52	0.15	0.03	1.20	1.38	0.09	0.12	6.20	7.47
5.27	1.65	1.90	0.09	0.08	0.40	0.09	0.03	0.01	1.36	0.29
5.12	0.86	0.21	0.04	0.02	0.75	0.63	0.04	0.04	2.17	1.68
4.97	2.59	3.13	0.13	0.15	0.83	0.32	0.04	0.00	2.83	1.31
4.82	1.34	0.41	0.06	0.01	1.25	0.60	0.06	0.03	4.23	2.07
4.67	1.28	0.72	0.06	0.03	4.43	3.49	0.19	0.17	17.12	15.59
4.52	1.59	1.92	0.06	0.06	2.34	2.13	0.11	0.13	8.46	8.25
4.38	0.45	0.03	0.02	0.00	5.59	3.53	0.30	0.18	18.15	10.62
4.23	2.10	1.98	0.08	0.07	5.20	5.25	0.24	0.24	13.67	13.66
4.07	1.36	1.78	0.05	0.06	4.60	2.03	0.24	0.14	17.79	12.14
3.93	0.13	0.13	0.01	0.01	0.44	0.59	0.03	0.04	1.75	2.55
3.77	1.20	1.45	0.08	0.11	3.52	4.08	0.04	0.04	11.42	10.94
3.63	1.34	1.74	0.08	0.11	1.74	2.32	0.11	0.14	5.28	7.18
3.40	19.11	1.60	0.81	0.11	3.49	3.65	0.15	0.16	7.28	7.91
3.10	3.03	4.26	0.14	0.20	1.81	2.17	0.08	0.10	2.73	4.36

---

[1] Values are means of 2 samples at the 0 and 0.9 m distance and 4 samples at the 0.3 m distance.

Table 2 (continued).

Relative elevation	NH_4^+ $\bar{x}$	NH_4^+ SD	NH_4^+ : Cl $\bar{x}$	NH_4^+ : Cl SD	NO_3^- $\bar{x}$	NO_3^- SD	NO_3^- : Cl $\bar{x}$	NO_3^- : Cl SD	NO sub 3 sup - $\bar{x}$	NO sub 3 sup - SD
m	mg kg^{-1}				mg kg^{-1}				mg L^{-1}	
Trench 2 - 0.9 m from trench										
5.57	2.97	2.05	0.05	0.02	1.27	0.77	0.07	0.09	1.82	4.09
5.42	0.48	0.06	0.02	0.01	0.11	0.15	0.00	0.01	0.40	0.78
5.27	1.22	1.08	0.06	0.06	0.12	0.47	0.01	0.03	0.94	1.09
5.12	0.24	0.33	0.01	0.01	0.27	0.27	0.01	0.01	0.37	1.03
4.97	2.15	2.40	0.09	0.10	1.69	2.00	0.07	0.08	6.80	8.79
4.82	7.67	12.55	0.36	0.59	1.34	1.01	0.05	0.04	4.05	4.24
4.67	0.21	0.18	0.01	0.01	1.16	1.40	0.05	0.06	2.65	5.40
4.52	2.83	1.47	0.12	0.07	3.90	0.30	0.16	0.00	14.24	1.86
4.38	1.60	1.69	0.08	0.09	2.68	3.62	0.09	0.12	8.19	11.90
4.23	2.18	2.53	0.19	.	4.33	3.98	0.12	0.15	12.78	11.40
4.07	0.18	0.07	0.01	0.00	1.53	1.24	0.07	0.05	6.20	6.29
3.93	0.43	0.30	0.02	0.02	2.17	0.87	0.11	0.05	5.60	6.58
3.77	1.86	2.73	0.10	0.16	3.08	4.59	0.11	0.14	6.76	9.56
3.63	9.73	12.34	0.39	0.51	6.90	2.78	0.24	0.05	14.12	5.91
3.40	3.56	2.93	0.14	0.12	4.58	2.95	0.21	0.14	5.46	16.92
3.10	5.51	6.47	0.19	0.18	1.98	1.84	0.09	0.11	5.97	7.14
Trench 3 - below trench										
4.97	25.02	34.75	1.17	1.63	0.22	0.22	0.01	0.01	0.31	0.59
4.92	44.24	50.98	3.06	3.66	0.81	0.26	0.05	0.02	2.17	0.59
4.88	4.33	3.58	0.25	0.20	0.51	0.45	0.03	0.03	0.90	1.62
4.82	13.64	12.55	0.89	0.89	0.85	0.58	0.05	0.03	2.00	3.83
4.77	1.53	1.37	0.09	0.09	0.48	0.61	0.03	0.03	1.39	2.05
4.63	6.28	5.64	0.37	0.33	1.02	0.80	0.06	0.05	3.32	2.61
4.47	0.13	0.29	0.01	0.02	0.18	0.43	0.01	0.02	0.80	0.94
Trench 3 - 0.30 m from trench										
5.76	0.99	0.99	0.06	0.05	0.19	0.22	0.01	0.01	0.50	0.51
5.61	2.01	1.46	0.12	0.07	0.64	0.79	0.04	0.04	1.66	1.68
5.46	2.98	1.89	0.18	0.13	0.75	0.47	0.05	0.03	2.20	1.42
5.31	30.98	51.03	1.77	2.94	0.19	0.26	0.01	0.01	0.55	0.78
5.16	14.03	7.80	0.73	0.32	0.35	0.29	0.02	0.01	0.91	0.69
5.01	28.07	20.86	1.29	0.87	1.52	2.08	0.08	0.10	5.11	7.34
4.86	2.45	2.59	0.11	0.11	0.44	0.09	0.02	0.00	1.08	0.21
4.71	5.98	1.28	0.28	0.08	0.23	0.12	0.01	0.01	0.59	0.35
4.56	13.61	8.55	0.71	0.44	6.48	10.01	0.31	0.48	15.08	22.65
4.42	4.52	2.73	0.23	0.12	2.37	1.76	0.12	0.08	6.35	3.93
4.26	0.45	0.14	0.02	0.00	0.94	0.41	0.05	0.02	2.54	1.29
4.11	47.21	60.94	2.44	3.13	0.79	0.52	0.04	0.03	2.22	1.72

Table 2 (continued).

Relative elevation	NH_4^+		$NH_4^+:Cl$		NO_3^-		$NO_3^-:Cl$		NO sub 3 sup -	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
m	mg kg^{-1}				mg kg^{-1}				mg L^{-1}	
Trench 3 - 0.9 m from trench										
5.76	1.35	1.40	0.07	0.07	0.33	0.26	0.02	0.01	1.10	0.86
5.61	30.60	50.65	1.64	2.72	0.87	0.44	0.05	0.02	3.12	1.50
5.46	2.29	1.87	0.12	0.09	2.22	3.17	0.09	0.13	5.98	7.64
5.31	22.44	36.15	0.91	1.41	0.52	0.57	0.03	0.03	1.44	1.64
5.16	2.84	3.34	0.12	0.13	0.50	0.08	0.02	0.00	1.29	0.06
5.01	5.41	5.83	0.26	0.27	0.89	0.60	0.05	0.03	2.71	1.64
4.86	7.17	7.30	0.35	0.33	0.89	1.17	0.05	0.06	2.86	3.96
4.71	3.60	5.23	0.17	0.24	3.82	2.74	0.19	0.13	10.31	3.78
4.56	26.99	50.62	1.26	2.31	3.69	1.24	0.20	0.05	10.84	3.28
4.42	28.40	48.15	1.31	2.22	8.89	8.01	0.41	0.37	21.96	16.48
4.26	0.83	0.86	0.04	0.05	3.98	2.40	0.20	0.12	10.16	6.04
4.11	2.13	0.58	0.12	0.04	4.82	3.00	0.25	0.13	13.00	4.60

Table 3. Distribution of NH_4^+, NH_4^+ : Cl, NO_3^-, and NO_3^- : Cl concentrations gravimetric basis; and NO_3^- in solution in soil cores[1] collected from Site 3, October, 1985.

Relative elevation	NH_4^+		NH_4^+ : Cl		NO_3^-		NO_3^- : Cl		NO sub 3 sup -	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
m	mg kg^{-1}				mg kg^{-1}				mg L^{-1}	
Trench 3 - 0.3 m uphill from trench										
5.43	9.03	5.00	0.51	0.27	1.89	0.58	0.11	0.03	7.12	1.79
5.33	11.22	2.35	0.70	0.14	2.17	1.75	0.14	0.11	8.59	6.43
5.23	2.79	1.62	0.15	0.09	1.08	0.43	0.06	0.02	5.43	2.12
5.13	1.38	0.36	0.08	0.02	7.06	6.99	0.45	0.45	45.06	47.60
5.03	0.75	0.34	0.04	0.01	0.89	0.28	0.05	0.01	4.57	1.34
4.93	0.57	0.13	0.03	0.00	1.67	1.56	0.09	0.09	9.73	12.62
4.83	0.55	0.20	.	.	1.02	0.36	.	.	4.73	3.54
4.73	0.48	0.15	.	.	1.14	0.62	.	.	5.07	3.25
4.63	0.53	0.17	.	.	1.25	1.06	.	.	4.91	5.11
4.53	0.54	0.20	.	.	1.31	0.46	.	.	4.11	2.07
4.43	0.50	0.09	.	.	0.92	0.22	.	.	2.59	0.80
4.33	0.38	0.14	.	.	1.66	0.97	.	.	4.70	2.84
Trench 3 - below trench										
4.51	4.46	5.59	0.24	0.28	10.44	8.13	0.64	0.58	27.24	24.84
4.46	3.96	3.61	0.24	0.19	6.12	5.24	0.45	0.45	26.71	29.25
4.41	2.13	0.88	0.14	0.05	11.05	6.36	0.74	0.42	49.00	35.97
4.36	1.49	1.39	0.10	0.11	9.55	10.86	0.67	0.82	41.10	51.87
4.31	1.05	0.58	0.06	0.05	6.68	6.39	0.45	0.51	29.86	35.33
4.26	0.51	.	0.03	.	11.65	.	0.79	.	59.85	.
Trench 3 - 0.3 m downhill from trench										
4.85	0.81	0.40	0.06	0.03	1.22	0.40	0.10	0.03	6.27	1.86
4.75	0.47	0.18	0.03	0.01	1.44	0.28	0.10	0.02	6.58	0.98
4.65	0.75	0.54	0.05	0.03	1.59	0.80	0.11	0.05	6.05	3.21
4.55	1.49	1.30	0.09	0.08	1.19	0.65	0.08	0.04	4.70	2.52
4.45	2.16	2.24	0.11	0.12	1.57	0.80	0.08	0.05	5.63	2.59
4.35	2.80	3.64	.	.	1.98	1.30	.	.	6.86	3.92
4.25	0.92	0.54	.	.	1.50	0.48	.	.	4.35	2.10
Trench 3 - 0.9 m downhill from trench										
4.52	0.86	0.62	0.05	0.03	0.72	0.04	0.04	0.00	4.07	0.46
4.42	0.91	0.01	0.05	0.00	0.95	0.36	0.06	0.03	4.03	1.06
4.32	0.94	0.55	0.05	0.03	1.10	0.50	0.06	0.02	4.25	1.94
4.22	0.61	0.00	0.03	0.00	1.06	0.00	0.06	0.00	2.74	0.00

---

[1] Values are means of samples from 2 to 4 cores.

Table 3 (continued).

Relative elevation	NH_4^+		NH_4^+ : Cl		NO_3^-		NO_3^- : Cl		NO sub 3 sup -	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
m	mg kg^{-1}				mg kg^{-1}				mg L^{-1}	
Trench 5 - below trench										
3.72	19.66	1.95	16.48	12.38	1.17	0.86	67.72	53.78		
3.67	1.42	0.80	8.54	7.45	0.63	0.57	34.09	29.47		
3.62	0.71	0.01	12.13	7.07	0.85	0.49	50.98	26.99		
3.57	0.69	0.18	13.65	2.62	0.95	0.15	55.83	4.33		
3.52	0.41	0.09	14.70	1.23	1.08	0.17	60.72	11.84		
3.47	1.12	0.32	6.65	4.39	0.44	0.25	26.37	14.99		
3.42	1.92	0.31	13.61	6.23	0.93	0.49	57.72	33.72		
3.37	0.67	0.55	13.02	9.31	0.94	0.72	55.34	45.12		
3.32	2.69	2.60	3.89	3.80	0.26	0.25	15.43	14.06		
3.27	2.19	2.49	13.27	9.24	0.95	0.66	58.83	45.77		
Trench 5 - 0.3 m downhill from trench										
4.10	0.45	0.09	0.02	0.00	0.57	0.19	0.03	0.01	3.44	1.07
4.00	0.38	0.10	0.02	0.00	1.25	0.54	0.07	0.03	7.52	3.41
3.90	0.32	0.05	0.01	0.00	1.24	1.28	0.07	0.07	7.26	7.49
3.80	0.46	0.05	0.02	0.00	2.56	2.87	0.14	0.15	14.85	16.43
3.70	0.24	0.08	0.01	0.00	2.88	3.16	0.17	0.17	14.47	15.56
3.60	0.69	0.42	0.04	0.03	1.34	1.17	0.09	0.09	5.84	4.97
Trench 5 - 0.9 m downhill from trench										
4.17	0.43	0.15	0.03	0.01	0.67	0.27	0.05	0.02	3.38	1.50
4.07	0.39	0.13	0.02	0.01	1.12	0.68	0.08	0.05	6.27	3.81
3.97	0.46	0.21	0.02	0.00	0.57	0.10	0.04	0.00	3.31	0.72
3.77	0.32	0.03	0.02	0.00	1.45	0.87	0.10	0.07	7.66	3.78
3.57	1.09	0.95	0.07	0.05	2.11	0.45	0.15	0.03	9.85	2.30
3.37	0.25	0.00	0.01	0.00	0.73	0.00	0.05	0.01	2.07	0.00
3.17	0.29	0.12	0.01	0.00	1.64	0.13	0.10	0.01	6.24	1.76
Trench 6 - below trench										
3.84	198.24	34.47	8.48	1.42	0.49	0.36	0.02	0.01	1.97	1.59
3.79	64.25	74.67	4.29	4.94	0.47	0.38	0.03	0.02	2.10	1.75
3.74	26.40	22.02	1.73	1.41	0.55	0.09	0.04	0.01	2.14	0.52
3.69	9.70	.	0.63	.	0.41	.	0.03	.	1.67	.
3.64	14.97	.	0.98	.	0.72	.	0.05	.	2.72	.
3.59	7.32	.	0.45	.	0.42	.	0.03	.	1.34	.
3.54	2.00	.	0.09	.	0.76	.	0.03	.	2.13	.
3.49	1.65	.	0.10	.	0.46	.	0.03	.	1.29	.
Trench 6 - 0.3 m downhill from trench										
4.33	0.64	0.24	0.05	0.02	0.64	0.49	0.07	0.05	3.40	2.58
4.23	0.76	0.06	0.05	0.00	2.01	1.18	0.15	0.10	9.75	6.38
4.13	1.23	0.61	0.09	0.05	3.48	1.23	0.26	0.11	15.43	4.89
4.03	10.14	13.91	0.75	1.01	5.53	1.01	0.40	0.11	20.06	4.28
3.93	32.24	46.61	2.18	3.21	2.85	1.37	0.19	0.10	8.04	4.24
3.83	14.83	21.54	0.77	1.09	0.72	0.59	0.04	0.03	1.93	1.61
3.73	8.95	8.83	0.49	0.49	0.61	0.03	0.03	0.00	1.55	0.07
3.63	2.25	1.73	0.11	0.08	0.44	0.11	0.02	0.01	1.08	0.32

Table 3 (continued).

Relative elevation	NH_4^+		$NH_4^+:Cl$		NO_3^-		$NO_3^-:Cl$		NO_3^-	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
m	mg kg^{-1}				mg kg^{-1}				mg L^{-1}	
					Trench 6 - 0.9 m downhill from trench					
4.33	5.29	6.80	0.37	0.49	1.58	1.45	0.11	0.11	7.26	5.88
4.23	0.57	0.16	0.04	0.01	0.87	0.39	0.06	0.03	4.52	1.97
4.13	0.40	0.19	0.02	0.01	1.11	0.68	0.08	0.06	5.24	3.65
4.03	0.42	0.24	0.02	0.01	1.29	0.52	0.08	0.04	5.44	2.61
3.93	1.24	1.49	0.07	0.08	1.72	1.48	0.10	0.09	5.97	5.63
3.83	5.24	5.58	0.30	0.32	2.20	1.72	0.13	0.10	6.93	5.66
3.63	0.89	1.02	0.05	0.05	0.74	0.41	0.04	0.02	2.17	1.40
3.43	0.56	0.32	0.03	0.01	0.79	0.28	0.05	0.02	2.27	0.37
3.23	0.62	0.25	0.03	0.02	0.87	0.29	0.04	0.00	2.41	0.43

14.0 APPENDIX B: SOIL WATER RETENTION DATA

Site	Hole	Depth[1]	Bulk Density g cm^{-3}	Pressure (cm of water)					
				13.5	49	98	306	612	918
1	1	1	1.29	0.502	0.490	0.484	.	0.477	0.468
1	1	1	1.27	0.523	0.495	0.479	0.463	0.453	0.445
1	1	2	1.51	0.556	0.556	0.556	0.552	0.509	0.506
1	1	2	1.40	0.403	0.403	.	0.400	0.392	0.381
1	2	1	1.31	0.482	0.482	0.481	0.476	0.473	0.467
1	2	1	1.27	0.486	0.486	0.486	0.486	0.466	0.459
1	2	2	1.37	0.436	0.434	0.431	0.431	0.423	0.419
1	3	1	1.26	0.521	0.521	0.518	0.512	0.506	0.496
1	3	1	1.39	0.501	0.495	0.495	0.495	0.489	0.486
1	3	2	1.40	0.430	0.423	0.413	0.402	0.392	0.384
1	3	2	1.43	0.435	0.430	0.417	0.403	0.392	0.381
1	4	1	1.31	0.513	0.513	0.509	0.509	0.501	0.490
1	4	1	1.29	0.498	0.492	0.490	.	0.488	0.478
1	4	2	1.27	0.486	0.486	0.485	0.477	0.476	0.473
1	4	2	1.26	0.531	0.531	0.531	0.531	0.531	0.522
1	4	2	1.38	0.453	0.450	0.426	0.426	0.414	0.400
1	4	2	1.29	0.480	0.480	0.476	0.476	0.471	0.464
1	5	1	1.26	0.437	0.429	0.426	0.419	0.412	0.403
1	5	1	1.39	0.452	0.450	0.449	0.449	0.439	0.437
1	6	1	1.43	0.468	0.468	0.465	0.455	0.447	0.445
1	6	1	1.40	0.440	0.433	0.426	0.417	0.409	0.404
1	6	2	1.63	0.542	0.541	0.539	0.536	0.531	0.526
1	6	2	1.18	0.536	0.536	0.535	0.533	0.529	0.528
2	0	1	1.49	0.464	0.429	0.410	0.388	0.370	0.361
2	0	1	1.31	0.486	0.425	0.405	0.383	0.362	0.353
2	0	2	1.30	0.449	0.423	0.410	0.392	0.382	0.379
2	0	2	1.20	0.447	0.407	0.390	0.373	0.359	0.340
2	8	1	1.40	0.498	0.454	0.440	0.420	0.404	0.400
2	8	1	1.21	0.475	0.426	0.407	0.391	0.376	0.358
2	8	2	1.25	0.557	0.543	0.527	0.502	0.452	0.419
2	8	2	1.35	0.524	0.505	0.486	0.472	0.440	0.418
3	1	1	1.47	0.434	0.409	0.389	0.368	0.359	0.348
3	1	1	1.57	0.381	0.368	0.344	0.320	0.302	0.286
3	1	2	1.57	0.379	0.344	0.323	0.305	.	.
3	2	1	1.65	0.370	0.371	0.366	0.333	0.319	0.313
3	2	1	1.47	0.408	0.388	0.360	0.341	0.330	0.320
3	3	1	1.66	0.396	0.387	0.380	0.367	0.359	0.350
3	3	2	1.48	0.464	0.462	0.458	0.449	0.440	0.429
3	4	1	1.68	0.366	0.347	0.336	0.318	0.305	0.287

[1] Depth 1 was 40 to 50 cm below the surface while depth 2 was 70 to 80 cm below the surface.

Virginia's Agricultural Experiment Stations

1—Blacksburg
Virginia Tech, Main Station
Dairy, Poultry, and all other topics

2—Steeles Tavern
Shenandoah Valley Agricultural Experiment Station
Beef, Forages, Fruit, Insect and Pest Control, Sheep

3—Orange
Northern Piedmont Agricultural Experiment Station
Alfalfa, Corn, Crops, Small Grains

4—Winchester
Winchester Agricultural Experiment Station
Fruit, Insect and Pest Control

5—Middleburg
Middleburg Agricultural Experiment Station
Beef, Forages

6—Warsaw
Eastern Virginia Agricultural Experiment Station
Field Crops, Insect and Pest Control

7—Holland Station, Suffolk
Tidewater Agricultural Experiment Station
Corn, Peanuts, Pest Control, Small Grains, Soybeans, Swine

8—Blackstone
Southern Piedmont Agricultural Experiment Station
Forages, Horticulture Crops, Small Grains, Tobacco, Turfgrass

9—Critz
Reynolds Homestead Agricultural Experiment Station
Aquaculture, Forestry, Wildlife

10—Glade Spring
Southwest Virginia Agricultural
Experiment Station
Beef, Burley Tobacco, Sheep

11—Hampton
Virginia Seafood Agricultural Experiment Station
Seafood

12—Virginia Beach
Hampton Roads Agricultural Experiment Station
Ornamentals, Vegetables, Insect and Pest Control

13—Painter
Eastern Shore Agricultural Experiment Station
Fruit, Field Crops, Herbs, Insect and Pest Control, Vegetables