

Bulletin 137
March 1983

**Wastewater Treatment
in Soil as a Function
of Residence Time
in the Root Zone**

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The work upon which this report is based was supported in part
by funds provided by the United States Department of the Interior.

Project A-088-VA
VPI-VWRRRC-BULL 137
3C

A publication of
Virginia Water Resources Research Center
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24060-3397

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ACKNOWLEDGMENTS

Several people made significant contributions of their time during this project, including Juel M. Albert, Leon D. Alley, Jan C. Carr, Gary S. Crouch, Thomas W. Rippon, David E. Starner, Chanchai Tiyanani, Candace E. Walker, and Donald L. Wingo, and their help is gratefully acknowledged. The authors are particularly grateful to Julie A. Petruska for assistance with laboratory analyses, to Phillip W. McClellan for invaluable help with graphical and tabular presentations of data, and to Margaret J. Stewart for guidance on statistical analyses. The authors would also like to thank Keith E. Saxton, United States Department of Agriculture, Agricultural Research Service, Washington State University, Pullman, for the use of the SPAW soil-water model.

Special acknowledgment is made to Dr. Saxton; Richard O. Hegg, Department of Agricultural Engineering, Clemson University, Clemson, South Carolina; and Frank J. Humenik, Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, who generously gave their time to a critical review of the manuscript. Acknowledgment also is made to Clara B. Cox for editorial processing and typesetting and to Gretchen S. Bingman for layout composition.

ABSTRACT

A laboratory study was conducted to determine nitrogen removal rates from a land-applied wastewater as a function of the length of time the wastewater remained in the root zone. A digital simulation model was used as an aid in describing soil-water (and wastewater) movement through the root zone under wet conditions (i.e., root zone 50-75 percent saturated). A procedure was developed to predict the rate and volume of drainage as a function of initial soil moisture content, amount of liquid applied, and time after liquid application. An exact relationship between nitrogen removals and wastewater residence time in the root zone could not be developed. However, removals of up to 95 percent of applied NH_4^+ -N were observed in an 18-cm-deep root zone when residence times were as short as 2 hr.

Key Words: Land Application, Land Treatment Design, Effluent Irrigation, Nitrate Pollution, Percolation, SPAW Model, Soil Water Model

INTRODUCTION

Land application of wastes is not a new concept. Animal and human wastes have been applied to land as fertilizer amendments at least as long as man has recorded agricultural history [Einarson and Link, 1976]. However, since revision of the Federal Water Pollution Control Act in 1972, land application has received renewed interest as a waste treatment alternative, particularly for wastewater. Stimulus for this interest was provided by establishment of a national goal to eliminate all discharges of pollutants to the navigable waters of the United States by 1985. This goal implied that the waterways of the nation would no longer serve as receivers for wastes and prompted investigation of alternative treatment methods.

Despite legislative and administrative impetus, land application has not become a widely accepted wastewater treatment alternative. Jorling [1977] attributed public reaction to using waste as the biggest impediment to implementing land treatment. Pollock [1979], assessing the lack of municipal land-application projects in Virginia, also cited public awareness as a problem, but listed factors such as cost, groundwater quality standards, and limited availability of suitable application sites as other deterrents to the use of land application. Most significantly though, Pollock observed that “. . . land application of wastewater is a highly complex field . . .” with which “. . . design engineers [in Virginia] have little or no first hand experience.”

The research reported herein was initiated on the premise that the unfamiliarity with land application and its consequent limited acceptance is chiefly due to a lack of adequate, easily used design criteria. This is not to say that design criteria do not exist. Extensive treatises on methods for designing municipal and industrial land treatment systems are available [U. S. Environmental Protection Agency, 1977; Loehr et al., 1979; Overcash and Pal, 1979], but they ignore the influence of process dynamics and do not promote a priori prediction of effluent quality or the development of optimum system designs.

One might contrast the situation just described for land treatment with that which exists for conventional wastewater treatment. In the latter case, engineers have at their disposal mathematical formulas that describe treatment processes and permit reliable prediction of final effluent quality. Similarly, because such formulas exist, an optimum system design

can be achieved by simulating different process modifications to determine their effect on effluent quality. Until a similar degree of knowledge is achieved for land treatment and translated into a readily usable format, design engineers will be reluctant to recommend the use of land treatment. Jewell and Seabrook [1979] concur: "Until the assimilation capacities of the soil system are known to researchers, disseminated, and understood, the designs [of land treatment systems] will be subject to questions and used only under highly conservative conditions."

REVIEW OF LITERATURE

I. Residence Time as a Concept

The concept of *residence time* (i.e., the time available for biological, physical, and chemical forces to interact with a waste) is basic to every form of wastewater treatment. It is well known that biological processes require a certain minimum reaction time to transform a waste because of the activity of the microbial population, type of waste involved, and environmental conditions under which the transformation takes place. In continuous treatment systems, such as activated sludge, this period is expressed as mean cell residence time [Adams and Eckenfelder, 1974], while for liquid batch systems it may simply be expressed as the time in which liquid remains in the reactor [Metcalf and Eddy, 1972]. Even purely physical processes such as sedimentation require that the liquid remains in the reactor long enough for particles of a desired size to settle.

The common link among the different expressions for residence time is reaction rate. In a soil system, factors that affect reaction rates include temperature, pH, soil moisture, oxygen supply, available nutrients, soil structure and texture, physical and chemical nature of the waste, and nature of the indigenous microflora [Reddy, Khaleel, and Overcash, 1980]. However, few attempts have been made to define reaction rates for nitrogen in the context of wastewater treatment in soil.

Nevertheless, virtually every individual step of the nitrogen transformation process in soil is rate dependent. Bazin and Saunders [1972] showed that nitrification in a column containing glass beads and marble chips, both inoculated with nitrifying bacteria, was inversely related to flow rate of ammonium sulfate through the column. Nitrate reduction (denitrification) was shown by Pilot and Patrick [1971] to be dependent upon moisture tensions in the loamy sand, very fine sandy loam, and silty clay loam that they investigated. Since moisture content and, therefore, moisture tension are related to moisture flow, it follows that denitrification is also dependent upon flow rate. Barber [1961] postulated that one of the two key processes that brought nutrients to the roots of plants for eventual uptake was the mass flow rate of soil water in the vicinity of the roots. It is therefore conceivable for a concentration of nutrients to develop at the root surface that cannot be assimilated by the plants as fast as the nutrients are being supplied. The need remains for a com-

prehensive procedure that quantitatively relates wastewater nitrogen transformations to the rate at which wastewater moves through the soil.

II. Nitrogen Models

Considerable effort has been expended in the last decade to satisfy the need for methods that predict the behavior of nitrogen in soil. In general, these efforts have taken the form of mathematical models developed from one of two approaches: deterministic or empirical. Deterministic approaches use physical laws and mathematical equations to describe natural processes. Empirical methods use regression equations fitted to existing data. *Tables 1* and *2* outline the key features of several of these models.

A. Deterministic Models

Beek and Frissel [1973] have developed the most detailed of the deterministic models. Using IBM's continuous simulation modeling program (CSMP) language, these researchers have included biochemical interactions such as production and decay of humus and microbial die-off, all of which are often ignored in most models. Hagin and Amberger [1974] followed a similar approach in developing a slightly less complex model for use in the Mediterranean region. Other deterministic models are listed in *Table 1*.

Assumptions regarding reaction rates, both microbiological and chemical, differentiate deterministic models. Mehran and Tanji [1974] assumed that all reactions followed first-order kinetics. Beek and Frissel [1973] and Hagin and Amberger [1974] took a more realistic approach and assumed microbial transformations to be functions of the type of substrate, the amount of substrate, soil-moisture content, soil temperature, and microbial population. Tanji et al. [1977, 1979] assumed constant reaction coefficients. Likewise, Saxton, Shuman, and Burwell [1977] assumed constant nitrification and mineralization rates. Duffy et al. [1975] assumed constant rate coefficients for nitrogen transformations but applied a different rate constant at different points in time of the computational sequence. Reuss and Innis [1977] assumed first-order kinetics and constant coefficients for mineralization and oxidation of ammonium to nitrite.

B. Empirical Models

Comparatively few researchers have adopted the empirical approach to model development. Dutt, Shaffer, and Moore [1972] used this procedure in attempting to simulate the movement of nitrogen and several other ions. Burns [1975, 1977] also employed an empirical procedure to develop a simple leaching equation applicable to soils in the British Isles. His equation is suitable for direct field use and can be varied depending on the initial distribution of fertilizer in the soil profile [Burns, 1977]. Duffy et al. [1975] have developed a more complex model for application to tile-drained soils of the Corn Belt region of the United States.

Although empirical models offer less insight into the actual processes that transform nitrogen in the soil environment, their inherent simplicity makes them more attractive as aids for the design of land-based wastewater treatment systems. Their main limitation is that they are usually site specific and are difficult to use in situations other than those for which they were developed. Deterministic models, however, while very descriptive, are often so difficult to understand and operate that they are not routinely used by design engineers. A relationship is needed to describe nitrogen transformations in the terrestrial environment that combines reliability, broad applicability, and ease of use.

MATERIALS AND METHODS

I. Materials

A Cecil gravelly sandy loam (Typic Hapludult, clayey, kaolinitic, thermic) was selected for use in this study because it satisfied the criteria of being suitable for actual land-application projects and occurring on a widespread basis. Sixteen undisturbed soil samples, each 15 cm in diameter and approximately 75 cm in length, were collected in polyvinyl chloride (PVC) pipe (ASTM D-2665, Charlotte Pipe and Foundry Co., Charlotte, North Carolina) using the method of Richards [1971]. This procedure involved slowly pushing the PVC pipes into the soil with a hydraulic pump and piston (*Figure 1*). Each column was fitted with a 10.5-cm diameter, 1-bar ceramic plate (604 D04-B1M1, Soilmoisture Equipment Corp., Santa Barbara, California) to provide suction at the base of the column and to increase the rate of moisture movement through the soil (*Figure 2*).

Micro-tensiometers were used to determine soil moisture content and moisture movement because more sophisticated moisture-sensing techniques were not available. The tensiometers were embedded in the columns at three depths below the soil surface—10.2 cm, 33.0 cm, and 61.0 cm. These locations corresponded to the mid-points of each soil horizon (*Figure 3*). The tensiometers were constructed with 0.95-cm diameter by 2.86-cm long, 1-bar ceramic cups (652X7-B1M1, Soilmoisture Equipment Corp., Santa Barbara, California) and nylon tubing (MYT009, Soilmoisture Equipment Corp.).

Soil-water samplers were also constructed with 0.95-cm diameter by 2.86-cm long, 1-bar ceramic cups and nylon tubing similar to the tensiometers. However, high flow (i.e., 50 ml/hr/cm) ceramic (652X7-B1M3, Soilmoisture Equipment Corp., Santa Barbara, California) was used to minimize the length of time necessary for sample collection. These devices were embedded to a depth of 7 cm and located on a spiralling pattern (*Figure 3*). Samplers were located at two depths below the soil surface—17.8 cm, which corresponded to the bottom of the A_p horizon, and 48.3 cm (*Figure 3*). Sample collection and column instrumentation details are given by Magette [1982].

Each column was placed in an environmental chamber and seeded to tall fescue (*Festuca elatior*, var. Redman) at the rate of 22.5 kg/ha., allowing

for 80 percent germination. Temperatures in the growth chamber were maintained at 24° C (daytime) and 18° C (nighttime). Lighting intensity was maintained at approximately 16,000 lx. During the study, suction at the base of each column was maintained through a vacuum system patterned after that of Cole [1968]. Construction details of both the environmental chamber and suction regulation system are given by Magette [1982].

II. Methods

A. Experimental Design

Three treatments (i.e., liquid residence times in the root zone) were selected for investigation. These treatments were induced by maintaining different suctions at the bases of different soil columns. Suctions of 1/3 bar, 1/2 bar, and 2/3 bar were selected as reasonable levels of soil tension that could be expected 70-cm deep in a soil being irrigated on a regular basis. Soil columns were randomly assigned to each treatment, forming a completely randomized design. Four columns were assigned to each of the three treatments. Group 1 corresponded to Treatment 1 (1/3 bar suction) and contained Columns 4, 5, 8, and 16. Group 2 (Treatment 2, 1/2 bar) contained Columns 10, 11, 12, and 14. Columns 6, 9, 13, and 15 comprised Group 3 (Treatment 3, 2/3 bar).

B. Liquid Applications

Distilled water applications began with the planting of fescue in July 1980 while the grass was becoming established. Liquid was applied at rates needed to promote good vegetative growth. Thereafter, both distilled water and synthetic wastewater were applied until the conclusion of the study. Applications were separated into three phases.

Phase 1: Programmed applications of both distilled water and wastewater continued through mid-March 1981 in an attempt to induce and observe different moisture flow rates through the root zone of each soil column. Since the rate of moisture movement in unsaturated soil is a function of soil moisture content, it was desirable to make each liquid application under approximately the same moisture conditions. To satisfy this criterion and permit better interpretation of results, wastewater and/or distilled water were added only when soil tension, as reflected by the tensiometers, was within prescribed limits. Liquid was thus applied whenever

soil suction at the 10.2-cm tensiometer was 550-600 millibars (mb). Equal volumes were applied to each column, usually 500 ml (2.74 cm) per application. Liquid was applied by drip irrigation from plastic bottles located above the columns. Each applicator was calibrated to provide an application rate of 2.54 cm/hr.

Phase 2: From mid-March until mid-August 1981, only tap water was applied to the columns while an attempt was being made to model the previously collected tensiometer and effluent data. Only wastewater was applied to the columns from mid-August to early September 1981. Thereafter, applications of wastewater were followed by a flush of distilled water until the experiments were terminated in mid-November 1981.

Phase 3: In the final set of experiments (September to mid-November 1981), flush water (distilled water) was used as a method of controlling the residence time of wastewater in the root zone. To achieve different residence times, flush-water applications were made at different intervals of time after wastewater applications. On one group of columns (Group 1, Columns 4, 5, and 16), flush water was applied 12 hr after wastewater. Flush water followed wastewater application by 24 hr on Group 2 (Columns 11, 12, and 14) and by 36 hr on Group 3 (Columns 6, 9, and 10). These time intervals were selected to represent a range of application cycles that would be used in typical land-based wastewater treatment systems.

The same suctions originally used on the different groups of columns also were maintained throughout these latter investigations. Three columns (rather than four as originally planned) were used in each group (treatment) in these experiments because problems were encountered during previous phases with some of the original 12 columns either in maintaining an airtight seal around the ceramic plates or in collecting soil-water samples from the 17.8-cm samplers. These columns were discarded from further study.

Two of the discarded columns were originally part of the same treatment (Group 3), so their elimination from the study left that treatment with only two operable columns. One original treatment (Group 2) had no losses, however, so a column from this treatment (Column 10) was transferred to make up the deficiency in Group 3.

C. Wastewater Additions

A synthetic formulation was developed for stock wastewater that approximated effluent from a typical anaerobic swine lagoon [Loehr, 1969; Koelliker and Miner, 1970]. *Table 3* gives the theoretical chemical composition of this stock wastewater. Stock wastewater was diluted tenfold to permit long-term application.

Wastewater additions generally paralleled distilled water additions during Phase 3 of the study. Application of wastewater during earlier phases, however, was more infrequent because sealing problems around the ceramic baseplates on the columns required a number of soil columns to be temporarily removed from the study for repairs. Only maintenance levels of moisture were applied during this period. Dates and volumes of wastewater additions are given in *Table 4*.

D. Volatilization Study

During Phase 3 of the study, a series of experiments was performed to assess the loss of nitrogen from the soil surface by ammonia volatilization. Experiments were performed with collection periods of 11, 23, and 35 hr corresponding to the rest periods that were maintained between wastewater and flushwater applications.

E. Computer Analysis

Tensiometers were used in this study to gather data to determine moisture flow rates through the root zone. The data contained significant variations that made interpretation and determination of trends very difficult. To aid in interpretation of these data, a computer-based moisture model was selected that simulated moisture conditions within the soil columns.

After reviewing soil-moisture models developed by Hillel [1977] and Saxton, Johnson, and Shaw [1974], the Soil, Plant, Air and Water Model (SPAW) of the latter researchers was chosen for this study. Since this model was originally designed to simulate watershed-scale hydrology, several modifications were necessary to adapt it for use in this study. Moisture movement routines, however, were retained essentially intact except for description of the infiltration process. Very small time steps were used to achieve a more continuous simulation of the infiltration

phase. In addition, the SPAW infiltration routine was modified to include Darcian flow theory for describing moisture movement. This change replaced the simple cascade concept.

The mathematical equation basic to both the infiltration and redistribution processes is the one-dimensional finite difference form of Darcy's flow equation and can be expressed as follows:

$$Q = \bar{K}(\theta) \left(\frac{P_2 - P_1 - \Delta Z}{\Delta Z} \right) \Delta t \quad (1)$$

where:

Q = Amount of flow;

$\bar{K}(\theta)$ = Average unsaturated hydraulic conductivity;

P_2 = Pressure in lower soil layer;

P_1 = Pressure in upper soil layer;

ΔZ = Difference in elevation between soil layer centroids; and

Δt = Time step.

When a soil layer became saturated, $\bar{K}(\theta)$ was replaced by K_{sat} (saturated hydraulic conductivity).

One-dimensional, vertical flow was assumed to be appropriate in this study because the plastic casings effectively prevented lateral moisture movement.

Geometric Model Structure: The geometric structure of the SPAW model is shown in *Figure 4*. The soil profile was divided into 5.08-cm or 7.62-cm layers. Equation 1 was solved for each of these layers to simulate moisture movement through the soil columns.

Model Calibration: The objective of the calibration process was to accurately simulate observed drainage from the base of each soil column. During calibration, attempts were made to find the parameter set that both met the primary objective and adequately described soil moisture con-

tent at the three tensiometer locations within the soil profile. Emphasis was placed on correctly simulating drainage volumes because measurements of drainage were considered much more accurate than the soil-tension measurements on which moisture content was based. Calibration of the model was basically a trial and error procedure in which several parameters in the model were systematically varied to obtain a parameter set that gave an acceptable match between simulated and observed drainage and soil moisture data. Agreement between simulated and observed drainage was good, and the moisture flow equation appeared to yield accurate results.

Model Usage: The data generated by the model were analyzed to determine liquid residence times in the root zone. Two procedures were attempted. In the first approach, residence time in the root zone was defined as the length of time necessary for liquid inputs to be balanced by losses (through evapotranspiration and drainage), taking into account the changes in moisture storage within the root zone. When this criterion was satisfied, the elapsed time was determined. This analysis was performed on each column.

The second approach involved a detailed examination of the moisture balance in the root zone between successive liquid applications. The objective of this analysis was to assess the magnitude of drainage from the root zone during and after liquid applications.

F. Wastewater and Leachate Sampling and Preservation

Samples of wastewater were collected for analysis each time wastewater was applied. Samples of leachate (soil water) at the 17.8-cm depth (i.e., below the root zone) were also collected each time wastewater was applied. All samples were frozen immediately after collection for chemical analysis.

Soil-water samples were obtained by means of porous cup soil-water samplers, each of which was attached to a collection flask. A suction of 38 cm Hg (1/2 bar) was applied to each flask. Collection periods of up to 24 hr were required to obtain sufficient sample for chemical analysis. Sufficient sample volumes could not be obtained at the 48.3-cm depth within a 24-hr period, so sampling efforts at this depth were discontinued.

Effluent samples were collected at the base of each column on a weekly basis during Phase 1 experiments (December 1980 through mid-March 1981). Samples were collected less regularly during the second phase (late July through early September 1981). From late September 1981 until termination of the experiments in November 1981, effluent samples were collected at weekly intervals. To prevent bacterial activity in the effluent samples during collection, 10 drops of concentrated H_2SO_4 were added to each vacuum collection flask.

G. Analytical Procedures

All soil-water, effluent, and synthetic wastewater samples were analyzed for Cl^- , NH_4^+ -N, and NO_3^- -N using specific ion electrodes (Models 94-17, 95-10, and 93-07, respectively, Orion Research, Cambridge, Massachusetts) and a Model 801 digital pH/mV meter (Orion Research). A Fisher pH electrode (Model 13-639-97, Fisher Scientific Co., Pittsburgh, Pennsylvania) and Fisher 620 Accumet pH meter (Fisher Scientific Co.) were used to analyze pH.

Selected samples of wastewater and soil water were analyzed for total nitrogen (to facilitate mass balance calculations) using a block digester (Industrial Procedure No. 321-74A, Technicon Industrial Systems, Tarrytown, New York) followed by steam distillation (semi-micro Kjeldahl procedure [Bremner, 1965]). Selected soil samples were analyzed for total nitrogen using the block digestion procedure of Nelson and Sommers [1972] but substituting Kelpak (Matheson Chemical Co., East Rutherford, New Jersey) reagents for the catalysts. The analysis was completed by steam distillation using the semi-micro Kjeldahl technique [Bremner, 1965].

Preliminary soil analyses were made by the Virginia Tech Extension Soil Testing Laboratory using standard techniques [Donohue and Gettier, 1980] for pH, NO_3^- -N, and percent organic matter. Mechanical analysis of soil was performed by the hydrometer method [Day, 1964].

H. Statistical Procedures

Wastewater applications were made under two experimental conditions. During Phases 1 and 2 of the study, liquid (including wastewater) was applied when soil tensions at 10.2 cm were 550-600 mb. Different residence times in the root zone were induced by different suctions at the

base of the soil columns. During Phase 3, suction at the base of each column was maintained as in Phases 1 and 2, but flush-water applications were added to achieve more positive control over wastewater residence time in the root zone.

Consequently, data from soil-water and effluent samples were segregated into two groups for statistical analysis. One group was composed of chemical data from samples collected during Phases 1 and 2 of the study (i.e., before September 10, 1981). Data from samples collected after September 10 were placed in a second group. In addition, soil-water sample data were analyzed separately from effluent data.

The Statistical Analysis System [SAS Institute, 1979] was followed for all statistical analyses. Univariate analysis was used to determine the variability of both soil-water and effluent sample data. Analyses of variance and, where appropriate, mean separation were made to determine possible treatment effects.

RESULTS

I. Residence Time Determinations

Tensiometer data were highly variable. To isolate differences between the rate of moisture movement through different soil columns and/or the same soil column when at different soil tensions, the data were smoothed using a computer-based soil-moisture model. This procedure involved adjusting several model parameters to achieve close agreement between simulated and observed soil tensions while simultaneously matching simulated with observed drainage ("Model Calibration" [p. 12]). Thus, use of the modified SPAW model allowed calculation of liquid residence time in the root zone (*Table 5*). These times were determined using a mass balance concept of liquid residence time.

Values given in *Table 5* represent times required for liquid additions to the columns to be balanced by drainage and evapotranspiration losses from the root zone. In some cases, tensiometers indicated that it was time for another liquid addition before all previously applied liquid had left the root zone. Thus, the values in *Table 5* do not always indicate the amount of time any single application of liquid was in the root zone.

Analyses of moisture balance in the root zone during and between individual liquid applications provided more insight into the fate of applied liquid. *Figures 5* through *12* are graphical representations of moisture balances in the root zone for individual columns during and after single liquid applications. In these *Figures* evapotranspiration, storage, and drainage are presented as percentages of applied liquid. For ease of comparison, *Figures* are presented for application periods that began when initial moisture content in the root zone of each column was approximately equal. These *Figures* are, however, representative of other application periods.

Drainage curves had a characteristic shape that indicated rapid drainage lasting for approximately 2 hr, followed by a much lower drainage rate. Rapid drainage occurred because liquid additions were made when the root zone was near saturation (50-75 percent saturated in most cases). This, in turn, occurred because the soil used in the study exhibited narrow ranges of moisture contents, as evidenced by the relatively flat moisture characteristic curves in *Figure 13*. For example, although only that portion of each characteristic curve between 0 and 1,000 mb tension is

shown in *Figure 13*, moisture retention between 0 and 15,000 mb soil tension was approximately 0.28 cm/cm in the A_p horizon, 0.09 cm/cm in the B_{21t} horizon, and 0.15 cm/cm in the B_{22t} horizon. Of these amounts, approximately 60 percent in horizons A_p and B_{21t} and 32 percent in the B_{22t} horizon were held between 0 and 700 mb (i.e., between tensions that were within the operating range of the tensiometers used in this study). Further, 80-86 percent of water held between 0 and 700 mb tension was actually held between 0 and 300 mb tension. (For agronomic purposes, free drainage is assumed to occur between 0 and approximately 300 mb tension.)

The experiments in this study were conducted while the root zone was maintained at soil tensions within the operating range of tensiometers (i.e., 0-700 mb). Consequently, liquid applications were made when the root zone was very near the point at which free drainage occurs. Because these conditions are presumed conducive to contaminant transport through the root zone, they would normally be avoided during operation of a land-based wastewater treatment system. However, as evidenced by the soil used in this study, these soil conditions may, in fact, be typical and unavoidable. Hence, a method was sought that would permit estimation of the amount of drainage that would occur as a result of wastewater applications in a land treatment system using soils similar to those studied in this investigation.

Drainage curves predicted by the modified SPAW model were separated into two segments—Segment I, consisting of the rapid drainage period, and Segment II, consisting of the gradual drainage period (*Figure 14*). Each segment was analyzed to obtain a simple, mathematical relationship to describe its shape.

Initial drainage was defined as the total amount of drainage that had occurred when the slope of the drainage curve (i.e., drainage rate) reached a maximum and began decreasing. The transition from Segment I to Segment II was arbitrarily assumed to occur at this point. (It is designated as the inflection point on *Figure 14*.) Analyses were conducted to obtain a simple, mathematical relationship to predict initial drainage and the drainage rate during Segment II.

Two procedures were used to estimate initial drainage. In the first method, initial drainage was approximated by *maximum potential drainage* (defined as the amount by which liquid applications exceeded unfilled pore

space in the root zone). Unfilled pore space was calculated as the difference between saturation moisture content and the soil moisture content at the instant prior to application of liquid. Thus, to determine maximum potential drainage, moisture content in the root zone was determined (just before each liquid application), unfilled pore space was calculated, and the resulting value subtracted from the amount of liquid applied. Statistical analyses indicated that there was no significant difference between actual initial drainage and estimates of initial drainage by maximum potential drainage except for Column 9 (*Table 6*).

The second method of estimating initial drainage involved statistical analysis of Segment II of the drainage curves. In this procedure, linear regression was used to determine the relationship between drainage and time for the gradually sloping portion of each drainage curve (i.e., Segment II). The intercepts from these regressions were then assumed to be approximately equal to initial drainage (*Figure 14*). Statistical analysis indicated that no significant difference existed (except for Column 9) in actual initial drainage and estimates of initial drainage using the intercepts of regression equations for this region of the curve (*Table 7*).

Because estimates of initial drainage by both methods described above were statistically the same as actual initial drainage, the estimates themselves were compared statistically. Another reason for these statistical comparisons was that maximum potential drainage is an easily determined quantity and, if no different from the intercepts of the regression equations describing Segment II of the drainage curves, can be used in conjunction with these equations to predict drainage at any time after liquid application. Drainage volumes predicted by each of these procedures were compared statistically using a paired *t*-test. Results from these tests, presented in *Table 8*, show that drainage predicted by the two methods was significantly different within Treatment 3, probably because both estimates of initial drainage were statistically different from actual initial drainage for one (Column 9) of the two columns in Treatment 3.

The rate of drainage after the point of inflection of each drainage curve is equal to the slope of the regression equations. Means of these slopes for each column are presented in *Table 9*. Duncan's multiple range test was used to test for statistical differences in these slopes among treatments. Results of this test are presented in *Table 10* and indicate that there were no significant differences ($P > 0.05$) in slope estimates among treatments.

From a treatment efficiency standpoint (i.e., comparison of contaminants introduced into the root zone with those exiting), the relationship between wastewater application and drainage is of importance in the design and operation of a land application system. The modified SPAW model confirmed that rapid drainage will occur from a near-saturated root zone as soon as the unfilled pore space is exceeded by liquid applications.

The relationship that was found based on this concept allowed a priori prediction of the amount of drainage to be expected from a given application of liquid. The validity of this procedure is illustrated in *Table 11*, which summarizes results of a *t*-test comparing drainage calculated using the procedure described above with observed drainage (i.e., that predicted by the modified SPAW model). Initial drainage from the root zone was calculated as maximum potential drainage, and the average slope of all drainage curves was used to describe drainage as a function of time after initial drainage. *Table 11* indicates no statistical differences ($P > 0.05$) between observed drainage and drainage predicted by empirical means.

While the relationships that were developed were based on simulated drainage, their theoretical basis rests on widely accepted concepts of moisture flow into and through the soil profile and moisture loss from the soil profile by evapotranspiration.

II. Nitrogen Additions and Removals

A. Additions

Seals around the suction plates on all columns required frequent repair, necessitating removal of the columns from operation for varying lengths of time. This situation, coupled with the fact that wastewater mixed prior to mid-August 1981 was proportioned incorrectly, resulted in nitrogen additions that were less than the target rate of 116 kg/ha. *Table 12* gives the cumulative amounts of NH_4^+ -N added to each column.

B. Removals

Results from analyses of soil samples for pH, percent organic matter, and NO_3^- -N are presented in *Table 13*. Designations *Before* and *After* refer to samples taken before wastewater was applied to the soil columns and those taken at the conclusion of the experiment, respectively. Without exception, very little change in soil organic-matter content took

place; however, dramatic reductions occurred in NO_3^- -N content, especially in the A_p soil horizon (upper 18 cm).

Summaries of data for soil-water samples collected before and after September 10, 1981, are contained in *Tables 14* and *15*, respectively. *Tables 16* and *17* contain summaries of data describing chemical characteristics of effluent samples collected before and after September 10, respectively. A summary of the total mass of nitrogen and chloride contained in these samples is presented in *Table 18*.

Table 19 contains data on the mass of nitrogen lost to the atmosphere via volatilization of NH_3 -N from wastewater after application. Data for cumulative volatilization at 35 hr could not be obtained because of equipment malfunction. Data from this experiment were variable and demonstrated no clear trend when compared on the basis of sample collection time.

Fescue was cut four times during the study. Yield, nitrogen concentration, and mass nitrogen removals are presented in *Table 20*. In the first three harvests, grass was cut approximately 7.5 cm above the soil surface. Yields on November 12, 1981, appear to be small in comparison to those obtained at other cuttings. However, these smaller yields can probably be attributed to the shorter growth period between this and the previous (August 11, 1981) harvest. On the final cutting, all above-ground vegetation was removed, which explains the relatively large yields recorded at this cutting despite the fact that the growth period was nearly equal to that of the previous harvest.

Table 21 summarizes mass nitrogen additions and removals. Here, wastewater additions include not only NH_4^+ -N, but organic and NO_3^- -N as well. Except for Column 10, additions exceeded losses. Unaccountable losses ranged from 0 (Column 10) to 53 percent (Column 5) of the applied nitrogen.

The important comparisons that must be made to evaluate how well the soil system removed nitrogen from the wastewater are between nitrogen additions to the soil surface and removals from the soil profile. Samples of wastewater as it moved through the soil profile were taken from beneath the root zone (at 17.8 cm) and at the base of the soil columns (70 cm).

Summary data presented in *Tables 14* and *15* permit several observations. Of particular interest are the significant reductions at the 17.8-cm depth in NH_4^+ -N concentrations from those in the applied wastewater (approximately 25 mg/l NH_4^+ -N). Removal efficiencies for this constituent ranged from 93 (Column 4) to 98 percent (Column 6) during Phases 1 and 2 of the study and from 95 (Columns 4 and 5) to 97 percent (Column 14) during Phase 3.

Possibilities that could account for the observed nitrogen loss include adsorption onto the ceramic cups of the soil-water samplers, adsorption onto clay particles, volatilization before moving into the soil profile, nitrification to NO_3^- -N, crop uptake, denitrification to nitrogen or nitrogen dioxide gas, or immobilization into organic nitrogen. Although it was not the objective of this study to ascertain their magnitude, measurements were made to estimate all of these pathways with the exception of adsorption and denitrification.

Comparison of NO_3^- -N concentrations found in soil-water samples below the root zone (*Tables 14* and *15*) with those in the applied wastewater indicates removals of NO_3^- -N on the order of 0-58 percent (Columns 16 and 14, respectively). It would appear that nitrification of NH_4^+ -N to NO_3^- -N was negligible or, if it did occur, the transformed NH_4^+ -N was readily used by the crop.

The assumption was made that the loss of NO_3^- -N (*Table 13*) from the 8-cm depth occurred uniformly throughout the entire A_p horizon, and the percentage loss of NO_3^- -N was then converted to mass removals. Comparison of these values with those for crop uptake indicated that in most cases crop removal of nitrogen exceeded what could have been supplied solely by soil nitrogen losses in the A_p horizon.

Examination of data on the quality of samples collected at the base of the columns added insight to the possible fate of applied nitrogen. Comparison of *Tables 14*, *15*, *16*, and *17* shows that relatively large increases in the NO_3^- -N concentration of liquid draining through the soil profile occurred between the 17.8-cm depth and the column bottoms. Two reasons can be given for this:

1. Movement of NO_3^- -N from soil horizons above, or
2. Nitrification of NH_4^+ -N that possibly moved past the root zone.

The extent of either of these sources cannot be readily determined without the use of labeled nitrogen isotopes.

III. Effects of Residence Time on Nitrogen Removals

A. Treatment Effects

Soil-water data collected at 17.8 cm were compared statistically according to date of sample collection to help identify possible variations in pollutant removals with time. *Tables 22* and *23* present results of ANOVA analyses of these data. The null hypothesis was that no significant differences existed among treatments.

In *Tables 22* and *23*, comparisons between calculated and critical F values are given as $Pr > F$ values, which indicate the probability that the calculated F will be exceeded. Thus, small $Pr > F$ values indicate significant differences among treatments because there is a small probability that a critical F value will exceed the calculated F .

Table 22 reveals no detectable significant differences among treatments during Phases 1 and 2 of the study for any of the three parameters tested (Cl^- , NH_4^+ -N, NO_3^- -N). *Table 23* indicates that differences among treatments were detected for NH_4^+ -N on occasion during Phase 3. Because sufficient sample for chemical analysis could not be collected on some dates, statistical comparisons could not be made.

B. Column Versus Treatment Interactions

ANOVA analyses were performed on soil-water data averaged during Phases 1 and 2 and during Phase 3 to investigate possible soil column variability. These analyses separated sources of variation in the observed data into those from treatment effects, sampling error, and experimental unit error. The null hypothesis tested was that no variability occurred among columns within a given treatment.

Results given in *Table 24* indicate that column variability within treatments was significant for NH_4^+ -N analyses during Phases 1 and 2. However, during Phase 3, NH_4^+ -N observations were not significantly influenced by within-treatment column variation, whereas column variation was significant for both Cl^- and NO_3^- -N.

Identical analyses were performed on data from effluent samples collected at 70 cm during these time periods. Results given in *Tables 25* and *26* indicate no detectable differences among treatments for any parameter during either time span.

Table 27 presents results of ANOVA analyses used to determine the significance of experimental unit error. This source of error was significant in NO_3^- -N analyses during Phases 1 and 2 and for all analyses during Phase 3.

Two explanations can be offered for the failure to observe differences in N removal rates. One explanation concerns the attainment of different wastewater residence times in the root zone. Difficulty was encountered at the initiation of the study in deducing moisture movement rates from tensiometer data. However, predictions by the modified SPAW model indicated that a large percentage of drainage from the root zone of columns in *all* treatment groups occurred within similar time spans (approximately 2 hr). In effect, then, probably little difference existed in liquid residence times in the root zone during Phases 1 and 2 of this study. Because wastewater was applied during Phases 1 and 2 under soil conditions similar to those for which the modified SPAW model was used, it is logical to assume that one reason no differences were observed in N removals was because different wastewater residence times were not attained. During Phase 3, however, more positive control over wastewater residence times was attempted by first applying the wastewater and then flushing it from the root zone at varying times after application. If, though, the initial application of wastewater had moved through the root zone in a manner similar to that in Phases 1 and 2, real differences in residence time would not have been achieved, despite the use of flush water.

The second and completely different explanation for the failure to observe differences in nitrogen removals as a function of wastewater residence time in the root zone is that the experimental design was not sensitive enough to detect the differences. In general, variations in observed data can be caused by treatment differences and sampling (experimental) error. In some instances, experimental unit error can account for a large portion of sampling error. Experimental unit error results from variations in the experimental units, which, in this study, were the soil columns.

The underlying assumption in establishing the completely randomized design was that no inherent variability occurred within the treatment

units. Although spatial variability of soil characteristics is well-known, this assumption of homogeneity was believed to be justified because the samples were collected close to one another (i.e., within a 3-m by 3-m area). If the assumption that soil characteristics were homogenous is true, the effect of the sampling device on soil structure and/or the interaction between the soil columns and the casing becomes immediately suspect as a cause for variability within experimental units.

Examination of data on the concentration of Cl^- in the effluent samples (*Tables 16* and *17*) does not lend support to either of these arguments however. In only two cases (Columns 9 and 11) during Phases 1 and 2 of the study was there evidence of *short circuiting* of wastewater through the columns. If there had been a massive disturbance of soil structure or if there had been a separation of the soil sample from the casing, concentrations of Cl^- in the effluent would have been little different from those in the applied wastewater.

Differences in crop growth are another possible source of experimental unit error in this study. Comparison of *Tables 24* and *27* reveals that experimental unit error was significant only for NH_4^+ -N in soil water samples and for NO_3^- -N in effluent samples in Phases 1 and 2. Conversely, experimental unit error was highly significant for all parameters except NH_4^+ -N in the soil water samples in Phase 3. The fact that this source of variation was so significant for effluent samples might reflect the influence of root penetration deeper in the soil profile as the experiment progressed and the crop matured.

SUMMARY AND CONCLUSIONS

A laboratory study was conducted to develop a relationship between residence time of a land-applied wastewater in the root zone and the degree to which nitrogen was removed from the wastewater. Undisturbed soil samples were collected in 15-cm diameter by 70-cm long plastic casings. The samples were instrumented with tensiometers, porous-cup soil-water samplers, and ceramic baseplates and were placed in an environmental chamber.

The use of tensiometers as moisture-sensing devices required that liquid additions be made frequently to maintain soil tensions within the operating range of the tensiometers. In addition, a soil was used that exhibited a rather narrow range in moisture contents between 0 and 15,000 mb soil tension. Consequently, when liquid and wastewater additions were made, soil tensions rapidly approached those at which free drainage of soil water is considered to occur. Depending on the soil, such moisture conditions would be normal for a properly designed land-based wastewater treatment system or could be created by a variety of natural or man-induced circumstances. An empirical procedure was developed to predict drainage from the root zone of a land-based wastewater treatment system operating in soils with physical characteristics similar to those encountered in this study. However, future investigations should include soils that exhibit a wider range in soil-moisture contents as a function of soil tension. In addition, more sophisticated soil-moisture monitoring equipment, such as dual gamma-ray attenuation, is absolutely essential to attain increased precision in determining bulk densities and movement of the moisture front.

Statistical analyses failed to reveal any effect of treatment (i.e., residence time in the root zone) on removals of nitrogen from the wastewater as it moved through the root zone. Experimental unit error was significant in some cases, however, and could have masked treatment effects. Comparison of the nitrogen content of applied wastewater with that of soil-water samples collected from beneath the root zone indicated large reductions in NH_4^+ -N concentrations as wastewater moved through the root zone. Effluent samples from the base of some soil columns indicated that perhaps some of the NH_4^+ -N removed from the wastewater had been nitrified and had moved through the soil profile as NO_3^- -N.

Although no correlation could be found to describe nitrogen removals

from a land-applied wastewater as a function of the time it was in the root zone, significant NH_4^+ -N reductions (up to 90 percent of applied NH_4^+ -N) were achieved within the root zone in as little as 2 hr. However, because the experiment was not designed to determine the exact nature of such reductions, the fate of this NH_4^+ -N cannot be determined with certainty.

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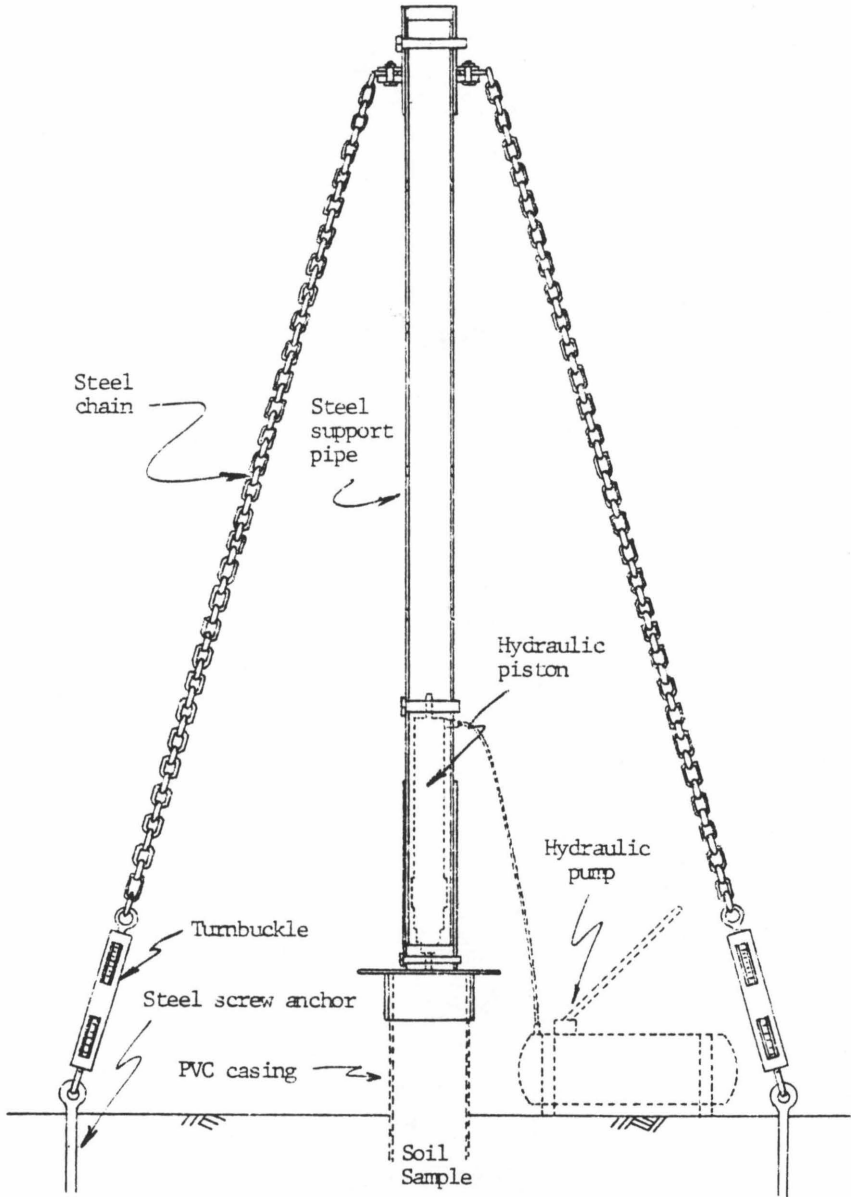
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FIGURES

FIGURE 1
Soil Sampler Used to Collect Undisturbed Samples*



*After Richards, 1971.

FIGURE 2
Cross Section of Suction Apparatus

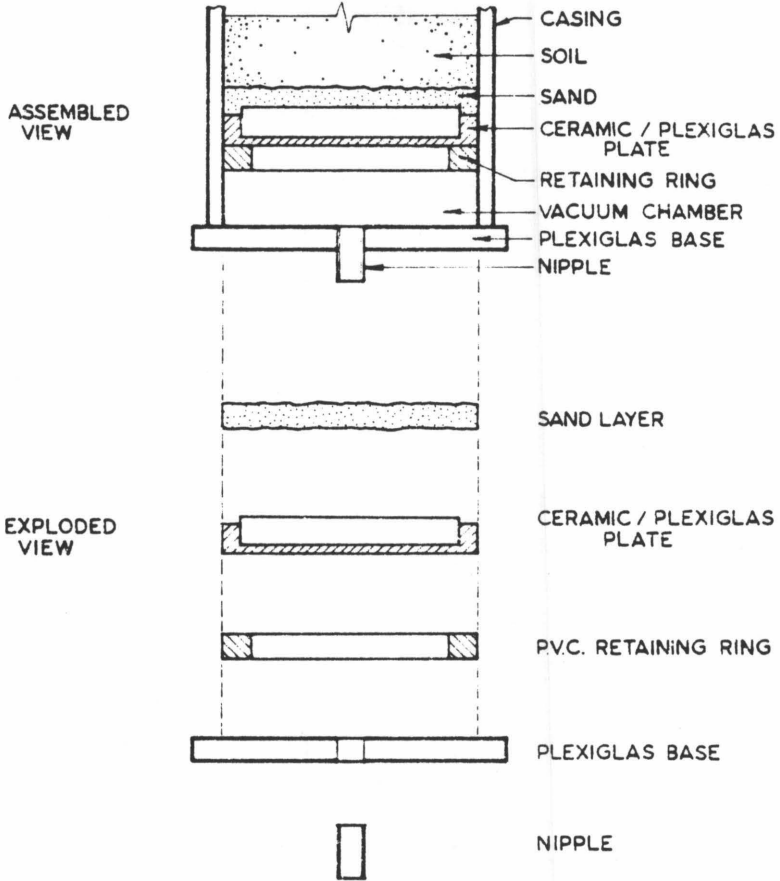
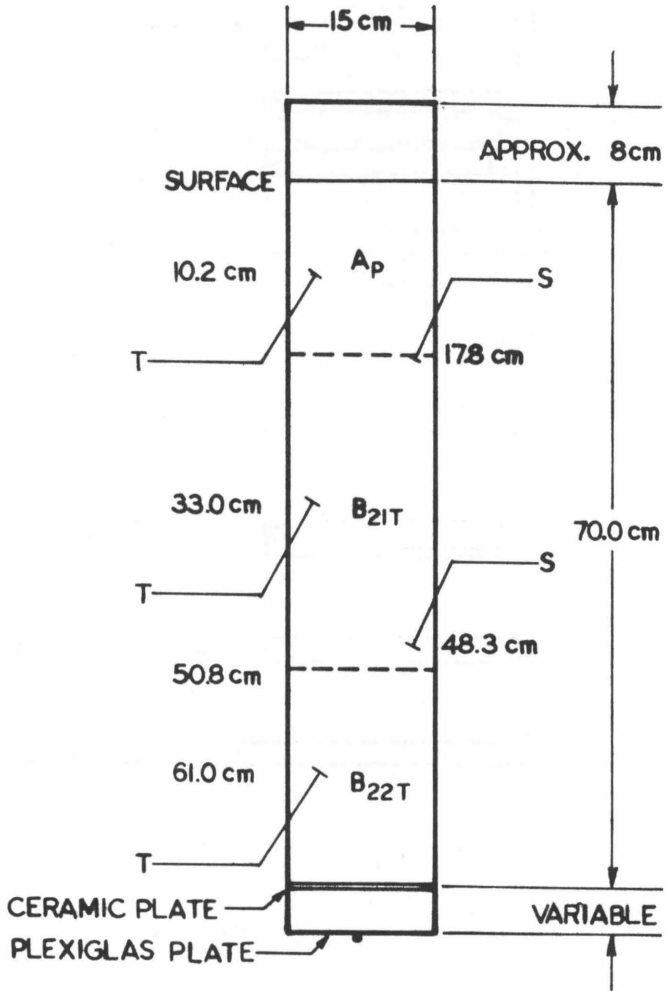


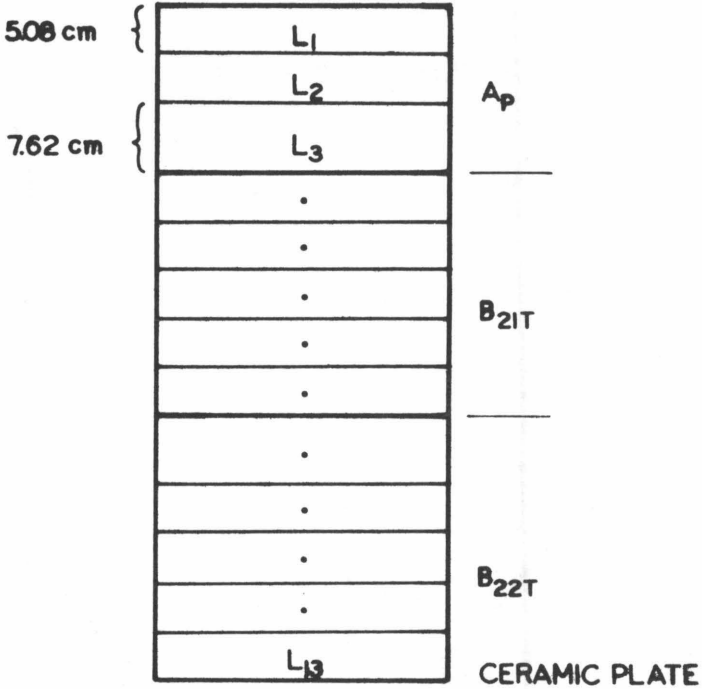
FIGURE 3
Cross Section of Typical Column



S = SUCTION CUP, DEPTH INDICATED

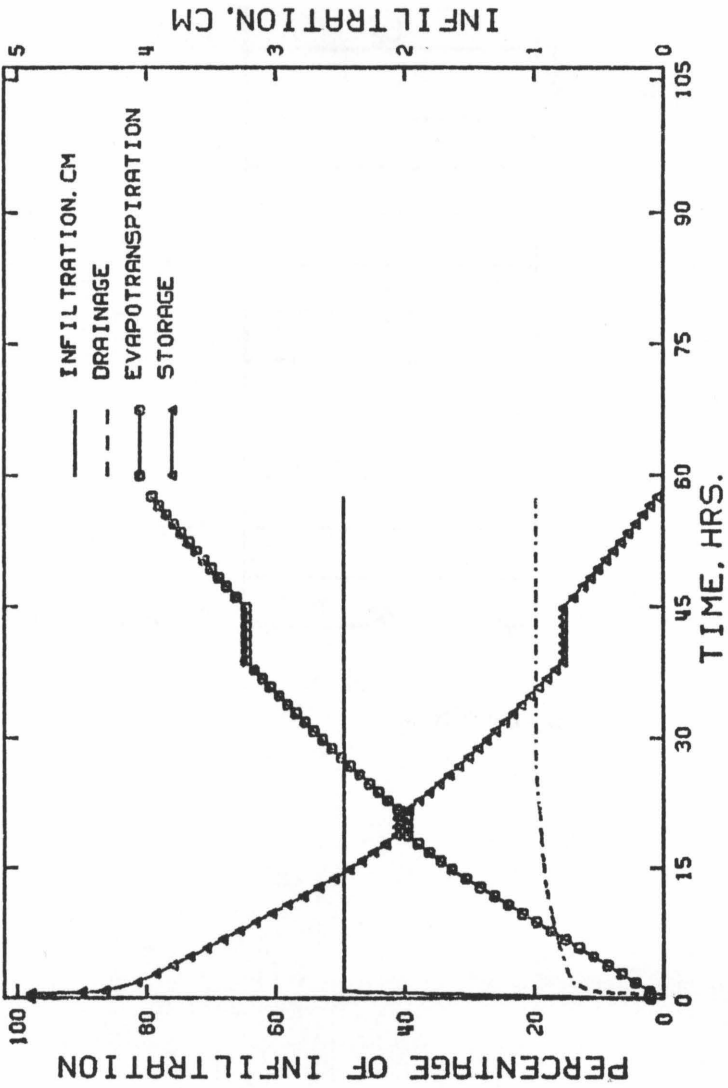
T = TENSIO METER, DEPTH INDICATED

FIGURE 4
Geometric Structure of Modified SPAW Model



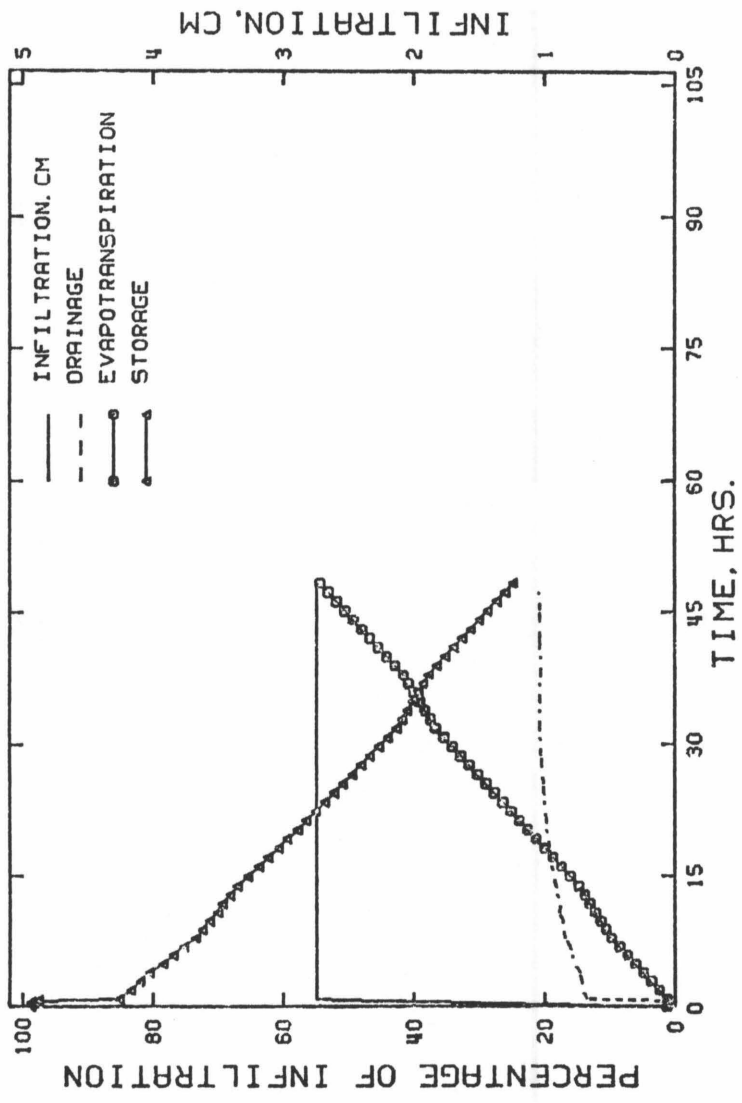
L = LAYER

FIGURE 5
Moisture Balance in Root Zone for Column 4, 1/3 Bar*



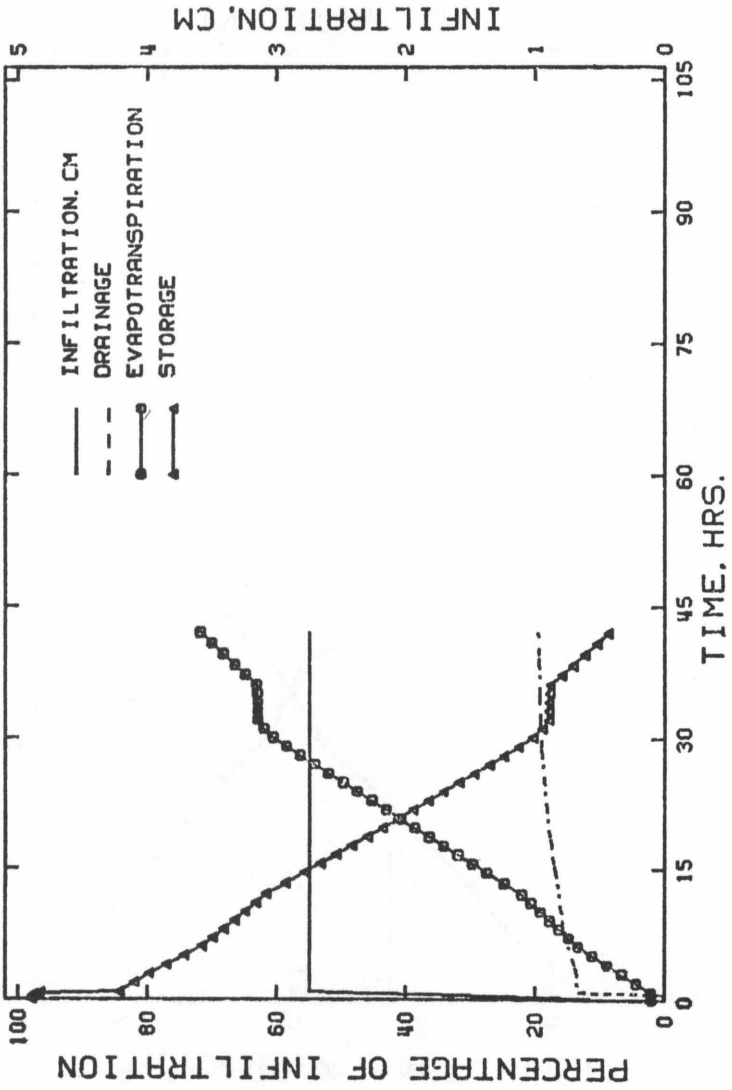
*Upper 5 cm are 42 percent saturated.

FIGURE 6
Moisture Balance in Root Zone for Column 5, 1/3 Bar*



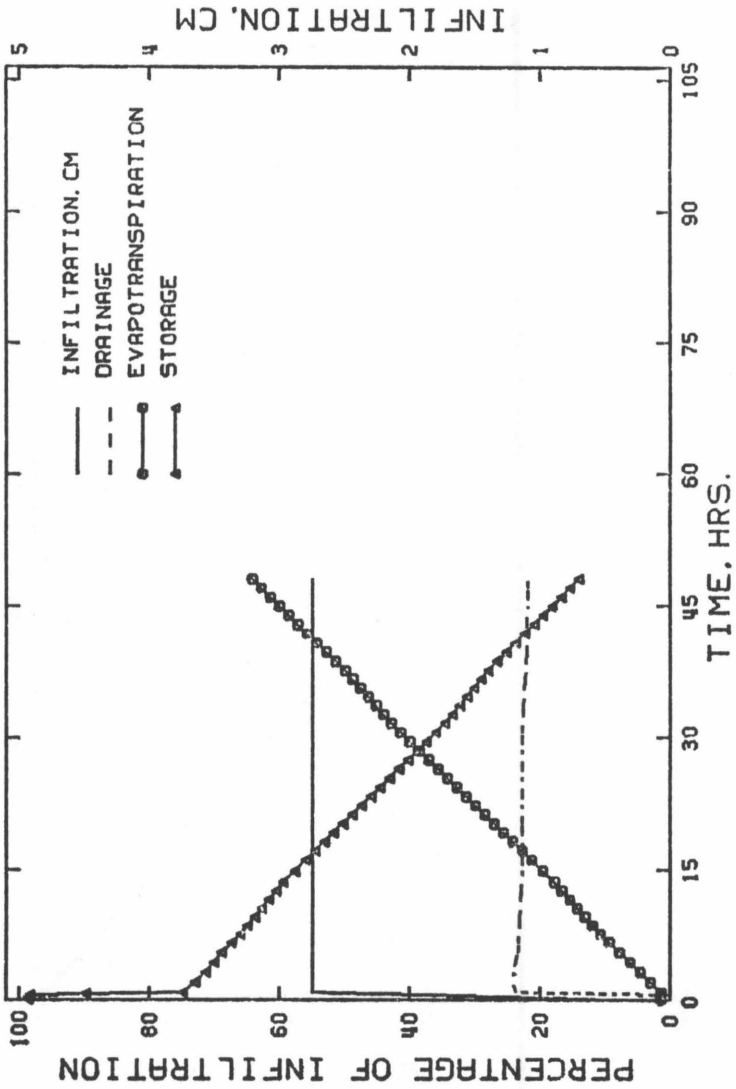
*Upper 5 cm are 41 percent saturated.

FIGURE 7
Moisture Balance in Root Zone for Column 16, 1/3 Bar*



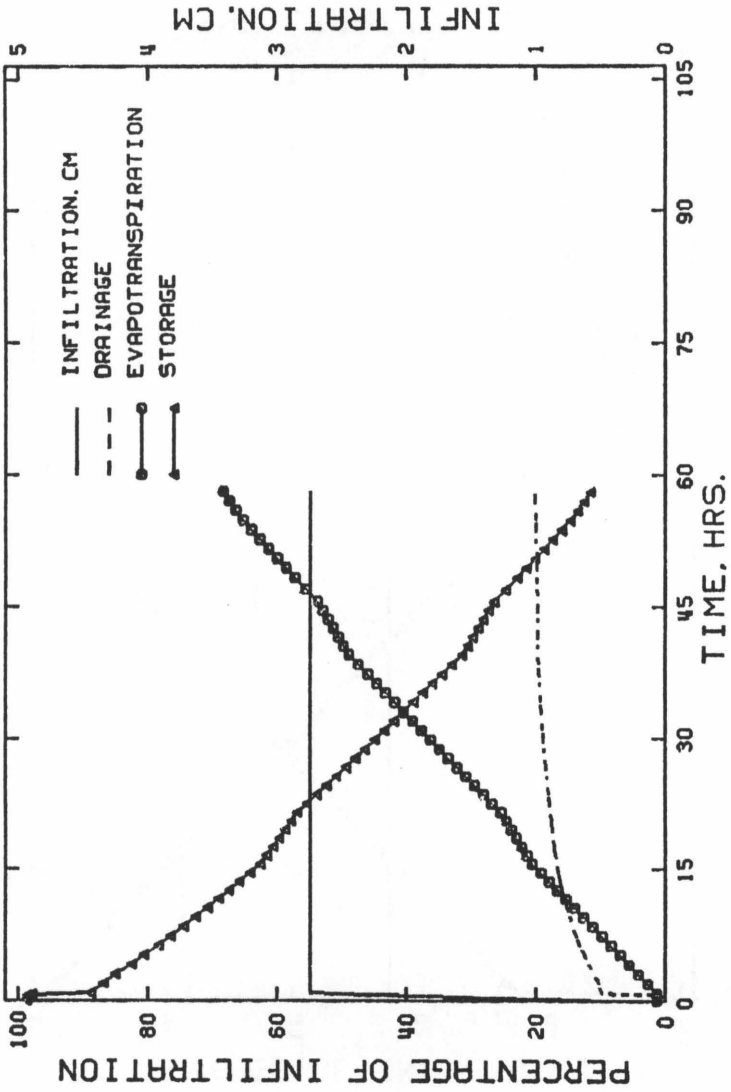
*Upper 5 cm are 42 percent saturated.

FIGURE 8
Moisture Balance in Root Zone for Column 12, 1/2 Bar*



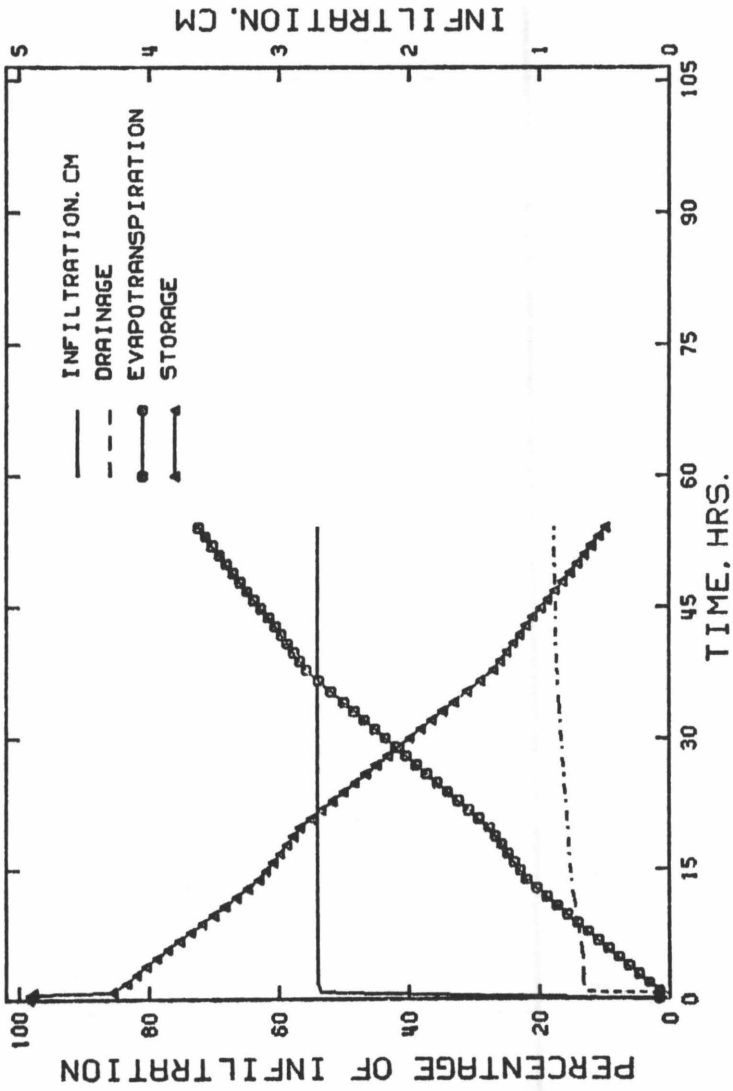
*Upper 5 cm are 42 percent saturated.

FIGURE 9
Moisture Balance in Root Zone for Column 14, 1/2 Bar*



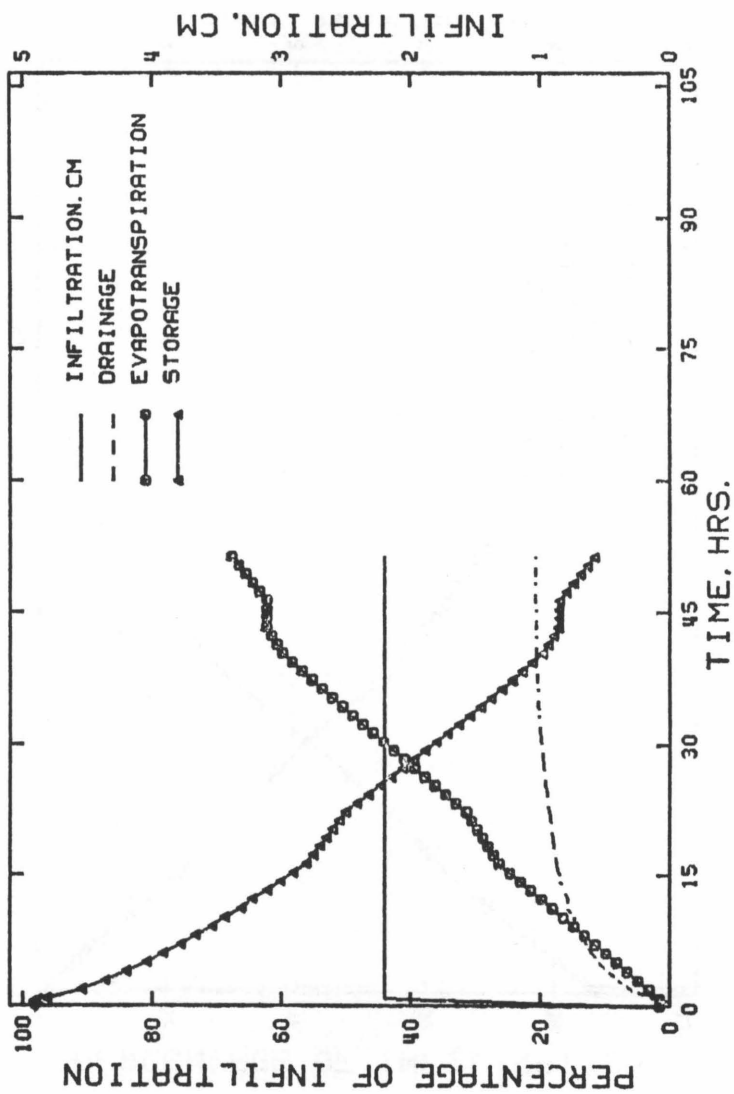
* Upper 5 cm are 42 percent saturated.

FIGURE 10
 Moisture Balance in Root Zone for Column 6, 2/3 Bar*



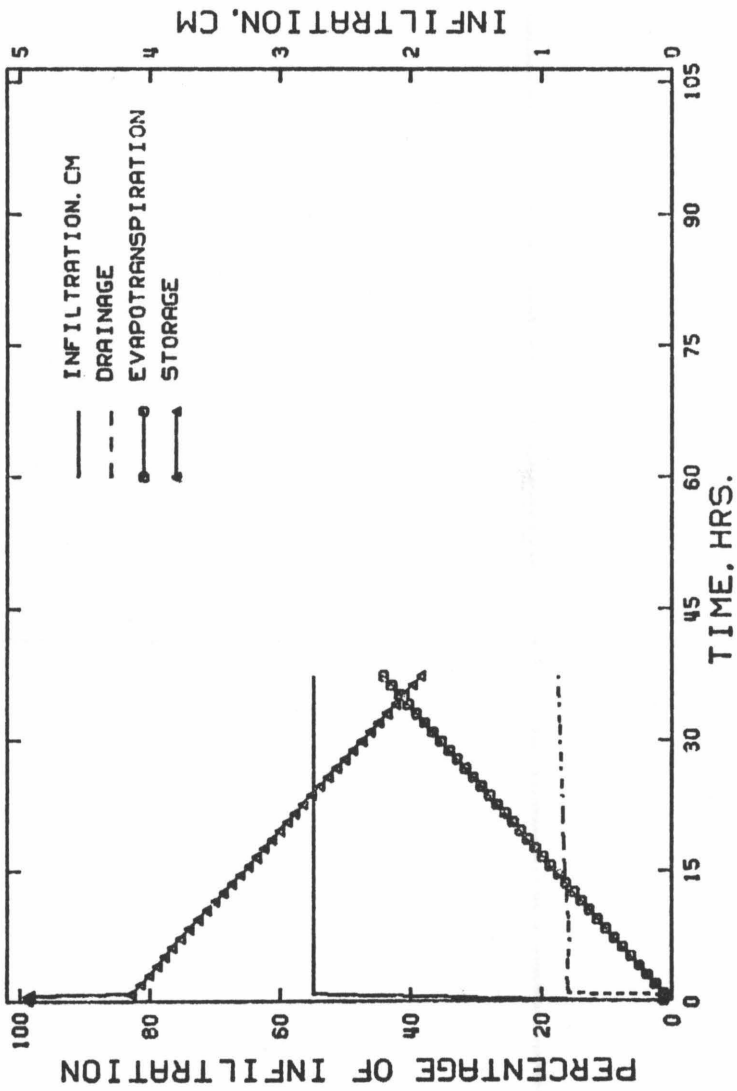
*Upper 5 cm are 41 percent saturated.

FIGURE 11
Moisture Balance in Root Zone for Column 9, 2/3 Bar*



*Upper 5 cm are 42 percent saturated.

FIGURE 12
Moisture Balance in Root Zone for Column 13, 2/3 Bar*



* Upper 5 cm are 43 percent saturated.

FIGURE 13
Moisture Characteristic Curves

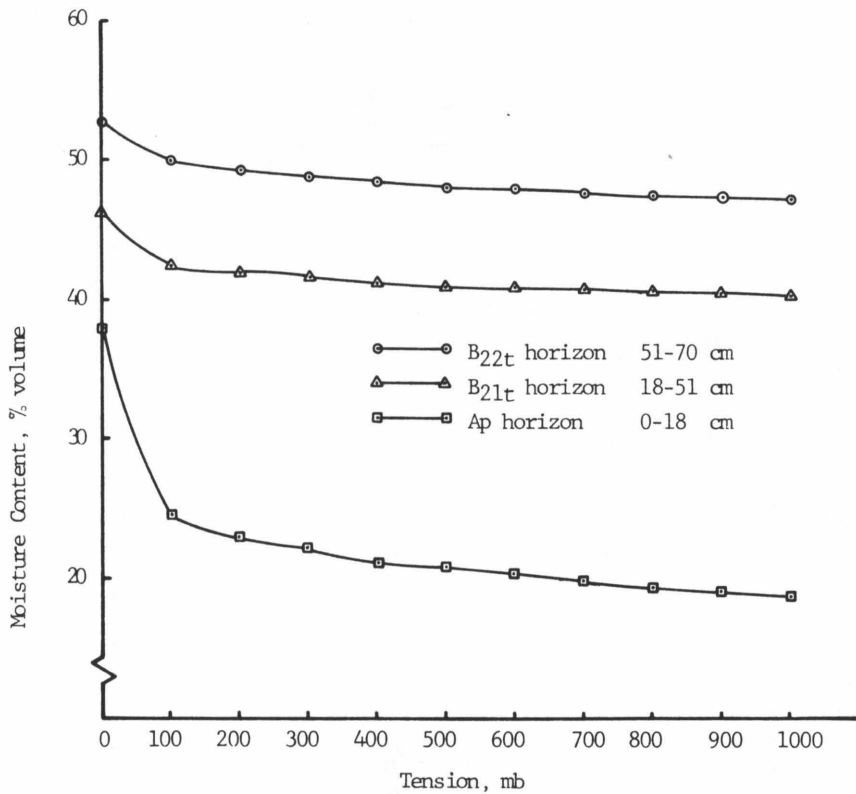
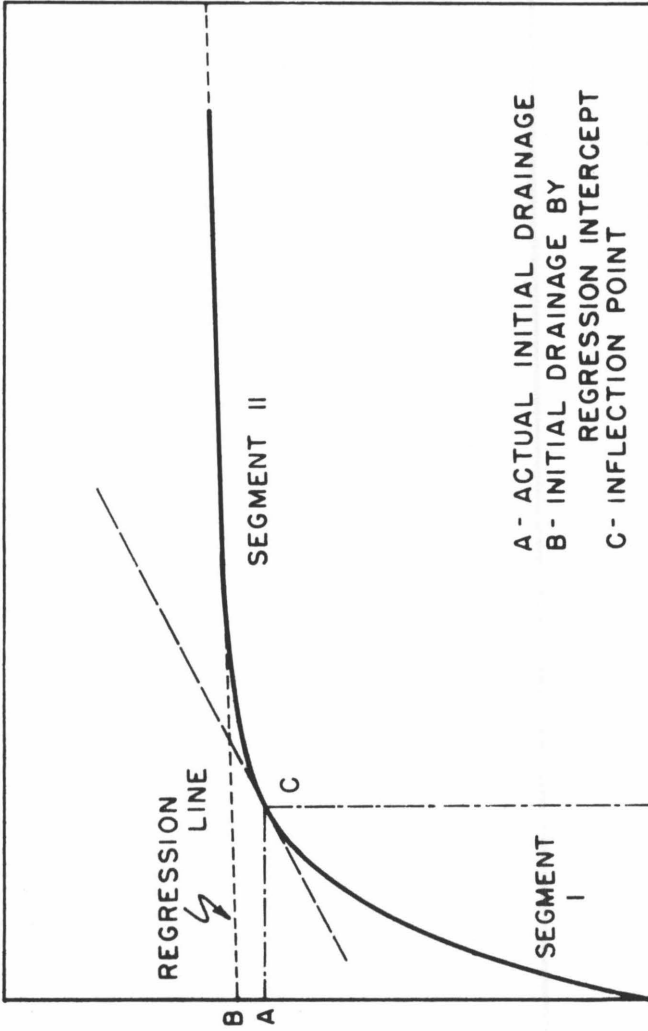


FIGURE 14
Separation of Drainage Curves for Statistical Analysis



TABLES

TABLE 1
Summary of Model Considerations

Researchers	Biological Transformations				Crop Growth Sub-Model	Verification
	Immobilization	Mineralization	Nitrification	Denitrification		
Dutt et al. (1972)	yes	yes	yes	no	no	lab
Saxton et al. (1977)	no	yes	yes	no	corn	field
Hagin and Amberger (1974)	yes	yes	yes	yes	corn	none
Beek and Frissel (1973)	yes	yes	yes	no	no	none
Burns (1975, 1977)	no	no	no	no	no	literature data
Mehran and Tanji (1974)	yes	yes	yes	yes	no	literature data
Reuss and Innis (1977)	yes	yes	yes	no	grassland	none
Duffy et al. (1975)	yes	yes	yes	yes	corn/soy beans	field
Addiscott (1977)	no	no	no	no	no	field
Cameron and Kowlenko (1976)	yes	no	yes	no	no	lab
Tanji et al. (1977, 1979)	no	no	no	yes	no	field

TABLE 2
Summary of Model Considerations II

Researchers	Layered Structure*	Approach†	Nitrogen Inputs						Leaching	Runoff	
			Precipitation	Fixation	Crop Residue	Organic		Fertilizers			Exchange
						Wastes	External				
Dutt et al. (1972)	y(var)	E	no	no	no	no	yes	yes	no		
Saxton et al. (1977)	n	D	yes	no	yes	no	yes	no	yes		
Hagin and Amberger (1974)	y(var)	D	no	no	yes	yes	yes	no	yes		
Beek and Frissel (1973)	y(20)	D	no	no	yes	yes	no	no	yes		
Burns (1975, 1977)	y(var)	E	no	no	no	no	yes	no	yes		
Mehran and Tanji (1974)	n	D	no	no	yes	no	no	yes	no		
Reuss and Innis (1977)	y(4)	C	yes	yes	yes	no	no	no	no		
Duffy et al. (1975)	y(11)	E	yes	no	no	no	yes	no	tile flow		

(continued)

TABLE 2 (continued)

Researchers	Layered Structure*	Approach†	Nitrogen Inputs						Leaching	Runoff
			Precipitation	Fixation	Crop Residue	External		Exchange		
						Organic Wastes	Fertilizers			
Addiscott (1977)	y(var)	D	no	no	no	yes	no	yes	no	
Cameron and Kowlenko (1976)	n	D	no	no	yes	no	no	yes	no	
Tanji et al. (1977, 1979)	n	D	yes	yes	no	yes	no	yes	return flow	

*y=yes; n=no; (x)=number of layers; var=variable.

†E=empirical; D=deterministic; C=combination.

TABLE 3**Theoretical Chemical Composition of Stock Synthetic Wastewater**

Organic Strength (COD)	2,000 mg/l
Volatile Acids	300 mg/l
Organic Nitrogen	60 mg/l
Fat	50 mg/l
Starch	249 mg/l
Glycerol	145 mg/l
NH ₄ ⁺ -N	250 mg/l
COD/TOC	2.75
pH	7.4

TABLE 4
Wastewater Additions

Date	Treatment and Column Number								
	1/3 Bar			1/2 Bar			2/3 Bar		
	4	5	16	11	12	14	6	9	10
12/16/80				A*	A		A	A	
12/17/80	A	A							
12/18/80								A	
12/20/80	A	A							
12/21/80			A	A				A	
12/31/80		A					A		
1/1/81	A		A						
1/2/81				A	A				
1/5/81	A	A	A	A	A		A	A	
1/10/81	B†	B	B	B	B	B	B	B	B
8/14/81	A	A	A	A	A	A	A	A	A
8/21/81	A	A	A	A	A	A	A	A	A
8/31/81	B	B	B	B	B	B	B	B	B
9/9/81	A	A	A	A	A	A	A	A	A
9/15/81	A	A	A						
9/17/81							A		
9/18/81				A	A	A		A	A
9/22/81	A	A	A						
9/28/81				A	A	A	A	A	A
9/29/81	A	A	A						
10/6/81	A	A	A	A	A	A	A	A	A
10/15/81	A	A	A						
10/16/81				A	A	A			
10/17/81							A	A	A
10/22/81	A	A	A						
10/23/81				A	A	A			
10/24/81							A	A	A
10/29/81	A	A	A						
10/30/81				A	A	A			
10/31/81							A	A	A
11/5/81	A	A	A						
11/6/81				A	A	A	A	A	A

*50 ml stock wastewater and 450 ml distilled water.

†100 ml stock wastewater and 900 ml distilled water.

TABLE 5
Range of Residence Times in Root Zone

Treatment	Column Number	Residence Time (hr)
1/3 Bar	4	21.0
		88.3
		63.2
		89.8
		61.5
		66.5
		120.3
		32.0
		53.8
		1/3 Bar
67.3		
47.5		
54.5		
52.5		
67.6		
58.3		
44.5		
37.5		
54.0		
1/3 Bar	6	54.4
		39.0
		34.5
		34.5
		138.8
		42.5
		40.5
		52.0
		44.8
		31.4
1/2 Bar	12	47.5
		78.8
		99.0
		47.5
		28.5
		212.6
		94.1
		42.2

(continued)

TABLE 5 (continued)

Treatment	Column Number	Residence Time (hr)
1/2 Bar	14	37.5
		54.9
		114.8
		150.8
2/3 Bar	6	93.5
		64.3
		44.8
		48.9
		59.5
		123.6
		73.3
2/3 Bar	9	24.5
		43.0
		52.2
		27.5
		92.5
		109.0
		49.0
		48.2
2/3 Bar	9	177.0
		51.5
		50.8
		46.4
		44.9

TABLE 6**Statistical Comparison of Observed and Estimated Initial Drainage
(by Maximum Potential Drainage)**

Treatment	Column Number	t	Pr > t	Significance
1/3 Bar	4	0.60	0.56	NS*
	5	-0.58	0.58	NS
	16	0.72	0.49	NS
1/2 Bar	11	1.39	0.19	NS
	12	-1.33	0.20	NS
	14	-0.95	0.37	NS
2/3 Bar	6	1.24	0.23	NS
	9	2.42	0.03	St

*Not significant at the 5 percent level.

†Significant at the 5 percent level.

TABLE 7**Statistical Comparison of Observed and Estimated Initial Drainage
(by Linear Regression)**

Treatment	Column Number	t	Pr > t	Significance
1/3 Bar	4	-0.08	0.94	NS*
	5	-1.51	0.16	NS
	16	-2.39	0.04	NS
1/2 Bar	11	-1.82	0.09	NS
	12	-1.09	0.29	NS
	14	-1.20	0.27	NS
2/3 Bar	6	-2.04	0.06	NS
	9	-2.59	0.02	St

*Not significant at the 5 percent level.

†Significant at the 5 percent level.

TABLE 8**Comparison of Initial Drainage Calculation: Linear Regression Analysis
Versus Maximum Potential Drainage**

Treatment	t Statistic	Significance Level
1/3 Bar	1.29	0.1250 NS*
1/2 Bar	-0.58	0.5673 NS
2/3 Bar	2.99	0.0057 HS†

*Not Significant at the 5 percent level.

†Significant at the 1 percent level.

TABLE 9**Mean Values for Slopes of Drainage Curves as Predicted by
Linear Regression Analysis**

Treatment	Column Number	Predicted Slope (cm/hr)
1/3 Bar	4	-0.0001*
	5	0.0025
	16	0.0026
1/2 Bar	11	0.0042
	12	0.0008
	14	0.0014
2/3 Bar	6	0.0020
	9	0.0023

*Negative slope indicates root zone was drier than lower profile and was adsorbing moisture from lower soil layers.

TABLE 10
Duncan's Multiple Range Test on Drainage Curve Slopes
Averaged within Treatments

Treatment	Mean Slope	Duncan's M. R. Comparison*
1/3 Bar	0.002127	A
1/2 Bar	0.001122	A
2/3 Bar	0.001564	A

*Means with the same letter are not significantly different at the 5 percent level of significance.

TABLE 11
Comparison of Observed Drainage and Empirically Predicted Drainage

Treatment	t	Pr > t	Significance
1/3 Bar	-0.65	0.5213	NS*
1/2 Bar	0.27	0.7889	NS
2/3 Bar	-1.77	0.0868	NS

*Not significant at the 5 percent level.

TABLE 12
Cumulative NH₄⁺ -N Applications

Treatment	Column Number	Target Application Rate (kg/ha.)	Actual Application Rate (kg/ha.)
1/3 Bar	4	116	67
	5		70
	16		70
1/2 Bar	11	116	67
	12		63
	14		54
2/3 Bar	6	116	63
	9		67
	10		54

TABLE 13
Selected Soil Analyses on Pre- and Post-Experiment Samples

Treatment	Column Number	Depth (cm)	Before			After		
			pH	Organic Matter (%)	NO ₃ ⁻ -N (ppm)	pH	Organic Matter (%)	NO ₃ ⁻ -N (ppm)
1/3 Bar	4	8	5.2	2.1	68.0	5.6	2.4	8.0
		33	4.8	0.9	8.0	5.0	0.9	3.0
		70	5.0	0.6	3.0	5.2	0.6	3.0
	5	8	5.3	2.1	70.0	5.9	2.2	5.0
		33	4.9	0.9	5.0	5.0	0.9	3.0
		70	4.9	0.6	3.0	5.2	0.7	3.0
	16	8	6.0	2.2	70.0	6.5	2.2	3.0
		33	4.7	0.9	13.0	4.9	1.0	3.0
		70	4.5	0.6	13.0	5.1	0.6	3.0
1/2 Bar	11	8	5.1	2.5	75.0	6.1	2.3	8.0
		33	4.9	1.0	13.0	4.9	0.9	3.0
		70	4.8	0.6	3.0	5.0	0.7	3.0
	12	8	4.9	2.1	75.0	5.7	2.3	3.0
		33	4.7	0.9	13.0	4.8	1.1	3.0
		70	4.9	0.7	5.0	5.1	0.7	3.0
	14	8	4.6	2.1	83.0	5.4	2.2	3.0
		33	4.7	0.9	13.0	5.0	1.0	3.0
		70	4.8	0.6	3.0	5.2	0.7	3.0
2/3 Bar	6	8	5.4	2.0	70.0	5.9	2.1	5.0
		33	4.8	0.8	13.0	5.0	1.1	3.0
		70	4.9	0.6	3.0	5.2	0.7	3.0
	9	8	5.7	1.8	68.0	6.6	1.8	8.0
		33	4.9	0.8	8.0	5.0	0.9	3.0
		70	4.8	0.6	3.0	5.2	0.7	3.0
	10	8	5.8	2.2	58.0	6.2	2.3	18.0
		33	4.8	1.1	18.0	4.9	1.1	3.0
		70	4.9	0.7	3.0	5.1	0.7	3.0

TABLE 14
Chemical Characteristics of Soil-Water Samples Collected
at 17.8 cm before September 10, 1981

Treatment	Column Number		Cl ⁻ (mg/l)	NH ₄ ⁺ -N (mg/l)	NO ₃ ⁻ -N (mg/l)
1/3 Bar	4	Mean	24.37	0.89	0.90
		S. D.*	19.04	0.17	0.53
	5	Mean	16.38	0.79	0.42
		S. D.	8.53	0.07	0.27
	16	Mean	11.44	0.69	2.03
		S. D.	7.51	0.14	1.33
1/2 Bar	11	Mean	29.51	0.74	18.35
		S. D.	15.84	0.07	38.78
	12	Mean	16.08	0.68	0.33
		S. D.	10.15	0.22	0.11
	14	Mean	11.44	0.69	2.03
		S. D.	7.51	0.14	1.33
2/3 Bar	6	Mean	16.36	0.26	0.54
		S. D.	10.92	0.74	0.22
	9	Mean	13.62	0.69	0.78
		S. D.	12.52	0.11	0.31
	10	Mean	29.13	0.50	0.95
		S. D.	15.95	0.19	0.06

*Standard deviation.

TABLE 15
Chemical Characteristics of Soil-Water Samples Collected
at 17.8 cm after September 10, 1981

Treatment	Column Number		Cl ⁻ (mg/l)	NH ₄ ⁺ -N (mg/l)	NO ₃ ⁻ -N (mg/l)
1/3 Bar	4	Mean	24.02	0.89	0.45
		S. D. *	6.54	0.33	0.07
	5	Mean	49.72	0.89	0.57
		S. D.	18.00	0.33	0.12
	16	Mean	69.57	0.57	0.95
		S. D.	41.17	0.28	0.33
1/2 Bar	11	Mean	33.57	0.54	0.63
		S. D.	10.31	0.25	0.14
	12	Mean	46.32	0.57	0.47
		S. D.	14.17	0.33	0.10
	14	Mean	33.46	0.43	0.37
		S. D.	10.27	0.25	0.07
2/3 Bar	6	Mean	60.43	0.74	0.68
		S. D.	19.16	0.43	0.23
	9	Mean	34.71	0.52	0.70
		S. D.	7.50	0.22	0.12
	10	Mean	46.07	0.51	0.74
		S. D.	10.43	0.22	0.36

*Standard deviation.

TABLE 16
Chemical Characteristics of Effluent Samples Collected
at 70 cm before September 10, 1981

Treatment	Column Number		Cl ⁻ (mg/l)	NH ₄ ⁺ -N (mg/l)	NO ₃ ⁻ -N (mg/l)
1/3 Bar	4	Mean	4.56	1.75	4.80
		S. D.*	2.64	3.05	8.32
	5	Mean	4.34	0.76	2.57
		S. D.	3.44	0.39	4.18
	16	Mean	6.87	1.35	33.34
		S. D.	7.18	1.34	55.50
1/2 Bar	11	Mean	20.40	0.86	5.32
		S. D.	54.22	0.69	8.40
	12	Mean	3.99	2.31	4.23
		S. D.	1.51	3.38	5.42
	14	Mean	8.92	11.86	82.15
		S. D.	7.98	33.52	187.88
2/3 Bar	6	Mean	7.51	1.23	28.91
		S. D.	4.28	0.93	55.29
	9	Mean	26.83	0.76	7.37
		S. D.	67.82	0.35	8.76
	10	Mean	4.49	0.42	1.50
		S. D.	4.52	0.15	0.60

*Standard deviation.

TABLE 17
Chemical Characteristics of Effluent Samples Collected
at 70 cm after September 10, 1981

Treatment	Column Number		Cl ⁻ (mg/l)	NH ₄ ⁺ -N (mg/l)	NO ₃ ⁻ -N (mg/l)
1/3 Bar	4	Mean	3.50	1.57	6.19
		S. D.*	2.03	1.22	10.65
	5	Mean	3.89	0.34	2.06
		S. D.	1.43	0.29	1.16
	16	Mean	5.02	1.92	7.68
		S. D.	1.42	1.55	6.81
1/2 Bar	11	Mean	4.48	1.70	6.87
		S. D.	1.35	1.49	4.71
	12	Mean	4.20	6.29	16.50
		S. D.	1.51	9.29	22.24
	14	Mean	No Drainage Occurred		
		S. D.			
2/3 Bar	6	Mean	6.69	27.31	42.11
		S. D.	1.44	46.85	73.08
	9	Mean	4.40	4.58	16.01
		S. D.	1.99	3.82	26.96
	10†	Mean	18.99	109.92	173.45
		S. D.	-	-	-

*Standard deviation.

†Data based on a limited number of samples, some of which had very small volumes but unusually high chemical concentrations.

TABLE 18
Cumulative Amounts of Selected Chemicals
in Soil-Water and Effluent Samples

Column Number	Ending Date	Cl ⁻ (mg)	NH ₄ ⁺ -N (mg)	NO ₃ ⁻ -N (mg)	Cumulative Volume (ml)
Soil-Water Samples at 17.8 cm					
4	10/31/81	5.50	0.22	0.16	248.50
5	10/24/81	1.92	0.06	0.03	74.50
16	10/31/81	5.50	0.11	0.28	171.00
11	11/1/81	3.22	0.06	1.03	109.50
12	11/1/81	7.09	0.11	0.08	197.50
14	11/1/81	4.44	0.06	0.05	143.00
6	11/2/81	2.46	0.06	0.04	68.50
9	11/2/81	5.81	0.13	0.18	217.00
10	11/2/81	13.13	0.17	0.28	327.00
Effluent Samples at 70 cm					
4	11/10/81	7.26	2.71	4.37	2128.00
5	11/10/81	12.72	1.77	3.98	3011.00
16	10/22/81	3.19	1.17	2.79	824.00
11	11/6/81	15.80	2.63	13.33	2271.00
12	11/6/81	5.76	3.00	6.66	1487.00
14	10/5/81	3.14	0.91	13.40	872.50
6	10/5/81	6.86	2.46	6.58	1183.00
9	11/11/81	16.75	1.85	5.95	1736.00
10	9/8/81	2.78	0.28	0.85	634.00

TABLE 19
Volatilization of Ammonia Nitrogen

Treatment	Column Number	Collection Time, Hr after Wastewater Addition	NH ₃ -N, μg
1/3 Bar	4	11	78.3
	5	11	49.8
	16	11	93.4
	16	12	107.6
1/2 Bar	11	23	77.8
	11	23	73.1
	12	23	33.7
	14	23	68.3
2/3 Bar	9	35	52.6
	6	9	*
	9	9	18.5
	10	9	16.1

*Equipment failure.

TABLE 20
Crop Yields and Nitrogen Removals

Treatment	Column Number	Yield (g)	Percent N	Total N (mg)	Yield (g)	Percent N	Total N (mg)	
			12/12/80				8/11/81	
1/3 Bar	4	15.95	0.82	130.8	8.10	0.71	57.5	
	5	7.68	0.76	58.4	6.00	0.82	49.2	
	16	14.24	0.88	125.3	11.10	0.51	56.6	
1/2 Bar	11	12.15	0.87	105.7	6.40	0.74	47.4	
	12	15.78	0.79	124.7	7.70	0.72	55.4	
	14	14.85	0.77	114.4	6.70	0.72	48.2	
2/3 Bar	6	8.52	0.90	76.7	4.90	0.89	43.6	
	9	3.52	1.06	37.3	7.60	0.89	67.6	
	10	13.78	1.01	139.2	7.20	0.68	49.0	
			11/12/81				1/31/82	
1/3 Bar	4	3.80	1.22	46.4	11.31	1.21	136.9	
	5	3.35	1.24	41.5	8.94	1.07	95.7	
	16	5.60	1.00	56.0	17.16	0.74	127.0	
1/2 Bar	11	3.10	1.12	34.7	12.01	0.91	109.3	
	12	3.25	1.08	35.1	11.66	1.18	137.6	
	14	3.75	1.08	40.5	18.85	0.74	139.5	
2/3 Bar	6	3.10	1.36	42.2	10.64	1.10	117.0	
	9	3.60	1.30	46.8	12.44	1.13	140.6	
	10	3.50	1.26	44.1	11.28	1.15	129.7	

TABLE 21
Mass Balance of Nitrogen for Entire Study Period

Treatment	Column Number	Additions mg, N		Losses mg, N			Difference mg, N
		Wastewater	Soil	Crop	Volatilization*	Effluent	
1/3 Bar	4	199.6	285.0	371.0	-	7.0	107.0
	5	211.4	309.0	245.0	-	6.0	269.0
	16	211.4	318.0	365.0	-	4.0	160.0
1/2 Bar	11	200.9	318.0	297.0	-	16.0	209.0
	12	188.9	342.0	297.0	-	10.0	168.0
	14	154.5	380.0	343.0	-	15.0	176.0
2/3 Bar	6	188.9	309.0	280.0	-	9.0	209.0
	9	200.8	285.0	293.0	-	8.0	187.0
	10	154.5	190.0	362.0	-	0.0	-0.2

*Negligible.

TABLE 22
**ANOVA Analysis of Soil-Water Sample Data for Treatment Effects:
 Phases 1 and 2**

Date	Cl ⁻		NH ₄ ⁺ -N		NO ₃ ⁻ -N	
	F	Pr > F	F	Pr > F	F	Pr > F
12/18/80	6.26	0.24 NS*	I†	I	I	I
12/22/80	0.01	0.92 NS	I	I	0.23	0.67 NS
1/2/81	I	I	I	I	I	I
1/6/81	0.74	0.54 NS	I	I	0.99	0.46 NS
1/11/81	3.44	0.13 NS	I	I	0.37	0.71 NS
8/15/81	0.73	0.52 NS	0.30	0.75 NS	1.83	0.25 NS
8/22/81	0.07	0.93 NS	0.56	0.60 NS	0.79	0.51 NS
9/1/81	0.67	0.55 NS	0.76	0.51 NS	0.61	0.58 NS
EP‡	0.28	0.76 NS	0.13	0.87 NS	1.62	0.28 NS

*Not significant at the 5 percent level.

†Insufficient data for analysis.

‡Entire period.

TABLE 23**ANOVA Analysis of Soil-Water Sample Data for Treatment Effects:
Phase 3**

Date	Cl ⁻		NH ₄ ⁺ -N		NO ₃ ⁻ -N	
	F	Pr > F	F	Pr > F	F	Pr > F
9/10/81	0.67	0.56 NS*	0.31	0.74 NS	3.45	0.13 NS
9/16/81	I†	I	I	I	I	I
9/24/81	0.48	0.65 NS	11.08	0.02 S‡	0.73	0.53 NS
9/29/81	I	I	I	I	I	I
9/30/81	1.19	0.36 NS	7.66	0.02 S	0.87	0.46 NS
10/7/81	0.05	0.94 NS	0.51	0.62 NS	4.49	0.07 NS
10/8/81	I	I	I	I	I	I
10/18/81	0.77	0.50 NS	3.70	0.10 NS	0.71	0.52 NS
10/25/81	0.10	0.90 NS	11.51	0.01 S	1.70	0.27 NS
10/31/81	0.74	0.52 NS	0.87	0.47 NS	1.19	0.37 NS
11/1/81	I	I	I	I	I	I
EP§	0.38	0.69 NS	2.93	0.13 NS	1.30	0.33 NS

*Not significant at the 5 percent level.

†Insufficient data for analysis.

‡Significant at the 5 percent level.

§Entire period.

TABLE 24**ANOVA Analysis for Experimental Unit Error
in Soil-Water Samples Collected at 17.8 cm**

Period	Parameter	F	Pr > F	Significance
Phases 1 and 2	Cl ⁻	1.98	0.10	NS*
	NH ₄ ⁺ -N	5.29	0.00	HS†
	NO ₃ ⁻ -N	1.04	0.41	NS
Phase 3	Cl ⁻	5.68	0.00	HS
	NH ₄ ⁺ -N	1.53	0.19	NS
	NO ₃ ⁻ -N	5.91	0.00	HS

*Not significant at the 5 percent level.

†Significant at the 1 percent level.

TABLE 25
ANOVA Analysis of Effluent Sample Data for Treatment Effects:
Phases 1 and 2

Date	Cl ⁻		NH ₄ ⁺ -N		NO ₃ ⁻ -N	
	F	Pr > F	F	Pr > F	F	Pr > F
12/17/80	I*	I	I	I	I	I
12/29/80	0.88	0.48 NS*	0.06	0.94 NS	1.19	0.39 NS
1/19/81	0.42	0.68 NS	0.77	0.52 NS	I	I
1/26/81	0.66	0.55 NS	I	I	1.73	0.26 NS
2/4/81	0.12	0.75 NS	I	I	3.15	0.17 NS
2/9/81	0.50	0.63 NS	I	I	0.38	0.70 NS
2/17/81	0.55	0.61 NS	I	I	1.22	0.38 NS
2/23/81	1.42	0.34 NS	I	I	0.67	0.57 NS
3/9/81	0.80	0.52 NS	I	I	0.33	0.75 NS
7/20/81	0.94	0.44 NS	0.06	0.93 NS	0.69	0.53 NS
7/27/81	3.13	0.37 NS	0.28	I	I	I
8/14/81	0.05	0.94 NS	2.24	0.22 NS	0.83	0.49 NS
8/31/81	1.04	0.41 NS	I	I	I	I
9/8/81	0.95	0.43 NS	1.17	0.38 NS	0.51	0.62 NS
EP‡	0.91	0.46 NS	1.07	0.41 NS	0.78	0.50 NS

*Insufficient data for analysis.

†Not significant at the 5 percent level.

‡Entire period.

TABLE 26
ANOVA Analysis of Effluent Sample Data for Treatment Effects:
Phase 3

Date	Cl ⁻		NH ₄ ⁺ -N		NO ₃ ⁻ -N	
	F	Pr > F	F	Pr > F	F	Pr > F
9/10/81	I*	I	I	I	I	I
9/14/81	1.02	0.45 NS†	I	I	I	I
9/16/81	I	I	I	I	I	I
9/21/81	5.78	0.06 NS	1.02	0.43 NS	0.90	0.46 NS
9/28/81	0.41	0.69 NS	0.70	0.55 NS	0.98	0.43 NS
10/5/81	0.61	0.62 NS	1.36	0.37 NS	1.57	0.31 NS
10/7/81	I	I	I	I	2.58	0.35 NS
10/16/81	0.93	0.51 NS	0.56	0.59 NS	0.03	0.88 NS
10/22/81	I	I	I	I	I	I
10/27/81	I	I	I	I	I	I
11/5/81	I	I	I	I	I	I
11/6/81	I	I	I	I	I	I
11/7/81	2.93	0.22 NS	1.07	0.40 NS	11.80	0.07 NS
11/8/81	I	I	I	I	I	I
11/10/81	I	I	I	I	I	I
EP‡	2.61	0.35 NS	9.11	0.20 NS	1.08	0.48 NS

*Insufficient data for analysis.

†Not significant at the 5 percent level.

‡Entire period.

TABLE 27
ANOVA Analysis for Experimental Unit Error
in Effluent Samples Collected at 70 cm

Period	Parameter	F	Pr > F	Significance
Phases 1 and 2	Cl ⁻	0.79	0.57	NS*
	NH ₄ ⁺ -N	1.25	0.29	NS
	NO ₃ ⁻ -N	2.23	0.05	S†
Phase 3	Cl ⁻	14.66	0.00	HS‡
	NH ₄ ⁺ -N	15.67	0.00	HS
	NO ₃ ⁻ -N	8.51	0.00	HS

*Not significant at the 5 percent level.

†Significant at the 5 percent level.

‡Significant at the 1 percent level.

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030 (1425)

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