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Using subsurface flow barriers to reduce nitrate leaching

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Using subsurface flow barriers to reduce nitrate leaching

by

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GENERAL INTRODUCTION

In recent years, both awareness and concern among the general public on our deteriorating environment have been growing. Groundwater is a very important natural resource which directly affects many human lives. In the United States, groundwater is the source of about 22 percent of the freshwater supply, and about 53 percent of the total population and 97 percent of the rural population use groundwater supplies for their drinking water (Moody, 1990). Thus, prevention, reduction, and remedy of groundwater contamination are very urgent and important subjects for scientists, engineers, administrators, and the general public. Although the contamination of groundwater can occur naturally, of major concern is contamination caused by human activities such as agricultural practices, waste disposal, spill and leak of toxic materials, mining, and so forth.

As modern agriculture developed, fertilizers and pesticides were used increasingly to attain greater productivity. Agriculture is considered to be one of the most widespread non-point sources of groundwater contamination. According to the Statistical Abstract of the United States compiled by U.S. Bureau of the Census (1989; cited by Moody, 1990), about 330 million acres were used for crop production in the United States in 1987, which was the largest areal extent among human activities related to the contamination of groundwater. Among agricultural chemicals, nitrogen fertilizer has been used most extensively, especially by corn producers. About one million tons of nitrogen fertilizer are used annually in Iowa. In some studies, more than 50 percent of the applied fertilizer nitrogen is not removed by the crop or stored in the soil, and leaching in the form of nitrate is thought to be a major reason for the losses (Blackmer, 1987). Nitrate that leaches below the rootzone has a possibility of entering groundwater supplies. Nitrate-nitrogen concentrations found in water in the vadose zone below agricultural fields are in the range of 5 to 100 mg/L (Bouwer, 1990). Nitrate-nitrogen concentrations in tile drainage in Iowa and elsewhere with row crop production usually exceed 10 mg/L, the drinking water standard (Gast et al., 1978; Baker and Johnson, 1981; Timmons and Dylla, 1981; Baker et al., 1985).

Because of the extent of groundwater contamination in agricultural areas and because of the loss of expensive fertilizer without returns to actual grain production, research on the leaching of fertilizer nitrogen and on the management of fertilizer application has been conducted for years. Nitrate-nitrogen is a water-soluble and non-absorbed anion. Therefore, the amount of water available and the chemical concentration (rate of fertilizer applied) at the given time are key factors for the leaching loss of nitrate-nitrogen. For instance, the climatological data of Ames, Iowa, shows that the mean rainfall during the May-June period exceeds the mean actual evapotranspiration for the land with corn, meaning that there is on the average a net downward movement of water. Hence, there is a potential for nitrate leaching along with the movement of water

(McBride, 1985). As the rate of fertilizer application increases, the potential for nitrate leaching increases (Gast et al., 1978; Baker and Johnson, 1981; Timmons and Dylla, 1981). When nitrogen fertilizer is broadcast, tillage treatments which create large cracks within the upper soil profile may allow more nitrate to leach than no-till treatments (Tyler and Thomas, 1977; Timmons and Dylla, 1981; Kanwar et al., 1985). Even when a solid form of nitrogen is banded in the subsoil, the presence of abundant water around the band and a supply of water from the soil surface can cause the dissolution of nitrate and subsequent rapid downward movement of the accumulated nitrate solution (Burns and Dean, 1964).

One direction in which recent studies on reducing leaching of nitrate-nitrogen have focused is to consider the multiple application of nitrogen fertilizer. Applications are made at a reduced rate so that the concentration of the applied nitrate in the soil profile is sometimes lower than that with a single high rate application. Baker and Timmons (1984) found that the multiple point injection of fertilizer resulted in higher corn yield than did deep-band or surface broadcast of the fertilizer for conventional, chisel plow, and no-till tillage systems. Kanwar et al. (1988) compared single and split (multiple) nitrogen applications in a no-till field. Their results showed that split fertilizer application whose total rate was lower than the rate for the single application reduced nitrate concentration in tile drainage while corn yields for both application methods were similar.

Another direction recent studies on reducing leaching of nitrate has focused is to use surface soil management to alter flow paths of infiltrating water. In sandy soil in Florida, Snyder and Ozaki (1971) and Snyder et al. (1974) reported that using siliconate spray to create surface water repellent soil mulches above banded fertilizer reduced nutrient leaching and increased nutrient uptake by crops as effectively as split application of fertilizers. Although the surface water repellent soil mulch was wet after rainfall, sufficient thickness of the mulch kept soil below dry. Bowers et al. (1975) reported that vertical straw mulches made from chopped crop residues placed in vertical soil cuts between seed rows diverted water away from banded fertilizer nitrogen at high rainfall intensities and reduced nitrate leaching from the bands. Hamlett et al. (1990) used a ridge tillage system to divert rain water away from banded fertilizer nitrogen. The fertilizer was banded in a 20 cm high ridge, 5 cm from the top of the ridge. Their results showed that nitrate and tracer bromide leaching from the ridge configuration was reduced compared to flat tillage configuration. Kay and Baker (1989) also reported that leaching loss of nitrate from ridge-till plots was significantly lower than from chisel-plowed plots.

Recently, a new method of fertilizer application was developed by Baker et al. (1989). A point-injector applicator enables one to apply fertilizer nitrogen more precisely in soil with little disturbance to soil, crop residues, and plant roots. It requires less power and fuel for the application of the fertilizer compared knife or tillage incorporation. It is easy to carry out multiple applications of fertilizer with this applicator. Kay and Baker (1989) reported that nitrate leaching was reduced significantly over other application methods when the point-injector applicator was used.

All of these studies indicated that reducing leaching of nitrate-nitrogen was achieved by their methods. However, there are some problems associated with the actual implementation of these methods as well. Multiple or split applications of fertilizer at a reduced rate certainly reduce chemical concentration in soil at a given time, and hence reduce a potential for leaching. However, the subsequent application of the fertilizer must be well timed for crop needs and the cost of fertilizer application as a whole must be taken into account for the affordability for farmers. In one study, ridge tillage showed some promising results (Hamlett et al., 1990) while in another study ridges did not have any significant effect on reducing nitrate leaching (Bowers et al., 1975). The height of the ridge and the location of the band within the ridge were different in these two studies, which indicates that these factors influence relative effectiveness of the ridge configuration to divert infiltrating water away from the banded fertilizer. Generally speaking, water diversion is better when the ridge is higher. With the same height of ridge, placing a fertilizer band higher or closer to the top of the ridge appears to protect the banded fertilizer. Creating a fertilizer band at a certain elevation within a ridge and clogging the space created by knife or injector without seriously destroying the original ridge configuration may be technically difficult. Using siliconate spray to create a water repellent soil mulch with a certain thickness may be economically feasible for some cash crops but may not be the case for corn production with large acreage. A point-injector applicator appears to be a good method to utilize. However, the injection of the fertilizer alone may make the applied fertilizer suceptible to leaching under certain climatic and soil moisture conditions if holes created by the penetration of wheel injector are left open. They may allow rain water to move directly to injected fertilizers enabling rapid leaching.

Another approach of reducing anion leaching which has not been explored is to utilize compacted soil. Normally, soil compaction, particularly by wheel traffic is considered to be a serious problem for the modern agriculture. As the mechanization of agriculture developed, the use of larger and heavier farm machines increased. The weight of a typical tractor increased by about seven fold from 1940's to 1970's (Voorhees, 1977a). As a result, soil compaction due to wheel traffic became a serious farm operation problem. Although there are some advantages to have soil compacted under certain soil and crop combinations as well as soil moisture and climatic conditions, usually the negative aspects of the soil compaction outweigh the advantages

(Voorhees, 1977a; 1977b; Voorhees and Hendrick, 1977). Difficulty for seed germination, restricted plant root growth, and difficulty for crops to take up nutrients result in reduced crop yields (Phillips and Kirkham, 1962; Voorhees, 1977b; Pollard and Elliott, 1978). Only a few reports show that soil compaction by wheel traffic results in reduced nitrate loss when nitrogen fertilizer is surface broadcasted (Abo-Abda et al., 1986) and increased crop yields when the fertilizer is banded and compaction takes place in the interrow (Chanhary and Prihar, 1974a; 1974b). Depending upon the climatic condition, wheat growth and yield could be increased or decreased under wheel traffic (Voorhees et al., 1985).

An idea proposed in this study is to utilize a localized small scale subsoil compaction. Studies have indicated in theory that the presence of a localized impermeable subsurface barrier should direct infiltrating water away from the barrier (Fig. 1). The region of the most reduced flow should occur adjacent to the line which passes through the point of bisection of the barrier and along with the barrier (Maâledj and Malavard, 1973; Babu, 1979; Kirkham and Horton, 1990). Soil compaction crushes larger voids and channels in the upper soil profile that may readily conduct rain water. The high bulk density of the compacted soil makes it difficult for water to permeate through the compacted soil (Reicosky et al., 1981). Because the surrounding uncompacted soil is more permeable, it is likely that much of the infiltrating water is directed toward more permeable

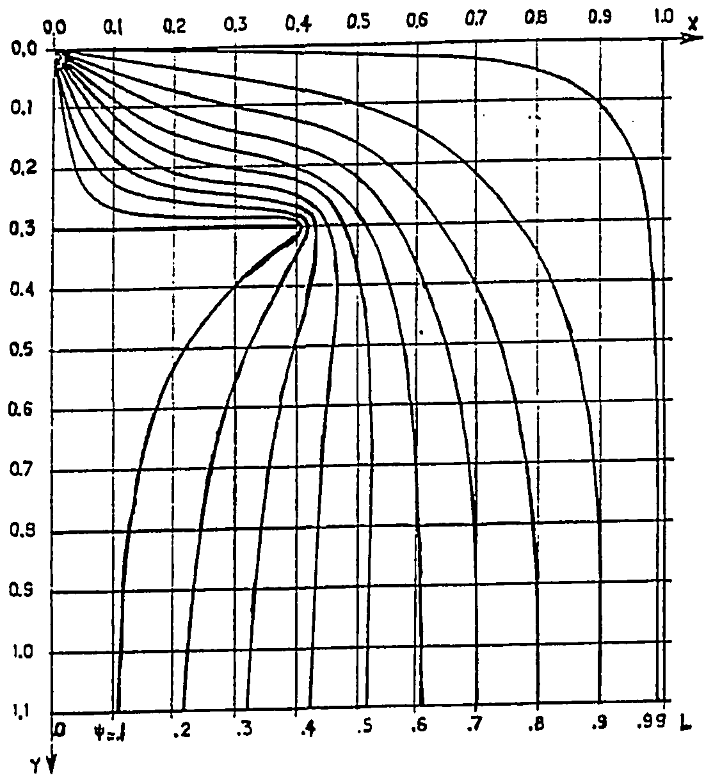


Figure 1. Stream functions showing flow from a line source affected by an impermeable subsurface barrier (Maâledj and Malavard, 1973)

surrounding soil when a compacted zone of soil exists in the subsoil. Therefore, when nitrate-nitrogen is placed under a compacted zone of soil, it may be relatively safe from being leached downward by infiltrating water. Because of the recent development of the point-injector applicator, it is possible to combine the point-injector applicator and some device to compact soil around the vicinity of the injected fertilizer to create a localized, small scale subsurface compacted soil barrier to give protection to the fertilizer against leaching when nitrogen fertilizer is applied to uncompacted or untrafficked fields.

The same principle can be applied to conventional fertilizer banding using a knife when fertilizer application is followed by a device that smears soil above the band. Smearing a soil above the band not only closes a crack created by the movement of the knife but also clogs large voids. Thus, smearing creates a subsurface zone which is less permeable than the surrounding soil and directs percolating water away from the band similar to a localized compacted soil layer.

Plant roots are capable of proliferating when negative root growth conditions such as soil compaction exist by exploring the environment favorable for root growth (Willis et al., 1963; Russell, 1977; Garcia et al., 1988). Thus, it is expected that corn roots can grow toward a banded fertilizer by going around a small scale subsurface compacted zone.

Explanation of Dissertation Format

This dissertation follows the alternate dissertation format of Iowa State University. It is divided into two sections. Each section was prepared in a format acceptable for publication in a refereed scientific journal. Section I, "Anion Leaching Characteristics of Repacked Soil Columns as Influenced by Subsurface Flow Barriers", will be submitted for publication in the soil physics division or soil and water management and conservation division of the Soil Science Society of America Journal. Section II, "Managing Soil-Water and Chemical Transport with Subsurface Flow Barriers", will be submitted for publication in the soil and water management and conservation division of the Soil Science Society of America Journal. General Summary and Conclusions follow these two sections. Literature cited in General Introduction and General Summary and Conclusions is listed under Additional References.

SECTION I. ANION LEACHING CHARACTERISTICS OF REPACKED SOIL COLUMNS AS INFLUENCED BY SUBSURFACE FLOW BARRIERS

ABSTRACT

The relative effectiveness of different types of subsurface barriers on delaying and reducing anion leaching was examined using repacked soil columns. Further, the effect of the size of a barrier against chloride leaching was investigated.

All of the barriers tested delayed the initial breakthrough of chloride and/or reduced the peak chloride concentration compared with the no-barrier case. Further, the emergence of the peak concentration was delayed when subsurface barriers were used indicating that subsurface barriers prolonged the resident time of chloride in the soil column. Among subsurface barriers used, a compacted soil layer above the applied chloride was most effective on delaying and reducing chloride leaching. The initial breakthrough of chloride was delayed by 0.9 relative pore volumes and the peak concentration was reduced by more than 50% compared with the no-barrier case. The appearance of the peak concentration was delayed by 1.2 relative pore volumes compared with the no-barrier case.

A 3-cm plastic disc, just large enough to cover the area with applied chloride reduced the peak concentration of chloride compared with the no-barrier case. A 5-cm diameter barrier, which had only an extra 2-cm cover to the applied chloride, started delaying the initial breakthrough of chloride and reduced the peak concentration by 40% compared with the no-barrier case. The emergence of the peak was also delayed by 0.6 relative pore volumes.

INTRODUCTION

Nitrogen fertilizer is one of the most essential and extensively used nutrients in crop lands. Leaching losses of nitrogen fertilizer is not only an economical problem for farmers but also an environmental problem for the general public. In some studies, more than 50 percent of the applied fertilizer nitrogen is not removed by the crop or stored in the soil and leaching as a form of nitrate is thought to be major cause (Blackmer, 1987). Nitrate that leaches below the rootzone has a possibility of entering groundwater. Numerous studies found that nitrate concentrations in tile drainage effluent from row-cropped fields, in Iowa and elsewhere, often exceeded the drinking water standard of 10 mg/L (Gast et al., 1978; Baker and Johnson, 1981; Timmons and Dylla, 1981; Baker et al., 1985).

Water-soluble anion such as nitrate can move with irrigation or rain water as it percolates to deeper soil depths. Nitrogen fertilizer is required to be in the rootzone in order for plants to absorb it. Thus, a means of reducing percolating water flow rate and/or protecting the applied fertilizer from percolating water should prove to help maintain fertilizer nitrogen in the rootzone for a longer period of time.

Studies have indicated in theory that the presence of a localized impermeable barrier should direct infiltrating water away from the barrier. The region of the most reduced flow should occur adjacent to the line which passes through the point of bisection of the barrier and along with the barrier. Maâledj and Malavard (1973) calculated stream functions from surface line sources when an impermeable barrier existed in the subsoil. Streamlines above the barrier were bent to go around the barrier. Some of the streamlines, then, moved toward the point of bisection below the barrier while the rest of stream lines moved away from the barrier. They found reduced flow rates just above and below the barrier.

Babu (1979) calculated equipotential lines for a steady state flow of water in unsaturated soil having an impermeable, isolated, circular barrier in subsoil. He found that the presence of the barrier, in some cases, caused an increase in water content and pressure head in soil above the barrier whereas the water content in the region below the barrier decreased substantially. It indicated that the infiltrating water was directed away from the soil below the barrier.

More recently, Kirkham and Horton (1990) showed that the total water flow through a homogeneous soil profile under saturated conditions was reduced most when an impermeable barrier was placed at the half way point between the soil surface and the bottom boundary of the soil profile. Again, the lowest flow rate occurred at the region adjacent to the line which passed through the point of bisection of the barrier.

Hence, it is conceivable that the leaching of nitrate can be reduced if the fertilizer is placed in a low flow region just above or below a localized subsurface water flow barrier. The recent development of a point-injector applicator (Baker et al., 1989) makes it possible to inject fertilizer nitrogen more precisely into soil with little disturbance to soil, crop residues, and plant roots. If the small portion of the soil above the injection point is compacted by a press wheel or other device, it will become a subsurface barrier to water flow because the high bulk density of the compacted soil make it difficult for water to permeate through the compacted zone (Reicosky et al., 1981). Instead, it is likely that much of the percolating water is directed away from the compacted soil and applied fertilizer because the surrounding soil is more permeable than the compacted region. Therefore, the applied nitrogen fertilizer is expected to be less susceptible to leaching than would be the case without a localized compacted zone.

The same principle can be applied to conventional fertilizer banding using a knife when fertilizer application is followed by a device that smears soil above the band. Smearing a soil above the band not only closes a crack created by the movement of the knife but also clogs large voids. Thus, smearing creates a subsurface zone which is less permeable than the surrounding soil and directs percolating water away from the band similar to a localized compacted soil layer.

The objectives of this laboratory study are: (1) to examine the relative effectiveness of different types of subsurface barriers on delaying and reducing anion leaching and (2) to identify the minimum size of a subsurface barrier that effectively delays and reduces leaching of anion.

MATERIALS AND METHODS

The soil used in this study had a sandy loam texture, and was sampled from Sparta loamy fine sand (sandy, mixed, mesic Entic Hapludolls) mapping unit. All of the transport experiments were conducted with a permeameter that consisted of an acrylic plastic cylinder (18.4 cm long and 13.9 cm inside diameter) clamped between two acrylic plastic plates.

In order to pack a soil column, air dry soil was incrementally moved into the cylinder through a funnel. Between increments, the sides of the bottom plate were tapped to ensure uniform packing. Once packed, the soil column was saturated with 0.01 N $CaSO_4$ solution by allowing the solution to flow from a mariotte reservoir through the bottom of the permeameter. The mariotte reservoir was raised incrementally over a period of hours until the solution was ponded at the soil surface.

Once saturated, the mariotte reservoir was connected to the top of the permeameter. The saturated hydraulic conductivity for the soil column was measured after achieving a steady state flow condition. Then, the soil column was allowed to drain under the influence of gravity for 12 hours before applying a chloride solution and any subsurface barrier to each soil column.

Before examining subsurface barriers, a preliminary study was conducted to study the solution density effect on anion leaching.

After the soil column was drained, 2.5 ml of either 4.0 N or 0.4 N $CaCl_2$ solution was injected at 4 cm soil depths using a hypodermic needle. The applied chloride was leached by $CaSO_4$ solution either immediately after the injection of $CaCl_2$ solution or some hours later.

In each transport experiment, 20 ml of 0.05 N $CaCl_2$ solution mixed with 5 g of the commercial horticultural grade vermiculite was packed into the central portion of the soil column between the 2 to 5 cm soil depths after excavating a hole, 3 cm in diameter and 5 cm deep. After applying the solution-vermiculite mixture and a subsurface barrier, the soil column was flushed by 0.01 N $CaSO_4$ solution and effluent exiting the bottom of the permeameter in each transport experiment was collected with a fraction collector and analyzed for chloride concentration using coulometric automatic titration (Adriano and Doner, 1982).

Three columns were constructed in this study. The columns A, B, and C were used for experiment 1 to 3, 4 and 5, and 6 to 9, respectively. Table 1 shows the measured soil and hydraulic properties of the soil columns.

Chloride breakthrough experiments with different types of subsurface barriers

A total of five experiments (experiment 1 to 5) were conducted to determine the relative effectiveness of different types of barriers on reducing leaching of chloride. Barriers used were: no subsurface barrier (NB treatment), a polyethylene disc placed above the chloride-vermiculite mixture (PA treatment), the same disc placed below the

Table 1. Measured soil hydraulic properties of soil columns

	Experiment		
	1 - 3	4 - 5	6 - 9
Column ID	A	B	C
Bulk density (Mg/m^3)	1.432	1.490	1.448
Saturated hydraulic conductivity (m/s)	1.760E-5	1.075E-5	1.669E-5
1 pore volume* (cm^3)	1283	1223	1268

* Particle density of the soil was assumed to be 2.65 Mg/cm^3.

mixture (PB treatment), a compacted soil layer created separately and placed above the mixture (CA treatment), and a compacted layer formed *in situ* above the mixture (CS treatment).

In experiment 1, no subsurface barrier was used (NB treatment). Soil was carefully removed from the top portion of the column to leave a hole, 3 cm in diameter and 5 cm deep at the center of the column. The chloride-vermiculite mixture was placed into the hole up to 2 cm from the soil surface. Slightly moistened soil was placed on top of the mixture to reconstruct the original surface configuration. Then, 0.01*N* $CaSO_4$ solution was applied from the top of the soil column through the mariotte reservoir. After the completion of the experiment, several more pore volume of the $CaSO_4$ solution were applied to flush any residual chloride out of the soil column. The column was, then, gravity drained for 12 hours. For experiment 2 to 5, leaching of chloride, flushing the soil column, and draining the column were done exactly same way as experiment 1. The only difference in the leaching procedure involves the placement of a subsurface barrier to the soil column.

In experiment 2, a disc, 9 cm in diameter, cut out of a clear polyethylene bag was placed in the column as a barrier. After carefully removing vermiculite used in experiment 1, a new chloride-vermiculite mixture was packed into the hole. Then, the surrounding soil was further removed to have a hole, 2 cm deep and 9 cm in diameter. The disc was placed flat on the bottom of the hole and the hole was filled with slightly moistened soil.

In experiment 3, the disc and vermiculite were removed from column A. A portion of soil, 9 cm in diameter and 2 cm deep, was first excavated to take the disc out. Then, vermiculite was removed from the hole, 3 cm in diameter and 3 cm deep as complete as possible. Then, soil was further excavated from the column to extend the hole to a depth of 5 cm with the same 9 cm diameter. The same polyethylene disc was placed flat on the bottom of the hole and the hole was filled with air dry soil. The new soil was saturated and drained to obtain similar initial water potential. The new chloride-vermiculte mixture was placed after 12 hour drainage period.

In experiment 4, a compacted soil layer, 0.5 cm thick and 9 cm in diameter was placed above the chloride-vermiculite mixture instead of the polyethylene disc using the column B. Prior to this experiment, the maximum bulk density of 1.9 Mg/m^3 and the corresponding optimum gravimetric water content of 0.12 Kg/Kg for the soil used in this study were determined by a compaction test based upon ASTM standard test D-698-78 Method A (1982). In order to create a 0.5 cm thick compacted soil layer with the maximum bulk density, the soil adjusted for the optimum water content was scooped into a mold, 10.1 cm in diameter, and was compacted by the rammer (3.2 kg and 7.5 cm in diameter) falling from 10 cm height. Then, the compacted soil layer was pushed out of the mold and trimmed to 9 cm in diameter.

In experiment 5, the soil above the chloride-vermiculite mixture was compacted _in situ_ to form the compacted soil layer within the soil column. After removing the compacted soil layer of experiment 4, the soil adjusted for the optimum water content was scooped into the hole. The rammer was dropped from 2 cm height to form compacted soil layer.

Chloride breakthrough experiments with different barrier diameter

Several polyethylene discs with varying diameter were placed above the chloride-vermiculite mixture (PA treatment) to identify the minimum size of the barrier that would effectively delay and reduce chloride leaching using the column C. Discs having diameter of 0.0 (NB treatment), 3.0, 4.0, and 5.0 cm were placed above the mixture and the resulting breakthrough curves were observed. To standardize the extent of disturbance caused by the excavation process, the top portion of the soil column was excavated to have a hole, 9 cm in diameter and 2 cm deep, before placing the chloride-vermiculite mixture regardless the barrier diameter.

RESULTS AND DISCUSSIONS

In order to examine the effect of subsurface barriers on chloride leaching, it is important to maintain the applied chloride at the designated soil placement depth until the leaching experiment begins. Burns and Dean (1964) showed that a high soil moisture content caused nitrate to dissolve from a band of $NaNO_3$, and $NaNO_3$ solution dropped out of the band under the influence of gravity. The injection of the highly concentrated $CaCl_2$ solution to a soil column under the gravity drained condition of this study also caused the applied solution to move downward immediately after the injection. This drop out phenomenon (solution density effect) resulted in an unusually early chloride breakthrough. Fig. 1 shows the extreme case of the drop out phenomenon when 2.5 ml of 4.0 N $CaCl_2$ solution was injected at a soil depth of 4 cm. Relative concentration was calculated as a ratio of the measured chloride concentration of the effluent sample to the maximum measured chloride concentration. Compared with the chloride breakthrough curve obtained by leaching chloride immediately after the injection, the breakthrough curve for leaching being delayed for 28 hours after the injection was shifted to the left by 0.3 relative pore volumes. It indicates that while waiting to add percolating water the applied $CaCl_2$ solution plume moved downward within the soil column. Fig. 2 shows the result of a similar experiment with the injection of 2.5 ml of 0.4N $CaCl_2$ solution. By diluting the solution, the drop out

Figure 1. Solution density effect on chloride breakthrough curve. After the injection of 2.5 ml of 4.0 N $CaCl_2$ solution, leaching experiment began either immediately or delayed for 28 hours

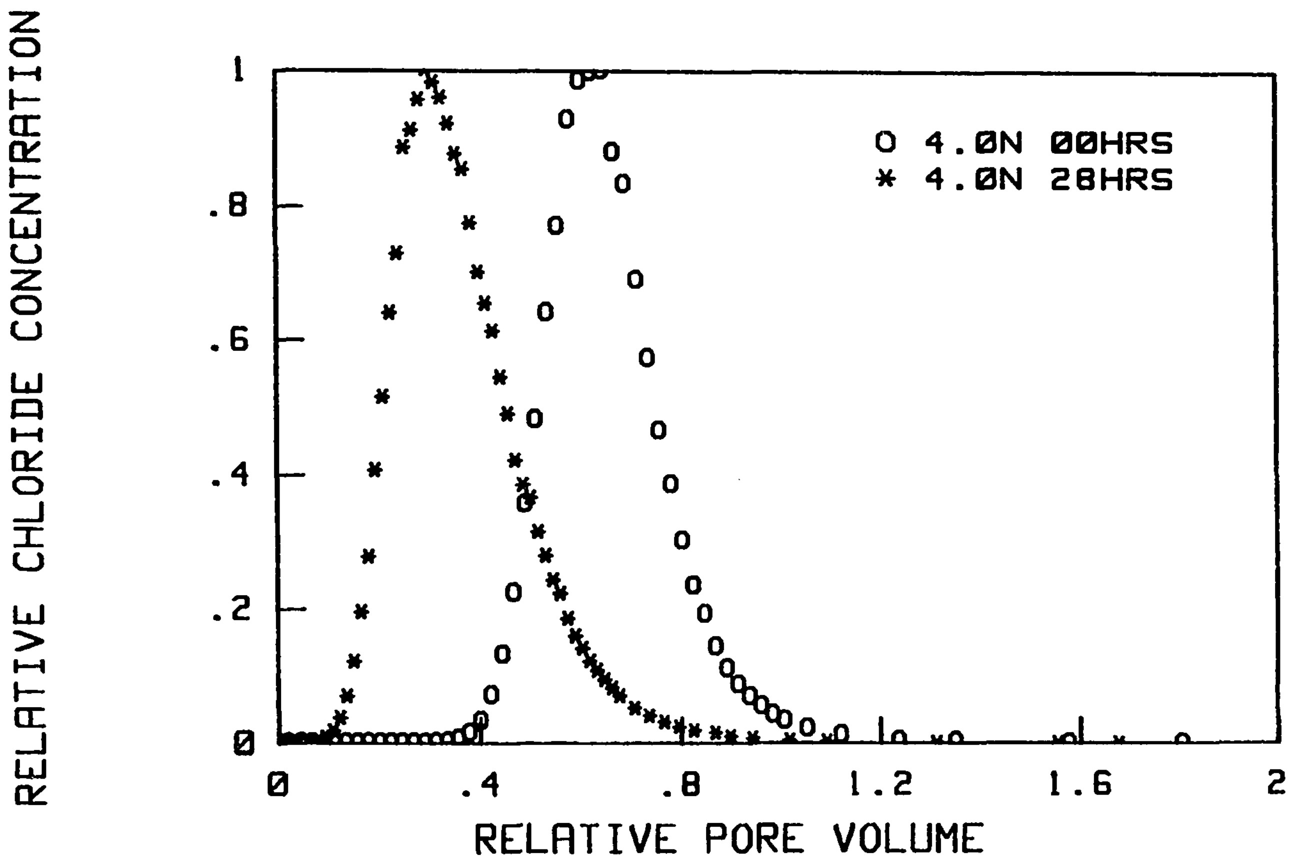
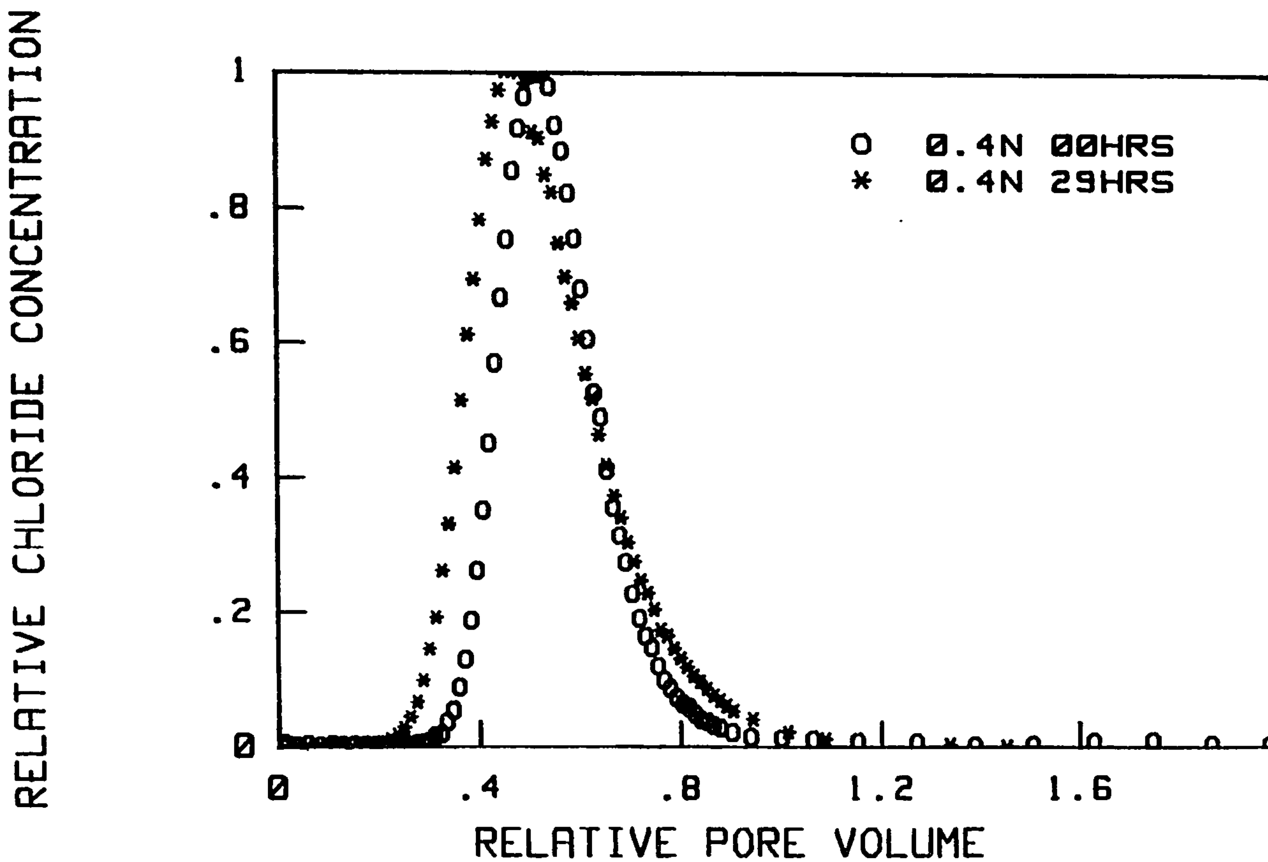

RELATIVE CHLORIDE CONCENTRATION
RELATIVE PORE VOLUME
O 4.0N 00HRS
* 4.0N 28HRS
0
.2
.4
.6
.8
1
0
.4
.8
1.2
1.6
2

Figure 2. Solution density effect on chloride breakthrough curve. After the injection of 2.5 ml of 0.4 N $CaCl_2$ solution, leaching experiment began either immediately or delayed for 29 hours


RELATIVE CHLORIDE CONCENTRATION
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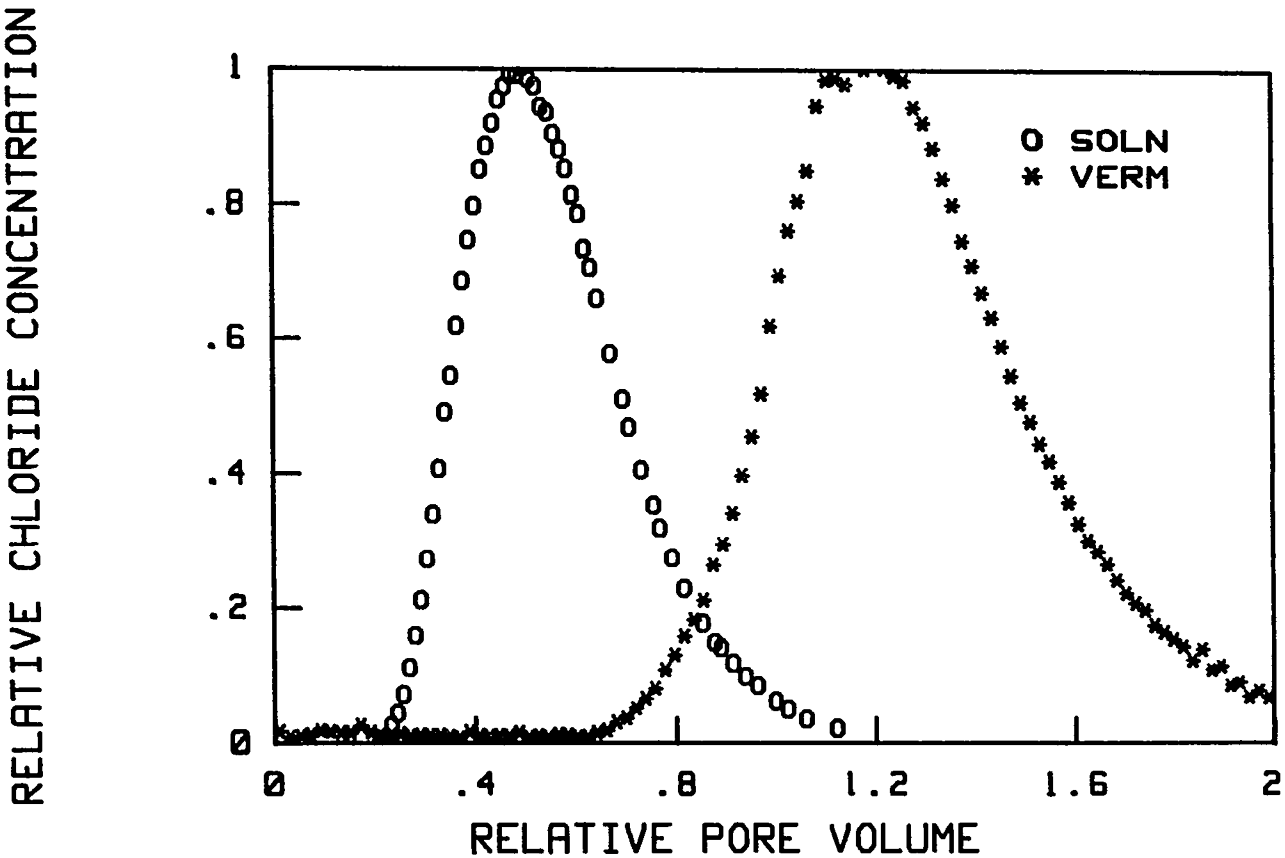
.4
.8
1.2
1.6
2
RELATIVE PORE VOLUME
O 0.4N 00HRS
* 0.4N 29HRS

phenomenon became much less prominent. However, delayed leaching of the applied solution showed more spread (dispersion) in the breakthrough curve than for the curve of immediate leaching.

In order to maintain applied solutions at the depth of placement, vermiculite particles were used as an absorbent. Fig. 3 shows the comparison between the injection of 2.5 ml of 0.4N $CaCl_2$ solution and the application of 20 ml of 0.05N $CaCl_2$ solution mixed with 5 g of vermiculite between soil depths of 2 to 5 cm. It is obvious from the figure that the use of vermiculite has delayed leaching of chloride drastically compared with the direct injection of solution. The breakthrough curve with vermiculite was shifted to the right of the solution injection curve by nearly 0.7 relative pore volumes. Despite the delayed chloride breakthrough, the shape of the curve was not much different from that of solution injection indicating that vermiculite released chloride readily whenever the infiltrating $CaSO_4$ solution was in contact with vermiculite. Vermiculite also satisfies the required essential condition to maintain the applied chloride until the leaching experiment begins. Thus, it seems that the use of vermiculite will better serve to study the true effect of subsurface barriers on chloride leaching than does solution injection because in coarse-textured soil it is difficult to keep injected chloride at the designated soil depth. Further, the use of vermiculite can make it possible to apply larger amounts and more concentrated solutions which may be important for field studies.

Figure 3. Chloride breakthrough curves for two different chloride application methods. SOLN denotes injection of 2.5 ml of 0.4 N $CaCl_2$ solution at 4 cm soil depth and VERM denotes the placement of 20 ml of 0.05 N $CaCl_2$ solution mixed with 5 g of vermiculite from 2 to 5 cm soil depth


RELATIVE CHLORIDE CONCENTRATION
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2
RELATIVE PORE VOLUME
O SOLN
* VERM

Effect of barrier types on chloride leaching

The effect of different types of subsurface barriers on chloride leaching is shown in Fig. 4. Relative concentration was calculated as a ratio of the measured chloride concentration of the effluent sample to the maximum measured chloride concentration of the NB treatment. In general, the results showed that all of the subsurface barriers except for the PB treatment delayed the initial breakthrough of chloride compared with the NB treatment. The appearance of the peak concentration was delayed and reduced substantially when subsurface barriers were used. Chloride was leached more gradually with the presence of barriers compared with the NB treatment resulting in a tailing of the effluent concentration. Chloride stayed in the soil profile for a longer period of time when subsurface barriers were present, as illustrated in Table 2.

The PA treatment delayed the initial breakthrough of chloride by about 0.3 relative pore volumes compared with the NB treatment. The breakthrough curve rather quickly reached the peak concentration although the peak concentration was reduced by 40% and appearance of the peak concentration was delayed by about 0.4 relative pore volumes compared with the NB treatment. The tailing of the curve was not as prominent as the breakthrough curve for the PB treatment. It seems that the low-flow region below the barrier was small to begin with and its effectiveness started diminishing as time passed possibly because of the intrusion of the infiltrating solution.

Figure 4. Effect of different types of subsurface barriers on chloride leaching. NB:no barrier, PA:polyethylene disc placed above the chloride, PB:polyethylene disc placed below the chloride, CA:compacted soil layer placed above the chloride, and CS:compaction _in situ_ above the chloride

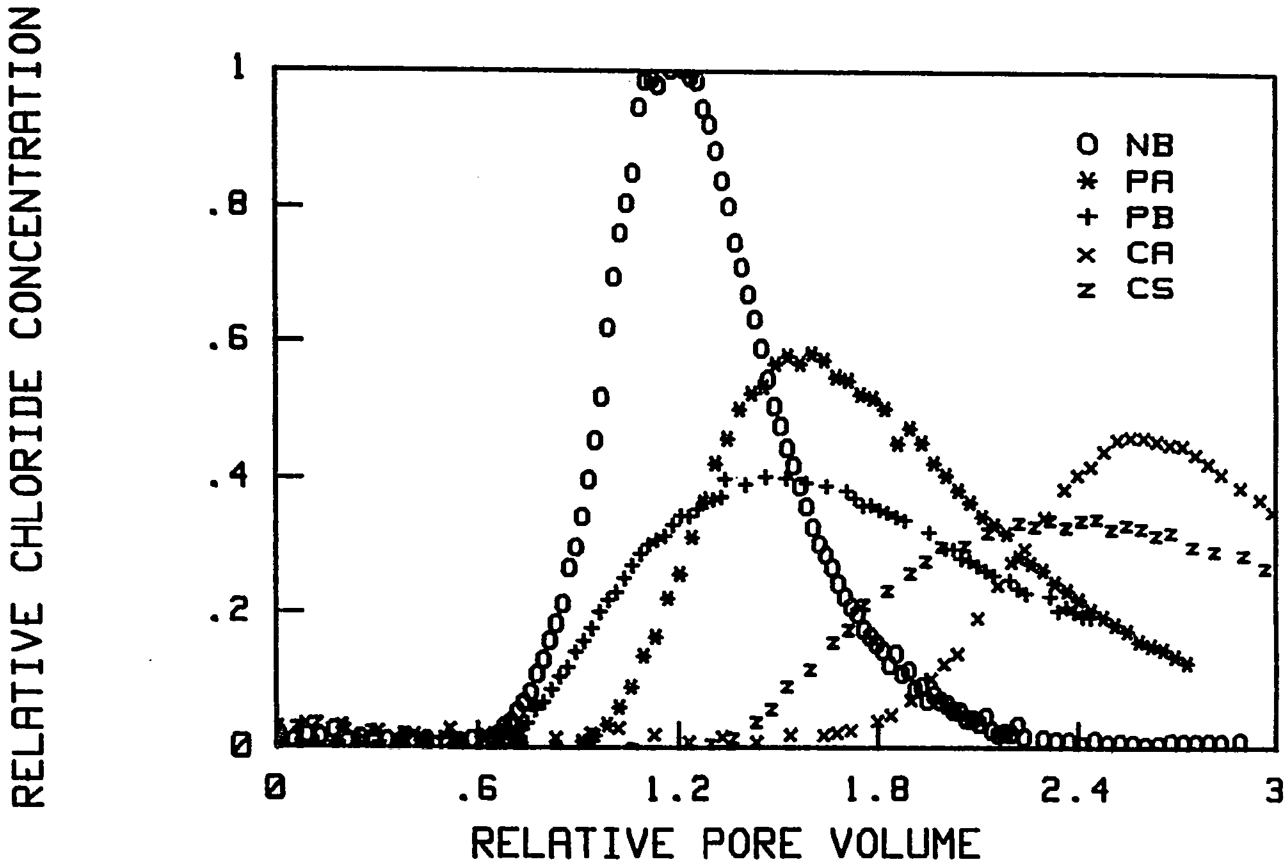
RELATIVE CHLORIDE CONCENTRATION
RELATIVE PORE VOLUME
0
.2
.4
.6
.8
1
0
.6
1.2
1.8
2.4
3
O NB
* PA
+ PB
x CA
z CS

Table 2. Fraction of the applied chloride leached out for different types of barriers with solution-vermiculite mixture

	Relative pore volume				
Treatment	0.6	1.2	1.8	2.4	3.0
NB	0.01	0.45	0.95	1.00	----
PA	0.00	0.06	0.54	0.87	----
PB	0.01	0.16	0.53	0.78	----
CA	0.02	0.04	0.07	0.26	0.64
CS	0.04	0.08	0.20	0.50	0.81

The PB treatment was expected to be more effective on delaying and reducing leaching of chloride than the PA treatment according to the theoretical studies (Maâledj and Malavard, 1973; Babu, 1979; Kirkham and Horton, 1990) because of the low-flow regions above and below the barrier. The solution containing chloride was thought to rest on the barrier and slowly move horizontally toward the edge of the barrier. Then, a portion of the chloride solution could move toward the point of bisection below the barrier in which another low-flow region existed. The possible reason why the PB treatment did not delay the initial breakthrough of chloride when chloride-vermiculite mixture was used is because the mixture occupied a rather large portion of the top portion of the soil column (3 cm in diameter and 3 cm long). Some part of the chloride-vermiculite mixture was in contact with $CaSO_4$ solution moving at higher flow rate than the solution at the center. Thus, dissolved chloride was carried away relatively readily and the initial breakthrough of chloride occurred as fast as the NB treatment. However, the breakthrough curve for the PB treatment showed lower peak concentration than the PA and CA treatments. The peak concentration was reduced by 60% and the emergence of the peak was delayed by 0.2 relative pore volumes compared with the NB treatment. The tailing of the PB treatment breakthrough curve was also more prominent than for the PA treatment, and chloride stayed in the soil column with the PB treatment for a longer period of time than for the PA treatment (Table 2). It seems that the majority of the chloride solution moved through the low-flow region above the barrier. Thus, chloride leaching was effectively reduced.

The CA treatment was most effective on delaying the initial chloride breakthrough which occurred at about 1.5 relative pore volumes, a delay of about 0.9 pore volumes compared with the NB treatment. It seems that the thickness of the compacted layer affected the size of the low flow region below the barrier and directed the infiltrating $CaSO_4$ solution farther away from the applied chloride. However, the breakthrough curve looked similar to that of the PA treatment once it reached the peak concentration. The peak concentration was reduced by slightly over 50% and the emergence of the peak was delayed by about 1.3 relative pore volumes compared with the NB treatment but was not much reduced compared with that of the PA treatment. These results indicate that the infiltrating solution may have eventually intruded into the originally low-flow region. Because the initial breakthrough of chloride was substantially delayed, however, this treatment had the least amount of applied chloride leached out at 3.0 relative pore volumes (Table 2).

The CS treatment, on the other hand, was not as effective on delaying the initial breakthrough of chloride as the CA treatment, which occurred at about 1.3 relative pore volumes, a delay of 0.7 relative pore volumes compared with the NB treatment. When the compacted layer was formed within the soil column, the rammer was dropped from a 2-cm height instead of the 10-cm height for the CA treatment in order to reduce change in the bulk density and water content of the soil below the compacted layer. It resulted in a less compacted layer positioned above the applied chloride than the CA treatment and probably allowed $CaSO_4$ solution to permeate through the compacted layer faster than for the CA treatment. However, the breakthrough curve for the CS treatment was the most gradual and had a flatter peak than any of the other breakthrough curves indicating that a localized compaction in situ above a banded fertilizer can delay and reduce leaching of nitrate. The peak concentration was reduced by more than 60% and the emergence of the peak was delayed by about 1.2 relative pore volumes compared with the NB treatment and it was the lowest among the subsurface barriers tested.

Effect of barrier diameter on chloride leaching

The effect of barrier size was examined using the PA treatment. Fig. 5 and Table 3 show the results of several chloride leaching experiments having the barriers with different diameters. Relative concentration was calculated as a ratio of the measured chloride concentration of the effluent sample to the maximum measured chloride concentration of the no-barrier (0-cm disc) treatment. The smallest, 3-cm disc was just big enough to cover the entire surface of the packed chloride-vermiculite mixture. It only reduced the peak concentration by about 10% compared with the no-barrier case but the general shape of the breakthrough curve was almost identical to that

Figure 5. Effect of different sizes of plastic sheet (barrier) placed above the applied chloride

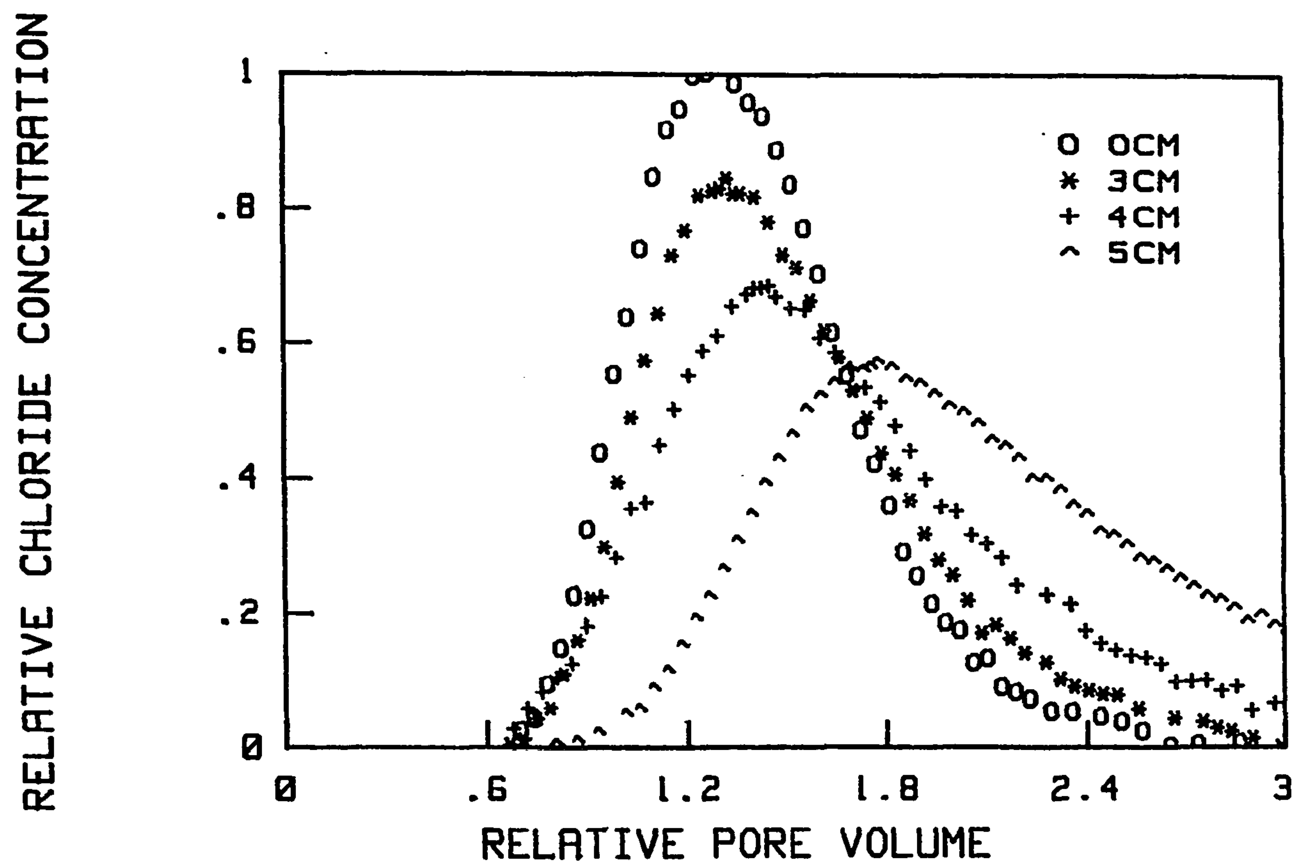
RELATIVE CHLORIDE CONCENTRATION
1
.8
.6
.4
.2
0
0
.6
1.2
1.8
2.4
3
RELATIVE PORE VOLUME
O 0CM
* 3CM
+ 4CM
^ 5CM

Table 3. Fraction of the applied chloride leached out for different size of barriers with solution-vermiculite mixture using a plastic sheet placed above the applied chloride

	Relative pore volume				
Barrier diameter	0.6	1.2	1.8	2.4	3.0
0 cm	0.00	0.29	0.88	0.99	1.00
3 cm	0.00	0.22	0.73	0.90	0.92
4 cm	0.00	0.17	0.63	0.86	0.94
5 cm	0.00	0.03	0.35	0.70	0.88

of no-barrier. The fraction of the applied chloride leached was decreased slightly from that of the no-barrier case shown in Table 3.

The 4-cm disc further reduced the peak concentration by about 30% and delayed the appearance of the peak concentration by about 0.2 relative pore volumes compared with the no-barrier case. The breakthrough curve for the 4-cm disc was more widespread than the curves for the 0-and 3-cm barriers.

A delay of the initial chloride breakthrough occurred when a 5-cm disc was used. The peak concentration was about 40% lower than that of no-barrier and appeared at 1.8 relative pore volumes, shifted to the right of the curve of the no-barrier treatment by 0.6 relative pore volumes. The shape of the curve was flatter than other breakthrough curves, and the tailing of the curve was prominent. Table 3 shows that the fraction of the applied chloride leached was less for 5-cm disc compared with other barrier sizes.

The results show that the presence of a small impermeable barrier placed above the applied chloride directed the infiltrating $CaSO_4$ solution away from the chloride resulting in reduced effluent peak concentration of chloride. The results also show that the 5-cm diameter barrier, which had only an extra 2-cm cover for the applied chloride-vermiculite mixture, began to delay the initial breakthrough of chloride and reduce chloride leaching significantly. It indicates that a relatively small-scale localized subsurface barrier has a potential to delay and reduce leaching of anions.

CONCLUSIONS

The solution density effect (drop out phenomenon) can be eliminated by using vermiculite as an absorbent. Although vermiculite drastically delayed chloride leaching compared with the direct solution injection, it maintained the applied chloride until the leaching experiment began and helped to study the true effect of subsurface barriers on chloride leaching.

The results show that subsurface flow barriers are effective for reducing and/or delaying leaching of chloride within repacked soil columns. A comparison between impermeable barriers placed either above or below applied chloride solution shows that the impermeable polyethylene disc placed below applied chloride solution is at least as effective in reducing chloride leaching as is a disc placed above the chloride. For the placement of barriers above the applied chloride, the compacted layer formed _in situ_ and the compacted soil layer prepared in a separate mold and placed above the applied chloride substantially delayed the initial breakthrough of chloride compared with a thin polyethylene disc. As a result, the chloride leaching was also substantially reduced with compacted soil layers compared with other types of barriers.

The smallest barrier size placed above the applied chloride that effectively delayed and reduced chloride leaching was a 5-cm disc, which only provided 2 cm of extra cover to the applied chloride-vermiculite mixture. Even the smaller 3- and 4-cm disc reduced the peak concentration compared with the no-barrier case.

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SECTION II. MANAGING SOIL-WATER AND CHEMICAL TRANSPORT WITH SUBSURFACE FLOW BARRIERS

ABSTRACT

The effect of subsurface flow barriers on delaying and/or reducing nitrate leaching was investigated with and without corn plants using field lysimeters.

In 1989, subsurface barriers delayed and reduced chloride and nitrate leaching and increased plant nitrogen uptake compared with the no-barrier case. A plastic sheet placed above the banded chemicals was the most effective barrier. It reduced the leaching of chloride and nitrate by 23 and 21%, respectively, and increased total nitrogen in corn shoots by 100% compared with the no-barrier case. The compacted soil layer reduced the leaching of anions by 12% and increased total plant nitrogen by 20% compared with the no-barrier case.

In 1990, lysimeters without corn plants were used to test two solution application methods, solution banding and solution-vermiculite mixture banding. For each banding method, subsurface barriers delayed the initial breakthrough of chloride and nitrate. The emergence of the peak concentration was also delayed when barriers were present. The comparison of each banding method within a barrier type revealed that vermiculite had a significant effect on delaying the initial breakthrough of chloride and nitrate, particularly for the no-barrier treatment. For the plastic sheet placed above the band, the combined effect of the barrier and vermiculite on chloride and

nitrate leaching was observed while the compacted soil layer caused delayed leaching of chloride and nitrate without reducing peak concentrations.

INTRODUCTION

Groundwater is a very important natural resource which directly affects many human lives. In the United States, groundwater is the source of about 22 percent of the freshwater used. About 53 percent of the total population and 97 percent of the rural population use groundwater supplies for their drinking water (Moody, 1990). Although contamination of groundwater can occur naturally, agriculture is considered to be one of the most widespread non-point sources of groundwater contamination. Among agricultural chemicals, nitrogen-fertilizer has been used most extensively, especially by corn producers. About one million tons of nitrogen-fertilizer are used annually in Iowa. In some studies, more than 50 percent of the applied fertilizer nitrogen is not removed by the crop or stored in the soil, and leaching as a form of nitrate is thought to be major reason for the losses (Blackmer, 1987). Leached nitrate has a possibility of entering groundwater supplies. Nitrate-nitrogen concentrations found in unsaturated soil below the rootzone of agricultural fields are in the range of 5 to 100 mg/L (Bouwer, 1990). Nitrate-nitrogen concentrations in tile drainage below row crops often exceed 10 mg/L, the drinking water standard (Gast et al., 1978; Baker and Johnson, 1981; Timmons and Dylla, 1981; Baker et al., 1985).

Nitrate-nitrogen is a water-soluble and non-adsorbed anion. Therefore, the amount of water available for leaching and the chemical concentration (rate of fertilizer applied) at a given time are key factors for the leaching loss of nitrate-nitrogen. One approach that recent studies on reducing leaching of nitrate-nitrogen have taken is multiple applications of the nitrogen fertilizer at reduced rates. With split fertilizer applications, the concentration of the applied nitrogen in the soil profile can be kept at a lower level than with a single, high-rate application. Baker and Timmons (1984) found that multiple applications of nitrogen using point injection resulted in higher corn yield than a single application using either deep-banding or surface broadcasting of the fertilizer. Kanwar et al. (1988) showed that a split fertilizer application with a lower total rate than the rate for the single application reduced nitrate concentration in tile drainage while corn yields for both application methods were similar. Although multiple or a split application of fertilizer may reduce chemical concentration at a given time, the subsequent application of the fertilizer must be well timed for corn needs. Risks associated with weather and the cost of the fertilizer application must also be considered.

Another approach for reducing nitrate leaching is to use surface soil management to alter flow paths of infiltrating water. Hamlett et al. (1990) showed that the leaching of nitrate and tracer bromide placed in a ridge tillage system was reduced compared with a flat tillage configuration. The ridge configuration directed excess rain water away from the fertilizer band, toward the furrows. Kay and

Baker (1989) also reported that leaching loss of nitrate from the ridge-till plots was significantly lower than from chisel-plowed plots. However, another study did not indicate that ridges had any significant effect on reducing nitrate leaching (Bowers et al., 1975). How high a ridge should be and where within the ridge fertilizer nitrogen should be placed must be explored. Further, positioning a fertilizer band at a certain elevation within a ridge and closing the opening created by the knife or injector without seriously destroying the original ridge configuration may be technically difficult.

An approach of reducing anion leaching which has not been explored is to utilize a subsurface water flow barrier. Studies have indicated in theory that the presence of a localized impermeable subsurface barrier should direct infiltrating water away from the barrier and reduce the flow rate in the vicinity of the barrier (Maâledj and Malavard, 1973; Babu, 1979; Kirkham and Horton, 1990). Thus, it is conceivable that nitrate leaching should be reduced if the fertilizer is placed in a low-flow region just above or below the barrier.

Soil compaction crushes the large voids and channels in the upper soil profile that may readily conduct rain water. The high bulk density of the compacted soil makes it difficult for water to permeate through the compacted soil (Reicosky et al., 1981). Rather, it is likely that much of the infiltrating water is directed away from the compacted soil layer and toward more permeable uncompacted soil.

Further, water flow just above and below the compacted soil layer should be reduced. It is, therefore, conceivable that a compacted soil zone will serve as a water flow barrier. Nitrate placed just below a compacted zone of soil is less likely to be immediately carried down by the infiltrating water.

Even when fertilizer is banded by using a conventional knife, it is possible to create a less permeable soil zone in the subsoil. By smearing soil above the band, the crack created by the movement of a knife should be clogged. Further, the smearing also causes the closure of voids and channels resulting in the formation of a soil crust above the banded fertilizer. The soil crust should be less permeable to infiltrating water than the surrounding undisturbed soil and serve as a subsurface water flow barrier. The movement of water near a smeared soil layer is expected to be similar to that for a compacted soil layer.

Plant roots are capable of compensating for the reduction of growth caused by unfavorable conditions, such as soil compaction, in part of rootzone by proliferating in more favorable soil zone (Willis et al., 1963; Russell, 1977; Garcia et al., 1988). Thus, it is expected that corn roots can grow toward banded fertilizer by growing around a compacted soil zone or a smeared soil zone.

This field study has three objectives. The first objective is to examine the effects of subsurface water flow barriers on reducing leaching losses of nitrate and chloride under typical climatic and soil moisture conditions in Iowa. The second objective is to study the effects of barriers on nitrogen uptake by corn plants. The third objective is to study effects of an absorbent (vermiculite) on the leaching of nitrate and chloride.

MATERIALS AND METHODS

Transport experiments were conducted in 1989 and 1990 at a USDA field research facility, consisting of 50 lysimeters, each with dimension of 38 x 38 x 210 cm, located west of Ames, Iowa. Each lysimeter was filled with Sparta loamy fine sand (sandy, mixed, mesic Entic Hapludolls). The average percent sand, silt, and clay content was 82.6, 9.6, and 7.8, respectively. The bulk densities of the soil in the lysimeters ranged from 1.33 Mg/m^3 to 1.38 Mg/m^3, with fairly uniform soil profiles in all cases (Stanley, 1978). Each lysimeter had its own drainage system so that effluent samples could be collected from the bottom of each of lysimeter separately.

Treatments examined in the 1989 study were: chemical band with no subsurface barrier (NB), polyethylene sheet placed above the band (PA), polyethylene sheet placed below the band (PB), compacted soil layer formed above the band (C), and check (N) with no subsurface barrier or application of chloride and nitrate. Thirty-five lysimeters were divided into seven blocks. Within each block, the five treatments were randomly assigned. Thus, each treatment was replicated seven times. To each lysimeter, 20 ml of 7.75 M calcium nitrate solution and 20 ml of 0.2 M calcium chloride solution were applied after absorption with 10 g of the commercial horticultural grade vermiculite used as an absorbent 24 hours prior to the placement in the lysimeters.

To position the subsurface barrier and to band the solution-vermiculite mixture for PA and C treatments, the central portion of the surface soil of each lysimeter, 15-cm wide and 10-cm deep, was excavated parallel to the drainage lines. Then, the second trench, 2-cm wide and 1-cm deep, was made at the bottom center of the original trench and filled with the solution-vermiculite mixture.

For the PA treatment, a polyethylene sheet, 15 cm wide, was placed flat on the bottom of the trench. For the C treatment, the excavated soil was scooped back into the trench to a thickness of about 2 cm. Then, about 20 ml of distilled water was sprayed on the soil and a rammer (3.2 kg and 7.5 cm in diameter) was allowed to fall 15 times from a height of 10 cm. These processes were repeated a total of three times to form the compacted soil layer. The average bulk density of the compacted soil layer was 1.69 Mg/m^3. For the PB treatment, the original excavation was 11 cm deep. After placing a polyethylene sheet flat on the bottom of the trench, the excavated soil was scooped back into the trench to form a soil layer, 1 cm thick. Then, the second trench was made and the solution-vermiculite mixture was placed. Finally, the rest of the trench was filled with the excavated soil to restore the original surface configuration. For the NB treatment, a 2-cm wide trench was made from the soil surface to a soil depth of 11 cm. The solution-vermiculite mixture, then, was carefully placed at the bottom of the trench as uniformly as possible. Then, the trench was filled with the excavated soil.

Corn seeds were planted in all of the lysimeters including the N treatment. Three corn seeds were planted 5-cm deep and 5 cm from the side walls on each side of the band for a total of six plants per lysimeter. Then, 40 ml of 0.525 M potassium phosphate solution was sprinkled on the surface of each lysimeter. One day after planting, the first irrigation of distilled water was applied with a sprinkling can. Four to five liters of water were applied per lysimeter at each irrigation. The irrigation interval was 3 to 4 days. The amount of water applied and the interval depended upon the amount of rainfall. Drainage effluent was collected at the bottom of each lysimeter throughout drainage periods using suction candles and a portable vacuum pump. Sampling interval was roughly 3 times a week. After a heavy rainfall, sampling was done more frequently. Effluent samples were analyzed for chloride concentration using coulometric automatic titration (Adriano and Doner, 1982) and for nitrate concentration using flow injection analysis (Ranger, 1981).

The plant samples were taken at three different dates. From each lysimeter, three plants were taken at 21 days after planting (DAP). Another two plants were taken at 38 DAP and the final plant was taken at 49 DAP. All plant samples were dried and analyzed for total shoot nitrogen using the Kjeldahl method (Bremner and Mulvaney, 1982).

A few days after the collection of the final drainage effluent, all the lysimeters with subsurface barrier and/or solution-vermiculite mixture were carefully excavated to remove the barriers and vermiculite. At the same time, observations were made of the position and the orientation of corn roots.

In 1990, a similar study of subsurface barrier effects on nitrate and chloride leaching was conducted using the same lysimeters but without the corn plants. The purpose of the study was to find out whether the differences observed among treatments on the nitrate and chloride leaching in 1989 were due to the use of the subsurface barriers or due to the use of vermiculite as an absorbent. The main treatments considered were the application of nitrate and chloride as a solution (S) or as a solution-vermiculite mixture (V). For each main treatment, 3 subtreatments, NB, PA, and C were applied. Thirty-five lysimeters were divided into five blocks. Within each block, six treatments plus a check treatment (N) were randomly assigned. Thus, each subtreatment was replicated five times.

In this study, 20 g of vermiculite were mixed with 40 ml of 3.875 M calcium nitrate solution and 40 ml of 0.5 M calcium chloride solution. For the solution form of banding, 40 ml of 3.875 M calcium nitrate solution and 40 ml of 0.5 M calcium chloride solution were dripped into the band position as uniformly as possible. The width of the excavated trench and barriers was 20 cm, otherwise treatments were similar to 1989. After replacing the soil, 4 L/day of distilled water were applied as irrigation to each lysimeter for three days using a sprinkling can. Then, drainage effluent sample collection and 2 L per lysimeter irrigation were carried out every day for 6 weeks. The soil surface of all the lysimeters were covered with styrene plates to prevent rain water from entering lysimeters. Effluent samples were analyzed for nitrate and chloride concentrations.

RESULTS AND DISCUSSIONS

Study of Subsurface Flow Barriers with Corn Plants

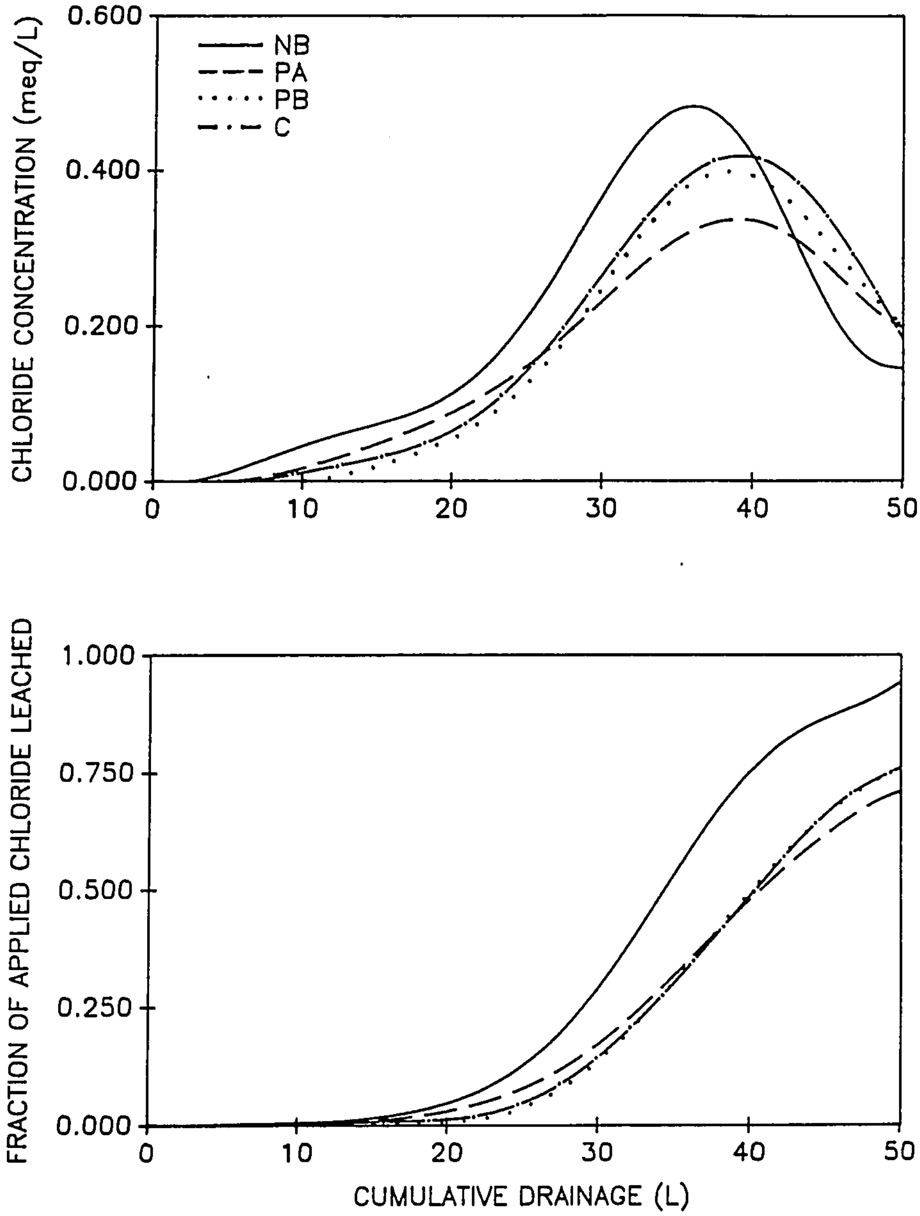
In 1989, three types of subsurface flow barriers, a plastic sheet placed above the chemical band (PA), a plastic sheet placed below the band (PB), and a compacted soil layer formed above the band (C), were tested for their relative effectiveness on delaying and reducing leaching loss of nitrate.

Chloride Leaching

The results of chloride leaching are summarized in Fig. 1. The top portion of Fig. 1 shows the chloride breakthrough curves and the bottom portion shows the cumulative leaching of the applied chloride. The check (N) treatment was used to correct measured chloride concentrations of drainage effluent samples for the background chloride concentration. The initial breakthrough of chloride for NB, PA, PB, and C treatments occurred at 2.4, 5.1, 10.1, and 6.7 L of the cumulative drainage, respectively. The peak concentration for NB, PA, PB, and C treatments occurred at 36.0, 39.0, 38.0, and 39.0 L of the cumulative drainage, respectively. The peak concentrations for PA, PB, and C treatments were reduced by 31.3, 16.7, and 12.5%, respectively, compared with the peak chloride concentration for the NB treatment, 0.48 meq/L.

The statistical analysis of the average total leaching loss of chloride at the conclusion of the experiment is shown in Table 1. Numbers in the table are the average percent loss of originally

Figure 1. Chloride leaching (1989 study). Chloride breakthrough curves (top figure) and cumulative mass of chloride leached out (bottom figure) for NB:no barrier, PA:plastic sheet placed above the band, PB:plastic sheet placed below the band, and C:compaction *in situ* above the band



CHLORIDE CONCENTRATION (meq/L)
0.600
0.400
0.200
0.000
NB
PA
PB
C
0
10
20
30
40
50
FRACTION OF APPLIED CHLORIDE LEACHED
1.000
0.750
0.500
0.250
0.000
CUMULATIVE DRAINAGE (L)

Table 1. Average leaching losses of chloride and nitrate (1989) after 50 L of drainage. Values in the table are the ratio of mass fraction of chloride or nitrate leached out to mass of the applied chloride or nitrate expressed as percentage

Treatment	Chloride	Nitrate
NB	92.50 a*	42.85 a
PA	70.32 c	33.72 b
PB	75.91 bc	37.72 b
C	81.47 b	37.62 b

* Numbers with same letter are not significantly different according to Duncan's multiple range test.

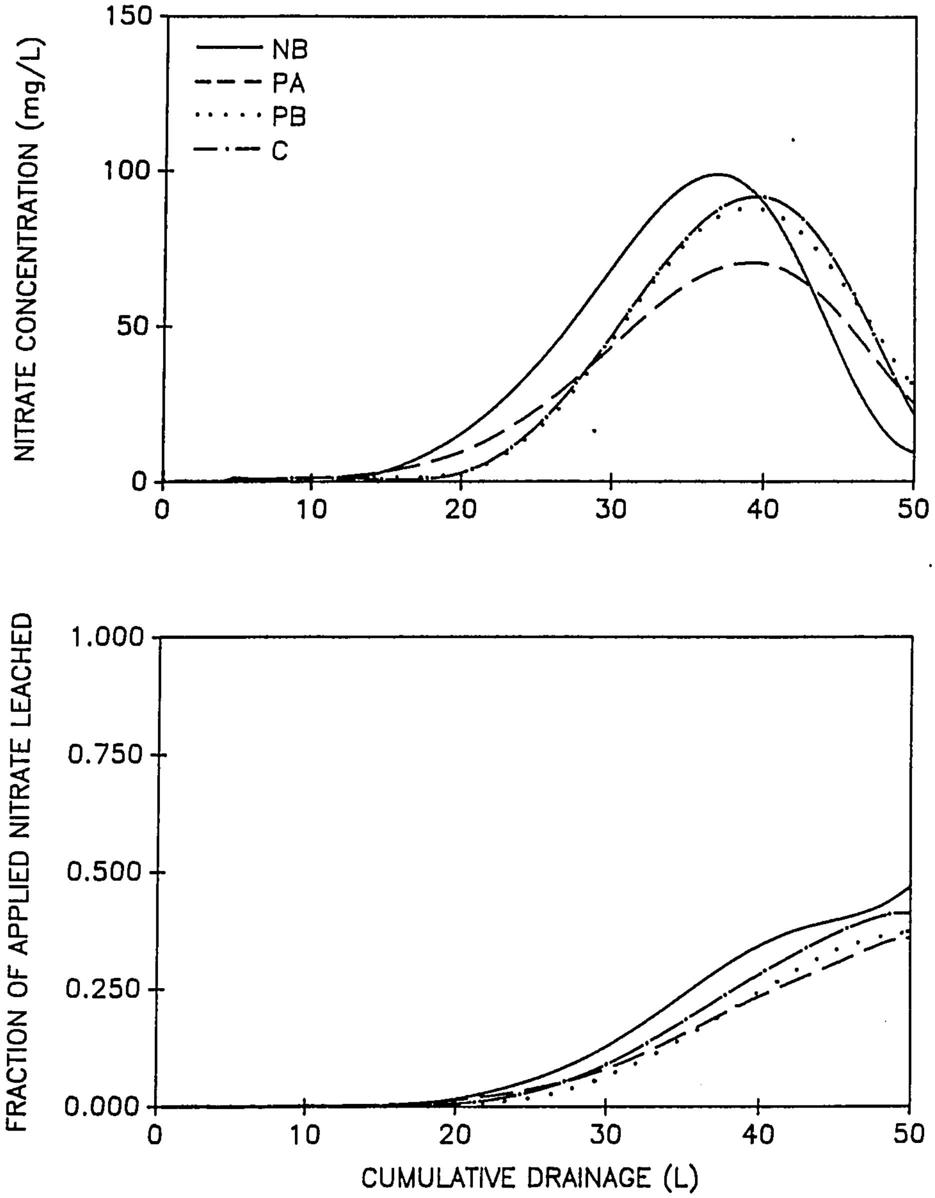
applied chloride to each lysimeter. According to the Duncan's multiple range test (Cochran and Cox, 1957), leaching loss of chloride was significantly reduced when subsurface flow barriers were used. Among three barriers tested, a plastic sheet placed above the band (PA treatment) was the most effective subsurface barrier to reduce leaching loss of chloride. A compacted soil layer above the band (C treatment) was not as effective on reducing leaching loss of chloride as the PA treatment. However, it significantly reduced leaching loss of chloride compared to the no barrier treatment.

Nitrate Leaching

The results of nitrate leaching is summarized in Fig. 2. The top portion shows nitrate breakthrough curves and the bottom portion shows the cumulative leaching of the applied nitrate. The check (N) treatment was used to eliminate the noise observed in early drainage effluent samples. The initial breakthrough of nitrate for NB, PA, PB, and C treatments occurred at 11.0, 11.0, 17.0, and 17.0 L of the cumulative drainage, respectively. The peak concentrations for NB, PA, PB, and C treatments occurred at 36.9, 39.4, 38.9, and 39.4 L of the cumulative drainage, respectively. The peak concentrations for PA, PB, and C treatments were reduced by 28.6, 12.1, and 8.1%, respectively, compared with the peak nitrate concentration for the NB treatment, 99.0 mg/L.

The statistical analysis for the leaching loss of nitrate is shown in Table 1. Numbers in the table are the ratio of the average

Figure 2. Nitrate leaching (1989 study). Nitrate breakthrough curve (top figure) and cumulative mass of nitrate leached out (bottom figure) for NB:no barrier, PA:plastic sheet placed above the band, PB:plastic sheet placed below the band, and C:compaction _in situ_ above the band



150
100
50
0
NITRATE CONCENTRATION (mg/L)
NB
PA
PB
C
0
10
20
30
40
50
1.000
0.750
0.500
0.250
0.000
FRACTION OF APPLIED NITRATE LEACHED
0
10
20
30
40
50
CUMULATIVE DRAINAGE (L)

total nitrate leached out to what was applied to each lysimeter as a fertilizer expressed as percentage. According to the Duncan's multiple range test, nitrate leaching was significantly reduced when subsurface barriers were used. Contrary to the results of chloride leaching, there was no statistically significant difference among subsurface barriers on the average total leaching loss of nitrate.

Table 2 summarizes the statistical analysis for nitrogen in the shoots of corn plants. Numbers reported are the ratio (percentage) of total amount of nitrogen in the shoots to amount of fertilizer applied to each lysimeter. Day 21, 38, and 49, correspond to the cumulative drainage of 20, 39, and 44 L, respectively, on Fig. 2. In general, the amount of nitrogen in the shoots of corn plants corresponded well to the nitrate breakthrough curves and the cumulative nitrate leached (Fig. 2). At 20 L of the cumulative drainage, the PB treatment had the lowest nitrate concentration in drainage effluent samples and the smallest fraction of the applied nitrate leached out resulting in the highest amount of nitrogen in the shoots. At 39 L of the cumulative drainage, the PA and PB treatments had a significantly larger amount of plant nitrogen. At 49 L of the cumulative drainage, the PA treatment had the least nitrate leached out and significantly higher plant nitrogen. As a total, the PA and PB treatments had a significantly higher plant nitrogen than any other treatments. The C treatment resulted in more plant nitrogen than the NB treatment but the difference was not statistically significant.

Table 2. Total plant nitrogen analysis (1989). Values in the table are the ratio of mass of nitrogen in plant samples to mass of nitrogen applied as a fertilizer expressed as percentage

Treatment	Day 21	Day 38	Day 49	Total
NB	1.04 b*	2.21 bc	1.72 bc	4.79 b
PA	1.15 b	4.24 a	4.13 a	9.52 a
PB	1.59 a	3.79 a	2.54 b	7.92 a
C	1.02 b	2.44 b	2.10 bc	5.77 b
N**	0.60 c	1.24 c	0.97 c	2.81 c

* Numbers with same letter are not significantly different according to Duncan's multiple range test.

** Numbers for the check (N) treatment are calculated as the ratio of mass of nitrogen in plant samples to mass of nitrogen applied as a fertilizer to other treatments.

Discussion 1989

In general, all of the subsurface barriers tested delayed and reduced leaching of chloride and nitrate compared with the case with no subsurface barrier. They also have increased the total nitrogen in the shoots of corn plants. The PA treatment has resulted in the greatest reduction of chloride and nitrate leaching. An impermeable barrier placed above the chemical band protected the applied anions well by directing the infiltrating rain and irrigation water away from the band. Further, the solution containing leached chloride and nitrate moved downward slower than water that was directed away from the chemical band. In theory, the flow rate is reduced the most just above and below an impermeable subsurface barrier under saturated flow conditions. Although the experimental condition was unsaturated, the solution containing chloride and nitrate was thought to be in this reduced flow region. As a result, both chloride and nitrate breakthrough curves were flatter for the PA treatment than any other treatments indicating the most gradual anion leaching. A prolonged residence time of nitrate in the soil profile increases nitrogen uptake by corn plants.

The PB and C treatments delayed the initial breakthrough of chloride and nitrate the most. However, the shape of the chemical breakthrough curves and the cumulative leaching curves for these two treatments were very similar to those for the NB treatment except for the reduced peak chloride and nitrate concentrations. Initially, for the PB treatment, it seems that part of the leached chloride and nitrate was intercepted and stayed on the impermeable barrier placed below the chemical band while part of the anions was flushed down with the infiltrating water. Subsequent rain or irrigation, however, probably continued to flush the chloride and nitrate that stayed on the barrier. Thus, chemical breakthrough was delayed but was not reduced as much as for the PA treatment.

For the C treatment, the compacted soil layer seems to have allowed the infiltrating water to penetrate and permeate through the compacted zone at a lower flow rate than that for the surrounding uncompacted soil. The compaction of sand is normally accomplished by combining a falling weight and a vibrator to increase interlocking of sand particles. The use of the falling rammer alone did increase the bulk density of the compacted soil layer but left relatively large voids that could have conducted infiltrating water within the compacted soil layer. Thus, the C treatment was not as effective as the PA treatment on reducing leaching of chloride and nitrate in this study. However, a study conducted in the laboratory with a fine-textured soil showed that a compacted soil layer was the most effective subsurface barrier on delaying and reducing leaching of chloride. Thus, it is possible for a localized, small-scale, compacted soil layer formed above banded fertilizer nitrogen to be an effective subsurface barrier to reduce leaching of nitrate.

Because labled nitrogen was not used, it is impossible to actually account for the amount of the applied nitrogen leached and taken up by corn plants. However, the apparent recovery of nitrogen both in the drainage effluent samples and in the corn shoots indicated that about 50% of the applied nitrogen at most was accounted for. Although the fate of the rest of the applied nitrogen was not investigated, denitrification and immobilization of the fertilizer nitrogen are thought to be responsible for the unaccounted nitrogen.

Corn roots proliferated under the presence of subsurface barriers, particularly the compacted soil layer during this study. Post-experiment excavation revealed that corn seminal roots had elongated directly into the band for all the treatments. The accumulation of laterals just above the barrier for the PB treatment and just below the barrier for the PA treatment was observed. For the C treatment, no visible seminal or lateral roots were found within the compacted region of the soil. Instead, roots went around the zone of the compaction and laterally elongated toward the band. The compaction did not seem to affect the total growth of corn roots or shoots.

Study of Subsurface Barriers with Solution and Solution-Vermiculite Mixture Applications

The effect of subsurface barriers on chloride and nitrate leaching for each banding method is summarized in Figs. 3 and 5, respectively. The effect of the solution and solution-vermiculite mixture banding on chloride and nitrate leaching is summarized in Figs. 4 and 6, respectively. The average total leaching of chloride

Figure 3. Chloride leaching (1990 study). Chloride breakthrough curves (top figures) and cumulative mass of chloride leached out (bottom fogures) for NB:no barrier, PA:plastic sheet placed above the band, and C:compaction <u>in</u> <u>situ</u> above the band compared by the same banding method

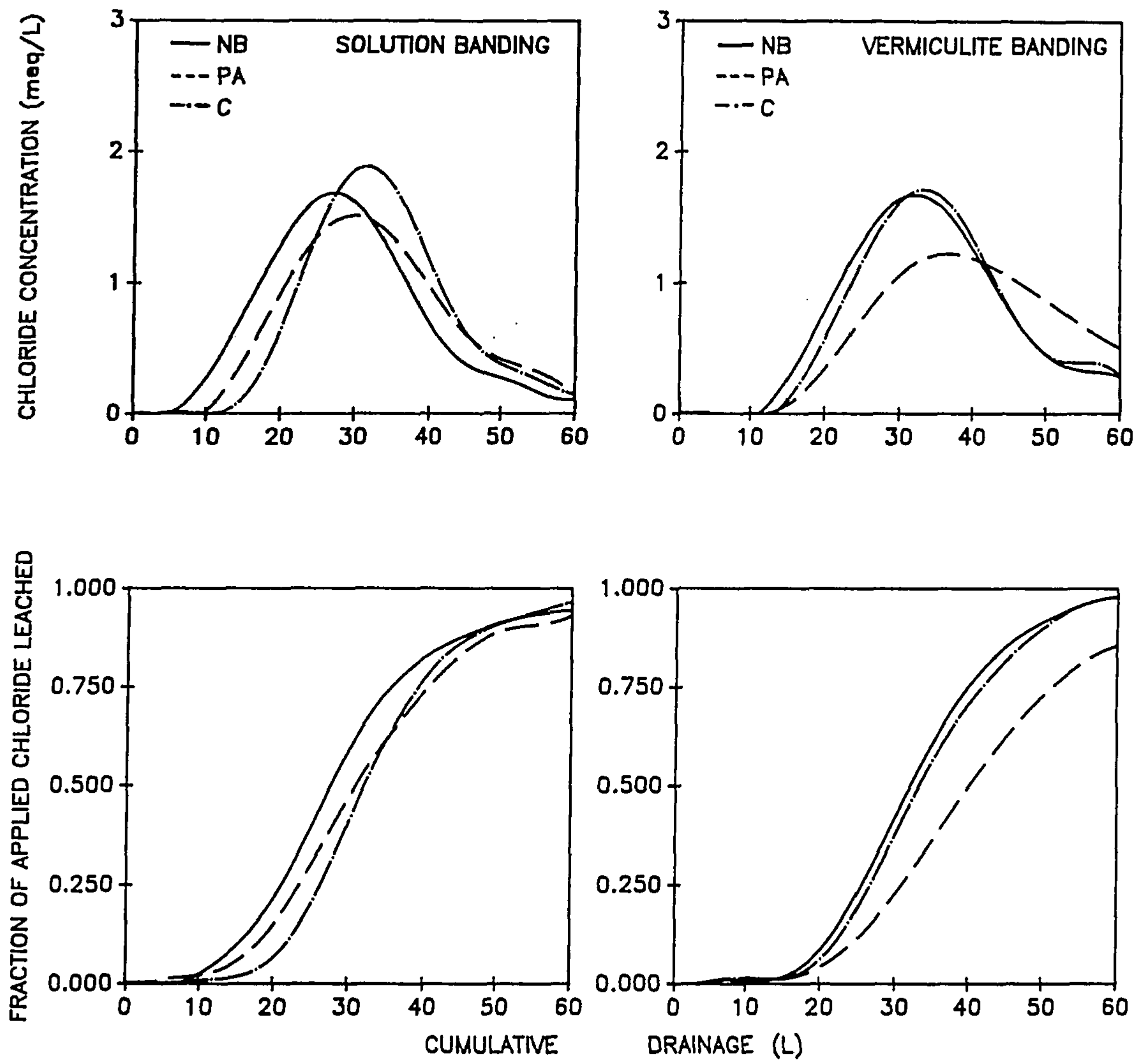
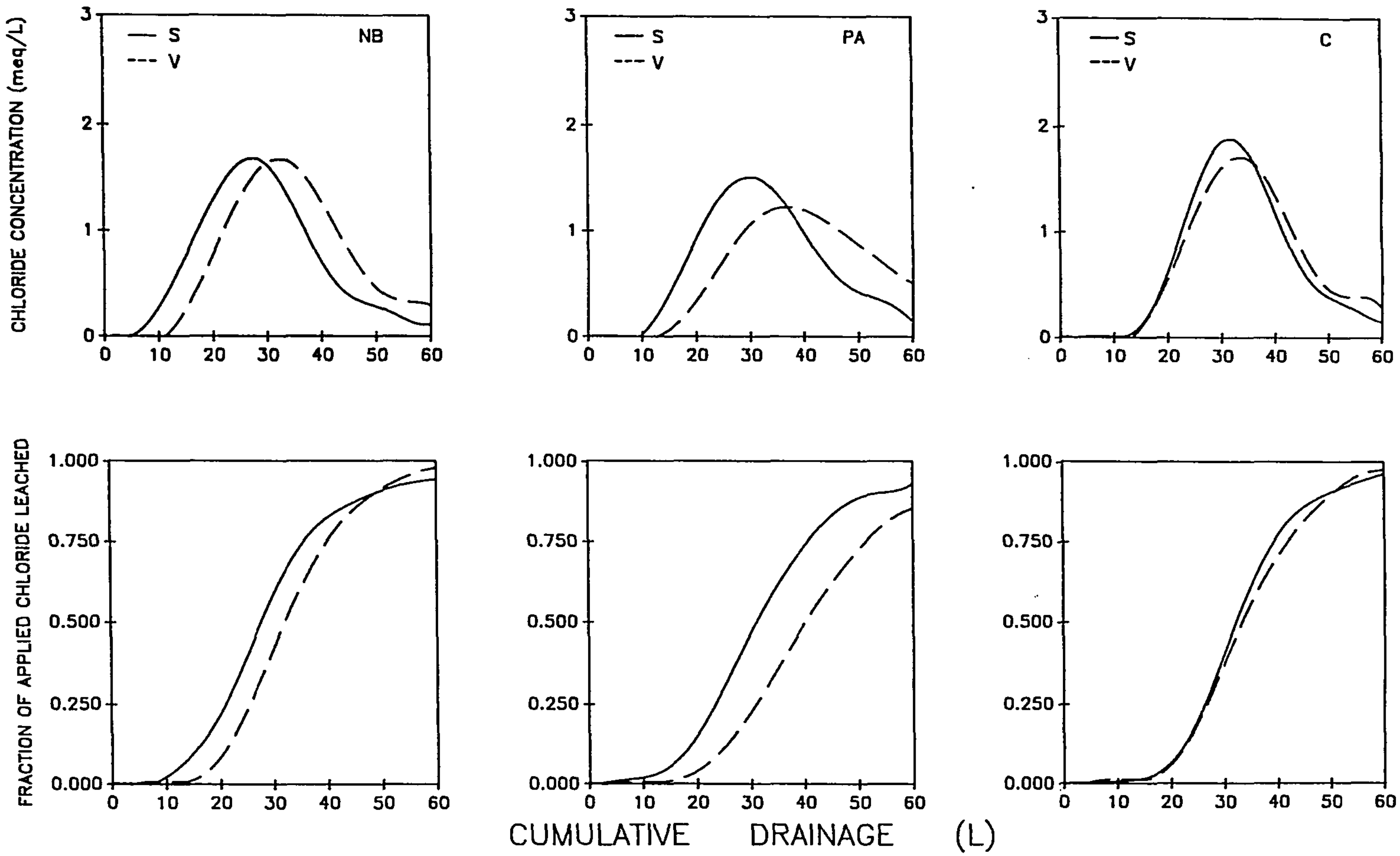

CHLORIDE CONCENTRATION (meq/L)
NB
PA
C
SOLUTION BANDING
VERMICULITE BANDING
0
1
2
3
0
10
20
30
40
50
60
FRACTION OF APPLIED CHLORIDE LEACHED
0.000
0.250
0.500
0.750
1.000
CUMULATIVE DRAINAGE (L)

Figure 4. Chloride leaching (1990 study). Chloride breakthrough curves (top figures) and cumulative mass of chloride leached out (bottom figures) for S:solution banding and V:solution-vermiculite mixture banding compared within the same subsurface barrier



CHLORIDE CONCENTRATION (meq/L)
— S
--- V
NB
PA
C
FRACTION OF APPLIED CHLORIDE LEACHED
0.000
0.250
0.500
0.750
1.000
0
10
20
30
40
50
60
CUMULATIVE DRAINAGE (L)

Figure 5. Nitrate leaching (1990 study). Nitrate breakthrough curves (top figures) and cumulative mass of nitrate leached out (bottom figures) for NB:no barrier, PA:plastic sheet placed above the band, and C:compaction *in situ* compared by the same banding method

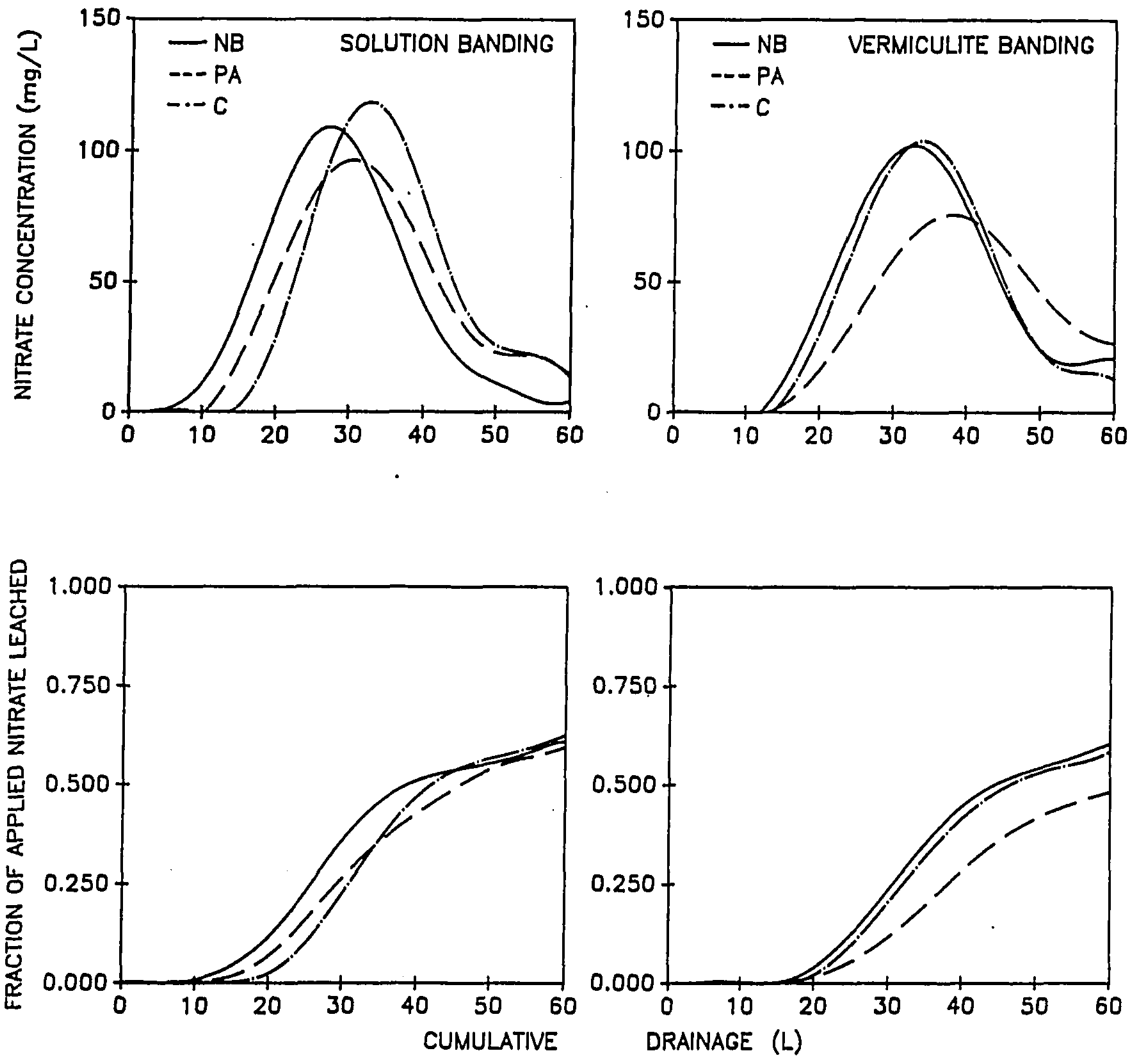
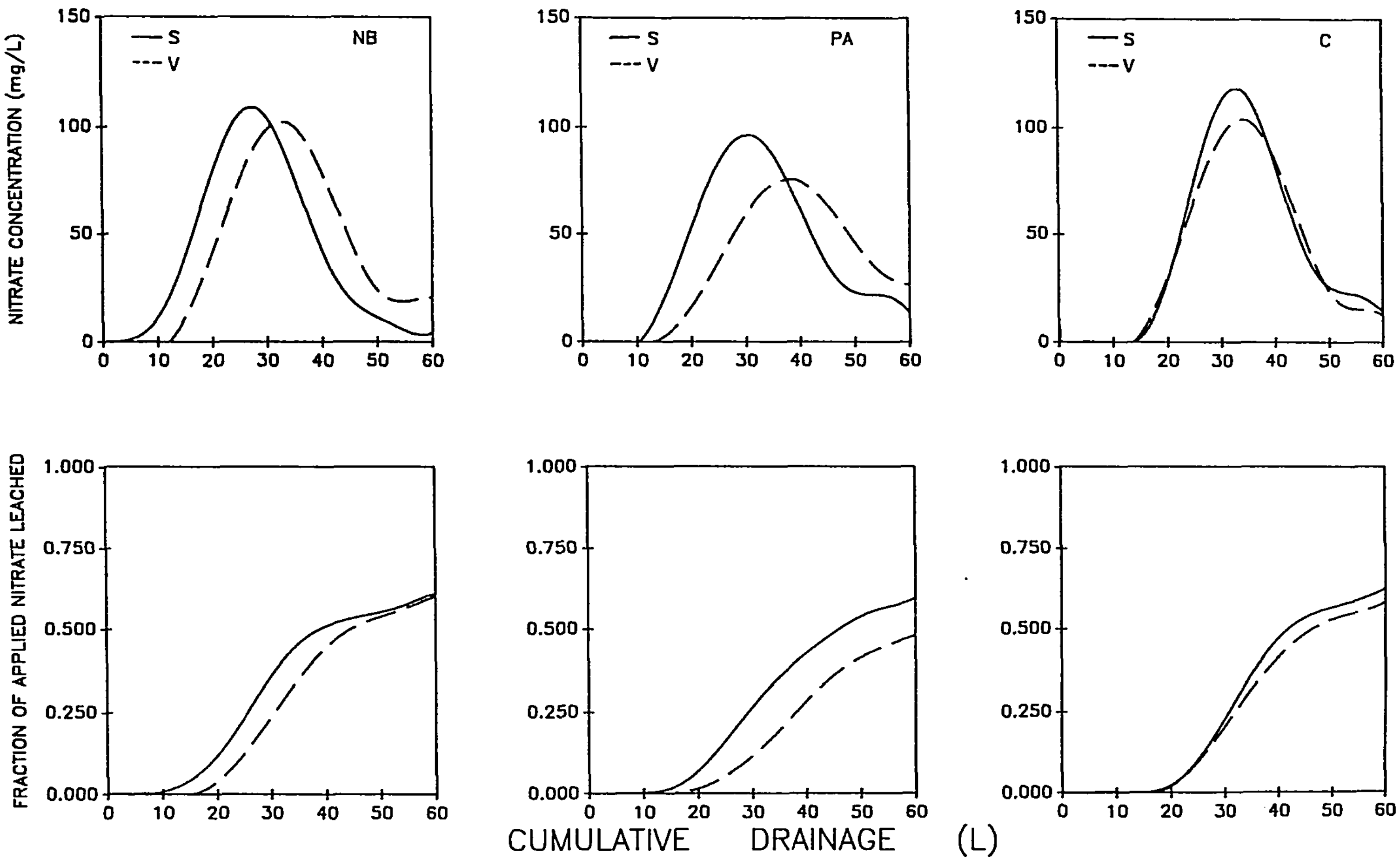

NITRATE CONCENTRATION (mg/L)
150
100
50
0
NB
PA
C
SOLUTION BANDING
VERMICULITE BANDING
0 10 20 30 40 50 60
FRACTION OF APPLIED NITRATE LEACHED
1.000
0.750
0.500
0.250
0.000
CUMULATIVE DRAINAGE (L)

Figure 6. Nitrate leaching (1990). Nitrate breakthrough curves (top figures) and cumulative mass of nitrate leached out (bottom figures) for S:solution banding and V:solution-vermiculite mixture banding compared within the same subsurface barrier


NITRATE CONCENTRATION (mg/L)
FRACTION OF APPLIED NITRATE LEACHED
CUMULATIVE DRAINAGE (L)
NB
PA
C
— S
--- V
150
100
50
0
1.000
0.750
0.500
0.250
0.000
0 10 20 30 40 50 60

and nitrate is summarized in Table 3.

Chloride Leaching

For the solution banding, the initial breakthrough of chloride for NB, PA, and C treatments occurred at 5.0, 9.5, and 11.3 L of the cumulative drainage, respectively. The peak concentrations and corresponding cumulative drainage volumes for the treatments NB, PA, and C were 1.68 meq/L at 27.0 L, 1.52 meq/L at 29.8 L, and 1.88 meq/L at 31.5 L, respectively. For the solution-vermiculite mixture banding, the initial breakthrough of chloride for NB, PA, and C treatments occurred at 11.7, 12.3, and 13.3 L of the cumulative drainage, respectively. The peak chloride concentrations for the treatments NB, PA, and C were 1.67 meq/L at 32.0 L, 1.23 meq/L at 37.0 L, and 1.71 meq/L at 33.3 L, respectively.

Nitrate Leaching

For the solution banding, the initial breakthrough of nitrate for NB, PA, and C treatments occurred at 3.2, 10.3, and 13.7 L of the cumulative drainage, respectively. The peak nitrate concentrations for the NB, PA, and C treatments were 108.7 mg/L at 27.0 L, 96.0 mg/L at 30.5 L, and 118.0 mg/L at 32.7 L of the cumulative drainage, respectively. For the solution-vermiculite mixture banding, the initial breakthrough of nitrate for NB, PA, and C treatments occurred at 12.0, 13.0, and 13.7 L of the cumulative drainage, respectively. The peak nitrate concentrations for the NB, PA, and C treatments were 102.0 mg/L at 32.3 L, 76.0 mg/L at 38.0 L, and 104.0 mg/L at 34.0 L of

Table 3. Average leaching losses of chloride and nitrate (1990) after 60 L of drainage. Values in the table are the ratio of mass fraction of chloride or nitrate leached out to mass of the applied chloride or nitrate expressed as percentage. The first letter of the treatment denotes a banding method, S: solution banding and V: solution-vermiculite mixture

Treatment	Chloride	Nitrate
SNB	94.43 a*	61.12 a
SPA	94.09 a	59.28 a
SC	95.70 a	61.46 a
VNB	97.17 a	60.04 a
VPA	85.72 b	48.17 b
VC	98.20 a	58.03 a

* Numbers with same letter are not significantly different according to Duncan's multiple range test.

the cumulative drainage, respectively.

Discussion 1990

For solution banding, a plastic sheet placed above the band and the compacted soil layer formed above the band delayed the initial breakthrough and the emergence of the peak concentration of both chloride and nitrate although only the PA treatment reduced the peak concentration (Fig. 3 and 5). This indicates that subsurface barriers altered the leaching characteristics of anions. On the other hand, only the PA treatment had a significant effect on chloride and nitrate leaching for solution-vermiculite mixture banding. The primarily effect of vermiculite was to delay the initial breakthrough of anions as shown in Fig. 4 and 6. Except for the C treatment, breakthrough curves were shifted to the right when vermiculite was used. A possible explanation is that the applied chloride and nitrate remained at the original soil depth of the chemical application until the leaching experiment began when vermiculite was used as an absorbent while the application of the solution alone resulted in the downward movement of the denser-than-water solution through the coarse textured soil immediately after the banding.

While almost all of the chloride or nitrate breakthrough curves resulted in a similar shape, both chloride and nitrate breakthrough curves for the PA treatment with the solution-vermiculite mixture were flatter than any other treatment combinations. The combination of the impermeable subsurface barrier above the band and the use of vermiculite resulted in the most effective treatment against leaching of anions. Although the experiment in 1990 was continued until almost all the applied chloride was accounted for, the PA treatment had a statistically significantly lower leaching loss of chloride and nitrate even under the intensive irrigation (Table 3).

The C treatment showed mixed results. For solution banding, the compacted soil layer delayed both chloride and nitrate leaching although the peak concentrations for chloride and nitrate increased. Breakthrough curves for the C treatment looked similar to those for the NB treatment, but they were shifted to the right showing the barrier effect. For solution-vermiculite mixture banding, the NB and C treatments resulted in essentially the same breakthrough curves for chloride and nitrate (Fig. 3 and 5). Fig. 4 and 6 show that solution and solution-vermiculite banding methods had essentially no difference for the C treatment except for the slight delay on the emergence of the peak concentration and slight reduction of the peak concentration for chloride and nitrate when vermiculite was used. As was the case in 1989 study, the compacted soil layer probably allowed irrigation water to permeate through the compacted zone because of the insufficient compaction of the soil. A possible explanation as to why the banding methods were not different for the C treatment is that soil containing the applied chemical solution was also compacted during the formation of the C treatment. Thus, irrigation water moved through the region at a reduced rate and the resulting chemical breakthrough curves were similar to those for solution-vermiculite mixture banding.

The leaching losses of the applied chloride and nitrate showed a distinctive difference as was the case in 1989 study (Table 3). Although intensive irrgation was applied within a short (6 weeks) period to create conditions favorable for leaching, about 40% or more of the applied nitrate was not accounted for while almost all the applied chloride was collected through the drainage effluent samples.

The results of both the chloride and nitrate leaching studies in 1990 suggest that the differences on leaching losses of chloride and nitrate observed among treatments in 1989 were indeed due to the use of subsurface barriers. Further, it was inferred that the solution-vermiculite mixture banding enabled the applied anions to stay at the original band location until the leaching study began. However, it was also found that the use of vermiculite as an absorbent somewhat exaggerated the effects of subsurface barriers because vermiculite itself could delay the leaching of anions.

CONCLUSIONS

Experimental data collected in 1989 showed that compared with the no-barrier treatment subsurface flow barriers delayed and reduced leaching losses of chloride and nitrate by directing the infiltrating water away from the banded chemicals under the intensive rainfall and irrigation scheme imposed on the study.

The most effective barrier to delay and to reduce leaching losses of chloride and nitrate was an impermeable plastic sheet placed above the chemical band. Although it was not as effective as a plastic sheet, the compacted soil layer formed above the band also delayed and reduced leaching losses of chloride and nitrate despite the fact that the compaction of the sandy soil by the falling rammer alone resulted in insufficient compaction.

At any given time or cumulative drainage volume, less nitrate leached out of the lysimeters with subsurface barriers than from lysimeters without any barriers. Thus, nitrate either remained in the band or in the soil profile for a longer period of time when subsurface barriers were used and was available for uptake by corn plants.

Experimental data collected in 1990 indicated that differences in leaching losses of chloride and nitrate among treatments used in 1989 were due to the subsurface barriers. The use of vermiculite as an absorbent delayed leaching of banded anions and added a more favorable effect on delaying and reducing leaching losses of chloride and nitrate than the use of a subsurface barrier alone.

The solution banding of highly concentrated chemicals showed the problem of the applied chemicals moving out of the band after the application to the lysimeters. This drop-out (solution density effect) of the chemicals made a subsurface barrier less effective against leaching. Although the use of the vermiculite changes leaching characteristics of chloride and nitrate to some extent, vermiculite made it possible to maintain the applied chemicals at the location of the band until leaching experiments began.

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GENERAL SUMMARY AND CONCLUSIONS

Subsoil management studies were conducted in the laboratory and in the field to delay and/or reduce nitrate leaching. Subsurface water flow barriers which, in theory, should direct infiltrating rain or irrigation water away from the barrier and create a shield or an umbrella below the barrier were studied for their effectiveness against nitrate leaching.

In the laboratory, two studies were conducted. Several different types of subsurface barriers were placed in soil columns either above or below the banded chloride. Their relative effectiveness on delaying and/or reducing chloride leaching was examined by comparing chloride breakthrough curves.

In general, all of the subsurface barriers tested delayed and/or reduced chloride leaching. A compacted soil layer placed above banded chloride was most effective in delaying initial breakthrough of chloride. The peak chloride concentration in effluent samples was also reduced greatly with a compacted soil layer. Compared with the no-barrier case, the initial breakthrough of chloride was delayed by 0.9 relative pore volumes. The peak concentration was reduced by more than 50% and the emergence of the peak was delayed by about 1.2 relative pore volumes. The thickness of the barrier has a significant effect on delaying chloride leaching.

The second laboratory study was conducted to study the effect of the barrier size using a plastic sheet placed above the banded chloride. It was found that a small barrier could delay and reduce chloride leaching. A 5-cm diameter barrier (disc), which had only an extra 2-cm cover for the applied chloride, started delaying the initial breakthrough of chloride. The peak concentration was reduced by 40% and the appearance of the peak was delayed by 0.6 relative pore volumes compared with the no-barrier case.

In the field, subsurface barriers were tested with and without corn plants. In 1989, three different types of barriers, a plastic sheet placed above the band, a plastic sheet placed below the band, and a compacted soil layer formed above the band (compaction in situ) were used along with corn plants. All of the subsurface barriers delayed and reduced nitrate and chloride leaching. Further, total plant nitrogen increased when subsurface barriers were used indicating that more fertilizer nitogen was available for plant uptake with subsurface barriers than without the barriers. Among the barriers tested, a plastic sheet placed above the banded chemicals was the most effective barrier which reduced the leaching of chloride and nitrate by 23 and 21%, respectively and increased total nitrogen in corn shoots by 100% compared with the no-barrier case. The compacted soil layer was the least effective barrier but it reduced the leaching of chloride and nitrate by 12% and increased total plant nitrogen by 20% compared with the no-barrier case.

In 1990, two chemical banding methods were examined. A plastic sheet placed above the band and a compacted soil layer formed above the band delayed the initial breakthrough of nitrate and chloride for the solution banding. The plastic sheet delayed the initial breakthrough of nitrate and chloride by 7.1 and 4.5 L of the cumulative drainage, respectively, compared with the no-barrier case. The compacted soil layer delayed the initial nitrate and chloride breakthrough by 10.5 and 6.3 L of the cumulative drainage, respectively, compared with the no-barrier case.

For the banding of solution-vermiculite mixture, vermiculite itself significantly delayed the initial breakthrough of nitrate and chloride by 8.8 and 6.7 L of the cumulative drainage, respectively, compared with the solution banding. Coupled with a plastic sheet placed above the banded chemicals, both nitrate and chloride leaching were delayed and reduced most. The peak concentrations of nitrate and chloride for the combination of the solution-vermiculite banding and the plastic sheet were reduced by about 30 and 27%, respectively, compared with the no-barrier case with the solution banding.

It was found that subsurface barriers did delay and reduce nitrate and chloride leaching. Although field studies were confined within the small scale lysimeter with a coarse-textured soil, it appears that a localized, small-scale subsurface barrier should protect the banded fertilizer. In the future, a small-scale, localized compaction above the injected fertilizer nitrogen or a smeared soil layer created above the banded fertilizer should be examined in an actual field setting. Using labeled nitrogen would further clarify the effect of subsurface barriers on delaying and reducing nitrate leaching and enhancing plant nitrogen uptake.

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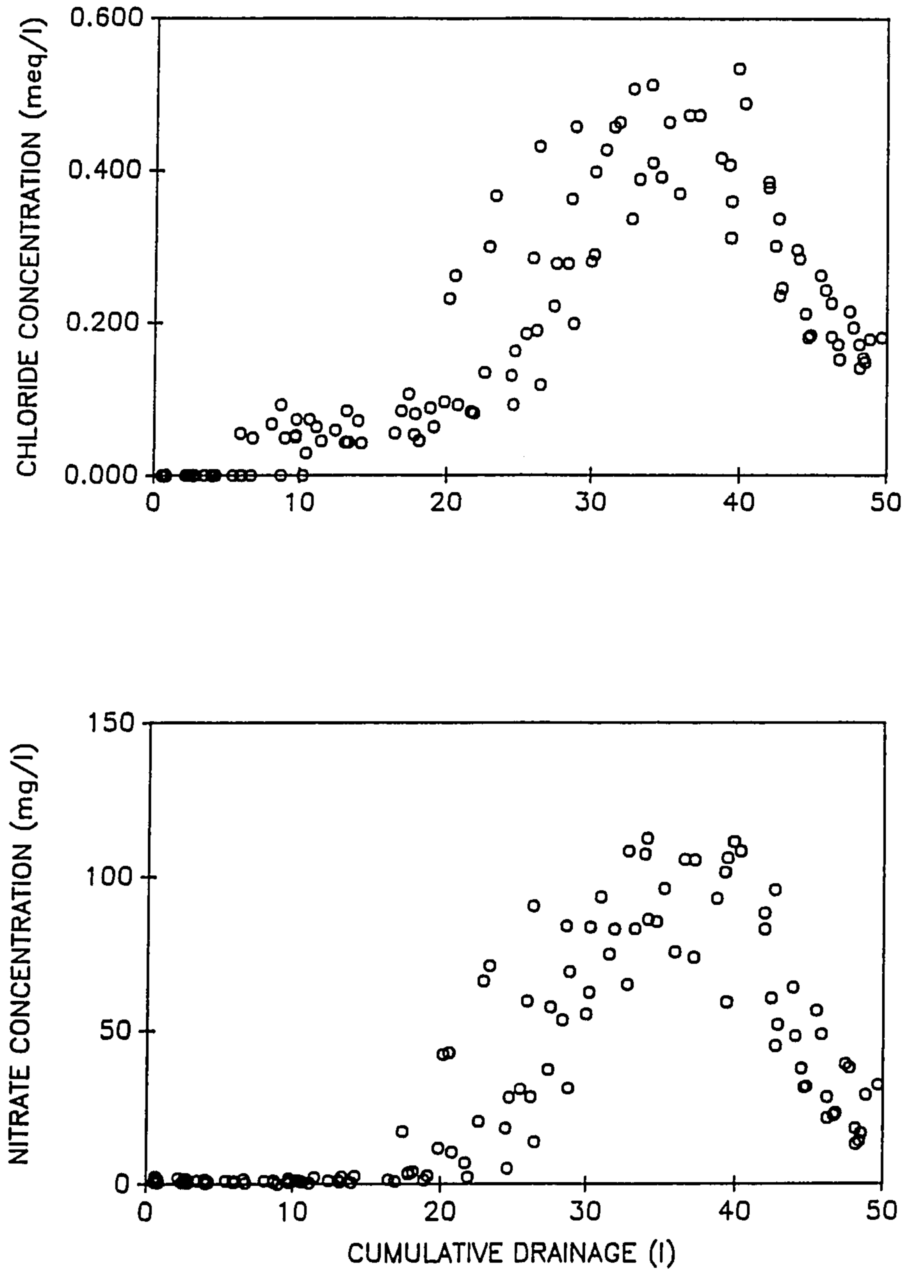
APPENDIX

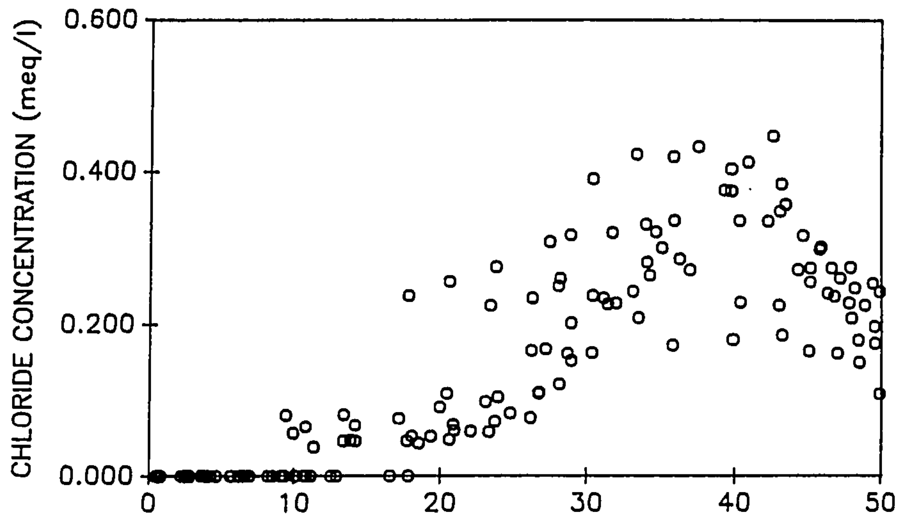
This appendix contains ten scatter plots for chloride and nitrate breakthrough data collected from the field study. The first four plots are for 1989 study. The number of data points for the NB, PA, PB, and C treatments were 126, 147, 147, and 126, respectively.

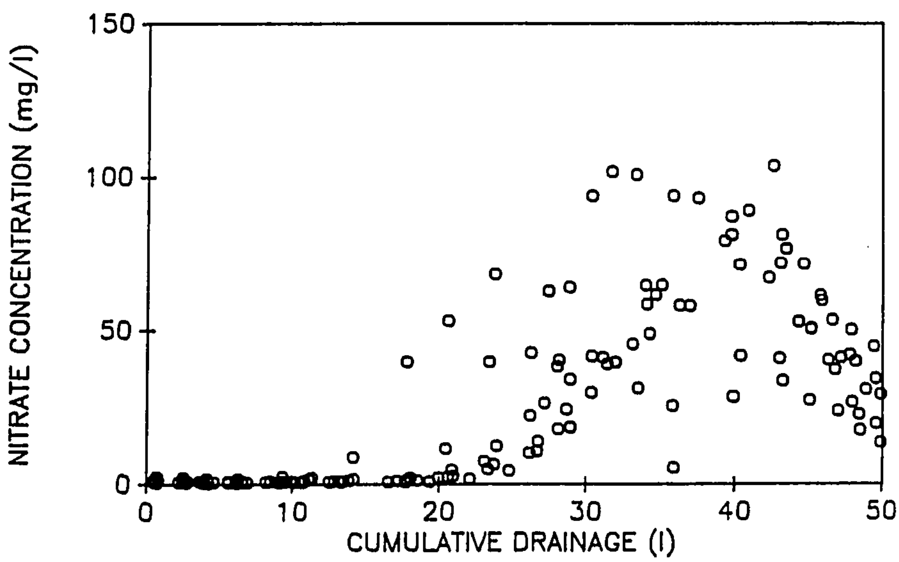
The other six plots are for 1990 study. The number of data points were 150 for each treatment except for the SPA treatment (120 data points). A title, "Solution" means both chloride and nitrate were banded as a solution form. "Vermiculite" denotes the banding of the solution-vermiculite mixture. A symbol following the banding method indicates the type of the subsurface barrier used.

NO BARRIER (NB) 1989

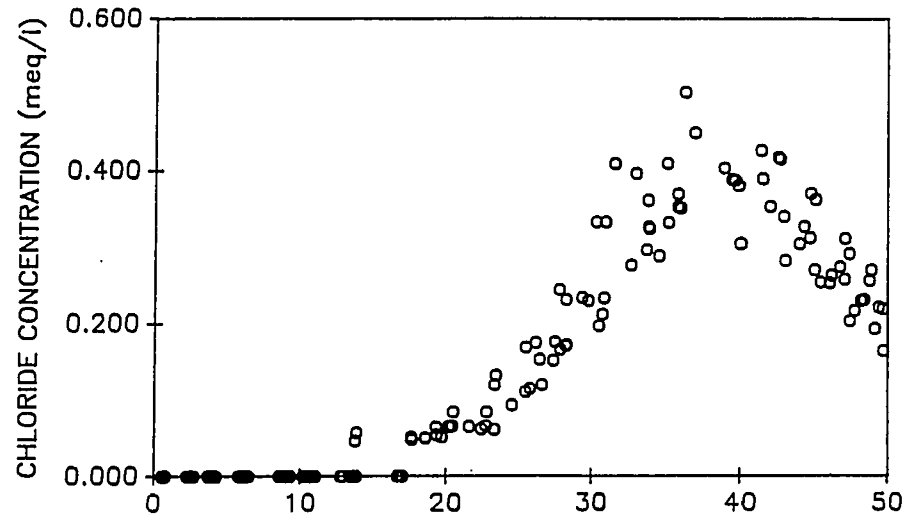


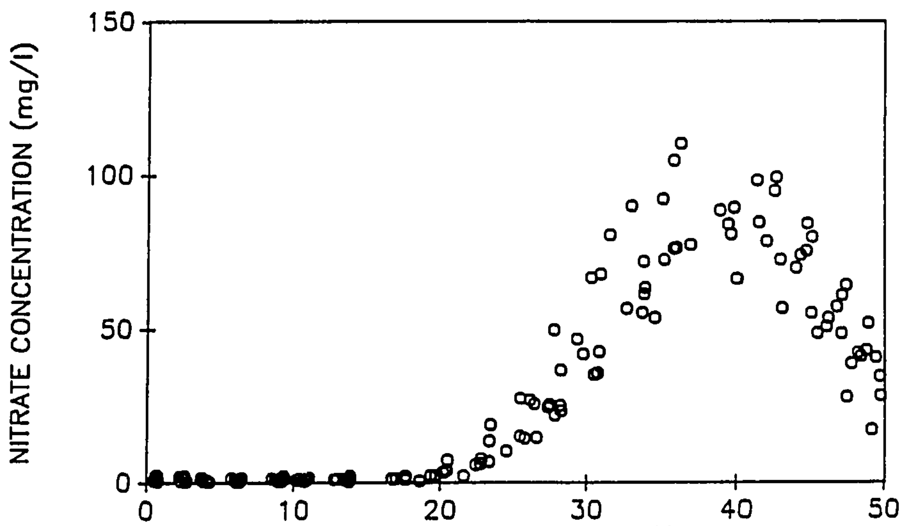
PLASTIC ABOVE (PA) 1989



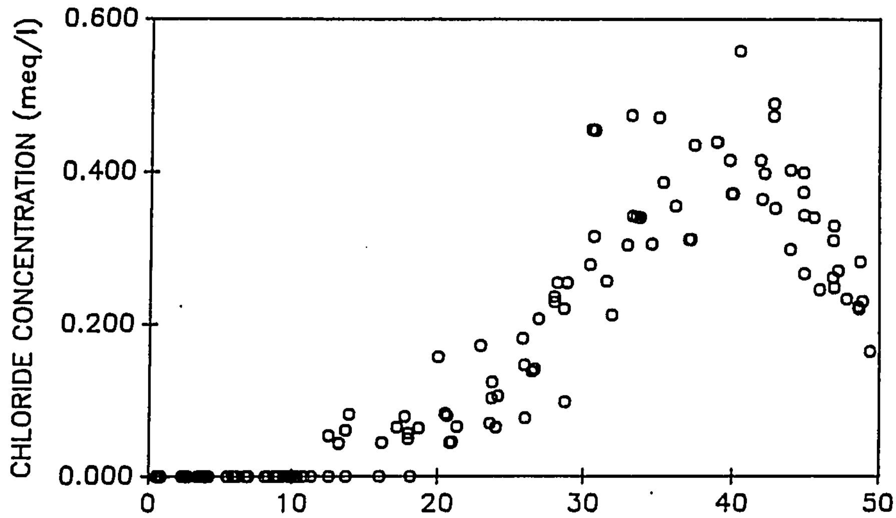


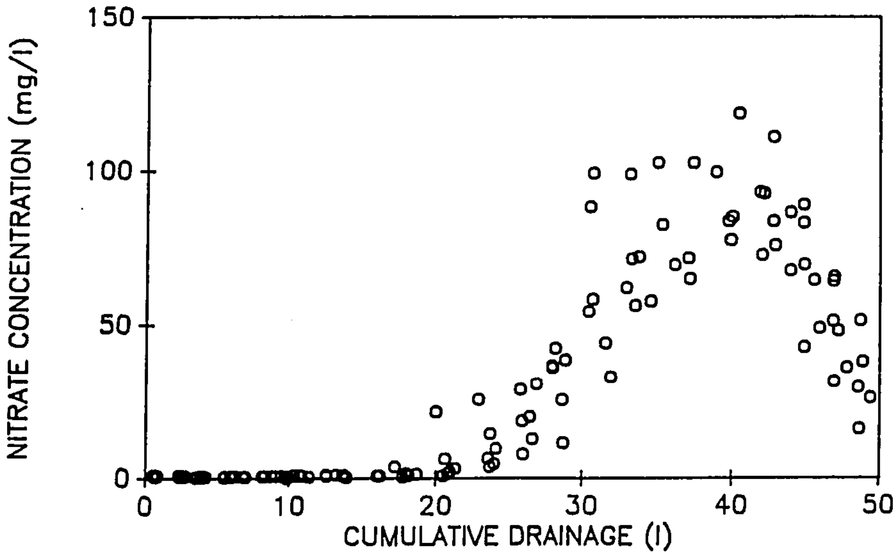
PLASTIC BELOW (PB) 1989

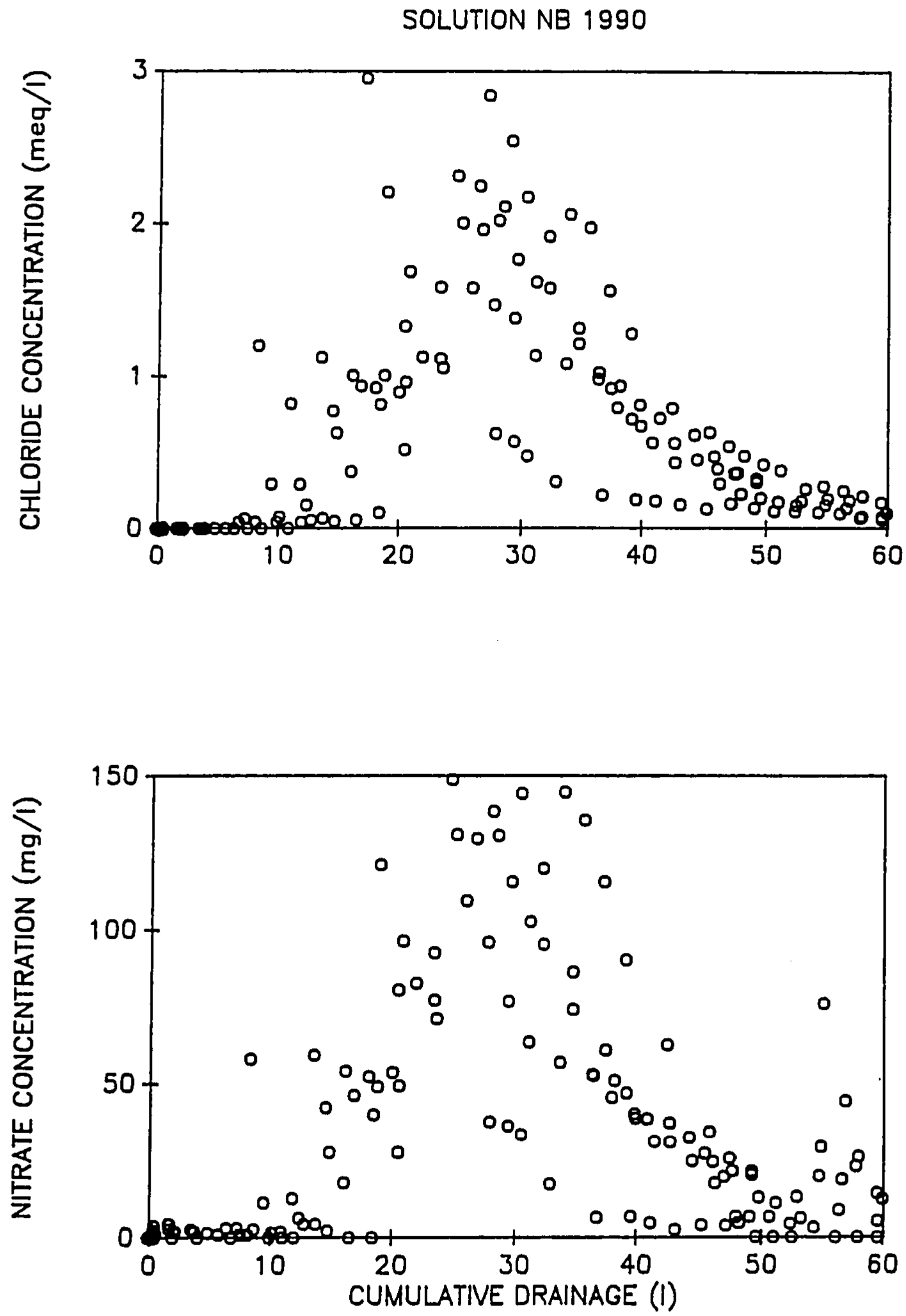




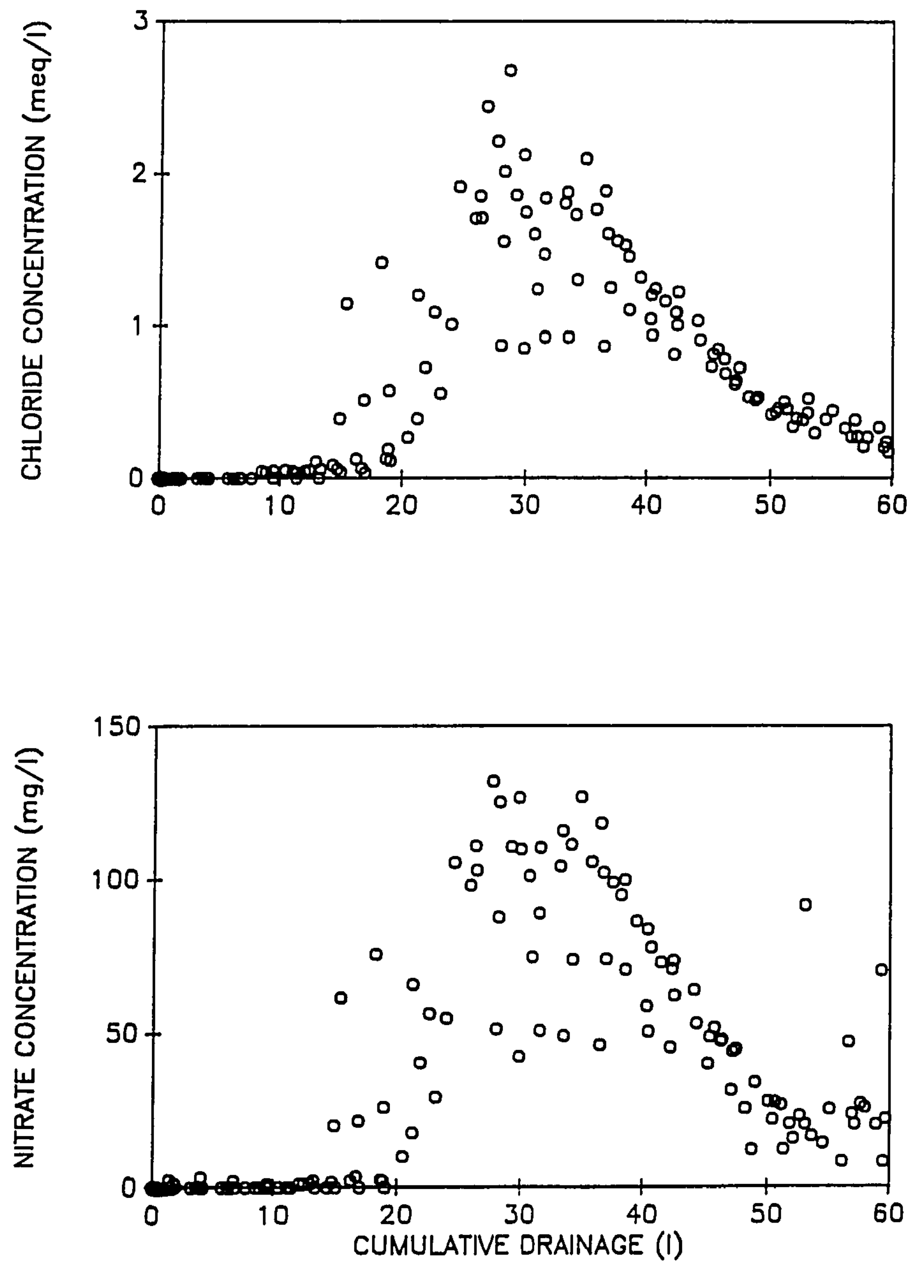
COMPACTED SOIL LAYER (C) 1989



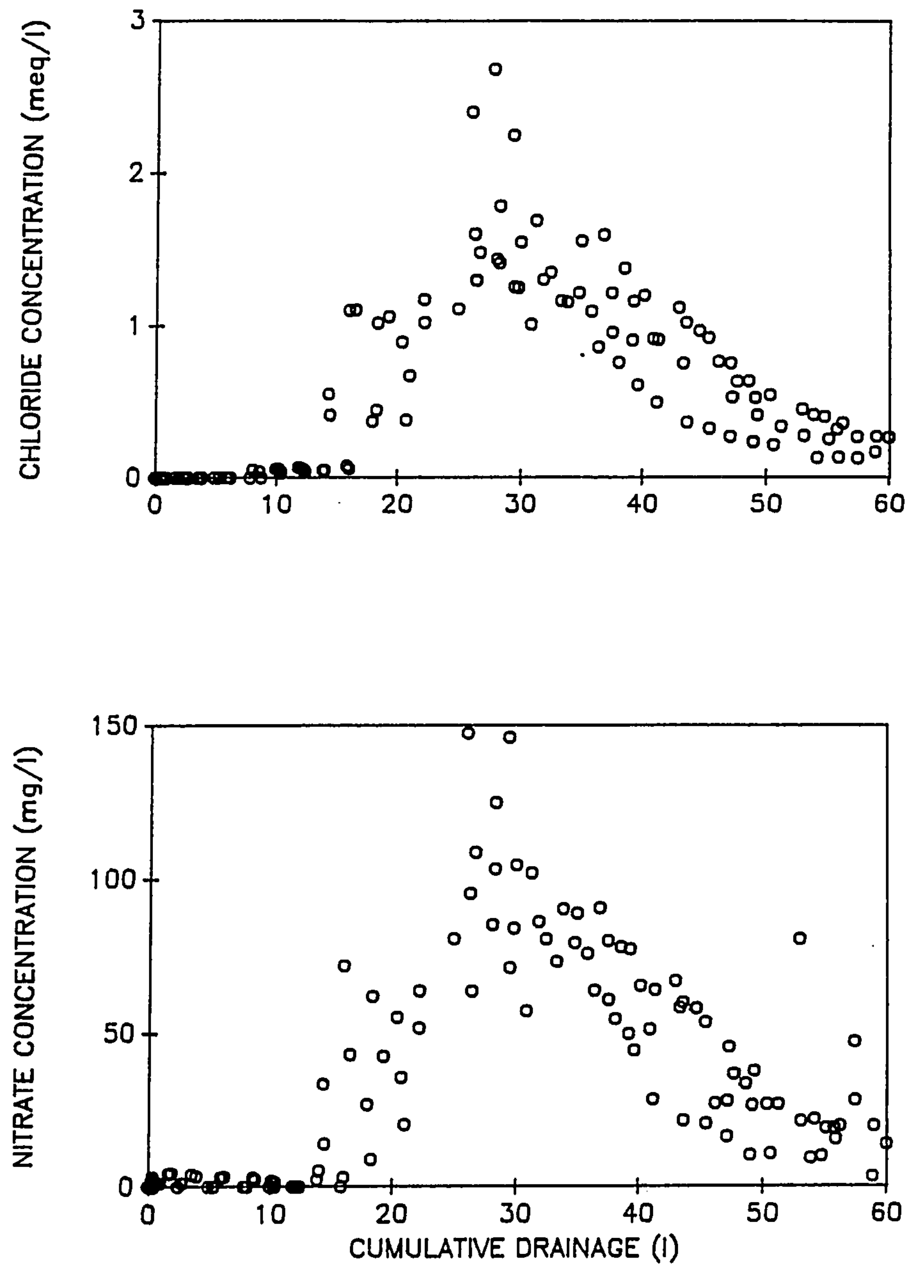



SOLUTION NB 1990
CHLORIDE CONCENTRATION (meq/l)
0
1
2
3
0
10
20
30
40
50
60
NITRATE CONCENTRATION (mg/l)
0
50
100
150
0
10
20
30
40
50
60
CUMULATIVE DRAINAGE (l)

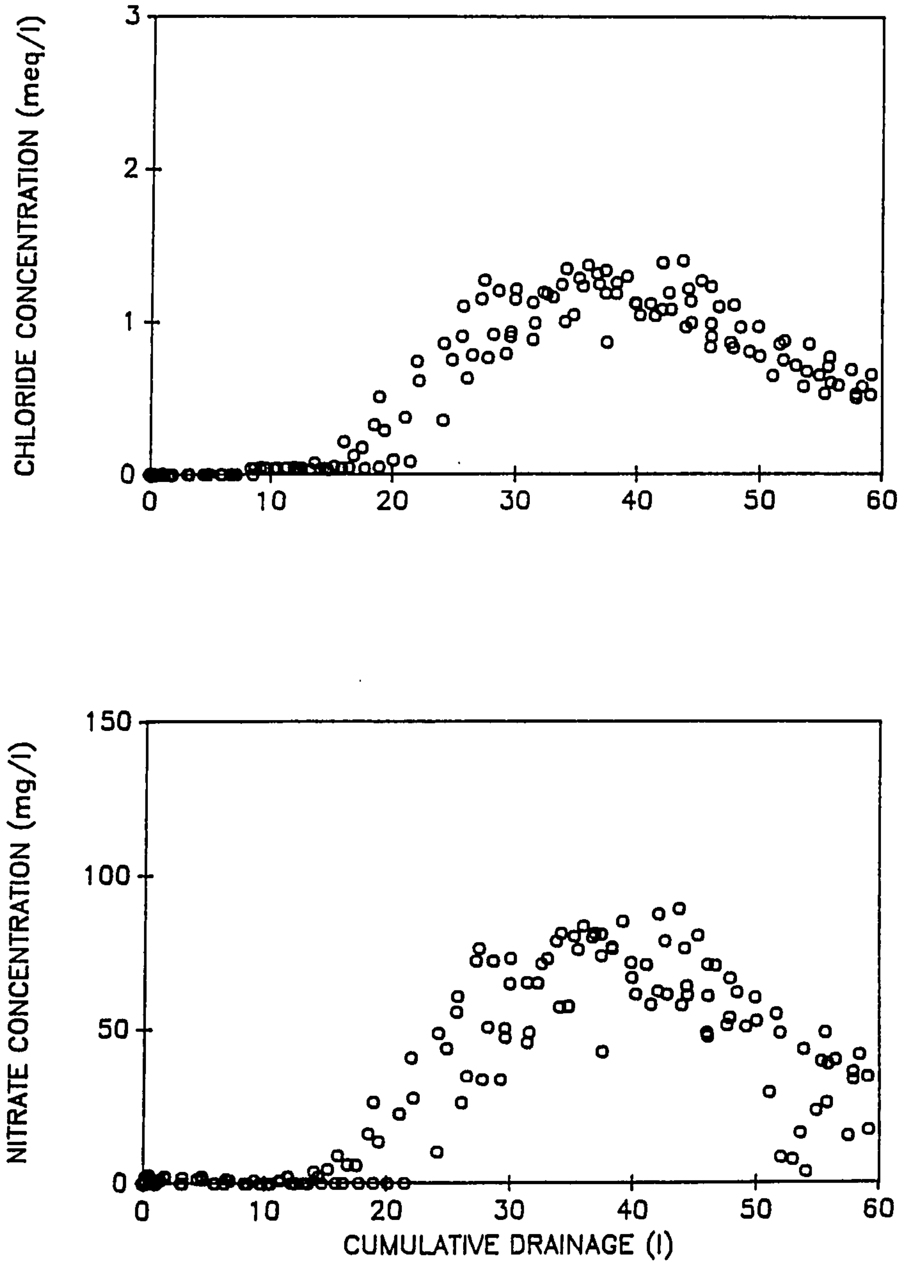
VERMICULITE NB 1990



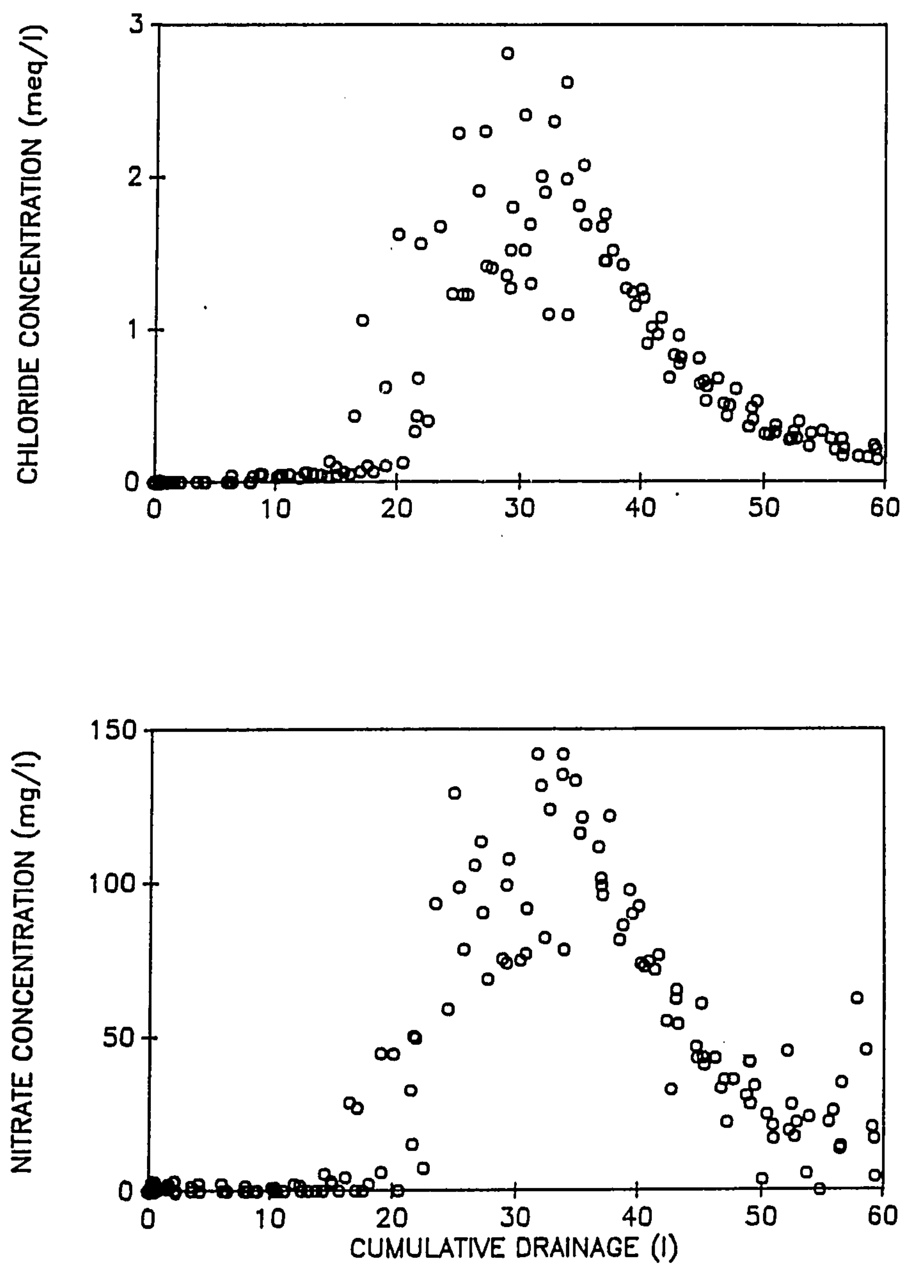
SOLUTION PA 1990



VERMICULITE PA 1990



SOLUTION C 1990



VERMICULITE C 1990