MEASUREMENT OF FLOW THROUGH THE UNSATURATED ZONE USING A PROTOTYPE FUNNEL LYSIMETER

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ABSTRACT

Prototype funnel lysimeters were constructed using 2-m dia. tree transplanting equipment. This equipment offers a possible means for quantitative, practical, and cost-effective measurement of flow in the unsaturated zone at the meter scale. The objective of this investigation was to develop and test the funnel lysimeter as a practical field methodology to conduct controlled quantitative tracer tests on large undisturbed soil samples. The steps to achieve this objective were to develop a working prototype, conduct tracer tests at sites with different field soils and a repacked soil in the laboratory, determine the characteristics of tracer breakthrough curves for the test soils, and assess the degree to sample disturbance caused by the lysimeter installation process.

Lysimeters were installed by temporarily excavating a 2-m³ soil sample using the tree transplanter and then replacing the sample after the installation of a sump and funnel-shaped impermeable liner. Tracer experiments were then carried out by applying solutes at the surface and sampling from the sump using an automatic sampler.

Seven funnel field lysimeters were installed in Minnesota over two field seasons in three different soil types. Experiments identified two distinct flow types; preferential and matrix flow. In a typical field experiment with the preferential-flow soil, discharge at the lysimeter sump occurred within 15 minutes of the start of a six minute tracer application; discharge of the tracer started after 23 minutes. For the matrix-flow soil, discharge to the sump typically took several hours to respond to tracer application. Drainage to the sump in the same cycle was composed of 100% antecedent water. The installation method does not lead to major disturbance of the soil but is more effective in sandy soils.

The experimental results indicate that the funnel lysimeter methodology is suited for wide application in subsurface hydrology because of its large sample size, a time scale resolution of minutes, and mass balance control. Essential technological improvements to the lysimeter and further tracer experiments are required to fully define the lysimeter flow characteristics.
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CHAPTER 1
INTRODUCTION

This report describes the development and testing of a new method to measure flow through the unsaturated zone. The method is for use on undisturbed soil samples at space scales of one to two meters. This scale of measurement is appropriate for studying the effects of solute flow along preferential pathways as well as through heterogeneous soils. The major experimental innovation of this research is the use of large diameter tree transplanting equipment to install the lysimeter. This equipment has been used to construct a conico-hemispherical drainage lysimeter which can be instrumented to measure discharge with a potential time resolution of minutes. The equipment is in the prototype stage but the results show that the potential merits of the experimental methodology address many of the current limitations of measuring unsaturated flow under field conditions.

JUSTIFICATION AND PROBLEM DESCRIPTION

The hydrology of the unsaturated zone is critical in the study of the processes of ground water recharge, plant-nutrient relations, contamination of soil and subsurface water and remediation of contaminated soils. Comprehensive description, measurement and modeling of soils to study solute transport is beyond our present capabilities. This is the result of soil heterogeneity and the complex hierarchy of soil properties and flow phenomena that occur at a variety of scales. It is also the result of the highly dynamic processes that characterize preferential flow phenomena in the unsaturated zone. Progress on these problems requires advances in: theory, computational ability, measurement methods and the calibration and validation of flow models. It is in the measurement methods that the lack of progress is most noticeable. Numerous reviews of this subject have pointed out the lack of advance in field experimental and measurement methods (Dane and Molz, 1991; Jury and Roth, 1989: Nielsen et al, 1989; Van Genuchten, 1991).

There is an expanding collection of theoretical models for describing flow for various idealized configurations of preferential flow (Beven and Germann, 1981; Bruggeman and Mostaghini, 1991; Hoogmoed and Bouma, 1980; Mitchell and van Genuchten, 1991). There has also been much work on the detailed geometrical description of preferential flow paths by staining (Bullock and Thomasson, 1979; Kung, 1990; Omoti and Wild, 1979; Ghodrati and Jury, 1990) scanning and image processing (Anderson and Peyton, 1992; Hanson et al, 1991; Warner and Young, 1991). Such work has provided the basis of the initial concepts of preferential flow, but knowledge of macropore morphology does not yield flow parameters for soil with preferential flow effects or help in calibrating and verifying models of unsaturated flow or solute transport. There are several reasons why it is difficult to advance past the qualitative description stage to one of quantitative measurement:

Size-the Representative Elementary Volume (REV) of soils with macropores or preferential pathways is larger than can be quantified by studies of conventional undisturbed soil columns, although even at this scale preferential flow effects are commonly seen. Suitable space scale for measurement is probably of the order of meters.

Sample disturbance-measurements must be taken in-situ or undisturbed, natural flow pathways may be destroyed.

Practicality-excavation of two cubic meters of soil or more in an undisturbed condition generally requires an elaborate and expensive field exercise.
LITERATURE REVIEW

The advection-dispersion model of solute transport in porous media has formed the basis of descriptions of solute movement in ideal homogenous porous media (Jury et al, 1991; Nielsen et al, 1989). Numerous analytical and numerical flow and transport models have been validated in column experiments of repacked soils (Haverkamp et al, 1977; Warrick et al, 1971) but the results consistently underestimate solute fluxes for undisturbed soil columns at greater measurement scales than the typical, 10 cm diameter, soil column (Elrick and French, 1966; Kissel et al, 1973; McMahon and Thomas, 1974). In general the larger the scale, the poorer the performance of models in predicting experimental results. This divergence from the theoretical behavior of matrix flow is attributed to soil-texture heterogeneity at a variety of scales and the widespread, if not ubiquitous, occurrence of preferential flow.

Preferential flow can occur in soils through various processes. Macropore flow is the term given to fluid flow occurring through channels, holes, cracks or fissures in soil. These features of soil structure normally comprise a minor portion of the total soil porosity but are significant because very rapid flow is possible due to large pore dimensions. Macropores can have physical or biological origins. Cracks or fissures can be formed by overconsolidation (stress relief), swelling and shrinking, or freezing and thawing of clays. Biological macropores are formed by small mammals, rodents, ants, and worms (Hole, 1981). Unstable flow is another form of preferential flow. A variety of physical conditions can lead to the development of an unstable wetting front and the phenomenon of 'fingering' (Glass et al, 1988; Hill and Parlange, 1972; Raats, 1973). Preferential flow can also occur as a result of subsurface focusing of solute flux by flow barriers in soil occurring at interfaces between soils types (Kung, 1990a and b).

Beven and Germann's review (1982) attributes the earliest scientific discussion of preferential flow to Schumacher (1864) and Lawes (1882). The first modern researchers to reiterate its widespread significance were Thomas and Phillips (1979). For a survey of recent work in the rapidly expanding field of research of preferential flow the reader is referred to the following anthologies: P.F. Germann (Editor) 1988, Approaches to Rapid and Far-reaching Hydrologic Processes in the Vadose Zone (Journal of Contaminant Hydrology, volume 3) M.Th. Van Genuchten, D.E. Rolston and P.F. Germann (Editors) 1990, Transport of Water and Solutes in Macropores (Geoderma, volume 46, numbers, 1-3) and most recently the Proceedings of the National Symposium of the American Society of Agricultural Engineers on Preferential Flow (Gish and Shirmohammadi, 1991).

RESEARCH PREMISES AND HYPOTHESES

The huge variability in pore sizes and its significance to solute movement in the unsaturated zone requires that any measurement technique is fully capable of measuring flow phenomena without scale bias. This restriction calls into question the measurement of soil parameters at discrete points or on small samples as is the case for soil-moisture probes, neutron probes, tensiometers or point sampling of solutes, even though such methods have previously indicated the presence of preferential flow characteristics in field situations (Biggar and Nielsen, 1976; Jury, 1982; Roth et al, 1991). Good mass balance for such experimental systems has been reported but the method is fundamentally incapable of ensuring this at sites exhibiting preferential flow.

From the foregoing discussion it is possible to define the characteristics of an ideal measuring system for flow through the unsaturated zone. The ideal measurement method must address the physical issues of; scale, mass balance, and measurement time resolution, as well as the issues of practicality, versatility and economy.

In detail the desired features of methodologies for measuring unsaturated zone flow are:
i) Appropriate scale; application of the principles of averaging embodied in the concept of the REV suggests that for full applicability sample volumes of 100 times the scale of the REV are required. The larger the sample size the greater the probability of inclusion of soil heterogeneity and preferential flow features. The upper bound of the ideal measurement scale is set by system response time. The larger the experiment scale the longer the travel times the slower the experiment.

ii) Closed mass balance; as in weighing lysimetry ensuring a closed mass balance requires isolation of the sample from all inputs except the one of interest. Similarly ensuring collection of all percolate requires a sealed drainage sump.

iii) Appropriate time resolution; study of flow processes in soils with pathways of preferential flow demand the capability of continuous or minute by minute monitoring and sampling.

iv) Standard equipment and experiment design; The power of a measurement technique is increased if results can be compared between experiments.

v) Ease of installation, measurement and interpretation; wide acceptance of a measurement technique depends on its overall effectiveness accounting for the value of the results, cost, labor requirements and level of technical complexity.

vi) Wide applicability; increases the capability for the cross comparison of results not only between sites but between different types of experiments.

None of the currently used methods fulfill all the requirements outlined above for measurements of flow in the unsaturated zone. The use of large tree transplanter equipment offers a possible technical solution to the fundamental requirement for a practical and cost effective field methodology. Tree transplanter are designed specifically for excavating large soil samples with minimal disturbance of the root system of a tree. Development of this method requires the investigation and resolution of the effects of unorthodox sample geometry and the non-uniform flow field.

The research reported here is based on three hypotheses:

i) that it is feasible to construct a funnel shaped lysimeter by excavating a large undisturbed soil sample with a tree transplanter.

ii) such a funnel lysimeter is capable both of measuring soil solute flow processes for both matrix and preferential flow;

iii) it is a practical field methodology with potential for wide use as an investigative tool in the science of subsurface hydrology.

OBJECTIVES

The principal objective of this investigation is to develop and test the funnel lysimeter as a versatile and practical field methodology for conducting controlled quantitative tracer tests on large, undisturbed soil samples capable of measuring soil hydraulic parameters at space scales of one meter or more.

This major objective was addressed by examining the performance of the funnel lysimeter equipment. Control experiments would entail using a repacked soil to represent matrix flow conditions. The sub-objectives therefore comprise:

i) Field equipment development; establishing a working field experimental system.
ii) Run tracer tests through the equipment at three sites with three different soil types.

iii) Run tracer tests through the equipment with a repacked soil sample to determine the matrix flow characteristics of the funnel lysimeter and compare the results with theoretical solutions derived for the experimental system.

iv) Assess the degree of soil disturbance caused during soil excavation by comparison of preferential pathways in the sample with in-situ soil conditions.

CHAPTER 2

EQUIPMENT and METHODOLOGY

To install the lysimeter a tree transplanter excavates a conico-hemispherical soil sample (Figure 1) and raises it out of the ground (Figure 2). While the transplanter remains in position a hole for a collector sump is excavated in the base of the hole using a post hole auger (Figure 3). Once complete, the collector sump, with attached pump tube, is placed in the hole. An impermeable liner is then arranged into a conical form in the hole with the cone apex (the lowest part) cupped into the top of the sump (Figure 4). An inner permeable geotextile liner is similarly arranged inside the first liner. The soil sample, still being held by the tree transplanter, is now carefully lowered and repositioned into the hole. (Figure 5) The blades are then slowly retracted thus completing the installation of the below ground equipment (Figure 6).

The investigation of the funnel lysimeter methodology is organized as follows;

i) development of lysimeter design, and installation of prototype lysimeters
ii) field discharge and tracer experiments,
iii) discharge and tracer experiments in a scale laboratory funnel lysimeter,
iv) theoretical analysis of flow and transport of solutes through the funnel lysimeter.
v) post experiment investigation of soil disturbance induced by lysimeter installation.

A laboratory scale funnel lysimeter model and finite element numerical models were used to conduct control experiments. Theoretical models conduct numerical and analytical experiments with ideal porous media. Effects of sample packing, small-scale heterogeneity and the uncertainty of flow conditions occurring at the interface between the soil and the geotextile are not investigated in these experiments. The laboratory model replicated the field conditions and the results include all these non-idealities but is not subject to excavation soil disturbance. Laboratory and numerical modeling therefore provide complementary information describing the hydrology of tracer tests with the funnel lysimeter.
Figure 1: Excavation using the Stocker tree transplanter

Figure 2: Temporary removal of the sample

Figure 3: Excavation of sump hole by auger
Figure 4: Installation of the impermeable liner

Figure 5: Replacement of the sample to the lined hole

Figure 6: Completed installation
FIELD EXPERIMENTS
The field equipment was developed through successive refinements, by trial and error. In 1991 two pilot installations were installed and tested. Numerous aspects of the installation method, construction and materials were redesigned. The 1991 experiences led to a standard design chosen for the construction of similar lysimeters at the three 1992 experimental sites. With a standard design the tracer experiment results for the different soil types could be compared. Further design improvements are now possible based on the 1992 field measurements.

SAMPLE EXCAVATION/REPLACEMENT
Tree transplanters manufactured by two companies were tested in the 1991 pilot study experiments; the Stocker 8 from Stocker MFG. Co. and the Big John 90 from Big John Inc. Both dig holes with a nominal surface diameter of 2.29 m (90 in) and both work by pushing metal blades into the soil to isolate a conico-hemispherical soil sample of about two cubic meters. The major features of the transplanters pertinent to the installation of the lysimeter are; the number of blades, the position of strengthening ribs and the pressure plate design (Figure 7). When the sample is temporarily removed from the ground the circular pressure plate holds the sample in position in the bucket. The ring also allows for clean removal of the blades after the sample has been returned to the hole. The inboard location of strengthening ribs on the Stocker blades is one disadvantage for using this machine for excavating large undisturbed soil samples. The ribs leave long grooves in the soil sample extending the full depth of the sample. The grooves were backfilled with sand to 30 cm below the surface and the upper section of the holes were sealed with a solution of Plaster of Paris and left to set.

After several trial excavations the following procedure was used for sample excavation. The pressure plate was placed over the selected site for the lysimeter. Each of the eight blades were then pushed into the soil to a depth of about 0.15 m. The digging sequence was alternated from side to side to advance the blades evenly. This technique ensures the highest degree of anchoring and machine stability and probably reduces torsion on the blades. The blades were then further advanced to about 0.5 m using the same sequence as before and the sequence was repeated until the blades were all fully extended and the soil sample had been completely isolated.

With the Big John machine the four blades are pushed into the ground one at a time as with the Stocker. The Big John machines tested were in poorer operating condition than the Stocker machine. At the same site the Big John required additional back and forth blade movements to complete the excavation process. The friction on individual blades during digging due to the larger blade area appears to reduce the effective digging power of the Big John. Common excavation
practice requires the Big John operator to lift the truck up on the hydraulics and then use the truck weight to help with downward thrust of the blades.

The initial trial excavations with both types of equipment revealed the importance of the general operating conditions of both machine types to the successful installation of an undisturbed soil sample. New or well-maintained transplanters excavate less disturbed samples than older equipment. If the transplanter blades are bent or twisted the excavation is more difficult, causes more edge disturbance and results in an irregularly shaped sample with a greater mismatch with the liners. The blades must be in good shape and meet snugly at the bottom, when fully extended.

In our trials, the Big John was not as successful as the Stocker in excavating undisturbed soil samples. Notwithstanding the more worn condition of the Big John equipment, the four blades do not provide the same degree of anchoring as eight blades of the Stocker. Despite the soil disturbance resulting from the inboard location of the strengthening ribs, the Stocker equipment was selected from the available machines for the minimum overall extent of soil disturbance.

LYSIMETER AND EXPERIMENTAL DESIGN

In the funnel lysimeter, the soil is isolated from its natural surroundings by the presence of an outer impermeable liner and an inner permeable geotextile liner. These liners funnel solutes into a collector sump. The solutes are pumped from this sump through pump tubes to an automatic water sampler (Figure 8).

![Figure 8: Conical lysimeter design and experimental setup](image)

Seven sets of liners were made, one for each of the field installations. Two types of impermeable material were used; a high density 1.5 mm (60 mil) thick PVC manufactured as Gundline® by Gundle Lining System Inc. and 0.15 mm (6 mil) thick, clear polyethylene sheeting. The Gundline® was originally chosen for its high tear and puncture resistance. It is manufactured for lining of sanitary landfills. In both cases the outer impermeable liners were made from a single circular piece of material cut from a large roll. The liner is made into a conical form on site after making a single radial cut from the center of the circle and overlapping the cut edges.

The inner permeable liner used was a filamentous polypropylene geotextile (Supac® 16 NP, Phillips Fibers Corporation). The manufacturers specifications for hydraulic conductivity of the geotextile are 0.25 cm/sec (Phillips Fiber Corp., 1990). Hydraulic conductivity measured through the plane of the fabric was 0.12 cm/sec (D. Misra, 1993, personal communication).
The collector sump was made using standard PVC pipe fittings and glued with Nova Weld® (PVC cement). Its main design features are a funnel shaped base to allow collection of samples at low discharge rates and a storage capacity of approximately 1.5 liters (Figure 9).

![Diagram of sump construction detail](image)

**Figure 9: Sump construction detail**

**Field Tracer Experiment System**

A combination of Fluorescein (FL), Rhodamine WT (RWT), Br⁻ and Cl⁻ were used in tracer solutions. Each tracer experiment used a tracer solution containing both a conservative tracer, either Br⁻ or Cl⁻, and a non-conservative, absorbing tracer, fluorescein or Rhodamine WT. Tracer solutions were applied to the soil surface from a single centrally positioned sprayer. The solutions were pumped from a reservoir using a submersible utility pump (Simer Geyser II, model 2305). The solute application area and application rate could be varied by use of gate valves controlling a recirculation hose. This functional, if not highly precise equipment was made up using hardware store quality components; pumps, hoses, hose connectors and garden sprinkler/sprayers.

The standard application of solute during a tracer test was 32 liters. This delivered an effective solute application depth of 12.6 mm for a circular irrigated area of radius 90 cm. The duration of the solute application was typically six minutes giving an application rate of 2 mm/min. Solutes were pumped from the collector sump using a 3700 series ISCO automatic sampler. The sampler has 24 one liter bottles.

Measurements of discharge to the sump were established by measuring the amount of solute collected in the sampling bottles of the ISCO sampler taken in a known interval. Fluorescein and Rhodamine WT concentrations were analyzed in the lab using a Turner Design Model 10-005 Fluorometer (Turner Designs, 1981). The samples were measured relative to four standards for each dye. The temperature of the samples and standards were carefully equilibrated. These data are thought to be accurate and precise to about ±5%. Bromide and Chloride concentrations were measured by ion chromatography using a Dionex Series 4000i (Bachman et al, 1986). Results are accurate to within ±2%.

**Soil Disturbance Analysis**

Disturbance of the soil sample results from the excavation and replacement by the tree transplanter. Additional disturbance may result from the poor fit of the liner system to the sample shape. Assessment of the disturbance was carried out after completion of all field tracer experiments by visual inspection of the whole sample during a process of careful hand-excavation. The excavation was conducted after the application of either Rhodamine WT or methylene blue. The staining...
clearly acting as paths of preferential flow, were natural soil features or created during installation of the lysimeter.

The soil stain was applied through the same irrigation set-up as the tracer applications with 32 liters of stain applied as 1% solution. RWT was used at St. Paul, methylene-blue at St. James and Princeton.

Spades, trowel and spatulas were used to excavate the soil in a series of slices 15 cm deep, across the width of the lysimeter. Positioning within the sample was recorded using a rectangular measurement grid set up around each lysimeter. This grid was used to guide the excavation of the slices and to record the observation of soil structures. The infilled (rib grooves) numbered clockwise from the origin of the rectangular grid were sometimes used as an additional reference system. The samples were excavated in two stages. On the one side the slices were taken horizontally, on the other, vertically. The vertical slices were excavated either in line with the dividing axis or radially from the center (Figure 10).

**Figure 10: Modes of excavation for soil disturbance survey**

**LABORATORY-SCALE PHYSICAL MODELING**

A laboratory-scale funnel lysimeter was designed to approximately 1:4 scale. An exact scale and geometrical replication of the field installation were waived in preference for a plain conical model geometry (Figure 11). The soil to be tested was sampled from one of the field sites, oven dried and then sieved to remove roots and other plant matter. The sample was thoroughly stirred and mixed before hand packing in the cone. The soil was packed dry and in layers. Each layer was tamped down using a one kilogram weight. The final sample surface was shaped to be slightly higher at the edges so that any ponding or runoff from the waterproof apron would be directed away from the edge of the sample and the exposed geotextile.
Tracer solutions were mixed in a bucket reservoir and input discharge was measured by timing the period for spraying a nominal 0.7-liter application (10 mm effective water depth). The spray system was adjusted to apply water in a circular area of 25 cm radius, giving an effective depth of applied solute of 3.6 mm. With spray duration of about 1 min 50 seconds the solute application rate was 2.0 mm/min. This last figure is similar to the application rate used in the field experiments although the effective rain depth differs. The limited range of adjustment possible in the solute application prevented consistency in all the measures of solute application.

The discharge rate was measured by collecting and weighing all the outflow in pre weighed 30 ml sample vials and recording the time of vial collection. Tracer concentrations were analyzed using the same methods as described for the samples.

After completion of the tracer experiments with the repacked soil sample a second series of experiments was conducted with the same soil but after the introduction of a single vertical macropore. The macropore was created by pushing a sharpened, one-eighth inch (3.2 mm) diameter stainless steel rod through the full depth of the soil from the surface.

DESCRIPTION OF TRACER EXPERIMENT TYPES

The hydrological characteristics of the field and laboratory lysimeters were investigated using a combination of Short Input Tracer (SIT) experiments and Multiple Input Tracer (MIT) experiments. Before either of these two experiments were conducted a Simple Infiltration-Discharge (SID) experiment was required.

The Simple Infiltration-Discharge (SID) experiment was used to determine the best tracer test procedure; application rates, discharge rates, as well as sample and data collecting methods for varying responses in different soils. This experiment is required before applying any tracer solutions to established if sample moisture content was sufficient to permit drainage to the sump.
The Short Input Tracer (SIT) experiment was a single sprayed irrigation application. The volume of tracer applied was selected to be representative of field conditions for a short but high intensity precipitation event typical of summer convectional rainfall. The Multiple Input Tracer (MIT) experiment was an aggregate of a series of SIT experiments. Although input discharge varied over the duration of the numerous applications the tracer input concentration was kept constant. The MIT experiment proved to be a practical procedure for investigating the solute transport characteristics of the field soils without the need for continuous and uniform solute input rates i.e. steady state flux conditions.

In a series of SIT experiments that comprises an MIT test only the first was useful for determining the experimental response to a tracer pulse input. Subsequent tests in the MIT sequence are identified as infiltration discharge (ID) experiments.

SITE DESCRIPTIONS
Three experimental sites were selected in Minnesota to investigate the effects of soil type. The soils at the three sites were:

i) Loamy sand at the Princeton Management Systems Evaluation Area (MSEA) in Sherburne County,
ii) Silt loam soil with macropores on the St. Paul Campus of the University of Minnesota
iii) Loam soil on private farm property near the town of St. James, Watonwan County (see Figure 12).

Soil textural classes and all other laboratory-measured soil parameters were determined from samples taken at different depths from each of the lysimeter experimental plots (Figure 13). The position of each installation was selected in the field to minimize problems with surface runoff to the sample margins and to help ensure irrigation uniformity.

Figure 12: Field site location map
Figure 13: Soil textural classes for the field sites.
FIELD EXPERIMENTS
Seven funnel lysimeters were installed over the 1991 and 1992 field seasons at the three selected sites. In 1991 two lysimeters were installed at the St. Paul site. In each case a series of SID (Simple Infiltration-Discharge) experiments were conducted to determine appropriate solute application volumes and intensity and the optimum sampling intervals. One SIT (single input tracer) experiment was conducted at each of the two lysimeters installed. The results were used to establish tracer experiment protocols and provide an initial assessment of the methodology. Using the results and experiences gained in 1991, a single experimental equipment design was selected for the 1992 lysimeter installations. In 1992 five lysimeters were installed. A third lysimeter was installed on the St. Paul site and two lysimeters at each of the other two sites. Further proposed improvements to the methodology, based on the 1992 experiments, are presented in the Equipment and Methods section of Chapter 4.

1991 Field Lysimeter Experiments, St. Paul
The first tracer tests through the field funnel lysimeter were carried out in August and September, 1991 in lysimeters 1 and 2 at St. Paul. Both of these tests were pilot experiments during which equipment and protocols were being developed. Some of the features of these tracer tests were never subsequently observed in any later test. The tracer discharge breakthrough curves (Figures 14 and 15) show some features observed in the 1992 season in lysimeter 3. Other features which were initially assumed to represent solute flow through the sample did not reoccur in the 1992 experiments and are now considered to be experimental effects. The 1991 results should therefore be interpreted with caution but are presented as the first indication that the funnel lysimeter method worked and showed preferential flow occurring through the soils at the St. Paul site. The 1991 experiments also provided two of the three SIT experiment results for the St. Paul site.

Figure 14: Semi-log tracer discharge breakthrough curve for St. Paul lysimeter 1

Q/Q₀ = Dimensionless Discharge (Q= sump discharge, Q₀= surface application rate)
Input discharge: 1.8 mm/min. for 7 mins.

Q/RW = Dimensionless Arrival Time (Q= sump discharge, R= tracer application rate)
Input tracer: 1.8 ppb for 7 mins.
In lysimeter 1, discharge to the sump began seven minutes after the start of tracer application. The sump was temporarily flooded because the sampler was not programmed to sample such rapid discharge response. Discharge increased rapidly to a test maximum at between 24 and 25 minutes. The discharge then dropped rapidly to a period of uneven discharge between 33 and 44 mins. Discharge subsequently decayed at a constant exponential rate until 300 mins (as indicated by the constant slope on the semi-log graph) and then at a slower exponential rate.

Tracer concentrations above background levels only began to occur after 21 mins. Values increased and reached an initial maximum at 32 mins. Both tracers then decreased in concentration before rising to the test maximum at 300 mins. An exponential decrease in concentrations of both tracers then followed. The abrupt drop in tracer concentrations at 6000 mins is matched by a rise in discharge. Both are considered to be associated with leakage into the sump because of a rise in water table occurring in response to heavy rainfall. The response of both tracers is congruent despite the major differences in their adsorption properties. The cumulative discharge to the sump during the test was 31 liters; 32 liters were applied. Approximately 4% of the tracer mass was recovered. The peak concentration for both tracers was approximately 10% of application concentration.

Of the seven funnel lysimeters installed only lysimeter 2 at St. Paul was installed with a Big John tree transplanter. The general features of the tracer and discharge response for this lysimeter were similar to those for lysimeter 1. In lysimeter 2, discharge to the sump started at 7 mins (Figure 15). The maximum rate of discharge occurred during this first minute of flow and decreased rapidly with uneven discharge rates recorded between 16 and 26 minutes. The subsequent discharge curve showed smooth decay in discharge rate through the end of the test.

Unlike the previous tracer test the first sample, taken at seven minutes, did contain measurable concentrations of Br. Measurable RWT appeared in the second sample at 8 mins. As in the first test, both breakthrough curves show two local maxima; at 11 mins and 20 mins for RWT and 16 mins and 23 mins for Br. In this test, however, the higher maxima occurred at the earlier time.

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**Figure 15:** Semi-log tracer discharge breakthrough curve for St. Paul lysimeter #2
During this test only 10.15 liters were recovered of the 32 liters applied. This contrast with the 31 liters return with lysimeter 1 is attributed to antecedent soil-moisture levels. The lysimeter 2 tracer test was conducted after a prolonged period of dry weather. The mass recovery of both tracers was comparable with results for lysimeter 1; 1.6 % for RWT and 6.6% for Br-. The peak tracer concentrations were approximately 80 % of applied concentration for Br- and 20 % for RWT.

1992 Field Lysimeter Experiments
St. Paul
A sequence of twenty Br- tracer applications were made to establish the MIT breakthrough curve (Table 1). An SIT test was conducted with RWT during application 14A. Peak discharge was about 9 % of the application rate, which is similar to the 17 % and 8 % of St. Paul lysimeters 1 and 2, in 1991 (Figure 16). The discharge breakthrough did not have the two discharge maxima or the period of uneven flow about the 20 to 50 minute elapsed time in both 1991 experiments. It is not known if this is the result of improved experimental protocols or different sample discharge response. The tracer response was consistent with the 1991 experiments. The increase in RWT concentration lagged discharge slightly, but the time to peak signal was within two minutes of the peak discharge. The RWT concentration decay rate was slower than for the discharge.

Table 1: Summary of Experiments for St. Paul Lysimeter #3 (1992)

<table>
<thead>
<tr>
<th>Application #</th>
<th>Tracer Type</th>
<th>Dates</th>
<th>Drainage Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dist. Water</td>
<td>6/13 - 6/14</td>
<td>21 hrs</td>
</tr>
<tr>
<td>2</td>
<td>12g Br / 6.4g RWT</td>
<td>6/14</td>
<td>7 hrs</td>
</tr>
<tr>
<td></td>
<td>flooded by rain</td>
<td></td>
<td>132 hrs</td>
</tr>
<tr>
<td>1A</td>
<td>12g Br</td>
<td>6/20/92-6/21/92</td>
<td>24 hrs</td>
</tr>
<tr>
<td>2A</td>
<td>12g Br</td>
<td>6/21/92-6/22/92</td>
<td>23 hrs</td>
</tr>
<tr>
<td>3A</td>
<td>12g Br</td>
<td>6/22/92-6/23/92</td>
<td>24 hrs</td>
</tr>
<tr>
<td>4A</td>
<td>12g Br</td>
<td>6/23/92-6/24/92</td>
<td>25 hrs</td>
</tr>
<tr>
<td>5A</td>
<td>12g Br</td>
<td>6/24/92-6/25/92</td>
<td>22 hrs</td>
</tr>
<tr>
<td>6A</td>
<td>12g Br</td>
<td>6/25/92-6/26/92</td>
<td>27 hrs</td>
</tr>
<tr>
<td>7A</td>
<td>12g Br</td>
<td>6/26/92-6/29/92</td>
<td>72 hrs*</td>
</tr>
<tr>
<td>8A</td>
<td>12g Br</td>
<td>7/4/92-7/6/92</td>
<td>52 hrs</td>
</tr>
<tr>
<td>9A</td>
<td>12g Br</td>
<td>7/6/92-7/7/92</td>
<td>24 hrs</td>
</tr>
<tr>
<td>10A</td>
<td>12g Br</td>
<td>7/7/92-7/8/92</td>
<td>25 hrs</td>
</tr>
<tr>
<td>11A</td>
<td>12g Br</td>
<td>7/8/92-7/9/92</td>
<td>22 hrs</td>
</tr>
<tr>
<td>12A</td>
<td>12g Br</td>
<td>7/9/92-7/10/92</td>
<td>21.5 hrs</td>
</tr>
<tr>
<td>13A</td>
<td>12g Br</td>
<td>7/10/92-7/12/92</td>
<td>88 hrs*</td>
</tr>
<tr>
<td>14A</td>
<td>12g Br / 1.0g RWT</td>
<td>7/15/92-7/23/92</td>
<td>192 hrs</td>
</tr>
<tr>
<td>15A</td>
<td>6g Br</td>
<td>7/23 - 7/27</td>
<td>102 hrs</td>
</tr>
<tr>
<td>16A</td>
<td>6g Br</td>
<td>7/27 - 8/3</td>
<td>189 hrs</td>
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<tr>
<td>17A</td>
<td>12g Br</td>
<td>8/3 - 8/4</td>
<td>22 hrs</td>
</tr>
<tr>
<td>18A</td>
<td>12g Br</td>
<td>8/4 - 8/5</td>
<td>19 hrs</td>
</tr>
<tr>
<td>19A</td>
<td>12g Br</td>
<td>8/5</td>
<td>5.5 hrs</td>
</tr>
<tr>
<td>20A</td>
<td>12g Br</td>
<td>8/5 - 8/7</td>
<td>40 hrs</td>
</tr>
</tbody>
</table>

*heavy rain, sump flooded due to rise in water table. Next experiment delayed.
C/Co=Dimensionless concentration (C=discharge concentration, Co=applied concentration).
Q/Qo=Dimensionless discharge (Q=output discharge, Qo=application rate)

Figure 16: Semi-log tracer discharge breakthrough curve for St. Paul lysimeter #3

All the SID breakthrough curves for the 20 tracer applications except 1A show spiked discharge responses (Figure 17). Times for the rises to peak discharge values (t_p) vary from 7 minutes for 19A to 30 minutes for 1A, but most values were about 10 minutes. The peak discharges were followed by smooth and rapid decreases in discharge. Peak discharge values varied greatly within the 20 experiments. Some of the variation can be explained by incomplete drainage of the soil sample during the previous application cycle.

The total discharge to the sump during applications 2A-20A was 460 liters; 76% of the 608 liters applied. The remainder is comprised of water lost to evapotranspiration and net leakage from the collector sump (leakage in during flooding, leakage out in periods of insufficient sampling frequency). During the same period, the total potential evapotranspiration, calculated using the Thornthwaite method (1944) and temperature data from the Climatological Observatory on the St. Paul campus (M. Seeley personal communication, 1993) was 598 l (21.9 l/day in June and 18.5 l/day in July). The pan evaporation rate was 21.9 l/day and 19.5 l/day for the same periods.

As occurred in the 1991 SIT experiments, tracers discharged in response to each application (Figure 18). With the exception of 13A, only a few samples were taken, from each application, for analysis of Br⁻. The tracer response was consistent throughout all the experiments. Tracer concentrations rose rapidly at early times of the experiments and then decreased in a saw-tooth shaped-curve.
Figure 17: Discharge breakthrough curves for St. Paul lysimeter #3 (A through 20A)

Q/Qo (%)

Peak value labels = moisture credit (l)

V/Vo

0 0.1 0.2 0.3 0.4 0.5 0.6

Q/Qo = Dimensionless Discharge (Q=sump discharge, Qo= Application rate),

V/Vo = Dimensionless Pore Volume (V=cumulative discharge volume, Vo=lysimeter pore volume)
Figure 18: Bromide breakthrough curve for 1A through 19A

Princeton
Two funnel lysimeters were installed at Princeton. Lysimeter 'I' was instrumented with thermocouples and TDR soil moisture probes. Lysimeter 'N' was not instrumented. A total of nineteen water applications were made on both lysimeters. Initial discharge to the sump began during the ninth set of 32-liter applications of water. A series of ten tracer tests were then conducted (Table 2).

During application 10, the first tracer test, discharge to the sump started immediately (Figure 19). The flow rates at this site were, however, significantly lower than at St. Paul. Peak discharge at Princeton was 30 ml/min compared with 1000 ml/min at St. Paul. As became obvious with the later applications, both the samples were at moisture-content levels considerably higher than field capacity when application 10 was started. Both lysimeters were therefore already draining in response to application 9 and possibly earlier.
Table 2: Schedule of Experiments for Princeton Lysimeters (N and I)

<table>
<thead>
<tr>
<th>Application #</th>
<th>Tracer Type (in 32 l water)</th>
<th>Dates</th>
<th>Drainage Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>water</td>
<td>8/14 - 8/17</td>
<td>73 hrs</td>
</tr>
<tr>
<td>2</td>
<td>water</td>
<td>8/17</td>
<td>2 hrs 50 mins</td>
</tr>
<tr>
<td>3</td>
<td>water</td>
<td>8/17</td>
<td>1 hr 20 mins</td>
</tr>
<tr>
<td>4</td>
<td>water</td>
<td>8/17 - 8/18</td>
<td>20 hrs</td>
</tr>
<tr>
<td>5</td>
<td>water</td>
<td>8/18</td>
<td>1 hr 40 mins</td>
</tr>
<tr>
<td>6</td>
<td>water</td>
<td>8/18</td>
<td>1 hr 20 mins</td>
</tr>
<tr>
<td>7</td>
<td>water</td>
<td>8/18</td>
<td>1 hr 5 mins</td>
</tr>
<tr>
<td>8</td>
<td>water</td>
<td>8/18 - 8/19</td>
<td>19 hrs 20 mins</td>
</tr>
<tr>
<td>9</td>
<td>water</td>
<td>8/19</td>
<td>3 hrs</td>
</tr>
<tr>
<td>10</td>
<td>12 g Br⁻/3 g RWT</td>
<td>8/19 - 8/26</td>
<td>168 hrs</td>
</tr>
<tr>
<td>11</td>
<td>12 g Br⁻</td>
<td>8/26 - 8/27</td>
<td>21 hrs 40 mins</td>
</tr>
<tr>
<td>12</td>
<td>12 g Br⁻</td>
<td>8/27 - 8/31</td>
<td>98 hrs</td>
</tr>
<tr>
<td>13</td>
<td>12 g Br⁻</td>
<td>8/31 - 9/2</td>
<td>49 hrs</td>
</tr>
<tr>
<td>14</td>
<td>12 g Br⁻</td>
<td>9/2 - 9/7</td>
<td>118 hrs</td>
</tr>
<tr>
<td>15</td>
<td>12 g Br⁻</td>
<td>9/7 - 9/14</td>
<td>172 hrs</td>
</tr>
<tr>
<td>16</td>
<td>12 g Br⁻</td>
<td>9/14 - 9/18</td>
<td>96 hrs</td>
</tr>
<tr>
<td>17</td>
<td>12 g Br⁻</td>
<td>9/18 - 9/21</td>
<td>70 hrs</td>
</tr>
<tr>
<td>18</td>
<td>12 g Br⁻</td>
<td>9/21 - 9/25</td>
<td>94 hrs</td>
</tr>
<tr>
<td>19</td>
<td>12 g Br⁻</td>
<td>9/25 - 9/27</td>
<td>60 hrs</td>
</tr>
</tbody>
</table>

Q/Q₀=Dimensionless discharge (Q=ouput discharge, Q₀=application rate)

Figure 19: Princeton (I) sump discharge hydrographs for applications 10 through 15
The discharge and tracer breakthroughs at the Princeton site were significantly different from the St. Paul site. Time to peak discharge normally exceeded 24 hours. Time to initial discharge response varied from about 8 hours at low moisture contents to a few minutes at the highest moisture contents at Princeton. The breakthrough curves show rounded maxima, even on a linear time scale, and are noticeably less peaked than St. Paul breakthrough curves. Excepting application 10, the tails of the discharge breakthrough curves are exponential in nature as they were at St. Paul.

RWT and Br⁻ tracers were both applied in application 10; Br⁻ continued to be applied through Application 19 (Table 2). RWT was never detected in the discharge of either lysimeter. The continued application of Br⁻ for the MIT experiment resulted in the appearance of Br⁻ in the sumps during application 12 for the instrumented site (the third tracer cycle) and application 14 for lysimeter N (the fifth tracer cycle). The Br⁻ concentrations in both lysimeters increased gradually and reached C/C₀ values of 0.39 for lysimeter I and 0.56 for lysimeter N during application 19 (Figure 20). Unlike the St. Paul results, none of the tracer applied at the surface of the Princeton site reached the sump during the same drainage cycle. All of the sump discharge that occurred during a cycle of solute application is antecedent moisture. Lack of time prevented continuation of the MIT experiment. It can be assumed that the tracer concentrations would have continued to increase to C/C₀=1. The total volume discharged to the sump of the non-instrumented site during applications 11 through 18 was 187.9, 73% of the 256 l applied. The corresponding figures for lysimeter I are; 177 l discharged, 69% of the applied volume. The calculated total potential evapotranspiration using data from the MSEA weather station (J. Lamb personal communication, 1993) for the same period was 291.5 l (10.8 l/day in August and 9.5 l/day in September).

\[ C/C₀ = \text{Dimensionless concentration (C=discharge concentration, C₀=applied concentration)} \]
\[ V/V₀ = \text{Dimensionless Volume (V=cumulative discharge volume, V₀=lysimeter pore volume)} \]

Figure 20: Cumulative Princeton Br⁻ Breakthrough from MIT experiments with 9 tracer applications.
St. James
Two lysimeters were installed at the St. James site. Post-experiment analysis of the distribution of the surface applied soil stain indicated that a significant amount of tracer had by-passed the soil in both lysimeters and flowed directly to the wick at the surface. The rapid discharge and tracer responses recorded at St. James are not considered to represent soil properties at the site. Tracer breakthrough data will not, therefore, be used to define hydrological properties of the soils at St. James and will not be used in the following discussion of results to the same degree as results from the other experiments.

LABORATORY EXPERIMENTS
The laboratory lysimeter experiments were carried out between July and December 1992 on one soil sample. Equipment design and experimental protocols had been previously resolved with a laboratory prototype. The soil used for the laboratory lysimeter was sampled from the Princeton site, immediately adjacent to the two field lysimeters. The schedule for laboratory experiments started with five SID tests and continued through twenty-four short input Br⁻ and FL tracer tests (Table 3). A further five short input RWT tracer tests were conducted in the same soil sample after the creation of the single macropore. The tests were conducted through the repacked soil specimen, as described in Chapter 2.

After sample wetting, most test cycles were conducted within a twenty four hour period. Overnight drainage was sufficient for the sample to reach a state close to field capacity. Noticeably reduced peak discharge rates occurred with intervals between tests greater than one day, i.e. on the first test of the week after a weekend break.

Over the 48 day period of experiments for applications 10 through 31 the following simple water balance can be constructed:

\[ \text{Input} - \text{Evaporation} = \text{Output} \quad (1) \]

The difference in volume of stored soil moisture is assumed to be negligible compared with the volume of the three balance variables. This assumption is acceptable if the balance is made on the aggregate of numerous experiments all with comparable discharge breakthrough curves. The volume of discharge measured at the sump during each drainage cycle was approximately 82% of the average applied volume of 735 ml (Table 3). Using equation (1) the average evaporation occurring during one application is 132 g. This is in fair agreement with the laboratory evaporation rate of 91 ml/day (12.3% of applied volume) measured over a five day period using a 1.5 kg soil column (Foster, 1993).
Table 3: Schedule of Experiments for Laboratory Lysimeter with Repacked Princeton Soil

<table>
<thead>
<tr>
<th>Application</th>
<th>Tracer Type</th>
<th>Start Date</th>
<th>Drainage Period</th>
<th>Discharge (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>dist. water</td>
<td>7/27</td>
<td>58 mins</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>dist. water</td>
<td>7/27</td>
<td>57 mins</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>dist. water</td>
<td>7/27</td>
<td>19 hrs 14 mins</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>dist. water</td>
<td>7/28</td>
<td>58 mins</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>dist. water</td>
<td>7/28</td>
<td>39 mins</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>dist. water</td>
<td>7/29</td>
<td>1 hr 43 mins</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>dist. water</td>
<td>7/29</td>
<td>24 hrs 43 mins</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>Br / FL</td>
<td>7/30</td>
<td>23 hrs 38 mins</td>
<td>362</td>
</tr>
<tr>
<td>9</td>
<td>Br / FL</td>
<td>7/31</td>
<td>2 hrs 45 mins</td>
<td>396</td>
</tr>
<tr>
<td>10</td>
<td>Br / FL</td>
<td>7/31</td>
<td>69 hrs 48 mins</td>
<td>662</td>
</tr>
<tr>
<td>11</td>
<td>Br / FL</td>
<td>8/3</td>
<td>25 hrs 34 mins</td>
<td>564</td>
</tr>
<tr>
<td>12</td>
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<td>23 hrs 47 mins</td>
<td>661</td>
</tr>
<tr>
<td>13</td>
<td>Br / FL</td>
<td>8/5</td>
<td>23 hrs 29 mins</td>
<td>625</td>
</tr>
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<td>14</td>
<td>Br / FL</td>
<td>8/6</td>
<td>287 hrs 23 mins</td>
<td>614</td>
</tr>
<tr>
<td>15</td>
<td>Br / FL</td>
<td>8/18</td>
<td>22 hrs 26 mins</td>
<td>437</td>
</tr>
<tr>
<td>16</td>
<td>Br / FL</td>
<td>8/19</td>
<td>28 hrs 30 mins</td>
<td>586</td>
</tr>
<tr>
<td>17</td>
<td>Br / FL</td>
<td>8/20</td>
<td>21 hrs 43 mins</td>
<td>632</td>
</tr>
<tr>
<td>18</td>
<td>Br / FL</td>
<td>8/21</td>
<td>74 hrs 24 mins</td>
<td>627</td>
</tr>
<tr>
<td>19</td>
<td>Br / FL</td>
<td>8/24</td>
<td>23 hrs 19 mins</td>
<td>556</td>
</tr>
<tr>
<td>20</td>
<td>Br / FL</td>
<td>8/25</td>
<td>23 hrs 56 mins</td>
<td>622</td>
</tr>
<tr>
<td>21</td>
<td>Br / FL</td>
<td>8/26</td>
<td>24 hrs 45 mins</td>
<td>581</td>
</tr>
<tr>
<td>22</td>
<td>Br / FL</td>
<td>8/27</td>
<td>25 hrs 11 mins</td>
<td>595</td>
</tr>
<tr>
<td>23</td>
<td>Br / FL</td>
<td>8/28</td>
<td>94 hrs 22 mins</td>
<td>579</td>
</tr>
<tr>
<td>24</td>
<td>Br / FL</td>
<td>9/1</td>
<td>25 hrs 15 mins</td>
<td>553</td>
</tr>
<tr>
<td>25</td>
<td>Br / FL</td>
<td>9/2</td>
<td>47 hrs 51 mins</td>
<td>586</td>
</tr>
<tr>
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<td>Br / FL</td>
<td>9/4</td>
<td>96 hrs</td>
<td>598</td>
</tr>
<tr>
<td>27</td>
<td>Br / FL</td>
<td>9/8</td>
<td>24 hrs 31 mins</td>
<td>680</td>
</tr>
<tr>
<td>28</td>
<td>Br / FL</td>
<td>9/9</td>
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<td>644</td>
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<tr>
<td>29</td>
<td>Br / FL</td>
<td>9/11</td>
<td>97 hrs</td>
<td>635</td>
</tr>
<tr>
<td>30</td>
<td>Br / FL</td>
<td>9/15</td>
<td>25 hrs 33 mins</td>
<td>649</td>
</tr>
<tr>
<td>31</td>
<td>Br / FL</td>
<td>9/16</td>
<td>24 hrs 54 mins</td>
<td>627</td>
</tr>
<tr>
<td>32</td>
<td>RWT</td>
<td>9/17</td>
<td>24 hrs 4 mins</td>
<td>597</td>
</tr>
<tr>
<td>33</td>
<td>RWT</td>
<td>9/18</td>
<td>241 hrs</td>
<td>626</td>
</tr>
<tr>
<td>34</td>
<td>RWT</td>
<td>9/28</td>
<td>22 hrs 40 mins</td>
<td>641</td>
</tr>
<tr>
<td>35</td>
<td>RWT</td>
<td>9/29</td>
<td>47 hrs 44 mins</td>
<td>662</td>
</tr>
<tr>
<td>36</td>
<td>RWT</td>
<td>10/1</td>
<td>23 hrs 31 mins</td>
<td>682</td>
</tr>
</tbody>
</table>

The elapsed time between the start of tracer application and first discharge, t₁, varied from 2.5 to 9.0 minutes depending upon the antecedent moisture conditions (Table 4). Peak discharge (Q₀) was generally about 2% of input application rates, Q₀ (Figure 21). A change in breakthrough curve shape occurred progressively during the sequence of experiments. This is attributed to biological activity and movement of fines in the sample.
Table 4: Summary of discharge breakthrough features for the laboratory lysimeter.

<table>
<thead>
<tr>
<th>App #</th>
<th>(t_i) (mins)</th>
<th>(t_p) (mins)</th>
<th>(t_{0.5-t_p}) (mins)</th>
<th>(Q_p/Q_o) (%)</th>
<th>Drainage Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.5</td>
<td>19.00</td>
<td>31.4</td>
<td>1.28</td>
<td>58 mins</td>
</tr>
<tr>
<td>2</td>
<td>4.8</td>
<td>22.50</td>
<td>36.2</td>
<td>1.50</td>
<td>57 mins</td>
</tr>
<tr>
<td>3</td>
<td>3.3</td>
<td>17.75</td>
<td>41.5</td>
<td>2.11</td>
<td>19 hrs 14 mins</td>
</tr>
<tr>
<td>4</td>
<td>4.3</td>
<td>22.50</td>
<td>36.4</td>
<td>1.95</td>
<td>58 mins</td>
</tr>
<tr>
<td>5</td>
<td>5.0</td>
<td>26.50</td>
<td>39.3</td>
<td>2.17</td>
<td>39 mins</td>
</tr>
<tr>
<td>6</td>
<td>4.2</td>
<td>27.50</td>
<td>39.0</td>
<td>2.03</td>
<td>1 hr 43 mins</td>
</tr>
<tr>
<td>7</td>
<td>4.0</td>
<td>29.25</td>
<td>41.0</td>
<td>1.93</td>
<td>23 hrs 38 mins</td>
</tr>
<tr>
<td>8</td>
<td>9.0</td>
<td>33.00</td>
<td>47.1</td>
<td>1.50</td>
<td>24 hrs 43 mins</td>
</tr>
<tr>
<td>9</td>
<td>5.5</td>
<td>41.75</td>
<td>53.9</td>
<td>1.64</td>
<td>23 hrs 38 mins</td>
</tr>
<tr>
<td>10</td>
<td>4.0</td>
<td>35.00</td>
<td>50.0</td>
<td>1.89</td>
<td>21 hrs 43 mins</td>
</tr>
<tr>
<td>11</td>
<td>2.5</td>
<td>33.00</td>
<td>44.2</td>
<td>2.08</td>
<td>74 hrs 24 mins</td>
</tr>
<tr>
<td>12</td>
<td>5.5</td>
<td>31.00</td>
<td>42.4</td>
<td>1.93</td>
<td>23 hrs 19 mins</td>
</tr>
<tr>
<td>13</td>
<td>3.5</td>
<td>33.00</td>
<td>48.3</td>
<td>2.01</td>
<td>23 hrs 56 mins</td>
</tr>
<tr>
<td>14</td>
<td>5.0</td>
<td>36.50</td>
<td>51.3</td>
<td>1.78</td>
<td>24 hrs 45 mins</td>
</tr>
<tr>
<td>15</td>
<td>4.3</td>
<td>37.50</td>
<td>54.7</td>
<td>1.74</td>
<td>25 hrs 11 mins</td>
</tr>
<tr>
<td>16</td>
<td>5.0</td>
<td>42.50</td>
<td>55.0</td>
<td>1.67</td>
<td>72 hrs 22 mins</td>
</tr>
<tr>
<td>17</td>
<td>8.0</td>
<td>41.50</td>
<td>50.8</td>
<td>1.71</td>
<td>25 hrs 15 mins</td>
</tr>
<tr>
<td>18</td>
<td>4.0</td>
<td>41.50</td>
<td>59.3</td>
<td>1.59</td>
<td>47 hrs 51 mins</td>
</tr>
<tr>
<td>19</td>
<td>4.0</td>
<td>43.50</td>
<td>67.1</td>
<td>1.48</td>
<td>96 hrs</td>
</tr>
<tr>
<td>20</td>
<td>6.5</td>
<td>46.00</td>
<td>71.4</td>
<td>1.58</td>
<td>24 hrs 31 mins</td>
</tr>
<tr>
<td>21</td>
<td>3.5</td>
<td>51.00</td>
<td>81.3</td>
<td>1.39</td>
<td>47 hrs 23 mins</td>
</tr>
<tr>
<td>22</td>
<td>9.0</td>
<td>51.00</td>
<td>75.3</td>
<td>1.46</td>
<td>97 hrs</td>
</tr>
<tr>
<td>23</td>
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<td>41.00</td>
<td>64.8</td>
<td>1.69</td>
<td>25 hrs 33 mins</td>
</tr>
<tr>
<td>24</td>
<td>4.0</td>
<td>44.00</td>
<td>65.5</td>
<td>1.71</td>
<td>24 hrs 54 mins</td>
</tr>
<tr>
<td>25</td>
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<td>14.75</td>
<td>9.6</td>
<td>7.47</td>
<td>24 hrs 4 mins</td>
</tr>
<tr>
<td>26</td>
<td>23 secs</td>
<td>13.58</td>
<td>12.3</td>
<td>6.93</td>
<td>241 hrs</td>
</tr>
<tr>
<td>27</td>
<td>30 secs</td>
<td>12.75</td>
<td>14.3</td>
<td>5.42</td>
<td>22 hrs 40 mins</td>
</tr>
<tr>
<td>28</td>
<td>40 secs</td>
<td>19.17</td>
<td>22.4</td>
<td>4.43</td>
<td>47 hrs 44 mins</td>
</tr>
<tr>
<td>29</td>
<td>30 secs</td>
<td>15.00</td>
<td>17.0</td>
<td>5.41</td>
<td>23 hrs 31 mins</td>
</tr>
</tbody>
</table>

\[t_i\] = Elapsed time to initial sump discharge  
\[t_p\] = Elapsed time to peak discharge  
\[t_{0.5-t_p}\] = Full width time interval at half maximum discharge  
\[Q_p\] = Peak discharge  
\[Q_o\] = Input application rate
Q/Q₀=Dimensionless discharge (Q=output discharge, Q₀=application rate)
Figure 21: Laboratory discharge breakthrough (applications 16 through 19)

The discharge response changed greatly after creation of the macropore (after application 32). In general the discharges with the macropore were greater but of shorter duration than the plain lab sample (Table 4 and Figure 22). FL and Br⁻ tracer tests show that, within the duration of a given application-drainage cycle on the no-macropore soil, no applied solute travels to the sump. All the discharge to the sump is antecedent moisture. In the MIT experiment the initial breakthrough of bromide occurred during the fourth tracer application. After the 24 tracer application the Br⁻ concentration had attained 0.77C₀ (Figure 23). The FL was never detected above background levels throughout the 24 applications.

The tracer breakthrough after creation of the macropore was significantly different. Detectable concentrations of RWT occurred from the first application. In the first experiment, macropore sample tracer concentration peaked at 0.6C₀. Solutes therefore travel from the surface through the sample-macropore flow system and wick to the sump within the same application-drainage cycle.
$Q/Q_0 =$ Dimensionless discharge ($Q$=output discharge, $Q_0$=application rate)

Figure 22: Comparison of laboratory discharge breakthrough before and after macropore creation (applications 31 through 33)

$C/C_0 =$ Dimensionless concentration ($C$=discharge concentration, $C_0$=applied concentration).

$V/V_0 =$ Dimensionless Volume ($V$=cumulative discharge volume, $V_0$=lysimeter pore volume)

Figure 23: Comparison of tracer breakthrough with and without the macropore
FINITE-ELEMENT MODELING
Two-dimensional axi-symmetric finite-element models of both the laboratory and field experiments were constructed by D. Misra (personal communication, 1993). Discharge flow models were calibrated to the results from the laboratory and Princeton lysimeters and are assumed to represent the pure matrix flow case. All the lysimeter experiments were conducted using pulse inputs. The prediction of the lysimeter discharge response therefore requires the solution of the transient flow problem. The Richards Equation that describes the matric potential or water content response of soils during transient flow is a second-order, non-linear, partial-differential equation, that can only be solved by numerical methods. All model parameters and inputs were derived from laboratory measurements on soil samples taken from the experimental sites. The only unknown inputs were that of the initial moisture and matric potential condition for the soil and the geotextile. To resolve this problem the model was calibrated with the experimental results assuming the samples to initially be at field capacity throughout, and the geotextile wick to have a specified water entry head of 30 cm suction.

POST TRACER EXPERIMENT SOIL-DISTURBANCE SURVEY
St. Paul silt loam.
No large-scale disturbance of the soil monolith was observable in either 1991 sample. The greatest disturbance occurred near the sample margins, especially in association with the blade ribs. Away from the ribs the zone of soil shear was less than 3 cm thick and barely distinguishable along much of the soil margin. For an area extending 10-20 cm either side of the rib groove the soil was often noticeably sheared and fissured. This type of disturbance generally extended less than 10 cm into the body of the sample. In lysimeter #1 fissure type voids in the sample were observed at both 66 cm and 94 cm depth (Figure 24). These fissures were filled with plaster of Paris which must have originated from the rib groove filling. It is quite possible therefore that these fissures are rib adjacent soil disturbance features. The soils were noticeably softer at the base of the sample. Although the soils are at a higher degree of saturation at this depth, compression and shearing of the soil occurred as a result of wrinkling of the stiff PVC liner.

The high density of wormholes was a very significant feature of this soil. Worm activity was observed at all depths in both samples. Continuous wormholes showing pink dye stained walls were noted at the sample margin at depths of one meter. Dye staining of root hairs and natural fine textured soil fissures was limited to the top few centimeters. Some wormholes were seen to conduct stain to soil fissures at greater depths.

Princeton loamy sand
The soil in both lysimeters at the Princeton site maintained its integrity during lysimeter installation. The soil staining showed no evidence of cracking or fissuring of the soil. The only indication of preferential flow in these two samples was increased stain intensity around large plant roots, in the top 10 cm (4 in). For the major part of the samples the blue stain was only discernible as a bluish hue to the soil under bright sunlit conditions. The very homogenous nature of the soil probably contributes to the impression of little disturbance because there are very few marker features to determine differential soil movement. Compounding this situation was the use of local soil to fill the rib grooves. If the clean, white silica sand had been used it would have been possible to discern the size of the rib grooves.
The soil had sufficient cohesive strength to support the excavated hole for the one hour it took to install the lysimeter. The very friable nature of the soil, however, made for very easy excavation with the tree transplanter. The parent material of this soil is sand deposited by glacial melt waters at the end of the last glacial cycle. The soil has not been subject to compaction by overburden pressures of overlying ice. The disturbed soil material properties are likely to be similar to the undisturbed properties. The upper horizons had already been disturbed by plowing and other agricultural practices.

**St. James loam**

The most noticeable disturbance of the soil samples occurred at the sample margins, particularly in the vicinity of the rib grooves. Disturbance by the ribs is greatest near the surface where the blade width and amount of blade travel are greatest. Near the surface the disruption is visible because of different colored soil from below was brought up to the surface in the vicinity of the rib. The area marked by this process has a lens shape on a horizontal surface, about 30 cm wide and 7.5 cm thick at its greatest. There is a sharp transition at the inner edge of this zone separating the transported soil and the in-situ soil which showed no visible disturbance. The size of the zone of sheared soil decreases in width and thickness with depth. In vertical cuts the disturbed zone was marked by a crack or fissure. At the sample margin in between the ribs, the disruption of the sample by shearing rarely extended more than 3 cm into the sample.
The lowest 30 cm of soil of the lysimeter lined with the thick PVC was noticeably softer than the soil in the lysimeter with the 0.15 mm (6 mil) polyethylene sheeting. Wrinkling of the thick, resilient PVC is thought to result in mechanical soil softening through shearing under compression. The main body of the soil samples showed no other evidence of disturbance due to the excavation and lysimeter installation. There were no cracks, fissures, or noticeable disruption of layering or small scale soil structure.

Notwithstanding the descriptions of soil disturbance, by far the greater proportion of both soil samples retained an undisturbed, monolithic structure with disruption limited to the margins of the sample.

SUMMARY
The field and laboratory experiments show three different classes of discharge breakthrough (Figure 25):

i) rapid breakthrough at St. Paul, and in the laboratory soil with the macropore.
ii) intermediate breakthrough for the laboratory soil with no macropores.
iii) slow breakthrough at Princeton.

The three soils showing rapid discharge also show similar tracer breakthrough (Figure 26). In all cases the tracer breakthrough follows the discharge breakthrough very closely. The tracer concentrations increase rapidly to their maximum but then decay slowly. The differences between the three sites is in the relative tracer concentrations.

\[ Q/Q_0 = \text{Dimensionless discharge (} Q = \text{output discharge, } Q_0 = \text{application rate)} \]

Figure 25: Comparative discharge breakthrough curves for all sites
Although the discharge breakthrough of the laboratory soil without macropores was of the intermediate type and the Princeton field soil was slow, their tracer breakthrough responses are similar. In neither case is tracer discharged during the same application drainage cycle, i.e. the discharge is comprised 100% antecedent water (Figure 27).

---

$C/C_0 =$ Dimensionless concentration ($C =$ discharge concentration, $C_0 =$ applied concentration).

Figure 26: Comparative RWT breakthrough curves for samples with rapid flow

$Q/Q_0 =$ Dimensionless discharge ($Q =$ outlet discharge, $Q_0 =$ application rate).

$C/C_0 =$ Dimensionless concentration ($C =$ discharge concentration, $C_0 =$ applied concentration).

Figure 27: Comparative tracer breakthrough curves for samples with intermediate and slow flow
The MIT experiments further strengthen the grouping of the solute flow properties of the experimental sites. The multiple application tracer breakthrough graph shows the plain lab soil and the Princeton experiments exhibited an initial multi-application period of antecedent moisture flow followed by a gradual increase in tracer concentration, the first part of an S-shaped curve. In contrast the rapid flow samples show a peak and trough for each solute application (Figure 28).

![Figure 28: Comparative tracer breakthrough curves for multiple applications](image)

\[
\frac{C}{C_0} = \text{Dimensionless concentration (C=discharge concentration, } C_0=\text{applied concentration),}
\]

\[
\frac{V}{V_0} = \text{Dimensionless pore volume (V=volume discharged, } V_0=\text{lysimeter pore volume)}
\]

The discharge-tracer experiments therefore permit the identification of two main solute flow types:

i) Preferential Flow, defined by the St. Paul, the laboratory macropore soil.

ii) Matrix Flow, defined by the range of response of the plain laboratory soil and the Princeton site.
CHAPTER 4

ANALYSIS and DISCUSSION

LYSIMETER DISCHARGE

Hydrographs

The discharge hydrographs for both the matrix and preferential flow share several common characteristics. The hydrographs all have skewed-right, single peaked curves (Figures 16, 19, 21 and 22). For the laboratory and St. Paul experiments the discharge recession was sufficiently short to reach near field capacity conditions between solute applications. Each of the discharge hydrographs represent an output response function or kernel for a single tracer application to a conical lysimeter from a field capacity, initial moisture content state. Each of the discharge hydrographs therefore constitutes an experimental repetition. The wide variation in the peak discharge values for the field preferential flow example (St. Paul lysimeters) indicates a high degree of sensitivity to the system initial conditions.

The drainage at Princeton was too slow for completion of a full hydrograph cycle between applications. For this site a synthetic response function was constructed using portions of the observed data from applications 10 and 15. The extended recession curve and zero initial discharge condition were modeled using the recession data from applications 10, 11, 14, and 15.

Discharge hydrographs during SID tests provide an initial indication of the nature of a soil's unsaturated flow properties. The rapid discharge response with both the St. Paul and lab macropore soils are associated with preferential flow of solutes as compared with the much slower discharge and solute response of the matrix flow examples. The term 'rapid discharge response' is relative and implies that there is a 'normal' discharge response expected of soil with no preferential flow characteristics. Flow through this hypothetical, ideal granular soil could be completely and accurately represented by continuum mechanics and numerical methods based on the Richard's equation (Richards, 1931).

Discharge through the laboratory and field conical lysimeters have been simulated by finite element models (D. Misra, 1993 personal communication). The model does not include the rib grooves. Trial and error adjustment of the model variables gave reasonable agreement with the laboratory and Princeton data (Figures 29 and 30). The values for peak discharge and time to peak were close to the observed data. Although exact fits were not achieved, the general form of the discharge breakthrough was similar to the observed data. These model results show that matrix flow is a reasonable conceptual model for the Princeton soil in both the laboratory and field lysimeters. The results also show that the lysimeter installation did not itself generate preferential flow in this soil type.

The simulated discharge for St. Paul shows significant divergence of the observed data from the matrix flow model. As the lysimeter installation method did not lead to preferential flow effects at the Princeton site the difference between the observed and modeled breakthrough curves for St. Paul are attributed to natural preferential flow through the soil (Figure 31).
Figure 29: Lab lysimeter discharge; observed data and finite element model

Figure 30: Princeton lysimeter N discharge; observed data and finite element model
$Q/Q_0 =$ Dimensionless discharge ($Q$ = output discharge, $Q_0$ = application rate)

Figure 31: St. Paul lysimeter discharge; observed data and finite element model

**Matrix Flow**

**Semi-Analytical Model**

The Richards Equation (Richards, 1931) describing transient flow in unsaturated porous media is derived by incorporating the Buckingham-Darcy equation into the water conservation expression. The Buckingham-Darcy equation assumes that the hydraulic conductivity of unsaturated soil is a function of the water content or matric potential and that the driving force for the movement of moisture in an unsaturated soil is the sum of the matric potential, $h$ and the gravitational potential, $z$. It may be written:

$$q = -K(h) \frac{\partial h}{\partial z} = -K(h) \frac{\partial}{\partial z}(h + z) = -K(h) \left( \frac{\partial h}{\partial z} + 1 \right)$$  \hspace{1cm} (2)

Where $K(h)$ is the unsaturated hydraulic conductivity (Jury, Gardner et al., 1991).

The matric potential form of the Richard’s equation is:

$$W(h) \frac{\partial h}{\partial t} = \frac{\partial}{\partial z} \left[ K(h) \left( \frac{\partial h}{\partial z} + 1 \right) \right]$$  \hspace{1cm} (3)

Where $W(h)$ is the water capacity function expressing the matric potential per unit increase in water content:

$$W(h) = \frac{d \theta}{dh}$$  \hspace{1cm} (4)
The Richard's equation is a second-order, non-linear differential equation. In general it can only be solved using numerical techniques and hence the use of the finite element method for modeling discharge from the conical lysimeter (Figures 29 through 31). For steady state conditions the Buckingham-Darcy equation is sufficient for describing the flow of water through unsaturated soil. If the water table is not too shallow and the vertical matric potential gradient is small the Buckingham-Darcy equation can be approximated by the gravity flow equation as follows:

\[ q = -K(h) \]  

(5)

Since \( K(h) \) is a function of \( h \) and \( h(q) \) is a function of \( q \), \( K \) may be written:

\[ K(h(q)) = K(q) \]  

(6)

If we assume that a representative value for the unsaturated hydraulic conductivity, \( K(\theta) \) in the lysimeter during the discharge cycle is: \( K(\theta) = K_s/2 \) then solute travel time can be estimated using a mean flow path length through the lysimeters, laboratory determined values of \( K(\theta) \), and the gravity flow equation (Table 6). The mean flow path length for a conical lysimeter of depth \( L \) is \( L/3 \) (Foster, 1993). It is useful to compare these travel time estimates with observed travel times. Average travel times are represented by; \( t_p \) for the time to discharge peak and \( t_m \) the time to the median cumulative discharge.

Table 6: Gravity flow estimates of unsaturated flow travel times.

<table>
<thead>
<tr>
<th>Lysimeter</th>
<th>Lab values</th>
<th>Calculated gravity flow travel times</th>
<th>Observed Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( K(\theta) ) (cm/min)</td>
<td>( t ) (mins)</td>
<td>( t_p ) (mins)</td>
</tr>
<tr>
<td>Lab</td>
<td>0.028</td>
<td>475</td>
<td>35</td>
</tr>
<tr>
<td>Princeton</td>
<td>0.1745</td>
<td>210</td>
<td>1784</td>
</tr>
<tr>
<td>St. Paul</td>
<td>0.00625</td>
<td>5540</td>
<td>31</td>
</tr>
</tbody>
</table>

The observed discharge of the laboratory lysimeter was about one order of magnitude faster than the gravity flow estimate. The observed \( t_p \) and \( t_m \) for the Princeton soil was about one order of magnitude slower than the gravity flow estimate. In contrast, the observed \( t_p \) for the St. Paul soil was over two orders of magnitude faster than the calculated value. The \( t_m \) was more than one orders of magnitude faster. Despite the range in the results for the two matrix flow soils (the lab sand and Princeton lysimeters) the preferential flow soil from St. Paul shows flow through the lysimeter at a rate about two orders of magnitude faster than the travel times calculated from laboratory measurements of \( K(\theta) \). Based on this simple analysis it is possible to suggest a method of screening for the presence of preferential flow in field soils. Preferential flow is likely where observed average travel times through the lysimeter are greater than one order of magnitude faster than gravity flow estimated travel times.
Preferential Flow
Pipe and Fracture Flow

The mechanics of preferential flow are commonly addressed by representing wormholes and biopores as cylindrical pipes; and cracks and fissures in terms of a series of parallel plates and apertures. Poiseuille's Law for pipe flow describes the steady state discharge, \( Q \), through a uniform, vertical cylindrical capillary as (Childs, 1969):

\[
Q = \frac{\rho g \pi r_c^4}{8 \nu}
\]

(7)

Where:
- \( g \) = gravitational acceleration
- \( r \) = density of the fluid
- \( r_c \) = the radius of the capillary
- \( \nu \) = the dynamic viscosity

Steady state discharge in a plane, vertical, laminar crack of width, \( w \) is (Childs op cit):

\[
Q = \frac{\rho g w^3}{12 \nu}
\]

(8)

A power law generalization has been proposed by Beven (1981) to approximate flux density for all types of macropores, \( q_{ma} \) as a function of water content:

\[
q_{ma} = b \theta_{ma}^a
\]

(9)

Where the \( ma \) subscript denotes the macropore, and \( a \) and \( b \) are fitting coefficients:

Equation (9) has been incorporated into dual continuum models with interacting domains of macropores and micropores (Beven and Germann, 1981; Germann and Beven, 1985; Germann, Pierce et al., 1986). The model assumes the macropores to be initially dry and to fill by the process of film flow. When the water application ceases, declining macropore flux is accounted for with a gradual reduction in hydrostatic head as the pores drain. Throughout this process water flows into and out of the microporous domain through the macropore walls. The macropore continuity equation is:

\[
\frac{\partial \theta_{ma}}{\partial t} = - \frac{\partial}{\partial x} (q_{ma}) - S
\]

(10)

where \( S \) is the source/sink term for exchange between the micropores and macropores.

This leads to an expression in the form of a kinematic wave equation (Lighthill and Whitham, 1955):

\[
\frac{\partial q_{ma}}{\partial t} = -c \left( \frac{\partial q_{ma}}{\partial x} + S \right)
\]

(11)

Where \( c \), the kinematic wave velocity is:

\[
c = \frac{\partial q_{ma}}{\partial \theta_{ma}} = a(\theta_{ma})^{\frac{1}{a}} \cdot q_{ma}^{(1-\frac{1}{a})}
\]

(12)

**Kinematic wave approximation**

(Germann and Beven, 1985) developed a kinematic wave approximation to their numerical model using three separate analytical solutions for the wetting and draining front arrival times, and the flux density of the subsequent draining of the profile.
The first solution describes the propagation of the wetting front. Initial and boundary conditions are for a square pulse input of duration, \( t_i \) and volume flux density of, \( q_{ma} \):

\[
\begin{align*}
    t < 0, & \quad 0 \leq z \leq \infty, & q(z, t) = 0 \\
    0 \leq t \leq t_i, & \quad q(0, t) = q_{ma} \\
    t_i < t, & \quad q(0, t) = 0
\end{align*}
\]  
(13)

The kinematic wave velocity of the wetting front, \( c_w \) is defined in (12), \( q_{ma} \) and \( \theta \) are related by the same relationship used in equation (9).

The maximum depth, \( z^* \), below which no macropore flow will occur due to macropore wall sorbance is:

\[
z^* = c_w/[s(a-1)]
\]  
(14)

Where the sorbance function, \( s \) is related to the source sink term of (10) by \( s = s\theta \) and is of the form:

\[
s = -\frac{1}{\theta(i)} \frac{d\theta}{dt}
\]  
(15)

The time at which the wetting front arrives at depth \( z \), \( t_w \) is:

\[
t_w(z) = -\frac{a}{(a-1)s} \ln \frac{1-z}{z^*}
\]  
(16)

The second analytical solution describes the propagation of the drainage front that starts at the cessation of surface input. The arrival time of the drainage front, \( t_d \) is:

\[
t_d(z) = t_i - \frac{a}{(a-1)s} \ln \frac{1-z}{z^*}
\]  
(17)

The equation for the volume flux density of the trailing wave \( q(z, t) \) is:

\[
q(z, t) = \begin{cases} 
    \frac{zs(a-1)}{\exp[(t-t_i)(a-1)s]-1} & \text{if } \theta(t) \neq \theta(i) \\
    0 & \text{otherwise}
\end{cases}
\]  
(18)

The flux density during the wetting period \((t_w - t_d)\) is constant and has the value \( q(z, t_d) \).

Flux density breakthrough curves were generated to model the laboratory and field experimental data. Initial values for \( a, b, \) and \( s \) were taken from the example reported by Germann and Beven (1981, op cit.) but provided only a poor match with the data. The model is not sensitive to the \( s \) parameter so curve-fits to lab application 34 and St. Paul application 5A were generated by trial and error adjustment of the parameters \( a \) and \( b \) (Figures 32 and 33).
Figure 32: Kinematic model of lysimeter flux density for the St. Paul soil

Figure 33: Kinematic model of lysimeter flux density for the laboratory soil with macropore
The rectangular peak of the discharge curve is the clearest artifact of the approximate nature of the model. Although the two model fits are for different soil types and lysimeters sizes the $a$ and $b$ parameters are comparable. For the fit to the laboratory data the values were $a=1.52$ and $b=0.024$. For the model fit to the field data the values were; $a=1.50$, $b=0.023$. The $a$ parameter is the exponent in the relationship between flux density and macropore moisture content (9); $b$ is the macropore conductivity (m/s). This model is not intended for simulation of matrix flow, and does not fit the lab and Princeton data well; but the best trial and error fit to the data for the plain lab lysimeter was achieved with $a=1.68$ and $b=0.00773$ (Figure 34). The wetting front arrival time is most sensitive to the $a$ parameter. Model fitting was achieved by adjusting $a$ to match the flux peak arrival time then adjusting $b$ to the peak flux density. Without preferential flow paths the $a$ parameter does not change by a large factor. The reduced $b$ value has the effect of shutting off macropore flow. The $b$ parameter, therefore has some physical significance as a crude index of preferential flow. It was not possible to achieve even this level of approximate model fit to the Princeton data because of the retarded nature of the discharge at that site.

![Figure 34: Kinematic model of laboratory lysimeter flux density](image)
**SOLUTE TRANSPORT**

**Piston-Flow Model**

In a one dimensional (1-D) piston-flow model of solute transport through a soil column, solute moves at a rate governed by Darcy's Law. Without dispersion, the solute front advances uniformly and the tracer concentration in the column effluent is zero until the displacement of one soil column pore volume (Figure 35).

![Diagram](image)

**Figure 35:** Piston flow transport

- **a)** movement of solute front in a soil column, **b)** tracer breakthrough at any point along x.

A similar piston-flow model can be constructed for the conical lysimeter. Let us assume that once the tracer reaches the margin of the sample after its transit through the soil, the flow through the wick is instantaneous. If tracer solution is applied across the entire surface area of the cone, the solute transit time at the circumference will be zero and a tracer breakthrough curve will have positive values from the origin (Figure 36). The longest flow path occurs at the axis of the sample and is equal to the cone height, L. When tracer molecules on this flow path reach the sample edge then one complete pore volume has been displaced, no antecedent water remains in the sample and \( C/C_0 = 1 \). For 1-D flow in a cylinder, it takes one pore volume to sweep through the pore space in the cylinder. For true 1-D flow to occur in the conical lysimeter, the wick must instantaneously drain all water arriving at the sample margin. Under these conditions it will take three pore volumes of solute to sweep through the entire sample for \( C/C_0 = 1 \) because the volume of a cone is one third of the volume of a cylinder of the same base area and height.

Applying these assumptions, an increasing volume of tracer solute \( V \) moves through the sample with a horizontal solute front. The solute displaces a volume of the antecedent phase, \( V_A \), which is pushed out of the sample through the wick. The excess tracer discharges into the wick behind the wetting front, \( V_t \) (Figure 36).
The total volume of effluent = volume of input or: \( V = V_a + V_t \)  
(19)

The concentration of tracer collected at the sump: \( \frac{C}{C_0} = \frac{V_t}{V} \)  
(20)

Dimensionless volume, or pore volumes: \( \frac{V}{V_0} \)

A theoretical breakthrough curve can therefore be derived by expressing the dimensionless concentration and volume in terms of the position of the advancing solute front by evaluating the integral:

\[
V(l) = \int_0^l \pi r^2 \, dl
\]

(21)

In the more general case where solute is only applied to a smaller area with radius, \( r_a \):

\[
V(l) = \pi r_a^2 \int_0^l \, dl \quad \text{for: } 0 \leq l \leq l_a
\]

(22)

and:

\[
V(l) = V_a + \pi r_0^2 \int_{l_a}^l \left[ 1 - \left( \frac{r}{r_o} \right)^2 \right] dl \quad \text{for: } l_a \leq l \leq L \quad \text{and where: } V_a = \pi r_a^2 l_a
\]

(23)

The breakthrough curves derived in this way for different values of \( r_a \), show that there is an initial volume of application required before the first tracer appears in the effluent (Figure 38). In reducing \( r_a \) from \( r_a = r_o \) in the limit where \( r_a \to 0 \) the pore volume required for \( \frac{C}{C_0} = 1 \) reduces from \( \frac{V}{V_0} = 3 \) for the conical case to \( \frac{V}{V_0} = 1 \) for a cylinder (Figures 38 and 39).
Values of $C/C_0$ = Dimensionless concentration ($C$ = discharge concentration, $C_0$ = applied concentration), $V/V_0$ = Dimensionless Volume ($V$ = cumulative discharge volume, $V_0$ = lysimeter pore volume).

Figure 37: Theoretical breakthrough for the lab cone piston-flow model

$$\frac{C}{C_0} = \frac{ra}{ro}$$

$\frac{V}{V_0}$

Figure 38: Variation of flow through volume, $V_0$ (shaded region) with radius of application, $r_a$ for 1-D flow in a funnel lysimeter.

$$r_a = \text{radius of solute application}$$

The experimental data show breakthrough curves with median tracer concentrations occurring at values less than $V/V_0 = 1$ (Figure 28). In a piston-flow model it is possible to account for this effect by considering the average degree of saturation of the pore space (Figure 39). It is possible to fit the piston-flow model to the data with degrees of saturation of 0.48 for the Princeton lysimeter and 0.68 for the laboratory lysimeter (Figure 40). Using these values the average volumetric moisture content was 0.22 for the Princeton lysimeter and 0.27 for the laboratory lysimeter. Although there are no independent measures of soil moisture content these values are consistent with the earlier tracer breakthrough of the Princeton lysimeter as compared to the laboratory lysimeter. The lower average moisture content entails a smaller volume of antecedent moisture and a lower unsaturated hydraulic conductivity.
C/C_0 = Dimensionless concentration (C = discharge concentration, C_0 = applied concentration),
V/V_0 = Dimensionless Volume (V = cumulative discharge volume, V_0 = lysimeter pore volume)
Figure 39: Piston flow model breakthrough curves for varying degrees of saturation, \( \lambda \)

C/C_0 = Dimensionless concentration (C = discharge concentration, C_0 = applied concentration),
V/V_0 = Dimensionless Volume (V = cumulative discharge volume, V_0 = lysimeter pore volume)
Figure 40: Br\(^-\) breakthrough curves using observed and piston-flow model data.
Advection-Dispersion Model
Solute fronts do not advance uniformly along soil columns and solute fronts are not abrupt as depicted in the piston flow model. Breakthrough curves exhibit spreading of the solute front due to the processes of hydrodynamic dispersion (Nielsen and Biggar, 1961; Biggar and Nielsen, 1962).

The bromide breakthrough curves for the laboratory and Princeton lysimeters (Figure 40) showed the first part of an S-shaped breakthrough curve typical for the 1-D advective dispersive transport of solutes. The displaced volume for the median tracer concentration at Princeton and the laboratory occurred at 0.42 and 0.62 pore volumes, respectively, whereas for a conservative tracer in a cylindrical soil column this figure is 1.0 pore volume. Notwithstanding the effect of the degree of soil saturation, this early tracer breakthrough is consistent with the fact that flow paths starting near the circumference of the cone have a shorter flow path in the soil and longer but faster, flow paths in the more permeable geotextile. In cylindrical soil columns, displaced volume is proportional to length of flow path and transit time. The effective flow distance is uniform across whole the discharge area and equals the column length (Figure 35). In the cone the area of discharge from the soil is not a circle but the outer surface of a cone. The average effective flow length is less than the depth of the cone, and is a function of radial distance from the lysimeter axis (Figure 36). From geometrical considerations the median flow path length is:

\[ l_{\text{med}} = L - \frac{L}{\sqrt{2}} \]  

Where:
- \( l_{\text{med}} \) = median flow path length through soil
- \( L \) = height of conical soil sample

For the general case where tracers are only applied over a circular area of radius \( r_a \):

\[ l_{\text{med}} = l_a + (L - l_a) \left(1 - \frac{1}{\sqrt{2}}\right) \]  

Where \( l_a \) is the flow path length at \( r_a \) (Foster, 1993).

The general advection-dispersion equation for one-dimensional solute transport through a homogenous medium during steady-state flow can be written:

\[ R \left( \frac{\partial C_r}{\partial t} \right) = D_h \left( \frac{\partial^2 C_r}{\partial x^2} \right) - \nu \left( \frac{\partial C_r}{\partial x} \right) \]  

Where:
- \( C_r \) = volume-averaged (resident) solute concentration
- \( D_h \) = coefficient of hydrodynamic dispersion
- \( \nu \) = average pore velocity
- \( x \) = distance
- \( t \) = time
- \( R \) = retardation factor

The range of flow path lengths can be considered a form of geometric dispersion. This dispersive effect is a macroscopic dispersion and should not be confused with hydrodynamic dispersion resulting from effects occurring at the microscopic scale as described by Bear and Bachmat (1991). To examine the value of this concept I modeled the effects of conical geometrical on breakthrough using an analytic solution to the 1-D advection-dispersion equation. The advanced arrival of the observed tracer breakthrough was incorporated by replacing the retardation factor
by a lumped geometrical factor, \( G \) which will also include any moisture content effects. The range in flow path lengths will be lumped under the dispersion coefficient that includes our new macroscopic dispersion as well as mechanical dispersion.

In their review of analytical solutions to the advection dispersion equation for short cylindrical laboratory soil columns, van Genuchten and Parker (1984) conclude that Lapidus and Admundson’s solution (1952) be used for effluent curves from finite length columns. The dimensionless concentration breakthrough for this solution is:

\[
\frac{C(T)}{C_0} = \frac{1}{2} \text{erfc}\left(\sqrt{P/4GT} \cdot (G - T)\right) + \frac{1}{2} \exp(P)\text{erfc}\left(\sqrt{P/4GT} \cdot (G + T)\right)
\]

where \( C_p \) = solute concentration in the column effluent, and \( C_0 \) is the input concentration. \( T \) is the number of pore volumes leached through a cylindrical column (\( V/V_0 \)), \( P \) is the column Peclet number, and \( L \) is the length of the column.

Boundary conditions are; mass conservation across the inlet boundary, and continuity of solute velocity across the lower boundary of the column.

Model fitting by trial and error proved to be straightforward, simplified by the knowledge that the retardation factor must be close to the measured \( V/V_0 \) at \( C/C_0 = 0.5 \). For the lab data a Peclet number of 20 in the model achieved close fit. The same value provides a reasonable fit for the Princeton data, especially for the larger pore volume data. A better overall fit is achieved with a slightly lower retardation factor and an increase of the Peclet number to 29 (Figure 41).

\[
T = \nu L, \quad P = \nu L/D
\]
Although the Advection-Dispersion model results in better fits than the piston flow model (Figure 38) no mechanistic model was defined to determine the fitting parameters in advance. The Peclet numbers of 20 and 29 obtained by curve fitting are consistent with other experiments. Peclet numbers for saturated soil columns are generally in the range 0.1 to 1. For unsaturated flow soil column studies values can be in the 100 range (Jacobsen, Leij et al., 1992).

Strictly speaking the Peclet number is the ratio of advective to diffusive transport. In the analytical solution it is calculated by $vL/D$ where $D$ is the coefficient of bulk molecular diffusion. In practice the coefficient also includes dispersive effects and so $D$ is implicitly the coefficient of hydrodynamic dispersion. In this analysis, therefore, the Peclet number is more a ratio of advective to dispersive transport. I have assumed that hydrodynamic dispersion is the sum of molecular diffusion and mechanical dispersion as usual, but have also included a macroscopic dispersion, $D_m$ resulting from geometric effects:

$$D_h = D_m + D_d + D$$  \hspace{1cm} (28)

Using plausible values of $v$, $L$, $D_m$, and $D_d$, possible values for this coefficient of macroscopic dispersion have been investigated. The magnitude of the macroscopic dispersion calculated in this fashion is highly sensitive to the value of hydrodynamic dispersion. For the matrix flow soils in these experiments estimated values for macroscopic dispersion range from zero to the order of $10^{-3}$ (cm$^2$/s) (Foster, 1993), a similar order of magnitude to that for mechanical dispersion.

**Transfer Function Model**

The piston flow and advective dispersive models used above are both inadequate for the development of a mechanistic description of the lysimeter flow and transport characteristics. The one dimensional assumption is a major simplification and neither model can account for the effect of the transient flow regime on solute transport. The pulsed nature of the tracer application results in greater solute dispersion through redistribution of moisture and solute in the drainage period between applications. This redistribution dispersion is not incorporated into the classic advection dispersion approach which is for steady state flow. The difficulties in studying the flow and transport through the conical lysimeter analytically, rather than numerically, all stem from over simplification of the flow mechanics. The concept of accounting for the sample geometry using retardation and dispersion coefficients did however lead to an analytical solution of the right form.

If the solute breakthrough curve is considered as a cumulative density function, a Transfer Function Model (TFM) can be used in favor of a deterministic approach (Jury, 1982; Jury and Sposito, 1986; Jury and Roth, 1990; Jury, Gardner et al., 1991). The transfer function approach is a method of characterizing a complex system by the manner in which it transforms a known input function into an output response. The method makes no attempt to describe the physical processes.

The transfer function for the transport of an inert solute may be written as (Jury et al., 1991):

$$C(I) = C[L,I]\int_0^I f_L(I') C_o(I-I') dI'$$  \hspace{1cm} (29)

Where $I$ is the cumulative net applied water, $I'$ is the value at the time of solute entry, $C_o$ and $C$ are the entry and exit solute concentrations, $f_L(I)$ is the pdf for the net applied water. This formulation of the transfer function permits the solute discharge to be expressed in terms of cumulative net applied water rather than an average flux rate. The benefit of this formulation is
that (29) applies for any time dependent water input rate. It is only valid if changes in water storage are small, but Jury offers no indication of model sensitivity to this problem. This formulation appears to provide for only a minor relaxation of the steady state flow requirement. The assumption that solute flow is a unique function of the net applied water has been shown to be reasonable in repacked soil experiments as well as some large field studies but not for soil with preferential flow (Jury, Gardner et al., 1991). The assumption has also not been tested for the mode of solute application used in the MIT experiments. Most of the reported practical applications of Jury’s transfer function model assume steady state flow and the log-normally distribution of solute travel times. This allows for the following analytical solution of the transport problem for a step input of solute (Jury, 1982):

\[ C(Z,l) = \frac{C_0}{2} \left[ 1 + \text{erf} \left( \frac{\ln(l/L/Z) - \mu}{\sigma \sqrt{2}} \right) \right] \] (30)

Where \( \mu \) is the mean of the distribution of \( \ln I \) and \( \sigma^2 \) is the variance. \( L \) is the depth of the outlet and \( Z \) is the depth for analysis. The solution assumes spatially uniform water application. For the purpose of using this approach on the data for the lab and Princeton lysimeters: \( I = \bar{i}_0 \) where \( \bar{i}_0 \) is the average input flux rate over the set of solute applications. The pulse input solution cannot be used to model preferential flow because the tracer breakthrough all occurs for the same value of cumulative net applied water.

The breakthrough curves show good agreement with experimental data (Figure 42). The experimental breakthrough curves show concentration increasing in a series of steps because the concentration is plotted as a function of applied, as opposed to the discharged, water volume. Unlike the piston-flow and advection-dispersion models no assumptions of the flow mechanics have been made. The task now is to determine what link the derived fitting parameters have with the lysimeter geometry. The position of \( C/C_0 = 0.5 \) is solely a function of \( \mu \) (Figure 43). The spread of the curve, however, is a function of both the mean and standard deviation (Figure 44). Fitting the model to the field and laboratory data can be largely achieved by varying the mean. Little change in standard deviation was needed to achieve differences between the field and laboratory model fits. With further experiments, it may be possible to determine the sensitivity of these fitting parameter to soil hydraulic properties and lysimeter shape.
C/C₀=Dimensionless concentration (C=discharge concentration, C₀=applied concentration).
I/V₀ = Dimensionless Volume (l=cumulative applied volume, V₀=lysimeter pore volume)

Figure 43: Variation of the transfer function model with μ (q constant)

C/C₀=Dimensionless concentration (C=discharge concentration, C₀=applied concentration).
I/V₀ = Dimensionless Volume (l=cumulative applied volume, V₀=lysimeter pore volume)

Figure 44: Variation of the transfer function model with θ (μ constant)
Empirically the field results could be approximated from laboratory experiments using the transfer function mean values in the equation:

\[ \mu_{\text{field}} = \beta \mu_{\text{lab}} \]  

(31)

In this case \( \beta = \frac{5.3}{2.69} = 1.97 \), where \( \beta \) is the preferential flow coefficient for the Princeton site. If a finite element model for solute transport in variably saturated porous media is developed that can reproduce lab tracer breakthrough curves for repacked specimens of the field soil preferential solute transport could be quantified alternatively on the basis of an enhanced hydraulic conductivity function, \( \beta K_s \), or \( \beta K(q) \).

The saturated hydraulic conductivity, \( K_s \) does not appear as a variable in any of the three solute transport models discussed because steady state or pseudo-steady state conditions are assumed. The rate of discharge is determined by the input rate (cumulative net applied water in the case of the transfer function model) or the hydraulic head. Under real field conditions and with the MIT application approach, steady state flow is not a good approximation. Soils are normally exposed to rainfall or irrigation events of limited duration and varying intensity. Heterogeneity in the soil with associated variability in moisture retention characteristics and hydraulic conductivity all act to transport solutes through the unsaturated zone at faster rates than with steady state flow, even under conditions of matrix flow.

METHOD DEVELOPMENT AND FUTURE RESEARCH

General

On the basis of the lessons and experience gained during this research several areas have been identified for improvements to the conical lysimeter methodology. The improvements can be categorized into the areas of technology, equipment calibration and methods of interpretation and resolution of the inverse problem. The first stage of any further work should focus on technological matters. With an improved prototype the results of further conical lysimeter experimentation will be of greater value.

Technological Improvements

Liner System

The field experiments indicated that a pre-shaped liner would reduce sample disturbance, installation time and labor requirements. It is recommend that a fiber glass mold of a typical lysimeter hole be made for use as a blank for forming new liners. The type of material for the liner molds should be fully researched to optimize:

i) material properties (tear resistance, flexibility, durability),
ii) physical properties (weight, permeability, chemical stability of materials) and,
iii) cost.

The new liner should incorporate the collector sump in a one piece, no-joint, water tight article with quick fit connectors for the pump tubes. This design objective would ensure no lateral or vertical upward movement of water into the lysimeter as experienced under some conditions with the present system.

Although the geotextile wick performed satisfactorily, tailored wicks would improve liner sample fit and avoid the problem of liner wrinkling that occurred at the base of the present lysimeters. Tailoring could be achieved effectively by sewing together eight segments of the geotextile shaped from the blades of the tree transplanter.
Surface Runoff Barrier
Because the highly permeable geotextile wick extends to the soil surface it is essential that tracer solutes be prevented from reaching the edge of the sample. Under such conditions solutes flow rapidly to the sump through the wick, bypassing the soil entirely. Attempts in the 1992 prototypes were insufficient to prevent this bypassing under all conditions. It is important that this field technique be applicable for the widest variety of soil types, vegetation or crop cover, at varying moisture conditions and water application rates. A suitable barrier must be used to prevent runoff to the sample edge at sites with soils with low infiltration capacity uneven ground surfaces and thick vegetal root mat. This could be achieved using a stainless steel ring with a cutting edge to penetrate through the root mat into the soil. The high material cost is justifiable in view of its reusability.

Solute Application/Plot Irrigation System
The irrigation systems used in this project were inadequate for experiments requiring accurate mass balance accounting. Critical equipment improvements are required therefore to achieve uniformity of solute application, the widest range of possible application rates, and consistent, repeatable tracer applications. To ensure even application rates and accurate and precise mass balance book keeping, spray application rates must be sufficiently consistent to permit precise calibration. Uniform spray application requires pumping at fairly high pressure.

New irrigation equipment for the field experiment could use a circular travel adaptation of the equipment of (Ghodrati, Ernst et al., 1990). The circular surface area of the lysimeter suggests the adoption of sprayheads arranged radially and driven by electric gear drive about the center point. The top of the stainless steel runoff barrier could serve an additional function as a guide for the path of the rotating arm (Figure 45). Tracer solution could be applied from a tank pressurized using a portable compressor.

![Diagram of irrigation system](https://example.com/diagram.png)

Figure 45: Improved plot irrigation system.

Environmental Control
The proposed one piece liner system, the run-off barrier and the irrigation system are all attempts at more rigorous control of the physical boundary conditions of the experiment. During the 1991 and 1992 field seasons one experiment was flooded by a torrential rain and an unseasonable two feet of snow covered another. A weather proof experimental canopy is strongly recommended as part of the standard experimental equipment.

An all weather tent type cover for the plots should be sufficient to permit solute applications to be conducted without interference from prevailing conditions. Uniform solute application and minimal wind-drift of spray applied solutes requires no-wind experimental conditions. Good
A quality camping type tent should suffice, with the proviso that the material be sufficiently transparent to allow light for continued growth of vegetation on the lysimeter.

**Soil Disturbance Analysis**

A full and rigorous study of the sample disturbance caused by the tree transplanter is essential for a full assessment of the conical lysimeter method. It should include description of visual indications of disturbance as well as physical measurement of soil disturbance. This analysis must recognize the potential significance of microfissures and fine soil structural features. Soil features at this size may offer the only possibility for comparing tree spade excavated and hand excavated soils.

Soil staining provides useful visual evidence of disturbance. The methylene blue dye proved to be superior to RWT for visual detection in soils. The 1% solutions used proved to be unnecessarily concentrated. Other workers have successfully used methylene blue concentrations of 0.03% (Bouma and Dekker, 1978). Physical measurements could include in-situ measures of soil strength such as cone penetrometer strength or shear vane resistance, as well as measurements taken on small core samples; bulk density, or laboratory shear strength tests. As disturbance appears to be concentrated near the sample margins measurement of the disturbance should attempt to measure any change in properties as a function of distance from the sample margin.

**Equipment Calibration**

Renewed field experimentation should only be undertaken following resolution of all the hardware issues discussed above. The battery of experiments conducted so far are still insufficient to fully characterize flow through the lysimeter. Further experiments are required to generate tracer breakthrough curves for the use in separating equipment effects from soil hydrological properties and to generate a definitive data set for use in modeling studies of macropore and preferential flow. The experiments should be conducted in parallel with numerical simulations using finite element variably saturated flow models.

The use of the proposed water-tight liner will permit measurement of the specific retention (field capacity) of the field sample, a parameter not normally measurable on large undisturbed soil samples. The specific retention could be calculated by measuring the volume of water draining under gravity, from the soil from a fully saturated state. Simple corrections would be necessary to correct for the storage of water in the liner, sump and pump tubes. The result would establish the first point on the moisture retention curve for a two cubic meter soil sample. It is a figure that is fundamentally impossible to measure on small core samples and is impractical if not impossible with all other current methods. Results from such an experiment could be of great significance in the modeling of preferential flow and the flow and transport of solutes through soils with field scale heterogeneity.

The use of a conical sample geometry is associated with both advantages and disadvantages as an experimental methodology. On the positive side the sloping sample-liner interfaces enable the measurement of an integrated signal of the hydrological properties of the soils at all depths. This is in contrast to vertical flow infiltrometers in which flow rates are always restricted to measurement of the properties of the horizon of lowest permeability. The major disadvantage resulting from the conical shape is the difficulty in resolving and separating equipment geometry effects from soil hydrological effects in the tracer breakthrough curves. This is a tractable problem for homogenous and isotropic soils, but for layered soil or soil exhibiting preferential flow the breakthrough curves will not provide a unique solution. Is rapid travel of tracer the result of a highly permeable but homogeneous upper horizon or the occurrence of macropores at a lower level? Measurement of vertical variation of permeability at the lysimeter sites from cored samples may help with this problem. Rapid discharge response can result either from preferential flow or as piston flow. The use of tracer technology will be crucial in determining
the proportion of preferential flow in such cases. One possible approach to this problem is to measure the effects of varying water application area and the selective isolation of portions of the wick liner using a variety of infiltrometer rings driven in from the surface (Figure 46). The same method could be used to study the vertical variation of soil hydraulic properties.

![Infiltrometer rings](image)

**Figure 46**: Conical lysimeter profile showing a series of infiltrometer rings for the investigation of tracer breakthrough as a function of application radius or soil layer heterogeneity.

It does not appear that the scientific application of the conical lysimeter will be restricted by technological problems. The proposed improvements will provide a higher degree of assurance that tracer breakthroughs are not the result of experimental vagaries resulting ad hoc equipment design and solute application method. The resolution of the inverse problem or interpretation of the tracer test results is the greater challenge. Will it be possible to design sufficient experimental permutations to resolve the large number of variables affecting the flow of solutes through the unsaturated zone? Resolution of this problem will need to be addressed with an open mind and a willingness to use a variety of analytical approaches. Modeling results will be used in the design of the field experimental schedule. Likewise results from the field work should be compared with simulation results to assess model calibration quality.

**CHAPTER 5
CONCLUSIONS**

From the information presented in this report the following conclusions have been drawn:

**It is feasible to use tree transplanter equipment to construct funnel drainage lysimeters.** The lysimeters allow experimentation on two cubic meter undisturbed soil samples and can be installed in approximately one hour.

- The funnel lysimeter method addresses many of the shortcomings of current methods of measuring flow and transport of solutes through soils. The large sample size allows the measurement of the properties of soils at the cubic meter range.

- The development of a one piece sealed liner is an essential improvement for future prototypes. It will make installation faster and easier; it will reduce soil disturbance; and the sealed system will increase range of possible experiment types because of close mass balance control.

- A surface runoff barrier is required to prevent ponded water from migrating from the application area to the exposed wick at the sample margin.
• Surface spray irrigators should be capable of spatially uniform application of solutes, consistent performance over a wide range of application rates. This requires improved irrigation equipment and the control of environmental effects (wind, temperature and humidity) by use of a canopy.

Soil disturbance is concentrated at the sample margins the integrity of the main body of the samples appeared unaffected by the installation method. Detailed quantitative assessment of sample disturbance is required.

• Sample disturbance is limited to a narrow zone near the sample margin. The greatest level of disturbance is concentrated near the transplanter blade strengthening ribs. Greater sample disturbance occurs in clay rich soils than in clay poor soils.

• Soil disturbance analysis should include both description of soil properties and physical measurement of the effects of the installation process. Methylene blue is a more useful soil stain than RWT. Physical measurement of disturbance should include in-situ strength measurements e.g. penetrometer resistance and measurement of physical properties of small cored samples.

Tracer experiments with the funnel lysimeter can be used to differentiate soils with preferential flow characteristics from matrix flow soils. With additional experimentation and design improvements it should be possible to establish quantitative measures of preferential flow.

• The measurement of preferential flow requires the measurement and sampling of soil and solutes with a time resolution of minutes.

• Preferential flow was associated with rapid discharge response and rapid discharge of applied solutes in response to short, moderate intensity irrigation events.

• Matrix flow is characterized by slow and smooth discharge response to short irrigation events and the absence of applied solutes in the lysimeter effluent. Discharge response of these soils in the funnel lysimeter can be successfully simulated by single continuum finite element models for variably saturated flow.

• Soil moisture content is the dominant control on the discharge hydrograph in both flow types. Increasing antecedent moisture content advances initial and peak discharge times and increases the peak discharge value. Discharge hydrographs for preferential flow soils are far more sensitive to antecedent conditions than are the matrix flow soils.

• Gravity flow equation estimates of travel times can be used as a screening technique for identification of preferential flow. Delay times for the initial discharge response of matrix flow soils were within one order of magnitude of the value estimated by the gravity flow equation. Initial discharge in preferential flow soils occurs faster than those estimated by the gravity flow equation by more than one order of magnitude.

• Steady state flow equations for fully saturated pipe and fracture flow greatly overestimate the flow velocities measured with the funnel lysimeter. Models using a power law generalization of preferential flow and account for filling and draining of macropores and flow into and out of the macropore through the macropore wall can however be calibrated to reproduce observed discharge breakthrough of preferential flow soils from the funnel lysimeter. Macropore conductivity can be used as a crude index of preferential flow, for preferential
flow soils its value was about 0.01 m/s; for matrix flow soils a value of 0.003 m/s was estimated.

The transport of Bromide solution through matrix flow soils in the funnel can be modelled successfully using current analytical approaches.

- A simple 1-D piston flow model has been described that indicates that average degree of saturation of the sample is a critical variable. Confirmation of the model requires further experiments during which sample soil moisture is measured.

- Good model fits to the bromide breakthrough curves can be achieved using an analytical solution for 1-D, steady-state advection-dispersion. Using this approach the mean flow path length of the cone is accounted for in the retardation (advancement) factor and the radial dependency of flow path lengths can be incorporated in the coefficient of hydrodynamic dispersion as a macroscopic dispersion factor.

- Estimates of the macroscopic dispersion indicate its value to be smaller than mechanical dispersion perhaps by an order of magnitude. Further investigation of dispersion coefficients using the funnel lysimeter could be conducted with a series of experiments using precisely sorted plastic bead porous media.

- Solute breakthrough curves can be successfully modeled using Jury’s transfer function approach. This method requires no assumptions regarding the mechanistic nature of the flow through the lysimeter. The two model fitting parameters are the mean and the variance of the logarithms of the depth of advance of the solute front. It is suggested that mean is sensitive to soil and transport parameters whilst the variance is more strongly sensitive to the lysimeter shape.

Designing the funnel lysimeter on fundamental scientific objectives has resulted in an experimental methodology with far broader potential than its original purpose. The features of large measurement scale, mass balance control, and collection of all percolates are of potential value throughout hydrology, environmental engineering and plant science.

- As originally desired the funnel lysimeter can be used for the characterization of large scale soil hydraulic properties for use in existing hydrologic models or for verifying new models incorporating preferential flow. For any given soil type the funnel lysimeter can also be used to study the fate and transport of conservative and non-conservative chemicals in large undisturbed soil samples.

- The investigation of leachate from a funnel lysimeter installed at a site with contaminated soil could be used to assess the potential environmental impact of the contamination. The lysimeter could then be used to evaluate soil remediation treatments either in the development stage or to aid in selection of a method for use on a site with contaminated soil. Funnel lysimeter experiments could also be used for determining the success of remediation and if clean-up requirements have been met.
CHAPTER 6
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APPENDIX
LABORATORY MEASURED SOIL CHARACTERISTICS
All laboratory work and data reduction conducted
by
Debasmita Misra
Department of Agricultural Engineering, University of Minnesota.

St. Paul site

<table>
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Table 1. Effective Porosity (n) and Bulk Density ($\rho_B$) of St. Paul Soil.

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Table 2. Saturated Hydraulic Conductivity of St. Paul Soil.

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Table 3. Initial Moisture Content of the St. Paul Soil Profile (Gravimetric moisture content, $\theta_d$ and Volumetric moisture content, $\theta$).
PARTICLE SIZE DISTRIBUTION
ST. PAUL SITE

Figure A-1: St. Paul site particle size distribution

SOIL MOISTURE RETENTION
ST. PAUL SITE

Figure A-2: St. Paul site soil moisture retention
Princeton Site:

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</tbody>
</table>

Table 4. Effective Porosity ($n$) and Bulk Density ($\rho_B$) of Princeton Soil.

<table>
<thead>
<tr>
<th>DEPTH (cm)</th>
<th>$K_S$ (cm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>0.123</td>
</tr>
<tr>
<td>60</td>
<td>0.644</td>
</tr>
<tr>
<td>80</td>
<td>0.307</td>
</tr>
</tbody>
</table>

Table 5. Horizontal Saturated Hydraulic Conductivity of Princeton Soil.

<table>
<thead>
<tr>
<th>DEPTH (cm)</th>
<th>$K_S$ (cm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.344</td>
</tr>
<tr>
<td>52</td>
<td>0.432</td>
</tr>
<tr>
<td>60</td>
<td>0.102</td>
</tr>
<tr>
<td>80</td>
<td>0.457</td>
</tr>
<tr>
<td>100</td>
<td>0.410</td>
</tr>
</tbody>
</table>

Table 6. Vertical Saturated Hydraulic Conductivity of Princeton Soil.

<table>
<thead>
<tr>
<th>DEPTH (cm)</th>
<th>$\theta_d$</th>
<th>$\theta_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.089</td>
<td>0.117</td>
</tr>
<tr>
<td>30</td>
<td>0.053</td>
<td>0.066</td>
</tr>
<tr>
<td>52</td>
<td>0.047</td>
<td>0.062</td>
</tr>
<tr>
<td>70</td>
<td>0.046</td>
<td>0.060</td>
</tr>
<tr>
<td>90</td>
<td>0.086</td>
<td>0.113</td>
</tr>
</tbody>
</table>

Table 7. Initial Moisture Content of the Princeton Soil Profile (Gravimetric moisture content, $\theta_d$ and Volumetric moisture content,$\theta_w$).

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Figure A-3: Princeton site particle size distribution

Figure A-4: Princeton site soil moisture retention
### Table 8. Effective Porosity (n) and Bulk Density (ρ_b) of St. James Soil.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>n (cm³/cm³)</th>
<th>ρ_b (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.499</td>
<td>1.095</td>
</tr>
<tr>
<td>25</td>
<td>0.524</td>
<td>1.232</td>
</tr>
<tr>
<td>45</td>
<td>0.449</td>
<td>0.964</td>
</tr>
<tr>
<td>50</td>
<td>0.483</td>
<td>1.281</td>
</tr>
<tr>
<td>85</td>
<td>0.463</td>
<td>1.345</td>
</tr>
<tr>
<td>105</td>
<td>0.419</td>
<td>1.413</td>
</tr>
<tr>
<td>Mean</td>
<td>0.473</td>
<td>1.222</td>
</tr>
</tbody>
</table>

### Table 9. Saturated Hydraulic Conductivity of St. James Soil.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>K_s (cm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.0135</td>
</tr>
<tr>
<td>25</td>
<td>0.0123</td>
</tr>
<tr>
<td>45</td>
<td>0.0018</td>
</tr>
<tr>
<td>60</td>
<td>0.0182</td>
</tr>
<tr>
<td>85</td>
<td>0.0074</td>
</tr>
<tr>
<td>105</td>
<td>0.0046</td>
</tr>
</tbody>
</table>

### Table 10. Initial Moisture Content of the St. James Soil Profile (Gravimetric moisture content, \( \Theta_d \) and Volumetric moisture content, \( \Theta \)).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>( \Theta_d )</th>
<th>( \Theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.246</td>
<td>0.269</td>
</tr>
<tr>
<td>7</td>
<td>0.284</td>
<td>0.311</td>
</tr>
<tr>
<td>20</td>
<td>0.251</td>
<td>0.309</td>
</tr>
<tr>
<td>22</td>
<td>0.268</td>
<td>0.330</td>
</tr>
<tr>
<td>34</td>
<td>0.231</td>
<td>0.282</td>
</tr>
<tr>
<td>35</td>
<td>0.262</td>
<td>0.320</td>
</tr>
<tr>
<td>45</td>
<td>0.251</td>
<td>0.242</td>
</tr>
<tr>
<td>48</td>
<td>0.237</td>
<td>0.304</td>
</tr>
<tr>
<td>55</td>
<td>0.247</td>
<td>0.316</td>
</tr>
<tr>
<td>67</td>
<td>0.241</td>
<td>0.295</td>
</tr>
<tr>
<td>82</td>
<td>0.216</td>
<td>0.290</td>
</tr>
<tr>
<td>95</td>
<td>0.209</td>
<td>0.255</td>
</tr>
<tr>
<td>105</td>
<td>0.225</td>
<td>0.318</td>
</tr>
</tbody>
</table>
Figure A-5: St. James site particle size distribution

Figure A-6: St. James site soil moisture retention
Laboratory Model:

<table>
<thead>
<tr>
<th>DEPTH (cm)</th>
<th>n (cm³/cm³)</th>
<th>ρ_b (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.387</td>
<td>1.356</td>
</tr>
<tr>
<td>10</td>
<td>0.412</td>
<td>1.373</td>
</tr>
<tr>
<td>MEAN</td>
<td>0.400</td>
<td>1.365</td>
</tr>
</tbody>
</table>

Table 11. Effective Porosity and Bulk Density of Soil contained in the Laboratory Scale Lysimeter Model.

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>K_s (cm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>0.0780</td>
</tr>
<tr>
<td>Below Surface</td>
<td>0.0343</td>
</tr>
<tr>
<td>MEAN</td>
<td>0.0561</td>
</tr>
</tbody>
</table>

Table 12. Saturated Hydraulic Conductivity of Soil contained in the Laboratory Scale Lysimeter Model.

Figure A-7: Laboratory soil particle size distribution

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Figure A-8: Laboratory soil moisture retention

Figure A-9: Moisture retention for the polypropylene geotextile liner