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WETTING FRONT INSTABILITY AS A RAPID AND FAR-REACHING HYDROLOGIC PROCESS IN THE VADOSE ZONE

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ABSTRACT

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Wetting front instability in the vadose zone causes the formation of fingers which can rapidly transport both water and solute to the phreatic surface. The development of the unstable flow field in laboratory experiments is described for an initially dry, two-layer sand system, in which the top layer has a finer texture than the bottom layer. The effect of repeated infiltration cycles and of initial moisture content at field capacity are presented. Fingers once formed in the dry porous media are found to not change location even after several infiltration events. Only saturation and subsequent drainage alters the finger structure within the chamber. In Eastern Long Island, New York, USA, field infiltration experiments using the combination of two dyes showed that water moved through finger-like structures.

INTRODUCTION

Understanding pollutant transport mechanisms through the unsaturated zone to the groundwater is of primary importance in predicting and avoiding groundwater contamination. Spatial variability of solute transport in the field has been found to cause predictions based on one-dimensional flow models to be misleading. Recent research primarily has been concerned with the description of horizontal variability of soil properties (e.g., Nielsen et al., 1973; Vieira et al., 1981; Wagenet et al., 1984) and with various forms of bypass flow due to cracks and other macropores (e.g., Beven and Germann, 1982; Tippkotter, 1983; Smettem and Collis-George, 1985; Richard and Steenhuis, 1988) as the major cause of nonuniform solute transport. However, in addition to flow variability caused by soil structure and property variation in the horizontal, current field and laboratory evidence (Hill and Parlange, 1972; Starr et al., 1978, 1986; Glass and Steenhuis, 1984; Diment and Watson, 1985; Glass et al., 1987) has shown flow variability where horizontal heterogeneity was minimal and according to the traditional conceptualization of unsaturated flow, one-dimensional flow should occur. For soils in which the hydraulic conductivity increases with

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depth but does not necessarily vary from point to point in the horizontal, the phenomenon of wetting front instability, often called "fingering", in which water and toxics move in columnar structures to groundwater at speeds on the order of the saturated pore velocity, can occur. The conditions for fingering due to a sudden increase in conductivity with depth are present along much of the eastern seaboard of the United States, on Long Island, in river valleys of post-glaciated regions and elsewhere. Toxic waste sites consisting of a semi-impermeable or leaky impermeable liner overlying porous media are another important example of a situation where fingering might occur.

As cited in a recent review paper (Hillel, 1987), to date there have been four theoretical analyses of the wetting front instability problem, three analytical, Raats (1973), Philip (1975) and Parlange and Hill (1976), and one numerical, Diment et al. (1982) and Diment and Watson (1983). In addition to the situation where the conductivity of the top layer is less than the bottom layer, the theoretical analyses of Raats (1973) and Philip (1975) each have further postulated instability for a number of other situations including infiltration of nonponding rainfall, an increase in the initial moisture content with depth, non uniform hydraulic conductivity which increases with depth but not necessarily layered, and movement into less wetting soil.

Although wetting front instability has been noted in a number of experiments (e.g., Tabuchi, 1961; Miller and Gardner, 1962, Peck, 1965; Smith, 1967), previous to our work there have been four reported experimental studies conducted in the laboratory specifically designed to demonstrate wetting front instability: Hill and Parlange (1972) for layered soils, White et al. (1976) for air pressure increase in front of the wetting front, Diment and Watson (1985) for both layered soils and redistribution following infiltration under different uniform initial moisture contents and Tamai et al. (1987) for redistribution following infiltration into glass beads. In addition there have been three field studies specifically designed to document the existence of the phenomenon in the field (Starr et al., 1978, 1986; van Ommen et al., 1988). Many other field studies where fingers were not considered in the experimental design have yielded results inconsistent with standard conceptualizations of water and solute movement (e.g., Smith, 1967; Grosby et al., 1968). Their results, however, might be accounted for by the process of wetting front instability.

Understanding of the phenomenon is not complete and its importance for field situations, that is, under what circumstances and in what soils it will occur, cannot be adequately assessed. It is clear that systematic quantitative laboratory experimentation and field experimentation together with theoretical analysis is needed if our understanding of wetting front instability is to be advanced and the question of its importance resolved. The purpose of current research into this subject should be to fill this need. Our approach is founded on experimentation designed to answer two essential questions. First, under what circumstances does wetting front instability occur and second, once the flow field has become unstable how can its behavior be described in terms of the relevant system parameters. The major thrust of our research has been in the layered soil system because its presence is ubiquitous in agricultural soils and is of particular relevance to agriculture on Long Island where we have conducted field research (Steenhuis et al., 1985). The results of our work, however, are of a more general nature and shed light on the general phenomenon of wetting front instability.

In Glass et al. (1988a) a theoretical framework for wetting front instability experimentation is developed through classical dimensional analysis. Relationships between system parameters and initial/boundary conditions and unstable flow field behavior are derived. Miller scaling (Miller and Miller, 1956) of these relationships allows their generalization to similar porous media with different mean grain sizes and shows the effects of coarseness and fluid properties. Preliminary results presented in Glass and Steenhuis (1984) support the scaling theory and found that the smaller the mean grain size, the wider and slower the finger. The effect on unstable flow field behavior of the flow rate through an initially dry fine over coarse textured layered sand system is explored in Glass et al. (1988b). Relationships derived previously through dimensional analysis between finger width, velocity, flow through individual fingers, and properties of the bottom layer are evaluated.

In this paper, we present the results of two experimental studies that begin to bridge the laboratory and the field. We emphasize qualitative description as, to our knowledge, many aspects of the flow behavior noted in the experiments have not been presented in detail before and yield insight into the behavior of wetting front instability in the field. In the first study, conducted in the laboratory, we explore the effect of initial moisture content and its nonuniformity on wetting front instability in a two-layered sand system with a fine layer overlaying a coarse layer. We describe in detail the movement of the infiltrating water and document the persistence of fingers over a sequence of infiltration cycles. The second study was conducted in the field. We present the results of three infiltration experiments conducted on Long Island, NY, USA, where the flow field was delineated through the use of two dyes with different adsorption coefficients as a way of looking for fingers in the field.

LABORATORY EXPERIMENTATION

Since it is rare that field soils are uniformly dry, it is important to understand the effect of initial moisture content and its distribution on wetting front instability. The effect of initial moisture content on the width of fingers can be seen in the photos of Smith (1967) showing a narrow finger moving down through dry sand to widen several fold when it entered a wetted region at the bottom of the experimental chamber. Initial moisture content also may affect the stability of the one dimensional wetting front. Diment et al. (1982) and Diment and Watson (1983, 1985) suggest increasing uniform initial moisture contents to have a stabilizing effect. However, Starr et al. (1978, 1986) found fingering to occur in field soils with high initial moisture content.

Laboratory experimental method

A two-dimensional flow field was created in a slab chamber 1 cm deep, 30 cm wide and 100 cm high. Horizontal gaps in the chamber every 10 cm allowed air to escape freely. Sieved silica sand fractions, denoted by U.S. sieve series numbers that define the top and bottom of the fractions, constituted the porous media used in the experiments. The 14-20 fraction was used for the bottom layer and the 40–50, 60–80, and 100–140 fractions formed more restrictive top layers. The sands were cleaned with soap and rinsed several times and dried before and between use to assure purity. The chamber was filled through a funnel/extension/randomizer assembly and then packed using a drop impact method. Layers were separated by a thin piece of cotton cloth to keep fine particles from filtering down into the bottom layer and to assure that layers could be easily separated after an experiment. The cotton cloth was not found to influence the flow field behavior. Further details of the experimental apparatus and cleaning, filling, and packing procedures were discussed in Glass et al. (1988b).

Distilled water with a constant, low non-adsorbing dye concentration (0.025% solution of USDA Red #3) was ponded to 1.5 cm and maintained throughout the duration of each experiment. Flow field data were recorded with time lapse photography on movie film. Data was obtained from the film by projecting it onto a screen and then tracing the wetting front position with time on acetate sheets. The velocity field at various times was visualized by injecting pulses of blue dye (1% solution of USDA blue #2) into the water supply. The flow out the bottom of the chamber was measured through a "drip section" which divided the outflow across the bottom of the chamber into 10 increments or sampling points each having a width of 3 cm. Each of the 10 sampling positions were isolated from each other by a thin metal barrier higher than the capillary fringe for the bottom layer sand so that the lateral movement of water in the saturated zone at the bottom of the chamber was restricted. The drip section enabled the monitoring of the flow rate through individual fingers and its change in time.

The initial moisture distribution was varied systematically by running three consecutive infiltration experiments in each of three two layer combinations (see Table 1). In the first experiment, denoted by a lower case "a" following the experiment number, the sand was initially dry. This experiment was conducted for twenty-four hours and then the chamber was sealed to inhibit evaporation and allowed to drain for twenty-four hours. The moisture content field at the end of the drainage cycle formed the initial moisture field for the second experiment. The second experiment, denoted by a lower case "b" following the experiment number, was then conducted for twenty-four hours. In preparation for the third experiment, the bottom layer was saturated several times and afterwards sealed and drained for another twenty-four hours. An almost uniform moisture content field (6%) in the bottom layer resulted and formed the initial condition for the third experiment also conducted for twenty-four hours and further denoted by a lower case "c" following the experiment number. In this way the first ("a") and third ("c") experiments represented the initial moisture content conditions (i.e. uniform) often used in analytical and numerical studies of infiltration flows. The second ("b") experiment mimics more realistically a field situation where initial moisture content varies from point to point.

TABLE 1

Summary of two-layer experiments

Experiment #	Top layer sand fraction	Initial moisture conditions
1a	100–140	Dry
1b		1 day drainage of A1a
1c		Saturation then 1 day drainage
2a	60–80	Dry
2b		1 day drainage of A2a
2c		Saturation then 1 day drainage
3a	40–50	Dry
3b		1 day drainage of A2a
3c		Saturation then 1 day drainage

Presentation of laboratory results

The infiltration experiments yield a clear qualitative description of the unstable flow field instigated by the increase in pore size across a textural interface, its development in time and the effect of the initial moisture. The qualitative aspects are identical for experiments 1, 2, and 3, so experiment 1 will be used as an example here. Figure 1 shows drawings of the wetting front position after various times since the onset of infiltration in experiment 1a.

For infiltration into initially dry two-layer sand systems ("a" experiments), flow in the finer top layer is characterized by an initially flat wetting front and vertical streamlines. The flow at the interface between the two layers shows that water passes into the bottom layer at discrete, fairly regularly placed locations or "point sources." Small fingers form under these sources and then many merge within the next 10 cm to form wider fingers. These fingers then pass into the fully developed finger zone which is characterized by fairly constant finger velocity, width and spacing. Occasionally in this zone, a merger of fingers will occur to produce a faster moving, wider finger.

Three stages in the development of the flow field in the initially dry experiments may be delineated. (a) an initial "rapid" period, (b) a transitional "slow" period and (c) a final period of almost no change. The initial "rapid" period is characterized by rapid change in wetting front position with time. This period is shown in Fig. 1 for experiment 1a. It continues until the descending fingers arrive at the water table or, in the case of the laboratory experiments, when they arrive at the bottom of the chamber.

The transitional "slow" period is characterized by very slow changes in wetting front position as wetting fronts diffuse laterally into the dry areas

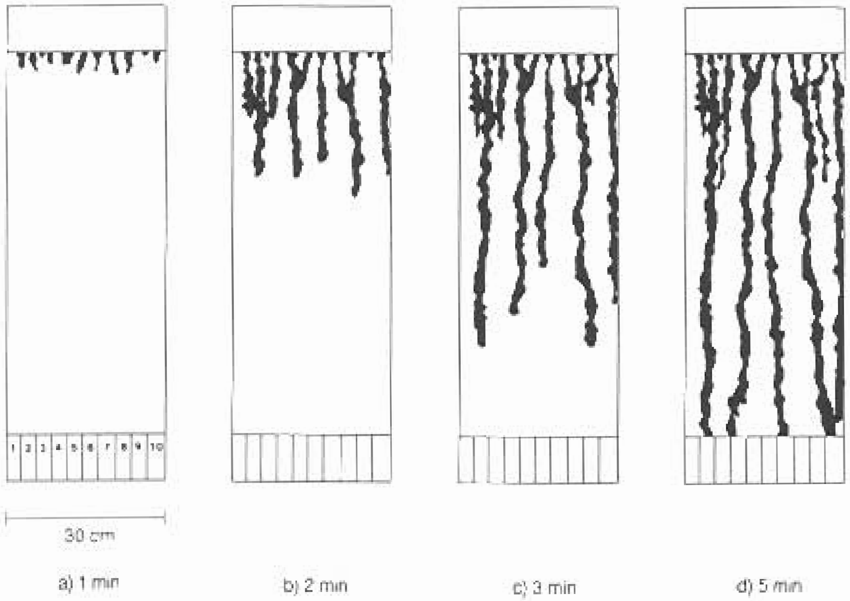

Fig. 1. Drawings of wetting front position in time after the start of infiltration for experiment 1a, an initially dry two-layer sand system. Wetting front position is drawn at one minute intervals. The finger areas which are formed during the first five minutes form the "core" areas that continue to conduct most of the flow in "a" and "b" experiments.

between fingers creating a less saturated "fringe" area around the more saturated original finger "core" areas. This period is shown in Fig 2 for experiment 1a. When a blue dye pulse is added, the core areas become blue while the fringe areas remain red demonstrating that most of the flux in the system continues to occur downward in the core areas. Occasionally during this period a finger itself will become unstable and a small split-off finger or "dendrite" may form and move slowly downward to the water table. This period ends when the lateral wetting fronts have diffused through all the porous media and some moisture is present at all locations.

The final period is characterized by no perceptible change in the flux direction or magnitude within the flow field. Moisture content differences are visible between the core areas and the fringe areas and the addition of blue dye verifies that most of the flow in the system continues to occur downward through the core areas. This period has been documented to last for at least 10 days of continuous infiltration (Glass, 1985) and may well last indefinitely.

In the "b" experiments performed with an heterogeneous initial moisture content left after drainage of the "a" experiments, fingers form in the same locations as in the "a" experiments. Movement in the former fringe areas is enhanced over the "a" experiment but the size and configuration of the core

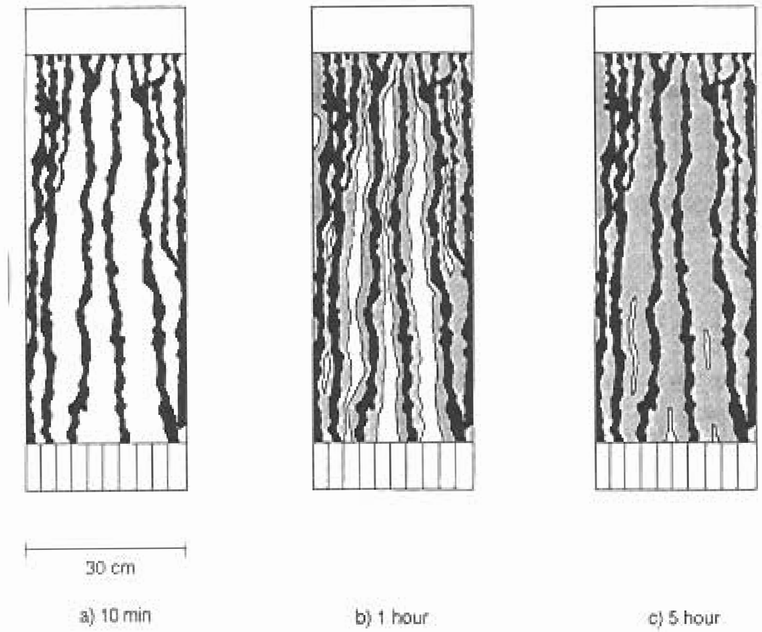

Fig. 2. The transitional "slow" period where wetting fronts move from initial core areas (2a, black regions) laterally creating a less saturated "fringe" area (grey regions) around the fingers is shown after one hour (2b) and five hours (2c). The majority of the flow continues to take place through the core areas within the wetted region.

areas match almost exactly with those of the previous initially dry experiment thus demonstrating the persistence of finger path. Basically, the heterogeneous, initial moisture content field formed by a previous unstable wetting cycle allows a rapid transition into the third and final flow period, seen in the "a" experiments, by enhancing movement in the fringe areas. As evidenced by dye tracer pulses, the majority of the flow continues to be conducted by the core areas with no change in flow field during the duration of the 24 hr infiltration cycle.

In the final "c" experiments, the initial moisture content in the bottom layer is at approximately 6%. The wetting front becomes wavy as it moves into the bottom coarse layer and the amplitude of the wave increases as the wetting front proceeds downward. Thus, the wetting front is indeed unstable, but since the wavelength of the disturbance is on the order of the width of the chamber, separate fingers cannot form. The dramatic finger structure found in the dry and heterogeneous initial moisture content distribution experiments is not observed. However, after the wetting front has reached the bottom of the chamber, blue dye pulses show an exaggeration of the initial wave form of the wetting front thus indicating faster movement of moisture in wide "core" areas associated with the location of the initial bulges in the wetting front. The flow field shown by the blue dye pulse was constant throughout the duration of this final 24-hour infiltration cycle.

The standard deviation of the flux distribution in the "a", "b" and "c" experiments at the bottom of the chamber – as monitored through the ten sampling positions of drip section – can be used as a measure of the uniformity of the flow field: the more uniform, the lower the standard deviation. Figure 3 gives the flux distribution for experiment 1 in time and the standard deviation ("position 11"). It can be seen that the standard deviation of the percent total flux across all ten sampling locations decreases from dry ("a") to heterogeneously wet ("b") to uniformly wet at field capacity ("c") initial moisture content conditions. In 1a, five fingers flow into the set of drip sections causing flow out of all but two of them. Over time, as lateral wetting fronts move into the dry sand between finger core areas, the fringe areas begin to contribute to the flux distribution by smearing out the effect of the core areas. Flow from the points with the lowest fluxes has increased while flow from those with the highest fluxes has tended to decrease, thus decreasing the standard deviation from 9.21 to 7.82 in 24 hours. In 1b, the standard deviation decreased to 5.28 and changed little during the 24-hour infiltration cycle. As has been described above, the core areas present in 1a are also core areas in 1b; however, the fringe areas were seen by dye pulses to be more active in conducting water than in 1a at 24 hours. The decrease in the standard deviation from the a to the b experiment shows this increased fringe area conductance as well. Experiment

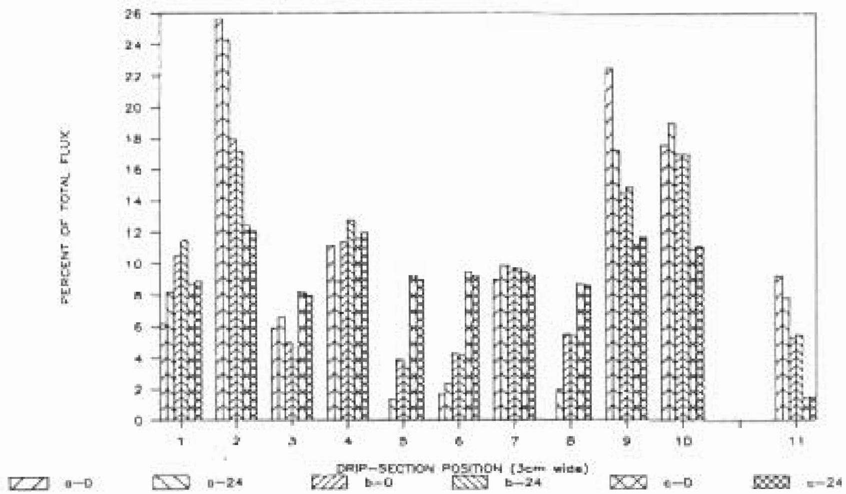

Fig. 3. Flux distribution out the bottom of the chamber for experiment 1. Position 1 through 10 represent the drip section. At each position the percent of the total flux within the first hour and at 24 hours for the "a", "b" and "c" experiments are given. In position 11, the standard deviation at each time period across the drip section is given.

1c shows a further reduction in the standard deviation of the flux distribution to a constant 1.45 throughout this final 24-hour infiltration cycle. Thus, the influence of high, uniform initial moisture content is to make the flow field on the scale of the chamber more uniform than the "a" or "b" experiment. However, the fact that the standard deviation is not lower than 1.45 supports the result of dye pulses that the flow is still not entirely uniform.

Summary of laboratory results

From the two-layer experiments, five major points can be remarked. First, the textural interface provides a very strong perturbation, discretizing the uniform flow at a number of discrete point sources. Second, under dry initial conditions, fingers that form have a dramatic moisture content structure – very wet inside the finger and very dry outside the finger. Third, over time, slow sideways diffusion of moisture from finger core areas takes place resulting in a steady flow field with finger core areas persisting and continuing to conduct most of the flow. Fourth, on subsequent infiltration cycles, flow remains concentrated in the same core areas as first delineated fingers, thus emphasizing the importance of slight variation of initial moisture content between past fringe and core areas on the heterogeneous moisture movement and the persistence of fingers. Fifth, when the initial moisture content is artificially uniform and high, fingers widen and can coalesce giving the appearance of an almost uniform flow field but with horizontal variation in flux still apparent.

FIELD EXPERIMENTATION

Traditional field techniques are not able to either detect fingers or adequately monitor solute transport through soils when they occur. The fingering process in the subsoil has been shown to have no effect on the infiltration as measured at the soil surface (Parlange and Hill, 1972). If tensiometers and neutron probes are installed in order to measure water flow or if soil core samples are taken to monitor solute transport, the measurements would not necessarily indicate that fingering is occurring and any inconsistencies between measurements would often be explained by faulty technique, experimental error, or by heterogeneities in porous media properties. To verify that fingering is occurring, the fingers themselves can be revealed through the use of dyes as was first shown by Starr et al. (1978). We employ similar methodology, but add the use of two dyes to document the existence of finger structures in eastern Long Island.

Site description

The site of the field experiment is on the grounds of Cornell University's Long Island Horticultural Research Farm located 4 km north of Riverhead, New York, and 1 km south of the Long Island Sound. The farm lies on a glacial outwash plain with soils typical of the region. Soil at the site is a Haven loam (NYS Soil Survey) with a high to moderate available moisture, good internal drainage, poor natural fertility, moderate permeability in the surface layer and high permeability in the substratum. Some characteristics of this soil are given in Table 2, taken from Steenhuis et al. (1979). It can be seen from the table that hydraulic conductivity increases dramatically with depth and thus fulfills the criteria for the occurrence of infiltration flow instability given by theory. This soil is not only representative of the soils on Long Island but of many gravelly to sandy soils along the Atlantic coast from Maine to Florida as well.

Previous to our work, several studies conducted at the site indicated extremely heterogeneous flow possibly due to fingering. A traditional infiltration study at the field site using one tensiometer at depths of 15, 30, 60, 90 and 120 cm below the surface and one neutron probe access hole was accomplished by Lecuona-Valenzuela (1980). This methodology was not designed for the detection of fingering, however, the comparison of the neutron probe data to the tensiometer data indicates the advance of the wetting front near the neutron probe to be much faster than near the tensiometer set. Steenhuis et al. (1985) studied natural recharge at the site using two circular plots 3 m in diameter instrumented with tensiometers in triplicate at depths of 30.5, 61, 91, and 122 cm and in duplicate at 152, 183, and 213 cm distributed in a single ring pattern with a 2.5 m-deep neutron probe access hole in the center of the plot. Data collected showed large variation between tensiometer readings at the same depth but located at different places in the plot. This variability of water movement in supposedly horizontally homogeneous soils instigated research to

TABLE 2

Description of the soil (Haven loam) at the field site (NYS Soil Survey)

Depth (cm)	Moisture content range		Depth (cm)	Average saturated hydraulic conductivity (cm day^{-1})
	Saturated	Air dry		
0–30	0.41	*	0–30	2.74×10^1
60	0.35	0.005	30–60	4.62×10^2
90	0.34	0.005	60–90	9.17×10^2
120	0.32	0.005		

Depth (cm)	Visual description of auger samples
0–8	Dark brown, clayey feel, organic matter present
8–27	Similar to 0–8 but with higher sand content
30	Distinct division between plow layer and lower horizons
29–45	Lighter brown than plow layer, less cohesive
45–61	Pebbles up to 10 mm diameter, increased size and number with depth
61–106	Orange brown sand with pebbles. Low cohesion
106–160	Sand becomes coarser, less orange
160–182	Sand layer very moist, sticks together, clay lenses present
182–196	Clayey layer, dark brown and very moist
196–200	Almost entirely pebbles 2.5 cm diameter
200–219	Coarse sand

determine the variability of unsaturated soil physical properties at the site. Over 100 soil samples, taken at two depths (15 cm above the plow pan and 15 cm below the plow pan), were analyzed in the laboratory for their hydraulic properties (Cooke, 1983). It was determined that little horizontal variability can be found at the site at either the 45 cm or the 15 cm depths. With these previous studies in mind a dye tracer study was planned in order to track the path of water movement through the soil profile during infiltration.

Field experimental method

One ponded infiltration experiment was conducted in each of three different land use areas at the site. The specific locations of the field infiltration experiments are shown in Fig. 4, a map of the Long Island Horticultural Research Farm. Location 1 had been in raspberries for three years until the

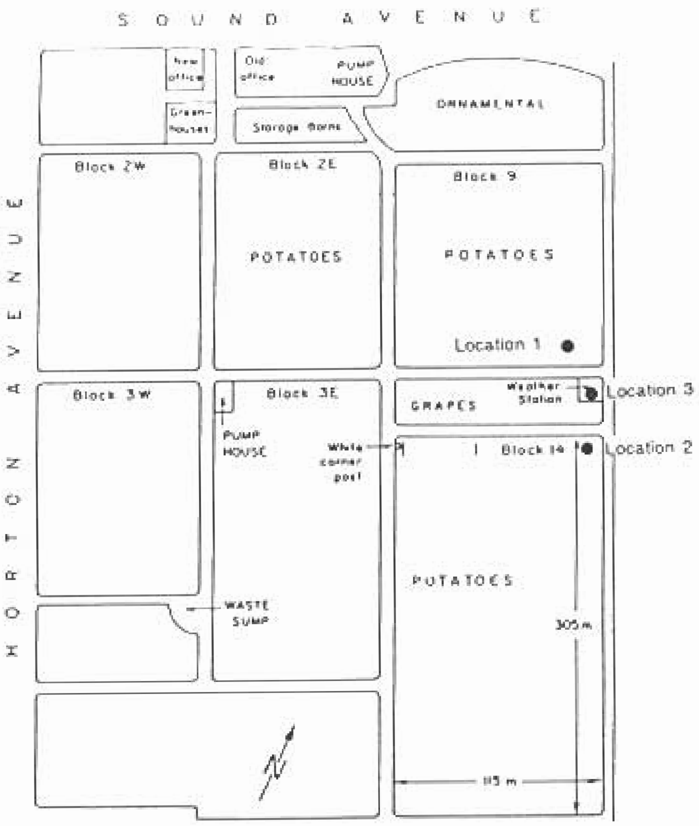

Fig. 4. Map of the grounds of Cornell University's Long Island Horticultural Research Farm showing the locations of the three field infiltration experiments.

spring before our experiment when they were removed, the field was disked and laid fallow until the time of the infiltration experiment. Location 2 had been in corn the year previously and was currently in potatoes. Location 3 had been in grass for at least 4 years.

An infiltration ring 1 meter in diameter was pounded into the topsoil to a depth of 30 cm. Some grease was applied to the inside surface before installation to insure a good seal and inhibit preferential movement of water around the sides of the infiltration ring. The top 5 cm of the soil inside the ring at locations 1 and 2 was homogenized and leveled with a trowel after ring installation. At location 3 the sod was left intact. The soil within 3 cm of the edge of the infiltration ring was then slightly compacted to insure against water movement down the sides of the ring.

With reference to the laboratory study above, in order to visualize fingers in a situation much like that of the "b" experiment the use of two dyes with different adsorbances would allow the delineation of fingers with their core and fringe areas. Two dyes were chosen as tracers which could be easily seen in the soil and which had much different absorbances in the soil. USDA green #2 food coloring was found to move almost with the wetting front in a laboratory test and so to be a good indicator of the extent of the infiltrating water body. Rhodamine WT was found to adsorb much more strongly than the green food coloring and so was chosen as the tracer to indicate high flow regions; that is, where rhodamine WT is found to penetrate deepest in the soil profile, the most flow is occurring. Infiltration was started by applying 5 cm of red colored water (rhodamine WT 1% solution). Green colored water (0.025% solution) was then added through a constant head device to maintain the ponding depth at 5 cm until a total of 43 cm had infiltrated.

As soon as ponding disappeared, the soil was carefully excavated to give horizontal flat surfaces approximately every 20 cm and photographs of the flat surface were made to show the location of dyed soil.

Results of field experiments

Previous work at the site had indicated that the subsoil at the site was horizontally layered and it was assumed to vary only slightly between the three locations as they were all within 50 m of one another. However, the stratigraphy of location 3 was extremely different below the 140 cm level due to the presence of erratically distributed discontinuous and non horizontal clay lenses. We describe below the dye pattern for each location in detail.

Flow through the top soil (to 30 cm) at location 1 was very nonuniform due to the combination of macropores along decaying raspberry roots and compaction between rows from tractor tires. At 7 cm depth, approximately 65% of the horizontal plane was dyed while the remaining 35% was the color of the original soil. The undyed areas were spread more or less evenly through the horizontal plane (small 1-cm diameter "speckles") and also in a 15-cm-wide strip between rows. At the top of the subsoil at 30 cm the blotchy pattern

disappeared and the dyed regions contained very few undyed "speckles" within green dyed regions. The strip of undyed soil beneath the tire runs perpetuated itself into the subsoil as can be seen in scale drawings made from color slides of horizontal cross-sections at 50, 70, 90, 115, and 140 cm depths shown in Fig. 5. The dye pattern indicates infiltration to be occurring in the subsoil mainly through columnar, finger like structures. One of these structures located beneath a large raspberry root in the top soil reached to a depth of 190 cm before green dye could no longer be detected by eye. Below this "tip" the sand was noticeably wetter indicating a deeper penetration of water than shown by the dye. This stands to reason since some water within the profile moves ahead of the advancing dyed water and also the green dye does adsorb slightly to the soil.

Movement in the topsoil at location 2 was not very influenced by macropores or uneven compaction as indicated by an evenly mixed red/green color throughout the topsoil. Drawings of the dye patterns within the subsoil at the 60, 100 and 160 cm levels are given in Fig. 6. While a number of flow regions can be seen at the 60 cm level, two major regions of flow designated by red core regions had developed. These two regions reached to 170 and 185 cm respectively before green dye could no longer be distinguished. The sand was noticeably wetter beneath these two regions again indicating an even deeper penetration of the infiltrating water.

At location 3, flow through the topsoil took place mainly through evenly distributed fine macropores associated with the sod. At the top of the subsoil the soil was green everywhere with many red speckles distributed evenly across the wetted region. Drawings of the dye patterns within the subsoil at the 60, 125, 170 and 180 cm levels are given in Fig. 7. At a depth of 60 cm the red speckles had coalesced to form several small red columnar regions which disappeared by 70 cm. At 140 cm a fairly horizontal clay layer was encountered by the infiltrating water. The clay layer had several breaks or holes through it and water moved through these. Below, an erratic mixture of coarse sand and clay layers was found extending down to 2 meters. The green dye indicated water to move through the sand layers in narrow finger like structures. When the next clay layer was encountered the finger would widen above it and move along the sloping layer until a hole through it was found. At the 170 cm level, 8 discontinuous areas were conducting the flow. By 190 cm all but two of these green regions had disappeared. The largest of these areas there encountered a gradually sloping clay layer which it followed into the side of the excavation hole at least 1 meter from where it encountered the layer.

Summary of field results

The use of the more highly adsorbed red and almost non-adsorbed green dyes allows the delineation of core areas where most of the flow was taking place (red) and fringe areas where the flow velocity was less (green). The dominance of vertical-versus-horizontal water movement in the coarse sandy subsoil is

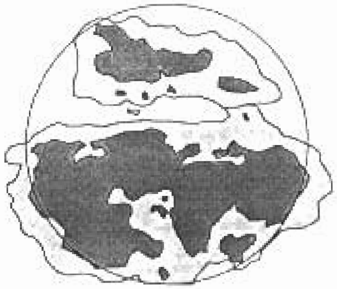

FIGURE 5a
Location 1
50cm depth

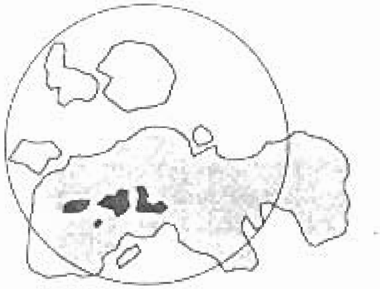

FIGURE 5c
Location 1
90cm depth

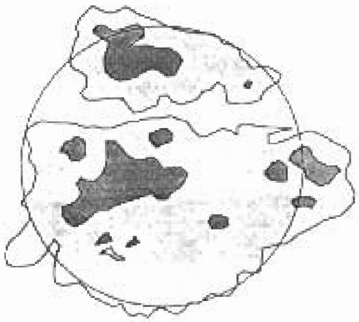

FIGURE 5b
Location 1
70cm depth

FIGURE 5d
Location 1
115cm depth

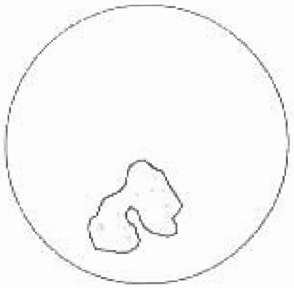

FIGURE 5e
Location 1
140cm depth

Fig. 5. Field infiltration experiment, location 1. Drawings of dye patterns at horizontal cross sections at depths of (a) 50 cm, (b) 70 cm, (c) 90 cm, (d) 115 cm and (e) 140 cm. Circle shows the position at the surface of the 1 meter diameter infiltration ring. Grey areas indicate green dyed regions while darker areas indicate red dyed regions.

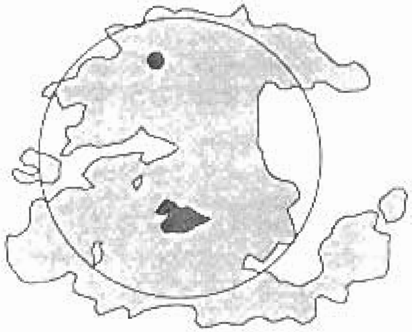

FIGURE 6a
Location 2
60cm depth

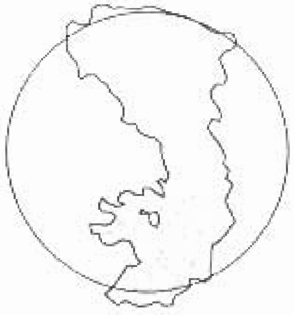

FIGURE 6b
Location 2
100cm depth

FIGURE 6c
Location 2
160cm depth

Fig. 6. Field infiltration experiment, location 2. Drawings of dye patterns at horizontal cross sections at depths of (a) 60 cm, (b) 100 cm and (c) 160 m. Circle shows the position at the surface of the 1 meter diameter infiltration ring. Grey areas indicate green dyed regions while darker areas indicate red dyed regions.

demonstrated in each experiment by the dyes. Most flow occurred directly beneath the ponded surface. The split in the flow field caused by the tractor tire run at location 1 also emphasizes the importance of the heterogeneous supply surface at the top of the subsoil as a determinar of where most or very little of the flow will occur; that is, given a supply surface where the flow is mainly concentrated in certain regions, finger core areas will grow beneath these regions.

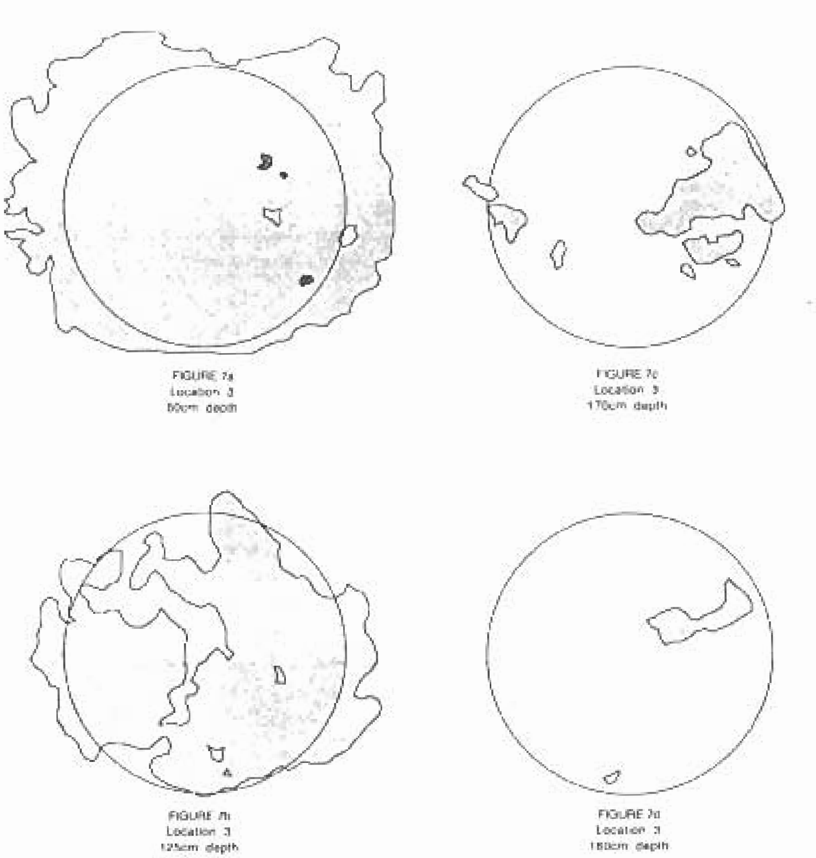

Fig. 7. Field infiltration experiment, location 3. Drawings of dye patterns at horizontal cross sections at depths of (a) 60 cm, (b) 125 cm, (c) 170 cm and (d) 180 cm. Circle shows the position at the surface of the 1 meter diameter infiltration ring. Grey areas indicate green dyed regions while darker areas indicate red dyed regions.

DISCUSSION

The laboratory study shows, as did Diment and Watson (1985) for a uniform initial moisture content of 2%, that for a uniform initial moisture content of 6%, the wetting front becomes very wavy with the wave amplitude increasing in time. Since the increase in amplitude with depth is a definition of front instability, the wetting front may be considered to be unstable even for initial moisture contents at field capacity. The fact that separate fingers do not form under uniformly high moisture contents is most likely due to the widening of fingers and their merger in a laterally constrained infiltration chamber. In

addition, this widening and merger seems to be found only if the initial moisture content is uniform – a condition not often found in nature.

The most striking result of the laboratory study is the effect of an heterogeneous distribution of moisture content as formed by a previous unstable flow field (the "b" experiments) on wetting front instability. In additional infiltration cycles, fingers form in the same locations as they did initially and have the same core areas which continue to conduct almost all of the flow. If the chamber is flooded so that the initial moisture content field is uniformized, these core areas are obliterated, thus emphasizing that they are not caused by the heterogeneities in the porous material either in the initial pack or by the reorientation of grains by the initial fingers themselves.

The field experiment demonstrates that fingers like structures will form with core areas present which conduct most of the flow. A comparison of the results of "b" experiments and the field experiments shows a close resemblance. Variation in initial moisture content has a much higher probability of occurrence in nature than a uniform distribution, especially where fingering is occurring. Thus, the field experiment not only demonstrates the occurrence of finger structures on Long Island, but, in combination with the laboratory results, emphasizes the need to look more closely at the initial condition of uniform initial moisture content commonly used in both laboratory experiments and theoretical discussions of infiltration phenomena.

The laboratory experiments demonstrate the nature of the textural interface as a discritizer of the flow field allowing water entry at discrete locations. The implication of this for field soils is important. In the field, disturbances in the form of heterogeneities are abundant. While at first glance, it may seem that the heterogeneities might swamp any instability that may occur, a closer look indicates heterogeneities and instability could combine to dictate a flow field much more heterogeneous than with either operating alone. Figure 8 shows the advance of fingers in a preliminary experiment with heterogeneities due to strong gradation of the sand when the chamber was filled through a funnel. Veins of finer sand pulled the finger tips sideways allowing them to merge and form stronger fingers. Numerous structures within the soil profile can cause the flow to concentrate during infiltration and once this has occurred, either within or at the top of a coarse textured layer, the flow can take place through fingers. In the laboratory, Glass et al. (1987) formed individual fingers from point sources at the top of a coarse layer. In the field, a large dead root from a mature raspberry bush at location 1 provided a preferred path for water flow through the top soil and initiated the growth of a finger that reached to a depth greater than 190 cm in 8 hours. Holes or breaks in clay layers at location 3 concentrated flow and fingers formed in the intervening coarse sand layers.

Wetting front instability has important implications for both monitoring and predicting the fate of toxics in the unsaturated zone. The usual practice in monitoring programs is to sample one or two locations. Consequently, if fingering is occurring then the sample might indicate a significant higher or lower movement than the "average". An increase in the speed with which the

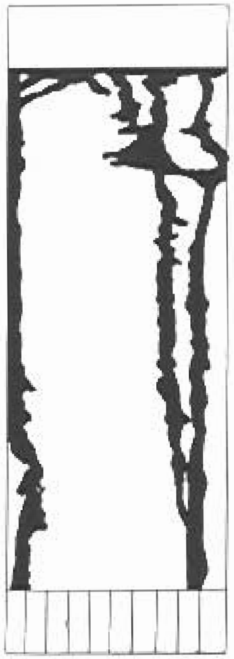

Fig. 8. Drawing of a preliminary experiment showing the effect of slight heterogeneities in the top 20 cm of the bottom layer.

pollutant is transported to the subsoil will also influence fate prediction since the breakdown of toxics is usually performed by microbial activity which decreases rapidly with depth. Thus, the fingering process can not only hasten the arrival of toxics, but also increase the loading due to shorter retention time in the root zone.

It is important that the implications of fingering be incorporated into current toxic monitoring and fate prediction procedures for areas where the phenomenon occurs. For this purpose we are currently conducting both laboratory and field studies to determine the effect of fingering on solute transport. Since water flow in the capillary fringe region is still vertical and, as we have shown in the laboratory experiments presented in this paper, fingers will widen and coalesce under high uniform moisture content, the use of suction lysimeters placed in the capillary fringe region above the water table shows promise as a field solute monitoring technique.

CONCLUSION

In a fine over coarse layered sand system, instability of the infiltration flow itself causes the formation of fingers in the bottom layer. Fingers, once formed,

persist from one infiltration cycle to the next. These conduits for the majority of the flow can only be destroyed by artificially uniformizing the moisture content within the bottom layer by saturation and drainage. In the field, finger structures were demonstrated through the use of two dyes in an unstructured coarse sand subsoil overlain by a fine topsoil. Not only were finger structures associated with the textural change but with regions of concentrated flow in the surface layer. Macropores in the topsoil supplied water nonuniformly to the unstructured and macropore-less subsoil causing the formation of fingers below. Other flow concentrating structures within the soil profile such as clay lenses and rocks play a similar role. The combination of instability, macropores and heterogeneities in the properties of the porous media leads to a much more complex water flow field than with any of them acting alone and poses a severe challenge for the modeling and monitoring of toxics within the vadose zone.

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