APRIL 1996

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WRRI Technical Completion Report No. 296

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TECHNICAL COMPLETION REPORT

Account Number 01423976

April 1996

New Mexico Water Resources Research Institute
in cooperation with
Department of Earth and Environmental Science
and Geophysical Research Center
New Mexico Institute of Mining and Technology

The research on which this report is based was financed in part by the U.S. Department of the Interior, Geological Survey, and the Chino Mines Company Grant Fund through the New Mexico Water Resources Research Institute.

DISCLAIMER

ACKNOWLEDGEMENTS

We are grateful for the large quantities of dry, clean perlite sand donated by the Grefco Mine at Socorro. Special thanks are due to the laboratory crew, Steve Bower, Jay Cabrales, Craig Stevenson, and Kelly Kriel, for their enthusiastic involvement and hard work in the laboratory.

A NATO travel grant enabled the authors to present this study at the International Workshop "Fingered Flow in Unsaturated Soil: From Field to Model" at Wageningen, The Netherlands, April 1994.

ABSTRACT

Field experiments were conducted in the Sevilleta dunes approximately 20 miles north of Socorro, New Mexico. After water application, the depth and stability of the wetting front was observed by digging an observation pit. Contrary to unstable wetting front theories in 1992, no instabilities were encountered and all wetting fronts appeared quite stable. These initial results indicated that existing wetting front theories were not yet adequate for the prediction of unstable wetting in New Mexico's soils. Therefore, we pursued a laboratory study under well-controlled conditions.

Lysimeter experiments were conducted in the laboratory to validate current wetting front instability theories with four different grades of sieved and air-dried perlite and quartz sand. Water was applied by a sprinkler system at rates within the range of natural precipitation rates in New Mexico. The experimental results show that wetting front instability will cause fingering phenomena in a homogeneous soil system. This observation confirms experimental and theoretical results of other researchers. The diameter of fingers was observed to be a function of the sand's grain size. Small fingers (3-4 cm diameter) were found in coarse sand (grain size 1.41-0.84 mm); large diameter fingers (12 cm diameter) were observed in fine sand (grain size 0.42-0.25 mm). Our experimental results in the coarse sand show that, for infiltration rates varying between 0.3 and 12 cm/h, finger diameters remain nearly constant. This observation also agrees with existing theories. However, at infiltration rates lower than 0.12 cm/h, the coarse sand experiments show that the wetting fronts became stable. For rates between 0.3 and 0.12 cm/h, the wetting is semi-stable; that is, there is incomplete wetting without distinct development of fingers. A similar trend is observed in the experimental results of sands with grain sizes of, respectively, 0.841-0.594 and 0.594-0.42 mm.

We used our laboratory results to develop a simple approach for evaluating wetting front stability in dry soils. The stability of wetting fronts in the top layer of a soil depends on the soil type and the intensity of the precipitation. Our approach distinguishes stability criteria for wetting events that cause a high, intermediate, and low infiltration rate. At high infiltration rates, wetting fronts are stable if the infiltration rate exceeds or equals the soil's saturated hydraulic conductivity. The stability criterion for low infiltration rates (less than approximately 0.2 cm/h for sand soils) is based on two characteristic times: a gravitational time and an infiltration time. The gravitational time, t_{grav}, indicates when gravity and capillarity each contribute equally to the process of infiltration. The infiltration time, t_{infil}, yields the duration of the infiltration event. Experimental and literature data show that in well-sorted laboratory sands, wetting fronts are stable when $t_{infil}<0.002\ t_{grav}$. This expression can be simplified as $Wi<0.002\ S^2$ with W the total amount of precipitation, I its intensity, and S the sorptivity at a slightly positive soil-water pressure. For intermediate infiltration rates, wetting fronts remain stable as long as W is smaller than the amount of water needed to wet a distribution layer near the surface. The application of stability criteria is demonstrated with a case study from the Sevilleta dunes near Socorro, NM.

Keywords: unstable wetting fronts, vadose zone, unsaturated flow

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INTRODUCTION

In many different environments, one-dimensional models have predicted negligible risk of groundwater contamination due to sufficient residence time of contaminants in the vadose zone. However, it has been determined that significant ground water pollution has occurred where these models predicted none. For example, in Nassau and Suffolk counties on Long Island (New York), wetting front instability is playing a major role in nonpoint source pollutant movement through the unsaturated zone. As a consequence, a field solute monitoring study conducted at Cornell University's Long Island Horticultural Research Farm failed to keep track of solute leaching through the subsoil, because the study was designed without considering the occurrence of wetting front instability (Steenhuis, 1994. Cornell University personal communication). In New Mexico, it is not understood how traces of tritium could have entered the drinking water supplies of a major city or how trichlorethylene from a shallow landfill could pollute the groundwater table at a depth of 180 meter (McQuillan, 1994, New Mexico Environment Department personal communication). It was shown that in Plainfield, Wisconsin sand water and solutes flowed through less than ten percent of the whole soil matrix at a depth of 3.0-3.6 meters and less than one percent between 5.6-6.0 meters (Kung 1990 a,b). In the Netherlands, Beugelink (1987) evaluated groundwater contamination by soil disinfectant 1,2-dichloropropane, which frequently is used against nematodes. Assuming only 1% leaching to the groundwater, he concluded that in the first half of the next century, the concentration 1,2-dichloropropane will be nine times higher than the drinking water standard.

The cause of these groundwater contamination cases is presumably the occurrence of preferential flow paths in the vadose zone. Such preferential flow paths can be caused by macropores such as cracks in swelling soils or old root channels, spatial variability of hydraulic conductivity, or by the occurrence of unstable wetting fronts. A stable wetting front is a horizontal wetting front which moves downward without breaking into fingers. The behavior of such a front can be simulated with one-dimensional computer models. Unstable wetting fronts begin as horizontal wetting fronts under certain conditions break into 'fingers' or 'preferential flow paths' as the front moves downward, much like rain running off a sheet of glass breaking into streams (Figure 1). These fingers facilitate the transport of contaminants to the groundwater at velocities many times those calculated if a stable horizontal front is assumed. For example, Hendrickx et al. (1988b) measured in a bromide tracer experiment that after five weeks with 120 mm precipitation bromide concentrations in the

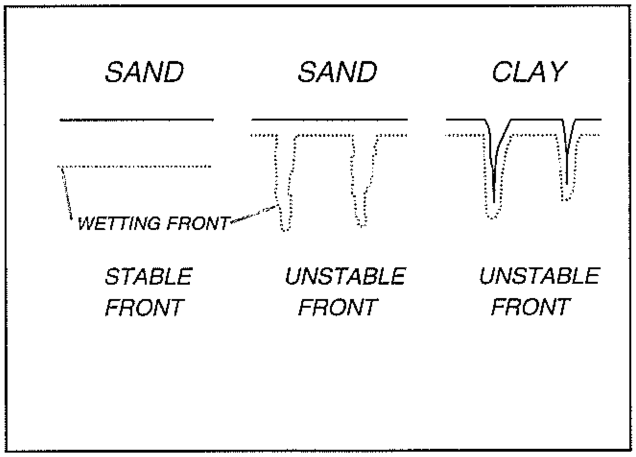

Figure 1. Graphic visualization of a stable and unstable wetting front in a homogeneous sand soil and a typical wetting front in dry clay soil.

groundwater are thirteen times higher under unstable wetting fronts than under stable wetting fronts.

The conditions under which unstable wetting fronts in field soils form are not yet fully understood. Recently developed soil physics theories (Glass et al. 1989a,c; Hillel and Baker 1988; Philip 1975a,b; Raats 1973; Tabuchi 1961) and experimental evidence (Glass et al. 1990; Hendrickx et al. 1988a,b; Hendrickx et al. 1993; Hill and Parlange 1972; Ritsema et al. 1993; White et al. 1976) indicate that fingers caused by unstable wetting fronts will occur in water repellent soils and in layered soils where the hydraulic conductivity increases with depth. For nonponding infiltration in dry homogeneous soils without layering, some theories predict fingers to occur (Raats 1973) and some theories predict fingers not to occur (Philip 1975a). Experimental evidence however shows that fingers do indeed occur in single-layered homogeneous soils during nonponding infiltration (Hagerman et al. 1989; Selker et al. 1989). It appears that the occurrence of fingers is especially likely in dry soils such as found in New Mexico. For example, Hendrickx et al. (1991) found that 400 mm natural precipitation in an initial dry wettable sand wetted only 15% of the total soil volume. The remaining 85% of the soil was not wetted and remained dry.

Investigating why unstable wetting fronts occur is difficult since so little is known about this phenomenon. The mathematical analysis of instability is cumbersome due to the highly nonlinear behavior of Richards' equation for unsaturated water flow through the soil. Therefore, Raats (1973), Philip (1975a,b), and Parlange and Hill (1976) use the Green and Ampt (1911) model for infiltration to study wetting front instability with a linear hydrodynamic stability analysis. This model linearizes the infiltration process by the use of a special diffusivity function which, unfortunately, is representative of only a few soil conditions. In New Mexico, this such condition occurs in dry sandy soils and in soils where a fine layer overlays a coarse layer. Another condition is found in water-repellent soils located in the Sevilleta and in water-repellent coal-mine spoils (Miyamoto et al. 1977).

Because wetting front instability is likely to play an important role in the transport of water and contaminants from the soil surface to the groundwater under New Mexico's deserts and irrigated lands, we proposed in 1991 to focus on three objectives:

1) Using field experiments, investigate with field experiments in the Sevilleta desert and on irrigated lands near Socorro the relations between amount of water applied, physical soil characteristics, antecedent soil moisture status, and occurrence of unstable wetting fronts and resulting preferential flow paths.
2) Quantify the relations between precipitation and/or irrigation regime, physical soil characteristics, antecedent soil moisture status, and occurrence of unstable wetting fronts.
3) Validate the Van Dam et al. (1990) approach for modeling preferential flow paths.

We were able to accomplish most of objectives one and two, but not objective three. The reason was that existing pre-1991 instability theories were not as complete as anticipated at the start of our research. Therefore, we had to put more emphasis on lysimeter experiments than expected. This report presents results from our three-year research activities.

METHODS AND MATERIALS

Field Experiments

All experiments were conducted in the Sevilleta dune field (Fig. 2), approximately 20 miles north of Socorro. The dune field was selected because its sand soils are the most vulnerable for unstable wetting caused by non-ponding precipitation.

During the summer of 1991, water was applied to the soil surface by a commercially available pesticide sprayer (Hendrickx et al. 1988b) After applying the water, the depth and stability of the wetting front was observed by digging out the entire soil volume under the sprinkler in layers of 10 cm thickness or less.

During the summer and fall of 1995, water was applied by a sprinkler system with eleven hundred drip needles in a sealed Plexiglass box at grid points 3 cm apart. The needles covered a circular area with a diameter of 1.2 m. The drop size from the needles (20G1, from Beckon and Dickinson) measured approximately 3 mm in diameter, which is close to the drop size of a storm rainfall in the United States (Bubenzer, 1979; Carter et al., 1974; Laws and Parsons, 1943). For low-flux experiments, smaller needles (30G1/2) were used to obtain a more uniform water distribution. Two variable-speed, gear-reduction motors were placed on two adjoining sides to control the north-south and east-west movements separately. The offsets in both directions could be adjusted so that we could obtain a random distribution of the water without a repetitious pattern. A Masterflex pump and a syringe pump were used for accurate flow control. The water application rate could be adjusted from 0.05 cm/h to 36 cm/h.

Lysimeter Experiments

Lysimeter experiments were conducted to examine wetting patterns in dry soils.
Experimental Sands. Four different grades of perlite sand and quartz sand were used: U.S. mesh size No. 14-20 (1.41-.841mm), 20-30 (.841-.594mm), 30-40 (.594-.42mm), and 40-60 (.42-.25mm). The particle size distribution was determined with a sieve analysis. The particle size distribution curves indicated that the sands were rather homogeneous. For our experiments, we needed to transport, dry, clean, and sieve approximately 10 m^3 sand. Perlite sand was chosen as the experimental material because it was made available to us by the Grefco Perlite Mine near Socorro at no cost. Some experiments were repeated in natural quartz sand to corroborate the experimental results observed in perlite sand.

Perlite is similar to quartz sand, but has a lower specific density of approximately 2.2 g/cm^3 compared to 2.65 g/cm^3 of quartz sand. This leads to a bulk density in the lysimeters of approximately 1.25 g/cm^3 and a porosity of 45%. Quartz sand has a higher bulk density of 1.54 g/cm^3 and a slightly lower porosity of 42%.

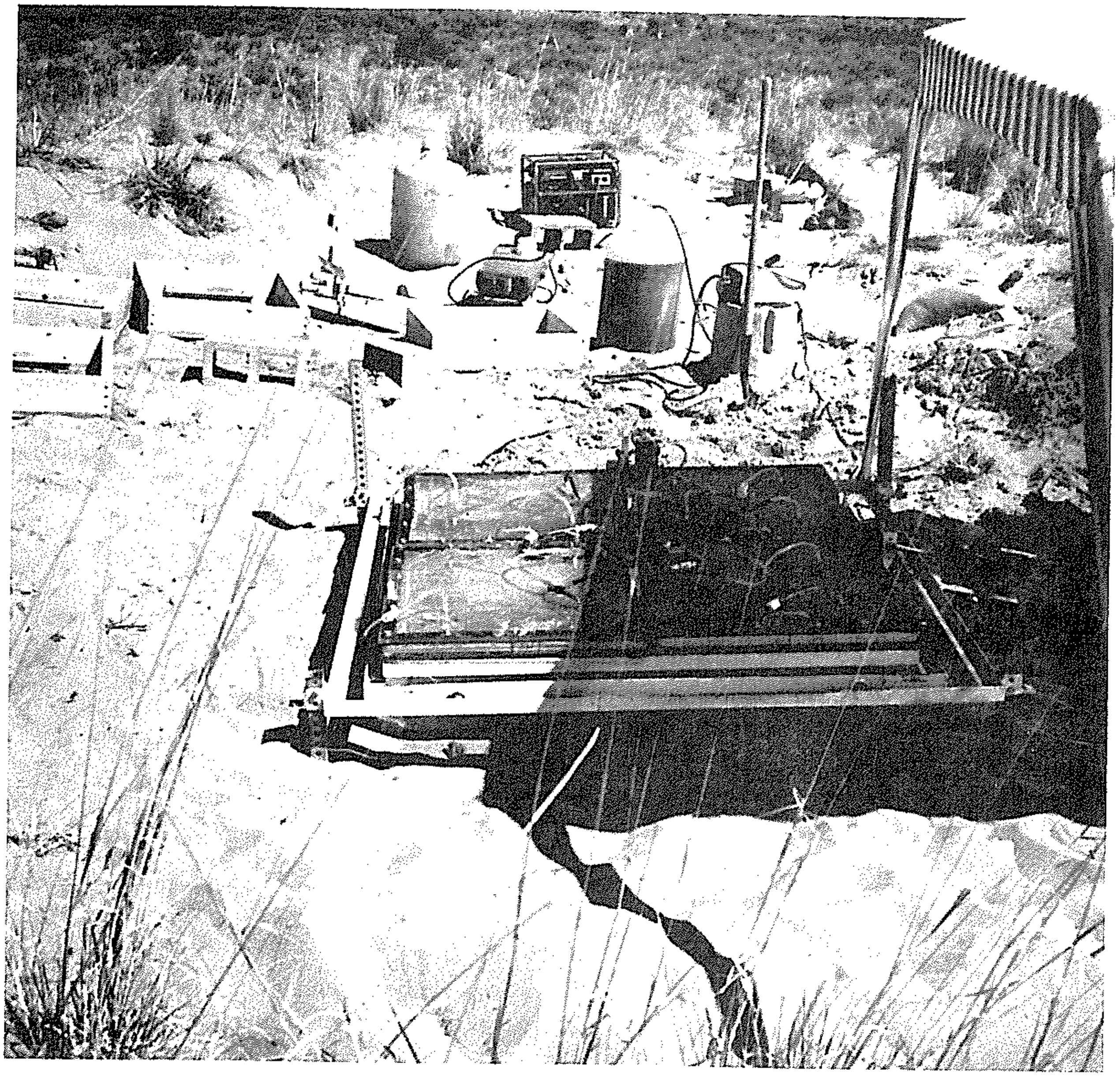

Figure 2. Sprinkler system on Sevilleta dune.

For each grade, we determined water retention curves with the hanging water column technique on 100 cm^3 dry samples that were taken in-situ from the lysimeters (Hendrickx 1990). The data were fitted with the RETC program of Van Genuchten et al. (1991). The saturated hydraulic conductivity was measured with the constant head method. Water-entry values were estimated gravimetrically from vertical capillary rise experiments (Glass et al. 1990). The sand was packed into a 10 cm diameter polyvinyl chloride (PVC) column consisting of twenty rings, each 1 cm high. The bottom part of this column was immersed into water until no further rise was observed. Next, the water content of each 1 cm layer was measured. After plotting the water contents versus the average height of the samples, water-entry values were determined, by definition, at the lowest water tension along the saturation portion of the wetting curve (Glass et al., 1989c). The sorptivities of the sand at the water entry value were determined with a tension infiltrometer (Ankeny et al., 1988).

There was some concern that the chemically bound water molecules of the perlite could be set free during drying of samples in the oven. Another concern was that perlite particles may still contain some water in their micropores after air-drying. However, tests revealed this was not the case: perlite sand behaves like quartz sand under those conditions.

Protocol for Lysimeter Experiments. The air-dried perlite and quartz sands were used to fill small (diameter 30 cm, height 50 cm) non-weighing lysimeters. Perlite was used also in a large lysimeter (diameter 100 cm, height 150 cm). The small lysimeters were designed after those employed by Glass et al. (1990) by stacking seven 10 cm high rings and filling them with sand. A funnel-extension-randomizer also based on the design of Glass et al. (1990) randomized the falling sand so that microlayering and grading due to particle size segregation was avoided. After filling, the top two layers were taken off and the surface of the column was smoothed. The weight of the two top layers helped to compact the underlying layers to a constant density of approximately 1.25 g/cm^3 for perlite sand and 1.54 g/cm^3 for quartz sand.

To study fingers with diameters larger than 30 cm, we used a large lysimeter (Fig. 3) consisting of 10 circular slabs, each 15 cm high. The inside diameter of the lysimeter was 100 cm. The slabs, with a gasket in-between, were bolted together so that a water- and air-tight connection was obtained. Forty-five outlets in the bottom prevented the air pressure from increasing during the infiltration experiments.

To fill the large lysimeter with perlite, we used a 1 m diameter funnel-extension-randomizer as described above. In addition, a 2-ton capacity crane was installed and a large quick-release loader was built to facilitate the filling process. The entire experimental setup involved two stories in our laboratory with a height of 8 meters.

Water Application. A sprinkler system was built by inserting eleven hundred drip needles in a sealed Plexiglass box at grid points 3 cm apart. The needles covered a circular area with 1.2 m diameter. The drop size from the needles (20G1, from Beckon and Dickinson) was measured as approximately 3 mm in diameter, which is close to the drop size of a storm rainfall in the United

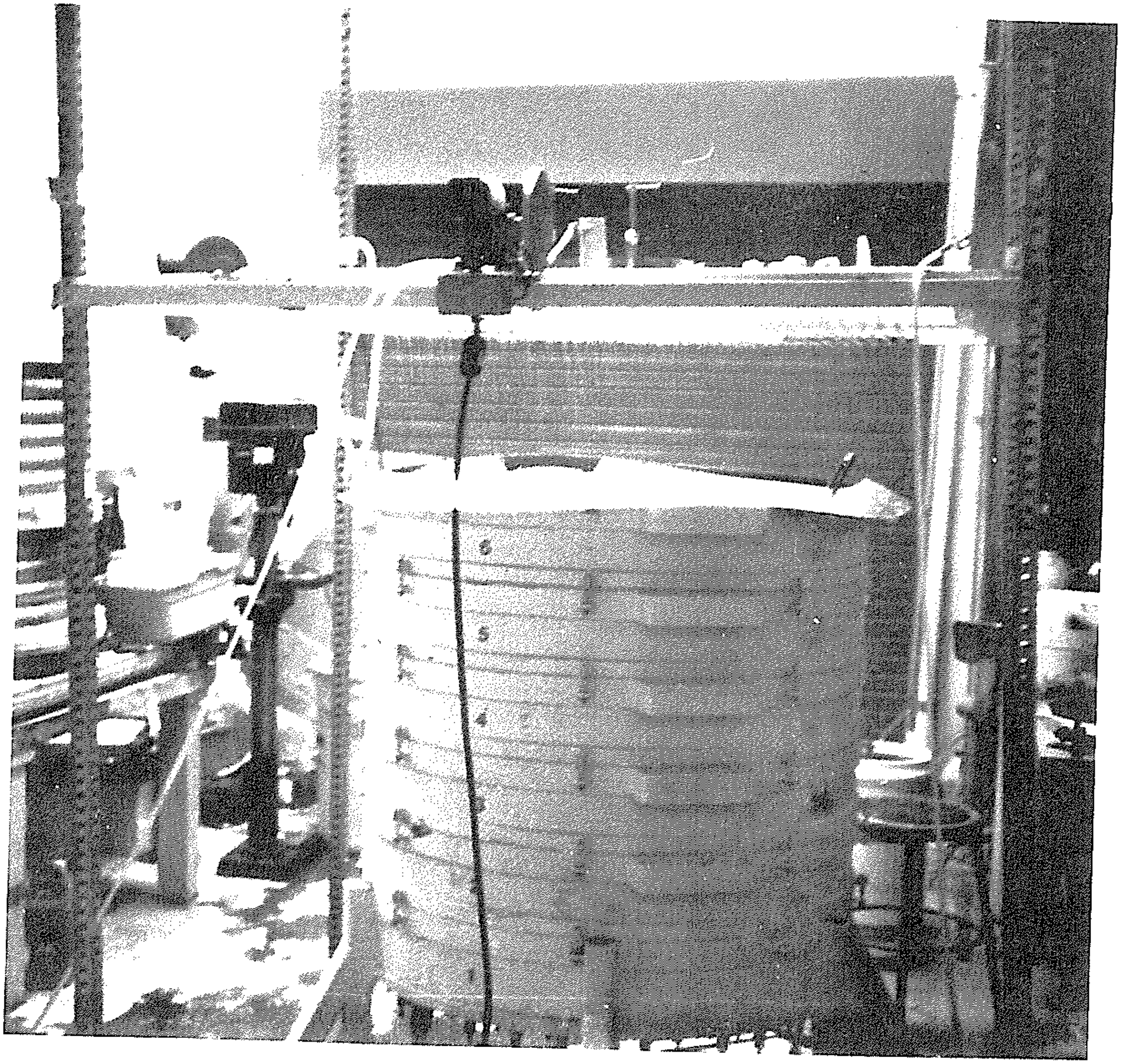

Figure 3. The large lysimeter with sprinkler system.

States (Bubenzer 1979; Carter et al. 1974; Laws and Parsons 1943). For low-flux experiments, smaller needles (30G1/2) were used to obtain a more uniform water distribution. Two variable-speed, gear-reduction motors were placed on two adjoining sides to control the north-south and east-west movements separately. The offsets in both directions could be adjusted in order to obtain a random distribution of the water without a repetitious pattern. A Masterflex pump and a syringe pump were used for accurate flow control. The water application rate could be adjusted from 0.05 cm/h to 36 cm/h.

The lysimeters were exposed to infiltration regimes representative of natural precipitation events in New Mexico and elsewhere in the world (Bubenzer 1979). The infiltration rates varied between 0.068 cm/h to 27 cm/h; the total amounts of applied water between 2.5 to 8 cm.

After water application, the lysimeters were excavated layer by layer to allow visual inspection of the flow pattern. Samples were taken within and outside the fingers to determine bulk density and water content. For each layer, we photographed the wetting pattern for later analysis of total wet area and finger diameter. One hundred and twelve experiments were conducted in initially dry sands.

RESULTS AND DISCUSSION

Field Experiments

Unstable wetting front theories in the early 1990's predicted the occurrence of instabilities in dry sand soils when water is applied at a rate less than the saturated hydraulic conductivity. However, we did not encounter instabilities in the sandy field soils at the Sevilleta dunes after water application and all wetting fronts appeared quite stable. Similar observations after heavy rainstorms in the fall of 1991 also indicated that the wetting fronts in the Sevilleta dunes were rather stable. These initial results indicated that existing wetting front theories were not yet adequate for the prediction of unstable wetting in New Mexico's soils. Therefore, we decided to pursue our studies in the laboratory under well-controlled conditions.

The 1991 summer field results were confirmed with well-controlled field experiments during the summer and fall of 1995. Again we only observed stable wetting fronts. For example, Figure 4 shows the stable front after an application of 12.5 cm with an intensity of 5 cm/h.

Lysimeter Experiments

Effect of Sand Grain Size on Finger Diameter. Visual inspection revealed that all experiments with infiltration rates between 0.3 and 12 cm/h gave rise to fingering. It is not possible to determine the total number of fingers due to the frequent merger of adjacent fingers. However, there were sufficient isolated fingers to allow the determination of finger diameter. The fingers that touched the edge of the column were not considered. Figs 4A-4D of Yao and Hendrickx (1996) show experimental results in perlite sand for different grain sizes at a depth of 30 cm under water application rates between 4.3 and 12.3 cm/h. It is evident that the finger diameter

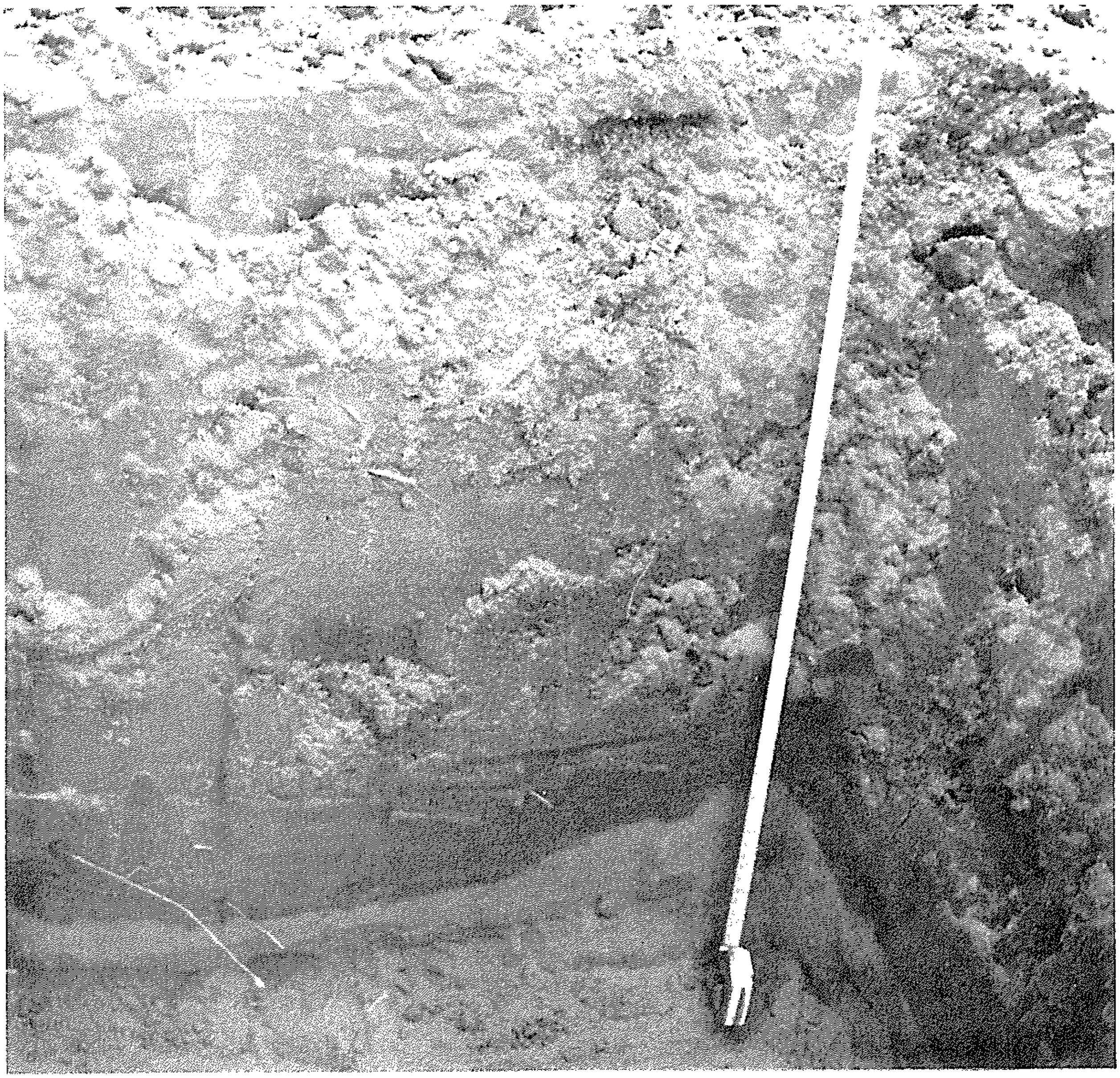

Figure 4. Stable wetting front at depth of 65 cm after application of 12.5 cm water at a rate of 5 cm/h.

increases with decreasing grain size, which verifies the following equation presented by Glass et al. (1991) under these relatively high infiltration rates.

In three-dimensional systems with dry soils, the finger diameter *d* of nearly saturated fingers can be calculated as:

$$d = 4.8\frac{S_w^2}{K_s(\theta_s - \theta_0)}[\frac{1}{1 - q/K_F}] \qquad (1)$$

where S_w is the sorptivity of the porous medium at water entry value, K_s is the saturated hydraulic conductivity, θ_s is the saturated water content, θ_0 is the initial water content, q is the infiltration rate and 4.8 is a coefficient derived from stability analysis (Glass et al. 1991). K_F is the hydraulic conductivity inside the finger, a value assumed to be close to K_s.

Effect of Decreasing Infiltration Rates on Finger Diameter. Figure 5A of Yao and Hendrickx (1996) presents both the finger diameters observed in the experiment in perlite sands and those predicted by Eq. (1). It is clear that the equation fails to provide a prediction of finger diameter at water infiltration rates below 1 cm/h. The two finger diameters of 30 cm at an infiltration rate of 0.2 cm/h indicate stable wetting because these fingers cover the entire horizontal cross section of the small lysimeters. The finger diameter behavior at decreasing infiltration rates observed in the 14-20 perlite sand (Fig. 5A of Yao and Hendrickx 1996) is similar to that observed in the quartz sand (Fig. 5A of Yao and Hendrickx 1996). The pictures of Fig. 6 of Yao and Hendrickx (1996) illustrate the relation between finger width and infiltration rate in 14-20 perlite and quartz sand. In perlite and quartz sand at rates of 9 and 8.6 cm/h, we observed finger diameters of 2.5 and 4 cm, respectively (Fig. 6A and B of Yao and Hendrickx 1996). At infiltration rates of 0.14 and 0.12 cm/h we observed large finger diameters that almost covered the entire column area (Figs. 6C and D of Yao and Hendrickx 1996). In quartz sand at a rate of 0.29 cm/h, we observed a finger diameter of 13 cm (Fig. 6E of Yao and Hendrickx 1996), while a rate of 0.13 cm resulted in a stable wetting front (Fig. 6F of Yao and Hendrickx 1996). The dry ring at the edge is a result of an edge cover used to prevent an edge effect. The above comparison between finger diameters observed in perlite and quartz sand demonstrates that the wetting processes in both sands are similar and are not being affected by their different physical properties.

These low-infiltration rate experiments increase our understanding of unstable wetting under natural conditions since they simulate the conditions at low-precipitation intensities. Figures 6A-6F of Yao and Hendrickx (1996) show a trend of widening finger diameters at lower infiltration rates. For the 30 cm diameter column, the finger diameters start to increase at rates below 1 cm/h (Figs. 6E and E of Yao and Hendrickx 1996) and stabilize at a rate of 0.12 cm/h (Figs. 6D and F of Yao and Hendrickx 1996). For fine grain size sand, the stabilization appears to start at a higher infiltration rate of 2 cm/h (Fig. 5 of Yao and Hendrickx 1996). The stabilization of wetting fronts at low-infiltration rates has not been reported as such although some investigators observed a change in wetting patterns. For example, Glass et al. (1989b) observed that under low-flow rates, the fingers tend to meander. This property allows fingers to touch each other, resulting in larger fingers. However, they still concluded that under low-infiltration rates finger diameters maintain their small size as suggested by Eq. (1).

Table 3 of Yao and Hendrickx (1996) shows the finger diameters predicted by Eq. (1) under intermediate flux conditions (> 1 cm/h). The predicted diameters increase when grain size becomes finer; sorptivity increases and saturated conductivity decreases. In general, Eq. (1) is able to predict finger diameters quite well for infiltration rates higher than 1 cm/h. However, the absolute accuracy may be off by a factor of 2.

These results demonstrate that wetting fronts stabilize under low- infiltration rates are representative of natural precipitation intensities. When gravity dominates the infiltration process at rates lower than the saturated hydraulic conductivity, fingers will occur with a diameter predicted by Eq. (1). However, when gravity plays little or no part and capillarity dominates, there is no mechanism to cause instability and, as a consequence, the wetting fronts will be stable and no fingers will form.

Prediction of Wetting Front Stability in Field Soils

One important objective of this study was to find criteria for the practitioner to predict whether unstable wetting could occur in a given field soil. Such a criterion can, for example, be used as a "red flag" in one-dimensional computer models that do not allow for unstable flow. Therefore, we used our lysimeter results as well as literature data to propose a procedure to analyze the stability of wetting fronts.

Three Stability Criteria. We can distinguish three characteristic infiltration regimes: one with high infiltration rates of the same order of magnitude as the saturated hydraulic conductivity, a condition in which viscous forces dominate the infiltration process; one with such low infiltration rates that capillary forces become dominant; and, one regime in which gravity forces play a major role to the extent that gravity-driven fingers may occur. Here we represent a stability criterion for each of these three regimes.

Stability Criterion for High Infiltration Rates: Theoretical analysis and experimental evidence have shown that the wetting front becomes stable if the infiltration rate exceeds the soil's saturated hydraulic conductivity. Therefore, the stability criterion for high infiltration rates becomes:

$$i \geq K_{sat} \qquad (2)$$

If this condition is met, one should check whether an increase of soil-air pressure may cause unstable wetting to occur in the field. For higher precipitation rates, criterion Eq. 2 indicates that unstable wetting is more likely to occur in coarse than in fine soils.

Stability Criterion for Low Infiltration Rates: Here we focus on wetting processes in which capillarity is the dominant force and gravity effects are negligible so that no gravity-driven instabilities can occur. One important parameter is the *gravitational characteristic time* t_{grav} as introduced by Philip (1969):

$$t_{grav} = \left(\frac{S_i}{K_i - K_o} \right)^2 \qquad (3)$$

where S_i and K_i are, respectively, the sorptivity and the hydraulic conductivity at the supply soil-water pressure, and K_o is the hydraulic conductivity at the initial soil-water pressure. Philip (1969) indicates that this characteristic time is somewhat qualitative as it represents only *the order of magnitude* at which the effect of gravity on infiltration equals that of capillarity. In order to use t_{grav} for the prediction of unstable wetting fronts, we will examine at which fraction of this characteristic time gravity forces are sufficiently reduced to prevent instabilities.

For infiltration into dry soil, we can replace $(K_i - K_o)$ in Eq. (3) by the infiltration rate, I, assuming that the conductivity of the wet soil is much higher than the dry soil and that the water flows under unit gradient. Eq. (3) is then rewritten as

$$t_{grav} = \left(\frac{S}{i} \right)^2 \qquad (4)$$

where S is the sorptivity measured at a slightly positive soil-water supply pressure for which substantial data are available.

The gravitational characteristic time, by itself, cannot predict instabilities. Therefore, an *infiltration characteristic time*, t_{infil}, is introduced that reflects the characteristics of the infiltration process,

$$t_{infil} = \frac{W}{i} \qquad (5)$$

where W is the total amount of water available for infiltration. For irrigation, t_{infil} is the duration of the infiltration event. It equals the total amount of irrigation water divided by the irrigation intensity. During storms, t_{infil} is the total amount of precipitation divided by the precipitation intensity. In principle, if $t_{infil} \ll t_{grav}$ gravity forces are not able to dominate the flow process and cause unstable wetting fronts. If $t_{infil} \gg t_{grav}$ gravity dominates the flow process and unstable wetting fronts may occur. The question that arises now is "what happens when t_{grav} and t_{infil} are of the same order of magnitude?" We examined our lysimeter data and data from other three-dimensional lysimeter experiments in homogeneous non-layered soils to determine the time where gravity causes instabilities by plotting, in Fig. 3 of Hendrickx and Yao (1996), t_{infil} against t_{grav}. Our data reveal that gravity effects were negligible and stable wetting fronts resulted for times less than $0.002t_{grav}$. The observation marked by a question mark, is an experiment that resulted in a wetting pattern not entirely stable nor entirely unstable. The experimental data reported by Selker et al. (1992) are all located in the lower left-hand corner of this figure, far away from the stable zone.

Based on the analysis of the experimental data presented in Fig. 3 of Hendrickx and Yao (1996), we establish that wetting fronts will be stable as long as

$$t_{infil} < 0.002\ t_{grav} \qquad \textbf{(6)}$$

The validity of this equation is limited to the well-sorted sands used in our experiments and those by Selker et al. (1992). Although the relationship needs more study, Eq. (4) seems, for now, a reasonable criterion. Inserting Eqs. (4) and (5) into Eq. (6), we find, after rearranging,

$$Wi < 0.002\ S^2 \qquad (7)$$

This stability criterion for low-infiltration rates seems quite useful for quick evaluation of the probability for stable wetting. However, application of this criterion "as is" may lead to erroneous results when low-infiltration rates change into intermediate ones. For example, for precipitation rates of 1 cm/hour criterion Eq. (6) leads to the conclusion that clay and loam soils which have typically a lower sorptivity than sand soils, are more susceptible for unstable wetting than sand soils. Although this conclusion by itself may be correct, theoretical analysis combined with experimental field and laboratory evidence indicates that unstable wetting in finer-textured soils results in finger diameters at least an order of magnitude larger than those found in coarse sands (Glass et al.1989b; Hendrickx and Yao 1996) and, thus, in a pseudo-stable wetting front. Therefore, an additional stability criterion is needed for intermediate infiltration rates.

Stability Criterion for Intermediate Infiltration Rates: In addition to an increase in finger diameter, we also observed, during our lysimeter experiments in finer-textured soils, an increase in the thickness of the distribution layer that feeds the fingers. Thus, a larger amount of water is needed to initiate fingered flow in a fine-textured soil than in a coarse-textured one. A plot of observed finger diameters against observed thicknesses of the distribution layer (Fig. 5 of Hendrickx and Yao 1996) reveals a strong correlation between the two variables. Therefore, it appears that Eq. (1) presented by Glass et al. (1989a) for prediction of finger diameter can also be used estimate the thickness of the distribution layer. Because the wetting front in the distribution layer is stable, Eq. (7) can provide an estimate of the **minimum** amount of water (W_{min}) that needed to infiltrate before unstable wetting fronts can form:

$$W_{\min} = d(\theta_d - \theta_o) \qquad \textbf{(8)}$$

where θ_d is the volumetric water content of the distribution layer. This criterion should be used whenever criterion Eq. (6) indicates that instabilities may develop, a condition most likely to occur under intermediate infiltration rates. For precipitation rates less than approximately 10% of the saturated hydraulic conductivity and $K_F \approx K_s$, the stability criterion for intermediate infiltration rates in dry non-layered soils becomes

$$W < 4.8 \frac{\theta_d}{\theta_s} \frac{S_W^2}{K_s} \qquad \textbf{(9)}$$

Using our lysimeter data, we find that in their well-sorted 14-20 and 40-60 sands, 0.1 and 1.5 cm of water, respectively, is needed for instabilities to develop. This indicates that even a very small amount of water may be sufficient to trigger unstable wetting fronts in these soils if applied at an appropriate rate.

Layered Soils. The stability criterion of Eq. (9) applies to dry homogeneous non-layered soils. A stability criterion for layered soils, where a fine less permeable layer overlays a coarse more permeable layer, can be expressed as

$$W_l < W_t + W_b \qquad \textbf{(10)}$$

where W_l is the minimum amount of water needed to trigger unstable flow in the layered system, W_t is the amount of water needed to wet the top layer to such an extent that at the layer interface, the water entry pressure of the bottom layer is exceeded, and W_b is the minimum amount of water needed to induce unstable wetting in the bottom layer. According to the theory (e.g., Hillel and Baker 1988), fingers form instantaneously at the interface and W_b equals zero. However, since experimental evidence (e.g., Hill and Parlange 1972) indicates that sometimes distribution layers develop at the interface, it seems reasonable to assume that W_b varies from zero to an amount calculated with Eq. (9). The amount of water needed to moisten the top layer, W_t, depends on the thickness of the top layer and the water-entry value of the bottom layer. More research is needed for the quantification of the minimum amount of water needed to trigger unstable wetting in layered soils.

<u>Case Study: The Sevilleta Dunes</u>: In the following case study of the Sevilleta dunes, we demonstrate in which manner precipitation and soil data can be used to predict unstable wetting in dry field soils. According to the theory and field observations in Dutch dune sands (Hendrickx and Dekker 1991), the Sevilleta dunes appear a prime site for the occurrence of unstable wetting since, at the beginning of the monsoon in July, a thick top layer of dry sand receives relatively large amounts of precipitation. Nevertheless, field observations after periods with precipitation and our field experiments did not reveal the characteristic wetting patterns of unstable wetting.

The occurrence of wetting front stability in the Sevilleta dunes can now be evaluated as follows. The soil-water pressure at water-entry from the wetting curve of Sevilleta dune sand is -15 cm,

S_w is 12 cm.hour$^{-1/2}$, and θ_d is approximately 0.11. Thus, stability criterion Eq. (9) indicates that at least 4.4 cm water is needed before instabilities can be triggered; this is reflected by the horizontal line in Fig. 8 of Hendrickx and Yao (1996). Next, we impose the stability criterion for high infiltration rates Eq. (2) by drawing a vertical line where the infiltration rate equals the saturated hydraulic conductivity of 43 cm/hour. Finally, we finish the graph by drawing the line representing stability criterion Eq. (5): $Wi<2.0$. The grey area in Fig. 8 of Hendrickx and Yao (1996) covers W-I combinations that will likely result in unstable wetting.

The precipitation regime is analyzed using standard rate-duration-frequency curves for point precipitation in order to obtain the total amount of precipitation, W, and its rate, I, for durations of 0.5, 1, 6, and 24 hours for return periods of 2, 10, and 100 years. Fig. 8 of Hendrickx and Yao (1996) shows the prevalent W-I combinations for the area. For example, for a 2-year return period, the total amount of precipitation in 0.5 hour is 2.5 cm with an intensity of 1.25 cm/hour; for a 100-year return period the total amount of precipitation in 6 hours is 6 cm with an intensity of 1 cm/hour. It is immediately clear from the graph that unstable wetting is not as common in the Sevilleta dunes as the theory would indicate. All precipitation events with a 2- and 10-year return period are located in the stable region of the graph. Even three precipitation events with a return period of 100 years fall into the stable region, indicating that the occurrence of conditions under which unstable wetting may occur in the Sevilleta dunes is relatively rare.

To verify the predicted unstable conditions in Fig. 8, of Hendrickx and Yao (1996) rather than waiting for unstable wetting to occur in the field, we conducted five laboratory experiments in a large lysimeter (diameter 1 m, depth 1.5 m) filled with Sevilleta dune sand following a procedure described by Yao and Hendrickx (1996). Three experiments were conducted at low-infiltration rates of 0.2, 0.1, and 0.09 cm/h with a total amount of applied water of 4.4, 4.7, and 8 cm, respectively. Two experiments were conducted at intermediate infiltration rates of 4.2 and 6.7 cm/h with a total amount of applied water of 6 and 8 cm, respectively. As shown in Fig. 8 of Hendrickx and Yao (1996), the low rate experiments were predicted to result in stable wetting, whereas the intermediate ones resulted in unstable wetting. Visually observing the wetting patterns in the large lysimeter seem to confirm our predictions on the basis of the three stability criteria. In Fig. 9 of Hendrickx and Yao (1996), the percent wetted area is plotted versus the depth. A steep decrease of wetted area with depth would indicate a stable wetting front, while a gradual decrease would indicate an unstable one. For example, the steep lines found during the application of 4.4 and 4.7 cm of water at rates of 0.2 and 0.1 cm/h, respectively, clearly indicate stable wetting. However, the gradual decrease of wetted area during the application of 8 cm of water at a rate of 6.7 cm/h indicates unstable wetting. Indeed, applying 8 cm at a rate of .09 cm/h resulted in a different relationship between wetted area and depth. Unfortunately, lack of dry sieved dune sand prevented us to obtain data to a greater depth, but the trend indicates that the much lower rate resulted in a more stable wetting front. Applying 6 cm of water at 4.2 cm/h seemed to create a wetting front that is neither stable nor unstable.

Details on the prediction of unstable wetting in field soils are presented by Hendrickx and Yao (1996).

CONCLUSIONS AND RECOMMENDATIONS

The most important conclusion of our experimental work is that the occurrence of unstable wetting not only depends on soil type, but also on the amount and intensity of the precipitation or applied irrigation water. This observation makes it possible to use readily available soil data and rainfall data (amount and intensity) to predict if unstable wetting will occur in a particular soil or not. Although the prediction method described in this report needs refinement, it certainly will suffice to distinguish between soil-climate combinations that are vulnerable for unstable wetting and those not vulnerable.

Our work shows that for the Sevilleta dunes in New Mexico, unstable wetting is an extreme event that may only occur once every fifty or one hundred years. Although this seems as a negligible probability, its effects may have a significant impact on groundwater quantity and/or quality. This is because unstable wetting only can be caused by relatively large amounts of rainfall (> 80mm). If preferential flow through fingers occurs under those conditions, it will lead to an increased recharge which is beneficial for the state's water supplies. On the other hand, the fingered flow also may cause an increased vulnerability for groundwater contamination where the soil surface or vadose zone has been polluted.

Although this study demonstrates that it is possible to understand the physics of unstable wetting and to some extent to predict its occurrence in the field, more work is needed for the extrapolation of our theoretical understanding toward water flow and contaminant movement through the field soils and deep vadose zones of New Mexico. With support of the National Science Foundation we are continuing our research efforts theoretically and in the field.

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