3011

FIELD MEASUREMENTS OF THE INFLUENCE OF ENTRAPPED AIR UPON PONDED INFILTRATION RATES

Jim Constantz and W.N. Herkelrath[1]

ABSTRACT

Field experiments were designed to measure the effects of air entrapment in the transmission zone upon infiltration rates in two soils. Infiltration rates were measured using a double-cap infiltrometer, and soil water contents were measured using time-domain reflectometry(TDR). Carbon dioxide flooding was used to reduce the amount of air entrapment in half of the infiltration experiments. TDR measurements indicated that CO_2 in the pore space rapidly dissolved into infiltrating water, resulting in complete water-saturation of the transmission zone for experiments preceded by CO_2 flooding. For a gravelly loam soil as steady infiltration rates were approached, the average volumetric water content in the top 35 cm of soil, as measured by TDR, was 0.38 cm^3cm^{-3} for control experiments and 0.43 cm^3cm^{-3} for CO_2 experiments. The average steady infiltration rate was 0.42 cm min^{-1} for the control experiments compared to 4.40 cm min^{-1} for the CO_2 experiments. For a sandy loam soil as steady infiltration rates were approached, the average volumetric water content in the top 35 cm of soil was 0.43 cm^3cm^{-3} for control experiments compared to 0.45 cm^3cm^{-3} for CO_2 experiments. The average final infiltration rate was 0.07 cm min^{-1} for the control experiments compared to 0.36 cm min^{-1} for the CO_2 experiments. These results suggest that at least some air resided in open channels or conduits within the soil, reducing the effective hydraulic conductivity of the transmission zone well below the saturated hydraulic conductivity of the soil.

[1]Hydrologist and Physicist, repectively; U.S. Geological Survey, 345 Middlefield Road, MS 496, Menlo Park, CA 94025 USA.

Encl. 3
8.3.1.2.2.1

Researchers have known for more than half a century that air residing in the pore space of soils reduces infiltration rates(Powers, 1934; Horton, 1940). Soil air influences infiltration through four processes: 1) air displacement out of the transmission zone, 2) air compression below the transmission zone, 3) air solution-dissolution within the transmission zone, 4) and air entrapment or retention within the transmission zone. One or all of these processes can influence infiltration rates, depending on boundary conditions and soil properties. Numerous workers have shown that air displacement can effect infiltration rates(e.g., Morel-Seytoux, 1973). During infiltration, air is displaced downward in advance of the wetting front(Wilson and Luthin, 1963), and sometimes, air is displaced upward through the infiltrating water(Adrian and Franzini, 1966). Air compression is extremely important where an impervious layer or water table exists near the soil surface(Adrian and Franzini, 1966; Jarret and Fritton, 1978; Linden and Dixon, 1973; Dixon and Linden, 1972; and Breckenridge, Jarret, and Hoover, 1978). Air solution into infiltrating water has been shown to be important when infiltration continues for an extended period(Bianchi and Haskell, 1966). However, air entrapment or retention in the transmission zone always influences the rate of water entry into soils(Christiansen, 1944). During infiltration, air is entrapped or retained in the soil's transmission zone as downward flowing water circumvents regions in the air-filled pore space(Bond and Collis-George, 1981). Air retained in the pore space of the transmission zone reduces the volume of water which can enter the soil over a given time period. In this study, experiments are designed to minimize the influence of air displacement, compression, and solution upon infiltration rates, in order to isolate and measure the influence of air entrapment in the transmission zone upon infiltration.

A physically based infiltration equation is useful in predicting the effects of air in the transmission zone upon infiltration rates. Green and Ampt(1911) derived an equation to describe vertical downward movement of water in a soil under ponded conditions. Their equation is based on the assumptions that water travels down into the soil with a sharp wetting front and that the transmission zone above the wetting front has a uniform water content. If the depth of ponding is h, the Green and Ampt equation can be represented by the following expression:

$$\underline{I} = K(\theta_t)[(h-\psi_w)/z] + K(\theta_t) \qquad (1)$$

where $\underline{I}$ is the infiltration rate, $K(\theta_t)$ is the effective hydraulic conductivity in the transmission zone, ψ_w is the matric potential at the wetting front, and z is the depth to the wetting front. Since $K(\theta_t)$ depends strongly upon the volumetric water content of the transmission zone, θ_t, the infiltration rate can be expected to be strongly influenced by entrapped air in the transmission zone. Furthermore, as z becomes large relative to the value for $h-\psi_w$, $\underline{I}$ approaches $K(\theta_t)$, and the influence of entrapped air upon $K(\theta_t)$ can be estimated if the value of θ_t is known.

Slack(1978) suggests that a soil has a fillable porosity available to infiltrating water, depending on the application rate and initial soil moisture conditions. This may imply that there is a single value for $K(\theta_t)$ for a given infiltration event, but the value would vary somewhat for different situations. As a first approximation, he indicates that for most fine-textured agricultural soils, the volumetric water content of the transmission zone, θ_t, is about 90% of the saturated volumetric water content, θ_s. Furthermore, the primary location of air within the pore space may strongly influence of the conductivity of the transmission zone. If air resides entirely in dead-end pore spaces, then $K(\theta_t)$ remains close to the saturated hydraulic conductivity, K_s, of the soil. However, if air blocks channels which are continuous conduits for transmission of water deeper into the soil when filled with water, then $K(\theta_t)$ is much less than K_s. Previous results indicate that $K(\theta_t)$ is lower than K_s(Bower, 1966). Based on the limited data available which relates infiltration rates to hydraulic conductivities, Bower(1969) concluded that $K(\theta_t)$ may range from $.4K_s$ to $.6K_s$.

To reduce the amount of entrapped air during infiltration, CO_2 has been injected into soils prior to tests. CO_2 is readily soluble in water and a pretreatment of CO_2 often results in complete saturation of the soil. In vented laboratory columns, Jarrett and Hoover(1985) reported at least a 50% increase in infiltration rates following CO_2 injections. Stephens and others(1983a, 1983b) reported large increases in borehole infiltration and air-entry permeameter experiment after CO_2 flooding. Furthermore, they found that infiltration rates, measured after CO_2 flooding, corresponded well with predicted K_s values.

In the present study, the infiltration rate and the volumetric water content of the transmission zone were simultaneously measured during a series of ponded infiltration experiments in which a pretreatment of CO_2 was used before half of the experiments. This was accomplished by using covered infiltrometers fitted with time-domain reflectometry probes for soil moisture content determinations. This experimental technique permitted: 1) measurements of the volume of air present in the transmission zone during infiltration, 2) measurements of the effect of this air upon infiltration rates, and 3) estimates of the reduction in the effective hydraulic conductivity due to air in the transmission zone.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

A double-cap infiltrometer was used to measure the ponded infiltration rates at two field sites. A detailed description of the double-cap infiltrometer is given by Constantz(1983). Essentially, the double-cap infiltrometer(DCI) is a scaled down double-ring infiltrometer which has a permanent drive plate attached to the upper rims of two nested cylinders. The DCI is driven about 10cm into the soil and equal water heads are established in the inner and outer cylinders using constant-head reservoirs. If equal heads are carefully maintained, water flow below the outer cylinder inhibits radial flow from occuring below the inner cylinder. The cumulative outflow from the reservoir is recorded as a function of time in order to estimate infiltration rates and cumulative infiltration.

Time-domain reflectrometry(TDR) was used to measure the volumetric water content in the soil beneath the inner cylinder of the DCI. A detailed description of TDR is given by Topp and others(1982). Briefly, TDR measures the apparent dielectric constant in the region between a pair of thin metal rods which have been inserted into the soil. The apparent dielectric constant can be related empirically to the soil's volumetric water content. In these experiments, a pair of 40cm long, 0.3cm diameter stainless steel rods, spaced

2.5cm apart, were driven 35cm into the soil at the center of each DCI. In this configuration, the TDR probe measured the average volumetric water content in the top 35 cm of soil. Figure 1 gives a cross-section of the DCI and TDR assembly with water ponding on the soil surface(the water supply reservoirs are not shown).

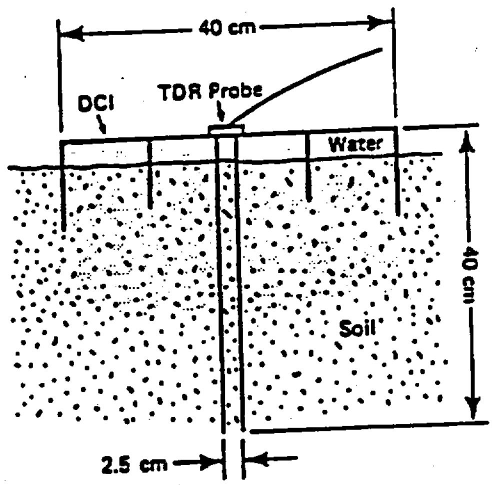

Figure 1. The double-cap infiltrometer(DCI) with the time domain reflectometry(TDR) probe inserted through the center of the inner cylinder.

Soil sites were choosen to avoid air compression during the ponded infiltration runs. Two soil sites were selected with well drained, highly porous structures which lacked any signs of erosion due to runoff. The water table was deep(>10m) and there were no impervious layers within 1m of the soil surface. The first site was located on Monte Bello Ridge in the Santa Cruz Mountain Range of Central California in a mature vineyard on Los Gatos Gravelly Loam. The soil at Site #1 is disced periodically, leaving the surface soil lose and free of vegetation. The second test site was located in the foothills to the east of Monte Bello Ridge supporting native oaks and mixed annual grasses. The soil at Site #2 is a Diablo Sandy Loam which contained desiccation cracks under a mat of dry grass at the initiation of tests. Table 1 gives several pertinent properties determined for both soils.

TABLE 1. SOME PERTINENT PROPERTIES OF THE SOILS AT EACH SITE

	Site #1	Site #2
Soil Series	Los Gatos	Diablo
Porosity	.43	.45
Gravel	18%	-
Sand	35%	62%
Silt	37%	20%
Clay	10%	18%
Class	gravelly loam	sandy loam

At both sites, two DCI units were driven about 10cm into the soil with approximately a 2m spacing between the units. To determine the effects of the TDR probes upon the infiltration rates, a preliminary infiltration experiment was run before inserting of the probes at each site. The DCI units were kept in place at the same location throughout each series of tests. Prior to each test, the soil was permitted to drain back to a specific moisture content within ±.03 cm^3cm^{-3}. Infiltration experiments were performed at about one week intervals, alternating between runs where a pretreatment of CO_2 was used and runs where no pretreatment was used. The CO_2 was injected through the inflow ports on the DCI (with the water manometers plugged) at 1.5 to 2.0 l/min for approximately 25 minutes. During experimental runs, the cumulative inflow into the inner cylinder was recorded after a constant ponding depth of 10 cm was established. The cumulative infiltration was calculated by subtracting the volume of water ponded in the inner cylinder from the cumulative inflow. The infiltration rate into the soil below the inner cylinder was recorded until a constant rate was approached or until the reservoir's water supply was exhausted. Tap water was used which had an electrical conductivity of .05 mmho of electrical conductivity, derived mainly from calcium, magnesium, and bicarbonate ions. Tap water was poured into the reservoirs a week before each test, to allow the gases in the water to equilibrate with the atmosphere prior to each infiltration run.

RESULTS AND DISCUSSION

The use of any infiltrometer represents what has been called "fractional wetting infiltration"(Philip, 1983). Fractional wetting infiltration is simply the wetting of only a portion of the soil surfaces; it occurs in several natural and man-made situations (drip or furrow irrigation, for example). When fractional wetting infiltration occurs where no air-impermeable layer exists near the soil surface, the influence of air compression and air displacement are probably negligible compared to the influence of air entrapment. For these experiments, this contention is supported by two observations. First, during control runs(no CO_2 treatment), air bubbles which were displaced vertically upward after ponding could be observed through the clear resin casing of the TDR probes. The volume of displaced air was small, amounting to no more than approximately 5 cm^3 during the entire ponded infiltration period. Second, as CO_2 was injected into the soil at 1.5 to 2.0 l min^{-1}, the resulting back-pressure at the soil surface was only 2 to 3 cm of water pressure. These observations indicate that these soils are extremely permeable to gas flow and do not contain confining layers near the surface. This suggests that neither air displacement or compression retarded infiltration below the DCI during these experiments.

As stated in the previous section, a preliminary experiment at each location was run without the TDR probes in place. Comparison of preliminary and all subsequent experimental results indicated that insertion of probes altered the soil sufficiently to cause the infiltration rates to increase as much as two or three-fold after probe insertion. However, though the absolute magnitudes of the results reported here were increased by probe insertion, the the relative magnitude of the control versus CO_2 infiltration rates were probably not affected.

Originally, it was hoped that the close spacing of the DCI units(~2m) would reduce the impact of spatial variability upon the experiments. At Site #1, the close spacing resulted in similar infiltration rates and cumulative infiltration at both locations. However, at Site #2, the infiltration properties at the two locations were sufficiently different to warrant subdividing the site into a north and south site, Site #2N and Site #2S. At Site #1, four experiments at each location were combined for analysis of results, while at Site #2N and Site #2S, six runs at each site were analyzed separately.

Figures 2,3, and 4 show cumulative infiltration versus time for all of the experimental runs (except the preliminary runs without TDR) at Sites #1, #2N, and #2S, respectively. Examination of all three figures indicates that the differences between control and CO_2 experiments are large compared to the variability measured within either treatment. For example, Figure 3 shows that Site #2N had more than 20 cm of cumulative infiltration after 30 minutes for all of the CO_2 treatments, while having less than 12 cm of cumulative infiltration for any of the control treatments after the same time duration. Figures 2 and 4 show similar differences for cumulative infiltration comparing the CO_2 and control treatment, suggesting that air which is entrapped or retained in the transmission zone during ponded infiltration greatly reduces water intake over a given time period.

Table 2 gives the results from all three sites for the CO_2 experiments compared to the control experiments. The table lists the initial and final volumetric water contents, the volume percent of air in the transmission zone, and the final infiltration rate for each case. As noted in the table, experimental runs were always initiated at nearly the same water content for a given site. The final water content in the transmission zone was reduced significantly in the control experiments by air entrapment, while the transmission zone was virtually water-saturated during the CO_2 experiments. Based on the porosity values reported in Table 1, the gravelly loam soil retained 12% air(by volume) in the transmission zone at the end of the control experiments. The sandy loam retained 4% air in the transmission zone at the end of the control experiments. The variability of the final water contents measured for a given experimental condition was about the same as the resolution of the TDR (±.005 cm^3cm^{-3}). Finally, the table gives the final ponded infiltration rates for control versus CO_2 experiments measured at each site. The results indicate that 12% air retention caused about a ten fold-decrease in the infiltration rate measured at Site #1, and 4% air retention caused at least a five-fold decrease in the infiltration rate measured at Site #2.

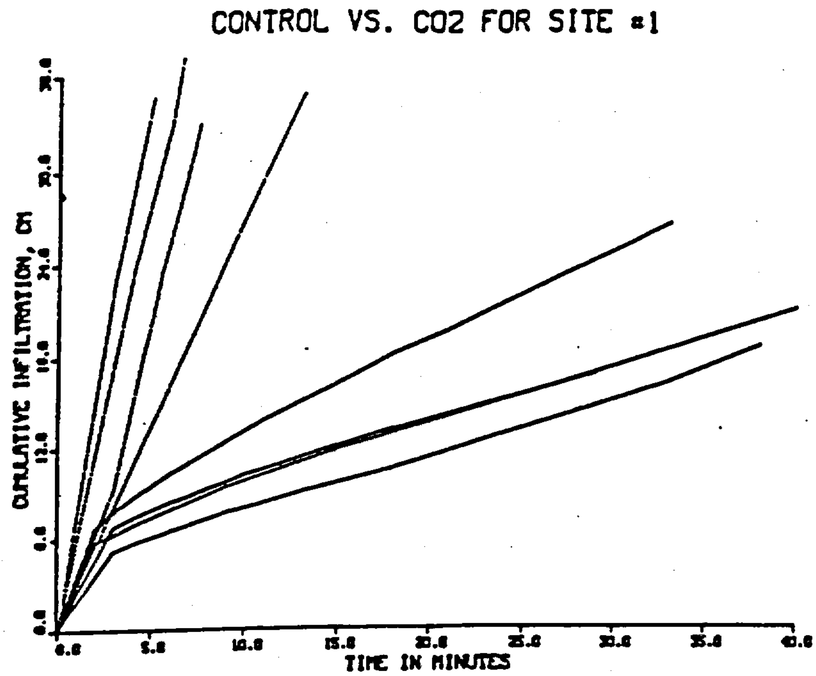

Figure 2. Cumulative infiltration for control runs(solid curves) and for CO_2 runs(dotted curves) at Site #1 on a Los Gatos Gravelly Loam.

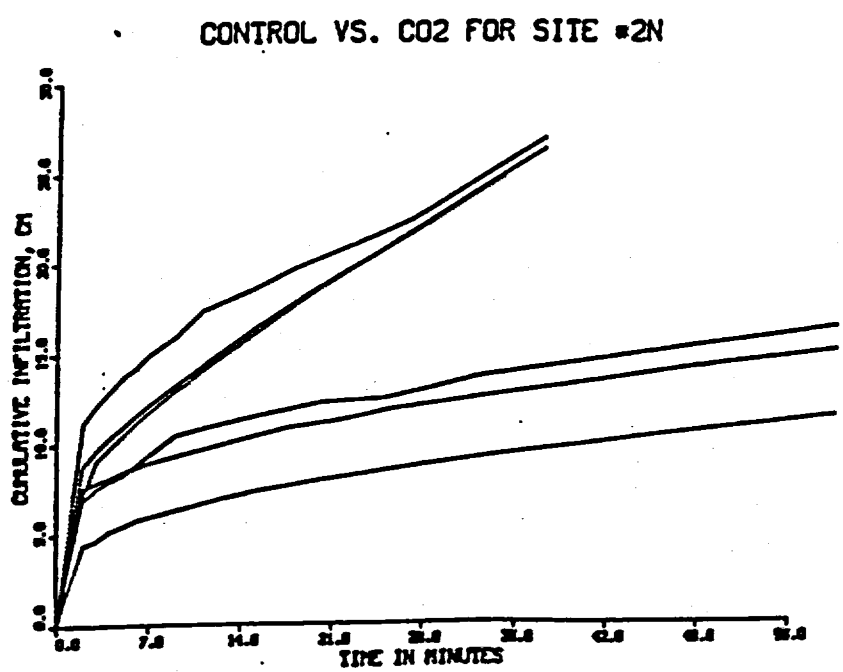

Figure 3 - Cumulative infiltration for control runs(solid curves) and for CO_2 runs(dotted curves) at Site #2N on a Diablo Sandy Loam.

CONTROL VS. CO2 FOR SITE #2S

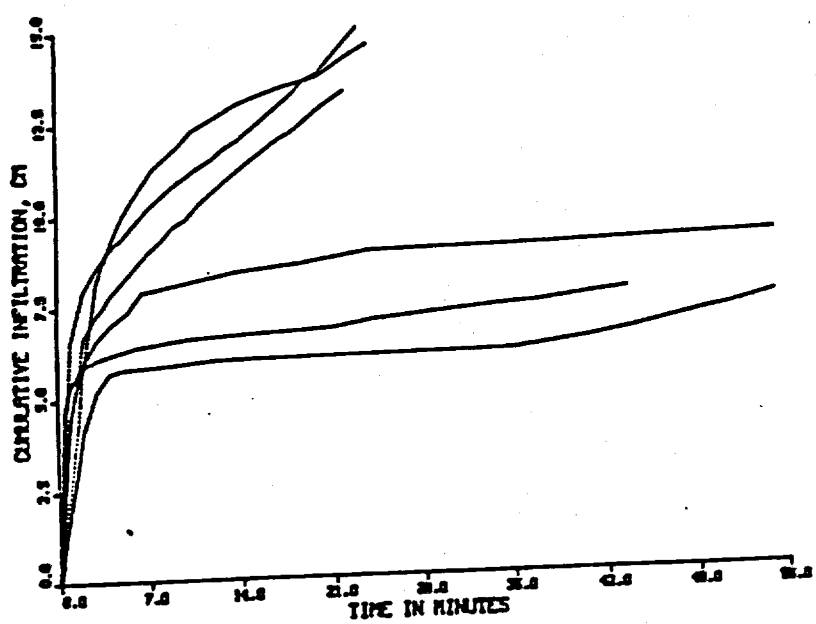

Figure 4 - Cumulative infiltration for control runs(solid curves) and for CO_2 runs(dotted curves) at Site #2S on a Diablo Sandy Loam.

TABLE 2. VOLUMETRIC WATER CONTENT, $\theta(cm^3cm^{-3})$, AIR VOLUME IN THE TRANSMISSION ZONE, v(%), AND FINAL INFILTRATION RATES, I, (cm/min) FOR CONTROL AND CO_2 RUNS, WHERE θ_i AND θ_f REPRESENT INITIAL AND FINAL WATER CONTENTS.

	Site #1		Site #2N		Site #2S	
	Control	CO_2	Control	CO_2	Control	CO_2
Runs	4	4	3	3	3	3
θ_i	.21±.03	.20±.03	.30±.03	.31±.01	.31±.02	.31±.02
θ_f	.38±.005	.43±.005	.43±.005	.45±.005	.43±.005	.45±.005
v	12%	<1%	4%	<1%	4%	<1%
I	.42±.09	4.4±1.1	.09±.004	.42±.08	.05±.03	.30±.07

Based on the Green and Ampt model, air in the transmission zone decreases the effective hydraulic conductivity in the transmission zone, $K(\theta_t)$, resulting in reductions in infiltration rates. Since the transmission zone was saturated during the CO_2 experiments, $K(\theta_t)$ for the CO_2 experiments represents a good approximation of K_s for the soil. Furthermore, as I approached steady state at large values of z, $K(\theta_t)$ approached the final value for I. Therefore, the final value for I during the CO_2 runs is a reasonable approximation of K_s and the final value of I for the control runs is a reasonable approximation of $K(\theta_t)$ for these soils. Based on this analysis using the Green and Ampt model, the results of this study indicate that air in the transmission zone caused $K(\theta_t)$ to be reduced to about $.1K_s$ for Site #1 and $.2K_s$ for Site #2. These differences between $K(\theta_t)$ and K_s are even greater than those reported by Bower(1966). In addition, since air in the transmission zone reduced $K(\theta_t)$ so sharply in these soils, these results imply that at least some air resided in open channels or continuous conduits, rather than dead-end pore spaces.

In conclusion, these experiments demonstrate that using TDR with a DCI unit in conjunction with CO_2 injections is an effective technique for examining the influence or air in the transmission zone upon ponded infiltration rates. The results indicate that infiltration rates are strongly influenced by air in the transmission zone, and that infiltration models which include a term for hydraulic conductivity should use a value as much as tenfold less than K_s. Furthermore, if a technique can be developed which controls the volume of air in the soil during infiltration experiments, a range of values for $K(\theta_t)$ can be generated near saturation for a given soil.

REFERENCES CITED

Adrean, D.D. and J.B. Franzini. 1966. Impedance to infiltration by Pressure build-up ahead of the wetting front. J Geoph. Res. 71(24):5857-5862.

Bianchi, W.C. and E.E. Haskell. 1966. Air in the vadose zone as it affects water movement beneath a recharge basin. Water Res. Res. 2:315-322.

Bond, W.J. and N. Collis-George. 1981. Ponded infiltration into simple soil systems: I. The saturation and transition zones in the moisture content profile. Soil Sci. 131:202-209.

Bower, H. 1966. Rapid field Measurement of Air Entry values and hydraulic conductivity as significant parameters in flow systems analysis. Water Res. Res. 2:729-738.

Bower, H. 1969. Infiltration of water into nonuniform soils. ASCE 95(IR4):451-461.

Breckenridge, R.P., A.R. Jarret, and J.R. Hoover. 1978. Runoff reduction by venting with shallow subsurface drainage. ASAE 28(2):476-479.

Christiansen, J.E. 1944. Effects of entrapped air upon the permeability of soils. Soil Sc. 58:355-365.

Constantz, J. 1983. Adequacy of a compact double-cap infiltrometer compared to the ASTM double-ring infiltrometer. In Advances in Infiltration. D. Slack ed. ASAE, St. Joseph, Mich.

Dixon, R.M. and D.R. Linden. 1972. Soil air pressure and water infiltration under border irrigation. Soil Sc. Soc. Am. Proc. 36:948-953.

Horton, R.E. 1940. An approach toward a physical interpretation of infiltration-capacity. Soil Sc. Soc. Am. Proc. 5:399-417.

Jarrett, A.R. and D.D. Fritton. 1978. Effects of entrapped soil air on infiltration. ASAE 21:901-906.

Jarrett, A.R. and J.R. Hoover. 1985. Evaluating the effect of increased concentrations of CO_2 on infiltration rate. ASAE 28:179-182.

Lewis, M.R. and W.R. Powers. 1938. A study of factors affecting infiltration. Soil Sc. Soc. Am. Proc. 3:334-339.

Linden, D.R. and R.M. Dixon. 1973. Infiltration and water table effects of soil air pressure under border irrigation. Soil Sc. Soc. Am. Proc. 37:94-98.

Morel-Seytoux, H.J. 1973. Two-phase flow in porous media. In Advances in Hdydroscience, V.T. Chow, ed., 9:119-202.

Powers, W.L. 1934. Soil water movement as affected by confined air. J. Agr. Res. 49:1125-1133.

Slack, D.C. 1978. Predicting ponding under moving irrigatin systems. ASCE 104(IR4)446-451.

Stephens, D.B., K. Lambert, and D. Watson. 1983. Influence of Entrapped Air on Field Determination of Hydraulic Properties in the Vadose Zone. In Characterization and Monitoring of the Vadose(Unsaturated) Zone. D.M. Nielsen and M. Curl, eds. National Water Well Association, Worthington, OH.

Stephens, D.B., S. Tyler, K. Lambert, and S. Yates. 1983. Field experiments to determine saturated hydraulic conductivity in the vadoze zone. In The Role of the Unsaturated Zone in Radioactive and Hazardous Waste Disposal, J.W. Mercer, ed. Ann Arbor Science, Ann Arbor, Mich.

Topp, G.C., J.L. Davis and A.P. Annan. 1982. Electromagnetic determination of soil water content using TDR: II. Evaluation of installation and configuration of parallel transmission lines. Soil Sci. Soc. Am. Proc. 46:678-684.

Wilson, L.G. and J.N. Luthin. 1963. Effect of air flow ahead of the wetting front on infiltration. Soil Sc. 92:136-143.