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Infiltration and Water Table Effects of Soil Air Pressure Under Border Irrigation[1]

D. R. LINDEN AND R. M. DIXON[2]

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ABSTRACT

Field studies investigated infiltration and water table responses to soil air pressure under border irrigation. The water table was depressed in the center and elevated near the edge of a border strip in response to differences in soil air pressure during an irrigation. Also, water table elevations indicated that infiltration and subsequent groundwater recharge rates were greater in the vicinity of a border dike than at the center of the border. An infiltration response was measured by: (i) venting soil air during an actual irrigation and (ii) pumping air into the soil during simulated irrigations. An actual border irrigation experiment indicated that displaced soil air pressure h_a (expressed as equivalent heads of water) rising to values of 13 to 24 cm of H_2O reduced infiltration over a 70-min period from 14.3 to 10.3 cm. Simulated border irrigation experiments indicated that displaced soil air pressure h_a must exceed surface head h_s to have significant influence on infiltration and that the first few minutes of infiltration may determine the h_a-to-h_s relationship and subsequent infiltration effects. In the simulated irrigations with h_s = 6.3 cm, total infiltration in 1 hour was 6.0 and 1.5 cm when h_a was 0 and 10 cm of H_2O, respectively. Infiltration was only slightly reduced during the first 5 min when h_a was 5 cm of H_2O.

Additional Index Words: soil gas pressure potential.

SOIL WATER MOVEMENT theory often neglects air pressure effects by assuming that air is displaced without significant pressure gradients and that the displaced air is free to escape from the system (9). However, border irrigation creates conditions where the lateral air escape route is long and tortuous, and air pressures greater than atmospheric develop. An expansion of water movement theory to include soil air pressure effects is essential to a full understanding of infiltration. Several workers using laboratory columns have attempted to measure and explain the effects that displaced soil air pressure may have on infiltration (4, 5, 7, 8, 10, 11). None of these studies, however, were conducted in the field where the boundary conditions at the edges and bottom of the flow system are not rigidly controlled, and none were on undisturbed soils where a system of macropores can drastically influence infiltration. The macropore system will be most affected by the small air pressures observed in the field. Dixon (3) points out that a displaced soil air pressure of only 3 cm of water can theoretically eliminate the large infiltration contribution of pores greater than 1 mm in diameter. In an earlier paper we reported on the time and spatial distribution of soil air pressure under border irrigation (2). We reported that soil air pressure h_a increased at a decreasing rate during the irrigation until the surface or ponded water subsided and that h_a was less in the vicinity of a border dike than at the center of the border. Soil air pressure also decreased in the downslope direction. We (2) also reported that an h_a (expressed as an equivalent head of water) rising to a maximum of 18 cm of H_2O reduced infiltration over a 200-min period from 15 to 10 cm. This paper further clarifies the nature of the soil air pressure effect on infiltration.

Soil air pressure can also affect a water table. Bianchi and Haskell (1) reported an apparent water table rise in jetted observation wells in response to soil air pressure beneath water spreading basins. This paper also presents some field results on the redistribution of ground water during border irrigation, that reflect real soil and boundary conditions.

MATERIALS AND METHODS

Three experiments were conducted to determine the infiltration and water table effects of soil air pressure. The first experiment sought water table responses and indirect information on the infiltration process by observing the water table during a border irrigation of alfalfa. The soil was a Dia loam and earthworms were abundant. Soil air pressure and water table elevation were measured with the apparatus shown schematically in Fig. 1. Air pressure was sensed over a large volume of soil to prevent the sensing point from being isolated by water from the main body of displaced soil air. Water level inside a piezometer relative to the initial position of 195 cm below the soil surface was determined with the bubbling apparatus. The peizometer did not serve as a vent for displaced soil air since it had no perforations above the water table. Thus it measured the resultant hydraulic head H. The water table is defined here as the locus of points in the soil water of zero capillary pressure. By this definition the soil water pressure at the water table always equals the soil air pressure. When soil air pressure h_a exceeded ambient atmospheric pressure, the water table position was found by subtracting the observed soil air pressure h_a from the resultant hydraulic head H. Water table responses were compared in the center and near the edge of a 70-m-wide border strip.

In the second experiment displaced soil air was vented to isolate the infiltration effect of soil air pressure. Infiltration was measured by a 1-m-square, variable head, border infiltrometer (2) during an actual irrigation. The experiment was conducted on a silty clay loam soil with border strips 30 by 180 m. Infiltration was measured at two side-by-side sites 10 m apart and 10 m from the nearest border dike. Displaced soil air pressure was held near atmospheric at one of the sites with apparatus similar to that shown schematically in Fig. 2. The

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[2] Soil Scientists, USDA, Univ. of Nevada, Reno, Nevada 89507.

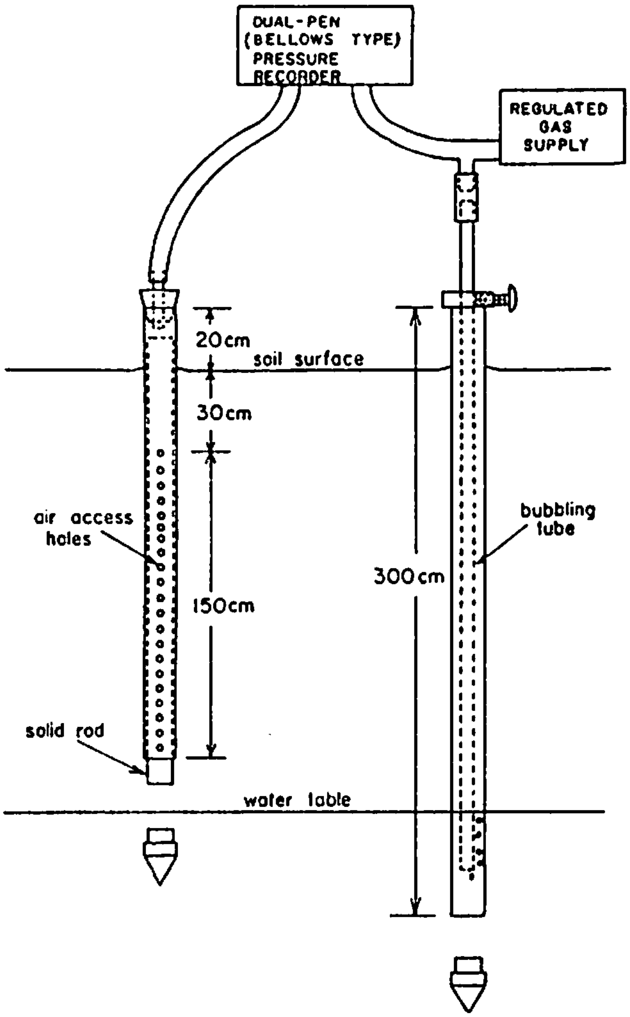

Fig. 1—Soil air pressure sensing apparatus and bubbling device for determining water table elevation changes during border irrigation.

pressure pump (f) was reversed to pump air out of the soil. The adjustable valve (g) was eliminated, and the bypass valve (e) was adjusted manually to keep the displaced soil air pressure near atmospheric. The connection between the pumping system and the auger hole (i) was replaced with a 43-cm-diameter cylinder driven into the soil over the auger hole. Air was pumped from the soil system through eight interconnected auger holes arranged in a 3-m-diameter circle around the infiltrometer. At the second site soil air was not vented to allow its pressure to rise naturally. During a subsequent irrigation, venting treatments were reversed between sites to isolate soil profile differences.

In the third experiment, soil air pressure was artificially created under simulated border irrigation on an East Fork loam soil. The border infiltrometer measured infiltration in the center square meter of a square area 3 m on a side. The air pump and pressure control device were arranged as in Fig. 2. Air was pumped into the soil through four interconnected auger holes arranged in a 2-m-diameter circle. Air pressure was controlled at the desired level by opening and closing a vent valve with a solenoid mechanism. The solenoid was activated by a float switch located in a manometer connected to the soil air pressure access tube. In contrast to the variable head of the field experiment the surface head h_s was controlled for all of the runs. Surface head h_s rose rapidly to a maximum of 6.3 cm in about 2 min and remained constant thereafter. Replicated runs were made with constant soil air pressures of 0, 5, and 10 cm of H_2O and a rising air pressure which reached a maximum of 10 cm of H_2O at 10 min and remained constant thereafter.

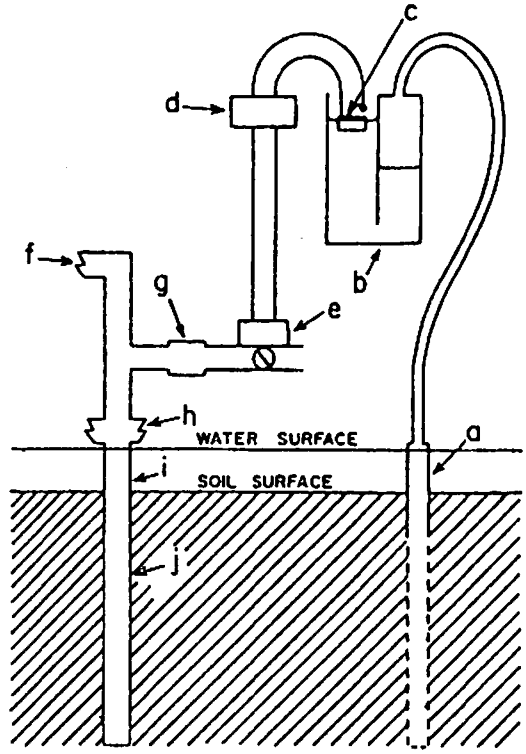

Fig. 2—Displaced soil air pumping apparatus: a, air pressure access tube; b, water manometer; c, float switch; d, power supply and isolation relay; e, solenoid operated valve; f, to high volume air pump (vacuum cleaner); g, adjustable check valve; h, T connection; i, pipe connection; j, 3.25 cm diameter auger hole.

RESULTS AND DISCUSSION

Shallow water tables responded to soil air pressure during border irrigation. Displaced soil air pressure h_a caused a depression (lowering) of the water table Z_w in the border center and an elevation near the edge as shown in Fig. 3. Zero time in Fig. 3 is the time the surface water front passed the piezometer. This water table response was caused by the addition of h_a to the initial piezometric head H. Shortly after the irrigation began h_a increased as did H, and as H was greater in the border center than near the edge, ground water was flowing away from the border center. This lateral difference in H slowly decreased while the difference in h_a remained nearly constant until about the time the head gates were closed (140 min) indicating that the ground water was being redistributed.

Air pressure also affects the water table by decreasing the volume of air bubbles entrapped below the water surface (6). This effect would cause the water table to decline as soil air pressure increased. It would thus be increasing the decline in the border center and decreasing the rise next to the border dike. The air bubble compression is probably a small factor in comparison to the ground water flow because the volume of entrapped air is small, as evidenced by simultaneous increase of water table elevation and air pressure in the vicinity of the border dike.

Indirect evidence that infiltration was greater near the border dike was obtained by considering differences in ground water recharge rates. This difference was analyzed by considering differences in piezometric head of the

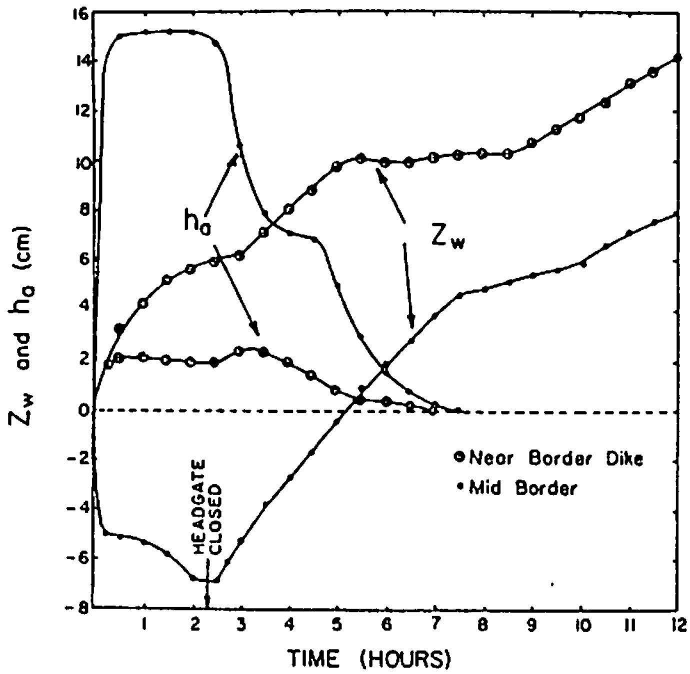

Fig. 3—Displaced soil air pressure h_a and water table elevation Z_w as functions of the time during and following a border irrigation for sites near a border dike and midborder. Z_w is relative to an initial position of 195 cm below the soil surface.

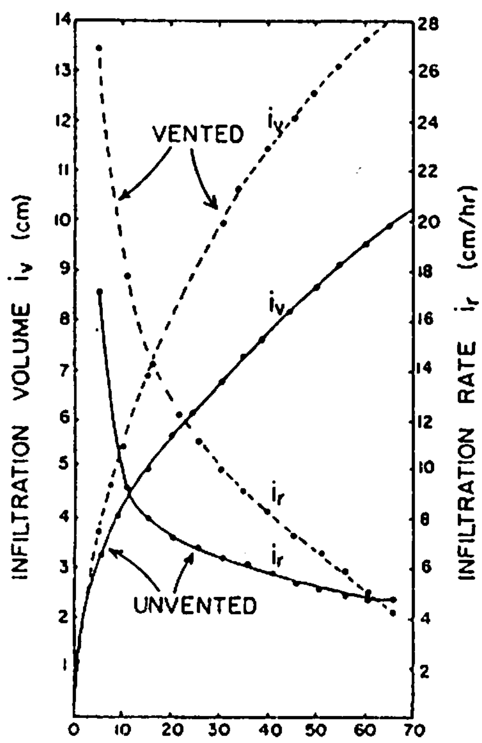

Fig. 4—Mean values of infiltration volume i_v and infiltration rate i_r as functions of time for vented and unvented displaced soil air.

ground water. The gradient in H after the head gates were closed (140 min) reached a value of about 0.3 cm/m and remained nearly constant for several hours after the irrigation (Fig. 3). For this gradient to remain constant, more water had to be recharging the ground water near the

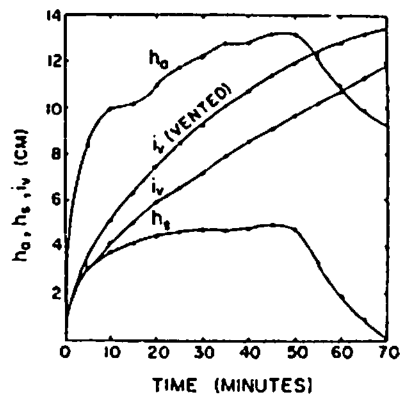

Fig. 5—Displaced soil air pressure h_a, surface head h_s, and infiltration volume i_v during a border irrigation and i_v during a subsequent irrigation when displaced soil air was vented as functions of time.

border dike than in the center of the border; however, it is difficult to quantitatively estimate the difference.

Accumulative infiltration i_v and infiltration rates i_r for the vented and unvented treatments are plotted in Fig. 4. Venting the displaced air increased mean total intake from 10.3 to 14.3 cm, with most of this increase occurring early in the irrigation. The effect of the soil air pressure on infiltration was maximum at about 10 min when the infiltration rate of the unvented (high air pressure) treatment was about one-half that of the vented treatment. Displaced soil air pressure h_a, surface head h_s, and infiltration volume i_v for the unvented treatment and i_v for the vented treatment for one of the replications are shown in Fig. 5. Soil air pressure h_a rose at a decreasing rate during the irrigation, reaching its highest value of 13.2 cm of H_2O when the head gates were closed. Soil air pressure h_a exceeded the surface head h_s throughout the irrigation, as evidenced by profuse bubbling over the entire field except around the venting apparatus. The reversed treatments had similar shaped curves except that the highest soil air pressure was 24 cm of H_2O at 50 min with a maximum surface head of 8 cm. Also, infiltration was greater when the soil air was vented. Several uncontrolled variables including: (i) inherent soil differences between the two sites; (ii) initial conditions, (iii) vegetative cover; (iv) surface head; and (v) time of inundation affected the results of this study and complicated interpretation. Mean infiltration curves plotted in Fig. 4, however, give some clues to the effect soil air pressure has on infiltration. If h_a is $> h_s + h_b$, (h_b = bubbling pressure of a representative large pore), that is if the displaced air is continuous to the surface and its pressure exceeds the hydrostatic pressure plus the capillary pull of a large pore, then water will not enter such a pore. Thus the large infiltration contribution of macropores can be negated by a small soil air pressure. The effect of soil air pressure on infiltration would be expected to be maximal initially and to decrease as infiltration proceeds, since the large pore contribution is greatest as water is introduced at the surface and decreases as flow into and through these pores decreases. Additionally, the large pores of this silty clay loam began shrinking when water was introduced so that their influence was diminishing with time.

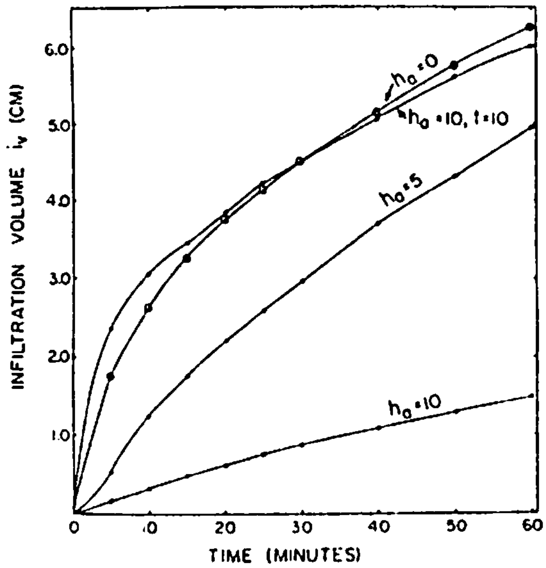

Fig. 6—Infiltration volume i_v for constant soil air pressures h_a of 0, 5, and 10 cm and a slowly rising soil air pressure, i.e., $h_a = 0$ at $t = 0$, $h_a/t = 1$ for $0 < t < 10$ min, $h_a = 10$ cm of H_2O for $t > 10$ min as functions of time. Surface head h_s was constant at 6.3 cm at $t > 2$ min.

Because of the variable conditions encountered in the field, a field-laboratory study was conducted to eliminate most of these variables and yet be applicable to a real soil. Accumulative infiltration for constant soil air pressures h_a of 0, 5, and 10 cm of H_2O are plotted in Fig. 6. An h_a of 5 cm of H_2O decreased infiltration significantly only during the first few minutes of the run. During the first 2 min of the 5 cm of H_2O soil air pressure run h_a was greater than h_s and some bubbling was evident. During the remainder of the run h_s was greater than h_a and only slight bubbling was apparent.

An h_a of 10 cm of H_2O reduced total intake in 1 hour from 6 to 1.5 cm. These data are a good indication that a small soil air pressure affects infiltration primarily by blocking the contribution of large pores. In this experiment when $h_a = 10$ cm, $h_s = 6.3$ cm, and h_b is taken as the difference ($h_b = h_a - h_s$) of 3.7 cm, the contribution of pores greater than 0.4-mm radius is blocked. When h_a was less than h_s, no effect on infiltration was evident.

Bubbling pressure h_b is defined in this discussion as the difference between soil air pressure h_a and surface head h_s ($h_b = h_a - h_s$). It is thus visualized as a function of the soil and of the boundary and wetting conditions. This point can be illustrated by considering the midborder-border dike soil air pressure comparison in Fig. 3. The soils and surface heads are similar but by virtue of position in the field, h_b varies across the border strip. Thus bounded soil columns would not simulate the field boundary conditions. The interactions of soil properties, depth to water table and areal extent of wetted surface are not understood and should provide fruitful future research.

Infiltration was also measured when soil air pressure rose from 0 at time 0 to a maximum of 10 cm of H_2O by 10 min, remaining constant thereafter. It can be seen (Fig. 6) that this magnitude of h_a had little effect on infiltration once the large pores were functioning. Greater air pressure was required to drain the large pores than was needed to

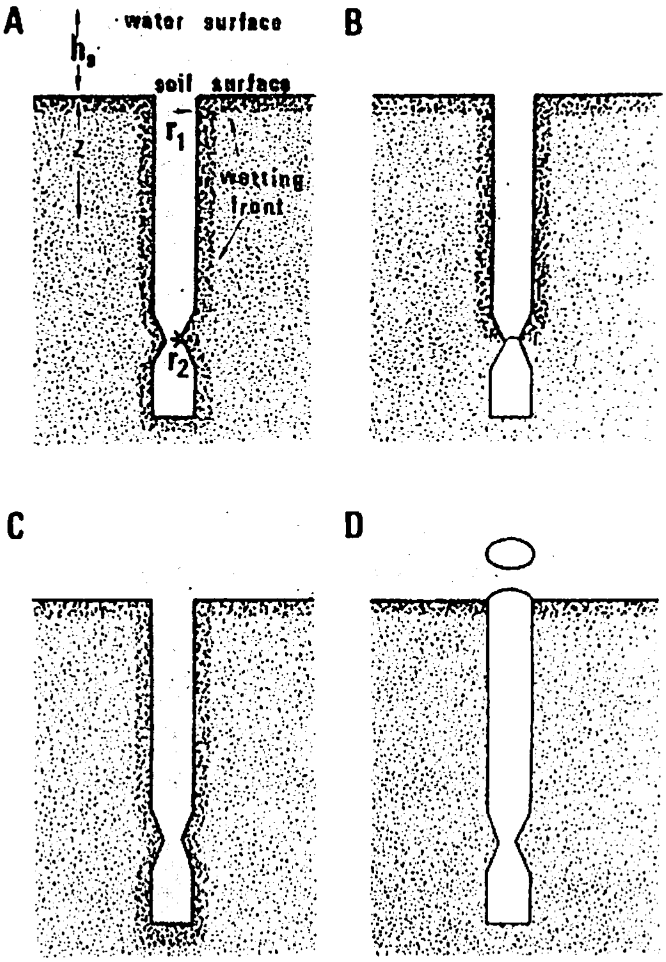

Fig. 7—Idealized large pore model showing degrees of functioning for various soil air pressures at different points and times: (A) full functioning $h_a < h_s + \frac{0.15}{r_1}$ $\left(\frac{0.15}{r_1} = \text{capillary pull of large pore} = \frac{2[73 \text{ dynes/cm}][\cos \theta]}{r_1[1.0 \text{ g/cm}^3][980 \text{ cm/sec}^2]}, \cos \theta = 1\right)$; (B) partial functioning $h_a > h_s + Z - h_l + \frac{0.15}{r_2}$ (h_l = water head loss within large pore); (C) partial functioning $h_a > h_s + Z - h_l + h_b$ (h_b = bubbling pressure of unstructured soil); and (D) nonfunctioning $h_a > h_s + \frac{0.15}{r_1}$ at $t = 0$.

prevent them from filling with water. Thus, many of the pores that were not contributing to infiltration during the constant air pressure run were contributing during this run. Bubbling pressure h_b, as defined, was the same after 10 min in this case as in the previous constant soil air pressure run. Entirely different infiltration responses were recorded for the two cases. Thus, under field conditions where h_a increases as infiltration proceeds, infiltration responses to air pressure would be expected to be a function of the soil and the boundary and wetting conditions.

As a partial explanation of these results a single pore model of a large pore infiltration system is proposed (Fig. 7) which assumes that the large pore is imbedded in an otherwise homogeneous soil. The large infiltration contribution of the macropore is rather straightforward since it can conduct high potential water to the subsurface area of the homogeneous material. This is pictured in Fig. 7A.

When h_a is greater than the surface head plus the capillary pull of the large pore as pictured in Fig. 7D the infiltration will be drastically reduced. Two situations are depicted in Fig. 7B and 7C which demonstrate that larger air pressures may be required to make the pore stop functioning than to prevent it from functioning. These two conditions may represent the slowly rising h_a experiment. Profuse bubbling occurred when h_a was 10 cm of H_2O during the entire run, indicating that many large pores were functioning only to vent air. Much slower bubbling from fewer locations occurred when h_a did not reach 10 cm of H_2O until after 10 min of infiltration, indicating that the pores were now conducting water downward and less air upward. These and similar extremes are probably all present in natural soil during border irrigation and may all be occurring within a meter square infiltrometer frame where simultaneous bubbling characteristics ranging from continuous large bubbles to intermittent small bubbles have been observed.

Within the preceding limitations some important conclusions can be drawn regarding the infiltration and water table effects of soil air pressure. When water infiltrates during border irrigation, soil air pressures rise above ambient atmospheric. These soil air pressures will cause a redistribution of ground water and a reduction in infiltration. In the range encountered in the field, h_a must exceed $h_s + h_b$ to significantly decrease infiltration. Infiltration effects may be determined during the first few minutes of infiltration when the h_a-to-h_s relationship is established. In conclusion, an expansion of water movement theory should include air pressure effects, and cannot disregard the macroporosity of real soils, because it is the macropores that are affected most by soil air phenomena.

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