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The Effect of Hydrophobic Substances on Water Movement in Soil During Infiltration[1]

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ABSTRACT

The effect of hydrophobic substances on water movement was studied by infiltrating water horizontally and vertically into soil columns packed with wettable and water repellent soils. Horizontal infiltration was 25 times slower in water repellent soil than wettable soil. In the water repellent soil, the water content decreased 20 to 25% between the water source and the wetting front. In contrast, water content dropped 10% in the same region of the wettable soil. Diffusivities calculated for the two types of soil suggested that hydrophobic substances had the greatest effect on water movement at the lower water contents. The orientation of the columns during water entry affected the shape of the soil-water profiles in the water repellent soil, but not in the wettable soil. The diffusivities calculated from horizontal infiltration experiments were not useful for predicting soil-water profiles during vertical infiltration into either the wettable or water repellent soils.

Additional Key Words for Indexing: unsaturated flow, wettability, diffusivity, soil-water relations.

HYDROPHOBIC SUBSTANCES in soil can restrict water movement and, thereby, create major problems in land management. Water repellent soils affect agricultural lands as well as wildlands (DeBano, 1969a). Water repellency affects both evaporation and infiltration (Letey et al., 1962a). The effect of a water repellent layer on infiltration has been analyzed theoretically by using the diffusion equation as a model for describing unsaturated flow (Gardner, 1969). Some horizontal infiltration data and their implications in a diffusion analysis have been reported previously (DeBano, 1969b).

This paper reports and discusses data obtained during horizontal and vertical infiltration into wettable and water repellent soils. The adequacy of the diffusion equation for describing unsaturated flow in water repellent soils is also considered.

EXPERIMENTAL PROCEDURE

Soil was collected in the San Gabriel Mountains of southern California on a brushland area that had been burned by wildfire in 1962. A water repellent layer which resisted water drop penetration for over 1 min was present below and parallel to the soil surface. Soil was carefully collected from the water repellent soil layer, and large rocks and pebbles were discarded. The soil material was later resieved through a 1-mm sieve in the laboratory before conducting infiltration experiments.

Previous work showed that hydrophobic substances in soil could be destroyed by burning (Krammes and DeBano, 1965). Consequently, half of the soil collected was heated in a muffle furnace at 300C for 20 min to destroy water repellency; the other half was left untreated.

Both chemical and physical analyses were made on the wettable and water repellent soils. The chemical analyses made were: pH, cation exchange capacity, and percent carbon. Cation exchange capacity was determined by ammonium saturation (Chapman, 1965). Percent carbon was obtained by dry combustion (Allison et al., 1965). Physical measurements included: particle density, specific surface, particle size analysis, and liquid-solid contact angles. Specific surface was measured with EGME according to the method outlined by Heilman et al., (1965). Particle size distribution was obtained by the hydrometer method before and after organic matter was destroyed (Day, 1965). A pycnometer was used to determine particle density. The liquid-solid contact angles were calculated from capillary rise data using ethanol and water (Letey et al., 1962b).

The wettable and water repellent soils were packed into separate plastic columns before running infiltration trials. Columns were made of 40 individual sections, each 1 cm thick with a 5-cm inside diameter, held together by tape. A mechanical soil packer was used to pack the wettable soil to an average bulk density of 1.07 g/cm^3 and the water repellent to 1.06 g/cm^3 (Jackson et al., 1962).

Water infiltrating into the soil column through a fritted glass plate was maintained at a slight negative head of 2 mbar (Neilsen et al., 1958). Infiltration trials were made horizontally, vertically upward, and vertically downward. Separate horizontal infiltration trials were run until the wetting front reached 10, 20, and 30 cm. Three replicates of infiltration trials to each of the three horizontal distances, vertically upward, and vertically downward were made for the two soils.

Volume of water infiltrating and distance to the wetting front were recorded systematically during all infiltration trials. When the wetting front reached the prescribed distance, the water source was quickly disconnected and the column sectioned immediately. The water content of each 1-cm section was determined gravimetrically.

Soil-water diffusivities were calculated from the data obtained during horizontal infiltration according to the method outlined by Bruce and Klute (1956). Soil-water diffusivity and soil-water tension data were used to calculate capillary conductivities at different water contents. Vertical soil-water profiles were then calculated from the diffusivity and conductivity data (Philip, 1955, 1957). The calculated vertical profiles were later compared to the actual profiles obtained from laboratory infiltration experiments.

RESULTS AND DISCUSSION

Chemical and Physical Changes

The burning treatment used to produce a wettable soil changed some chemical and physical properties of the soil

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(Table 1). Organic matter was not completely destroyed in the wettable and water repellent soils before being analyzed (Table 1), because it was felt that the organic material represented an important part of the phenomenon under study. However, burning reduced the amount of carbon by 1.62%. The loss of organic matter reduced both the cation exchange capacity and specific surface. The decrease in clay produced by burning probably resulted from an aggregation of the < 2-μ particles which were not adequately dispersed before running the hydrometer analysis. It was found later that when the organic material was completely destroyed with hydrogen peroxide, the percent clay was nearly the same in the wettable and the water repellent soils.

Horizontal Infiltration

The wetting front moved about 25 times faster in the wettable than in the water repellent soil (Fig. 1). Although some changes in physical properties resulted from burning, the difference in size between the two soils was enough to account for the 25-fold difference in penetrability. Calculations based on capillary rise with ethanol showed that burning decreased the average pore radius only 2.3×10^{-2}mm.

A good linear relationship existed between the square root of time and distance to the wetting front during infiltration into the two soils, although there was slightly more variation around a best fit regression line for the water repellent soil than for the wettable soil (Fig. 1). The variation in the water repellent soil was probably produced by uneven wetting that caused the wetting front to advance irregularly during infiltration. An obvious nonzero intercept was present in the relationship between distance to the wetting front and the square root of time for the water repellent soil. The nonzero intercept probably reflected an initial wetting resistance commonly observed in water repellent soils.

The soil-water profiles delevoped during 10- and 30-cm horizontal infiltration trials differed between the wettable and water repellent soils (Fig. 2). Percent water decreased rapidly between the water source and the wetting front in the water repellent soil and was 20 to 25% less at the wetting front. In contrast, the water content in the wettable soil decreased about 10% between the water source and a well-defined wetting front. Apparently the water repellent soil did not wet completely when the wetting front passed. This produced a sloping moisture profile and poorly defined wetting front.

Table 1—Physical and chemical properties of the experimental soils

Soil	Particle size* Sand	Particle size* Silt	Particle size* Clay	Particle density	Liquid solid contact angle	Specific surface	pH 1:1	Cation exchange capacity	Carbon
	%	%	%	g/cm³		m²/g		meq/100g	%
Wettable	63.0	33.3	3.7	2.60	58°	14.68	6.9	11.8	3.10
Water repellent	62.7	29.7	7.7	2.51	80°	28.35	5.3	21.5	4.72

* Percent sand, silt, and clay in the < 1-mm fraction.

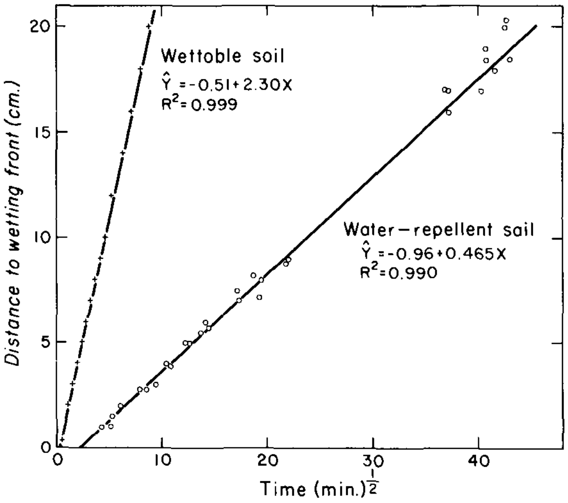

Fig. 1—Time-distance relationship during a 20-cm horizontal infiltration trial in soil columns filled with wettable and water repellent soils.

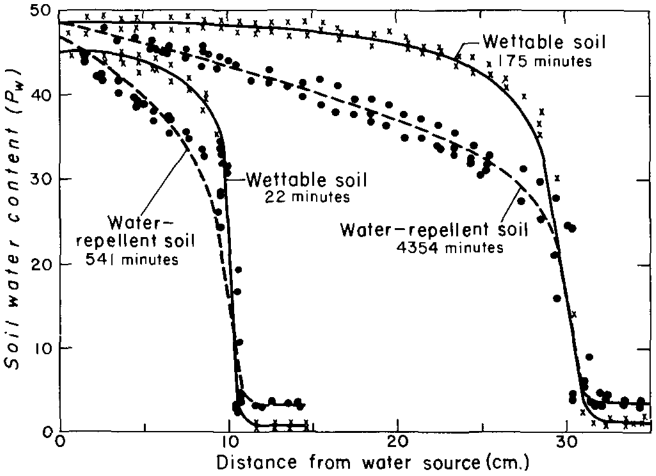

Fig. 2—Soil-water content distributions developed during 10- and 30-cm horizontal infiltration trials into columns packed with wettable and water repellent soils.

Diffusivity Anaylsis

The soil-water diffusivities calculated for the water repellent soil were smaller than those for the wettable soil at all relative water contents (Fig. 3). Three replicates for the three horizontal infiltration distances were combined to construct graphs relating diffusivity to relative water content for each soil. The graphs (Fig. 3) suggested that the largest differences in diffusivity between the wettable and water repellent soils were present at both the lower and higher relative water contents. The ratios of diffusivity in the wettable soil to that in the water repellent soil were found to decrease between relative water contents from 0.10 to 0.60 (Table 2). At relative water contents above 0.60, the ratios again increased for some unknown reason. Above 0.60 it was difficult to calculate reliable diffusivities in the wettable soil because the soil-water profile between the wetting front and the water source had very small slopes which yielded large diffusivities.

Some scatter was present among the data points at the lower water contents in the wettable soil (Fig. 3). This

Table 2—Ratios of soil water diffusivities at different relative water contents $(\theta_x - \theta_i)/(\theta_s - \theta_i)$ calculated from horizontal infiltration trials to 10, 20, and 30 cm in soil columns filled with wettable and water repellent soils*

Relative water content	Diffusivity, cm²/min		Diffusivity ratio: wettable /water repellent
	Water repellent	Wettable	
0.90	2.3×10^{-1}	5.8	25.2
0.80	1.8×10^{-1}	1.35	7.5
0.70	1.3×10^{-1}	4.5×10^{-1}	3.5
0.60	7.3×10^{-2}	2.0×10^{-1}	2.7
0.50	2.5×10^{-2}	1.3×10^{-1}	5.0
0.40	1.0×10^{-2}	9.3×10^{-2}	9.3
0.30	3.3×10^{-3}	6.6×10^{-2}	14.5
0.20	3.3×10^{-3}	6.6×10^{-2}	20.0
0.10	2.0×10^{-3}	4.7×10^{-2}	23.5

* θ_x is the water content at distance (x); θ_i is the initial water content; and θ_s is the water content of the soil adjacent to the water source.

variation occurred in a region near the wetting front where the soil-water profile was changing rapidly. Precision between replicates was difficult to obtain on this part of the curve because small differences in distance produced large differences in water content. This variation was not present in the water repellent soil because the water content profile sloped more gently at the wetting front, allowing the slope to be measured with greater precision.

The results of the diffusivity analysis suggest a way water could move in water repellent soils. Supposedly, when liquid water moves through a dry soil it creates a large number of liquid-solid interfaces. If part or all of the particle surfaces are coated with hydrophobic substances, then these interfaces should possess large wetting angles. These large angles would prevent water from moving readily as a liquid, and under these conditions possibly water transfer as a vapor may be important. Most likely hydrophobic substances do not completely cover the soil particles, and numerous wettable sites are probably available for water adsorption. After water has been adsorbed, then some of the interfaces may coalesce and form a somewhat continuous layer of water having fewer interfaces to hinder liquid flow. Therefore, as water content increases, the water repellent soil should transmit more nearly like a wettable soil. This appeared to be the case when relative water content is between 0.10 and 0.60.

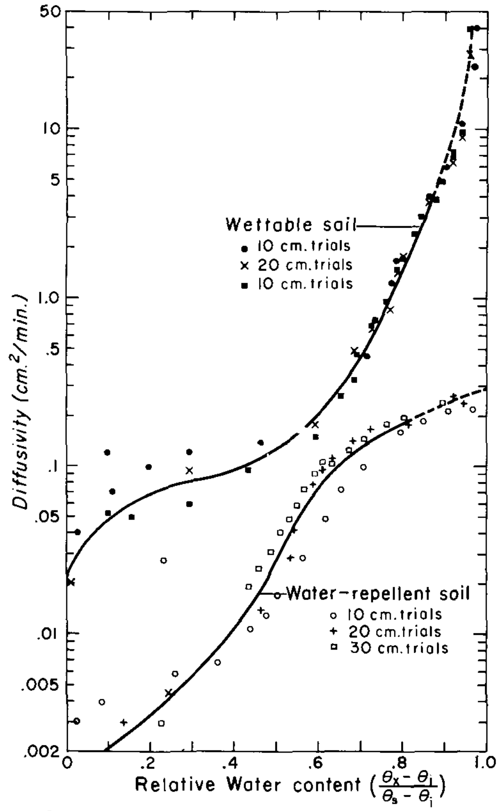

Fig. 3—Soil-water diffusivities at different relative water contents in wettable and water repellent soils.

Vertical Infiltration

Experimental Profiles—The shape of the soil moisture curve in the water repellent soil was sensitive to the orientation of the column during water entry (Fig. 4). When gravity and capillary forces complemented each other during downward flow (upper curve, Fig. 4), a pronounced knee-shaped soil-water profile developed. When gravity and capillary forces acted oppositely during capillary rise, the water content decreased rapidly between the water source and the wetting front (lower line, Fig. 4). The soil water profile developed during horizontal infiltration occupied an intermediate position.

The orientation of the soil column did not affect the shape of the soil-water profiles of wettable soil. The soil-water profile took only 7 min longer to develop in the upward direction than in the downward direction, and the two profiles were identical in shape.

The predominance of a vapor flow mechanism in the water repellent soil may have been responsible for the effect orientation had on the shape of the soil-water profile. Gravity may have caused a shift in the water transfer mechanism. For example, in the upward direction the weaker capillary forces may restrict liquid flow, and vapor transfer would predominate. Vapor flow could produce the diffuse wetting front observed. In the downward direction with gravity complementing capillary forces, liquid flow may have occurred even with numerous hydrophobic surfaces present. Liquid flow would be more conducive to

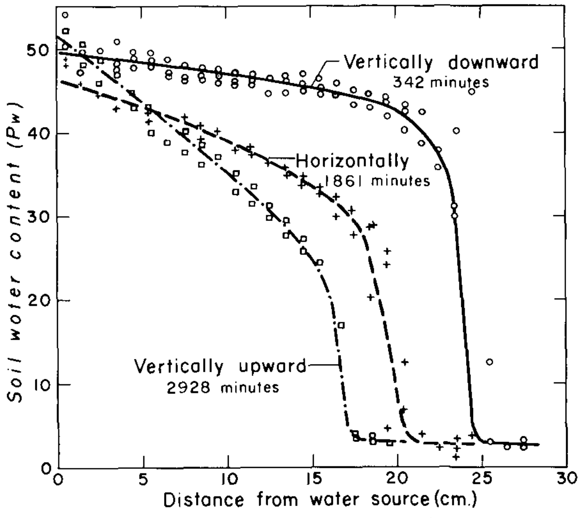

Fig. 4—Soil-water content distributions developing in a water repellent soil after water entered vertically upward, vertically downward, and horizontally.

the well-defined wetting front observed during downward infiltration.

Although the data above suggest a change in the water transfer mechanism in water repellent soils, more refined experiments are necessary to assess these phenomena. Experiments specifically designed to separate liquid and vapor flow such as described by Jackson (1965) and Anderson et al., (1963) should be helpful for determining the magnitude of each water transport mechanism.

Calculated Profiles—The diffusion equation was not a useful model for calculating soil-water profiles during vertical infiltration. The calculated depths after water had infiltrated into the wettable soil for 42 min were 25% greater than those obtained by laboratory experiment. In the water repellent soil, the deviations between the calculated and experimental depths were even larger than in the wettable soil.

The lack of agreement between experimental and calculated soil-water profiles probably resulted in part from the unreliable soil-water diffusivities at the higher water contents in the wettable soil. In the water repellent soil, the errors most likely originated in the soil-water tension data used to calculate capillary conductivities. Soil-water tensions obtained by pressure outflow techniques may not be reliable, because water tends to become trapped in the sample and cannot attain equilibrium with the applied pressure (DeBano, 1969b).

SUMMARY AND CONCLUSIONS

Hydrophobic substances in water repellent soils significantly decreased infiltration. The lower infiltration rates probably result from the larger wetting angles at the soil-water interfaces. The large angles do not permit the soil to wet completely and, thereby, produce a diffuse wetting front in the water repellent soil. In the wettable soil, sharp well-defined wetting fronts are present during infiltration.

Results of a diffusivity analysis suggested that hydrophobic substances had the greatest effect on unsaturated flow at the lower water contents. As soil-water increased, the hydrophobic substances had less effect on water movement. At the lower water contents, the numerous soil-water interfaces having large wetting angles probably hindered liquid water movement. Perhaps at these low contents water was transferred primarily by vapor diffusion.

The shape of the soil-water profiles developed in the water repellent soil was affected significantly by the orientation of the soil columns during water entry. When water entered in a vertical upward direction, water content dropped significantly between the water source and a diffuse wetting front. Infiltration in the horizontal direction also produced a soil-water profile which changed considerably between the water source and the wetting front. But when infiltration proceeded in a downward direction in the water repellent soil, the water profile was similar in shape to that developed in the wettable soil. The changing shape of soil-water profile may have reflected a difference in the moisture transfer process. In the wettable soils, the shape of the profile did not change when the columns were oriented differently.

Although the diffusion equation did not appear useful for predicting soil-water profiles during vertical infiltration in either the wettable or water repellent soils in this study, it did point to some inadequacies in the model. For example, the method used to obtain capillary conductivities was unsatisfactory, and other methods may have yielded more reliable data. Also, the use of pressure outflow techniques for defining soil-water tension relationships in the water repellent soil was questionable. More reliable soil-water capillary conductivity and tension data may have improved the prediction power and made the diffusion model useful for describing water movement through water repellent soils.

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