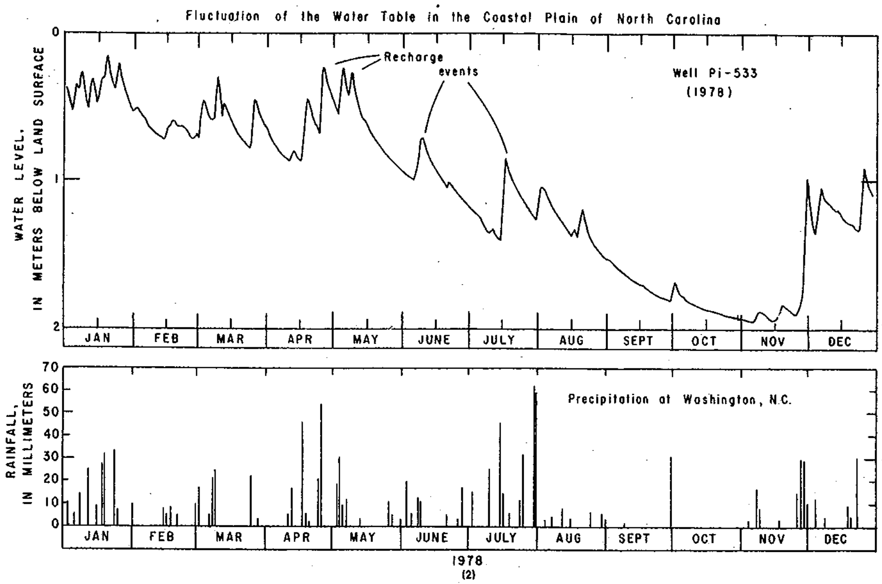


Figure 15. Fluctuation of the Water Level Showing Recharge and Discharge in Observation Wells.

during the growing season. Thus, discharge areas include not only the channels of perennial streams but also the adjoining flood plains and other low-lying areas.

One of the most significant differences between recharge areas and discharge areas is that the areal extent of discharge areas is invariably much smaller than that of recharge areas. This size difference shows, as we would expect, that discharge areas are more "efficient" than recharge areas. Recharge involves unsaturated movement of water in the vertical direction; in other words, movement is in the direction in which the hydraulic conductivity is generally the lowest. Discharge, on the other hand, involves saturated movement, much of it in the horizontal direction—that is, in the direction of the largest hydraulic conductivity.

Another important aspect of recharge and discharge involves timing. Recharge occurs during and immediately following periods of precipitation and thus is intermittent. Discharge, on the other hand, is a continuous process as long as ground-water heads are above the level at which discharge occurs. However, between periods of recharge, ground-water heads decline, and the rate of discharge also declines. Most recharge of ground-water systems occurs during late fall, winter, and early spring, when plants are dormant and evaporation rates are small. These aspects of recharge and discharge are apparent from graphs showing the fluctuation of the water level in observation wells, such as the one shown in Figure 15. The occasional lack of correlation, especially in the summer, between the precipitation and the rise in water level is due partly to the distance of 20 km between the weather station and the well.

Capillarity and Unsaturated Flow

Most recharge of ground-water systems occurs during the percolation of water across the unsaturated zone. The movement of water in the unsaturated zone is controlled by both gravitational and capillary forces.

Capillarity results from two forces: the mutual attraction (cohesion) between water molecules and the molecular attraction (adhesion) between water and different solid materials. Figure 16 shows that a consequence of these forces, water will rise in small-diameter glass tubes to a height h_c above the water level in a large container.

Most pores in granular materials are of capillary size, and as a result, water is pulled upward into a capillary fringe above the water table in the same manner that water would be pulled up into a column of sand whose lower end is immersed in water, as Figure 17 shows. Table 4 shows the approximate capillary rise in selected granular materials.

Table 4. Approximate Height of Capillary Rise (h_c) in Granular Materials

Material	Rise (mm)
Sand:	
Coarse	125
Medium	250
Fine	400
Silt	1,000

Steady-state flow of water in the unsaturated zone can be determined from a modified form of Darcy's law. Steady state in this context refers to a condition in which the moisture content remains constant, as it would, for example, beneath a waste-disposal pond whose bottom is separated from the water table by an unsaturated zone.

Steady-state unsaturated flow (Q) is proportional to the effective hydraulic conductivity (K_e), the cross-sectional area (A) through which the flow occurs, and the gradients due to both capillary forces and gravitational forces. Thus,

$$Q = K_e A\left(\frac{h_c - z}{z}\right) \pm \left(\frac{dh}{dl}\right) \qquad (8)$$

where Q is the quantity of water, K_e is the hydraulic conductivity under the degree of saturation existing in

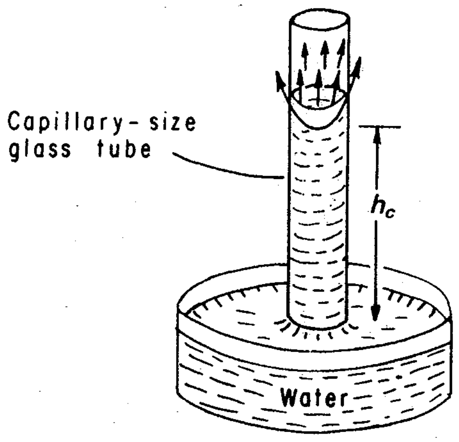


Figure 16. Capillarity

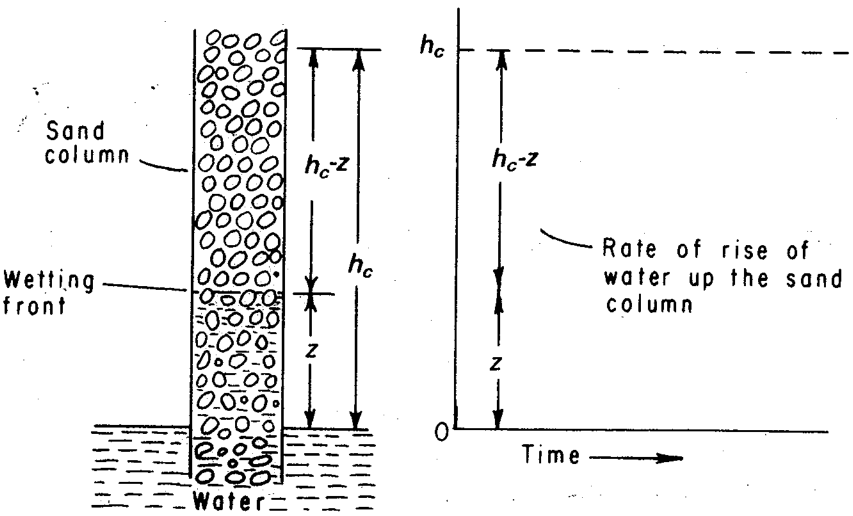


Figure 17. Capillary Action in a Column of Sand

the unsaturated zone, $(h_c - z)/z$ is the gradient due to capillary (surface tension) forces, and dh/dl is the gradient due to gravity.

The plus or minus sign is related to the direction of movement—plus for downward and minus for upward. For movement in a vertical direction, either up or down, the gradient due to gravity is 1/1, or 1. For lateral (horizontal) movement in the unsaturated zone, the term for the gravitational gradient can be eliminated.

Figure 17 shows that the capillary gradient at any time depends on the length of the water column (z) supported by capillarity in relation to the maximum possible height of capillary rise (h_c). For example, if the lower end of a sand column is suddenly submerged in water, the capillary gradient is at a maximum, and the rate of rise of water is fastest. As the wetting front advances up the column, the capillary gradient declines, and the rate of rise decreases.

The capillary gradient can be determined from tensiometer measurements of hydraulic pressures. To determine the gradient, Figure 18 shows it is necessary to measure the negative pressures (h_p) at two levels in the unsaturated zone. The equation for total head (h_t) is

$$h_t = z + h_p \qquad (5)$$

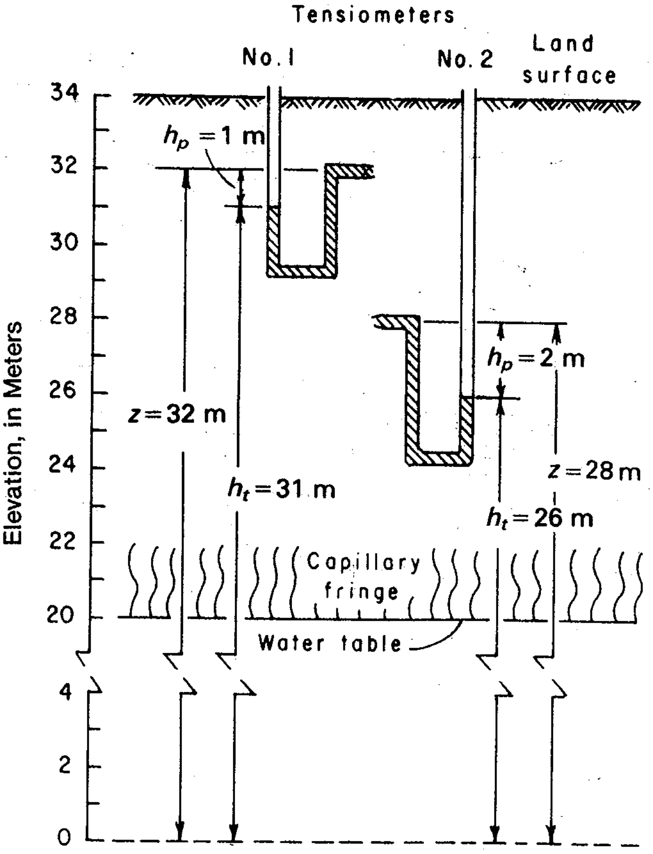
where z is the elevation of a tensiometer. Substituting values in this equation for tensiometer No. 1 in Figure 18, we obtain

$$h_t = 32 + (-1) = 32 - 1\,d = 31\,m$$

The total head at tensiometer No. 2 if 26 m. The vertical distance between the tensiometers is 32 m minus 28 m, or 4 m. Because the combined gravitational and capillary hydraulic gradient equals the head loss divided by the distance between tensiometers, the gradient is

$$\frac{h_L}{L} = \frac{h_{t(1)} - h_{t(2)}}{z_{(1)} - z_{(2)}} = \frac{31 - 26}{32 - 28} = \frac{5\,m}{4\,m} = 1.25$$

This gradient includes both the gravitational gradient (dh/dl) and the capillary gradient ($[h_c - z]/z$). Because the head in tensiometer No. 1 exceeds that in tensiometer No. 2, we know that flow is vertically downward and that the gravitational gradient is 1/1, or 1. Therefore, the capillary gradient is 0.25 m m^{-1} (1.25 – 1.00).



Datum Plane (National Geodetic Vertical Datum 1929)

Figure 18. Tensiometer Measurements for Measuring the Capillary Gradient

The effective hydraulic conductivity (K_e) is the hydraulic conductivity of material that is not completely saturated. It is thus less than the (saturated) hydraulic conductivity (K_S) for the material. Figure 19 shows the relation between degree of saturation and the ratio of saturated and unsaturated hydraulic conductivity for coarse sand. The hydraulic conductivity (K_S) of coarse sand is about 60 m d^{-1}.

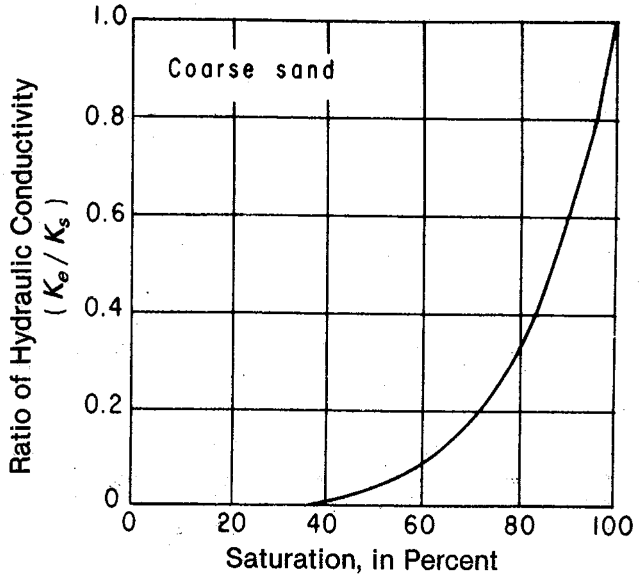


Figure 19. Relation Between Degree of Saturation and the Ratio of Saturated and Unsaturated Hydraulic Conductivity for Coarse Sand

Stratification and Unsaturated Flow

Most sediments are deposited in layers (beds) that have a distinct grain size, sorting, or mineral composition. Where adjacent layers differ in one of these characteristics or more, the deposit is said to be *stratified,* and its layered structure is referred to as *stratification.*

The layers comprising a stratified deposit commonly differ from one another in both grain size and sorting and, consequently, differ from one another in hydraulic conductivity. These differences in hydraulic conductivity significantly affect both the percolation of water across the unsaturated zone and the movement of ground-water.

In most areas, the unsaturated zone is composed of horizontal or nearly horizontal layers. The movement of water, on the other hand, is predominantly in a vertical direction. In many ground-water problems, and especially in those related to the release of pollutants at the land surface, the effect of stratification on movement of fluids across the unsaturated zone is of great importance.

The manner in which water moves across the unsaturated zone has been studied by using models containing glass beads. Figure 20 illustrates one model containing beads of a single size representing a nonstratified deposit, and Figure 21 shows another model consisting of five layers, three of which were finer grained and more impermeable than the other two. The dimensions of the models were about 1.5 m × 1.2 m × 76 mm.

In the nonstratified model, water introduced at the top moved vertically downward through a zone of con-

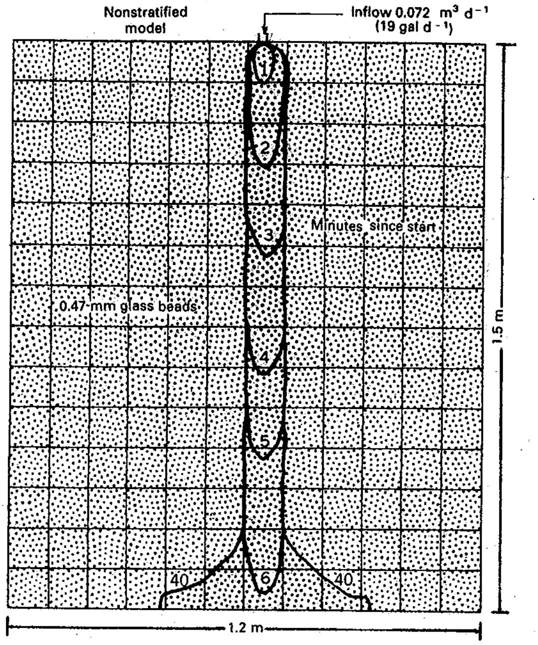


Figure 20. Single-Size Bead Model Illustrating Water Movement Across the Unsaturated Zone.

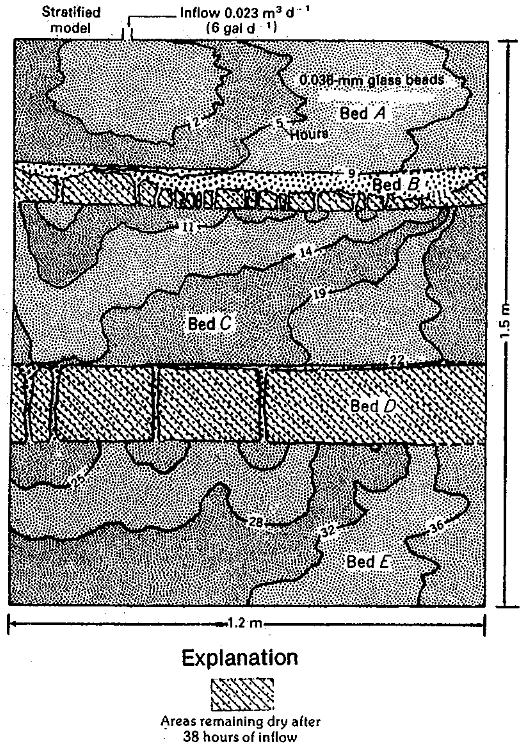


Figure 21. Five-Layer Model Illustrating Water Movement Across the Unsaturated Zone.

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