Model Decentralized Wastewater Practitioner Curriculum

Water Movement & Soil Treatment

Module text

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December 2004

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Citation of Materials

Gustafson, D., J. Anderson, A. Amoozegar, and D.L. Lindbo. 2005. Water Movement & Soil Treatment Text. *in* (D.L. Lindbo and N.E. Deal eds.) Model Decentralized Wastewater Practitioner Curriculum. National Decentralized Water Resources Capacity Development Project. North Carolina State University, Raleigh, NC.

Soil Water Movement

I. Principles of Soil Water Flow

Water is the main carrier for the transport of pollutants through soils. Therefore, knowledge of water flow pattern and magnitude is essential in designing land-based waste disposal systems (e.g., septic systems), as well as for conducting environmental assessments.

Water moves through the soil as a result of forces acting on it. In general, for most practical cases the major forces that act on water in the soil are those related to gravity (gravitational potential), attraction of solid particles for water and capillary rise of water in soil pores in the unsaturated zone (matric potential), and water pressure within the saturated zone (submergence potential). In the unsaturated zone, where soil pores are filled with both air and water, the matric potential is taken to be negative while in the saturated zone, where almost all the pores are filled with water; the submergence potential is taken to be positive. For gravitational potential, an arbitrary reference elevation must be selected. For points above the reference elevation the gravitational potential is taken to be positive and for points below the reference elevation the gravitational potential is considered to be negative. Only matric potential or submergence potential can be present at any one location. At the boundary between saturated and unsaturated zones (e.g., at water table), both matric and submergence potentials are taken to be zero.

To assess water movement in soils the cumulative effect of the forces that act on water, referred to as total soil water potential or total potential (equal to the sum of the matric and gravitational potentials in the unsaturated zone and sum of the submergence and gravitational potentials in the saturated zone) must be considered. For practical applications, the total soil water potential and its components are expressed on weight basis (i.e., expressed per unit of weight of water), with dimensional units of length (e.g., cm, in, ft). When expressed on weight basis, the gravitational potential is called gravitational head, and both the matric potential and submergence potential are called pressure head. No confusion should occur because only matric potential or submergence potential will be present at any given point and time within the soil. The total soil water potential expressed on weight basis is called total hydraulic head or hydraulic head. [NOTE: In literature different symbols are used to present total hydraulic head, gravitational head, and pressure heads in the saturated and unsaturated zones. In this document we show total hydraulic head by H, gravitational head by z, pressure head in the saturated zone by h_p, and pressure head in the unsaturated zone (i.e., matric potential) by h.]

Between two points water always moves from the point at higher potential (i.e., higher total hydraulic head) to the point at lower potential (lower total hydraulic head). When there is no soil water movement, the total hydraulic head (H) at every location within the soil volume under consideration is a constant. The difference between the total hydraulic head between two points (ΔH) determines the direction of water flow, and the rate of change of the hydraulic head along the flow path between the points (length L), referred to as gradient ($\Delta H/L$), determines the rate of movement of water between them. The rate of water movement between the two points also depends on the hydraulic conductivity of the medium. Hydraulic conductivity can be defined as a measure of the ability of soil (or any porous medium) to transport water.

II. Darcy's Law

In his work with sand filters over a century ago, a French engineer named Henry Darcy observed that increasing the head of water over a sand column of a given length increases the rate of water flow through the column (Fig. 1). After a number of experiments, he determined that the quantity of water (Q) flowing through water-saturated sand filters of length L and cross sectional area A during a time period t is proportionally related to the hydraulic gradient $\Delta H/L$ by

$$Q/(At) = K_{sat} \times \Delta H/L \qquad [1]$$

where K_{sat} is the saturated hydraulic conductivity of the medium. The above equation, known as Darcy's law, was later expanded to cover water flow in both saturated and unsaturated soils. In its general form Darcy's equation can be written as

$$Q/(At) = v = K(h) \times \Delta H/L \qquad [2]$$

where v is referred to as flux density or flux, $K(h)$ is the soil hydraulic conductivity as a function of soil water pressure head (h) in the unsaturated zone (i.e., matric potential), and $\Delta H/L$ is the gradient. For saturated soils, (i.e., when $h = 0$), $K(h)$ is equal to K_{sat}. In this equation all the parameters are taken to be positive and the direction of the flow is determined based on the differences in the total hydraulic heads at the two points under consideration.

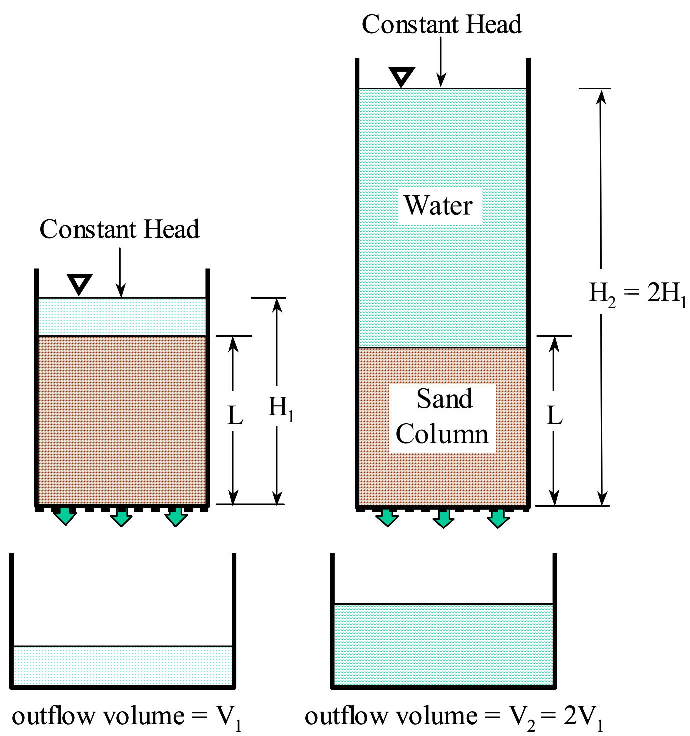

Figure 1. Schematic diagram of sand columns showing the effect of total hydraulic head on water flow through the columns.

Darcy's law has been accepted as the physical law governing soil water movement and applies to both saturated and unsaturated flow under steady state or transient conditions. This law simply states that the rate of movement of water through a soil is proportionally related to the hydraulic gradient (i.e., the driving force acting on water) and the conductivity of the medium (i.e., a measure of the ability of soil to transmit water). Darcy's law is an integral part of any model describing water movement through porous media.

III. Water Flow through Soils

The direction of water flow depends on the direction of the decrease in hydraulic head, and the rate of water movement depends on the magnitude of the hydraulic gradient and hydraulic conductivity of the medium. For example, consider that water is applied to one end of a horizontal soil column of known cross sectional area under a constant hydraulic head, H_1, and exits the other end of the column under a constant hydraulic head, H_2 (Figure 2). Knowing the saturated hydraulic conductivity of the column and applying Darcy's law (Eq. [1]), one can determine the quantity of water that can pass through the column during a specified time period. Conversely, knowing the flux and gradient, one can calculate a saturated hydraulic conductivity based on the flow rate through the column.

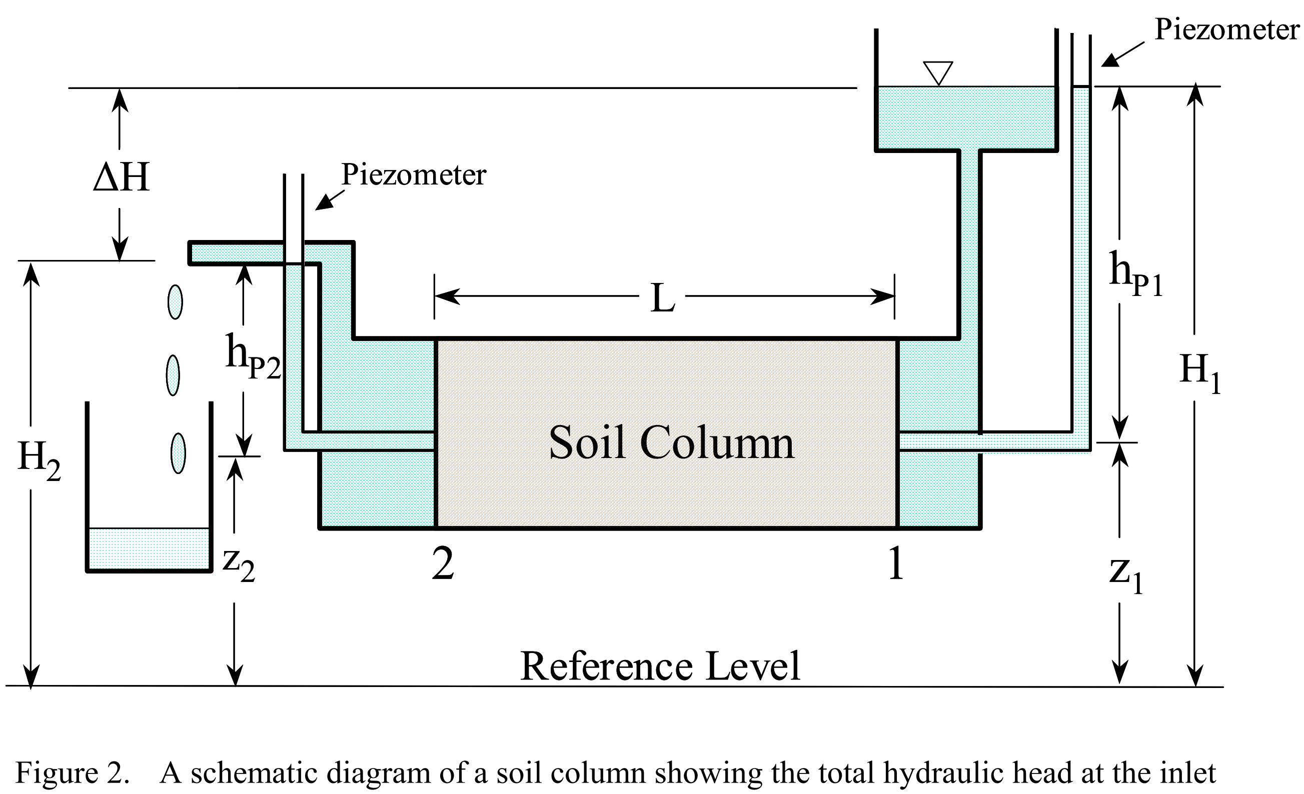

Figure 2. A schematic diagram of a soil column showing the total hydraulic head at the inlet (H_1) and at the outlet (H_2)

A. Saturated flow

Generally speaking, continuous large pores and fractures in a soil conduct water at a faster rate than smaller diameter pores or tight fractures. When the soil is saturated, most of the water passes through large tubular pores created by roots and animals or the planar voids between soil peds (often referred to as macropores). Although the interparticle pores or pores inside soil peds (referred to as matrix pores) may be filled up with water, the rate of water movement is relatively slow in these pores as compared to the macropores. Under saturated conditions, the hydraulic conductivity (i.e., K_{sat}) of the soil is a constant value at any given time for any given point within the soil body. Within a soil volume, K_{sat} varies from location to location (spatial variability) as well as in different directions (directional conductivity due to anisotropic nature of soils). In addition to spatial and directional variabilities, K_{sat} may change with time (temporal variability) due to changes in temperature and other factors. Any measured K_{sat} value represents an average conductivity of the volume of the soil under consideration.

B. Unsaturated flow

During the drainage process of a saturated soil volume with no water input, water initially moves out of the larger pores due to gravity. Subsequently, water moves out of the smaller pores due vertical drainage, plant root uptake, evaporation from the surface, or other factors. As water moves out of this volume of soil, the soil water content (represented by θ) decreases and the tendency of the soil for holding to water increases (i.e., pressure head h, a negative value, decreases by becoming more negative). Consequently, the flow path for water becomes narrower and the ability of the soil to transmit water (represented by conductivity) decreases as the soil water content decreases. Mathematically speaking, the unsaturated hydraulic conductivity (K_{unsat}) depends on the soil water content or soil water pressure head, and is represented by $K(\theta)$ of $K(h)$. If the relationship between soil water content (θ) and pressure head (h) (also known as soil water characteristic curve) is known, then Darcy's law can be written in terms of soil water content in place of pressure head.

C. Steady state and transient flow

The rate of water movement through a volume of a soil under a steady state condition is constant (i.e., does not change with time), whereas under transient conditions the rate of flow changes with time. For example, the ground water flow is considered to be under steady state if it flows toward a natural drainage system at a constant rate with no change in the total hydraulic head or volume of saturation. Near a well pumped intermittently, on the other hand, the flow is under transient conditions. Another example is the transient condition in the unsaturated zone around the trenches of a septic system with no ponding, or around the emitters of a drip system receiving wastewater intermittently (with each dosing cycle).

D. Infiltration and soil water profile

Water may enter the soil under an array of conditions. Under a rainfall event or a spray irrigation system, water is applied to the soil surface fairly uniformly in a relatively large area. In an infiltration gallery, water is applied to the soil in a relatively small area. Water applied to a trench enters the soil through the bottom and perhaps sidewalls of the trench. Under any of these conditions, a general pattern for the soil water distribution with depth (referred to as soil water profile) can be established. For example, when the rate of water application by a spray irrigation system to the soil in a relatively large flat area equals or exceeds the maximum rate of infiltration into the soil, the zone immediately below the soil surface becomes saturated (and ponding may occur). This zone is called saturation zone (Fig. 3). The volume of the soil below this saturation zone is referred to as the transmission zone. In this unsaturated zone soil water content is fairly uniform (for a uniform soil). At the end of the transmission zone is the wetting zone where water content decreases rapidly with depth. At the leading edge of the wetting zone (referred to as wetting front) the hydraulic gradient (mainly due to matric potential) is relatively high and the wetted zone advances into the dry soil rather rapidly despite the low unsaturated hydraulic conductivity of the zone.

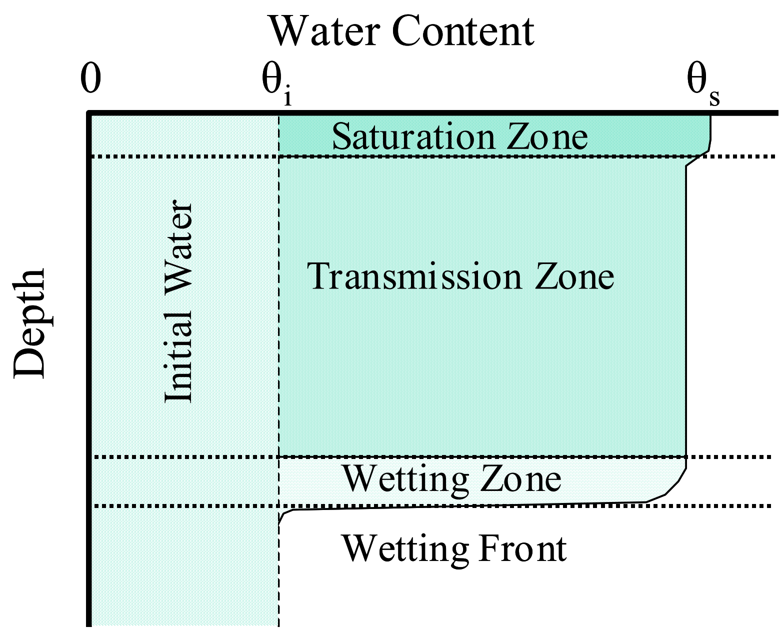

Figure 3. A schematic diagram showing the soil water distribution with depth during the infiltration of water into an initially moist uniform soil

E. Infiltration rate and cumulative infiltration

The rate of water entry into the soil from a surface (e.g., surface of the land, bottom or side of a trench) is referred to as the infiltration rate. The rate of infiltration into a dry or moist soil decreases with time mainly due to an increase in soil water content and a decrease in hydraulic gradient (Figure 4A). If infiltration continues, the rate of water entry into the soil reaches a constant value (steady state condition) that is considered to be the same as the saturated hydraulic conductivity of the soil volume near the infiltrative surface. The total amount of water entering the soil since the start of infiltration into the soil is referred to as the cumulative infiltration (Fig. 4B). The slope of the flat portion of the cumulative infiltration curve at large time is the final infiltration rate.

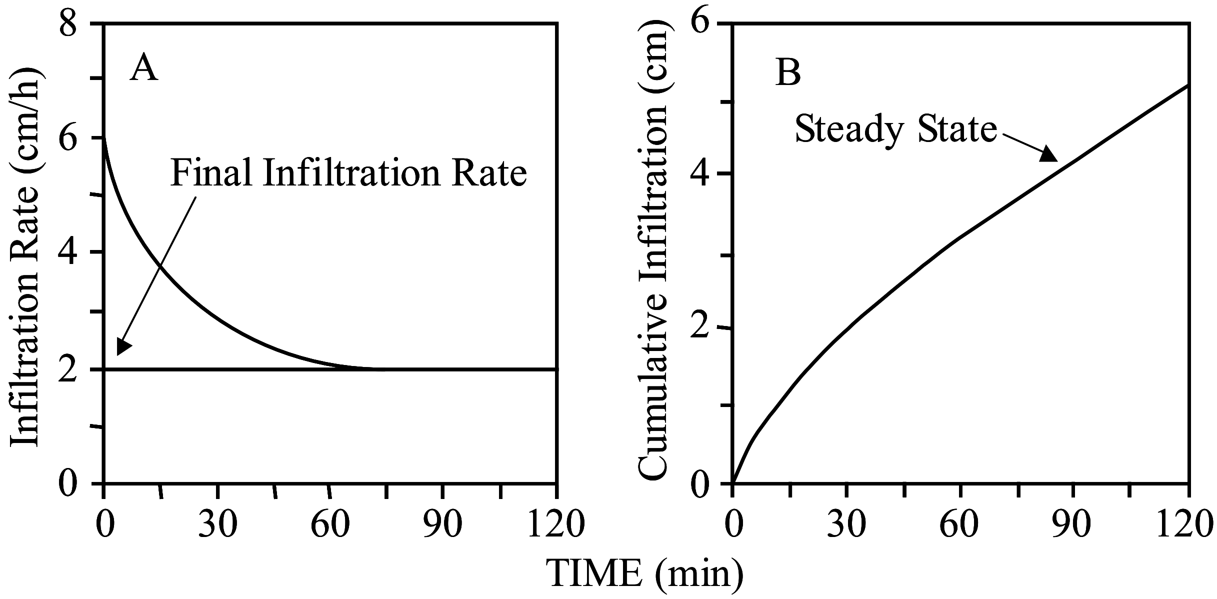

Figure 4. Infiltration rate (A) and cumulative infiltration (B) as a function of time

1. Effect of initial soil water content on infiltration rate

The rate of water entry into the soil (referred to as infiltration rate) depends on the amount of water in the soil (Figure 5). The wetter the soil, the lower is the initial rate of water infiltration into the soil.

2. Runoff occurrence

Runoff occurs when the rate of rainfall (or water application to the soil) exceeds the final infiltration rate of a soil. Using the infiltration curve for a given initial soil water content, the amount of runoff can be estimated based on the rate and duration of the rainfall event (Figure 6).

III. Application to On-Site Systems

In a commonly used septic system wastewater containing dissolved and suspended pollutants is applied to a series of trenches dug into the soil in the drainfield area. Whether wastewater is applied to the drainfield by gravity (e.g., conventional septic system) or by a distribution system using a pump (e.g., low pressure pipe or low pressure distribution system), the volume of wastewater entering the trenches daily must infiltrate the soil and move away

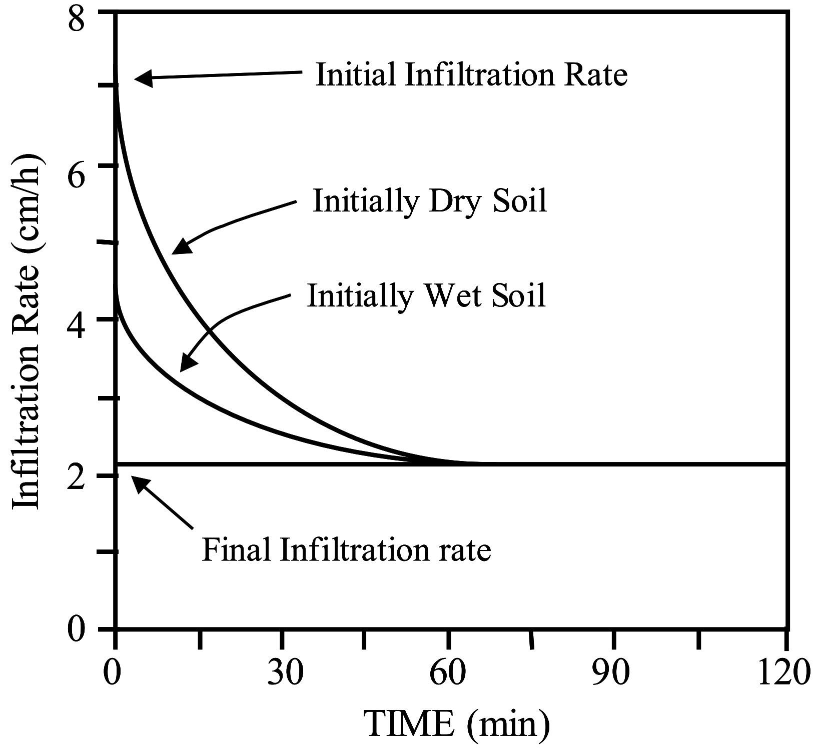

Figure 5. The rate of infiltration into a soil under wet and dry initial conditions

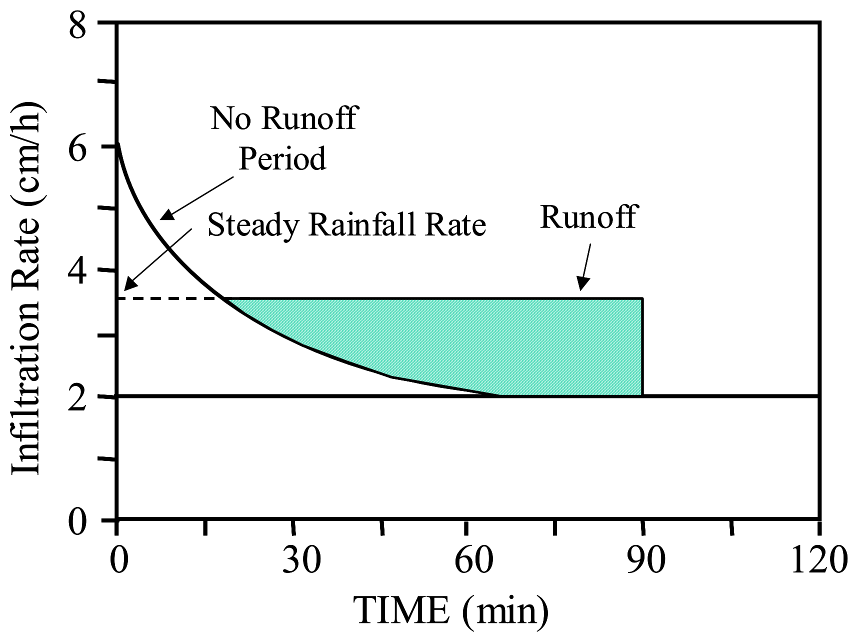

Figure 6. The infiltration rate and the amount of runoff generated at a site for a 90-minute uniform rainfall event.

laterally from the drainfield or percolate vertically to a deep aquifer within each 24-hour period. Otherwise, ponding in the trenches and eventually surfacing of effluent may occur, and/or soil in the drainfield area becomes saturated, preventing the wastewater from receiving treatment by soil in the drainfield area.

In a septic system where wastewater is applied to the trenches by the force of gravity wastewater generally enters the beginning of each trench. If the rate of wastewater application exceeds the infiltration capacity of the soil in the first few feet of a trench, ponding occurs and wastewater runs down along the trench similar to the occurrence of runoff (see Fig. 6). As ponding occurs, the infiltrative surface increases, but is always limited to the wetted perimeter along the bottom and sidewalls of the trench. When wastewater reaches the end of the trench, ponding is occurring throughout the length of trench. In general, continuous ponding creates an environment that favors the formation of a biological clogging mat. A biological clogging mat reduces the infiltration capacity of the soil in the trenches, which results in a greater depth of ponding. Ponding and eventual formation of a biological clogging mat can also occur in systems in which wastewater is dispersed over the entire drainfield in doses, as in low pressure pipe (LPP) systems.

Once wastewater enters the soil from the bottom and sidewalls of the trenches (or from emitters in a drip system), it moves away from the trenches due to a gradient that is created by the application of wastewater. If the rate of wastewater application exceeds the capacity of the soil to transmit the added water vertically under unsaturated conditions, the soil becomes saturated. A saturated soil does not generally provide treatment for wastewater; therefore, it is undesirable to have the saturated zone reaching the bottom of the trenches within a prescribed distance (referred to as separation distance). In general, water in a saturated zone created below the bottom of the trenches must move laterally away from the drainfield. In flat areas, movement of water occurs as a result of the formation of a mound, which increases the lateral gradient for water movement. In sloping areas, the cumulative effects of the land slope and potential mounding determines the hydraulic gradient. Based on Darcy's law, as described earlier, other factors that determine the magnitude of the lateral flow from the drainfield are the saturated hydraulic conductivity of the saturated zone and the product of the thickness and width of the saturated zone (i.e., the cross sectional area or window through which lateral flow occurs). Figure 7 presents a schematic diagram of the cross sectional view of a septic system on a gently slopping ground, showing the movement of water in the unsaturated and saturated zone in the drainfield area. More detailed discussion of the movement of water from the drainfield is presented in another section.

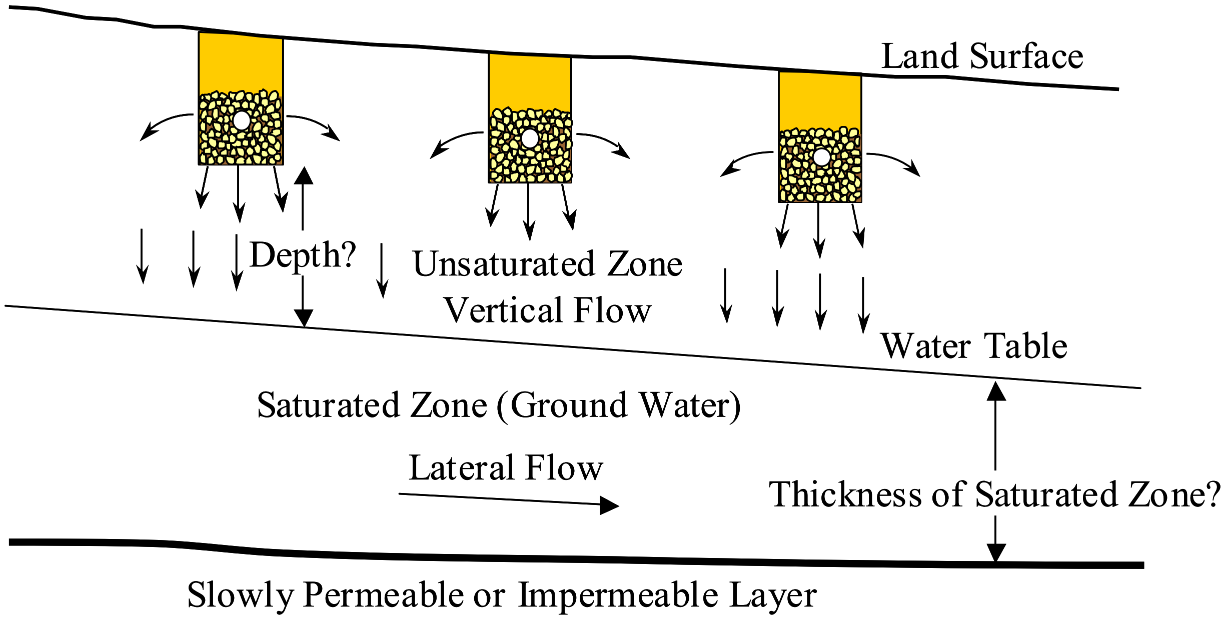

Figure 7. Schematic diagram of the cross section of three trenches installed on a gently sloping ground indicating the requirement for knowledge of the minimum depth of unsaturated zone below the trenches. Also shown is the thickness of the saturated zone where lateral flow occurs.