# Unsaturated Zone Hydrology for Scientists and Engineers

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# 14

# Drainage in Soil Water and Ground Water

## INTRODUCTION

In many areas throughout the world, there is either an abundance or a shortage of water. For agriculture, an ideal condition is one where the water table is deep, and there is unrestricted flow of excess water or salt from the root zone through the soil. In an industrial setting such as that at a landfill, one would prefer conditions with restricted movement of moisture through the soil away from the site or a very deep (even nonexistent) water table is desired. Also, in the latter case, it would be an advantage to have minimal amounts of rainfall since this means less potential for contamination from chemicals moving away from the site to ground water via infiltration, runoff, and drainage. Ideal conditions are rare, and drainage of excess water can pose a problem. Anytime excess water from drainage operations enters the soil, the potential for environmental hazards and a threat to water quality exists. The water-quality aspects due to runoff, infiltration, and other parameters was previously discussed (chapters 11 and 12); the hydraulic aspects of drainage will be discussed in this chapter. Also, the purpose here is to give a brief introduction to the principles involved in drainage. For a more detailed discussion, the reader is referred to Luthin (1957), Luthin (1966), and Van Schilfgaarde (1974).

## 14.1 PROBLEMS ASSOCIATED WITH DRAINAGE

Drainage is the removal of excess surface and subsurface water by means of various water-conveying devices (e.g., artificial drains, pipes, and ditches). Poor drainage can cause a variety of pollution problems; prime examples are the rising of a water table beneath a landfill (or other waste-storage site), or developed wetlands, as well as the possibility of leaching and surface runoff (see chapter 11). Leaching and runoff can affect the potential contamination by accidental spills. When the water table rises beneath a spill, the ground water comes in direct contact with the contaminant, which can then be transported through the soil at (typically) much faster velocities than normally occur through the vadose zone. As the ground water rises and falls, it causes a washing (or leaching effect) on the contaminant that increases its concentration in ground water. In agriculture, poor drainage usually enhances the development of saline and sodic soils, and can cause severe plant growth problems. Regardless of the industry, anaerobic conditions produced by poor drainage can cause the reduction of various oxidized forms of both organic and inorganic compounds; the resulting toxic substances accumulate and can cause serious harm to the environment. Also, such reducing conditions favor the denitrification process, and can produce large amounts of nitrous oxide. Nitrous oxide emitted as an end-product of denitrification contributes to the destruction of stratospheric ozone; it is transported slowly to the stratosphere where it either photolyses to $N_2 + O_2$, or reacts with singlet oxygen to produce $N_2$ plus $O_2$ or NO. The NO thus produced reacts with stratospheric ozone to produce $NO_2$ and $O_2$ (Finlayson-Pitts and Pitts 1986).

Although drainage can reduce contamination of the environment in many instances—and provide a greater land base for construction of homes, businesses, and industry—drainage is not appropriate for all situations. For instance, in some areas there will always be a "trade-off" or "balancing-act" between what is perceived as good for man and what is best for the environment; examples of this are wetland areas. Wetlands generally are characterized by shallow fresh water; some may even be dry part of each year. They can be called marshes, bogs, or swamps, but can also include coastal beaches and estuaries, lakes, rivers, and poorly drained farmlands. The main types of wetlands are defined by the dominant vegetation and—because the water within a wetland does not flow like that in a stream or movement in a lake—a wetland can have extreme spatial heterogeneity. For example, a small pool lined with cattails or reeds can be directly adjacent to a large patch of saw grass inhabited by a wide variety of birds and other wildlife, which can be interspersed with small stands of trees or pockmarked by open pools of water that are filled with submerged water weeds or have inundated bottoms.

In recent ecological and regulatory literature, the term "wetland" refers to any site whose soil development, biotic community, or hydrologic behavior is dominated by a periodic saturation of water. Since saturation can be a nuisance, much time and effort has been spent in attempts to drain wetlands or in some instances, to fill them. Because wetlands have become rare due to residential, industrial, and agricultural development, their importance has finally been realized and more effort is now spent to understand and protect them. The bulk of legal and technical work associated with wetlands has been in their identification and delineation. The federal government is committed to a "no net loss" policy because of the benefits associated with wetlands; laws at the local, state, and federal level have been instituted with regard to the use and development of these areas. Wetlands show an increasing value for improving water quality by: acting as riparian zones around various industrial sites to effectively treat polluted water, including municipal wastewater (Ward and Elliot 1995); promoting deposition of soil erosion; acting as sites for ground water recharge; becoming flood control buffers; acting as detention areas to slow the flow of runoff. Because wetlands are shallow, pollution hazards associated with them are intensified when a drainage network is poorly designed, or when the drainage system deteriorates due to inadequate maintenance. Consequently, it is the development of these wetland areas that result in pollution, not just the fact that they may be poorly drained. As a result, the benefits of wetlands and whether or not they should be drained, need to be carefully balanced against their development for commercial purposes, as well as the need to minimize effects of such development—by proper drainage versus the benefits of leaving the wetlands undeveloped for recreational, esthetic, or wildlife habitat resources.

Several factors influence drainage. These include: **(1) Recharge rate**—the rate at which water is added to ground water. If supply is greater than the discharge or drainage rate, the water table will rise; when supply equals drainage rate, a steady-flow condition will exist, and when recharge is less than the drainage rate, the water table will fall; **(2) Hydraulic conductivity**—the greatest effect observed with this parameter is in the event of soil-profile layering, in which one layer greatly retards water flow, thus causing a difference in the flow pattern; **(3) Hydraulic pressure** of the ground water and subsequent water-table configuration that can affect the horizontal level of the water table and—in instances where a confined aquifer is present—can exhibit artesian pressure; and **(4) Physical parameters of the drain/drainage**

**device**—these include drain diameter/ditch size; inlet openings in drainage devices; depth to drain from land surface; horizontal drain spacing; embedding materials (typically, coarse gravel); tendency of drains to clog; and of course, the type of medium in which the drains/ditches are installed.

## 14.2 TYPICAL DRAINAGE SITUATIONS UNDER FIELD CONDITIONS

### Flow in an Unconfined Aquifer

Aquifers that are close to the soil surface, and with continuous layers of various materials of high permeability that extend to the base of the aquifer, are called unconfined aquifers. These aquifers have a ground water table that is at atmospheric pressure. From the principles discussed in chapter 6, we see that water flow in this case is primarily caused by gravity. The upper boundary of the unconfined aquifer is typically taken as the water table, where pressure is atmospheric. A drainage theory to investigate flow in an unconfined aquifer was developed by Dupuit (1863) and later extensively used and popularized by Forchheimer (1930); consequently, the theory is aptly named the Dupuit–Forchheimer (D–F) theory. This theory assumes that: **(1)** streamlines in a gravity-flow system are horizontal and uniform throughout the aquifer's depth; and **(2)** the flow velocity associated with each streamline is proportional to the slope of the water table, but independent of the depth of the water-saturated medium. In this case, the proportionality factor is the hydraulic conductivity used in Darcy's law.

Strict adherence to the theory, although offering useful results, can be meaningless in the physical sense. For example, observe the four streamlines above the water table in figure 14.1 at points A, B, C, and D. To take them purely as horizontal (as suggested in the first assumption) is absurd. Despite this, the exact discharge from a canal to a ditch—as in the Florida Everglades case study (discussed at the end of this chapter)—or to a well tapping an

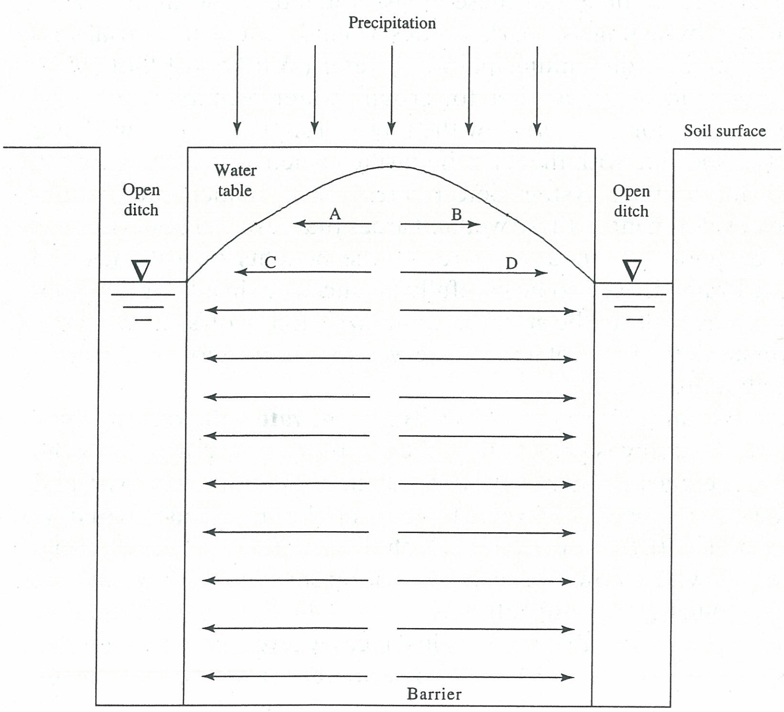


Figure 14.1 Horizontal flow lines of the Dupuit–Forchheimer theory for open-ditch drainage (after Kirkham 1971). Note that the barrier is arbitrarily drawn at the bottom of the ditches. In field situations, the bottom of the ditch could be any distance above the barrier.

unconfined aquifer, can be computed using D–F theory. Also, at distances larger than about twice the aquifer thickness from the drain or well, D–F theory provides excellent predictions of the water-table height. The D–F theory is widely used in drainage design for land reclamation in many parts of the world. An excellent treatise on the Dupuit–Forchheimer theory is given by Kirkham (1971), who shows its applicability to drainage between two parallel ditches in a homogeneous soil.

## Flow Toward a Well

Assuming a homogeneous and isotropic soil, the idealized solution for steady, radial ground water flow to a well in an unconfined aquifer can be found. Using the representation in figure 14.2, the rate of flow $q_r$ of water into the well is determined by using Darcy's law in the following form:

$$q_r = K\frac{A\,\Delta H}{\Delta r} \tag{14.1}$$

where $q_r$ is the flow rate $(L^3\,T^{-1})$; $A$ is the area in the medium through which water flows toward the well $(2\pi rh)$; $H$ is the height of the water table above the impermeable stratum $(L)$ and is found as previously discussed $(h_2 - h_1)$; $r$ is the radius of the cylindrical area $(L)$; and $\Delta H/\Delta r$ is the hydraulic gradient.

Substituting the value for $A$ $(2\pi rh)$, separating the variables, and integrating between the limits $r = r_0$ where $h = h_0$, as well as $r = r_1$ where $h = h_1$, then

$$\int_{h_0}^{h_1} h\,dh = \frac{q_r}{2\pi K}\int_{r_0}^{r_1}\frac{1}{r}\,dr \tag{14.2}$$

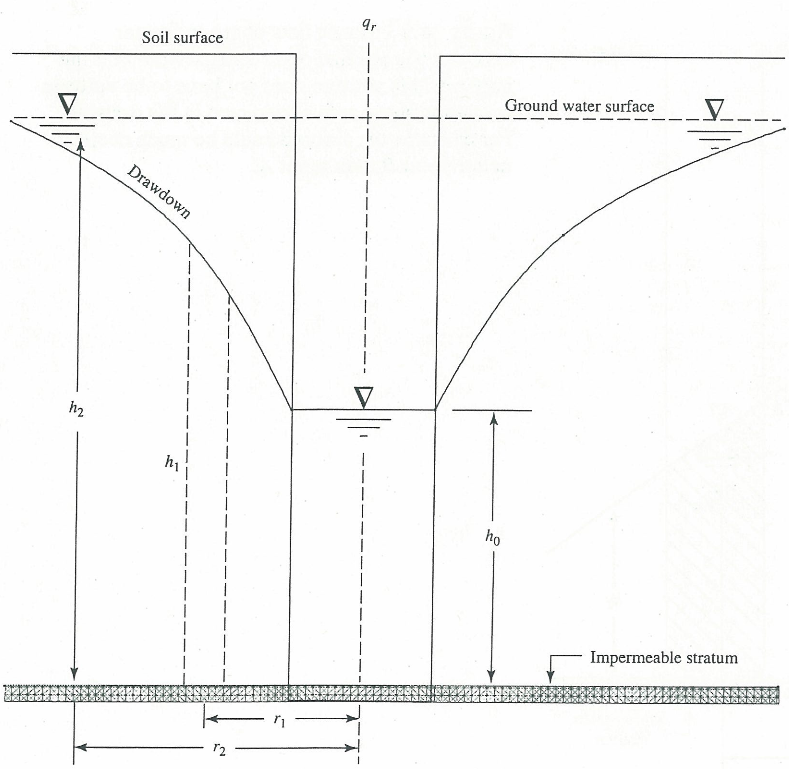


Figure 14.2 Steady radial flow (seepage) toward a fully penetrating well in an unconfined aquifer

or

$$\frac{h_1^2 - h_0^2}{2} = \frac{q_r}{2\pi K} \ln \frac{r_1}{r_0} \tag{14.3}$$

Solving for $q_r$ we have

$$q_r = \pi K \frac{h_1^2 - h_0^2}{\ln\left(\frac{r_1}{r_0}\right)} \tag{14.4}$$

which yields the discharge into a fully penetrating well from steady, radial ground water flow.

### Flow between Parallel Ditches

For a condition in which two parallel ditches have a different water-table elevation—as in points A and B in figure 14.3—the flow $Q_r$ can be determined using Darcy's law. The difference in elevation between points A and B establishes a steady flow between the two ditches, for which the discharge through a unit width of the medium (perpendicular to the drawing plane) is

$$Q_r = -Kh\frac{dh}{dx} \tag{14.5}$$

A decrease in pressure head with flow distance is indicated by a minus sign in the above equation. Where $Q_r$ is the volume of flow per unit time through the aquifer (unit width basis), $h$ is the height of the free water surface (often called the depression line) above the impermeable stratum ($L$), and $dh/dx$ is the hydraulic gradient. Performing the same mathematical

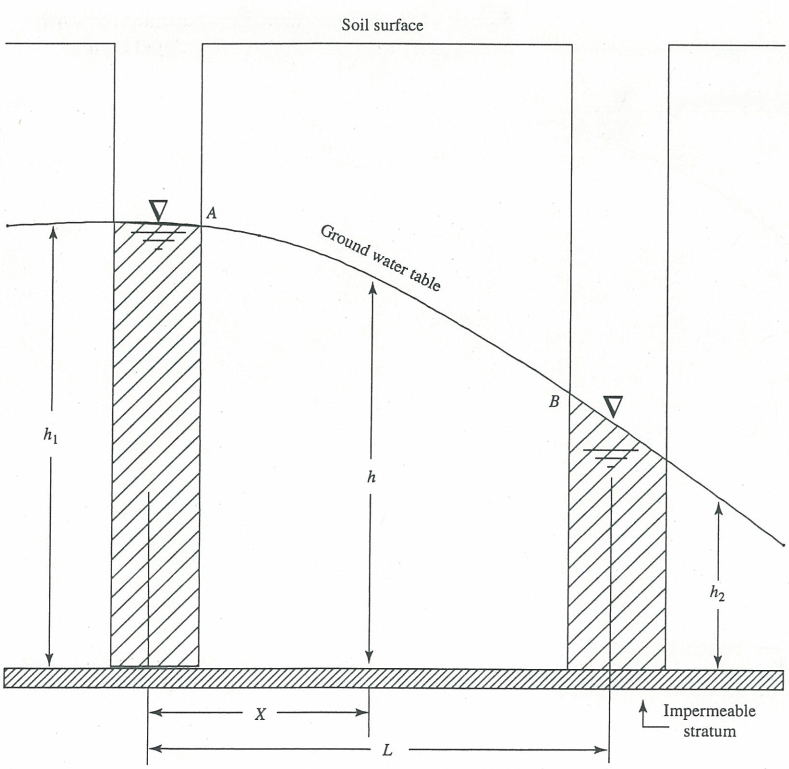


Figure 14.3 Steady flow of ground water between two parallel open ditches. Note that the impermeable stratum does not have to be uniform across the study area as depicted in the drawing. For example, the stratum could be much deeper under point $B$ than point $A$.

operations as for equation 14.4 and integrating between the limits for $h$ from $h_1$ to $h_2$, and for $x$ from 0 to $L$, then

$$\frac{Q_r}{K}\int_0^L dx = -\int_{h_1}^{h_2} h\,dh = \int_{h_2}^{h_1} h\,dh \tag{14.6}$$

and

$$Q_r = K\frac{(h_1^2 - h_2^2)}{2L} \tag{14.7}$$

Equation 14.7 is commonly called the Dupuit equation. A full derivation can be found in Fetter (1994). Equation 14.7 gives the discharge per unit length along the ditch. To obtain the equation for the height of the water table, we apply the continuity principle so that

$$Q_r = K\frac{(h_1^2 - h^2)}{2x} \tag{14.8}$$

which results in

$$h_x = \sqrt{h_1^2 - \frac{x}{L}(h_1^2 - h_2^2)} \tag{14.9}$$

Equation 14.9 yields the height of the water table above an impermeable aquifer base.

## Flow with Uniform Recharge

By assuming steady, uniformly distributed precipitation or irrigation, flow between two parallel ditches can be illustrated (see figure 14.4). For steady conditions, a maximum height $h_m$ is maintained midway between the ditches, no flow occurs through the vertical plane $h_m$, and water on either side of the plane flows toward the nearer ditch. Horizontal flow toward the ditch (through vertical plane $x$) is equal to surface recharge between vertical plane $x$ and the line denoting $h_m$. As a result, the flow rate $Q_x$, moving horizontally through the vertical plane (of unit width), is expressed as

$$Q_x = -R\left(\frac{S}{2} - x\right) \tag{14.10}$$

where $R$ is the rainfall or recharge rate (units of $L\,T^{-1}$), $S$ is the distance between ditches ($m$), and the term in parentheses is the surface area per unit width over which recharge takes

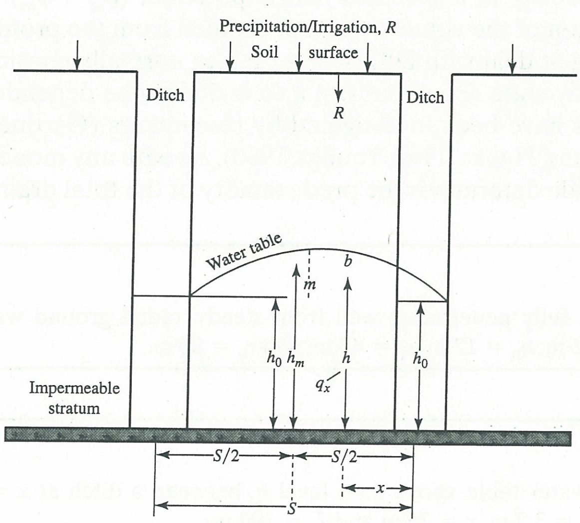


**Figure 14.4** Steady water flow toward parallel open ditches with uniform recharge, where $q_x = R(S/2 - x)$

place. If the Dupuit (1863) assumption is used, the flow rate $Q_x$, moving horizontally through the vertical plane (of unit width) is expressed as

$$Q_x = -Kh\frac{dh}{dx} \tag{14.11}$$

where $h$ is the height of the water table above the impermeable stratum ($L$), and $x$ is the distance from the center of the right ditch to the point on the impermeable stratum that is intersected by the line $h$ ($m$). If we equate the last two equations, separate the variables, integrate and substitute $h = h_m$ and $x = S/2$, we obtain

$$(h^2 - h_0^2) = \frac{R}{K}(Sx - x^2) \tag{14.12}$$

This is Hooghoudt's equation (Ghildyal and Tripathi 1987; Hooghoudt 1937) for the elliptical shape of the water table between drains.

## Evaluation of Falling Water Tables

Most of the equations discussed above are based on the assumptions that fixed volumes of soil will be drained when drains or ditches are installed, and that the soil is homogeneous. This tends to imply to the reader that there is also a fixed (or drainable) porosity, and that the specific volume of soil being considered will drain instantaneously. However, based on the physical and chemical factors discussed in chapters 2, 4, 8, 9, and 10, the volume of water drained gradually increases, due to increased matric potential. Consequently, the drainable porosity is a function of the matric potential and can be written (Luthin 1966) as

$$V_{dw} = \int_{\psi_{m_2}}^{\psi_{m_1}} \phi_d(\psi_m)\, d\psi_m \tag{14.13}$$

where $V_{dw}$ is the volume of water drained per unit volume of soil ($L^3$), $\psi_m$ is the matric potential or soil pressure/soil suction (kPa), and $\phi_d$ is the drainable porosity (unitless). By considering a soil that has a falling water table, an approximate expression of drainable porosity can be written such that

$$V_{dw} = \frac{a}{2}(\psi_{m_1}^2 - \psi_{m_2}^2) \tag{14.14}$$

where $a$ is the drained porosity at a specified matric potential ($\phi_d = \psi_m$). Equation 14.14 gives a reasonable prediction of the volume of water drained from the profile.

Drainage problems that deal with falling water tables normally consider the transient process as a series of steady-state drops, but can also include time dependency for vertical drainage. Many such cases have been investigated by researchers (Gardner, 1962; Jackson and Whisler, 1970; Jensen and Hanks, 1967; Youngs, 1960). As with any modeling scheme, the validity of assumptions made determines the predictability of the total drainage.

### QUESTION 14.1

Calculate the discharge to a fully penetrating well from steady, radial ground water flow. Assume $K = 2.4 \times 10^{-3}$ m/s, $h_1 = 14.2$ m, $h_0 = 12$ m, $r_1 = 40$ m, and $r_0 = 80$ m.

### QUESTION 14.2

Calculate the height of the water table above base level $h$, between a ditch at $x = 0$ and a ditch at $x = L$, assuming $h_1 = 4$ m, $h_2 = 3.2$ m, $x = 25$ m and $L = 100$ m.

## 14.3 GROUND-WATER DRAINAGE

### Water Tables and the Capillary Fringe

The water table is the upper surface of the saturated zone of free ground water. Free ground water is defined as water neither confined by artesian conditions nor subject to the forces of surface tension. At the water table, the total water potential is zero (atmospheric pressure). Thus, the water table is the imaginary surface separating the unsaturated zone from the saturated zone. The water table in soil is not an observable, physical surface, because capillary water (capillary fringe) is just above the water table and decreases in amount gradually upward. Auger holes, piezometers, wells, and drains that are open to the atmosphere fill to the true water-table level when bored or driven into the water table.

When an auger hole is drilled to locate the water table in a fine- or medium-textured soil, it is often difficult to recognize the top of the saturated zone due to the gradual change from unsaturated to saturated soil at the capillary fringe. It may take hours—or even days—for an auger hole to register the water table in low-conductivity soils. Small wells or piezometers react more quickly than large ones, because less water needs to flow through the soil to fill the smaller openings. Water in the capillary fringe can be a significant proportion of ground water moving toward subsurface drains; as much as 20 percent or more under some conditions (SCS, 1971).

An auger hole or piezometer should penetrate the saturated zone only a short distance ($< 1$ m) if the water-table location is to be measured accurately. This is particularly important where upward flow (or water under confined conditions) is tapped by a deeper hole. An auger hole that penetrates two or more aquifers in a stratified soil containing confined water, registers the highest hydraulic head modified by water movement through the well from the aquifers of higher hydraulic head to those of lower hydraulic head. These characteristics of the water table have a significant impact on the kinds of field measurements to be made, on the types of measurement devices to be used, and on the data interpretations for a ground water drainage system design.

At the water table, the component of potential energy is zero relative to atmospheric pressure. Therefore, the hydraulic head $h$ (of a point at the water table) is the distance of that point above the datum or above an impermeable boundary (see figure 14.5). The water-table slope represents the hydraulic gradient of flow only under certain conditions. Hydraulic gradient differs greatly from the water-table slope if there is a significant upward or downward component of flow such as that occurring: in the vicinity of a pumping well or subsurface drain; in flow from artesian aquifers; and in unsaturated seepage from canals. Figure 14.5 shows this difference between the slope $S_L$ of the water table and hydraulic gradient. The hydraulic gradient of the water table is the difference in hydraulic head $h$ at two points, divided by the distance between the points measured along the flow path $L_P$.

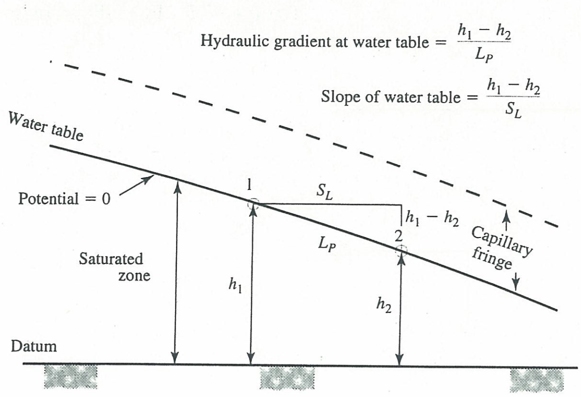


Figure 14.5 Difference between slope of the water table and hydraulic gradient

On flat surfaces and with parallel flow, the water-table slope is essentially the hydraulic gradient, because $S_L$ is nearly equal to $L_P$. It needs to be noted that the water table is not invariably a flowpath; water can be flowing upward into (or downward from) the unsaturated zone, thus crossing the water table.

## Equipotential Lines, Streamlines, and Potential Flow

In a given flow system, each "particle" of water in the system has its corresponding hydraulic head. All particles (or points) with the same hydraulic head lie in an equipotential surface. The force that tends to produce flow acts in the direction of greatest hydraulic gradient (i.e., normal to the equipotential surface). Whether or not the flow actually moves in the same direction as the line of force depends on whether the soil has the same hydraulic conductivity in all directions. If the soil is isotropic—that is, if its hydraulic conductivity is the same in all directions—the path of flow is along the lines of force, perpendicular to the equipotential surfaces.

If the soil has a higher hydraulic conductivity in one direction than in another direction, the flowpath is not perpendicular to the equipotential surface; such a soil is said to be anisotropic. Soil and rock often have bedding planes and fractures, causing them to be anisotropic. The paths of flow in anisotropic soils are perpendicular to the equipotential surfaces at points where the lines of force are exactly parallel to (or normal) to the bedding planes or fractures.

Figure 14.6 shows a two-dimensional flow system in the $X$–$Z$ plane, with an isotropic soil. Figure 14.7 shows another soil, with a line of force normal to the equipotential line, at an angle $b$ to the vertical axis $Z$. In this soil—which is anisotropic—the horizontal hydraulic conductivity $K_h$ is larger than the vertical hydraulic conductivity $K_z$. The direction of flow is not along the line of force but rather along a line closer to the horizontal axis. It can be shown (Viessman et al. 1977) that the angle the flowpath makes with the horizontal is (see figure 14.7)

$$a = \tan^{-1}\frac{K_z}{K_h \tan b} \tag{14.15}$$

Thus, the flow pattern can be computed and drawn for an anisotropic system if the equipotential lines are known, and if the relative hydraulic conductivities $K_z$ and $K_h$ are known. In analyzing the flow direction of ground water, the investigator needs to be aware of the effects of anisotropy on the flow pattern.

Flow in the saturated zone is often studied by using graphic representations of the hydraulic head and the flowpaths. Cross-sections are taken through the flow problem area, usually in vertical planes. Lines connecting points of equal hydraulic head plotted on such planes are called equipotentials. Lines indicating flowpaths plotted on the planes are called

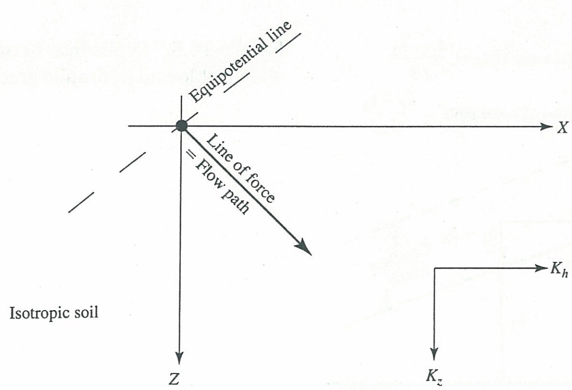


Figure 14.6 Flow direction in an isotropic soil

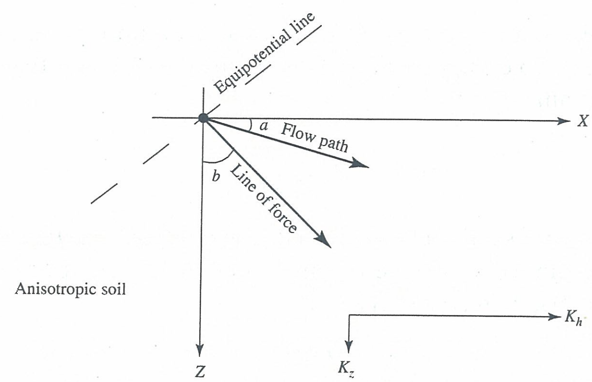


Figure 14.7 Flow direction in an anisotropic soil

streamlines, which are normal to the equipotentials. The two-dimensional graph showing equipotentials and streamlines for a flow system (or part of a flow system) is called a flow net.

There are actually an infinite number of equipotentials and streamlines, but it is convenient to draw only a limited number such that the rate of flow between each pair of streamlines is equal, and potential drop between successive equipotentials is the same. For isotropic systems, the distance between the streamlines is made equal to the distance between the equipotentials, thus forming a series of squares. Where the streamlines are curved, the squares are distorted, but they become more nearly "perfect" as the number of lines is increased, and approaches true squares as the number of equipotentials and streamlines increases.

## Construction of Flow Nets

For two-dimensional flow, the manner in which a flow net is used in problem solving is explained by considering figure 14.8. This schematic shows a portion of a flow net constructed so that each square is formed by a pair of equipotentials and streamlines. After a flow net is constructed, it can be used to analyze the flow rate using geometry and Darcy's law.

Remembering that the potential $h$ is given by $(p/\gamma + z)$ and referring to figure 14.8, the hydraulic gradient $G_h$ between two equipotentials is given by

$$G_h = \frac{\Delta h}{\Delta s} \tag{14.16}$$

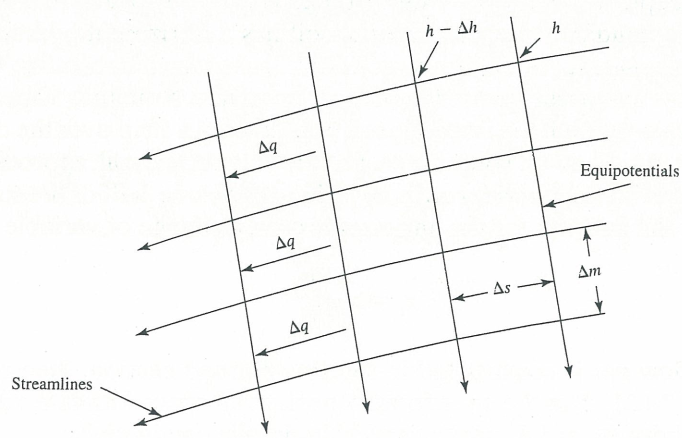


Figure 14.8 Schematic of an orthogonal flow net in an isotropic soil

where $\Delta h$ is the change in hydraulic potential between two equipotentials, and $\Delta s$ is the orthogonal distance between two equipotentials. By applying Darcy's law, the incremental flow between two adjacent streamlines is

$$\Delta q = K\,\Delta m\left(\frac{\Delta h}{\Delta s}\right) \tag{14.17}$$

where $\Delta m$ represents the cross-sectional area for a flow net, of unit width normal to the plane of the diagram. If the flow net is constructed in an orthogonal manner and composed of approximately square elements, then $\Delta m \approx \Delta s$ and

$$\Delta q = K\,\Delta h \tag{14.18}$$

If there are $n$ equipotential drops between the equipotential lines, then

$$\Delta h = \frac{h}{n} \tag{14.19}$$

where $h$ is the total potential change over the $n$ spaces. If the flow is divided into $m$ sections by the streamlines, then the discharge per unit width of the medium is

$$Q = \sum_{i=1}^{m} \Delta q = \frac{Kmh}{n} \tag{14.20}$$

When saturated hydraulic conductivity is known, the discharge can be computed using equation 14.20, with knowledge of the flow-net geometry. Where the flow net has a free surface (or line of seepage), the entrance and exit conditions are useful. A comprehensive discussion of entrance and exit conditions is given in U.S. Department of Interior (1978).

Construction of flow nets is difficult where the hypothetical-flow velocity becomes either infinite or zero. These conditions can occur when: a boundary coincides with a streamline; there is a discontinuity along the boundary that abruptly changes the slope of the streamline; or where a source (or sink) exists in the flow net (e.g., a drain or a well). A description of flow-net construction for these types of flow conditions can be found in Davis and DeWiest (1966) and Viessman et al. 1977.

Flow nets can be constructed in anisotropic media, for which the saturated-hydraulic conductivity in one direction is greater than in another direction. This is the case for most stratified sediments, in which the flow proceeds more easily along the planes of deposition than across them. Figure 14.9 illustrates two flow nets in saturated soils, each taken in a vertical plane at right angles to a drain with the soil saturated to the surface and an impermeable layer at twice the drain depth $d$ ($2d$). Figure 14.9a is for an isotropic soil; whereas figure 14.9b is for the same boundary conditions, except that the soil has a horizontal hydraulic conductivity 16 times its vertical conductivity (anisotropic). Numbers on each streamline indicate the percent of the total flow that occurs to the left of that streamline. Note that 50 percent of the flow that reaches the drain through the isotropic soil originates in a strip over the drain, and covers approximately one-fourth of the source area. For the anisotropic soil, approximately one-half of the flow originates in a much wider strip, covering nearly one-half of the source area.

To construct the flow net for the anisotropic case, a change of variable is made

$$x_t = x\sqrt{\frac{K_v}{K_h}} \tag{14.21}$$

and an isotropic flow net is constructed in the transformed section, then replotted to true scale. In equation 14.21, $x_t$ is the transformed horizontal-space variable for the horizontal hydraulic conductivity $K_h$, and $K_v$ is the vertical hydraulic conductivity.

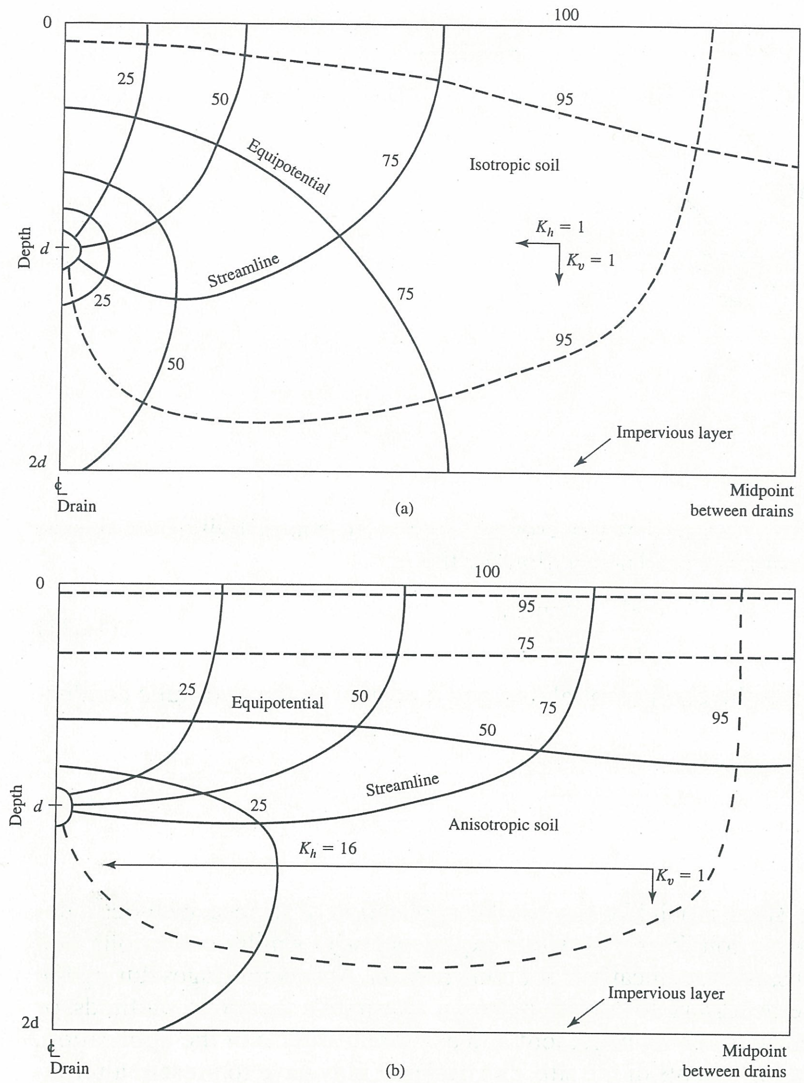


Figure 14.9 Flow nets in (a) isotropic and (b) anisotropic soils

When streamlines from a soil with a given hydraulic conductivity $K_1$ cross the boundary of a soil with a different hydraulic conductivity $K_2$, the streamlines are refracted similar to the optical refraction of light rays as shown in figure 14.10. This refraction adheres to the following law:

$$\frac{K_1}{\tan \theta_1} = \frac{K_2}{\tan \theta_2} \tag{14.22}$$

This relation shows that flow proceeds from a coarse-grained medium (I) to a fine-grained medium (II). The flow elements of figure 14.10 are squares in medium I, but rectangles in medium II. If a flow net with squares on both sides of the boundary and like-flow quantities is required, the potential drops $\Delta h_1$ and $\Delta h_2$ in the media must satisfy

$$\frac{\Delta h_2}{\Delta h_1} = \frac{K_1}{K_2} \tag{14.23}$$

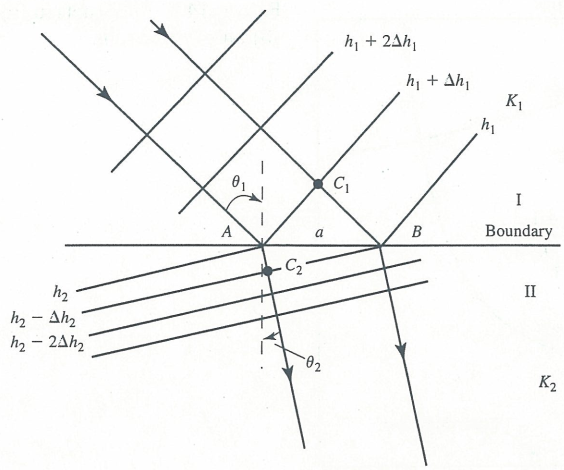


Figure 14.10 Refraction of streamlines at soil boundaries

Equipotentials are also refracted when crossing hydraulic conductivity boundaries, such as two different, horizontal strata. The relation for this is

$$\frac{K_1}{K_2} = \frac{\tan \alpha_2}{\tan \alpha_1} \tag{14.24}$$

where $\alpha$ is the angle between the equipotential line and a normal to the hydraulic conductivity boundary.

## 14.4 DRAINAGE DESIGN

### Elements of Drainage Design

Installation of a drainage system, much like any similar application of science, includes a desired goal; a survey of existing conditions; previous experience with similar conditions; and preparation of designs, plans, and specifications for construction. At several stages during the design procedure, it can be necessary to choose between alternative locations, methods, or materials. The choice depends on the management and economic aspects of the application, as well as on the physical requirements of the site. The designer may have to present alternative methods or intensities of drainage to the owner, so that he or she can make a final choice.

The technical design elements are generally the same for small or large drainage systems, but public and institutional factors are often involved, also. These factors include: the drainage organization (drainage enterprise); legal requirements for rights-of-way and water disposal (or use); financial arrangements; and cost allocation. Drainage projects require complete and detailed documentation of the surveys, plans, and construction.

### Development of Drainage-Design Criteria

Design criteria are developed in two general ways: **(1)** from empirical data collected through evaluation of existing drainage systems; and **(2)** from a theoretical analysis of the problem, applying physical laws and testing the theory through evaluation of existing drainage systems. An example of empirical criteria are the drainage coefficients used in design of drains in humid areas (SCS 1971). Such coefficients are the removal rates for excess water—which provide a certain degree of protection—found by experience with many installed drainage systems. Such protection has been carefully assessed against observed responses; measurements of flow from drainage systems providing good drainage; and measured water-table heights. Because empirical criteria are based substantially on experience and assessments of numerous interrelating factors, care has to be taken in transposing their use from one location to another.

## Drainage Coefficients

The SCS (1971) provides step-by-step methods for applying drainage coefficients for the design of drains. The drainage coefficient is that rate of water removal necessary to obtain the desired protection (or lowering) of the water table from excess surface and subsurface water. In humid areas, it is common practice to express the drainage coefficient for ground water drainage in units (of depth) of water removed in 24 hours. This coefficient is closely related to the climate and infiltration characteristics of the soils; therefore, there is similarity in drainage coefficients within areas of similar climatic and soil characteristics. The reader is referred to SCS (1971) for a detailed treatment of the drainage-coefficient method.

Theoretical analysis applies proven principles (or laws) to problems that have known limiting conditions. The resulting mathematical expression explains the observed action of existing drainage systems, thereby permitting the rational design of new systems. Usually several variable-site factors enter the expression. An example of the theoretical analysis is the Hooghoudt equation (equation 14.12) for spacing subsurface drains (Hooghoudt 1937). In the form of Hooghoudt's equation (given alone) the variables are: hydraulic conductivity of the soil, depth to an impermeable layer; depth to the water table at midpoint between the drains; and the rate water is removed. By substituting known—or estimated—values for these variables, the equation can be applied to a variety of sites, as long as the site conditions are within the limits for which the equation was derived. This last requirement is important when using this kind of theoretical approach. Another method to approximate drain spacing is to use equation $S^2 = 4K/R(h^2 - h_0^2)$. Thus, to determine the required drain spacing to maintain the water table at a desired level: the depth to the impermeable stratum; the desired (or target) height of the water table; average infiltration flux; and $K$ all must be known. Average drain spacing for various soil types is given in table 14.1 Whichever method is used to establish drainage-design criteria, it is evident that its value depends not only on sound analysis of the drainage situation, but also on an evaluation of installed drains to check their performance.

## Theoretical Analysis

Equation 14.12 presented Hooghoudt's equation for spacing of vertical-walled ditches. This equation can be extended to a layered soil and to pipe drains. Rearranging equation 14.12

$$R = \frac{4K(h_m^2 - h_0^2)}{S^2} \tag{14.25}$$

TABLE 14.1 Average Depth and Spacing of Drain Tubes versus Soil*

| Medium | Spacing (m) | Depth (m) | Hydraulic conductivity (cm/day) |
|---|---|---|---|
| Peat | 70 | 2 | 18.5 |
| Sandy loam | 50 | 2 | 9.5 |
| Fine, sandy loam | 35 | 1.5 | 4.3 |
| Loam | 25 | 1.5 | 1.3 |
| Clay loam | 20 | 1 | 0.30 |
| Clay | 15 | 1 | 0.15 |

*Source:* Data from Ghildyal and Tripathi (1987)
*Columns 1–3 represent average values (midrange) based on soil type.

and replacing $h_m^2 - h_0^2$ by $(h_m + h_0)(h_m - h_0)$ and noting (see figure 14.4) that $(h_m + h_0) \cdot (h_m - h_0) = (2h_0 + m)m$. Then,

$$R = \frac{8Kh_0m + 4Km^2}{S^2} \tag{14.26}$$

When $h_0 = 0$,

$$R = \frac{4Km^2}{S^2} \tag{14.27}$$

The $R$ term in equation 14.27 represents the contribution to the drains per-unit area from the soil above the water level in the drain. It follows that the other term in equation 14.26 ($8Kh_0m/S^2$) is the contribution from the soil between the plane of the drain-water level and that of the impermeable boundary. If the hydraulic conductivity above the plane of the drain-water level is $K_1$ and that below is $K_2$, then the solution for such a two-layered soil system is

$$R = \frac{8K_2h_0m + 4K_1m^2}{S^2} \tag{14.28}$$

If the vertical-walled ditches are replaced by circular drain pipes, so that the water level in the drain pipe is the same as in the ditches, the streamlines to the drain are no longer horizontal—as they were for the vertical-walled ditch—but radial. As the streamlines converge on the pipe drain, flow velocity and therefore—by Darcy's law—head loss also, increases. To account for the convergence losses of the pipe drain, Hooghoudt developed a second equation in the same form as equation 14.28, but replaced $h_0$ by an equivalent depth $d$, which is smaller than $h_0$ and is a function of $h$, $S$, and pipe radius $r_0$. If $d$ is substituted for the real depth to the impermeable boundary instead of $h$, the equation for spacing of a pipe drain is

$$R = \frac{8K_2dm + 4K_1m^2}{S^2} \tag{14.29}$$

The diameter of the pipe drain does not have a large effect on drain spacing (Withers and Vipond, 1980). In practice, the drain backfill generally is more permeable than the surrounding soil, and flow is greater than that predicted by the above equations.

The steady-state drainage assumption is invalid when inflow occurs over short, widely separated time periods. This type of situation often occurs when irrigation of an agricultural area or "dosing" of a soil-treatment system causes a rise in the water table, which falls during the remainder of a given time period. The Bureau of Reclamation (U.S. Department of the Interior, 1978) has presented a drainage equation for the case of a fluctuating water table. The basic assumptions for this equation are similar to those for steady flow. These assumptions are: **(1)** the soil is homogeneous and isotropic; **(2)** the problem is two-dimensional; **(3)** streamlines are horizontal, a correction necessary for the effect of convergence to a pipe; **(4)** the velocity along the streamlines is proportional to the slope of the water table; and **(5)** an impermeable boundary exists below the drains.

The solution to such a problem is found from the "heat-flow" equation, and takes the form of a parabola. To arrive at an exact solution, an initial shape of the water-table surface has to be assumed. The Bureau of Reclamation's (U.S. Department of the Interior, 1978) solution assumes that this initial shape is described by a fourth-degree parabola of the form

$$h = \frac{8m}{S^4}(S^3x - 3S^2x^2 + 4Sx - 2x^4) \tag{14.30}$$

where $m$ is the initial height of the water table in meters above the plane of the drains, $S$ is the drain spacing in meters, and $h$ is the height of the water table at a distance $x$ from the drain. A simplified version of the drain spacing equation is

$$S^2 = \frac{\pi^2 KDt}{\phi_d \log_e\left(1.16\dfrac{h_0}{h_t}\right)} \tag{14.31}$$

where $\phi_d$ is the drainable porosity in percent by volume, $D$ is the average thickness (in meters) of the aquifer from the impermeable boundary to the water table, $h_0$ is the initial height of the water table, and $h_t$ is the height of the water table after a time interval $t$. Allowance for convergence can be made by substituting the equivalent depth to the impermeable boundary for the actual depth, as in Hooghoudt's method for steady-state flow.

## 14.5 CASE STUDY: THE FLORIDA EVERGLADES

Drainage in the form of open ditches and canals has been practiced extensively in the Florida Everglades for the past several decades, primarily because the areas now under production were previously under water, and would have remained so if not for man's efforts to tame the land. This is due primarily to the heavy rainfall received in the region (75–175 cm annually) and the desire of sugar cane, sod, citrus, vegetable crops, and cattle industries to produce these products on the very rich, typically nearly saturated soils that predominate in the area. In addition, the increase in population in the region has required greater levels of water control and management to allow for residential development.

For years, many inhabitants of Florida looked at the Everglades as a swamp to be drained, while many others considered it a wonderful ecosystem to be preserved and protected. Before development, the Everglades began in the center of the Florida peninsula (near Orlando) and expanded south through the marshy Kissimmee River area to Lake Okeechobee (meaning "land of big water" in the Seminole Indian language) and on down the peninsula to Miami and Homestead, to the Florida Bay and Gulf of Mexico. The Everglades is really a "river of grass," and was one of the most perfectly balanced ecosystems in the world. Since drainage projects first began about 110 years ago—and in earnest about 60 years ago—the vast areal expanse of the Everglades has steadily decreased. Because of the devastating threat of complete destruction from the drainage projects and onslaught of increasing population, the Everglades National Park was established in 1947 and signed into law by President Harry Truman. However, long before this—beginning in 1837, during the three Seminole Wars—the U.S. Army drove the Seminole Indians deep into the swamp, then could not force them out. Because of the difficult terrain and vicious mosquitos as well as other insects, the Army eventually left the Indians alone.

Slowly, very affluent people began migrating to places like West Palm Beach and other areas further south, toward Miami; many of these looked at Florida as a developer's dream. As a result, politicians began pushing for the transformation of the Everglades and instructed the U.S. Army Corps of Engineers to dredge, dike, divert, and provide flood control and drainage—all for the purpose of creating dry lands for establishing new homes, businesses, industry, and farms.

By the early 1950s, even the Seminole Indians had become involved. Although many did not like what was happening to their habitat, they needed to find employment and wanted to make their homes once again away from the deepest parts of the swamp. As more tourists and entrepreneurs moved into the Dade and Broward County areas (which include the cities of Miami and Fort Lauderdale), the Seminoles set up shop and began selling Indian handicrafts to tourists, serving as guides in the swamp, and staging very popular "alligator wrestling" shows. With a steady population growth, increased pressure was put on the Everglades. More and more water was pumped out, resulting in a loss of over 50 percent of the Everglades' original surface area, as well as the destruction of much wildlife habitat. The drainage and flood-control projects initiated by the U.S. Army Corp of Engineers have made it possible for the inhabitants of Florida to live there. Without these projects and the accompanying mosquito control, as well as current technologies such as air conditioning, very few individuals would want to live in the Everglades region of Florida. Today, approximately 1,500 miles of canals, ditches, and levees scar the landscape and constrict the flow of water, generally from the north to the south.

Prior to the beginning of the drainage projects, rain that fell in the northern part of the Everglades near Orlando produced a gradual rise in the overall water level. The slow flow took about a year to reach the area within and surrounding Everglades National Park, and the flow was very consistent well into the dry season, providing habitat for over 600 species of wildlife and 900 species of plants. Currently—even with the existing level of technology—the U.S. Corp of Engineers and South Florida Water Management District cannot duplicate the natural conditions of flow that existed prior to drainage initiation. This has had a devastating effect on both the Everglades and Everglades National Park, truly about all that remains of the Florida Everglades; the Park is comprised of about 1.5 million acres. In addition to the ditches and canals, it was decided that a plant that requires an abundant amount of water could help dry the "Glades," thus melaleuca trees were imported and now grow as noxious trees all over south Florida. Many counties have declared war on them by physically cutting them down and spraying with herbicides, but they are very well adapted and persistent, making control difficult.

The drainage and flood-control projects have created man-made droughts in the region, killing off large areas of cypress and saw grass swamps. Additionally, flow of freshwater from the main peninsula into Florida Bay had been greatly curtailed, resulting in hypersalinity of the Bay. This resultant salinity has killed sea grass and many other marine organisms, and denuded the bay bottom. Compounding the problem, Lake Okeechobee has become a storage basin for providing water for the inhabitants of South Florida, but agriculture, cattle, and related industries around the Lake have contributed large amounts of phosphorus and nitrates from fertilizers and animal waste to the Lake itself. The phosphorus has caused eutrophication in many areas around the Lake. Activity from sod, citrus, vegetable crop, and sugarcane industries have contaminated the water that drains into the Everglades region with nitrates, phosphates, herbicides, and pesticides, further compounding the devastating effects of both low water levels and contamination.

During the 1980s, the U.S. Congress finally decided they had to act to save the Everglades and passed the Everglades National Park Protection and Expansion Act, which was signed into law by President George Bush. More recently, an "Everglades Initiative" has begun with funding from Congress. The goal of the initiative is to attempt to solve the problems that are causing the devastation of the Everglades. Many scientists are cooperating in the project from agencies such as the U.S. Geological Survey, U.S. Army Corps of Engineers, South Florida Water Management District, University of Florida, Florida State University, University of Miami, and many other state, federal, and local representatives. However, because so many agencies are involved, lack of bureaucratic coordination makes cleanup still more difficult. This has resulted in a federal task-force being established for coordination purposes.

The Everglades Initiative has obtained solutions to some of the water-management problems faced by South Florida, in terms of amounts of storage before pumping from one area to another. In the beginning of the drainage projects, the U.S. Army Corps of Engineers straightened the Kissimmee River for more effective flow. Prior to this, it had been a long, meandering river. Because of the initiative, it has been discovered that the river (in its original course and form) acted as a filtering system for contaminants, especially fertilizers used in agriculture. As a result, the river is being returned to its natural course and the contaminant level downstream is gradually being reduced. Although positive actions are occurring, it should be remembered that it took decades to cause the problem, and so will likely take several decades to correct it.

The main predicament in this instance is that—although drainage of wet areas is ideal for construction of businesses, homes, farms, and other purposes—a plan should be developed that will allow harmony between man and the existing environment. The Everglades is a very large and complex ecosystem. As with other projects or ecosystems, it should have been thoroughly studied before any drainage projects were developed or initiated; due to impatience and greed for development, this was not done. This is not unique to the Florida Everglades, but is occurring worldwide. In each instance, however, there is a price to pay. Whenever man competes with the environment, the environment is usually devastated and eventually, the populace within the region also suffers. Economically, it would be much cheaper to develop a sound plan before starting such a project than to pay for the results afterward. However, the criteria by which such a plan might be judged can be highly subjective. For example: had the canals and ditches been sized, constructed, and located in different areas—then perhaps the need to purchase additional areas from private citizens for wetlands control; to pay hundreds of agencies; contractors, and scientists to investigate the problem; and to spend countless hours trying to find solutions—the problem could have been avoided. Although drainage projects can serve a very useful purpose, simply knowing how to perform drainage is not enough. We need to consider both the purpose of the drainage and the overall effects of the drainage on the environment. If we learn from past mistakes, we can minimize costly future mistakes.

## SUMMARY

This chapter has briefly discussed the basic principles involved in drainage and some of the common problems associated with it. While drainage can be thought of as a water-quality issue, this is not entirely true. Essentially, the effects of drainage can be harmful to the environment, but the causes of drainage are hydraulic in principle. The reader is urged to consult the references for texts and other articles related to drainage principles.

## ANSWERS TO QUESTIONS

**14.1.** Using figure 14.2 as an example and equation 14.4, we obtain:

$$q_r = \pi(2.4 \times 10^{-3}\,\text{m/s})\frac{[(14.2\,\text{m})^2 - (12\,\text{m})^2]}{\ln\left(\dfrac{40\,\text{m}}{80\,\text{m}}\right)} = -0.63\,\text{m}^3\,\text{s}^{-1}$$

What does the negative sign indicate?

**14.2.** Using equation 14.9, we obtain:

$$h_x = \sqrt{(4\,\text{m})^2 - \frac{25\,\text{m}}{100\,\text{m}}[(4\,\text{m})^2 - (3.2\,\text{m})^2]} = 3.82\,\text{m}$$

## ADDITIONAL QUESTION

**14.3.** Approximate the drain spacing to be used for a landfill; assume $K = 2.3 \times 10^{-5}$ m/s, that $R = 0.003$ m/d, $h = 4$ m, and $h_0 = 3.2$ m.