NATIONAL ENGINEERING HANDBOOK

SECTION 16

DRAINAGE OF AGRICULTURAL LAND

CHAPTER 1. PRINCIPLES OF DRAINAGE

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CHAPTER 1. PRINCIPLES OF DRAINAGE

Scope

This chapter presents basic principles and theories concerning the removal of excess water from agricultural land. In various branches of science, certain laws of flow have been discovered that apply to the movement of water on the land surface, within channels, and through the soil. Also, much empirical information providing a basis for the empirical methods of drainage design has accumulated over the years. Review of these fundamentals as they apply to drainage should be helpful to the engineer in correctly appraising drainage problems in the early stages of their investigation and working out their practical solution. A knowledge of drainage principles is necessary in developing local standards for drainage design. Existing drains need to be evaluated. Where local information for design criteria is lacking, experience from other places may need to be adapted for local use.

Although the fundamental equation for flow in saturated soils--Darcy's Law (1)* --has been known for many years, its application to most drainage problems is complex. Several approximate methods for solving these subsurface-flow problems have been developed. The basic assumptions in these methods are presented briefly in this chapter. Their limitations in practical application to field situations are also discussed.

Elements of Drainage Design

Generally, the installation of a drainage system, like any similar application of the sciences, includes a desired goal, a survey of existing conditions, previous experience with similar conditions, and preparation of designs and plans. In Soil Conservation Service operations, the principal elements of drainage design are crop requirements, site investigations, design criteria, and plans and specifications. Each of these elements will be treated in detail in this and in other chapters of this Section of the National Engineering Handbook.

At several points in the design procedure, it may be necessary to choose between alternate locations, methods, or materials. The choice depends on the management and economic aspects of the farm or ranch as well as on the physical requirements of the site. The designer may need to present to the landowner alternate methods or intensities of drainage, so that the owner may make the final choice.

The same technical design elements for individual farm systems are present for large group-drainage systems, but public or community-type factors also are involved. These factors include the drainage organization (drainage enterprise), legal requirements for rights-of-way and water disposal or use, financial arrangements, and cost allocation. Such projects require complete, detailed documentation of the surveys, plans, and construction.

*Numbers in parentheses refer to references listed at end of each chapter.

Classification of drainage methods

The methods used for land drainage may be classified in two broad categories--surface drainage and subsurface drainage--depending on the way the water is removed.

1. In surface drainage, land surfaces are reshaped as necessary to eliminate ponding and establish slopes sufficient to induce gravitational flow overland and through channels to an outlet. Surface drainage may be divided into works which

    a. remove water directly from land by land smoothing, land grading, bedding, and ditching

    b. divert and exclude water from land by diversion ditches, dikes, and floodways.

2. In subsurface drainage, ditches and buried drains are installed within the soil profile to collect and convey excess ground water to a gravity or pumped outlet. The drop in pressure resulting from discharge induces the flow of excess ground water through the soil into the drains.

    a. Interceptor drains are used to prevent entry upon the land when ground water moves laterally. Drains are oriented approximately at right angles to the direction of ground-water flow.

    b. Relief drains are used when land surfaces are nearly flat, flow velocities low, or interception of ground water ineffective. Drains are commonly (but not necessarily always) oriented approximately parallel with the direction of ground-water flow.

Development of drainage-design criteria

Design criteria are developed in two general ways: (a) from empirical data collected through evaluation of existing drainage systems, and (b) from a theoretical analysis of the problem, applying known 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. Such coefficients are the removal rates for excess water, found by experience with many installed drainage systems, to provide a certain degree of crop protection. Such protection has been assessed carefully against observed crop response and production, measurements of flow from drainage systems providing good drainage, and measured heights of water table. Since empirical criteria are based substantially on experience and assessments of numerous interrelating factors, care must be taken in transposing their use from one locality to another.

Theoretical analysis applies proved principles or laws to problems having known limiting conditions. The resulting mathematical expression explains the observed action of existing drainage systems and permits the rational design of new systems. Usually several variable site factors enter the expression. An example of the theoretical analysis is the ellipse equation for spacing subsurface drains in irrigated land, where known site characteristics are accounted for in the equation. In one form of the ellipse equation, the variables are hydraulic conductivity of the soil, depth to impermeable layer, depth to the water table at midpoint between the drains, and rate water is to be removed. By substituting known or estimated values for these factors, the equation may 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 all important in using this kind of theoretical approach.

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 evaluation of installed drains to check their performance.

Types of Drainage Problems

Successful drainage of a wet area depends on a correct diagnosis of the problem. At some sites, a brief field study and comparison with previous installations under similar conditions may be a sufficient basis for design. More complex drainage problems require more detailed reconnaissance and preliminary surveys to determine the source of damaging water, how water reaches the wet area, and what design criteria apply. The drainage system may be designed, however, only after the nature of the problem has been identified.

The following typical drainage problems have been divided into surface and subsurface problems for convenience. Actually, wet land may involve both surface and subsurface water, and the drainage design should consider their interdependence.

Surface-drainage problems

Flat and nearly flat areas of land are subject to ponded water caused by:

1. Uneven land surface with pockets or ridges which prevent or retard natural runoff. Slowly permeable soils magnify the problem.

2. Low-capacity-disposal channels within the area which remove water so slowly that the high water level in the channels causes ponding on the land for damaging periods.

3. Outlet conditions which hold the water surface above ground level, such as high lake or pond stages, or tidewater elevations.

Sources of surface water are rainfall or snowmelt on the area itself, irrigation-surface waste, runoff or seepage from adjoining higher land, or overflow from stream channels.

Surface-drainage methods, such as land grading or smoothing and field ditches, are used on fields to collect and convey surface water to natural channels or constructed disposal systems. Inadequate outlets may require downstream-channel improvement, levees with culverts and flapgates, or drainage pumps. Diversion systems are efficient in preventing or reducing the ponding of surface water where the source is outside the area to be protected. These and other features of surface-drainage systems will be described more fully in other chapters.

Subsurface-drainage problems

Subsurface-drainage problems arise from many causes. Flatland tends to be poorly drained, particularly where the subsoil permeability is low. There are many wet areas, however, where there is no evident connection between the area of seepage, or a high water table, and the topography of the site. High water tables may occur where the soil is either slowly or rapidly permeable, where the climate is either humid or arid, and where the land is either sloping or flat.

For these reasons, it is convenient to classify subsurface-drainage problems by the source of excess ground water and the way it moves into and through the problem area. This method of identifying subsurface conditions is especially useful for the more complex drainage problems because it also indicates the kind of drainage system needed. The reconnaissance and preliminary surveys are carried out to obtain the needed information on ground-water occurrence and other site conditions. Detailed information is in Chapter 2, Drainage Investigations. As experience with subsurface-drainage problems accumulates for a given area, the amount of preliminary information needed to identify certain problem types usually is reduced. New areas or new kinds of drainage problems require greater emphasis at the preliminary stage of planning.

The following examples illustrate some of the more important types of subsurface-drainage problems. Particular emphasis is given to the source and direction of ground-water flow. Detailed design of drainage systems for subsurface drainage is discussed in Chapter 4, Subsurface Drainage. Refer to the figures in Chapter 4 for illustration of most of the drainage problems described below.

Basin-type free-water table

In valley bottoms and on wide benchlands, the free ground water saturates the sediments down to the first impervious barrier. Typically, the water table slopes gently downvalley. This large, very slowly moving body of ground water is fed by springs, surface streams, or subsurface percolation around the perimeter of the valley; and by infiltrating rainfall, irrigation losses, or surface runoff on the valley floor itself. Eventually, the ground water discharges effluent seepage at streambanks or at the ground surface in low areas, or except for ground water used by plants or that pumped from wells, it escapes through aquifers at the lower end of the valley or benchland. Height of the water table fluctuates with the seasonal variation of accretions to the ground-water basin. The general slope of the water table varies only slightly in response to these changes in inflow. Where salts are present in the soil, they tend to move upward to the surface as capillary rise replenishes the evaporation from the ground. Phreatophytes grow where the water table is close to or at the surface.

Relief drains may be used to lower the water table in such areas, unless soil permeability is too low. The ground-water slope is too nearly flat and the pervious sediments are too deep for efficient interception (except, perhaps, at the sides of valleys near the base of the hills or the alluvial cones). Where economically feasible, pumped-drainage wells are sometimes used to lower the basin-type water table.

Water table over an artesian aquifer

Ground water may be confined in an aquifer so that its pressure surface (elevation to which it would rise in a well tapping the aquifer) is higher than the adjacent free-water table. The pressure surface may or may not be higher than the ground surface. Such ground water is termed artesian. Pressure in the aquifer is from the weight of a continuous body of water extending to a source higher than the pressure surface. Leaks at holes or weak points in the confining layer above the aquifer create an upward flow, with hydraulic head decreasing in the upward direction. The ground water moves in response to this hydraulic gradient and escapes as seepage at the ground surface above, or it escapes laterally through other aquifers above the confining layer.

A water table supported by artesian pressure usually is more difficult to lower and maintain at the desired height than a water table not subject to such pressure. This is because water is continuously replenished from the higher source and because it is difficult to remove or control water at the source. Wet areas overlying water under artesian pressure require relatively deep and closely spaced drains, relief wells, or pumped-drainage wells that tap the aquifer. Such areas may be impractical to drain.

The drainage system required to control artesian flow may depend on the kind of underlying material. The upward flow from the source aquifer may reach the water table through a stratum of fairly uniform material, or it may pass through fractures or other narrow openings in sandstone, clay, lava, limestone, or other materials that in themselves are practically impermeable. Surface seeps in some places are caused by artesian flow that wells up through relatively small openings in the confining material, causing ground-water mounds or surface seeps. This kind of seep usually may be drained by placing a relief drain as deep as practicable through the seepage zone. Additional intercepting drains may be needed to pick up flow that escapes laterally above the confining layer.

Perched-water table

In stratified soil, a subsurface-drainage problem may be caused where excess water in the normal root zone is held up by a layer of low permeability so that the perched water is disconnected from the main body of ground water. This may occur when surface sources build up a local water table over the slowly permeable layer. Lateral percolation is too slow to drain the perched water naturally.

Drainage systems for perched-water tables are based on the particular site conditions. Usually they consist of relief drains, but an interception drain may be effective in cutting off lateral seepage into the wet area. Theoretically, perched water could be drained downward by drilling vertical drains (wells) through the restrictive layer. A collection-drain system probably would be necessary, however, and the vertical drains might be impractical outlets for economic or other reasons. Perched-water tables in irrigated areas may be subject to control by reducing seepage from canals, by improving irrigation practices, or by providing adequate surface drainage.

Lateral ground-water flow problems

This group of subsurface-drainage problems is characterized by more or less horizontal ground-water percolation within or toward the crop-root zone. The flow pattern is strongly influenced by soil stratification and other natural barriers to flow.

Adjacent soil layers often have permeabilities that differ a hundred or a thousand fold. According to Darcy's law of flow, the effective velocity under a given gradient varies directly with the permeability. Flow of ground water is discussed further in the section on "Subsurface-Drainage Principles." All significant flow may be limited to the more permeable layers. The depth, orientation, and inclination of the strata determine the drainage method and location. For example, hillside seepage may appear where ground water moves laterally over bedrock or over a layer of fine sediments to a point where it emerges at the surface. One or more intercepting drains may be used to cut off the flow which otherwise would reach the root zone.

Alluvial fans and valley bottoms commonly contain sand or gravel deposits. These occur in a variety of ways, as in deep extensive layers, narrow "stringers" (old streambed locations), lenses, or in highly stratified soil profiles. Such rapidly permeable deposits may serve as channels for ground-water movement in some places at high rates of flow. A soil layer of low permeability overlying such an aquifer may create a degree of confinement, which in turn develops an upward hydraulic gradient, particularly if the lower end of the aquifer is closed or of reduced permeability. Interception drains are effective where the aquifer is close enough to the surface so that it is feasible to cut off the flow. Relief wells or pumping may be used where interception is not practical.

Subsurface soil masses of low permeability, such as clay lenses and offshore clay bars formed in the geologic past, are local barriers to ground-water flow. They may cause the water table to be held to a high level and the flow to escape around or over the barrier. Permeable layers that become thinner or gradually decrease in permeability in a downstream direction have a similar effect on the water table. Drains placed just upslope from the restriction usually are effective in these situations. Irrigation canal seepage creates another kind of lateral ground-water flow problem. An intercepting drain at the toe of a canal bank or river levee may cut off much of the flow that would reach the wet area where a horizontal barrier forms a convenient "floor" for interception. However, the designer must consider the steeper hydraulic gradient such a drain causes and evaluate its effect on the canal-seepage loss and on the stability of the embankment against sloughing or piping. River seepage through or under levees creates similar problems.

These examples illustrate the unlimited variety of subsurface-drainage problems. The principles of interception, relief, or pumped-well drainage may be applied to each according to the pattern of subsurface flow. The pattern of flow becomes known from a field investigation of soil stratification, water source, and water table or pressure data.

Differences in Drainage in Humid and Arid Areas

Drainage in humid areas has to do largely with excess water resulting from precipitation; in arid and semiarid areas, the need for drainage arises principally from irrigation, with foreign ground water an important source in some areas.

Surface-drainage systems may be required in either humid or in irrigated areas. Surface drainage is usually an integral part of irrigation systems on slowly permeable soils or in areas of high precipitation rates.

The purpose of subsurface drainage is to lower the water table to a point where it will not interfere with plant growth and development. The minimum depth at which the water level should be maintained varies according to both the crop requirement and the soil. One of the principal factors in the height of the water table in arid areas is control of salinity and alkalinity in the soil and ground water. This is a major reason for the difference in the subsurface drainage of humid and of arid climates.

The depth of drains in humid climates is generally 3 to 5 feet. Water is relatively pure, there usually is a natural excess of water over plant requirements, and there is a net downward movement of ground water.

Soils in semiarid or arid climates require subsurface drains at least 5 to 7 feet deep. Most of the water needed by the crop is added by irrigation. Usually ground water is somewhat saline because of salts in the soil, the irrigation water, or both. A water table as high as 24-30 inches below the surface, suitable in many humid areas, would create a harmful salt concentration in the root zone in arid areas.

Crop Requirements

Effects of excess water on crops

The growth of most agricultural crops is sharply affected by continued saturation of any substantial part of the root zone or by ponded water on the surface. Poorly drained soils depress crop production in several ways:

1. Evaporation, which takes heat from the soil, lowers soil temperature. Also, wet soil requires more heat to warm up than does dry soil, due to the high specific heat of water as compared to that of soil. Thus, the growing season is shortened.

2. Saturation or surface ponding stops air circulation in the soil and prevents bacterial activity.

3. Certain plant diseases and parasites are encouraged.

4. High water table limits root penetration.

5. Soil structure is adversely affected.

6. Salts and alkali, if present in the soil or ground water, tend to be concentrated in the root zone or at the soil surface.

7. Wet spots in the field delay farm operations or prevent uniform treatment.

Drainage requirements determined by crops

Different crops have widely differing tolerances for excess water, both as to amount and time. While water itself may not be injurious to plant roots, saturation of the root zone results in an oxygen deficiency and accumulation of toxic gases. A short term of oxygen deficiency can reduce water uptake, nutrient uptake, and root respiration and build up toxins which leads to death of cells and roots, and, if extended, the death of the plant itself. However, complete saturation of roots over an extended period may cause no serious damage if it occurs during dormant periods of plant growth or flow from drainage is sufficient to supply some oxygen and remove toxic gases. The designer of a drainage system recognizes these differences in crop requirements by selecting an appropriate degree or intensity of drainage (often termed the drainage requirement) for the site. The drainage requirement is based on (a) the maximum duration and frequency of surface ponding, (b) the maximum height of the water table, or (c) the minimum rate at which the water table must be lowered. The local drainage guide indicates the drainage criteria required for various crop-soil combinations. Further information and guidance can be obtained from reports of continuing research on effects of flooding, water table depths and soil gases on agricultural crops (2).

Crop growth and the water table

The water table may be defined as the upper surface of the saturated zone of free, unconfined ground water. (A more accurate definition has been made in terms of water pressures and film tensions.) The soil-moisture content for a significant height above a water table is substantially greater than field capacity. For this reason, plant-root growth is affected by a water table much more than the height of water table alone indicates.

Another important feature of water tables is their fluctuation, both seasonal and short-period. Water tables are seldom static. They respond to additions and depletions of ground water from natural or artificial causes. Sources such as distant-influent seepage from precipitation and streamflow are seasonal, and their effects on the wet area may be delayed for months or even years. Direct precipitation and irrigation-percolation wastes, of course, may change the water-table height almost immediately.

Pumping from deep wells may cause a gradual lowering of the water table as water is taken from a large basin of free ground water. In other areas, pumping may make significant immediate changes in the height of water table due to pressure changes in confined water which "supports" the water table.

In the field of drainage, it is important to think of the true relation of the water table to root development and crop production. The term "water table" is sometimes misleading. Capillary forces and fluctuating ground-water flows result in soil-moisture conditions that are different from the erroneous concept of a sharp break from saturation to a much lower moisture content such as field capacity. A considerable amount of ground water is present and moves through the saturated and nearly saturated soil immediately above the water table.

Surface-Drainage Principles

Surface drainage is accomplished in two general ways: (a) excess water is collected and removed from the ground surface within the area affected; or, (b) by means of construction outside the area, water is diverted away from the area to be protected. In either case, the system is conveniently divided into three functional parts:

1. Collection system. Bedding, field ditches, row ditches, or diversion ditches are part of the system that first picks up water from the land.

2. Disposal system. This is the part of the system that receives water from the collection system and conveys it, usually in an open ditch, to the outlet.

3. Outlet. This is the end point of the drainage system under consideration.

Fundamentally, surface drainage uses the potential energy that exists due to elevation to provide a hydraulic gradient. The surface-drainage system creates a free-water-surface slope to move water from the land to an outlet at a lower elevation. The design of collection systems, such as bedding or field ditches in flatland is based mostly on empirical criteria; i.e., the design is based on field observations of drainage-system performance. The rate at which surface water must be removed from the land is a function of the crop requirement and the source of excess water.

The water-surface profile is the starting point in the design of the disposal-system ditches. In open ditches, the hydraulic gradeline is the water-surface profile. Usually, the survey of the surface-drainage outlet establishes the lower hydraulic-control point for the design of the disposal system. Other control points are the land elevations at critical low areas and restrictions in the ditch, such as culverts, bridges, and weirs. The design of a disposal system involves, therefore, the computation of a water-surface profile through the control points, for known or trial ditch cross sections.

Bernoulli's theorem is used to compute the hydraulic gradeline for steady-flow conditions. Losses of head due to friction are computed by an open-channel formula, usually Manning's. Head losses at constrictions causing nonuniform flow, such as at bridges or culverts, are computed by formula using appropriate loss coefficients. The field survey must include sufficient information for evaluation of the roughness and cross-section factors, including head loss through obstructions.

In drainage design, nonsteady flow may occur as in discharge into tidal streams. Such problems may sometimes be solved by dividing time into convenient increments within each of which the varying flow may be taken as a constant, mean-flow rate.

Subsurface-Drainage Principles

Forms of soil water

Gravity water

Water that is free to move downward through the soil by the force of gravity is called gravity water. At saturation, all pores are filled and the soil holds the maximum amount of water that can be absorbed without dilation. (Dilation is the bulking or flotation of soil grains.)

Capillary water

Capillary water is held in the soil against gravity. It includes the film of water left around the soil grains and the water filling the smaller pores after gravity water has drained off.

If gravity water is allowed to drain from a saturated soil (not influenced by a water table), the quantity of capillary water held is called field capacity. Close to the water table, the quantity of capillary water held in a granular material is greater than field capacity. The amount of water held at a given point depends on the distance above the water table, as well as on the soil pore sizes and shapes. This form of capillary water is sometimes called fringe water. Just above the water table, fringe water completely fills the capillary pores, and in this relatively narrow zone, saturation occurs at slight negative pressure (tension). Openings so large that capillary rise in them is negligible are called supercapillary openings. Examples of materials containing supercapillary openings are gravel, boulders, some forms of lava, structurally fractured rock or clay, solution openings in rock, and soil containing root holes.

Hygroscopic water

When a granular material is completely dried by heating, then exposed to the air, it absorbs atmospheric moisture. This water, when in equilibrium with the atmospheric moisture, is called hygroscopic water.

The water table 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, water pressure is at atmospheric pressure. Thus the water table is the imaginary surface separating capillary water (under tension) from the free ground water below.

The water table in granular material is not an observable, physical surface because capillary water saturates the material just above the water table and decreases in amount gradually upward. An exception is water in supercapillary openings, in which the water is in equilibrium with the atmosphere. Auger holes and piezometers are supercapillary in size and open to the atmosphere, and so they fill to the true water-table level when bored or driven just into the water table.

When an auger hole is bored to locate the water table in a fine or medium-textured soil, the observer finds it difficult to recognize the top of the saturated zone because of the gradual change from moist to saturated soil. Also, it may take hours or even days for an auger hole to register the water table in slowly permeable soils. Small wells or piezometers react more quickly than large ones because less water need flow through the soil to fill the smaller openings.

Water in the capillary fringe may be a significant proportion of ground water moving toward subsurface drains--as much as 20 percent or more under some conditions.

An auger hole or pipe should penetrate the saturated zone only a short way if the water-table elevation is to be measured accurately. This is particularly important where upward flow or confined flow would be tapped by a deeper hole. An auger hole that penetrates two or more aquifers in a stratified soil containing confined water would register the highest hydraulic head modified by leakage from the aquifers of higher hydraulic head to those of lower head.

These characteristics of the water table have a significant bearing on the kind of field measurements to be made, on the devices used to make the observations, and on the interpretations of data for drain-system design.

Principles of flow in the saturated zone

Flow of water in the saturated zone involves mechanical, chemical, and thermal energy, and molecular attraction. A full discussion of soil-water movement is in numerous publications on soil physics and soil permeability. Here only the mechanical forces tending to move water through soils will be considered.

Hydraulic head

In saturated flow through soils, as in open channel flow, the total energy content (E) of water is the sum of the kinetic, pressure, and gravity components. As expressed in Bernoulli's equation:

$$E = \text{kinetic energy} + \text{pressure potential} + \text{elevation potential.}$$

Velocities in ground-water flow are almost always low, making the velocity (kinetic) term negligible. Essentially, then, the energy causing flow is the sum of the two potential energy items, pressure and elevation. This potential for flow is called "hydraulic head."

In the English system of units, energy is expressed foot-pounds. Hydraulic head is conveniently expressed as the energy content per unit weight of water, or foot-pounds per pound, which is feet, dimensionally. Thus, the hydraulic head (fig. 1-1), at a given point is:

$$H = \frac{P}{W} + Z$$

where H = hydraulic head, ft.; P = pressure at the point referred to the atmosphere, lb/ft^2; W = specific weight of the water, lb/ft^3; and Z = elevation of the point above a datum, ft.

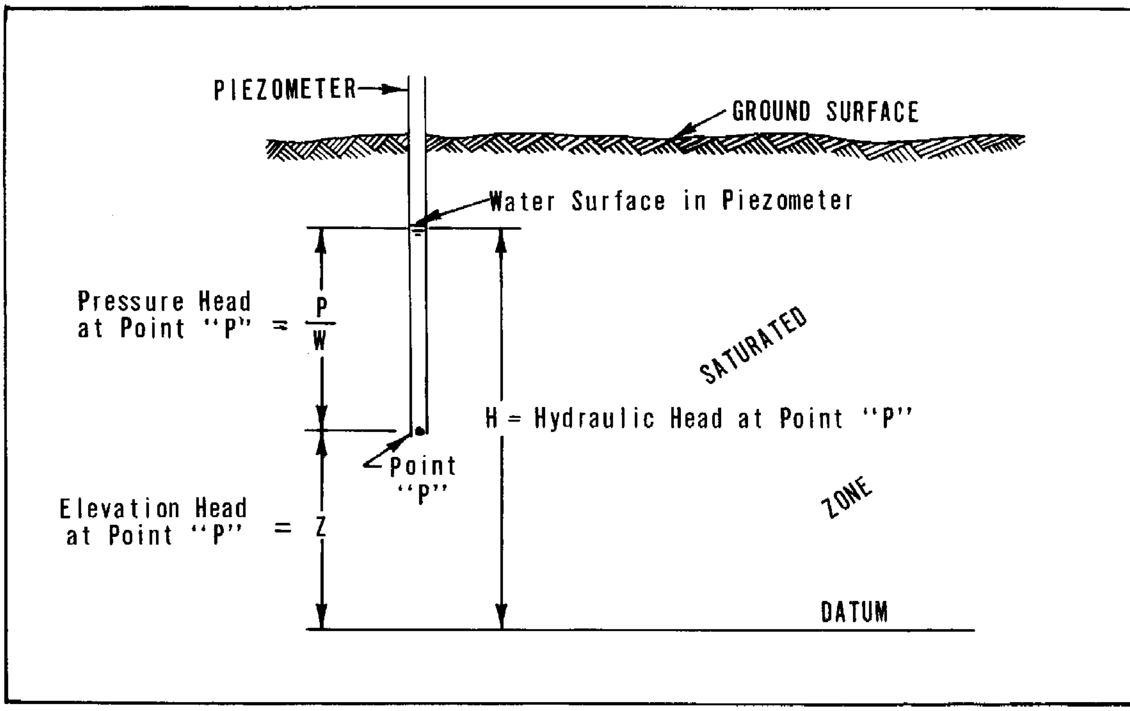

Figure 1-1, Illustration of hydraulic head

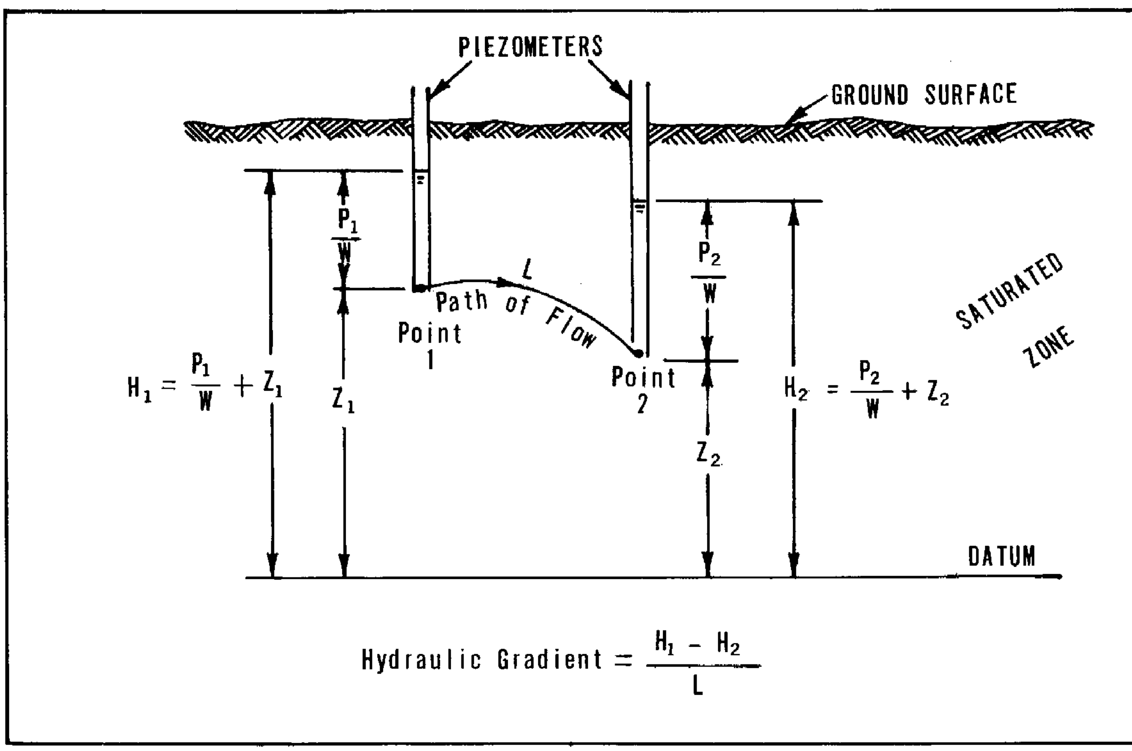

Figure 1-2, Illustration of hydraulic gradient

Piezometers convert pressure at a point to a physical pressure head the height of the water column in the piezometer. This height is not hydraulic head, since it is only the term P/W in the equation. To find the hydraulic head at the point (lower end of the piezometer) the elevation (Z) of the point above the datum must be added to the pressure head. The elevation of the water surface in the piezometer, referred to the datum, is P/W + Z, and so is numerically equal to the hydraulic head at the lower end of the piezometer.

Hydraulic gradient

Ground-water flow results from the force "available" to move water through the soil due to differences in energy content; i.e., differences in hydraulic head. This is analagous to the flow of heat or electricity, where flow is due to differences in temperature (heat potential) or differences in voltage (electrical potential). Hydraulic gradient is the difference in hydraulic head at two points, divided by the distance between the points measured along the path of flow (fig. 1-2). In this figure, the plane of the paper is a vertical surface through the path of flow.

$$\text{Hydraulic Gradient} = \frac{H_1 - H_2}{L}$$

$$= \frac{\left(\frac{P_1}{W} + Z_1\right) - \left(\frac{P_2}{W} + Z_2\right)}{L} \qquad \text{(Eq. 1-1)}$$

where L = distance measured along the path of flow, ft.

Subscripts 1 and 2 refer to the points of the higher and lower hydraulic head, respectively; other units are defined in the preceding paragraphs.

In a given flow system (fig. 1-3) each "particle" of water in the system has its corresponding hydraulic head. All particles or points, of a given hydraulic head (H_1) lie in the corresponding equipotential surface (H_1). All points of hydraulic head H_2 lie in the equipotential surface H_2, and so on. The force tending to produce flow acts in the direction of greatest decrease in hydraulic head; i.e., normal to the equipotential surface, as F at point P, or F' at point P'. The magnitude of this force is proportional to the hydraulic gradient at the point.

At the water table, the pressure component of energy (P/W) is zero relative to atmospheric pressure. Therefore, the hydraulic head H of a point at the water table is Z, the elevation of the point above the datum.

Water-table slope represents the hydraulic gradient of flow only under certain conditions. Hydraulic gradient may differ greatly from the water-table slope where there is significant upward or downward component of flow such as in the vicinity of pumping wells or subsurface drains, in flow from artesian aquifers, and in unsaturated seepage from canals. As shown in figure 1-4, slope of the water table is $\frac{H_1 - H_2}{S}$ (or tangent of the angle) by definition. S is the horizontal projection of the path of flow L. But the hydraulic gradient is $\frac{H_1 - H_2}{L}$ (or sine of the angle). On flat gradients and with parallel flow, the water-table slope is essentially the hydraulic gradient because S = L nearly (tangent is nearly the same as the sine for small angles). It should be noted that the

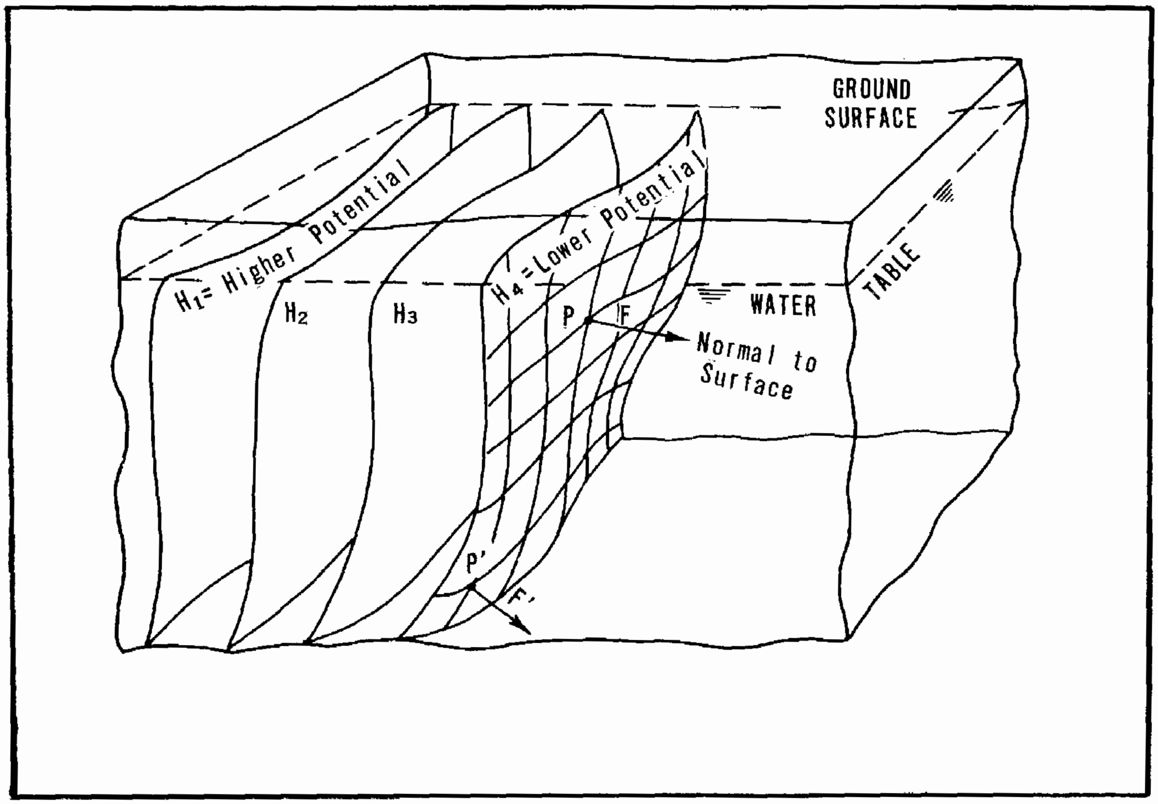

Figure 1-3, Equipotential surfaces

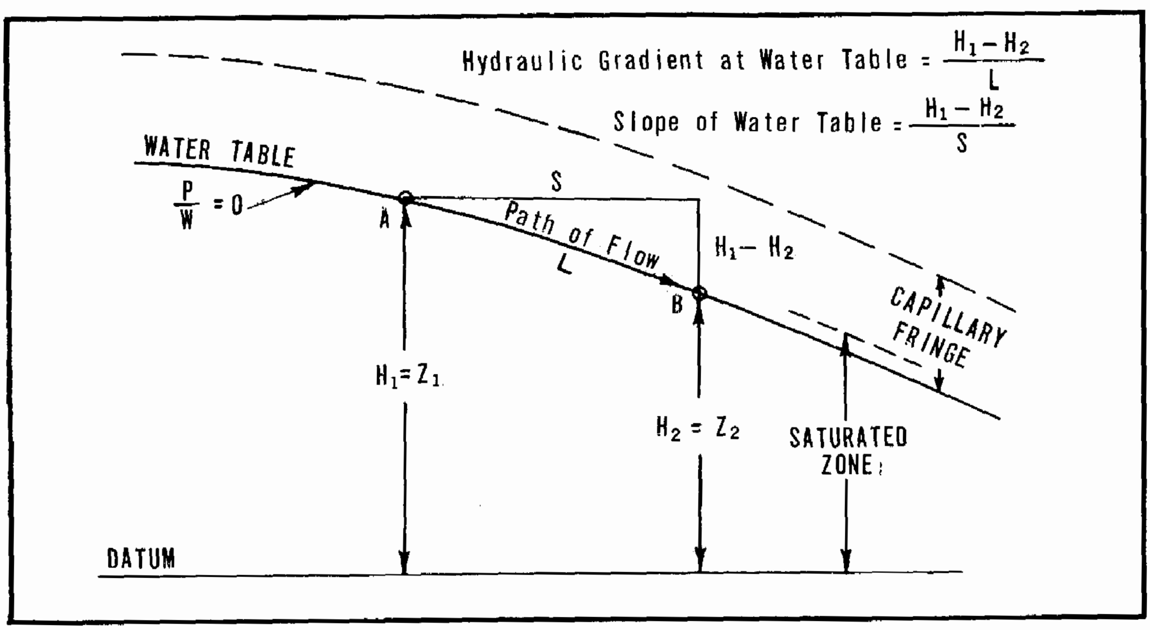

Figure 1-4, Difference between hydraulic gradient and slope of the water table water table is not invariably a path of flow; water may be flowing down from or up into the unsaturated zone, thus crossing the water table.

Paths of flow (streamlines)

The force due to hydraulic gradient tends to move water along the line of force normal to the equipotential surfaces. Whether the flow moves actually 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," i.e., if its hydraulic conductivity is the same in all directions, the path of flow will be along the lines of force and perpendicular to the equipotential surfaces.

If the soil has a higher hydraulic conductivity in one direction than in another direction, the path of flow will not be perpendicular to the equipotential surface. Such a soil is said to be "anisotropic." Water-laid soils often have bedding planes or particle orientation causing them to be anisotropic. The paths of flow in anisotropic soils will be perpendicular to the equipotential surfaces at points where the lines of force are exactly parallel to or normal to the bedding plane. A soil with microstratification (thin layers with widely different hydraulic conductivities) will cause water to flow in a way similar to the flow in an anisotropic soil.

Many flow systems common in soil drainage may be studied in two dimensions rather than three, because of uniformity in the third dimension. Equipotential lines then represent the intersection of the plane of the paper with the equipotential surfaces. An example of this representation is the flow into a system of parallel drains, where the flow is at right angles to the drains.

A two-dimensional system on the X-Y plane is illustrated in figure 1-5. The soil is isotropic (hydraulic conductivity is uniform in all directions) in figure 1-5. Figure 1-6 shows another soil, with a line of force normal to the equipotential line and at an angle b to the vertical axis Y. But in this soil, which is anisotropic, the horizontal hydraulic conductivity K_h exceeds the vertical hydraulic conductivity K_v. The direction of flow is not along the line of force, but along a line closer to the horizontal axis. It may be shown that the angle the path of flow makes with the horizontal is

$$a = \tan^{-1} \frac{K_v}{K_h \tan b}$$

Thus, the flow pattern may be computed and drawn for an anisotropic system if the equipotential lines are known, and if the relative hydraulic conductivities K_v and K_h are known.

In analyzing the direction of flow of ground water, the investigator should be aware of the effect of anisotropic soils on the flow pattern.

Flow nets and boundary conditions

Flow in the saturated zone often is studied by means of graphic representations of hydraulic head and paths of flow. Cross sections are taken through the problem area, usually in vertical planes. Lines connecting points of equal hydraulic head

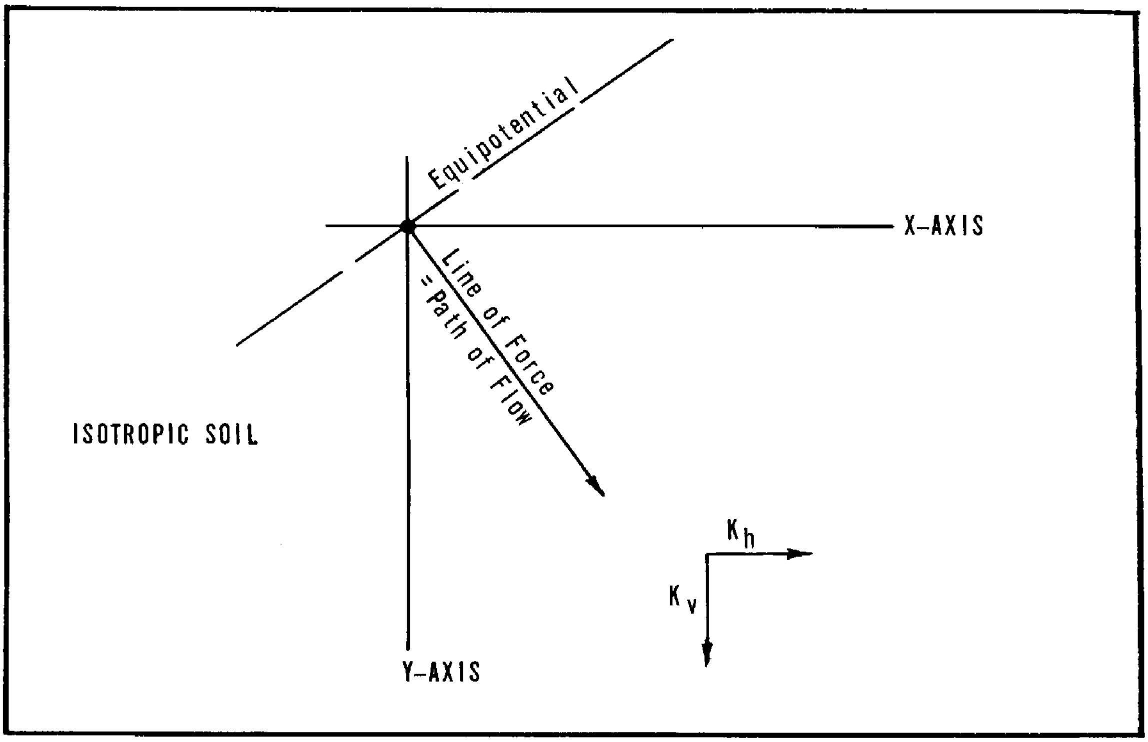

Figure 1-5, Flow direction in isotropic soil

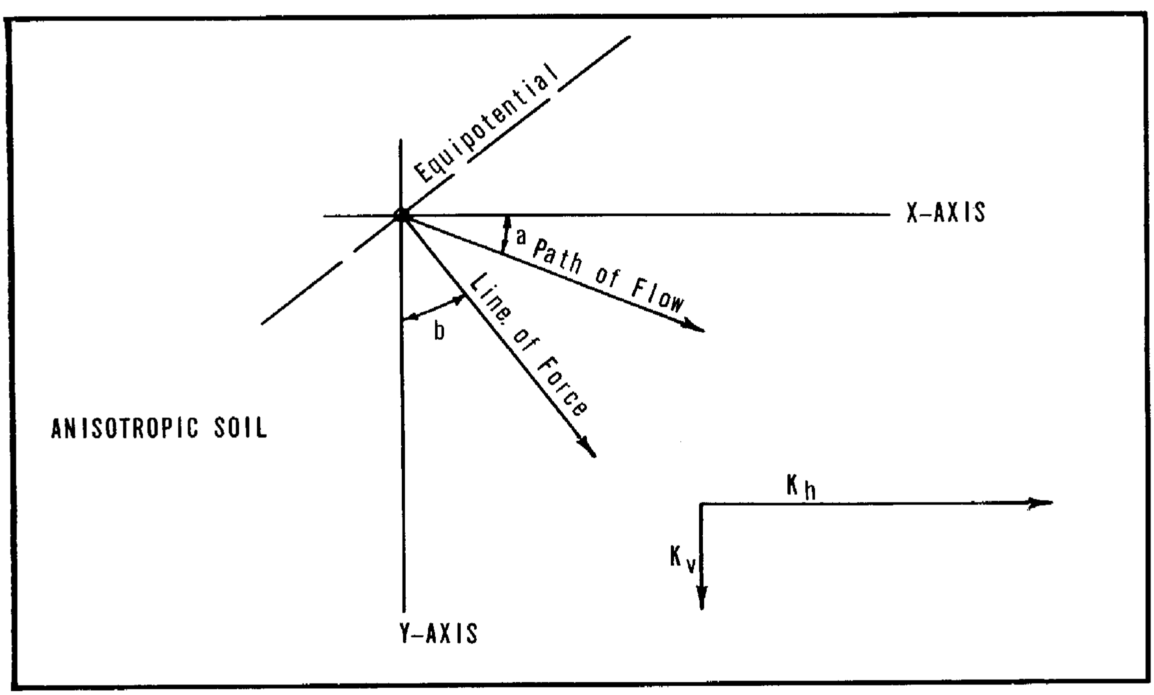

Figure 1-6, Flow direction in anisotropic soil on such planes are called equipotential lines, or "equipotentials." Lines indicating the paths of flow are called "streamlines." A graph showing equipotentials and streamlines for a flow system or part of a flow system is called a "flow net."

The flow net is the result of the operation of Darcy's Law in a system where there are certain sources of water and certain constraints to flow. These conditions that govern the pattern of flow in a ground-water system, when taken together, are called "boundary conditions." Topography, location and quantity of water source, stratigraphy, and drain locations are the principal items making up the boundary conditions. A field survey of these elements is a basis for (a) isolating the flow system to be studied, and (b) designing the drainage system.

Figure 1-7 illustrates two flow nets in saturated soils. Each is 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. The drain is one of several equally spaced drains. The upper flow net is for an isotropic soil. The lower flow net is for the same boundary conditions except that the soil has a horizontal permeability 16 times its vertical permeability (anisotropic). Numbers on each streamline indicate the percent of the total flow which occurs to the left of that streamline. Note that 50 percent of the flow reaching the drain through the isotropic soil originates in a strip over the drain and covering about one-fourth of the source area. For the soil with horizontal permeability 16 times greater than the vertical, 50 percent of the flow originates in a much wider strip, covering nearly one-half of the source area.

If the water source were cut off at the soil surface, the water table would drop in both cases, but the drop would be much more uniform in the second case. This same effect is observed in layered soils, except that the flow net, while having the same general shape, would show sharp breaks in direction where the lines crossed from one stratum to another.

Flow nets may be plotted from actual field measurements of hydraulic head in piezometers. A drainage problem is sometimes reproduced in a laboratory tank model, from which flow data may be taken more readily. Electrical analogs provide additional useful tools for setting up some drainage problems. Flow nets are readily plotted from electrical analog data. There are also methods of computing arithmetically the hydraulic head throughout actual or idealized flow systems. However, numerical methods are tedious for complex problems.

Flow nets are used to study such special problems as the depth and spacing of drains, the best location for a drain conduit designed to intercept flow over an impermeable layer, the effect of pervious backfill in less permeable soil, the quantity of flow entering the bottom half of a buried drain, and canal seepage. Such special conditions may justify flow-net analysis for an individual drain design, but this technique is more often employed in research or evaluation work.

Permeability and hydraulic conductivity

"Permeability" of a porous medium such as soil is its capacity to transmit fluids. It is used as a qualitative term; i.e., it is used as a term for this property of soil. The term is also modified to describe the relative ease of transmission, as "rapidly permeable," or "slowly permeable."

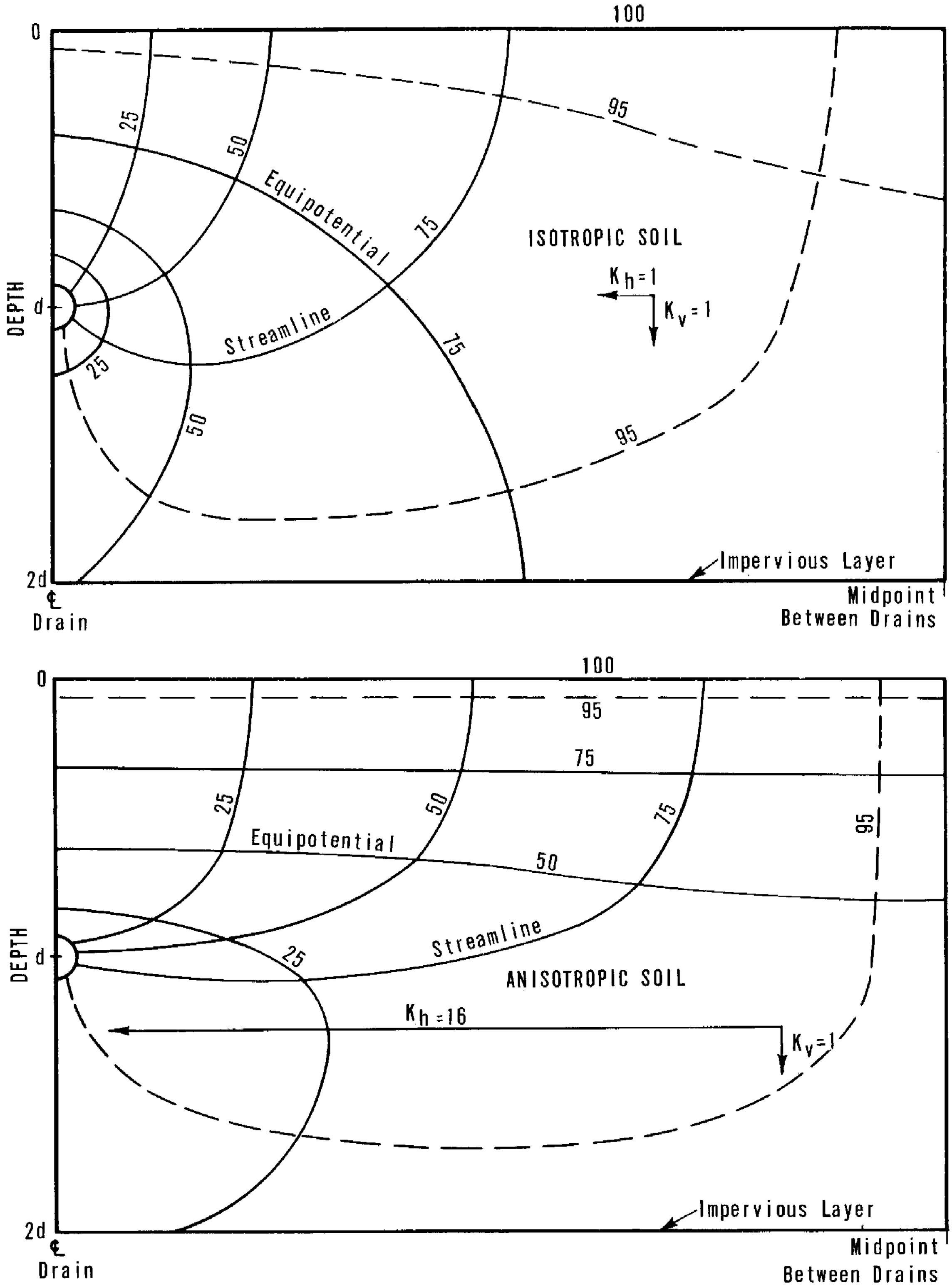

Figure 1-7, Streamlines and equipotentials

"Hydraulic conductivity" of a soil is a numerical value for permeability. It is equal to the proportionality factor K in the Darcy equation. The Darcy equation is an expression of effective velocity of flow as a function of hydraulic gradient and the transmission properties of the soil and water. It was found that effective velocity is proportional to hydraulic gradient, all other things being equal:

$$v = Ki$$

where v = effective flow velocity, dimensions $\frac{L}{T}$

(Effective flow velocity is the velocity with respect to the total area of the porous medium--not the void area alone. It may be defined as the quantity of flow per unit of time divided by the total area of the porous medium producing that quantity of flow.)

K = a factor, dimensions $\frac{L}{T}$

i = hydraulic gradient, dimensionless

Thus, hydraulic conductivity is the effective velocity of flow when the hydraulic gradient is unity. In drainage design, it is convenient to express v and K in inches per hour. Darcy's Law is valid for flow velocities in almost any natural drainage situation.

Hydraulic conductivity depends on properties both of the soil and of the transmitted water. A high value is associated with high porosity, coarse open texture, and highly developed structure. Soils do not vary greatly in porosity, but a few large pores are more effective in contributing to high conductivity than many small pores. Fine-textured soils may depend almost entirely on the structural pores for their conductivity. The quality of the water transmitted, particularly the salinity and alkalinity, may have a marked effect on hydraulic conductivity.

Soil within a drainage-problem area seldom has uniform permeability. This variation is exhibited in two important characteristics: the soil may be nonhomogeneous due to stratification, barriers, or other distinct masses; or it may have a higher permeability in one direction than another, even though homogeneous. Soils with this latter quality are called "anisotropic" (see section on "Paths of Flow").

Rate of flow

The rate of flow (Q) passing a given cross-sectional area of saturated soil (A) is the product of the area and the effective velocity of flow through the section (v):

$$Q = Av$$

Combining this expression with the Darcy Law

$$v = Ki$$

we have the expression

$$Q = AKi.$$

This equation may be used to estimate the quantity of flow in simple drainage problems, such as might be found in hillside interception over a sloping, impermeable layer. In more complex flow problems, both the hydraulic gradient and the hydraulic conductivity vary throughout the flow region and analysis is more difficult. Also, the boundaries of flow may be difficult to determine. For these problems, it usually is impractical to define completely the area, permeability, and hydraulic gradient, so less direct methods of estimating flow are employed. These are discussed in Chapter 4, Subsurface Drainage.

Sink formation in subsurface drainage

Subsurface drainage is accomplished by placing below the water table an artificial channel in which the hydraulic head is less than it is in the soil to be drained. Thus a hydraulic gradient toward the channel is induced, and a "sink" is created. The sink is maintained, of course, by removing water from the artificial channel by gravity or by pumping.

Two factors determine the rate at which water moves toward the sink at any point: The hydraulic gradient and the hydraulic conductivity. This is in accord with Darcy's Law. Total flow to the sink involves hydraulic conductivity throughout the whole soil mass through which water moves to the sink. The flow net delineates the extent and pattern of flow throughout this soil mass, as discussed on the preceding pages.

The desired control of the water table is accomplished (a) by locating the sink vertically and horizontally so as to take advantage of the more permeable soil masses, and (b) by controlling the hydraulic gradient. Hydraulic gradient may be controlled through depth of the sink, spacing of the sinks, and (in methods of drainage) the pressure at the sink. In Equation 1-1

$$\text{Hydraulic gradient} = \frac{(\frac{P_1}{W} + Z_1) - (\frac{P_2}{W} + Z_2)}{L}$$

these three controls affect Z_2, L and P_2, respectively.

Drainage devices that are used to form sinks are buried drains, ditches, relief wells (upward flow), vertical drains (downward flow), and pumped wells. The hydraulic head in buried drains and in ditches depends on the water-surface elevation because the water is at atmospheric pressure. Relief wells, at their lower ends where the sink usually is formed, operate under a pressure dependent on the elevation of their outlets--or of the water surface in the drain into which they discharge, if submerged. Pumped wells create sinks which may be either at atmospheric pressure or above atmospheric pressure, depending on the soil stratification and whether the sink in question is above or below the water level in the pumping well.

Theories of Buried Drain and Open Ditch Subsurface Drainage

Water movement in the saturated zone may be analyzed by applying Darcy's Law to the particular set of boundary conditions at the drainage-problem site. If it were possible by field surveys to determine the exact location of impermeable layers, the location and hydraulic head of all inflow to and outflow from the system, permeability in all parts of the system, time and rate of changes in flow, symmetry of the system--all the factors which affect the amount and pattern of flow--then the problem would be completely defined and subject to direct and exact solution.

Drainage problems are seldom so completely defined in practice, however. Usually they consist of a more or less complex combination of different problems. The procedure is to determine the boundary conditions, first approximately, then in as much detail as necessary by means of the reconnaissance and preliminary surveys. Certain situations or sets of boundary conditions are recognized as problem types for which experience or analysis has given us design criteria. After identification of the problem type, the necessary field measurements and investigations are made so that design criteria may be applied. For some drainage problems, there are few numerical criteria, if any, and the designer relies mostly on good judgment. But in all drainage problems the basic procedure is that previously outlined.

Drainage theories have been developed to describe or to attempt to describe the action of a given saturated flow system. They are useful in getting an approximate solution to actual field problems. To use them, the designer must compare the field situation with the underlying assumptions on which the drainage theories are based. He then applies such of them as his judgment indicates are most applicable. Both steady state and nonsteady state problems are encountered in drainage work. The following approximate theories have been applied to one or both types of problems.

Classification of drainage theories by basic assumptions

Horizontal flow theories

These approximation theories are based on two assumptions: (a) that all streamlines in a gravity flow system are horizontal, and (b) that the velocity along these streamlines is proportional to the slope of the free-water surface, but independent of depth.

Although it can be shown that these are erroneous assumptions, (see "Hydraulic Gradient" page 1-12) the theory of horizontal flow gives sufficiently accurate results if its application is restricted to situations where the flow is largely horizontal. Three field conditions of this kind are:

1. Open ditches that are shallow compared to their spacing and that penetrate to or are close to an impermeable layer.

2. Open ditches that are excavated in stratified materials.

3. Buried drains under conditions 1 and 2, particularly if the backfilled trench is more permeable than the undisturbed material.

One expression of the horizontal flow theory is the ellipse equation, of which the tile-spacing formula developed by Donnan (3) is one form. Application of the ellipse equation is discussed in Chapter 4, Subsurface Drainage.

Visser (4) in another application of the ellipse equation, extended it to apply to nonsteady state problems. His method was developed for conditions in the Netherlands, but according to Van Schilfgaarde, Kirkham, and Frevert (5), the method possibly could be applied profitably in irrigated areas of the arid regions.

Radial flow theories

A tile line may be thought of as a horizontal well, with water approaching the tile along radial streamlines. This analogy is the basis for the radial flow theories, which assume (a) a homogeneous isotropic soil of infinite depth, and (b) a flat water table. This method can give a good approximation of actual flow conditions if the curvature of the water table is small (as with a low rainfall rate and relatively high permeability), and if below the drain there is no layer of greatly reduced permeability.

Combined horizontal and radial flow theories

Hooghoudt (6) and Ernst (7) have developed solutions of the flow problem by combining the radial and horizontal flow hypotheses. These solutions correct the major shortcoming of the ellipse equation (neglect of convergence of flow near the drain). They are valuable and reliable approximations for the steady-state problem of removing steady rain or equivalent accretion.

Hooghoudt modified the ellipse equation by introducing an "equivalent depth," and he prepared extensive tables of the equivalent depth for solution of steady-state problems. Visser (4) reports on a nomographic solution based on the same general assumptions as Hooghoudt's method, and Van Beers (8) has developed nomographs for calculation of drain spacing according to the Hooghoudt and Ernst formulas.

Van Deemter's (9) hodograph analysis

This is a mathematical analysis involving the solution of certain differential equations so as to satisfy the boundary conditions. Van Deemter used this analysis to study tile drainage, but his results apply only to tile running full.

In summary, the approximate solutions obtained by application of these theories are simpler than exact solutions which may be available for some problems, and they provide solutions to other problems for which no other methods are yet known. It is important, however, that the following inherent limitations be recognized so that the method which is most nearly applicable may be applied:

1. Horizontal flow theory (ellipse equation).--Use where the flow is largely horizontal, as for drains shallow compared to their spacing with all impermeable layers at or close to the bottom of the drain.

2. Radial flow theory.--Apply it to homogeneous isotropic soil of great depth, with a flat or nearly flat water table.

3. Combined horizontal and radial theories (as Hooghoudt's).--Use for situations where the impermeable layer is either shallow or deep, by using Hooghoudt's equivalent depth or the nomograph published by Visser.

4. Van Deemter's hodograph analysis.--Apply Van Deemter's analysis only to tile drains running just full, or to problems where the water table stands immediately above the drains.

Transient flow concept

The drainage of irrigated land presents problems which are different from those in humid areas. The rise and fall of the water table in irrigated areas generally follows a cycle which is related to the application of irrigation water during the growing season and the termination of irrigation water use in the off season. Contrasted with the steady-state ground-water conditions in humid areas the storage and discharge of ground water in irrigated areas follows a transient or nonsteady-state regimen. The Bureau of Reclamation has developed a method for drain spacing based on the transient-flow concept which gives consideration to the wide diversity of soils and ground-water conditions prevailing in Western United States. A theoretical formula, which incorporates most of the factors involved, was developed by R. E. Glover, and procedures for use of the formula were developed by Lee D. Dumm, both engineers for the Bureau of Reclamation (10). The transient-flow concept has been in use by the Bureau for several years, and through experience with its use many refinements have been made (11). Van Beers' (8) nomographs for calculation of drain spacings include one for the Glover/Dumm formula and its use is recommended when using metric units.

Techniques for applying drainage theories

The foregoing are the principal theories of saturated flow toward drains. A number of techniques have been used to apply these and other fundamental approaches to the solution of actual drainage problems.

Mathematical analysis

This method is illustrated by Kirkham's (12) analytical solution of the problem of several tube drains equally spaced above an impermeable layer, using the method of images. For problems involving curved streamlines and stratified soil, this method is lengthy and involved. Laplace's fundamental flow equation, which combines Darcy's Law with the equation for continuity of flow, is the starting point for most mathematical analyses of drainage problems. The application of Laplace's equation is an "exact" method, but its complexity in solving actual problems has lead to the approximate theories described in the preceding section.

Relaxation method

The relaxation method is a numerical analysis. It is a simple and powerful tool but usually is tedious to use.

Essentially, the relaxation method is the application of the Laplace equation by trial to points on a plane through the flow system. The boundary conditions must be known. A square grid is oriented conveniently on the plane, and numerical values are assigned to the potential along the boundaries in accordance with the site conditions. At each point of intersection of the grid, arbitrary or estimated numerical values are assigned. Then these numbers are adjusted until the value at each grid point is the arithmetic mean of the four values at the adjacent points.

Stratification, anisotropic conditions, and other variations may be accounted for by appropriate adjustment in the procedure. Luthin and Day (13) have used the method to apply to unsaturated flow. The relaxation method was used to construct the nomographic solution of the combined horizontal and radial flow theories previously described. The method has been applied to both steady- and nonsteady-state problems.

Electrical analog

Laplace's equation is the differential equation for electric potential distribution in conductors. Consequently, electric-model tests of ground-water flow may be based on the analogy between Darcy's Law and Ohm's Law (hence the name "electrical analog"). Conductor paper may be used to represent a plane in the flow region, on the boundaries of which potentials are placed to represent the actual problem boundary conditions.

A vacuum-tube voltmeter is used to measure the potential at various points on the plane, and from these data the flow net may be drawn. Resistance networks have been used in place of the conductor paper, particularly to study the effect of stratified soils on flow into drains.

Models

Sand or soil is sometimes placed in tanks so as to reproduce idealized field conditions for convenient study. The Hele-Shaw channel--Todd (14)--is a model which substitutes the flow of a viscous liquid between closely spaced plates for the flow of water through soil. Models are useful in testing the validity of approximate drainage theories.

Design Criteria

Criteria for design of drainage systems are essentially the specifications for conditions which must exist in a particular area for it to have the optimum level of water control required by the kind of agriculture to be practiced. These criteria consist of two items: (a) the rate of water removal necessary to provide a certain degree of crop protection, and (b) the optimum depth to water table.

The rate of water removal, often referred to as the drainage coefficient, may be expressed as a certain depth of water to be removed from the watershed per day, or as a rate of flow per unit of area, as cubic feet per second per square mile. For consideration of precipitation and runoff characteristics, the rate of removal should be based on a curve which varies according to the size of the drainage area.

Optimum depth to water table is that depth required for best plant-soil-water-air relationship, and which is feasible to maintain under existing conditions. A certain tolerance is necessary since it is not possible to maintain a particular depth exactly.

Several factors must be considered in selection of design criteria for a particular project. These include the requirements of crops to be grown as related to water needs and tolerance to excess water, soils, climate, salinity in the soil or in irrigation water, and economics. Within a particular watershed the criteria may be determined by a detailed analysis of all factors involved or by use of empirical methods based on experience with similar problems and consideration of the physical data available.

Drainage Coefficients

Criteria for design of drainage disposal systems by the Soil Conservation Service is based largely on empirical methods. Formulas for rates of removal have been used in the United States for over 50 years and have been refined by experience and gaged data. When planning drainage improvements in the Cypress Creek Drainage District, Desha and Chicot Counties, Arkansas, 1911-15, S. H. McCrory and Associates (15) developed a formula for determining the rate of runoff for drainage design. This formula now known as the Cypress Creek Formula, may be expressed as follows:

$$Q = 35M^{5/6}$$

where Q = rate of runoff at any point in the system from the drainage area above the point - in cubic feet per second.

M = drainage area in square miles.

The coefficient 35 was based on gaged runoff from different parts of the watershed, and consideration of the probable effect that drainage improvements would have on the rate of runoff.

Drainage systems have been installed on millions of acres of land in the alluvial valley of the Mississippi River by use of the Cypress Creek Formula, and slight modifications of it, and its validity has been proven by the successful functioning of these systems. By substituting a variable coefficient, C, for the 35 in the formula, and selecting a value for the coefficient based on the characteristics of a particular watershed and the degree of protection desired, the formula can be used for computing surface drainage removal rates in most of the United States.

The selection of a drainage coefficient, or the rate of water removal, for a particular drainage system, should be based on the water tolerance of crops to be grown and the physical characteristics of the area. Climate, soils, topography and crops are always important factors to consider. Where irrigation is practiced the quantity and quality of the irrigation water and irrigation water management practices also must be considered.

Research by Stephens and Mills (16) has resulted in a way to relate the coefficient in the Cypress Creek Formula to the particular characteristics of a watershed and the level of protection justified. This is discussed in Chapter 5 of this Handbook.

Drainage coefficients for surface drainage

A drainage coefficient for a surface drainage system should consider the characteristics of precipitation in the area as well as other climatic factors, topography, crop tolerance to excess water, soils, and irrigation. Stream gage records and studies made of the flow of excess precipitation from flatland watersheds indicate that the rate of flow per unit of area decreases as the total contributing area increases. The rate of change, as indicated by the exponent of M in the Cypress Creek Formula, varies somewhat between watersheds and with the intensity and duration of a particular storm. However, analysis of considerable stream gage data and experience with use of the Cypress Creek Formula support the $^5/_6$ exponent used in it for flatland watersheds. The procedure developed by Stephens and Mills for relating the coefficient in the Cypress Creek Formula to the characteristics of a watershed and the level of protection desired can be used to develop curves for rapid determination of runoff from areas with certain characteristics and for the required level of protection for specified cropping patterns.

Drainage coefficients for subsurface drainage

Whether the excess water results from precipitation, excess irrigation water, leaching water or ground-water flow from outside the area the flow into subsurface drains is more uniform and extends for longer periods of time than does the flow into surface drains. A drainage coefficient for subsurface drainage is related to the source of the excess water, to the rate of flow of the excess water through the soil, and to the tolerance of crops in the cropping system to excess water.

As the rate of flow through the soil is slower than overland and extends over a longer period of time, drainage coefficients for subsurface drainage are usually much smaller than for surface drainage. They are usually specified as a depth of water to be removed in 24 hours or one day. In humid areas the rate of removal specified is usually uniform for large areas, but in arid and semiarid irrigated areas the rate of flow per unit of area decreases as the size of the area increases because of the rotation of irrigation within large project areas and non-uniformity of other sources of excess water.

Drainage coefficients for pumping plants

Drainage coefficients for pumping plants are based on the criteria used for design of the drainage system which delivers water to them. Characteristics of flow to the pumping plant, whether surface, subsurface, or both, should be considered in determining the pumping capacity of the pumps. Most pumping plants are designed with a certain amount of storage in the forebay of pumps, which should be considered in relating the flow from the contributing area to the pumping capacity required. Surface drainage systems usually have substantial storage capacity below the elevation which will result in crop damage and which can be utilized to reduce the pumping capacity required (17). The flow from subsurface systems is much more uniform and less forebay storage is needed.

Drainage coefficients for watershed protection

Watershed-protection plans should be developed to create good conditions for plant growth, including protection against excess surface water and control of soil-moisture content. To assure these conditions, all multiple-purpose or flood-prevention channels, into which lands requiring drainage must outlet, should have capacities no less than those based on the applicable drainage coefficients. Where lands requiring drainage are planned for protection by flood-water-retarding structures and channels, the channel system should provide no less protection than that established by the drainage coefficient. Such a design requires that the entire watershed area be taken into account. Flow from flood-water-retarding structures should be added to the flow from unprotected uplands and flood-plain lands which is based on appropriate drainage coefficients for such unprotected land.

Special requirements for flatland

In considering the runoff from flatlands requiring drainage systems, it is important to consider the influence of extensive surface-drainage systems on the required capacity of the main ditches. Flatlands may have a large amount of surface storage in shallow depressions and a low rate of runoff before installation of water collection and disposal systems. As drainage collection and disposal systems are installed, both surface storage and time of concentration decrease. The long-range trend of agricultural development needs to be studied in determining the coefficients applicable to main drainage ditches for extensive areas of flatland.

Depth to water table

Optimum depth to water table is the subject of considerable research in the United States; and also in the Netherlands, where water tables can be controlled within close limits throughout the growing season in much of the country (18). One of the main factors involved is the quality of water. If it is free from salts, indications are that the water table needs to be only as deep as required to provide sufficient root zone depth for support of plants to be grown and to support tillage equipment. As roots generally do not penetrate deeper than approximately one foot above the water table the depth to water table should be approximately one foot more than the depth of the root penetration desired. Where salts are present the water table must be deep enough to prevent capillary flow from bringing dissolved salts up into the root zone.

Pumped-Well Drainage

Pumped wells have effectively drained land in some locations. Though costly and restricted to favorable geologic conditions, pumped wells are versatile and may have an economic advantage over other methods of lowering and maintaining a desirable water-table level.

Pumped-well drainage is based on the following principles:

1. A pumped well, like other forms of artificial drainage, increases the flow energy gradient by creating a sink within a saturated zone.

2. Energy which the well makes available to the ground-water flow system is derived from the motor which lifts the water from the sink.

3. The increased gradient must extend to the crop-root zone in such degree as to control the water table within the desired area and to the desired level.

4. The increased energy gradient may be in the form of drawdown; i.e. water table slope toward the well; or it may be in the form of a pressure gradient where the ground water is confined. In either case, at a given point in the saturated zone, the quantity (P_2) is decreased in the expression:

$$\text{Hydraulic gradient} = \frac{\left(\frac{P_1}{W} + Z_1\right) - \left(\frac{P_2}{W} + Z_2\right)}{L} \qquad \text{(Eq. 1-1)}$$

thus increasing the gradient toward the well. See "Hydraulic head" and "Hydraulic gradient" pages 1-10 to 1-14.

Classes of pumped wells

Water-table wells

Water-table wells remove water directly from the free ground water, creating a drawdown surface in the water table.

Confined-aquifer or artesian wells

These wells remove water from a fully saturated aquifer which is confined by impermeable or slowly permeable layers.

Theories of flow into pumped wells

Flow into wells is a function of the drawdown, and usually is expressed in the general form:

$$Q = f\ (y_1,\ y_2,\ r_1,\ r_2)$$

where y_1 and y_2 are the depths of water (or hydraulic head) at distances r_1 and r_2 from the well, respectively.

Water-table wells

The approximations of Dupuit are the basis for the equation:

$$Q = \pi K \frac{y_2^{\,2} - y_1^{\,2}}{\log_e\ (r_2/r_1)}$$

where Q = flow into well, with dimensions L^3/T

K = hydraulic conductivity, L/T

y_1, y_2, r_1, r_2 as previously defined, in units of L

(L = length and T = time)

This equation neglects the curvilinear flow due to the drawdown shape. The error is not large if r_1 and r_2 are sufficiently large so that the curvature is negligible. The equation may be used to predict the draw-down curve and radius of effective influence. It is useful also for computing the hydraulic conductivity from field-pumping tests. Two or more observation wells are installed at different distances from the pumped well. The nearest observation well should not be closer to the pumped well than 100 times the well radius.

Confined-aquifer or artesian wells

Corresponding to the equation for unconfined aquifers, the Dupuit equation for confined aquifers becomes:

$$Q = 2\pi Km \frac{y_2 - y_1}{\log_e (r_2/r_1)}$$

where Q = flow into well, with dimensions L^3/T

K = hydraulic conductivity, L/T

m = thickness of aquifer, in units of L

y_1 and y_2 = depth from bottom of aquifer to pressure surface, at distances r_1 and r_2 from the well, respectively, all in units of L.

Additional information on the hydraulics of wells may be obtained from NEH, Section 18, Ground Water, pp 1-12 to 1-18.

Basis for design of pumped-drainage wells

The above equations are for the equilibrium or steady-state condition. Similar relations have been derived for use in the nonsteady state, such as in situations where pumped wells continue to deplete stored water.

Pumping from confined aquifers usually is steady throughout the season because the aquifers are deep and replenish slowly and uniformly. But water-table wells may be used for either short-time drawdown or near-constant seasonal discharge. Therefore, their design should be based on two considerations:

1. Capacity should be sufficient to lower the water table after irrigation, heavy precipitation, or other influent seepage, in a relatively short time to avoid crop damage.

2. Capacity should be sufficient to remove at least the seasonal net replenishment, which is the ground-water replenishment less depletions from causes other than the pumped well in question. Shorter pumping periods may be required for this analysis, such as 1-, 2-, or 3-month periods.

Advantages of pumped-well drainage

A high initial and operating cost for a pumped well for land drainage may be offset by a number of its advantages over a shallow drain system. Some of these are:

1. The water table may be lowered to much greater depths.

2. Deep strata may be much more permeable than those nearer the surface.

3. Productive land which would be occupied by open drains is saved.

4. Maintenance costs are less than for open drains and may be less than for closed drains.

5. Pumped water may be a valuable supplement to the irrigation-water supply.

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