Chapter 9
Drainage of Agricultural Lands

Contents

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For the maximum growth of plants, it is essential to provide a root environment that is suitable for it. Water logging has an effect on the uptake of nutrients by plants. Drainage provides favorable condition for root growth, enhance organic matter decomposition, reduce salinity level above the drain, and maintain productivity of the land. For successful drainage design, the complex interaction of water, soil and crop in relation to quality of water must be well understood beforehand. The knowledge of drain material (drainage conveyance conduit) and placement technique of the drain (including selection of envelop material and its design with respect to soil bedding) are also of great importance. Judgment of alternate design options, and, monitoring and evaluation of the system after installation are demanded for successful outcome from the drainage projects. Disposal and treatment issues of drainage effluent are of concerns now-a-days. This chapter discusses all of the above points.

9.1 Concepts and Benefits of Drainage

9.1.1 Concepts

Drainage is the removal of excess water from the root zone area. The drainage problem is caused by excess of water either on the surface of the soil or in the root zone beneath the surface of the soil. The removal of water from the surface of the land and the control of the shallow groundwater table (referred as drainage) improves the soil as a medium for plant growth. The sources of excess of water may be precipitation, irrigation water, snowmelt, overland flow, artesian flow from deep aquifers, flood water from channels, or water applied for special purposes as leaching salts from the soil.

9.1.2 Goal and Purpose of Drainage

Drainage is used in both humid and arid areas. The main goal or objective of providing drainage is to increase production and to sustain yields over long periods of time.

The purpose of drainage is to provide a root environment that is suitable for the maximum growth of plants. The drainage serves the following or one of the following purposes:

- Remove extra water from the crop root zone
- Control salinity buildup in the crop root zone and soil profile.

9.1.3 Effects of Poor Drainage on Soils and Plants

Water that fills the soil pores not only displaces the air in the soil but also obstructs the gases which are given off by the roots to escape. The oxygen content in the soil is limited not only because of small amount of oxygen dissolved in the water but also because of extremely low through sub-soils.

After the dissolved O_2 in water-logged soil has been consumed, an aerobic decomposition of organic matters takes plane. This results in the production of reduced organic compounds and complex aldehydes. Mineral substances in the soil are altered from the oxidized state to a reduced state, and toxic concentration of ferrous and sulfide ions may develop within a few days after submergence of the soil.

Water logging generally leads to a deceleration in the rate of decomposition of organic matter. Thus nitrogen (N_2) tends to remain logged up in the organic residues. N_2, therefore, is often a limiting factor to plant growth on poorly drained soil.

Water logging has an effect on the uptake of nutrients by plants. This is shown by certain symptoms which develop under circumstances of water logging. These symptoms are yellowing, reddish, or stippled (dotted) appearance of the leaves.

In some sensitive plants, prolonged water logging damage the root system, and consequently the plants die due to lack of nutrient and water uptake.

9.1.4 Benefits from Drainage

9.1.4.1 Major Benefits

(a) Makes favorable soil condition for plant roots to grow
(b) Increases the availability of plant nutrients
(c) Reduces the hazard of toxic substances in the soil
(d) Helps in the decomposition of organic matter and thereby increases the availability of N_2.
(e) Extends the period of cultivation
(f) Provides a better environment for crop emergence and early growth
(g) Can reduce soil compaction

9.1.4.2 Additional Benefits

Drainage helps to get ride of the following problems:

(i) Ponding of water during the summer may cause scalding (burn by hot water) of the crops.
(ii) A health hazard is created by mosquitoes which breed in ponded field.
(iii) A high water table prevents the soil to warm up readily in spring and thus affect seed germination.
(iv) Plant diseases are more active under water-logged conditions. Fungus growth is particularly prevalent (most common).
(v) Bearing capacity of water-logged soil is low. Thus, create problem with construction and compaction of soil by animals and machines.

9.1.5 Types of Drainage

Drainage may be either natural or artificial. In case of natural drainage system, water flows from the fields toward low-land, then to swamps or to lakes (in some places local name is “khal” or “bill”) and then to rivers, through natural system. In some cases/soils, the natural drainage processes are sufficient for plant growth and production of agricultural crops, but in many other soils, artificial drainage is needed for efficient agricultural production.

Artificial drainage is divided into two broad classes: (i) surface, and (ii) subsurface. Some installations serve both purposes.

9.1.5.1 Surface Drainage

Surface drainage is the removal of water that collects on land surface. It is a system of drainage measures, such as open drains and land forming, to prevent ponding by diverting excess surface water to a collector drain.

Fig. 9.1 Schematic view of surface drain

Many fields have depressions or low spots where water ponds. Surface drainage techniques such as land leveling, construction of shallow ditches or waterways can allow the water to leave the field rather than causing prolonged wet areas (Fig. 9.1). The water from field plots flows toward drain or shallow ditches through artificial down-slopes. Then shallow ditches discharge into larger and relatively deeper drain called collector drain. The collector drain is connected to the lake or other deep water bodies.

A surface drainage system always has two components:

– Open field drains to collect the ponding water and divert it to the collector drain
– Land forming to enhance the flow of water toward the field drains

9.1.5.2 Subsurface Drainage

Subsurface drainage is the removal of excess water from the soil profile. This is normally accomplished by buried pipe drains or deep open drain. Subsurface drainage increases the productivity of poorly drained soil by lowering the water table, and providing higher soil aeration.

Deep Open Drain

This type of drainage channel is deeper than the natural normal drainage channel (Fig. 9.2) and usually constructed with an excavator; often with a bulldozer or grader shaping the spoil. It is appropriate for

- small catchments
- where the soil is compact and stable

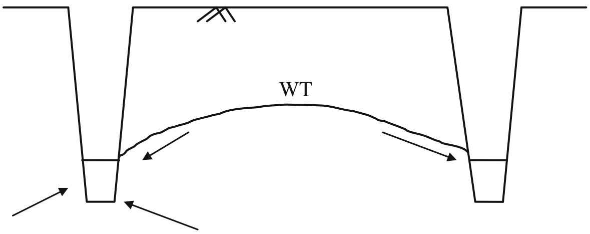


Fig. 9.2 Schematic of deep open drain

- where a suitable outlet is available to dispose of the quantity and quality of water collected
- where it can be used as alone or with other system (as outlet of normal surface drain)

Deep open drain has the potential in turning salt-affected land into productive. It directs surface and subsurface water away from the landscape, taking with it the salt that has accumulated in the soil.

Buried Pipe Drain

A network of perforated tubes or pipes is installed 0.8–1.5 m below the soil surface. The excess water from the root zone flows into the pipe through the openings (Fig. 9.3). The pipes convey the water to a collector drain. A gentle slope of the pipe (0.5–1.0%) is provided toward the collector drain. The drain pipe may be made of plastic, concrete, or clay. These tubes are commonly called "tiles" because they were originally made from short lengths of clay pipes known as "tiles." In clay and concrete pipes, water enters the pipes through the small spaces between the tiles, and drain away. In plastic pipes, water enters into the drain through perforation distributed over the entire length of the pipe. The buried pipe lowers the water table to the depth of the pipe or tiles over the course of time (several days).

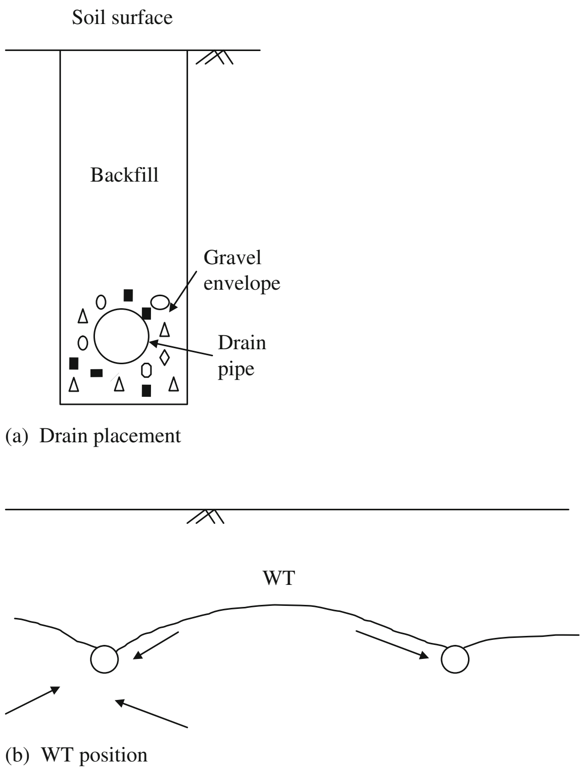
Typical Length of Different Pipe Drain

Plastic: 100–200 m long, 10–15 cm diameter
Clay and concrete: 25–30 m long, 5–10 cm diameter.

9.1.6 Merits and Demerits of Deep Open and Buried Pipe Drains

There are some merits and demerits of each of the drain systems – deep open and buried pipe drain. They are summarized below:

Fig. 9.3 Buried pipe drain system (**a**) drain position (**b**) water-table position during operation



Deep open drain	Buried (subsurface) pipe drain
1. Causes loss of cultivable land, that otherwise could be used for crops	1. Causes no loss of cultivable land
2. Restricts the use of machines	2. Does not restrict the use of machines
3. It requires a large number of bridges or culverts for road crossing and access to the field	3. Does not require
4. Requires frequent maintenance	4. Maintenance requirements are very limited
5. Cost of construction is lower compared to the cost of buried pipe system	5. Total cost of the system is higher compared to deep open drain due to material cost, equipment, and skilled manpower involved
6. Effective and/or economic life is short	6. Effective and/or economic life is long
7. Allows for removal of much larger volumes of water in a shorter time span than subsurface drainage	7. Allows for removal of lower volumes of water in a shorter time span

9.1.7 Difference Between Irrigation Channel and Drainage Channel

Drainage channel can be distinguished from the irrigation channel with the following characteristics:

Irrigation channel	Drainage channel
1. Irrigation channel network spreads from the source toward the field	1. Drainage channel networks convergence from the field toward the main drain
2. Irrigation channel is normally elevated from the plot or at least at equal level to the field plot	2. Drainage channel is certainly lower than the field plot
3. In some instances, irrigation channel may be used as drainage channel (e.g., channel at lower part of field can be used as drainage channel of upper part)	3. Drainage channel can not be used as irrigation channel without structural modification

9.2 Physics of Land Drainage

Drainage systems are engineering structures that remove water according to the principles of soil physics and hydraulics. To understand the mechanism how drainage influence the water balance in the soil and control the subsurface hydrology, we should understand the basic concepts regarding soil (pore space) water and their retention or release characteristics.

9.2.1 Soil Pore Space and Soil-Water Retention Behavior

The soil bulk volume consists of both solid and pore space (Fig. 9.4). The proportion of pore space in bulk volume depends primarily on soil texture. The typical range of pore space is 30–55%. For practical implications, soil pores can be classified as follows:

Pore type	Pore diameter
Micro-pore	<0.01 mm
Meso-pore	0.01–0.2 mm
Macro-pore	>0.2 mm

Water is held within the pore space by weaker capillary forces. Around the soil particles, water is held as “film” by stronger adsorptive forces. Within the saturation range of a soil, the classification of total water is illustrated in Fig. 9.5.

Fig. 9.4 Schematic of solid and pore space in soil bulk volume

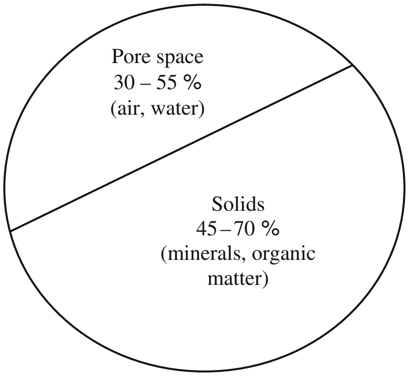
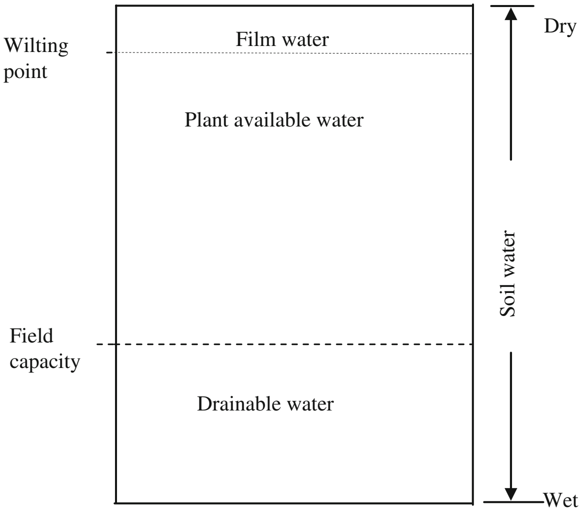


Fig. 9.5 Schematic representation of different types of water in soil



9.2.2 *Some Relevant Terminologies*

9.2.2.1 Void Ratio (*e*)

It is defined as the ratio of the volume of voids or pore spaces (V_p) to the volume of solid particles (V_s). That is, void ratio,

$$e = \frac{V_p}{V_s}$$

It represents the proportionate amount of pore volume and solid volume.

9.2.2.2 Porosity

It is the ratio of volume of voids or pores to the bulk or total soil volume (solid plus pores). That is,

$$\eta = \frac{V_\mathrm{p}}{V} = \frac{V_\mathrm{p}}{V_\mathrm{p} + V_\mathrm{s}}$$

It represents proportionate amount of pore volume and bulk volume.

9.2.2.3 Relation Between Porosity and Void Ratio

$$\eta = \frac{V_\mathrm{p}}{V_\mathrm{p} + V_\mathrm{s}} = \frac{1}{1 + \frac{V_\mathrm{s}}{V_\mathrm{p}}} = \frac{1}{1 + \frac{1}{e}} = \frac{e}{1 + e}$$

or

$$\eta = \frac{e}{1 + e} \tag{9.1}$$

9.2.2.4 Moisture Concentration

The moisture concentration is defined as the volume of water per unit volume of soil.

9.2.2.5 Pore Water

Water that is held in the soil pores is termed as pore water.

9.2.2.6 Drainable Pore Space or Drainable Porosity (P_d)

Drainable pore space or drainable porosity is the air-filled pores present when the soil is drained to field capacity (i.e., after gravity drainage). Alternatively, the macropore spaces which releases or drains water due to gravity drainage is termed as drainable porosity. This can be estimated as

$$P_\mathrm{d}\ (\%) = \text{soil porosity}\ (\%) - \text{soil moisture at field capacity}\ (\%)$$

It is influenced by soil texture and structure. Coarse-textured (sandy) soils have large drainable porosity, whereas fine-textured (clayey) soils have smaller drainable porosities (Table 9.1). This implies that for a certain amount of water drained, a sandy soil shows a smaller water-table drop than that of a clay soil.

Table 9.1 Typical drainable porosity in different textured soils

Soil texture	Drainable porosity (%)
Sandy	20–30
Loam	12–18
Clayey (clays, clay loam, silty clays)	5–12

Physical meaning of drainable porosity (P_d)

By definition,

$$\text{Drainable porosity (\%)} = (\text{Volume of drainable pore spaces in total volume of soil}) \times 100/\text{total volume of soil}$$

Another way of expressing drainable porosity is the quantity of water drained (d_d, mm) from a given drop in water table (h), expressed as percentage. That is,

$$P_\mathrm{d} = \frac{d_\mathrm{d}}{h} \times 100 \tag{9.2}$$

A P_d of 8% means that draining 8 mm of water lowers the water table by 100 mm.

9.2.2.7 Drainable Water

Drainable water is that water which can be drained from a saturated soil by gravity or free drainage. The amount of drainable water in the soil depends on the amount of "drainable pore space" or drainable porosity. In drainage system, drainable water is expressed in units of depth (meter or millimeter). Expressing drainable water in this way assumes that its depth applied to a unit area (i.e., square meter or hectare). The volume of water from this depth can be computed simply by multiplying the depth of drainable water by the area of drainage (area of interest), making sure to keep the units consistent.

In the field, the soil moisture is not constant but changing with time and varies throughout the soil profile – from ground surface to a particular depth. Soil closer to the water table is wetter than soil closer to the ground surface. This means that as moving up from the water table, the soil pores contain proportionately less water. The change in proportion of air-filled and water-filled pores between the ground surface and water table (after the downward flow of excess water) is illustrated by the curved line in Fig. 9.6. At some height above the water table, the soil moisture will have drained to field capacity. Poorly drained soils may have water tables at or very close to the soil surface for prolonged period of time. Under such condition the proportion of air-filled pores in the soil profile is very small, and that's why the soil lacks proper aeration to support plant growth.

Suppose a pot with soil have no holes at the bottom for water to escape. The pot is watered until water spills over the top. At this point the soil is saturated and no air in the soil pores. If a hole is then made at the bottom of the pot, the free or "drainable" water will drain out and the soil will be left at field capacity. In case of

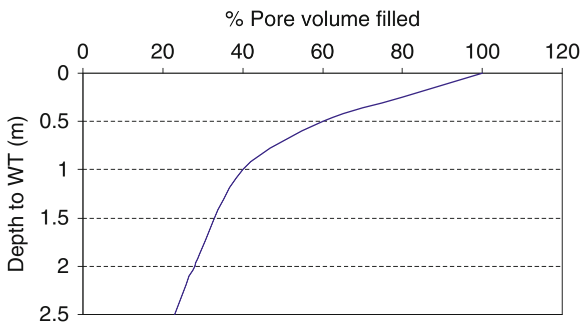


Fig. 9.6 Schematic of proportion of water-filled pores with depth to water table

subsurface drain, the excess water from the soil profile drains by the same process through the drain until the water table is lowered to the drain.

"Drainable water" can be measured directly from a predetermined drainage area following the above procedure. It can also be estimated indirectly from drainable porosity, as

$$\text{Drainable water (m}^3) = \text{drainable porosity (\%)} \times \text{drainable volume (m}^3)$$

i.e., $D_{\mathrm{w}} = P_{\mathrm{d}} \times D_{\mathrm{v}}$.

9.2.2.8 Drainable Pore Volume Under Negative Pressure (or Suction)

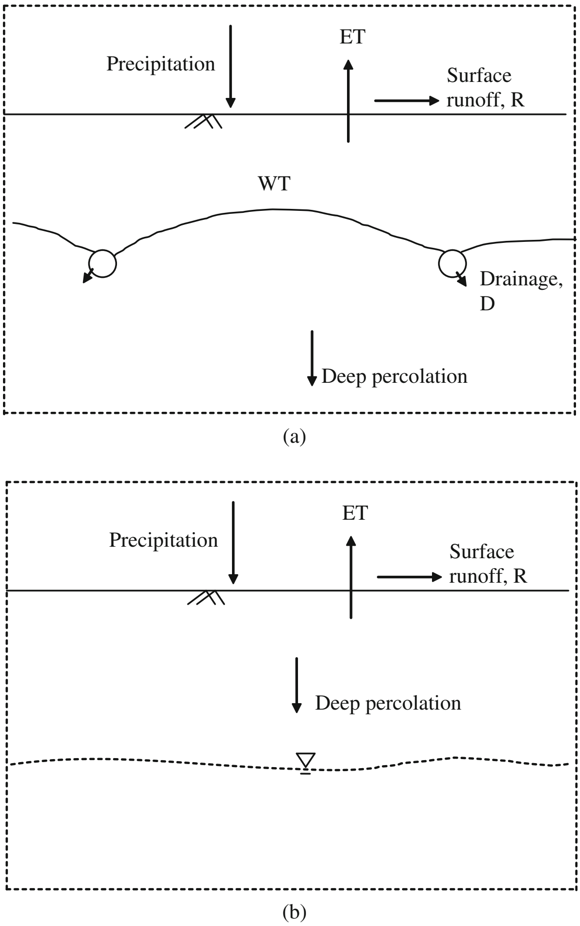
The drainable pore volume at certain suction represents the volume of water that can be drained from a unit (or particular) volume of soil, when the soil-moisture pressure decreased from atmospheric pressure to some specific negative pressure.

9.2.3 Water Balance in a Drained Soil

In a crop-soil system, the term "water balance" describes the fate of precipitation and various components of water flow in and around the soil profile. Drainage affects soil-water, and thus other components of the water balance are also affected. Subsurface drainage influences the hydrology of heavily drained regions significantly and permanently, by substantially reducing surface runoff, shortening periods of surface pondage, and lowering of water table. Water balance on a soil profile with good natural drainage and in an artificially drained soil profile is depicted in Fig. 9.7

In the typical natural drainage system, precipitation (rainfall, snowmelt) (*P*), irrigation (*IR*) (if applied) are the major water input to the system affecting surface runoff (*R*), crop evapotranspiration (*ET*), deep percolation (*DP*), and changes in soil-water storage (*S*). Assuming that no water enters the soil from adjacent areas by horizontal flow, the water balance can be mathematically expressed as

Fig. 9.7 Schematic of water balance of (**a**) artificial drained (*upper one*) and (**b**) natural drained soil



$$P + IR - R - ET - DP = S \tag{9.3}$$

If the deep percolation continues, there is an opportunity for the water table to rise. It is evident from the water balance that the amount of deep percolation depends on the extent to which the precipitation and/or irrigation input to the soil is reduced by R, ET, and S.

In case of artificially drained soil profile, similar water balance equation holds true. However, the drainage flow becomes a major component of the water leaving the system. The water balance equation can be written as

$$P + IR = R + ET + DP + S + D \tag{9.4}$$

As in case of natural drainage, the amount of drainage is dependent on how much precipitation is lost to R, ET, and the drainage capacity itself. In artificial drained soil, runoff component is greatly influenced due to change in air/water filled pores. After draining the water, the soil has more pore volume available for water infiltration during the next rain because of the larger volume of empty pores. Consequently, more infiltration and less runoff may occur with an artificially drained soil compared to a poorly drained (or with no artificial drained) soil.

The amount of infiltration in drained soil depends on many factors such as the nature and timing of the next rain, soil texture (pore space and its distribution), hydraulic conductivity, and depth of drain and spacing. The amount will be greater when the difference between the shallow (initial) and deep water level (final) is greater, and soil texture is coarser. Smaller rains of low intensity will reduce the total runoff rate, because proportionally more water will have an opportunity to infiltrate and pass through the drainage system. Smaller rains may cause surface runoff on the undrained soil and no surface runoff at all on the drained soil. However, if one or more rains occur before the drained soil has had time to drain the previous water adequately, water balance differences between the two soils will be lessened.

9.2.4 Sample Workout Problem

Examples 9.1

An agricultural soil contains 47% pore space, and the moisture content after gravity drainage is 39% (by volume). Find the void ratio, drainable porosity, and drainable water volume from a 20 m × 15 m plot having 1.0 m root zone depth.

Solution

$$\begin{aligned}\text{We know, void ratio} &= (\text{volume of void/volume of solid}) \\ &= \text{vol. of void}/(100 - \text{vol. of void}) \\ &= 47/(100 - 47) \\ &= 0.886\end{aligned}$$

$$\begin{aligned}\text{Drainable porosity} &= \text{total porosity} - \text{water content after gravity drainage} \\ &= 47 - 39\% \\ &= 8\%\end{aligned}$$

$$\begin{aligned}\text{Drainable water volume} &= \text{drainable porosity} \times \text{drainable soil volume} \\ &= (8/100) \times (20 \times 15 \times 1\ \text{m}^3) \\ &= 24\ \text{m}^3\end{aligned}$$

Ans.: Void ratio = 0.886, drainable porosity = 8%, drainable water volume = 24 m^3.

9.3 Theory of Water Movement Through Soil and Toward Drain

9.3.1 Velocity of Flow in Porous Media

Discharge velocity V is defined as the quantity (or volume) of water being discharged from a soil column per unit cross-sectional area of the column per unit time, i.e., $V = Q/A$.

The discharge velocity is useful when we are mainly concern with the amount of water flowing through a porous medium, but does not relate to the time of travel of this water. The flow can occur only through the pores, thus the velocity across any cross-section must be taken as some kind of average over the cross-section.

Let "m" be the ratio of the effective area of pore (A_p) to the total area (A) of the indicated section, then

$$m = \frac{A_\mathrm{p}}{A}$$

or, $A_\mathrm{p} = A \times m$

Then,

$$Q = AV = A_\mathrm{p} V_\mathrm{av} = mAV_\mathrm{av} \tag{9.5}$$

where V_av is an average velocity through the pores of the cross-section.

9.3.2 Some Related Terminologies

9.3.2.1 Drainage Intensity/Drainage Coefficient/Drainage Requirement

Drainage intensity *or* drainage coefficient is defined as the depth of water (mm) that is removed or to be removed per day (i.e., in 24 h) from a field for successful growth of crop or land amelioration. Its unit is mm/d (millimeter per day).

9.3.2.2 Drainage Density

It is the length of drain per unit area.
Drainage density, D_d (m/ha) = (total length of drain in an area, m)/(area of the land, ha)

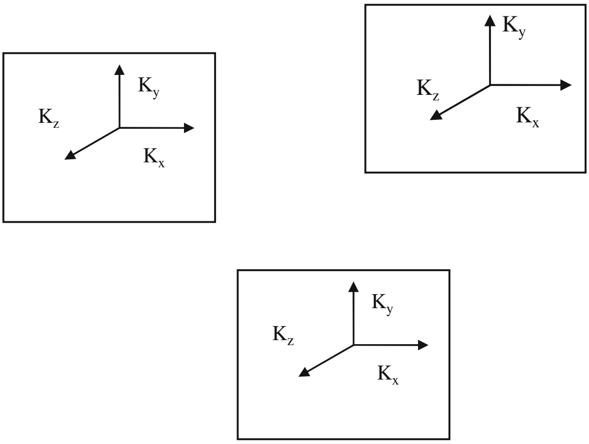
9.3.2.3 Head

It is the energy (potential) of water at a point of interest, expressed as water height (m).

9.3.2.4 Water Table

Free water surface in soil, where soil-water pressure equals zero.

Fig. 9.8 Schematic of homogeneous and isotropic soil



9.3.2.5 Equipotential Line

It is the line of equal hydraulic head or potential.

9.3.2.6 Homogeneous and Isotropic Media

A media (here soil) is termed as homogeneous with respect to a certain property (say, hydraulic conductivity), if the property is same at every point of the media. For example, for homogeneous soil, $\frac{dK}{dS} = 0$. That is, the value of K does not change with space or distance.

A media is termed as isotropic with respect to a certain property, if the property is same in all directions at a particular point. That is, for isotropic soil, $\frac{dK}{dx} = \frac{dK}{dy} = \frac{dK}{dz}$.

Thus, a homogeneous soil may or may not be isotropic. Similarly, an isotropic soil may or may not be homogeneous.

A soil is termed as homogeneous and isotropic (with respect to a certain property, say, hydraulic conductivity), if the property (hydraulic conductivity) is same in all places in the media and also in all directions (Fig. 9.8). That is, for homogeneous and isotropic soil, $\frac{dK}{dS} = 0$ and $\dfrac{dK}{dx} = \dfrac{dK}{dy} = \dfrac{dK}{dz}$

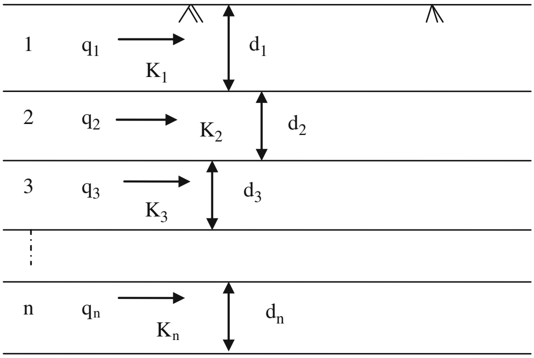
9.3.3 Resultant or Equivalent Hydraulic Conductivity of Layered Soil

Theoretical derivation from Darcy's equation and experimental determination of soil hydraulic conductivity (K) has been described in Chapter 4 (*Soil*), Volume 1. Here, only the equivalent or resultant hydraulic conductivity will be discussed.

9.3.3.1 Resultant Horizontal Hydraulic Conductivity

Consider a soil column having n layers, and the depth (m) and horizontal hydraulic conductivity (m/d) of the layers are $d_1, d_2, d_3, \ldots d_n$ and $K_1, K_2, K_3, \ldots K_n$, respectively (Fig. 9.9). Assume that the hydraulic gradient in the horizontal direction is gradφ.

Fig. 9.9 Schematic of horizontal hydraulic conductivity



The total depth of the layers, $D = d_1 + d_2 + d_3 + \ldots d_n$

Flow through unit width of layer d_1 under gradφ hydraulic gradient, $q_1 = A_1 V_1 = (1 \times d_1) \times (K_1 \text{ grad}\varphi) = K_1 d_1 \text{ grad}\varphi$

Similarly,

Flow through "d_2", $q_2 = K_2 d_2 \text{ grad}\varphi$
Flow through "d_3", $q_3 = K_3 d_3 \text{ grad}\varphi$
Flow through "d_n", $q_n = K_n d_n \text{ grad}\varphi$

Total flow through the layers,

$$Q = \sum_{i=1}^{n} q_i = (K_1 d_1 + K_2 d_2 + K_3 d_3 + \cdots + K_n d_n)\text{grad}\varphi$$

or,

$$Q = \sum K_i d_i \text{ grad}\varphi \tag{9.6}$$

Now, we assume that the equivalent horizontal hydraulic conductivity of the whole column (layers) is K_H (m/d). Then,

$$Q = D \times K_H \text{grad}\varphi = \sum d_i \times K_H \text{ grad}\varphi \tag{9.7}$$

where D is the depth of soil column.

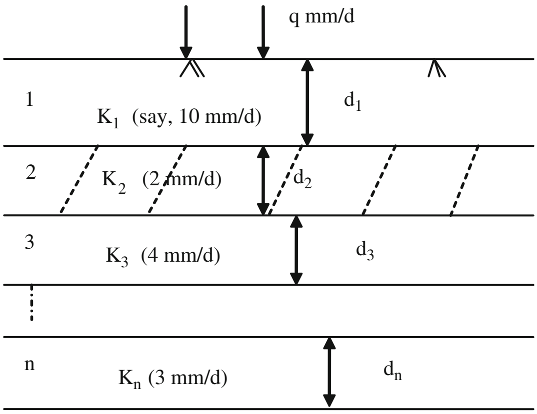
Equating the Eqs. (9.6) and (9.7), we get

$$K_H = \frac{\sum K_i d_i}{\sum d_i} \tag{9.8}$$

9.3.3.2 Resultant Vertical Hydraulic Conductivity

Consider a soil column having n layers, and with different thickness and hydraulic conductivity for each layer (Fig. 9.10). Now, we are interested to know the resultant (or equivalent) hydraulic conductivity for the soil column.

Fig. 9.10 Schematic of vertical soil layer with differential hydraulic conductivity



For explanation purpose, assume that layer-2 is relatively impervious than the other layers (sample values are given within the parenthesis). Assume that constant input, q (rainfall or irrigation rate), is higher than the lowest conductivity value (K_{min}) of the layers (here K_2). Although the layer-3 is relatively more pervious than the layer-2, the resultant flux or hydraulic conductivity will be limited by this layer. That is, if $q \geq K_{\text{min}}$, the unit flux or flux density will be controlled by the K_{min}. This is because, the K, Darcy's proportionality constant, or the hydraulic conductivity of the media, is the flux density (or in short "flux") under unit hydraulic gradient ($m^3/m^2/d$), not the flow velocity (m/d). In some text books, it is erroneously treated and expressed as flow velocity.

If the supply flux (q) is smaller than the K_{min}, the resultant vertical conductivity (K_V) will be limited by the q. Thus,

$$\begin{aligned} K_V &= K_{\text{min}}, \text{ if } q \geq K_{\text{min}} \\ &= q, \text{ if } q < K_{\text{min}} \end{aligned} \tag{9.9}$$

In reference to Fig. 9.10, at the top of layer-2 (i.e., at the bottom of layer-1), positive pressure will exist, since the incoming flux is higher than the outgoing flux. In contrast, at the top of layer-3 (i.e., at the bottom of layer-2), negative pressure will exist, as the outgoing flux capacity is higher than the incoming flux.

9.3.3.3 Resultant Conductivity of Horizontal and Vertical Direction

Resultant conductivity of horizontal hydraulic conductivity (K_{H}) and vertical hydraulic conductivity (K_{V}) can be obtained as

$$K' = \sqrt{K_{\mathrm{H}} \times K_{\mathrm{V}}} \tag{9.10}$$

9.3.4 Laplace's Equation for Groundwater Flow

Groundwater flow can be described by Laplace's equation. Laplace's equation combines Darcy's equation and equation describing mass continuity.

In general form, Darcy's equation can be written as

$$q = V \times 1 = K_i \times 1 = K\frac{\mathrm{d}h}{\mathrm{d}S} \tag{9.11}$$

where K is the hydraulic conductivity, i is the hydraulic gradient, dh is the head difference with the distance dS.

For a three-dimensional system, it can be written as

$$V_x = K\frac{\mathrm{d}h}{\mathrm{d}x},\ V_y = K\frac{\mathrm{d}h}{\mathrm{d}y},\ V_z = K\frac{\mathrm{d}h}{\mathrm{d}z}$$

For steady-state condition (no change in storage), mass continuity equation can be written as

$$\frac{\mathrm{d}V_x}{\mathrm{d}x} + \frac{\mathrm{d}V_y}{\mathrm{d}y} + \frac{\mathrm{d}V_z}{\mathrm{d}z} = 0$$

Putting the values of V_x, V_y, and V_z, we get

$$K_x\frac{\mathrm{d}^2 h}{\mathrm{d}x^2} + K_y\frac{\mathrm{d}^2 h}{\mathrm{d}y^2} + K_z\frac{\mathrm{d}^2 h}{\mathrm{d}z^2} = 0 \tag{9.12}$$

For homogeneous and isotropic soil system, $K_x = K_y = K_z$

Thus, the above equation reduces to

$$\frac{\mathrm{d}^2 h}{\mathrm{d}x^2} + \frac{\mathrm{d}^2 h}{\mathrm{d}y^2} + \frac{\mathrm{d}^2 h}{\mathrm{d}z^2} = 0 \tag{9.13}$$

which is the well-known Laplace's equation for groundwater flow.

9.3.5 Functional Form of Water-Table Position During Flow into Drain

Position of water table during flow into drain (steady or unsteady) can be described by the following functional form:

$$\mathrm{WT} = \int (I, K, d, S, D, ..) \tag{9.14}$$

where

WT = water-table depth (or position)
$\int$ = function
I = recharge from rainfall or irrigation
K = hydraulic conductivity of soil (vertical and horizontal direction, both upper and lower layer of drain)
d = depth of drain from the soil surface
S = drain spacing
D = depth to impervious layer from the drain

9.3.6 Theory of Groundwater Flow Toward Drain

9.3.6.1 Steady State Problems

The steady-state drainage situation is one where a constant uniform accretion rate, I, is recharging the water table and the drain tubes are simultaneously draining the soil profile. After some time, a state of equilibrium will be established in which the water table does not change shape, and the drain discharge is constant (Fig. 9.11).

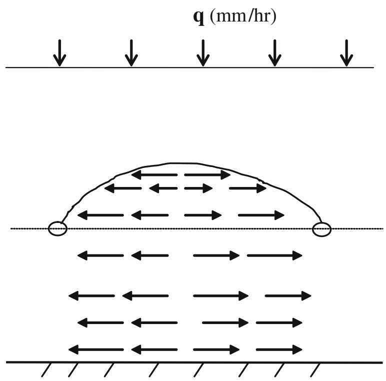


Fig. 9.11 Schematic of Dupuit-Forcheimer assumptions

Two types of approximate solutions of steady-state drainage condition have been proposed and are widely used:

(1) Based on horizontal flow assumption
(2) Based on radial flow assumption

Most techniques applied in analyzing the flow of water to subsurface drains are based on one-dimensional horizontal flow assumptions. Most solutions also assume that water percolates vertically from the soil surface through the unsaturated soil-water zone, so that the flux through the soil surface is also that through the water table. It is also commonly assumed that at steady state, the water table height at the top of the drain is negligible and that the drains do not flow completely full, a realistic assumption in all but extreme events and in systems with submerged outlets.

Horizontal Flow Assumption

Dupuit-Forcheimer's Assumption for Unconfined Flow

These assumptions regarding configuration of the flow and potential lines allow to derive solution of the flow of water toward drain without the use of Laplace's equation. These assumptions can be stated as follows:

(i) The flow lines (streamlines) are horizontal
(ii) The equipotential lines are vertical
(iii) The flow velocity in the plane at all depths is proportional to the slope of water table only and independent of the depth in the flow system.

The schematic of Dupuit-Forcheimer assumptions is shown in Fig. 9.11.

9.3.6.2 Non-steady State Drainage Situation

The non-steady state drainage situation is one in which the water table varies (falls or rises) with time. Although the non-steady state situation arises or exists in some cases and also in some parts of the operational period, steady-state assumptions are made for simplicity.

9.3.7 Sample Workout Problems

Example 9.2

A 1.2 m deep soil column consists of three layers, having 0.50, 0.4, and 0.3 m depth of the layers. The horizontal hydraulic conductivity of the layers are 0.20, 0.15, and 0.25 $m^3/m^2/h$, respectively. Determine the resultant horizontal hydraulic conductivity of the soil column.

Solution

We know

$$K_{\mathrm{H}} = \frac{\sum K_i d_i}{\sum d_i}$$

Putting the values,

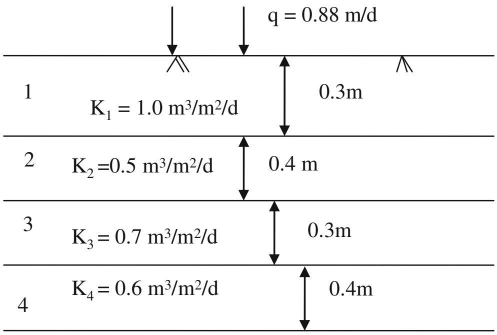
$$K_{\mathrm{H}} = \frac{(0.20 \times 0.50) + (0.15 \times 0.4) + (0.25 \times 0.3)}{1.2}$$
$$= 0.235\ \mathrm{m}^3/\mathrm{m}^2/\mathrm{h}\ \text{(Ans.)}$$

Example 9.3

A field soil has four distinct soil layers within 1.4 m depth from the surface. The depth and vertical hydraulic conductivity of the layers are 0.3, 0.4, 0.3, and 0.4 m; and 1.0, 0.5, 0.7, and 0.6 $\mathrm{m}^3/\mathrm{m}^2$/d, respectively. A constant water supply of 0.88 m/d is provided at the soil surface. What will be the resultant hydraulic conductivity of the soil column through the bottom of the soil layer? Comment on the pressure distribution at the up and bottom of the second layer.

Solution

The soil layers are schematically depicted in figure below:



The second layer has the lowest conductivity and it is less than the supply (0.88 m/d), and hence, the vertical water movement will be restricted by this layer. Thus, the resultant hydraulic conductivity at the bottom of the layers will be 0.5 $\mathrm{m}^3/\mathrm{m}^2$/d.

At the top of the second layer (that is at the bottom of the first layer), the supply or the conductivity is higher than the conductivity of the second layer, thus positive pressure will exist. On the other hand, at the top of the third layer, the conductivity is higher than the conductivity (or the supply) of the second layer, thus negative pressure will exist at the bottom of the second layer.

9.4 Design of Surface Drainage System

9.4.1 Estimation of Design Surface Runoff

The runoff to be used in drain design is termed as "design runoff." Surface runoff to be generated from an area (design runoff) can be determined from the equations such as "Rational method" or "SCS method." Details of these methods are described in Chapter 6 (*Land and Watershed Management*), this volume. According to Rational method, peak surface runoff rate (Q) is

$$Q = CIA$$

where Q is the runoff rate (m^3/h), A is the area from where runoff generates (drainage area) (m^2), I is the peak rainfall intensity (m/h), and C is the runoff coefficient (dimensionless). Runoff coefficient is the fraction of rainfall which contributes to runoff. For agricultural field, its value ranges from 0.5 to 0.7 depending on initial soil moisture, rainfall intensity and duration, and soil condition/coverage. For design purpose, the value of I can be taken from long-term (20–50 years) peak rainfall records.

9.4.2 Design Considerations and Layout of Surface Drainage System

A network of surface drains is needed to remove the excess water (from rainfall and/or irrigation runoff) from the agricultural field. Drain layout should be based on the topography, shape of the farm/catchment, direction of natural slope, position of farm buildings and roads, and position/existence of natural depression, channel, or river. Drain layout should be done with consideration of minimum length of run and minimum crossing of roads. This will minimize wastage of land and minimize cost for culverts. Sometimes, land grading serves the purpose of surface drainage.

Sample typical layout of a farm/catchment is given in Fig. 9.12

9.4.3 Hydraulic Design of Surface Drain

Hydraulic design of surface drain (also termed as "drainage channel") is similar to the design of an open irrigation channel, as described in Chapter 1 (*Water Conveyance Loss and Designing Conveyance System*) of this volume. The capacity of the drainage channel should be based on the design peak surface runoff from the

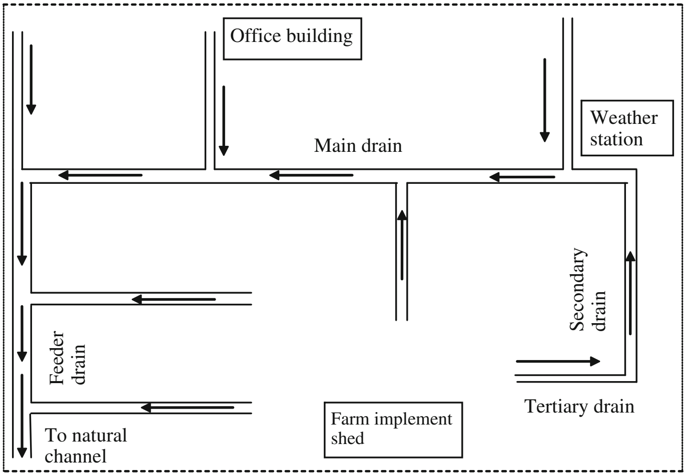


Fig. 9.12 Sample layout of surface drainage system in an agricultural farm

"drainage area" of the drain. "Drainage area" of a drain is the area from which the runoff falls to that drain.

For concrete channel, both rectangular and trapezoidal type can easily be constructed. For earthen channel (or earthen vegetative waterway), only trapezoidal type with smoothing of bottom corners is recommended.

9.4.4 Sample Work Out Problem

Example 9.4

Surface drainage should be planned for a new agricultural farm to drain out irrigation tail-water and seasonal rainfall runoff. Maximum rainfall intensity at the site in 20 years record is 35 mm/h. The tertiary drain would have to carry runoff from 4 ha land. The secondary drain would have to carry thrice of tertiary, and the main drain to carry discharge of four secondary drain (of similar flow). Determine the design discharge capacity of the (a) tertiary, (b) secondary, and (c) main drain.

Solution

We know, $Q = CIA$
Here,

Drainage area, $A = 4\,\text{ha} = 4 \times 10{,}000\,\text{m}^2 = 40{,}000\ \text{m}^2$
Design rainfall intensity, I = 35 mm/h = 9.72222E − 06 m/s
Runoff coefficient, $C = 0.6$ (as of agricultural land)

Putting the values, discharge capacity for the tertiary drain,

$$\begin{aligned} Q_t &= 0.6 \times 9.72222\text{E-}06 \times 40{,}000 \text{ m}^3/\text{s} \\ &= 0.233 \text{ m}^3/\text{s} \end{aligned}$$

Discharge capacity for the secondary drain, $Q_s = Q_t \times 3 = 0.233 \times 3 = 0.7 \text{ m}^3/\text{s}$
Discharge capacity for the main drain, $Q_m = Q_s \times 4 = 0.7 \times 4 = 2.8 \text{ m}^3/\text{s}$(Ans.)

9.5 Equations/Models for Subsurface Drainage Design

9.5.1 Steady-State Formula for Parallel Drain Spacing

9.5.1.1 Hooghoudt's Equation

Definition Sketch

Hooghoudt's equation is widely used in subsurface drainage design. It can also be used for sloping land and to account for entrance resistance encountered by the water upon entering the drains. Hooghoudt's equation for drain spacing (Hooghoudt, 1940) can be described as

$$S^2 = \frac{4k_a h^2}{q} + \frac{8k_b d_e h}{q} \tag{9.15}$$

where

S = drain spacing (L)
q = drainage coefficient (L/T)
k_a = hydraulic conductivity of layer above the drain (L/T)
k_b = hydraulic conductivity of layer below the drain (L/T)
h = height of water at the midway between drains under stabilized condition (L)
d_e = equivalent depth (L)

The first term of the equation gives the spacing for the flow above the plane of the bottom of the drain, while the second term gives the spacing for the flow below the plane. The definition sketch of elements of Hooghoudt's drain spacing equation is given in Fig. 9.13

Here, "D" is the actual depth of impervious layer from the drain, and "d_e" is the equivalent depth of "D" to correct the resistance due to radial flow, which was assumed as horizontal flow. "Equivalent depth" represents the imaginary thinner soil layer through which the same amount of water will flow per unit time as in the actual situation. The resulting higher flow per unit area introduces an extra head loss, which accounts for (and thus resembles to) the head loss caused by converging flow lines.

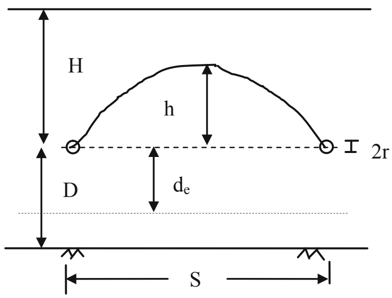


Fig. 9.13 Schematic of definition sketch of Hooghoudt's drain spacing formula

Hooghoudt's Equation Under Different Situation of Drain Placement

If the drain lies on the impervious layer, i.e., $D = 0$ (in Fig. 9.13), then consequently $d_e = 0$, and the Eq. (9.15) reduced to

$$S^2 = \frac{4k_a h^2}{q} \tag{9.16}$$

If the head of water above the drainage base is too small and the flow from below the drain dominates, then the flow above the drain can be neglected and thus the Hooghoudt's formula reduces to

$$S^2 = \frac{8k_b d_e h}{q} \tag{9.17}$$

Assumptions in Hooghoudt's Formula

Hooghoudt's formula is based on Dupuit-Forcheimer assumptions. The assumptions of Hooghoudt's formula can be summarized as follows:

- The soil is homogeneous
- Darcy's law is valid for flow of water through soil into the drain
- The drains are evenly spaced
- An impermeable layer underlies the drain
- There is a vertical recharge uniformly distributed in the horizontal plane
- Surface inflow rate, from irrigation or rainfall, is equal to the inflow to the drain
- The hydraulic gradient at any point in the flow regime is equal to the slope of water-table above the point
- The diameter of the drain is small compared to saturated thickness below the drain
- The drains have no entrance resistance
- The flow through drain is half-full

Limitations of Hooghoudt Equation

The Hooghoudt's equation assumes an elliptical water table, which occurs below the soil surface. Sometimes excess precipitation may raise the water table to the soil surface, and ponded water remains on the surface for relatively long periods. For such conditions, the application of Hooghoudt's equation based on the D–F assumptions has limitations to calculate the subsurface drainage flux into the tile drains. In case of surface ponding, the D–F assumptions will not hold and the streamlines will be concentrated near the drains with most of water entering the soil surface in that vicinity (Kirkham, 1957).

Estimation of Equivalent Depth

The equivalent depth can be obtained as (Hooghoudt, 1940)

$$d_e = \frac{\pi S}{8 \ln \dfrac{S}{\pi r_0}} \tag{9.18}$$

where r_0 is the radius of drain.

Moody (1966) proposed the following approximation for d_e:

$$\begin{aligned} d_e &= \frac{D}{1 + (D/S)[(8/\pi)\ln(D/r_0) - 3.4]}, \quad 0 < \frac{D}{S} \le 0.3 \\ &= \frac{S}{(8/\pi)[\ln(S/r_0) - 1.15]}, \quad \frac{D}{S} > 0.3 \end{aligned} \tag{9.19}$$

Closed-Form Solution for Equivalent Depth

Van der Molen and Wesseling (1991) developed closed-form expression for the equivalent depth (d_e) that can replace the Hooghoudt's tables:

$$d_e = \frac{\pi S}{8}\left[\ln \frac{S}{\pi r} + F(x)\right] \tag{9.20}$$

where

$$x = \frac{2\pi D}{S}$$

and

$$F(x) = \sum \frac{4e^{-2nx}}{n(1 - e^{-2nx})}, \text{ with } n = 1,3,5\ldots$$

The $F(x)$ converges rapidly for x>0.5.

The above equation must be solved iteratively, as both "d_e" and "S" are unknown.

Van Beer Equation

Van Beers equation for equivalent depth is (ILRI, 1973):

$$d_{\mathrm{e}} = \frac{D_S}{1 + \frac{8D}{\pi S} \times \frac{8D_S}{\pi^2 r}} \tag{9.21}$$

where, r is radius of drain pipe (m), D is drain depth (m), D_s is thickness of the aquifer below drain level.

Moustafa (1997) suggested from field investigation that a 5m depth instead of infinity for the impermeable layer in Nile Delta should be used in design purpose.

Important Parameters in Hooghout Drain Spacing Equation (and also in Others) and Their Interpretation

Form the equations of (9.15), (9.16) and (9.17), it is revealed that drain spacing is directly related to the hydraulic conductivity of the soil (K), and inversely related to the drainage discharge/outflow (q) from the field. So, these two parameters (input values) should be determined/estimated accurately.

K of Soil

If the estimated K value is less than the actual one, calculated drain spacing will be lower, and hence more financial involvement compared to actual need (i.e. financial loss). On the other hand, if the estimated K value is higher than the actual field value, the drain spacing will be higher than the actual need. Thus, there is a possibility of prolonged standing water in the root zone, and hence chance of crop loss.

q Value

The reverse will be true in case of q value.

9.5.1.2 Donnan's Formula

Donnan proposed the following formula for parallel drain spacing:

$$S^2 = \frac{4\,k}{q}\left[(D+h)^2 - D^2\right] \tag{9.22}$$

Solving for algebraic functions, the above equation reduces to

$$S^2 = \frac{4kh^2}{q} + \frac{8kDh}{q}$$

which is similar to Hooghoudt's equation.

9.5.2 Formula for Irregular Drain System

Most investigations, both theoretical and experimental, have focused on parallel drainage systems with equally spaced tiles. However, in many watersheds (e.g., as those in Illinois), parallel systems do not occur as frequently as irregular systems. Irregular tile systems predominate in areas where the majority of the tiles drain small depressional areas, and thus tile lines are placed at irregular angles and spacings. In these systems, a constant spacing parameter does not exist or cannot be easily defined.

Irregular and parallel tile systems are hydraulically different, as a single tile draws water from a semi-infinite distance on either side (Fig. 9.14), while the region of influence of each tile in a parallel system is constrained by the neighboring tiles.

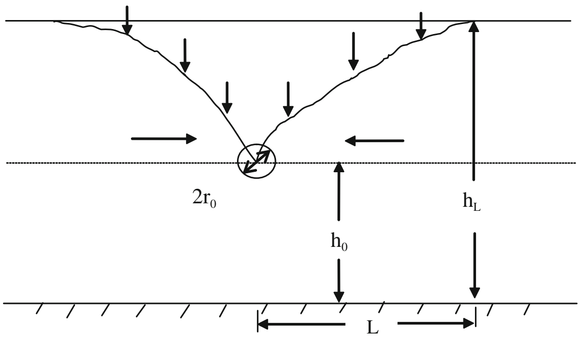


Fig. 9.14 Schematic of flow to single drain

Cook et al. (2001) derived equation for random and irregular tile drainage system. Their equation is

$$q_0 = \frac{K}{L}(h_L^2 - h_0^2) \tag{9.23}$$

where

q_0 = the flow rate at the tile drain from each side (m^3/s)
K = hydraulic conductivity (m^3/m^2/s)
L = the distance at which the water table becomes essentially horizontal (m)
h_L = height of water table above the impervious layer at distance L (m)
h_0 = height of drain above the impermeable layer (m)

The total drain outflow would be twice q_0, since water flows into the drain from both sides. It should be noted that this is identical to the result for parallel systems if L is replaced by the half spacing, $S/2$.

9.5.3 Determination of Drain Pipe Size

The pipe size should be 25–50% higher than the maximum design discharge, to compensate possible reduction in the net capacity of pipe due to deposition of silt. Discharge carrying capacity of the pipe can be calculated using Manning's equation (which is described in Chapter 1, this volume).

9.6 Design of Subsurface Drainage System

9.6.1 Factors Affecting Spacing and Depth of Subsurface Drain

Factors which influence drain spacing and depth include

- root zone depth of the proposed crop
- sensitivity of the crop to water logging or salinity
- soil texture (coarse or fine)
- salinity level of soil and/or groundwater
- depth of groundwater table
- root zone depth at saline sensitive growth stage
- depth of impervious soil layer
- hydraulic conductivity of the soil (horizontal and vertical direction)

9.6.1.1 Soil Salinity

Salinity distribution data of soil profile should be considered when selecting the drain depth.

9.6.1.2 Impact of Soil Texture on Drain Depth

Upflow *or* capillary rise of water through capillary tube (resembled to soil pore) can be expressed as

$$h_{cr} = \frac{2\tau}{r\rho}\cos\theta \tag{9.24}$$

where

h_{cr} = capillary rise of water (cm)
r = radius of tube (cm)
ρ = density of water (g/cm^3)
τ = surface tension (g/cm)
θ = angle of contact between meniscus and wall of tube (deg.)

Taking density of water, $\rho = 1$ gm/cm^3, $\tau = 0.074$ g/cm (for water of 20°C), and neglecting the angle (i.e., $\theta = 0$), we get

$$h_{cr} = \frac{0.15}{r} \tag{9.25}$$

From the Eqs. (9.24) and (9.25), it is revealed that the h_{cr}, the capillary rise or height of upflow, is inversely proportional to the radius of the capillary tube. Thus for soil of clay type, i.e., soils having smaller diameter of pore, capillary rise will be higher. For the sandy soil, due to larger diameter of pore, the reverse will be true. Therefore, to minimize rise of groundwater within the root zone (or target soil depth), drain should be placed at greater depth in clayey or fine-textured soil than the coarse-textured soil (for similar crop and hydro-geologic condition).

9.6.2 Data Requirement for Subsurface Drainage Design

Data required for proper design of a subsurface drainage system include

- soil layering
- depth to layers restricting vertical flow
- soil hydraulic properties (for each layer)
- depth to water table
- salinity status of soil and ground water
- sources of drainage water other than deep percolation
- cropping pattern and crop root zone depth
- type of irrigation system
- irrigation schedule
- irrigation efficiency
- climate data

Soils data collection and analysis is common to all design procedures. Sampling and investigation of the soil must be done up to below the depth of potential drain placement (2–4 m) to determine the presence of a restricting layer. The soil salinity profile above the drain is useful to determine the need for remediation. The soil salinity profile below the drains is needed because this will be indicative of the potential salt load when the drains are in operation.

If the soil properties vary considerably within a farm, the area should be divided into “sub-areas” or “blocks.” Then, drain spacing should be calculated for each sub-areas or blocks.

9.6.3 Layout of Subsurface Drainage

Layout of installing subsurface drain depends on shape of the farm/catchment, topographical feature, and drainage disposal facility. A typical layout is given in Fig. 9.15.

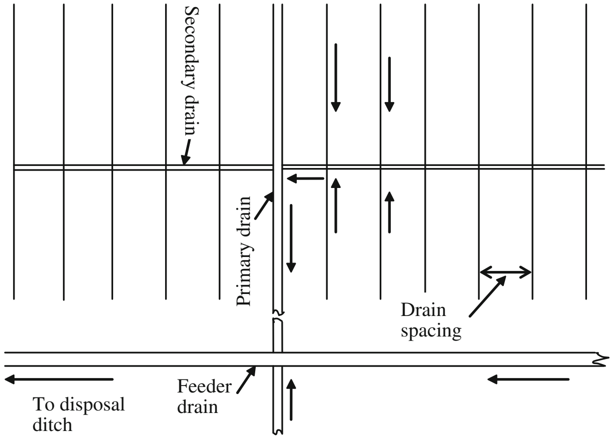


Fig. 9.15 Schematic of a typical layout of subsurface drainage system

9.6.4 Principles, Steps, and Considerations in Subsurface Drainage Design

9.6.4.1 Principles

The design of a subsurface drainage system requires developing criteria that

- specify the operation of the system and the physical configuration that fulfill the drainage objective(s).
- consider irrigation and drainage systems as an integrated water management system.
- minimize deep percolation losses through improved irrigation water management (source control)
- characterized by establishing the water-table depth at the mid-point between laterals and the drainage coefficient (that specifies the maximum volume, expressed as depth of water to be removed in a 24-h period)
- Specify option regarding reuse of drainage water for irrigation or stimulation of *in situ* use by crop through control of water table.

In arid areas an additional design criterion is the control of salt accumulation by capillary rise into the crop root zone, which is accomplished by managing the mid-point water-table depth to minimize upward flow of water and salt from the shallow ground water.

9.6.4.2 Steps

In designing subsurface drainage system in a command area or watershed, the following steps and procedures need to be followed:

(i) Investigate the soil profile and geo-hydrologic condition including groundwater quality
(ii) Measure the quality of proposed irrigation water
(iii) Estimate the sources of drainage water other than irrigation
(iv) Review and analyze the climatic data of the area
(v) Select appropriate crop(s)/cropping pattern
(vi) Measure the hydraulic conductivity of the root zone soil
(vii) Estimate drainage requirement or drainage coefficient
(viii) Optimize the depth of drain placement and lateral drain spacing (considering permissible mid-way water-table depth for the selected crop/cropping pattern, in situ crop water-use plan by capillary rise*, and cost of drain).

Different combinations of drain depth and spacing will result in same drainage coefficient. But the water quality of drainage may be different. For a particular drainage intensity, shallow depth of drains requires narrow spacing, thus drainage cost increases with decreasing drain depth.

First, a drain depth is specified and the spacing is calculated based on the recharge schedule and the mid-point water-table depth criteria. Subsequently, the drain depth will be varied to calculate a range of depths and spacing, and economic analysis should be performed for each case. The most economic drain depth and spacing is then selected from analyses of several drain system configurations.
(ix) Determine lateral pipe size and main pipe size (capable of carrying the maximum drainage rate)
(x) Design the drain envelop material
(xi) Design the drainage disposal system, or decide regarding reuse of drainage water for irrigation
(xii) Design the pump size to pump the maximum drainage discharge from the field (if need to be pumped)

* In situ use by the crop will affect the drainage design by reducing the irrigation requirement and the deep percolation losses that will be included in the drain system design procedure.

The USBR recommends installation of drains at a depth of 2.4 m, if possible, to provide a balance between the system cost and spacing.

9.6.4.3 Estimation of Drainage Requirement or Drainage Coefficient

For estimation of drainage requirement (or drainage intensity, or drainage coefficient), following steps may be followed:

- collect long-term rainfall and other weather data for the project area
- calculate daily average rainfall, evaporation, and evapotranspiration rate for the target crop season
- perform water-balance

Under natural rainfall condition, water balance can be expressed as

$$P = \mathrm{ET} + R + D$$

or

$$D = P - \mathrm{ET} - R \tag{9.26}$$

where

P = rainfall rate (mm/d)
ET = evapotranspiration rate (mm/d)
R = surface runoff amount, mm/d (if surface runoff is feasible)
D = deep percolation *or* subsurface drainage amount (mm/d)

The "*D*" value will indicate the drainage coefficient or drainage requirement. Instead of average rainfall, peak rainfall of 10–20 years recurrence interval may be used. Procedure for such determination has been described in Chapter 3 (*Weather*), Volume 1.

Drainage Requirement for Salinity Control

For salinity control purpose, leaching requirement (LR) should be calculated. Procedure for calculating LR has been described in Chapter 8 (*Management of Salt-Affected Soils*), this volume.

9.6.4.4 Criteria and Considerations

The USBR (United States Bureau of reclamation) recommends a minimum water-table depth from 1.1 to 1.5 m below land surface midway between lateral drains, depending on the crop rooting depth. From past records, this should result in achieving at least 90% of maximum crop production (US Department of Interior, 1993). The midpoint water-table recommendation ensures that the soil oxygen status is maintained in the root zone and reduces capillary transport of water and salt from shallow groundwater into the root zone and to the soil surface due to evaporative demand.

Deep placement of the drains generally results in a wide drain spacing that lowers the system cost relative to shallow one. However, in many cases deep placement has been shown to result in an excessive salt load being discharged with the drainage water (Christen and Skehan, 2001; Ayars et al., 1997). This is because the soil is normally more saline than the irrigation water salinity in most cases (Ali and Rahman, 2009; Ayars et al., 1997).

9.6.5 Controlled Drainage System and Interceptor Drain

9.6.5.1 Controlled Drainage

Introduction

In the past, subsurface drainage systems were typically designed to discharge water continuously, without regard to the environmental consequences and the effects on crop production. This philosophy has changed in humid areas of the world, as the environmental consequences and crop production impacts have been researched. Recently, controlled drainage has been identified as a potential management method in humid areas to reduce nitrate loading to surface water (Ayars et al., 2006; Hornbuckle et al., 2005; Lalonde et al., 1996; Doty and Parsons 1979).

Principle of the Method

In this drainage system, the water table is maintained at a shallower depth by a control structure which reduces deep percolation below the root zone by reducing hydraulic gradients and increases potential capillary upflow, as evapotranspiration depletes soil-water in the root zone (Fig. 9.16).

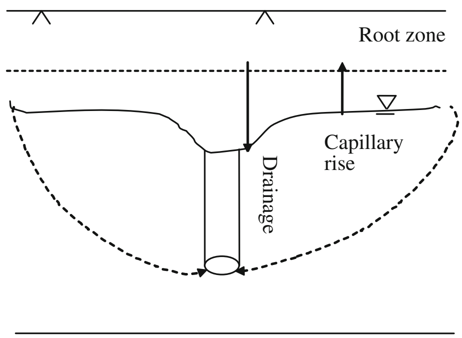


Fig. 9.16 Schematic of control drainage system

The flow lines are shallower than in the uncontrolled system and are more concentrated when close to the soil surface. In soil profiles with zones of lower soil salinity at the soil surface, this system results in decreased drain water salinity compared to the uncontrolled system. The reduced drain flows and lower salinity result in much reduced salt loads.

Management of Control Drainage System

Traditional drainage does not need much management aspects, but simply letting the system run continuously. In control drainage, active management measures are needed to regulate flow and reduce the impact of saline drainage water on the environment. The goal may be to reduce total drainage flow, reduce contaminant load, improve irrigation efficiency, or some combination of these outcomes. The effectiveness of drainage system management will depend on the crop, the ground water quality, and the water table position. Field research and model studies suggest that shallower placement of drainage laterals and reduced depth to mid-point water table will result in reductions in drainage volumes and salt loads.

9.6.5.2 Interceptor Drain

Where it is not practical to drain water out of a pocket point by other means (or if constraints exists), a collector system should be provided to drain water from the drainage layer. Collector systems may include plastic pipe slotted at the edge, or drain pipe installed in a longitudinal collector trench. This will limit the longitudinal seepage distance in the drainage layer, minimizing the drainage time and preventing the buildup of a hydrostatic head under the surface layer (Fig. 9.17).

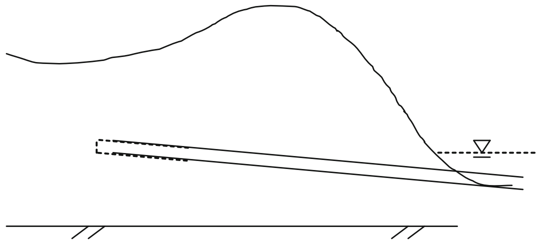


Fig. 9.17 Schematic representation of interceptor drain

An interceptor drain may be defined as the drain that is constructed for the purpose of intercepting or cutting off groundwater which is moving down-slope. Its source may be of different origin. Interceptor drain may be either open or close construction.

Donnan (1959) raised several issues regarding interceptor drain: (1) How deep should the interceptor drain be placed? (2) How far upslope will the drawdown be effective? (3) Where does the post-installation water table become asymptotic coincide with the undisturbed (original) water table? (4) What is the shape of the drawdown curve on the down slope side? (5) How much of the total flow is intercepted? (6) What is the required capacity of the drain? (7) Should the drain be open or closed? He concluded in the way: drain should be placed as deep as it is practical (open ditch at the bottom of impervious layer), drawdown upslope will depend on the initial slope of the water table, down slope will be dependent on the water level in the drain device, the quantity of flow will vary directly with the depth of flow intercepted, and both open and tile drain are equally efficient.

9.6.6 Sample Workout Problems

Example 9.5

In an agricultural command area, the long-term average of daily maximum rainfall and evapotranspiration are 70 and 6 mm, respectively. The surface runoff on catchment basis can be considered as 40% of the rainfall. If the proposed crop does allow ponding water more than 24 h, determine the subsurface drainage requirement for survival of the crop.

Solution

Considering water balance on daily basis,

$P = \mathrm{ET} + R + D$
or, subsurface drainage, $D = P - \mathrm{ET} - R$
Given,
$P = 70$ mm
$\mathrm{ET} = 6$ mm
$R = 70 \times 0.4 = 28$ mm
Putting the values, $D = 70 - 6 - 28 = 36$ mm

That is, daily drainage requirement is 36 mm, or 1.5 mm/h (Ans.)

Example 9.6

In a saline agriculture, estimate the drainage requirement for successful crop production from the following information:

Crop: Wheat
$\mathrm{EC_e} = \mathrm{EC_{dw}} = 8.0$ dS/m
$\mathrm{EC_{iw}} = 1.5$ dS/m
$\mathrm{ET} = 5$ mm/d (peak rate)

Solution

$$\mathrm{LR} = \frac{D_{\mathrm{dw}}}{D_{\mathrm{iw}}} = \frac{\mathrm{EC_{iw}}}{5\mathrm{EC_e} - \mathrm{EC_{iw}}} = \frac{1.5}{5 \times 8 - 1.5} = 0.038$$

$$D_{\mathrm{iw}} = \frac{\mathrm{ET}}{1 - \mathrm{LR}} = \frac{5}{1 - 0.0389} = 5.202$$

$$D_{\mathrm{dw}} = 5.202 - 5.0 = 0.202 \text{ mm/d}$$

Considering irrigation application efficiency, $E_{\mathrm{a}} = 0.8$, that is 20% is lost to deep percolation; the excess application is

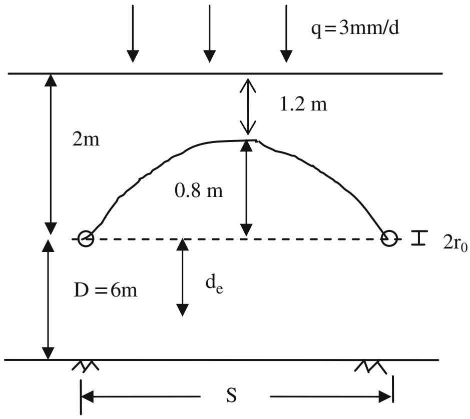
$$= \frac{5}{0.8} - 5 = 1.25 \text{ mm/d, which is greater than } 0.202 \text{ mm/d}$$

Thus, the drainage coefficient, or drainage requirement = 1.25 mm/d (Ans.)

Example 9.7

A subsurface drainage should be provided through an agricultural farm of several kilometers long. Average expected recharge to the water table in the area is about 3 mm/d. It is required to maintain the water table not closer than 1.2 m from the soil surface. The value of hydraulic conductivity up to 2.0 m is 40 mm/d, and below that is 42 mm/d. Relatively, impervious layer exists 8 m below the soil surface. Determine the drain spacing.

Solution



We know, Hooghoudt's drainage equation is

$$S^2 = \frac{4k_a h^2}{q} + \frac{8k_b d_e h}{q}$$

Given,

$q = 3$ mm/d $= 0.003$ m/d
$k_a = 40$ mm/d $= 0.04$ m/d
$k_b = 42$ mm/d $= 0.042$ m/d
$D = 6$ m
Assuming drain diameter = 20 cm. Thus, $r_0 = 20/2 = 10$ cm $= 0.1$ m
Placing the drain at 2.0 m below the surface, $h = 2.0 - 1.2 = 0.8$ m
Determination of equivalent depth (d_e):
We know,

$$d_e = \frac{\pi S}{8 \ln\left(\frac{S}{\pi r_0}\right)}$$

Writing the above formula and drain spacing formula in Excel worksheet, and solving for a series of values (trial values) for the variable "S" and "de," we can find that

when $S = 9.8$ m, then $d_e = 1.1$ m, and new value of $S = 9.98$, which is close to 9.8.

Thus, taking $d_e = 1.1$ m,

$S = 9.98$ m (Ans.)

9.7 Envelope Materials

9.7.1 Need of Using Envelop Material Around Subsurface Drain

Water moves to the drain due to hydraulic gradient. The hydraulic gradient that develops at the drain openings is often high enough to cause piping of soil material through the openings. For this reason an adequate amount of protective materials (termed as "envelope material") is needed around subsurface drain.

The functions of placing envelop material around subsurface drain conduits are the following:

(i) Prevent the movement of soil particles into the drains which may settle and close the drains (Barrier function)
(ii) Provide material in the immediate vicinity of the drain openings that is more permeable than the surrounding soils, thus increasing effective diameter of the drain (Hydraulic function)
(iii) Provide suitable bedding for the drain (Bed material function)

9.7.2 Need of Proper Designing of Envelop Material

The envelope material should be selected such that the material or any combination of materials gives adequate protection against siltation, yet providing relatively unrestricted water movement from the soil to the drain. To fulfill the objective of using envelope material, proper selection of envelope material and design is a must. Good design aims to assure an optimum combination of performance, long survive, and reasonable cost.

9.7.3 Materials for Envelope

Materials used for subsurface drain have included almost all permeable porous materials that are available economically in large quantities. Granular mineral materials such as coarse sand, fine gravel, and crushed stone have been used for decades in arid and semi-arid countries as a drainpipe envelope.

Envelope materials can be categorized into three groups:

(a) *Organic envelopes*: organic materials that are used as envelope materials. Frequently used materials are sawdust, chaff, cereal straw, flax straw, cedar, leaf, bamboo, corncobs, wood chips, reeds, heathers, bushes, grass sod, and coconut fiber.
(b) *In-organic/mineral envelopes*: the most common and most widely used envelope materials are naturally graded coarse sands and fine gravels.
(c) *Man-made/synthetic envelopes*: this type includes fiberglass, geo-textile sheets (<0.5 mm), successors of glass fiber sheets. Synthetic materials are relatively inexpensive and can be manufactured at large quantities of exact specification.

9.7.4 Design of Drain Envelope

9.7.4.1 Steps

The steps for designing drain envelope materials are the following:

- Make a mechanical analysis of both the soil and the proposed envelope material
- Prepare particle size distribution curve for each material
- Decide by some set of criteria whether the envelope material is satisfactory or not.

9.7.4.2 Criteria for Selecting Envelope Material

Many researchers have done work on specification of envelope materials, and different ratios were recommended. Terzaghi (1922), Karpoff (1955), Juusela (1958), Kruse (1962), Soil Conservation Service of USDA (SCS, 1971, 1988, 1994), the United States Army Corps of Engineers (US Army Corps of Engineers, 1941, 1978), the United States Bureau of Reclamation (USBR, 1973, 1978, 1993), Stuyt (1992) sequentially improved and suggested criteria for envelop materials. More recent work was carried out by Vlotman et al. (1994, 1995, 2000) and Stuyt et al. (2005).

Design Criteria for Synthetic Fiber Envelope

Dierickx (1993) and Vlotman et al. (2000) made detail review of various proposed retention criteria, primarily for geotextiles. The ratio of O_{90}/d_{90} is frequently used, with O_{90} and d_{90} the envelope pore size and the soil particle size, respectively, for which 90% of the pores or particles are smaller. Vlotman et al. (2000) propose that the retention criteria O_{90}/d_{90} will range from 2.5 to 5 for envelope thickness ranging from 1 to 5 mm.

Stuyt et al. (2005) suggested the following criteria for synthetic fiber envelope: for thickness $\geq$5 mm, $O_{90}/d_{90} \leq 5$; for thickness between 3 and 5 mm, $O_{90}/d_{90} \leq 4$; for thickness between 1 and 3 mm, $O_{90}/d_{90} \leq 3$; and for thickness $\leq$1 mm, $O_{90}/d_{90} \leq 2.5$. They noted that $O_{90}/d_{90} \geq 1$ minimized the risk of mineral clogging.

Design Criteria for Granular Mineral Envelopes

For gravel envelope, Vlotman et al. (2000) suggested the following criteria for the coarse boundary envelop material: for filter retention, $D_{15c}<7d_{85f}$; for gradation curve guide, $D_{60c}=5D_{15c}$; segregation criteria, $D_{100}<9.5$ mm. For the fine boundary envelope materials, the criterions are the following: for hydraulic, $D_{15f} = >4d_{15c}$; for gradation curve guide (bandwidth), $D_{15f} = D_{15c}/5$ (based on $C_u^b \leq 6$ and bandwidth ratio ≤ 5); for hydraulic criterion, $D_5 > 0.074$ mm; for gradation curve guide (bandwidth), $D_{60f}= D_{60c}/5$; for retention criteria (bridging), $D_{85}= D_{60c}$.

In the above criterion, symbols "D" and "d" refer to particle size distribution of the gravel and base soil, respectively, where number gives the percentage with a smaller diameter. For example, D_{50} is the diameter of the sieve where 50% passes. The "C_u" means uniformity coefficient and the superscript "b" means base materials. The indices c and f in the subscripts refer to the upper and lower particle size diameters of the base-soil and the gravel.

Design Criteria by SCS (1971)

The SCS has combined other researcher's results into a specification. Their criterions are

$$\frac{D_{50f}}{D_{50b}} = 12 \text{ to } 50$$

$$\frac{D_{15f}}{D_{15b}} = 12 \text{ to } 40$$

Other criterions: filter materials should pass 1.5 in. sieve, 90% should pass the 0.75 in. sieve, and no more than 10% should pass the 0.01 in. sieve.

If the filter and base materials are nearly uniform, a filter stability ratio of less than 5 is generally safe, i.e., $\frac{D_{15f}}{D_{85b}} < 5$.

The uniformity co-efficient, C_u, (D_{60}/D_{10}) was also considered as a design factor. A low uniformity co-efficient indicates a uniform material. Kruse (1962) considered envelope material with a C_u of 1.78 to be uniform.

9.7.4.3 Envelope Thickness

As the amount of envelope material requirement increases with the square of the diameter, it is important to judicious selection of envelope thickness. The US Bureau of Reclamation recommended a minimum thickness of 10 cm around the pipe. The SCS (1971) recommends 8 cm minimum thickness.

9.7.5 Use of Particle Size Distribution Curve in Designing Envelop Material

Particle size distribution curve shows the relationship between grain size and percent larger (or finer) at that size. Particle size distribution curves of the soil and the proposed envelope material enable the selection of an envelope material, which best suits the soil. In designing, we have to compare the two particle size distribution curves and decide by the set of criteria (described earlier) whether the envelope materiel is satisfactory or not.

In determining maximum size of the perforations or joint openings of the drainage pipe, the 85% size of the envelope material is used from the particle size distribution curve.

9.7.6 Drain Excavation and Envelope Placement

Excavating and trenching machines, driven by steam engines, were introduced in 1890. Trenchers dig a trench at the required depth and grade and place the drain pipe at the bottom of the trench. Several types of trenchers are produced in various sizes and a wide range of capacities. They can install pipes to a depth of about 3 m in trenches up to 0.50–0.60 m in width. Trenchers have been developed in different modified models so that they can also be used to install drains in stony soils, in orchards, or in soils with high water tables.

Water enters the drain through the sides and bottom of the drain. The hydraulic gradient that develops at the drain openings is often high enough to cause piping of soil material at the openings. For this reason an adequate amount of envelope material is needed under the drain pipe as well as on top.

Where drains are laid manually, a layer of envelope material is placed and leveled to the design grade in the bottom of the trench (before the drain is laid). The drain pipe is then put into place and covered with envelope material to the required depth. The trench is then backfield with soil. Trenching machines can be fitted with two-hoppers for placing envelope material under and over a drain on a continuous basis.

Care should be taken to protect the drain-envelope system immediately following installation. No heave loads, mechanical or hydraulic, should be imposed until the loose back-fill material in the trench is consolidated naturally.

9.8 Models in Drainage Design and Management

Nowadays, models are useful and easy-to-way tool to design surface and subsurface drains, and management of drainage system. Some of the existing models are described below:

9.8.1 DRAINMOD

DRAINMOD is a deterministic hydrologic model developed to simulate a soil-water regime of surface and subsurface water management systems (Skaggs, 1978). It predicts surface runoff, infiltration, evapotranspiration, subsurface drainage, and seepage from tile drained landscapes. A basic relationship of the model is a water balance for a vertical soil column of unit surface area, which extends from the impermeable layer up to the soil surface, and located midway between adjacent drains.

9.8.2 CSUID Model

The Colorado State University Irrigation and Drainage (CSUID) model is a simulation model that can be used in the design and management of conjunctive irrigation and drainage systems (Manguerra and Garcia, 1995). The model is based on the numerical implementation of a quasi three-dimensional finite-difference model, which solves the Richards equation and the advective-dispersive transport equation for one-dimensional vertical flow and salt transport in the variably saturated zone above the water table; and it also solves the depth-averaged Boussinesq equation and two-dimensional advective-dispersive transport equation for areal flow and transport in the fully saturated zone below the water table. It is capable of drainage designing and management.

9.8.3 EnDrain

"EnDrain" is a software tool that calculates drainage discharge, hydraulic head, and spacing between parallel subsurface drains, pipes, or open ditches; with or without entrance resistance (Oosterbaan et al., 1996). It shows the curve of water table. The drain spacing calculations are based on the concept of the energy balance of groundwater flow. However, the traditional concepts based on the Darcy and water balance or mass conservation equations are also used. The program allows for the presence of three different soil layers with different hydraulic conductivity and permeability – one layer above and two below drain level. "EnDrain" can be used for the reclamation of saline soils. The software is free, and can be downloaded from the site: http://www.waterlog.info/

9.9 Drainage Discharge Management: Disposal and Treatment

9.9.1 Disposal Options

There are limited number of options available when trying to decide where and how to dispose of agricultural drainage water into the natural hydrological system.

The common option is to return the water either to natural depressions or lakes or rivers, or to salt sinks, such as ocean, or to return the water either to the land as part of the irrigation water supply. The options available to any single project may be limited because of water quality concerns. Downstream beneficial uses of any surface water body to which drainage water is added must be protected. For example, it may not be appropriate to discharge saline drainage water into a river of lake, when that surface water body is being used for domestic or agricultural water supplies. Disposal of runoff and drainage waters into natural depressions has been practiced for centuries. The impounded waters are dissipated by evaporation, seepage, and transpiration losses. The use of constructed disposal basins for saline agricultural drainage waters are also common worldwide where there are constraints on discharging into natural salt sinks such as the oceans and inland closed basins. In the Murray-Darling basin in Australia, some of the constructed evaporation basins are intended to hold saline water only temporarily. The stored waters are then released during high river flows.

9.9.2 Treatment of Drainage Water

Treatment approaches of drainage water can be divided into three general categories:

– physical
– chemical
– biological

Many processes exhibit both physical and chemical aspects and so are sometimes called physical/chemical or physiochemical treatment.

The first step in the selection of any treatment process for improving drainage water quality is to thoroughly define the problem and to determine what the treatment process has to achieve. In most cases, either regulatory requirements or the desire to re-use the water will be the driving force in defining the treatment issues to be selected for a particular drainage water. A thorough knowledge and understanding of these water quality criteria is required prior to select any particular treatment process.

An introductory description is given below for the most common treatment methods, which have application in treating agricultural drainage water. More detailed description of common treatment processes and design procedures of treatment plant (Waste water treatment) can be found in "Wastewater treatment" texts/books.

9.9.2.1 Physical/Chemical Treatment

Particle Removal

Several physical processes aim to remove suspended particulate matter. Subsurface drainage water itself is usually low in suspended particles. These processes might be used in an overall treatment process for the removal of particulates formed in another stages of the treatment, such as removal of bacteria from a biological system or removal of precipitates formed in a chemical treatment process. Particle removal unit processes include sedimentation, flotation, centrifugation, and filtration. Filtration further includes granular media beds, vacuum filters, belt presses, and filter presses.

Adsorption

Adsorption is the process of removing soluble contaminants by attachment to a solid. A common example is the removal of soluble organic compounds via adsorption onto granular activated carbon (GAC). GAC is useful for its ability to remove a wide range of contaminants. Certainly, if pesticides were a concern for the drainage water being examined, the use of GAC adsorption would be a leading candidate for treatment.

Another treatment for removing volatile compounds for water is air stripping. In a conventional counterpart of air stripping operation, the contaminated water is distributed at the top of a tall reactor vessel that is packed with materials or structures with a high surface area. As the water moves downward, clean air is introduced at the bottom of the reactor and moves upward. As the water and air make contact, volatile compounds are transferred from the liquid phase to the gas phase according to gas transfer theory.

Distillation

Distillation is a thermal process used for salt removal. Heat is used to vaporize the water, leaving the salts behind. The water vapor is condensed to a high quality water. The process is energy intensive. Reverse osmosis is used for desalination applications.

9.10 Economic Considerations in Drainage Selection and Installation

Economic analysis should be carried out before undertaking a drainage project. The result of economic analysis will help in deciding whether drainage system installation is feasible from economic point of view, or which type of drainage (e.g., surface (deep drain) or subsurface, or, random field lateral *or* uniform drainage) is more economical. Sometimes, the economic criterion is not only deciding criteria, but also depends on the national/regional food security issue, national priority, and government policy.

Detail procedure for performing economic analysis and decision criteria (along with sample example) has been discussed in Chapter 11 (*Economics in Irrigation Management*), Volume 1.

9.11 Performance Evaluation of Subsurface Drainage

9.11.1 Importance of Evaluation

Subsurface drainage is instrumental in the improvement of non-productive soils, and it can assist in avoiding unsuitable soil conditions during farming operations. Knowledge of subsurface drainage performance is important in order to use reclaimed land rationally, and to apply the scarce available financial means to repair improperly functioning drains.

9.11.2 Evaluation System

Discharge (q) and water-head midway between drains (h) are two important design parameters of subsurface drainage. To evaluate the performance of subsurface drainage, these two parameters, and water-head on top of the drains, are to be measured and compared with the design (and/or expected) value under the prevailing conditions. Measurement of water table should be carried out every 3–5 days depending on rainfall amount, ET demand, and hydraulic conductivity. The measurement should be continued for a reasonable length of time (at least one season or a part), and in several plots.

If the design parameters differed significantly from the designed/expected value, it indicates that original design criteria are not satisfied. The causes of drain malfunctioning may include the drains are too widely spaced, drain envelope materials are not properly designed, changes in hydraulic conductivity of the soil from the measured/gauged one (may be due to erroneous measurement of K, compaction of soil due to traffic or natural compaction/settlement). More elaborate measuring set-up as well as long-term observation may be needed to ascertain the causes of failure or drain malfunctioning. Under natural rainfall condition, low rainfall can results in small discharge and low head.

In addition to the piezometer on top of the drain (which measures the water-head above the drain), another piezometer may be connected to the drain to ascertain whether the head above the drain is due to entrance resistance or to backpressure in the drain.

If we consider the drain center as reference level, the total head loss in the system (h_t) can be expressed as

$$h_t = h_m - r_0$$

where

h_m = head in the piezometer midway between drains (or the height of the groundwater table midway between drains above drain level) (m)
r_0 = outside radius of the drain (m)

The approach flow head loss or the head loss in the vicinity of the drainage system (drain pipe and envelope material), h_{ap}, is given by (Rimidis and Dierickx, 2003):

$$h_{ap} = h_v - r_0$$

where h_v is the head in the piezometer in the vicinity of the drain pipe (usually 40 cm away from the drain center). The approach flow resistance (W_{ap}) is

$$W_{\text{ap}} = h_{\text{ap}}/qL$$

where q is the specific discharge (m^3/d/m) and L is the drain spacing (m).

Measured data can be expressed in equation similar to Hooghoudt equation. Rimidis and Dierickx (2003) expressed their experimental evaluation data in the form:

$$q = Ah_{\text{t}}^2 + Bh_{\text{t}}$$

The above equation is similar to the well-known equation of Hooghoudt (1940):

$$q = \frac{4Kh_{\text{t}}^2}{L^2} + \frac{8Kdh_{\text{t}}}{L^2}$$

where

$$A = 4K/L^2, \text{ and B} = 8Kd/L^2$$

9.12 Challenges and Needs in Drainage Design and Management

To meet the challenge of a sustainable irrigated agriculture, minimum impact on the environment should be ensured. Controlled drainage, a comparatively new approach of drainage management, is suffering from lack of design criteria for both humid and arid regions. Ayars et al. (2006) urged for development of new design criteria and management methods for controlled drainage system that should have minimum impact on environment.

Drain installation and maintenance still require a huge investment and skill operators. Low-cost drainage material with robustness should be sought in order to bring the technology to common farmers, who need it.

Relevant Journals

– Trans. ASAE
– Journal of Irrigation & Drainage Engg., ASCE
– ASAE Papers
– Land Management and Reclamation
– Irrigation and Drainage System
– Applied Engineering in Agriculture
– Irrigation Science

– Agricultural Water Management
– ICID Bulletin
– Egyptian Journal of Irrigation & Drainage
– Soil Science Society of America Journal
– Agronomy Journal
– Journal of Soil Water Conservation
– Journal of Environ. Quality

FAO/World Bank Papers

– FAO Irrigation and Drainage Paper 60 (Materials for Subsurface Land Drainage Systems, 2000)
– FAO Irrigation and Drainage Paper 61 (Agricultural drainage water management in arid and semi-arid areas, 2003)
– FAO Irrigation and Drainage Paper 62 (Guidelines and computer programs for the planning and design of land drainage systems, 2007)
– FAO Training Manual: Drainage of Irrigated Lands (Irri. Water Management Training Manual No.9, 1996)
– World Bank Technical Paper 195 (Drainage Guidelines, 1992)

Questions

(1) What are the benefits of drainage? Is drainage necessary in arid region?
(2) How you will assess the need of drainage in an agricultural farm?
(3) What factors will you consider during investigation and design for a drainage problem area?
(4) What suggestions will you made to lessen the drainage outflow from an area?
(5) What is drainable pore volume?
(6) Distinguish among homogeneous, isotropic, and homogeneous and isotropic media.
(7) Deduce the partial differential equation for flow through the homogeneous, anisotropic soil media. From this, derive the equation for homogeneous and isotropic soil.
(8) Derive an equation for calculating resultant/equivalent horizontal hydraulic conductivity for layered soil.
(9) Briefly describe the design steps and principles of surface drainage system.
(10) Discuss the conditions of resultant vertical conductivity for layer soil.
(11) Define with neat sketch the Hooghoudt's drain spacing equation for layered soil.
(12) What do you mean by "equivalent depth" in Hooghoudt's drain spacing equation?
(13) Draw a schematic layout for a surface drain design in a farm.

(14) What are the factors to be considered in designing subsurface drainage system?
(15) Briefly describe systematically the design procedure of subsurface drainage.
(16) Draw a schematic layout for a subsurface drainage system.
(17) How you will estimate the drainage intensity in an area?
(18) What is controlled drainage? Briefly discuss its principle and procedure.
(19) Do you think that envelop materials should be used around subsurface drain? Justify your answer.
(20) Why envelope materials should be designed and selected with proper care?
(21) Name some envelope materials from organic, mineral, and synthetic group.
(22) What are the design criteria for selecting envelope material? Briefly describe the procedure for selection and design of envelope material.
(23) Briefly describe the use of particle size analysis curve in designing envelope material.
(24) What are the methods of placing drain and envelop?
(25) What are the methods of disposing drainage outflow?
(26) How the drainage outflow can be treated?
(27) Narrate the economic considerations in drainage design and material selection.
(28) Briefly explain the concept, principle, and procedure of performance evaluation of drainage system.
(29) What are the challenges and needs in drainage design and management?
(30) A soil contains 42% moisture (by volume) at saturation. The moisture content becomes 35% when the capillary pressure is raised to 100 cm of water. Find the drainable porosity, void ratio, and the drainable water volume at 100 cm water tension from a (10 m $\times$ 10 m) plot of 1.0 m depth.
(31) A soil column consists of 3 layers, having 0.50 m depth of each. The horizontal hydraulic conductivity of the layers (from to bottom) are 0.25, 0.15, and 0.30 $m^3/m^2/h$. Determine the resultant horizontal hydraulic conductivity of the soil column.
(32) A surface drainage should be provided within an agricultural farm. Maximum rainfall intensity at the site in 20 years record is 40 mm/h. The tertiary drain would have to carry discharge from 5.0 ha land. The secondary drain would have to carry of 4 tertiary, and the main drain to carry discharge of 5 secondary drains (of similar discharge). Determine:

    (a) drainage outflow to be generated at tertiary, secondary, and main drain level
    (b) performance of hydraulic design of the secondary and main drainage canal

(33) Determine the drain spacing of parallel subsurface drains if the hydraulic conductivity of the soil is 15 cm/d, the recharge rate is 12 cm/d, drain diameter is 12 cm, drains are placed at 2.0 m deep, the water table is to be no closer than 1.2 m to ground surface, and the impervious layer is 3 m below the ground surface.
(34) A subsurface drainage should be provided through an agricultural farm. Maximum rainfall intensity at the site in 20 years period is 80 mm/d. The

secondary drain would have to carry 15 of tertiary, and the main drain to carry discharge of 4 secondary drain (of similar flow). It is required to maintain the water table not lower than 1.0 m from the soil surface. The soil is uniform in texture and other hydraulic properties. The value of K is 6 mm/d. A relatively impervious layer exists at 1.8 m depth from the surface. Determine:

(a) drain spacing at tertiary level
(b) size of secondary and main drain pipe to carry the generated outflow
Assume standard value of any missing data.

(35) It is proposed to design a subsurface drainage system to leach water through the root zone in an area where surface irrigation will be practiced with poor quality water. Parallel perforated GI pipe drains are to be laid to a slope of 3 in 1,000, so that the drains could discharge freely into the main collector ditch. Hydraulic conductivity of the soil is 10 mm/d. Calculate the drain spacing required to meet the requirements given below.

Irrigation water EC = 0.15 dS/m
Salt tolerance level = 1.8 dS/m
Maximum crop rooting depth = 0.8 m
Mean ET rate = 4.0 mm/d

Assume standard value of any missing data.

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