

# Drainage Engineering



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Drainage Engineering

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### Lesson 1 Introduction to Land Drainage

#### 1.1 What is Drainage?

Irrigation and drainage constitutes a subset of water resources system and are crucial for human survival. Land drainage, or the combination of irrigation and land drainage, is one of the most important input factors to maintain or improve agricultural productivity. To enlarge the present cultivated area, more land must be reclaimed than the land that is lost due to urban/industrial development, roads and land degradation. However, in some areas, land is a limiting resource, whereas in other areas, agriculture cannot expand at the cost of nature.

Drainage is a reverse process of irrigation. It is broadly defined as the removal (disposal) of excess water from a land (usually agricultural land). The terms '**drainage**', '**land drainage**', '**agricultural drainage**' and '**field drainage**' are used as synonyms in practice. Since drainage (land drainage) is necessary not only for the removal of excess surface water or groundwater but also for removing salts from the soil, a precise definition of drainage has been given by the constitution of the International Commission on Irrigation and Drainage (ICID, 1979). According to ICID (1979), land drainage is defined as follows:

“Land drainage is the removal of excess surface and subsurface water from the land to enhance crop growth, including the removal of soluble salts from the soil”.

The above definition of land drainage (or drainage) is well known and is used worldwide.

#### 1.2 Objectives of Drainage

Plant roots require a favorable environment to extract water and nutrient solutions to meet the plant's requirement. For most crops, soil moisture ranging from field capacity to 50% of the field capacity in the root zone is considered ideal. Only a few crops such as rice and jute need standing water on the field at certain stages of their growth. Chemically, a neutral and non-saline soil is ideal for proper growth and yield of most food crops. Excess water and/or high salt concentration in the root zone or at the land surface do not allow the plant roots to function normally. As a result, the plant growth and yield are adversely affected. In the extreme cases of water logging and salinity, the seeds may not germinate and the plants may wilt permanently. The result is a loss of agricultural production. Land drainage, as a tool to manage excess surface water and groundwater levels, plays an important role in maintaining and improving crop yields:

- Drainage prevents a decrease in the productivity of arable land due to rising water tables and the accumulation of salts in the root zone.
- Drainage is the only way to reclaim the land which is not cultivated due to water logging and salinity problems.



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Agricultural land drainage in essence is both a preventive and a curative measure for the prevention of physical and chemical degradation of soils and for the reclamation of already degraded lands. Thus, drainage of agricultural lands is an effective technique to maintain a sustainable agricultural system as well as to avoid environmental damage.

### 1.3 Drainage Problems in India

Water logging and salt accumulation are major constraints to sustainable agricultural production in most countries of the world, especially in developing countries (including India). In India, drainage problem is acute in the states of Punjab and Haryana, while it also prevails in the command areas of other states. Broadly speaking, water logging is a situation of an agricultural land when the root zone gets saturated. Such a condition restricts normal air circulation, reduces the oxygen level and increases carbon dioxide level in the root zone. On the other hand, salt affected soils are those in which the concentration of salts in the root zone adversely affects the normal root activity. Both the water logging and salt affected soils produce detrimental effects on crop growth and yield as well as cause environmental degradation. Water logging and salinity of agricultural lands are caused due to natural causes or artificial causes (i.e., human interventions). Important natural causes are high rainfall during the rainy season, unfavourable topography, backwater entry from rivers, seawater intrusion, high evaporation during long dry periods, and the salts present in the soil. On the contrary, important human factors are unscientific management of land and irrigation water, use of poor-quality water for irrigation, adoption of unscientific and non-sustainable cropping pattern, and obstruction of natural outlets because of urbanization and construction of highways and railways.

#### 1.3.1 Definition, Classification and Impact of Water logging

##### (1) What is Water logging?

Generally, the term '**water logging**' refers to the condition of a land (soil) in which the water table comes within or very near the root zone due to which crop yields decrease below the normal yield or the land cannot be used for cultivation. The soil becomes waterlogged when the water fills up all the pore space present in the soil profile, and it remains waterlogged when drainage facility is inadequate or absent. This type of water logging is quite common in irrigated agricultural lands and is known as '**subsurface water logging**' or simply '**water logging**'. According to FAO (FAO, 1973), waterlogged areas are those where soils are temporarily saturated or where the water table is too shallow such that capillary rise of groundwater encroaches upon the root zone and may even reach the soil surface. Moreover, water logging also occurs when water is stagnant on the land surface for considerable time due to absence of a proper outlet and insignificant infiltration. This type of water logging is known as '**surface water logging**'.

##### (2) Classification of Water logging

The working group on problem identification in Irrigated Areas, constituted by the Ministry of Water Resources, Government of India (MOWR, 1991) adopted the following norms for the identification of waterlogged areas:

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- (i) **Waterlogged Area:** Water table within 2 m from the land surface.
- (ii) **Potential Area for Water logging:** Water table between 2-3 m from the land surface.
- (iii) **Safe Area:** Water table below 3 m from the land surface.

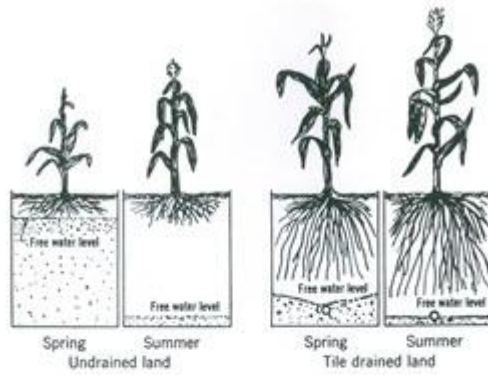
The above categorization does not consider the time of the year or type cropping season in relation to the water table depths and runoff accumulation over the crop land. Crops vary greatly in their rooting depth and susceptibility to water logging. The dry season crops are more susceptible to water logging than the wet season crops. Therefore, it will be useful if the categorization of waterlogged areas is linked with the crop season or time of the year. The common approaches to express the water table depth from the soil surface are: (a) pre-monsoon (April/May) depth to water table, (b) post-monsoon (October/November) depth to water table, (c) seasonal (monsoon/winter/summer) or annual average depth to water table, and (d) sum of the number of days when water table is shallower than a specified depth. Out of these four approaches, the first two are the simplest approaches to express the water table depth from the soil surface.

A deep water table at pre-monsoon reduces the chances of soil salinization and ensures successful crop production during monsoon (kharif) season. A deep water table in the post-monsoon period helps maintaining timeliness of field operations for the winter (rabi) season crops. Keeping these facts in view, the following norms are suggested for the classification of different categories of waterlogged areas in India and other South Asian countries (Bhattacharya and Michael, 2003):

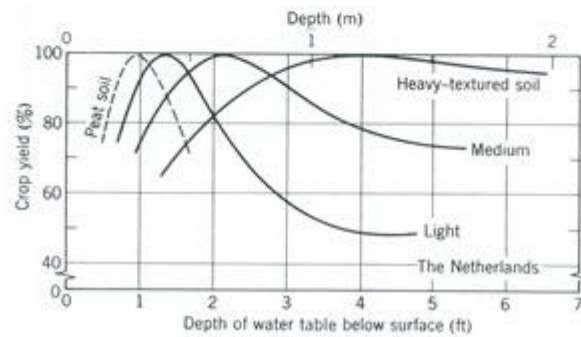
- (i) **Waterlogged Area:** Water table is within 2 m from soil surface during pre-monsoon (April/May) or water table is within 1 m from soil surface during post-monsoon (October/November).
- (ii) **Critical Area for Water logging:** When the water table is between 2 and 3 m from the soil surface during pre-monsoon and/or between 1 and 2 m during post-monsoon, it is considered as critical. In a critical area, water logging condition may develop within a short period of time if suitable measures are not adopted. Such measures are location specific and may comprise providing a drainage system, land development and scientific management of irrigation water.
- (iii) **Potential Area for Water logging:** In monsoon Asia, irrigated areas with water table between 3 and 5 m during pre-monsoon may be considered as potential areas for water logging.

### (3) Impacts of Water logging

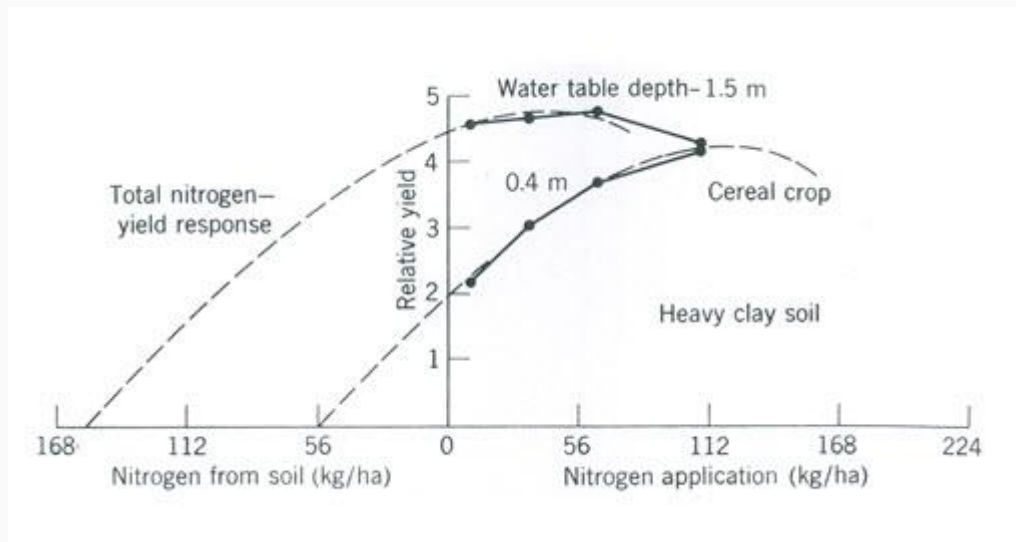
The physical effects of water logging are: (i) lack of aeration in the root zone, (ii) difficulty in soil workability, and (iii) deterioration of soil structure. If the water logging prolongs for considerable time, it produces its chemical effect which is known as soil salinization. Both water logging and soil salinity adversely affect the growth and yield of crops (Figs. 1.1, 1.2 and 1.3). The extent of crop damage depends upon the magnitude, duration and frequency of the waterlogged condition and the degree of soil salinity.



**Fig. 1.1. Root development of crops grown on drained and undrained land.**  
(Source: Schwab et al., 2005)



**Fig. 1.2. General relationship between crop yield and constant water table depth during growing season in the Netherlands.** (Source: Schwab et al., 2005)



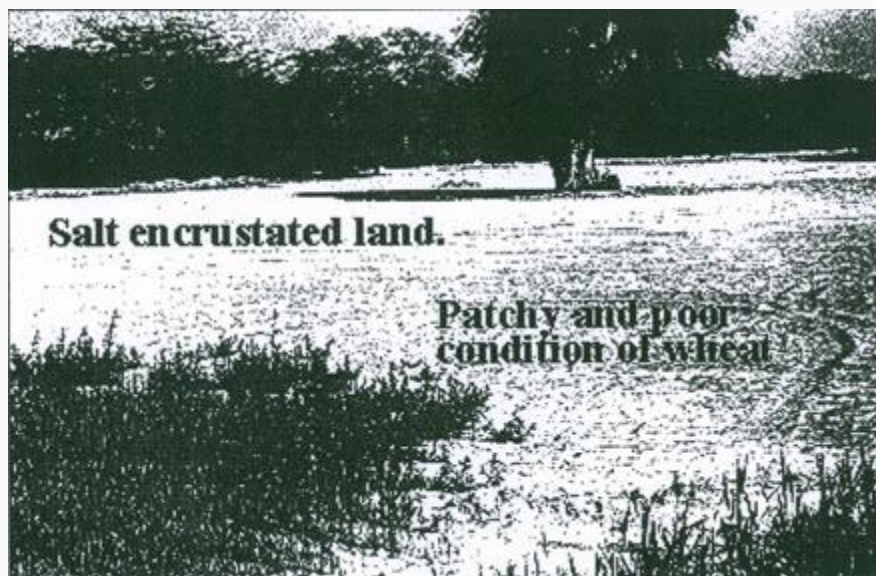
**Fig. 1.3. Influence of water table depth on nitrogen supplied by the soil.** (Source: Schwab et al., 2005)



### 1.3.2 Salt Build-up in Soils

Soluble salts in the parent rocks which have weathered to form soil, seawater intrusion and high evaporation are the major natural causes for the salinisation of agricultural lands. Under a monsoon climate much of the accumulated salts are washed or leached out during the rainy season. However, high evaporation during the remaining dry and hot months in the year draws up the saline groundwater at shallow depths towards the land surface. The salts are left behind after the water evaporates (Fig. 1.4). Furthermore, important anthropogenic causes for salinity development are the use of poor quality water for irrigation and the excess application of irrigation water.

Salt problem is a major cause of decreasing agricultural production in many of the irrigated areas. Irrigation with water of low salinity but with dominant anion, and migration of sodic salts in arid climate promote salinity. The main causes of soil salinity and sodicity (alkalinity) are: (i) irrigation mismanagement; (ii) poor land leveling; (iii) leaving land fallow during dry periods especially in regions of shallow water table; (iv) improper use of heavy machinery resulting in soil compaction; (v) leaching without adequate drainage, and (vi) adoption of improper cropping patterns and crop rotations. In irrigated agriculture, scientific management of water and land is the key to avoid water logging and salt problems.



**Fig. 1.4. Surface salt due to evaporation from shallow and saline groundwater (Najafgarh Block of Delhi).**

**(Source: Bhattacharya and Michael, 2003)**

Salinity is a major problem in many non-irrigated areas also where cropping is based on limited rainfall. In rain fed agriculture, surface drainage is required to prevent water logging and flooding of low lands which lead to soil salinity hazards. Salinity in dryland areas has been a threat to land and water resources in many parts of the world. In rainfed agricultural lands of coastal areas, seawater intrusion is the main cause of salinization during dry periods. In semi-arid areas of the world, the scarcity and the variability of rainfall and high potential evapotranspiration affect the water and salt balance in the soil. Low humidity, high temperature, and high wind velocity induce upward movement of soil solution resulting in a high

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concentration of salts at the land surface and within the root zone. In arid regions, various types of Sodium, Magnesium and Calcium salts are concentrated mainly in Chloride and Sulphate forms. In less arid regions, Sodium salts in the Carbonate and Bicarbonate forms enhance the formation of sodic soils due to the adsorption of Sodium in the soil exchange complex.

Table 1.1 presents approximate information on the waterlogged and salt affected areas in some of the states of India. In this table, waterlogged areas include within and outside the irrigated regions as well as coastal saline lands.

**Table 1.1. Geographical, waterlogged and salt affected areas of some states in India (Bhattacharya and Michael, 2003)**

Sl. No.	State	Geographical Area (Mha)	Waterlogged Area (Mha)	Salt Affected Area (Mha)
1	Andhra Pradesh	27.44	0.339	0.813
2	Bihar	17.40	0.363	0.400
3	Gujarat	19.60	0.484	0.455
4	Haryana	4.22	0.275	0.455
5	Karnataka	19.20	0.036	0.404
6	Kerala	3.89	0.012	0.026
7	Madhya Pradesh	44.20	0.057	0.242
8	Maharashtra	30.75	0.111	0.535
9	Orissa	15.54	0.196	0.400
10	Punjab	5.04	0.199	0.520
11	Rajasthan	28.79	0.348	1.122
12	Tamil Nadu	12.96	0.128	0.340
13	Uttar Pradesh & Uttaranchal	29.40	1.980	1.295

### 1.3.3 Drainage Problems in Rainfed Areas

The progress of the net sown area and its break-up into unirrigated and irrigated areas in India is shown in Fig. 1.5 (FAI, 1998). Although the unirrigated area has decreased with increasing irrigation development, about 80 Mha of the cropped land is still unirrigated (rainfed). As the pace of irrigation development has slowed down in recent years, much of the cultivated area

may remain unirrigated in the future. Thus, it is irrigation rather than drainage which should be of concern for rainfed areas. However, due to the diversity of climate and soil, even rainfed areas experience excess water during monsoon season and excess salts during dry season (non-monsoon season). For example, land inundation during the monsoon season and high soil salinity during the dry season prevent cultivation in the coastal areas of Medinipur District, West Bengal. Vast flat lands in south-western Haryana and south-western Punjab, despite a low annual rainfall, get waterlogged due to sudden rains and lack of drainage to clear out the runoff fast. Lands in the plains of Bihar and Uttar Pradesh (U.P.) are uncultivable during monsoon due to excess water. Thus, drainage is relevant even in the unirrigated areas to ensure crop production.

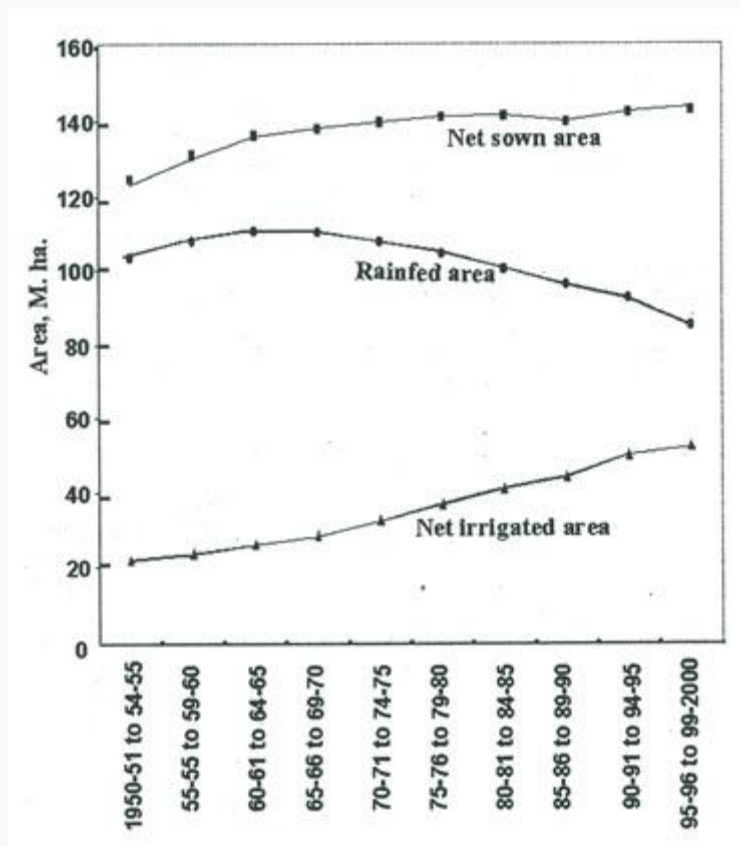


Fig. 1.5. Progressive development of net sown, irrigated and rainfed areas in India during 1950-2000

(the last values are extrapolated). (Source: FAI, 1998)

### 1.3.4 Technical Limitations and Current Status of Land Drainage

Making major changes in the physical, morphological, and chemical properties of the land and water resources are infeasible. Equally infeasible is to change the climate of a region. However, the occurrence of water logging and salinity problems can be substantially reduced when proper attention is given to the factors listed above. The man-made causes, which are mainly concerned with the development and use of land and water resources, are theoretically easier to prevent and even to rectify. The rectification is, however, expensive, and the prevention has proved to be elusive up to now. Therefore, we are seriously concerned about the adverse impacts of water logging and salinity on agricultural production. Also, agriculture sector needs a serious attention

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because of the fact that while land and the water resources are limited in quantity and degradable, human population is gradually increasing in most Asian and African countries. This necessitates more agricultural productivity per unit of land and water, which will be possible only if further deterioration of land and water resources is avoided or minimized, degraded lands are reclaimed and these two vital resources are utilized judiciously.

Among the various activities in the agricultural production system, drainage is perhaps the most neglected in India as well as in many other developing countries. The misuse of irrigation water is slowly but inevitably leads to drainage problems. Of great relevance in the context is the history of land and groundwater degradation due to their unscientific use in different parts of the world. In 1876, the Reh Commission had cautioned against undermining the importance of agricultural drainage in the irrigated areas of India. According to (Bower and Hufschmidt, 1984), irrigation and drainage, as practiced in the developing countries, is functionally inefficient, technology primitive, economically unremunerative and environmentally degrading. Also, in the past, there have been an unspecified number of recommendations of a large number of seminars and symposia, highlighting the necessity of land drainage in enhancing and sustaining agricultural production. Most recently, there are the crisp observations of the Standing Committee of Agriculture (Lok Sabha Secretariat, 1996) of the 11<sup>th</sup> Lok Sabha of India, on the undesirable neglect of the agricultural drainage in the irrigated areas of India. Thus, modernization of irrigation and drainage is urgently needed in India as well as in many other developing countries across the world.



### Lesson 2 Land Drainage Systems

#### 2.1 Sources of Excess Water

Direct rainfall constitutes the major and most common source of excess water in an area. However, another major source of excess water in many cold and moderate climates is snowmelt water during spring seasons. Other sources of excess water are irrigation, seepage, runoff and flood water, which are mostly of local importance.

The occurrence of excess rainfall applies especially to humid climates. However, it may also occur in semi-arid climates following the common type of intense, heavy storm or in general during the rainy season. The drainage load from rainfall not only depends on the amount of rainfall but also on the storage capacity of the soil and on the rate of evapotranspiration. Part of the rainfall may be stored beneficially in the soil profile or be readily evaporated so that only the remaining excess water needs to be removed from the land.

#### 2.2 Design Considerations for Land Drainage

In the ICID definition of drainage given in Lesson 1, the phrase 'the removal of excess water' indicates that land drainage (or drainage) is an action by man (i.e., artificial action) who must know how much excess water should be removed. Therefore, when designing a system for a given area, drainage engineers should use certain criteria to determine whether or not water is in excess. Water balance of the area to be drained is the most accurate tool to calculate the volume of water required to be drained (Bos and Boers, 1994).

Before carrying out the water balance of an area, a number of field investigations should be undertaken which would result in adequate hydrogeological, hydropedological and topographic maps (Bos and Boers, 1994), among other information. Also, all subsurface water inflows and outflows must be measured or estimated. The precipitation and relevant evapotranspiration data from the area under investigation should be analyzed. In addition, all relevant data on the hydraulic properties of the soil should be collected. The above processes in drainage surveys call for a sound theoretical knowledge of various subjects related to the field of Soil and Water Engineering. Detailed information on field investigations required for the design and implementation of drainage systems is given in Smedema and Rycroft (1983), Ritzema (1994), and Michael and Ojha (2006).

In some cases, a proper identification of the source of 'excess water' can avoid the construction of a costly drainage system. Some examples are as follows (Bos and Boers, 1994):

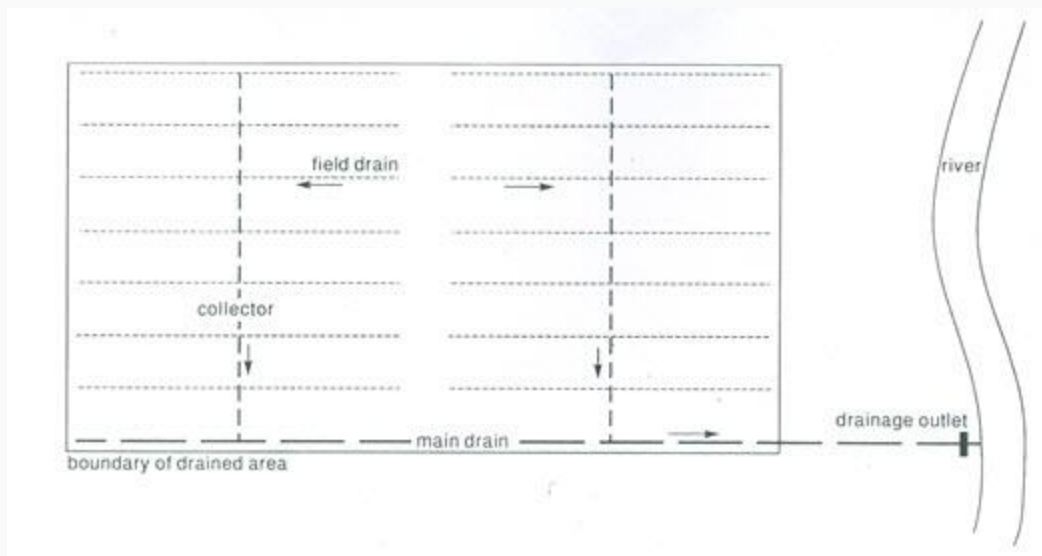
- If irrigation water causes water logging, the efficiency of water use in the water-supply system and at the field level should be studied in detail and improved.
- If the surface water inflow from surrounding hills is a major cause of excess water in an area, this water could be intercepted by a hillside drain which diverts the water around the agricultural area.



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- If the problem of surplus water is caused by an inflow of saline groundwater, this groundwater inflow could be intercepted by a series of tubewells, which can dispose of effluent into a drain that bypasses the agricultural land.
- If an area is partially inundated due to the insufficient discharge capacity of a natural stream, a renovation of the stream may solve the drainage problem.

However, if the origin of excess water lies in the agricultural area itself (e.g., excess rainfall or extra irrigation water to meet the leaching requirement for salinity control), then the installation of drainage facilities within the agricultural area should be considered. Usually, drainage facilities consist of: (i) a drainage outlet, (ii) a main drainage canal, (iii) some collector drains, and (iv) field drains (also called 'lateral drains') as illustrated in Fig. 2.1.



**Fig. 2.1. Schematic diagram of a drainage system. (Source: Bos and Boers, 1994)**

The main drainage canal is often a canalized stream which runs through the lowest parts of the agricultural area. It discharges its water into a river, lake, or sea by means of a pumping station or tidal gate located at a suitable outlet point (Fig. 2.1). Main drainage canals collect water from two or more collector drains. Although collector drains preferably also run through local low spots, their spacing is often influenced by the optimum size and shape of the area to be drained by a field drainage system. However, the layout of collector drains is still somewhat flexible because the length of field drains can be varied and sub-collector drains can be designed. Furthermore, the length and spacing of field or lateral drains are kept as uniform as applicable. Note that both the collector drains and the field drains can be either open drains or pipe drains, which are decided based on a number of factors such as topography, soil type, farm size, and the method of field drainage.

### 2.3 Types of Drainage Systems

Three most commonly used techniques for removing (draining) excess water are: (a) surface drainage, (b) subsurface drainage, and (c) vertical drainage (also known as 'tubewell drainage'). Besides these conventional drainage techniques, there is an emerging non-conventional drainage technique known as biodrainage which is described in Lesson 12. An introduction to the

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conventional drainage techniques is presented below, and their details are provided in later lessons.

### 2.3.1 Surface Drainage

Surface drainage can be defined as (ASAE, 1979): “Surface drainage is the removal of excess water from the soil surface in time to prevent damage to crops and to keep water from ponding on the soil surface, or, in surface drains that are crossed by farm equipment, without causing soil erosion”. Surface drainage is a suitable technique where excess water from rainfall or surface irrigation cannot infiltrate into the soil and move through the soil to a drain, or cannot move freely over the soil surface to a natural/artificial drainage channel. Surface drainage problems occur in flat or nearly flat areas, in the areas having uneven land surfaces with depressions or ridges preventing natural runoff, and in the areas where there is no outlet. A detailed discussion of surface drainage technique is provided in Lesson 3.

### 2.3.2 Subsurface Drainage

Subsurface drainage is defined as ‘the removal of excess soil water in time to prevent damage to crops because of a high water table’. Subsurface drainage problems occur in the areas having shallow water table (e.g., canal commands), which occurs due to substantial groundwater recharge and sluggish subsurface outflow. Subsurface field drains can be either open ditches or pipe drains, but nowadays they are mostly pipe drains. Pipe drains are installed underground at depths normally ranging from 1 to 3 m (Bos and Boers, 1994). Excess groundwater enters the perforated field drains and flows by gravity to an open or closed collector drain. A detailed discussion of subsurface drainage technique is provided in Lesson 4.

### 2.3.3 Vertical Drainage

Vertical drainage or tubewell drainage can be defined as the ‘control of an existing or potential high water table or artesian groundwater condition’. It is accomplished using shallow or deep tubewells; sometimes open wells are also used. Most tubewell drainage systems consist of a group of wells spaced with a sufficient overlap of their cones of depression so as to control the water table at all points in an area. When draining newly-reclaimed clay soils or peat soils, the drainage engineer has to estimate land subsidence due to drainage of these soils, because this will affect the drainage design (Bos and Boers, 1994). The problem of land subsidence can also occur in the areas drained by tubewells. A detailed discussion of vertical drainage technique is provided in Lesson 12.

Irrespective of the technique used to drain a given area, it is evident that the drainage technique must fulfill the local need to remove excess water. These days, the ‘need to remove the excess water’ is strongly influenced by a concern for the environment. The design and operation of all drainage systems must ensure sustainable agriculture in the drained area and must minimize the pollution of rivers and lakes from irrigation return flow or drainage effluent (Bos and Boers, 1994). The quality of drainage effluent is generally inferior because it often contains significant amounts of sediments, agricultural chemicals (fertilizers and pesticides) and other contaminants. Therefore, proper disposal of drainage effluents is a serious concern in most canal commands of the world, especially in developing countries.

### Lesson 3 Design of Surface Drainage Systems

#### 3.1 Introduction

Drainage can be either natural or artificial. Natural drainage is often inadequate, and hence artificial (man-made) drainage is required. There are two types of artificial drainage: surface drainage and subsurface drainage (FAO, 1985). Broadly speaking, surface drainage is the removal of excess water from the surface of the land. It is the oldest drainage practice and is defined as (ICID, 1982):

“The diversion or orderly removal of excess water from the surface of land by means of improved natural or constructed channels, supplemented when necessary by shaping and grading of the land surface to such channels”.

As mentioned in Lesson 2, surface drainage is applied primarily on flat lands where slow infiltration, low permeability, or restricting layers in the profile prevent the ready absorption of high-intensity rainfall. Therefore, this drainage system is intended to eliminate ponding and prevent prolonged saturation by accelerating flow to an outlet without causing soil erosion or siltation. Two primary methods of surface drainage are land grading and field ditches. The selection of surface drainage facilities for individual field areas depends largely on the topography, soil characteristics, crops, and availability of suitable outlets. Note that surface drainage may be required even though subsurface drains are installed.

#### 3.2 Components of Surface Drainage System

The negative effects of poor surface drainage on agricultural productivity can be summarized as follows:

- Inundation of crops, resulting in deficient growth.
- Lack of oxygen in the root zone, hampering germination and the uptake of nutrients.
- Insufficient accessibility of the land for mechanized farming operations.
- Low soil temperature in spring time (applicable to temperate regions).

To improve the growing conditions of crops in the field by ensuring the timely and systematic removal of excess water, the land surface should be smooth and should have a continuous slope to allow the overland flow of water to a collector point. From this collector point, water should flow to the area's natural or constructed main drainage system of field and collector drains. Therefore, the design of a surface drainage system has two components: (a) the shaping of the surface by land forming, which is defined as changing the micro-topography of the land to meet the requirements of surface drainage or irrigation; and (b) the construction of open drains (field drains and laterals) to the main outlet.

### 3.2.1 Land Forming

Land forming is broader term than land grading in surface drainage, which is defined as 'the process of changing the natural topography so as to control the movement of water onto or from the land surface'. It includes one or a combination of practices such as land leveling for irrigation; land grading or shaping for irrigation, drainage and water conservation; and shallow field ditches which can be crossed with farm machinery (Schwab et al., 2005). Land forming also includes grading work for erosion control, for instance, contour benching or earthwork for parallel terracing. Land smoothing is generally referred to as the final operation of removing the minor differences in elevations that result from the operation of scrapers or other large earth-moving equipment. Note that the terms 'land grading', 'land shaping', and 'land leveling' are synonymous (Schwab et al., 2005).

Land grading is essential to the development of surface irrigation systems. This practice has been adopted in more humid regions as a method for improving surface drainage on flat lands (Coote and Zwerman, 1970). Grading land for both surface irrigation and drainage is quite practical and compatible.

### 3.2.2 Field Drains and Field Laterals

To prevent ponding in low spots, surface runoff from fields need to be collected and transported through field drains and field laterals towards the drainage outlet of the area. A field surface drain is a shallow graded channel, usually with a relatively flat slope, which collects water within a field (ICID, 1982). A field lateral is the principal ditch for field or farm areas adjacent to it. Field laterals receive water from row drains, field drains and, in some areas, from field surfaces (ICID, 1982). Detailed discussion is provided in Section 3.5.

### 3.3 Design Consideration for Land Grading

Although land leveling is the term generally associated with surface irrigation, land grading is synonymous but somewhat more descriptive. For most conditions, a sloping plane surface rather than a level surface is desired. Slopes, cuts, and fills are influenced by soil, topography, climate, crops to be grown, and the method of irrigation or drainage. The major problem with land grading is the effect of removing topsoil and its influence on plant growth. Reduced growth may occur on the fill areas, although the exposure of the subsoil in the cuts is usually a more serious problem. Stockpiling the topsoil and placing the spoil over the cut areas is a practical solution, where the cost can be justified.

Establishment of a uniform design slope is more important for surface irrigation than for drainage. Having a variable slope for drainage is not usually objectionable, provided flow velocities are not erosive. Thus, the topography places a severe limitation on the length and degree of slope as well as the location of the slope change. The required accuracy of leveling depends largely on its effects on crop production. For crops sensitive to excesses or shortages of water, a greater precision is required. For flood irrigation, the land slope in both directions may be restrictive, whereas the length-of-run and furrow grade are most critical for furrow irrigation. In semi-humid to humid climates, land grading can be made compatible for both drainage and irrigation. For irrigation purposes, the largest flow occurs at the upper end of the slope.

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However, for drainage, rainfall enters along the entire slope length with highest runoff at the lower end. These factors should be carefully considered in design.

Moreover, the design of land grading for surface drainage should also take into consideration the type of crops to be grown. Three most important field situations can be distinguished:

- (i) Crops will be planted in rows and the field surface is shaped into small furrows. For example, corn, potatoes, sugarcane, etc.
- (ii) Crops will be planted by broadcast sowing or in rows, but on an even surface. For example, small grains, hay crops, etc.
- (iii) Crops will be planted in basins designed for controlled inundation. For example, wetland rice, and basin irrigation.

**In the first situation** (where crops are planted in rows), the length and slopes of the field to be graded should be selected in such a way that erosion and overtopping of the small furrows is avoided. Table 3.1 presents recommended row lengths and slopes for some soil types.

**Table 3.1. Row slopes and row lengths for land grading (Source: Coote and Zwerman, 1970)**

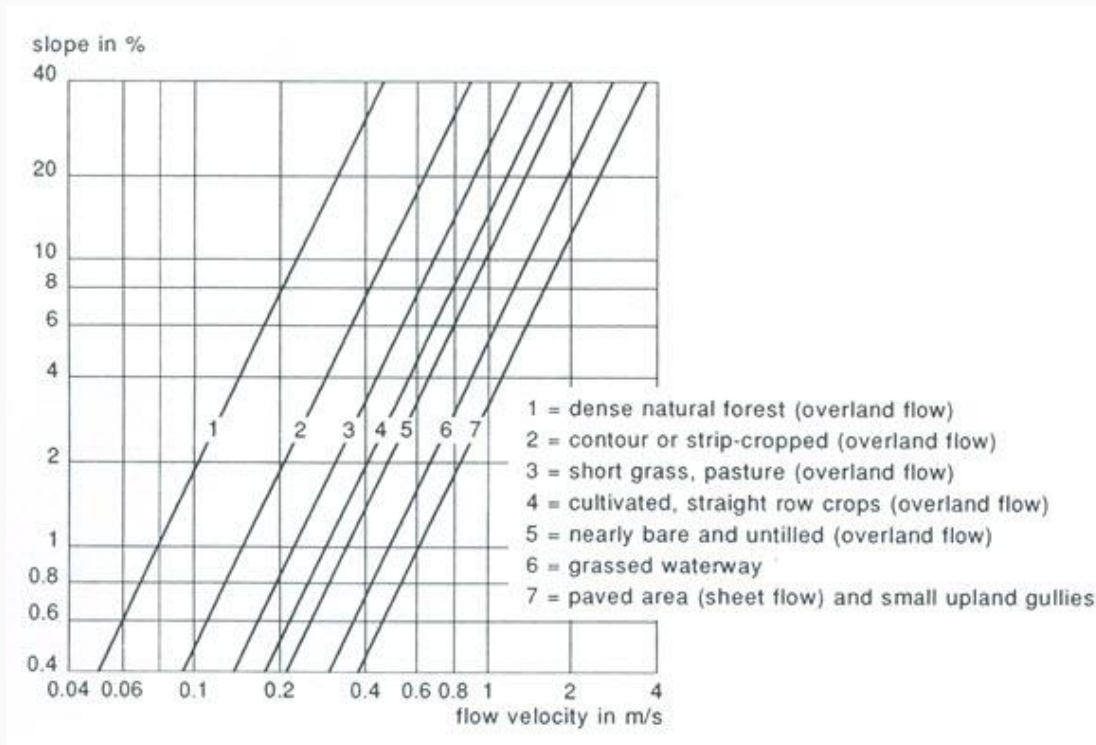
Sl. No.	Soil Type	Row Grade (%)	Row Length (m)
1	Coarse-textured soil (sandy)	0.1 - 0.3	300
2	Fine-textured soil (clayey)	0.05 - 0.25	200
3	Fine-textured soil (clayey) with high organic-matter content	0.1 - 0.5	200 (flat) 400 (gently sloping)
4	Medium-textured soil (loamy)	0.05 - 0.25	300
5	Medium-textured soil (silty loam) with impervious hard-pan at depth	0.5	150
6	Medium-textured soil (silty loam) with shallow impervious clay B horizon	³0.2	60
7	Moderately coarse-textured soils (sandy loam) with structured clay B horizon at depth	³0.15	200

To prevent erosion, flow velocities in furrows should not exceed 0.5 m/s. In highly erodible soils, the row length should be limited to about 150 m, but slightly erodible soils allow longer rows up to 300 m. In these long furrows, adequate head should be available to ensure that the water flows towards the field drains. The direction of rows (and related small furrows) is not necessarily perpendicular to the slope, but can be selected in a way that meets the above recommendations.



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**In the second situation**, where crops are planted on an even land surface (no furrows), the surface drainage takes place by sheet flow which is always in the direction of maximum slope. In this situation, flow resistance is much higher than in small furrows and the flow velocity with the same land slope is less. However, even after careful land grading and smoothing, sheet flow always has a tendency to concentrate in shallow depressions, and gullies are easily formed. The relation between flow velocities and slopes for sheet flow under different soil covers is shown in Fig. 3.1.



**Fig. 3.1. Relation between slope and flow velocity. (Source: SCS, 1971)**

From the point of view of transport duration for low flow velocities, it is recommended to limit the field length in the flow direction to 200 m or less. The amount of water that drains from graded fields as described for the first and second situations can be calculated by the Curve Number method.

**In the third situation**, which contains basins for irrigation or for water conservation, the surface is leveled by earthmoving machinery (large basins) or with simple farm implements (small basins in traditional rice farming). Leveled fields are surrounded by field bunds. Any excess water from basins is usually drained through an overflow in the field bunds that spills the water directly into a field drain. In large rice fields (up to 6 ha in Surinam), under fully mechanized farming; the overflow is replaced by a gated culvert with a diameter of up to 0.6 m. In this situation, bunds are made by earthmoving machinery and are often used as farm roads.

In general, land grading is done with a combination of conventional earthmoving equipment and specially designed machinery (Haynes, 1966). The benefits derived from land grading will often depend on good maintenance in subsequent years. The land should be smoothed each time a field has been plowed. This will ensure settlement in fill areas and will erase dead furrows and back furrows. A small leveler or plane powered by a tractor can be used for this purpose.

### 3.4 Land Grading Calculation

A land-grading design comprises estimation of the best field slope from a topographic and soil survey taking into account the plans for irrigation and drainage systems and field roads. The area should be cleared of vegetation and the surface prepared for the operation. Land grading/leveling is an intensive practice and much expenditure can be saved if the area is carefully divided into sub-areas having almost the same slope and soil conditions.

Field data are normally obtained from a topographic survey (standard grid survey using a surveying instrument) with ground elevations taken to the nearest 0.01 m on a 30-m square grid for horizontal control. Elevations are taken at other critical such as highs and lows between grid stakes, and the water surface in the supply ditch or in the drainage outlet. These days, laser surveying (using laser-controlled equipment consisting of a laser transmitter and a tractor-operated scraper fitted with a laser receiver) is also used for obtaining elevations of the land surface. Laser survey is more accurate and less time consuming than the conventional grid survey (Schwab et al., 2005). After obtaining a desired balance between cuts and fills, the volume of earthwork is computed.

Of the several methods available for calculating cuts and fills, two widely used methods are plane method and profile method, which are discussed in this lesson. Computer software is commercially available or one can develop his own computer program to solve land grading/leveling problems.

#### 3.4.1 Plane Method

The plane method is so called because the resulting land surface has a uniform downfield slope and a uniform cross slope. The plane method, also known as the 'method of least squares', makes it possible to calculate a balanced cut-and-fill for regular as well as for irregular fields. The step-by-step procedure is as follows:

**Step 1:** Complete the design and construction survey.

**Step 2:** Determine the initial elevation at each grid point ( $E_i$ ).

**Step 3:** Subdivide the area into sub-areas, each of which can be leveled to a plane surface.

**Step 4:** Locate the centroid of the sub-area ( $x_c, y_c$ ).

To give equal cut and fill, the plane must pass through the centroid. The centroid of a rectangular field is located at the intersection of its diagonal. The centroid of a triangular field is located at the intersection of lines drawn from its corners to the midpoints of the opposite sides.

The centroid coordinates of an irregular field are given as follows:

$$x_c = \frac{\sum m_y x}{n}, \quad \text{and} \quad y_c = \frac{\sum m_x y}{n} \quad (3.1)$$

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Where,  $x_c, y_c$  = coordinates of the centroid of the sub-area (m),  $x, y$  = coordinates of the grid lines (m),  $m_x$  = number of grid points on grid line in x direction,  $m_y$  = number of grid points on grid line in y direction, and  $n$  = total number of grid points ( $\hat{a}m_x = \hat{a}m_y = n$ ).

**Step 5:** Calculate the average elevation of the sub-area at the centroid ( $E_c$ ) as:

$$E_c = \frac{\sum E_i}{n} \quad (3.2)$$

Where,  $E_c$  = average elevation of the sub-area at the centroid (m),  $E_i$  = initial elevation of grid point (m), and  $n$  = total number of grid points.

**Step 6:** With the desired  $s_x$  and  $s_y$  slopes, in x and y direction respectively, and the average elevation  $E_c$  ( $E_c$  usually has to be lowered 1 or 2 cm to satisfy the desired cut/fill ratio), the new elevation of the grid points can now be calculated. The new plane passes through the centroid, and hence the elevation of the origin ( $E_o$ ) will be:

$$E_o = E_c - s_x x_c - s_y y_c \quad (3.3)$$

The new elevations of the grid points will be:

$$E_n = E_o + s_x x - s_y y \quad (3.4)$$

After being graded, soil will settle in the filled areas and expand, after being plowed, in the cut areas. To take this into account, calculations for cuts and fills must be adjusted prior to grading (SCS, 1983). Table 3.2 summarizes some recommended cut/fill ratios for different soil types.

**Table 3.2. Cut/fill ratios for various soils (Source: Coote and Zwerman, 1970)**

Sl. No.	Soil Type	Cut/Fill ratio
1	Coarse-textured Soils (sandy)	1.1 : 1 to 1.2 : 1 or 110 to 120%
2	Medium-textured Soils (clay-loam)	1.2 : 1 to 1.3 : 1 or 120 to 130%
3	Fine-textured Soils (clayey)	1.3 : 1 to 1.4 : 1 or 130 to 140%
4	Organic Soils	1.7 : 1 to 2.0 : 1 or 170 to 200%

Using the plane method, we avoid unnecessary earthmoving and find the best fitting plane for any area. If it is obvious from the topography that the best fitting slope is outside the limits (e.g.,

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imposed by erosion hazards), we omit the next calculation and apply the acceptable limit. For non-rectangular fields, the best-fitting slopes  $s_x$  and  $s_y$  can be calculated as:

$$s_x (\sum x^2 - n x_c^2) + s_y [\sum xy - n x_c y_c] = \sum xE_i - n x_c E_c \quad (3.5)$$

$$s_y (\sum y^2 - n y_c^2) + s_x [\sum xy - n x_c y_c] = \sum yE_i - n y_c E_c \quad (3.6)$$

Where,  $\sum x^2$  = sum of the square abscissa of each grid point ( $m^2$ ),  $\sum y^2$  = sum of the square ordinate of each grid point ( $m^2$ ),  $\sum xy$  = sum of the products of the coordinates of each grid point ( $m^2$ ),  $\sum xE_i$  = sum of the products of abscissa and elevation of each grid point ( $m^2$ ),  $\sum yE_i$  = sum of the products of ordinate and elevation of each grid point ( $m^2$ ), and  $n$  = total number of grid points.

Note that for rectangular areas, the term  $\sum xy - n x_c y_c$  becomes zero.

**Step 7:** Finally, calculate the volume of earthwork. Knowing the initial and new elevation, we can determine the cut and fill in each grid square and can calculate the total volume of soil to be moved as:

$$V = \sum C \times A \quad (3.7)$$

Where,  $V$  = volume of soil to be moved ( $m^3$ ),  $\sum C$  = sum of all cuts ( $m$ ) ( $C = E_i - E_n > 0$ ), and  $A$  = area of grid square ( $m^2$ ).

**Example Problem on Plane Method** (Source: Coote and Zwerman, 1970):

An irregular-shaped field has to be leveled. A topographic survey was made with the use of a 25 m grid, the grid lines being set out in the direction of the rows (direction of y-axis in Fig. 3.2). In this figure, the elevations are indicated above at the left of the grid points.

The average row length is 225 m. We are dealing with a fine-textured (clayey) soil, so the row grade can vary between 0.05 and 0.25% (Table 3.1). The required cut/fill ratio is 1.40.

**Solution:** The plane method is used to calculate required cuts and fills. The calculations are as follows (see also Fig. 3.2):

Using Eqn. (3.1):  $x_c = 88.68$  m equal  $y_c = 123.11$  m.

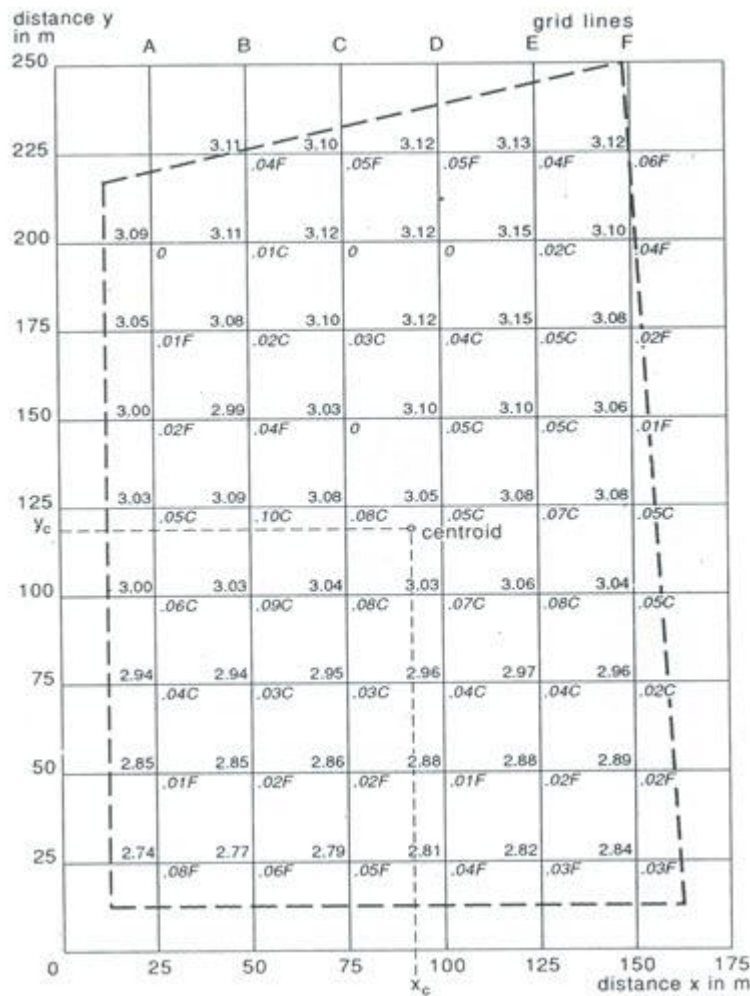


Fig. 3.2. Plane method of land grading.

(Source: Coote and Zwerman, 1970)

Using Eqn. (3.2):  $E_c = \sum E_i / n = 159.44 / 53 = 3.01 \text{ m}$

$nx_c^2 = 416\,792$ ,  $ny_c^2 = 803\,314$ ,  $nx_c y_c = 578\,632$ ,

$nx_c E_c = 14139$ , and  $ny_c E_c = 19629$ .

Now,  $\sum x^2 = 511\,250$ ,  $\sum y^2 = 1\,018\,125$ ,  $\sum xy = 585\,000$ ,

$\sum x E_i = 14183$ , and  $\sum y E_i = 19967$ .

Using Eqn. (3.5):  $s_x(511\,250 - 416\,792) + s_y(585\,000 - 578\,632)$

$= 14183 - 14139$

And using Eqn. (3.6):  $s_y(1\,018\,125 - 803\,314) + s_x(585\,000 - 578\,632)$

$= 19967 - 19629$ .



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\  $s_x = 0.00036 \text{ m/m}$  or 0.036%, and  $s_y = 0.00158 \text{ m/m}$  or 0.158%.

From Eqn. (3.3),  $E_o = 3.01 - 0.00036 \times 88.68 - 0.00156 \times 123.11 = 2.78 \text{ m}$ , and from Eqn. (3.4),  $E_n = 2.78 + 0.00036x + 0.00156y$ .

By definition, the plane of best fit has equal cuts and fills:

Row No. →	A	B	C	D	E	F	å
Cuts	0.12	0.19	0.18	0.18	0.25	0.09	1.01
Fills	0.17	0.19	0.17	0.13	0.13	0.22	1.02

To satisfy the required cut/fill ratio of 1.40, the plane of best fit is lowered 0.01 m. The cut/fill ratio now becomes:

Row No.→	A	B	C	D	E	F	å
Cuts	0.20	0.22	0.22	0.22	0.29	0.12	1.28
Fills	0.09	0.16	0.13	0.10	0.10	0.18	0.76

Therefore, Cut/fill ratio =  $1.28/0.76 = 1.68$ .

This cut/fill ratio is higher than the required one. If this is not acceptable, the calculation can be repeated with a lowering of 0.005 m. In the present case, we can assume that the accuracy of leveling is around 0.01 m, and hence we can accept the calculated cut/fill ratio of 1.68. This results in a total earthwork volume (V) as:

From Eqn. (3.7),  $\text{m}^3$ , **Ans.**

For each grid point in Fig. 3.2, the final cut or fill is shown below on the right of the grid point.

### 3.4.2 Profile Method

Profile method is generally appropriate for land grading on comparatively flat lands. It is not as accurate as the plane method, but it should be adequate for surface drainage. The new grade of the field will not be uniform, but will be continuous to the field drains. With this method, ground profiles are plotted and a grade is established that will provide an approximate balance between cuts and fills and will restrict haul distances (distance between the center of the mass of excavation and the center of mass of the fill) to reasonable limits. The step-by-step procedure is as follows:

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**Step 1:** Complete the design and construction survey.

**Step 2:** Plot the elevations of the grid points on each grid line in the direction of the greatest slope or the direction in which row drainage is desired.

**Step 3:** Draw a profile of the existing land surface along the grid line.

**Step 4:** Draw a new profile for each grid line by trial and error, knowing the allowable slope limits and the desired cut/fill ratio.

**Step 5:** Plot the cross profiles to check whether they exceed the limits (these limits need not be the same as those chosen for the row grade).

**Step 6:** Calculate the volume of earthwork.

On the basis of earthmoving calculations, haul distances, and the location at which land grading/leveling operation is to take place, a drainage contractor is able to prepare a cost estimate for the land grading/leveling operation.

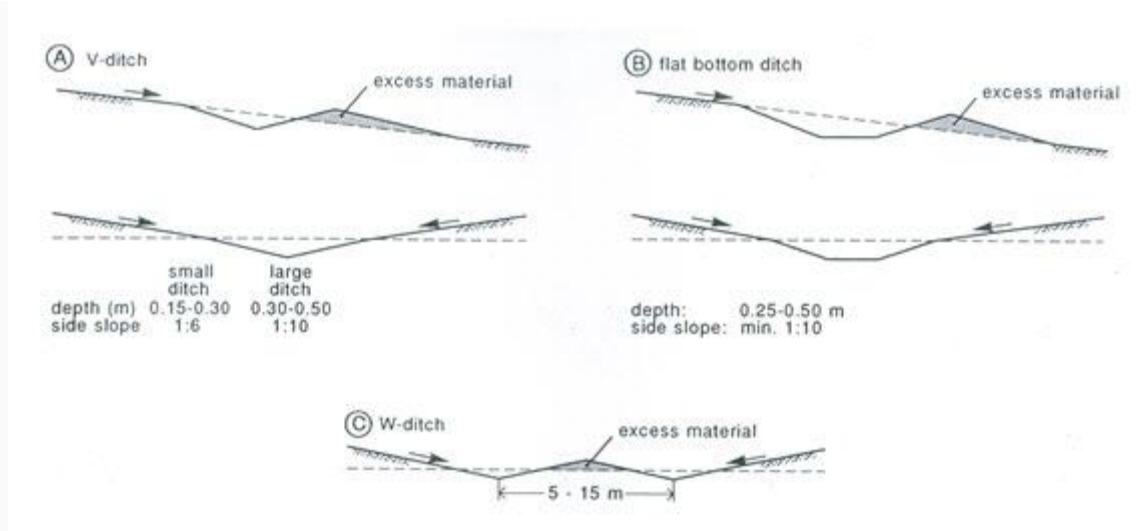
### 3.5 Design Consideration for Field Drains and Field Laterals

#### 3.5.1 Design Consideration for Field Drains

Field drains for a surface drainage system have a different shape from field drains for a subsurface drainage system. Field drains for surface drainage have to allow farm equipment to cross them and are easy to maintain with ordinary mowers. Surface runoff reaches the field drains by flow through row furrows or by sheet flow. In the transition zone between drain and field, flow velocities should not induce erosion.

Field drains are shallow and have flat side slopes. They are often constructed with land planes as used in land forming. Simple field drains are V-shaped. The dimensions of V-shaped field drains are determined by the construction equipment, maintenance needs, and crossability for farm equipment. Side slopes should not be steeper than 6 to 1. Nevertheless, long field drains in conditions of high rainfall intensities, especially where field runoff from two sides accumulates in the drain, may require a higher transport capacity than provided by a simple V-shaped channel.

Without increasing the drain depth too much, the capacity can be enlarged by constructing a bottom width, creating a shallow trapezoidal shape. Recommended dimensions of V-shaped and trapezoidal drains are given in Fig. 3.3. All field drains should be graded towards the lateral drain with grades between 0.1 and 0.3%.



**Fig. 3.3. Types of passable field collector ditches.**

**(Source: Smedema and Rycroft, 1983)**

### 3.5.2 Design Consideration for Field Laterals

Field laterals collect water from field drains and transport it to the main drainage system. In contrast to the field drain, the cross-section of field laterals should be designed to meet the required discharge capacity. Besides the discharge capacity, the design should take into consideration that in some cases surface runoff from adjacent fields also collects directly in the lateral, requiring a more gentle side slope. Field laterals are usually constructed by different machinery than field drains (i.e., excavators instead of land planes). The recommended dimensions for field laterals are given in Table 3.3.

Field laterals less than 1 m deep are usually constructed with motor graders or dozers. The soil is placed near either side of the lateral. Scrapers are needed when the excavated soil is to be transported some distance away. Under wet conditions, excavators are used. Maintenance requirements should be considered during design; for example, if the field laterals are to be maintained by mowing, side slopes should not be steeper than 3 to 1. Finally, special attention should be given to the transition between field drains and laterals, because differences in depth might cause erosion at those places. For discharges below  $0.03 \text{ m}^3/\text{s}$ , pipes are a suitable means of protecting those places. However, for higher discharges, open drop structures are recommended.

Table 3.3. Recommended dimensions for field laterals (Source: ASAE, 1980)

Sl. No.	Type of Drain	Depth (m)	Recommended Side Slope (H : V)	Maximum Side Slope (H : V)
1	V-shaped	0.3 to 0.6	6 : 1	3 : 1
2	V-shaped	>0.6	4 : 1	3 : 1
3	Trapezoidal	0.3 to 1.0	4 : 1	2 : 1
4	Trapezoidal	>1.0	1.5 : 1	1 : 1

### 3.5.3 Layout and Design of Field Drains and Laterals

#### (1) Random Field Drain System

Random field drains are best suited to the drainage of scattered depressions or potholes where the depth of cut is not more than 1 m. In cross section, they are a flat 'V' or parabolic in shape (Schwab et al., 2005). The layout of a typical random field drain system is shown in Fig. 3.4. The design of field drains is similar to the design of grass waterways. Where farming operations cross the channel, the side slope should be flat, i.e., 8:1 or greater for depths of 0.3 m or less and 10:1 or greater for depths over 0.6 m. Minimum side slope of 4:1 is desired if the field is farmed parallel to the ditch.

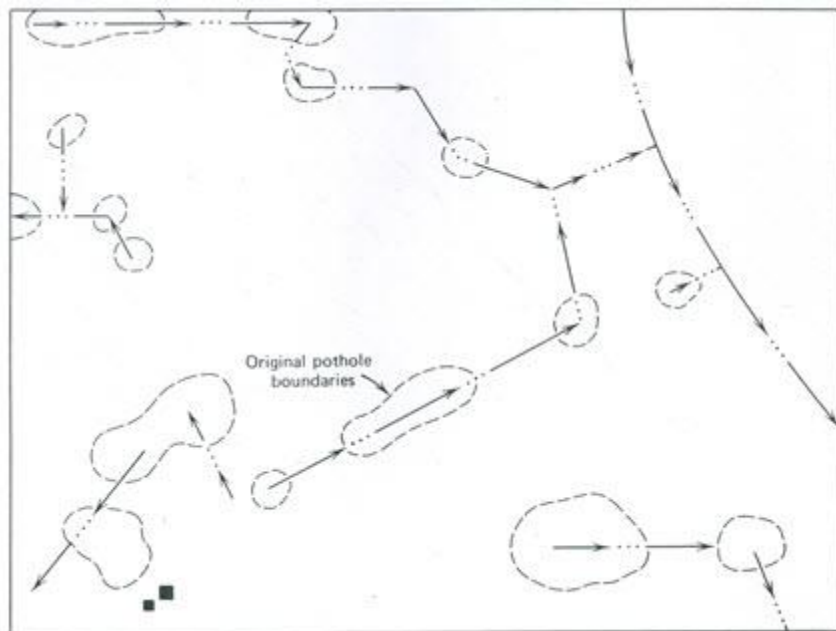


Fig. 3.4. A random field drain system. (Source: Schwab et al., 2005)

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The depth is determined primarily by the topography of the area, outlet conditions, and capacity of the channel. The grade in the channel should be such that the velocity does not cause erosion or sedimentation. Minimum velocities vary with the depth of flow; however, these range from about 0.3 to 0.6 m/s for depths of flow less than 1 m. The maximum grade for sandy soil is about 0.2% and for clay soils, 0.5%. The minimum grade is 0.05%. The roughness coefficient in the Manning's equation may be taken as 0.04, if more reliable coefficients are not available. The capacity of the drain is usually not considered for areas less than 2 ha provided the minimum design specifications are met. However, where the area is larger than 2 ha, the capacity should be based on a 10-year return period storm, making allowances for minimum infiltration and interception losses. Since most field crops are able to withstand inundation for only a short period without damage, it is desirable to remove surface water within 12 to 24 hours.

Generally, the channel should follow a route that provides minimum cut and least interface with farming operations. The outlet for such a system may be a natural stream, constructed drainage ditch, or protected slope if no suitable ditch is available. Where the outlet is a broad, flat slope, the water is permitted to spread out on the land below. This type of outlet is practical only if the drainage area is small.

### (2) Bedding Field Drain System

Bedding is a method of surface drainage consisting of narrow-width plow lands in which the dead furrows run parallel to the prevailing land slope (Fig. 3.5). The area between two adjacent dead furrows is known as a bed. Bedding is most practicable on flat slopes less than 1.5%, where the soils are slowly permeable and pipe drainage is not economical. Studies have shown that the leveled land provides slightly better yield than the bedded land (Schwab et al., 2005).

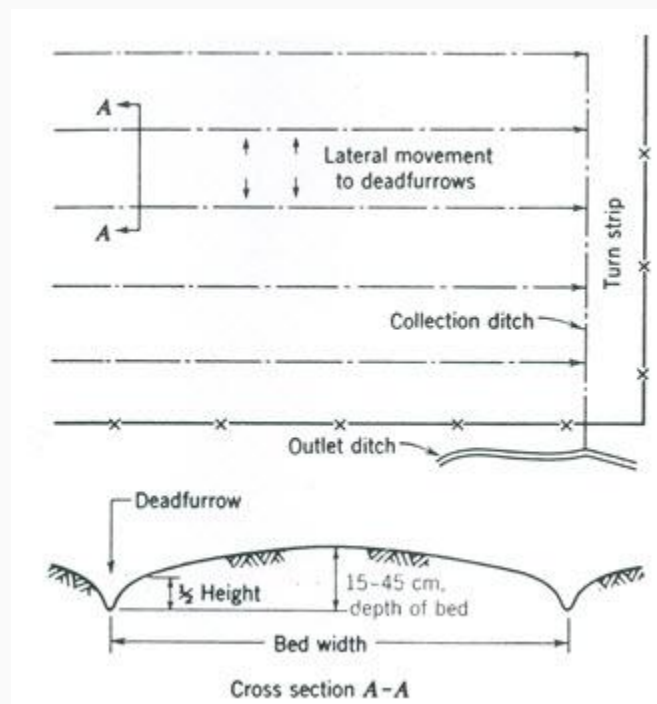


Fig. 3.5. Bedding field drain system. (Source: Schwab et al., 2005)

The design and layout of a bedding system involves the proper spacing of dead furrows, depth of bed, and grade in the channel. The depth and width of the bed depend on land slope,

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drainage characteristics of the soil, and cropping system. Bed widths recommended for the Corn Belt region of the United States vary from 7 to 11 m for very slow internal drainage from 13 to 16 m for slow internal drainage, and from 18 to 28 m for good internal drainage. The length of the beds may vary from 90 to 300 m. In the bedded area, the direction of farming operation may be parallel or normal to the dead furrows. Tillage practices parallel to the beds have a tendency to retard water movement to the dead furrows. Plowing is always parallel to the dead furrows.

### (3) Parallel Field Drain System

Parallel field drains are similar to bedding except that the channels are spaced farther apart and may have a greater capacity than the dead furrows. This system is well adapted to flat, poorly drained soils with numerous small depressions that must be filled by land grading (Schwab et al., 2005).

The design and layout are similar to those for bedding except that drains need not be equally spaced and the water may move in only one direction. The layout of such a field system is shown in Fig. 3.6. As in bedding, the turn strip is provided where ditches border a fence line. The size of the ditch may be varied, depending on grade, soil, and drainage area. The depth of the ditch should be a minimum of 0.2 m and have a minimum cross-sectional area of 0.5 m<sup>2</sup>. For trapezoidal cross sections, the bottom width should be 2.4 m (ASAE, 1986). The side slopes should be 8:1 or flatter to facilitate crossing with farm machinery. As in bedding, plowing operations must be parallel to the channels, but planting, cultivating, and harvesting are normally perpendicular to them. The rows should have a continuous slope to ditches. The maximum length for rows having a continuous slope in one direction is 180 m, allowing a maximum spacing of 360 m where the rows drain in both directions. In very flat land with little or no slope, some of the excavated soil may be used to provide the necessary grade; however, the length and grade of the rows should be limited so as to prevent damage by erosion. On highly erosive soils that are slowly permeable, the slope length should be reduced to 90 m or less.



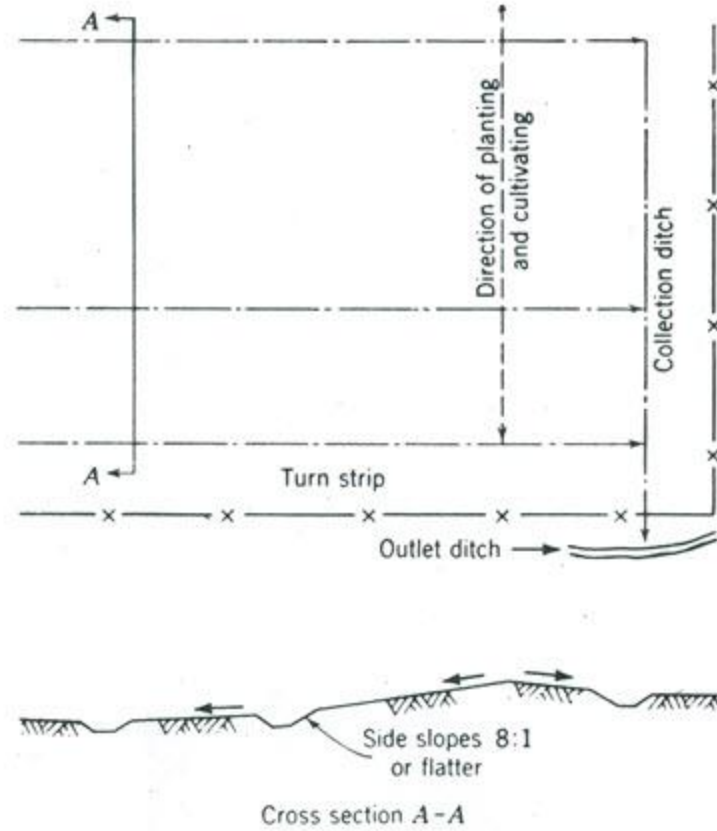


Fig. 3.6. Parallel field drain system. (Source: Schwab et al., 2005)

As mentioned earlier, the cross section for field drains may be V-shaped, trapezoidal, or parabolic. The W-drain shown in Fig. 3.7 is essentially two parallel single ditches with a narrow spacing. All of the spoil is placed between the channels, making the cross section similar to that of a road. The advantages of the W-drain are that it: (i) allows better row drainage because spoil does not have to be spread, (ii) may be used as a turn row, (iii) may serve as a field road, (iv) can be constructed and maintained with ordinary farm equipment, and (v) may be seeded to grass or row crops. On the other hand, the disadvantages of the W-drain are that: (i) the spoil is not available for filling depressions, (ii) a greater quantity of soil must be moved, and (iii) a larger area is occupied by drains. The minimum width for W-drains varies from about 5 to 30 m depending on the size. The W-drain is best adapted to relatively flat land where the rows drain from both directions.

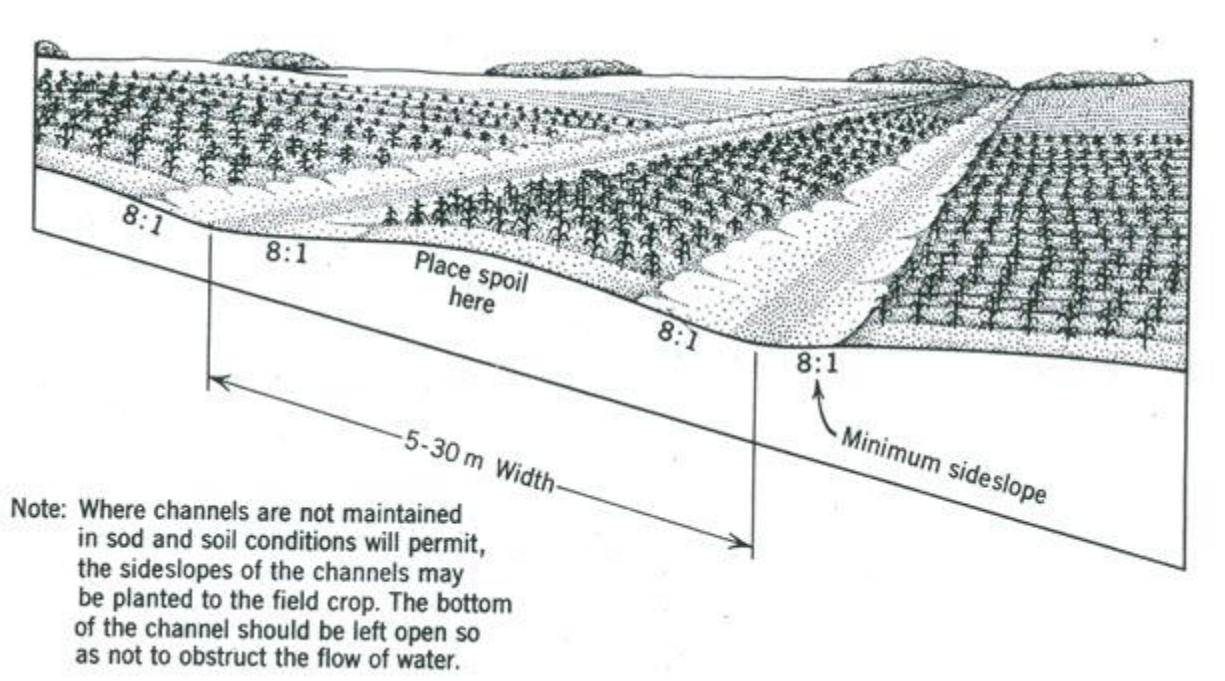


Fig. 3.7. W-drain or double field drain for surface drainage.(Source: Schwab et al., 2005)

#### (4) Parallel Lateral Ditch System

The parallel lateral ditch system is similar to the field drain system except that the ditches are deeper. These drains shown in Fig. 3.8 cannot be crossed with farm machinery. For clarity, the minimum size for open ditches is 0.3 m deep and side slopes are steeper than 6:1. The purpose of lateral open ditches is to control the water table and to provide surface drainage. These ditches are applicable for draining peat and muck soils to obtain initial subsidence prior to subsurface drainage. For the same depth to water table, ditches provide the same degree of surface drainage as pipe drains.

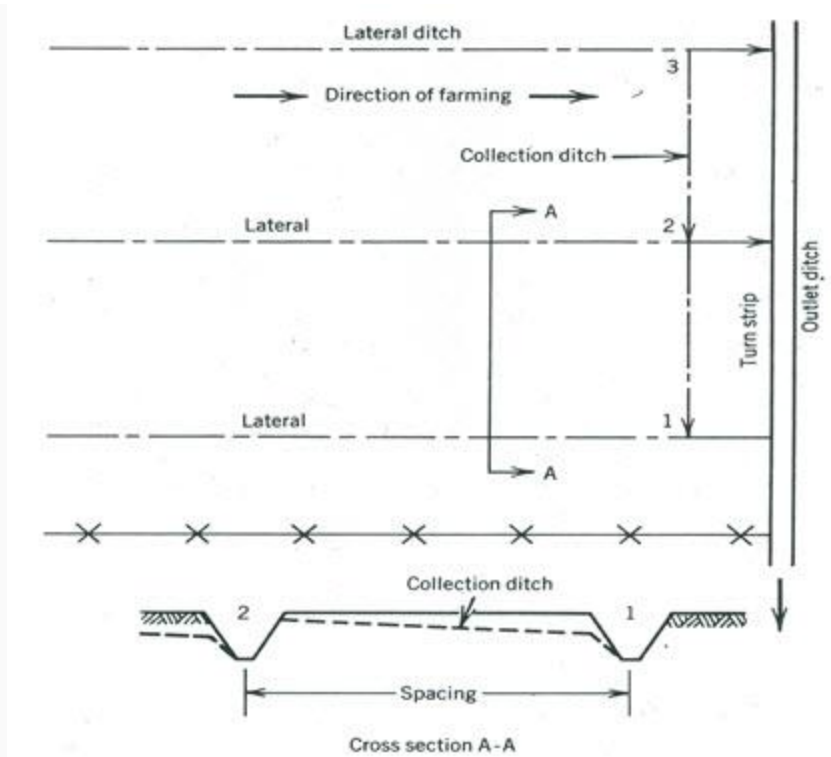


Fig. 3.8. Parallel lateral ditch system for water table control and surface drainage.

(Source: Beauchamp, 1952)

The design specifications for lateral ditches are given in Table 3.4. Since lateral ditches are considerably deeper than collection ditches, overfall protection must be provided at outlets 1 and 2 as indicated in Fig. 3.8. This protection may be obtained with a suitable permanent structure, by providing a gradual slope near the outlets, or by establishing a grassed channel. Since these ditches are too deep to cross with farm machinery, farming operations must be parallel to the ditches. A collection ditch, row drain, or quarter drain should be provided for row drainage. As in other methods of drainage on flat land, the surface must be graded and smoothed and large depressions filled or drained by random field ditches.

Table 3.4. Ditch specifications for water table control (Source: Schwab et al., 2005)

Sl. No.	Parameter	Sandy Soil	Other Mineral Soils	Organic Soils, Peat and Muck
1	Maximum Spacing	200 m	100 m	60 m
2	Minimum Side Slope	1:1	:1	Vertical to 1:1 <sup>a</sup>
3	Minimum Bottom Width	1.2 m	0.3 m	0.3 m

4	Minimum Depth	1.2 m	0.8 m	0.9 m
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**Note:** <sup>a</sup> Vertical for raw peat to 1:1 for decomposed peat and muck.

For water table control during dry seasons, dams with removable crest boards are placed at various points in the open ditches to maintain the water surface at the required level. During wet seasons, the crest boards are removed and the system provides surface drainage (Schwab et al., 2005). In highly permeable soils such as sands, peat, and muck, crop yields may be increased by controlled drainage. Deep permeable soils underlain with an impervious material provide the best conditions for successful water table control. The water level may be regulated by gravity, pumping, or a combination of gravity drainage and pumping. The depth at which the water table is to be maintained depends mainly on the crop to be grown, soil type, topography, seasonal conditions, and climatic conditions. Note that in organic soils, a high water table is desirable to provide water for plant growth, to control land subsidence, and to reduce fire and wind erosion hazards. In these soils, the water table should be maintained from 0.5 to 1.2 m below the soil surface depending on the crop type (Schwab et al., 2005).

### (5) Cross-Slope Ditch System

The drainage of sloping land may be feasible with cross-slope ditches. Such channels usually function both for surface drainage and for erosion control. Where designed specifically for the control of erosion, these drains are called terraces. Diversion ditches are sometimes used to divert runoff from low-lying areas, thereby reducing the drainage problem.

The cross-slope ditch system is adapted primarily to soils with poor internal drainage where subsurface drainage is not practicable and for land with slopes of 4% or less having numerous shallow depressions (Schwab et al., 2005). This land is generally too steep for bedding or field drains because farming up and down the slope results in excessive erosion.

### 3.6 Maintenance of Surface Drainage System

Field surface drains can usually be maintained by normal tillage operations. Such maintenance is particularly important on flat land because a very small obstruction in the channel may cause flooding of a sizable area (Schwab et al., 2005). Tillage implements should be lifted when crossing ditches to avoid blocking the channel. If this procedure is not followed, the channel should be kept open by dragging or shaping a smooth channel in the bottom of the drain. When the soil is wet, equipment should not cross dead furrows, field drains, or grass waterways. Moreover, livestock can also damage such channels during rainy seasons, and hence pasturing at other times is desirable. Plowing parallel to shallow surface drains, leaving the dead furrow in the channel is generally adequate for maintenance. Minor depressions between drains should be filled by land grading.



### Lesson 4 Design of Subsurface Drainage Systems

#### 4.1 Purpose and Benefits of Subsurface Drainage

Subsurface drainage is the removal of excess water from the root zone. It is accomplished by deep open drains or buried pipe drains (FAO, 1985). Subsurface drainage is an important conservation practice. Poorly drained lands are usually topographically situated so that when drained, they may be farmed with little or no erosion hazard. Many soils having poor natural drainage are, when properly drained, rated among the most productive soils in the world.

Specific benefits of subsurface drainage are: (i) aeration of the soil for maximum development of plant roots and desirable soil microorganisms; (ii) increased length of growing season because of earlier possible planting dates; (iii) decreased possibility of adversely affecting soil tilth through tillage at excessive soil water levels; (iv) improvement of soil water conditions in relation to the operation of tillage, planting and harvesting machines; (v) removal of toxic substances, such as salts, that in some soils retard plant growth; and (vi) greater storage capacity for water, resulting in less runoff and a lower initial water table following rains. Through these benefits drainage enhances farm productivity by: (a) adding productive land without extending farm boundaries, (b) increasing yield and quality of crops, (c) permitting good soil management, (d) ensuring that crops may be planted and harvested at optimum dates, and (e) eliminating inefficient machine operation caused by small wet areas in fields. In arid regions irrigation and drainage are complementary practices. In some areas leaching of soluble salts through a drainage system is essential before the land can be developed. Drainage is often a necessity as a result of excess water that accumulates from low efficiencies in the conveyance and application of water for irrigation. Although these losses can be reduced, they cannot be entirely eliminated. The benefits of drainage can be realized only when the soil is potentially productive if drained. Government regulations may require leaving soil undrained as a range land or as a recreation and wildlife area.

#### 4.2 Types of Subsurface Drainage Systems

If one has decided to install a subsurface drainage system, one has to make a subsequent choice between **well drainage**, **open drains**, **pipe drains**, and **mole drains**. Well drainage and mole drainage are applied only in very specific conditions (refer to Lessons 8 and 12). Also, mole drainage is mainly aimed at a rapid removal of excess surface water, not controlling water table. Therefore, the usual choice is between open drains and pipe drains (Cavelaars et al., 1994). This choice has to be made at two levels: (a) for field drains, and (b) for collectors. If the field drains are to be pipe drains, there are still two options for the type of collectors: (i) they can be open drains so that we have a 'singular pipe-drain system', or (ii) they can be pipe drains so that we have a 'composite pipe-drain system'.

Open drains have the advantage that they can receive overland flow directly, but the disadvantages often outweigh the advantages. The main disadvantages are: loss of land, interference with the irrigation system, splitting-up of the land into small parcels that hamper

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mechanized farming operations, and the burden of maintenance. Nevertheless, there are cases where open drains are used exclusively, e.g., peat soils and very saline land under a monoculture of rice.

Moreover, a combined system of surface and subsurface drainage may be more appropriate in certain field situations. Salient examples are as follows:

1. A soil profile with a layer of low permeability below the root zone, but good permeability at drain depth: This is a soil profile that can be found in alluvial soils throughout the world. After a heavy rain, a perched water table forms in the root zone, which cannot be lowered rapidly enough without some form of surface drainage. Subsurface drainage subsequently lowers the water table to a normal depth. An alternative solution could be to break up the impeding layer by subsoiling, especially if the impeding layer is less than about 0.3 m thick.
2. Areas with deep frost penetration and snow cover during winter: When the snow melts and the topsoil thaws, but soil at some depth is still frozen, a perched water table will form and will damage a crop of winter grain. The same measures as in the previous example are required here;
3. Irrigated land in arid and semi-arid regions, where the cropping pattern includes rice in rotation with 'dry-foot' crops (e.g., as in the Nile Delta in Egypt): Subsurface drainage is needed for salinity control of the dry-foot crops, whereas surface drainage is needed to evacuate the standing water from the rice fields (e.g., before harvest).
4. Areas with occasional high-intensity rainfall that causes water ponding on the land surface, even if a subsurface drainage system is present: The ponded water could be removed by the subsurface drainage, but this may either take too long time or require very narrow drain spacings. Under such circumstances, it would be more efficient to remove the ponded water by surface drainage.

### 4.3 Design of Pipe Drainage Systems

Pipe drainage is probably the most widely used subsurface drainage method worldwide. Pipe drainage projects can vary widely in scope and size. A project may be a single farm, or it may cover several hectares of land. In this lesson, we will assume a comprehensive large-scale pipe drainage project, because it offers a suitable field setting to discuss all the relevant aspects of a pipe drainage system.

#### 4.3.1 Layout of Pipe Drainage Systems

In this section, we shall discuss the most important considerations that lead to a designed spatial arrangement of a subsurface drainage system in an area (i.e., showing all the items on a map). These considerations involve the choice between a singular system and a composite system, the location and alignment of drains, subsurface drainage in rice fields as a special case, and the use of multiple small pumping stations (Cavelaars et al., 1994). A brief description on singular and composite drainage systems is provided below.

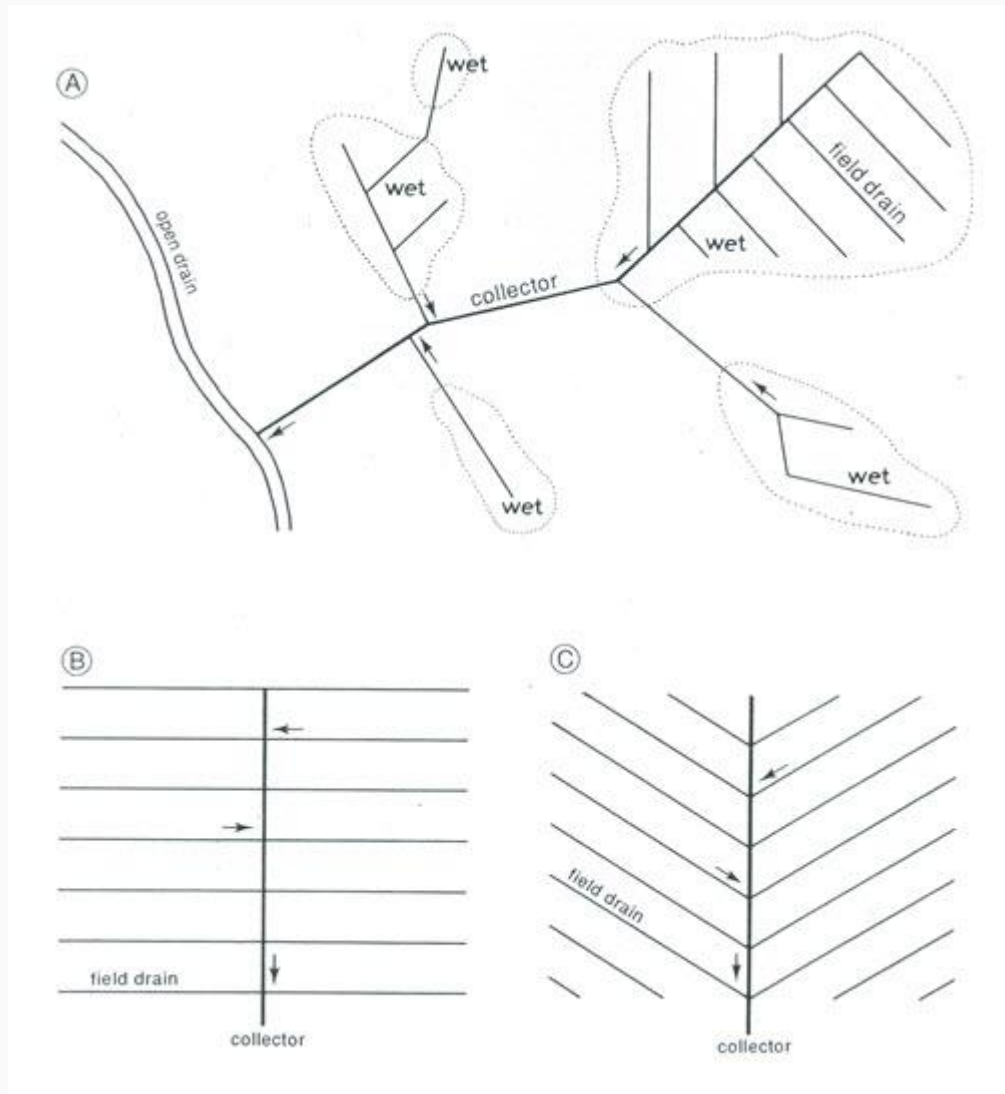
##### (1) Overview of Singular and Composite Drainage Systems



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In a singular pipe drainage system, each field pipe drain discharges into an open collector drain. In a composite pipe drainage system, the field pipe drains discharge into a pipe collector, which in turn discharges into an open main drain. The collector system itself may be composite with sub-collectors and a main collector.

The layout of a pipe drainage system is called a 'random system' when only scattered wet spots of an area need to be drained, often as a composite system (Fig. 4.1A). A regular pattern can be installed if the pipe drainage network uniformly covers the project area. Such a regular pattern can either be a 'parallel grid system' wherein the field drains join the collector at right angles (Fig. 4.1B), or a 'herringbone system' wherein they join at sharp angles (Fig. 4.1C). Note that both the regular patterns may occur as a singular system or a composite system.



**Fig. 4.1. Different layout patterns for a composite pipe drainage system: (A) Random system; (B) Parallel grid system; and (C) Herringbone system. (Source: Cavelaars et al., 1994)**

### (2) Selection Criteria for Singular and Composite Drainage Systems

The choice between a singular and a composite system must be based on a number of factors such as the desirability of open drains, head loss, and costs. A singular system implies a

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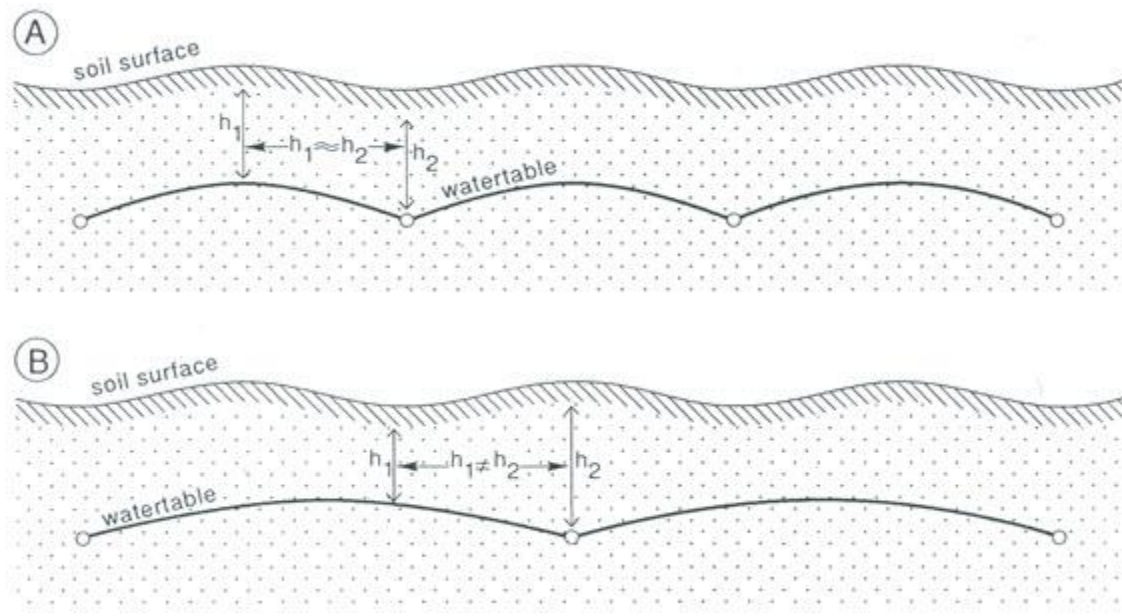
comparatively dense network of open collector drains (maximum spacing in the order of 500 m). These open drains have disadvantages as discussed in Section 4.2, but they may be desirable for other reasons, for example, to provide open water storage and additional surface drainage in high-rainfall areas. A composite pipe system, supplemented by an independent system of shallow surface drains could be another option.

In many flat areas in temperate regions, a natural network of open drains exists before the introduction of a subsurface drainage system. Turning such drains into open collectors may then be convenient, thereby deciding against a composite system (Cavelaars et al., 1994). There are certain advantages and disadvantages of a singular drainage system. Singular drainage system has many pipe outlets, which are vulnerable to damage. Conversely, the maintenance of a singular system is easier and can be done by using standard flushing equipment. Another major consideration is that the construction costs are normally higher for pipe collectors, but the long-term maintenance costs are much lower than for open collectors. Further, in low-lying flat areas, the costs of the main drainage system and pumping station also have to be considered.

However, in irrigated areas with a rather complex infrastructure of roads, irrigation canals, and small farm plots (e.g., as in Egypt), composite systems are generally preferred (Cavelaars et al., 1994). Open collector drains can interfere too much. Singular systems with open collector drains are feasible in the areas where the infrastructure has been fully remodelled under a land consolidation scheme (e.g., as in Iraq), or in newly reclaimed areas. Such considerations have led to a general practice of selecting singular systems in the flat areas of temperate climates and, occasionally, in the irrigated land of arid regions, whereas composite systems are selected in sloping land and, commonly, in the irrigated land of arid regions (Cavelaars et al., 1994).

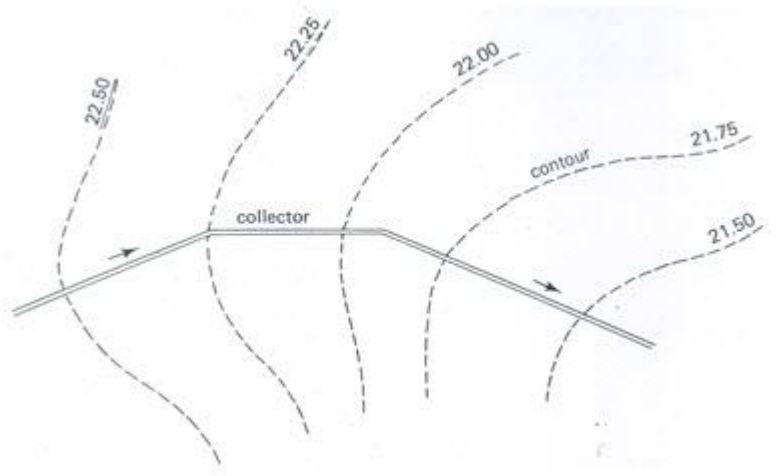
### 4.3.2 Location and Alignment of Drains

The problem is how to draw a drainage system on the map. In many cases, there are several options open to drainage design engineers. However, two main factors viz., topography and existing infrastructure should provide guidance. Optimum use should be made of the existing topography in order to achieve a depth-to-water table as uniformly as possible throughout the area. In the case of uneven topography, the drains will, as much as possible, be situated in the depressions. Fig. 4.2 shows an example of a flat area in a temperate climate, where, fields usually have a regular pattern of shallow depressions, which are the remains of old surface drainage systems. Fig. 4.2A shows how to install field drains in these depressions, even if the spacing does not exactly match with the calculated spacing. Fig. 4.2B shows how it should not be done. A second example (Fig. 4.3) shows where the collector is to be installed in a 'thalweg', which is the line joining the lowest points along a valley.



**Fig. 4.2. Location of field drains in relation to field topography: (A) Well-adapted; (B) Poorly adapted.**

(Source: Cavelaars et al., 1994)



**Fig. 4.3. Location of the collector adapted to the contour lines. (Source: Cavelaars et al., 1994)**

In an area with a uniform land slope (i.e., with parallel equidistant contours), the collector is preferably installed in the direction of the main slope, while the field drains run approximately parallel to the contours (Fig. 4.4A). To take advantage of the slope for the field drains also, a herringbone system can be applied. Other alternatives are collectors parallel to the contours, and the field drains down the slope (Fig. 4.4B), and collectors and field drains both at an angle to the contours (Fig. 4.4C). A major drawback of the latter two alternatives is that the field drains are only on one side of the collector. The inherent greater total collector length and the consequent higher costs make these solutions suitable only under special conditions.

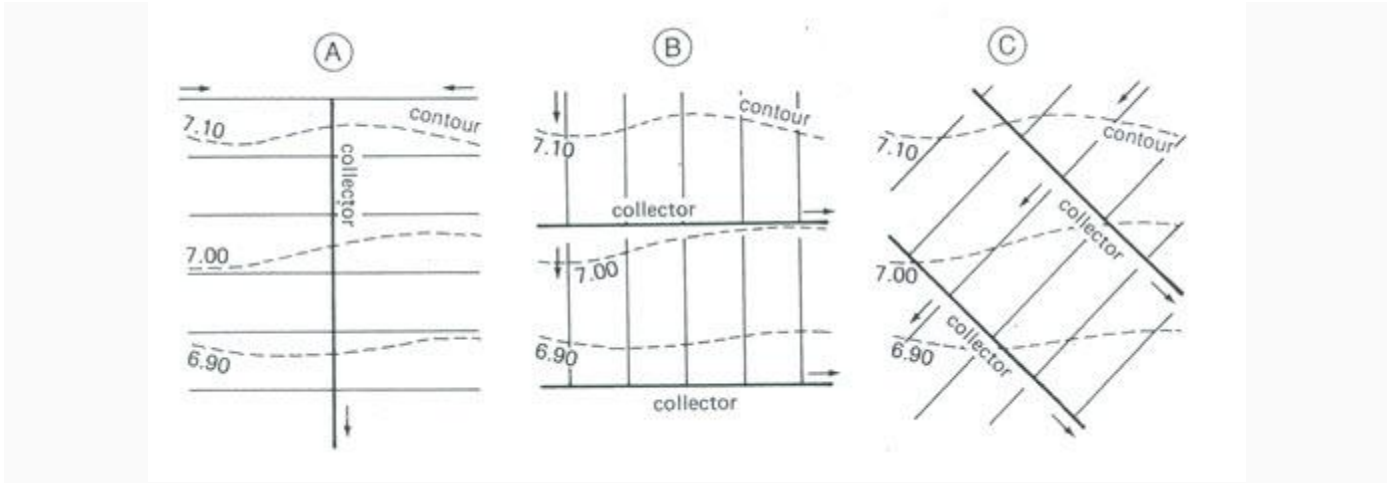


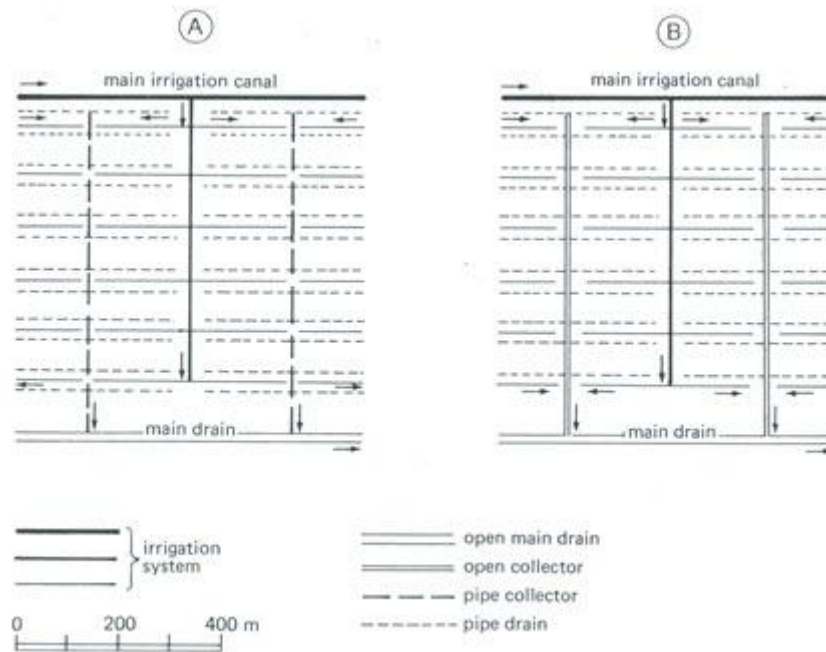
Fig. 4.4. Pipe drainage layout adapted to a uniform slope of the land surface:

- (A) Collector in the direction of the slope;
- (B) Field drains in the direction of the slope;
- (C) Collector and field drains at an angle to the slope. (Source: Cavelaars et al., 1994)

When an infrastructure exists, it has almost certainly been designed without consideration being given to a pipe drainage system. Only when the area has originally been developed under a large-scale scheme, there is a chance that pipe drainage can be introduced in a rational way. Where the infrastructure is very old and has developed gradually in the course of history, the pattern is generally far from regular and allowances have to be made. To design a pipe drainage layout in such an area implies continuous compromises (Cavelaars et al., 1994).

**Firstly**, it has to be verified whether boundaries between farm holdings have to be respected as limits for pipe drainage units. It may vary from country to country and even from project to project. As an example, in The Netherlands and other Western European countries, pipe drains are as a rule installed on an individual farm basis. However, in large-scale drainage schemes in Pakistan (Khairpur) and Egypt (the Nile Delta), one drainage unit (i.e. the area served by a collector) serves the area of several farm holdings, so that collectors, and even field drains, commonly cross holding limits. **Secondly**, an important guideline is to keep crossings of pipe drains with channels and roads to a minimum. Especially if composite systems are installed, however, some crossings are unavoidable. The general rule is then to install the field drains parallel to the tertiary irrigation/drainage channels, and the collectors at right angles.

In new reclamation or land-consolidation schemes, the entire network of roads, irrigation canals, open drains, and pipe drains can be designed simultaneously, which logically offers the best possibility of an optimum layout. Fig. 4.5 shows two possible options for such a case: a composite system (Fig. 4.5A) or a singular system (Fig. 4.5B).



**Fig. 4.5. Irrigation and drainage layout in a new land consolidation area: (A) Composite drainage system with pipe collectors; (B) Singular drainage system with open collectors. (Source: Cavelaars et al., 1994)**

### 4.3.3 Structures of Pipe Drainage Systems

The pipe drainage system consists not only of pipes but also of additional provisions for connection, protection, inspection, maintenance, etc. In this section, we will discuss the most common structures of a pipe drainage system such as 'pipe outlets', 'pipe drain connections', 'closing devices', 'drain bridges', and 'surface water inlets'. These structures constitute integral parts of a pipe drainage system, and hence they are very important for the complete design of a pipe drainage system.

#### (1) Pipe Outlets

A good drain outlet is of great importance due to the fact that a high percentage of failures of drainage systems are due to faulty outlets. The requirements of a good drain outlet are (Schwab et al., 2005): (i) to provide a free outlet with minimum maintenance, (ii) to discharge outflow without serious erosion or damage to the pipe (iii) to keep out rodents and other small animals, (iv) to protect the end of the drain against damage from the tramping of livestock as well as excessive freezing and thawing, and (v) to prevent the entrance of flood water where the outlet is submerged for several hours.

The two main types of outlets for pipe drainage systems are (Schwab et al., 2005): gravity outlet and pump outlet. Gravity outlets are the most common, which include other pipe drains, artificial waterways, natural channels, and wells. Pump outlets may be considered where the water level at the outlet is higher than the bottom of the pipe outlet for any extended period. Outlet ditches should have sufficient capacity to carry surface runoff and drain flow. Where the drainage system is connected to other pipe drains, the outlet should have sufficient capacity to



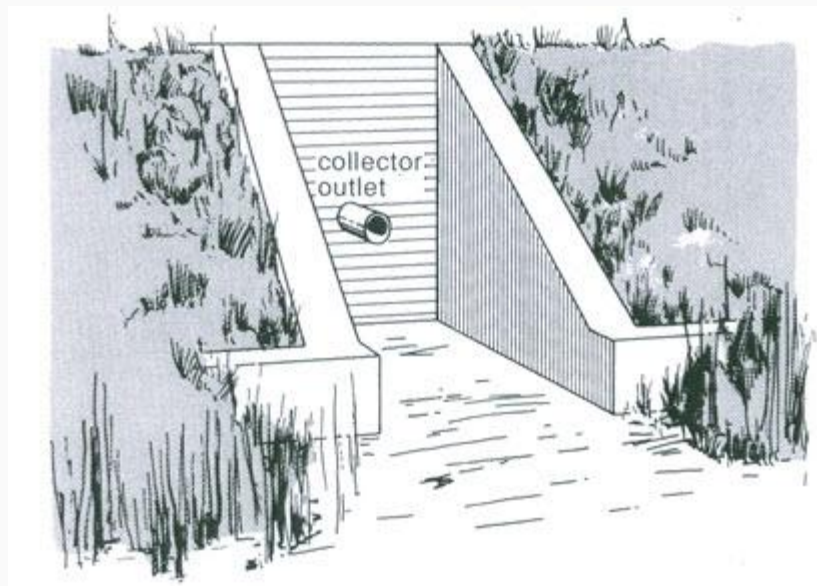
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carry the additional discharge. Some type of grille or flap gate over the end is desirable to prevent entry of rodents. If there is danger of flood water backing up into the drain, an automatic flood or tide gate may be installed in place of the flap gate.

Moreover, the end of the outlet pipe should be 0.3 m or more above the normal water level in the ditch. To prevent damage caused by high velocities in the ditch or failure from snow loads, the exposed end of the pipe should not extend beyond the bank more than one third its total length. The minimum total length should be 5 m, and the diameter should be the same or larger than the drain pipe size. In connecting the metal pipe to the drain, a concrete collar may be installed. Where available, drop inlets and other permanent structures are suitable for stabilizing the outlet. Other types of outlets are vertical drainage outlets, which are essentially wells extending into a porous soil layer or open rock formation in the lower horizons.

Generally, vertical outlets are not recommended because of greater uncertainty in determining their capacity and the risk of groundwater pollution. In horizontal outlets at the place where a subsurface pipe discharges into an open drain, the side slope of the drain is subject to erosion by the normal drain outflow, while additional water may also lead to local erosion of the backfilled trench. This additional water may come from surface irrigation or from water that leaves the pipe through joints or perforations just before the outlet. The same spot is further vulnerable because small animals (e.g., frogs, rats, etc.) may enter the drain and block it.

For collector outlets (few in number), it is common to build a concrete or masonry structure. In order to avoid problems with the mechanical maintenance of open drains, the outlet structure can be built in a recessed area (Fig. 4.6).



**Fig. 4.6. Collector outlet in a recessed area. (Source: SCS, 1971)**

Field drain outlets in a singular drainage system are many, and hence they should generally be inexpensive. An additional requirement is that the outlet should not obstruct the mechanical maintenance of the open drains. Two possible solutions are as follows:

- Provision of a long outlet pipe: The outlet pipe should be long enough so that the discharge does not fall on the side slope, rather it should fall on the water surface of the



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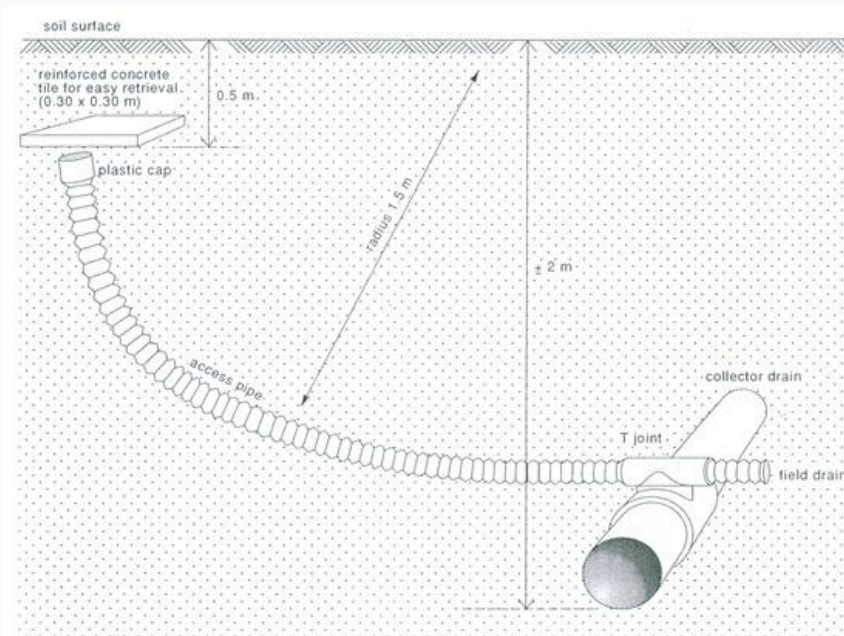
open drain. The additional length to the pipe outlet should be provided such that it can be temporarily removed to allow mechanical ditch cleaning.

- Provision of a drain pipe that does not protrude from the side slope: In this case, the side slope is protected by a chute made of flexible material such as plastic reinforced with glass fiber.

Note that cheap outlet structures are easily damaged. Therefore, regular inspection and repair of outlet structures is required. Additional precautions for collector and field drain outlets are to provide a removable grating in order to prevent the entry of small animals into the pipe (especially for relatively large diameter pipes) and to prevent additional water flow at the end of the trench. For this purpose, the last section of the pipe should have neither perforations nor open joints; no envelope material (especially no gravel) should be applied near the outlet; and the last few metres of the trench backfill should be well compacted over the entire depth of the trench.

### (1) Pipe Connections

There are two main types of connections: blind junctions and manholes (or inspection chambers). Blind connections are direct connections between field drains and collectors by means of cross-joints or T-joints. It is recommended to have the field drain inflow at a somewhat higher level than the collector (a 'drop-in' of about 0.10 m). Blind connections can be provided with special arrangements so that the field drains can be cleaned by flushing without having to excavate and dismantle the connection (Fig. 4.7).



**Fig. 4.7. Connection of field drain to collector drain with access pipe to allow entry of jetting or rodding equipment.(Source: Cavelaars et al., 1994)**

A manhole allows inspection and maintenance of the field drains and the collector. The lid may be either above or below the land surface (Fig. 4.8), depending on the need for frequent inspection. A disadvantage of having the lid at the surface is that farmers tend to use the

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structure as an outlet for excess irrigation water, which will inevitably lead to extra sedimentation in the drain. If the lid is underground, the location should be well recorded for easy retrieval. A useful help is to cast some iron in the lid so that it can easily be found later with a metal detector.

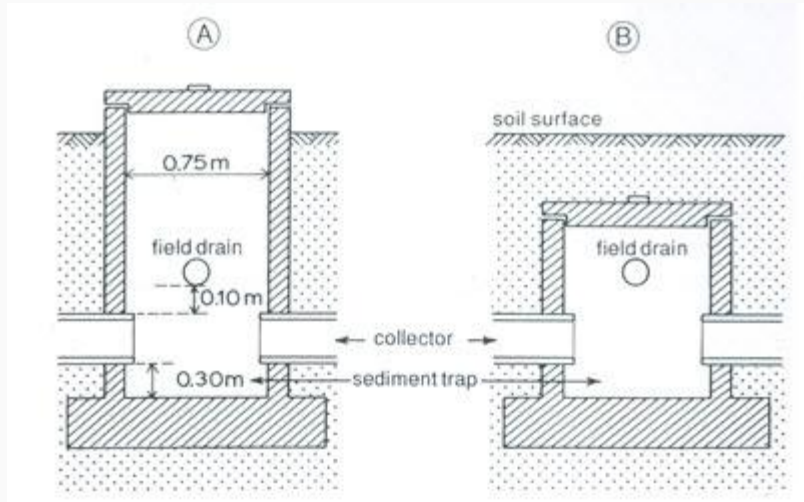


Fig. 4.8. Manhole: (A) Cover above soil surface; (B) Buried cover.

(Source: Cavelaars et al., 1994)

Recommendations for the construction of manholes include the floor to be some 0.20 to 0.30 m below the collector invert, thus allowing for a 'silt trap', from which sediment can be easily removed. A drop between the field drain and the collector of about 0.10 m is recommended. To allow access by a man, the inside diameter of the manhole should be at least 0.75 m, and, if the structure is deep, a ladder of iron bars should be cast in the wall. The manhole can be made of pre-cast segments, of cast-in-place concrete, or of masonry.

### (1) Closing Devices and Outflow Regulators

There may be reasons to close or reduce pipe outflow temporarily (e.g., if the field is under rice). A device can be designed for installation in a sub-collector or in a field drain, either at its outflow into an open drain or at its outflow into a collector. Various types of closing devices and outflow reducers have been tested, but none seems to have progressed beyond the prototype stage. Fig. 4.9 shows an example of a regulating device for sub-collector flow, to be installed in a manhole. Even if working properly, a regulating device for each field drain means a very vulnerable system, which would require meticulous maintenance.

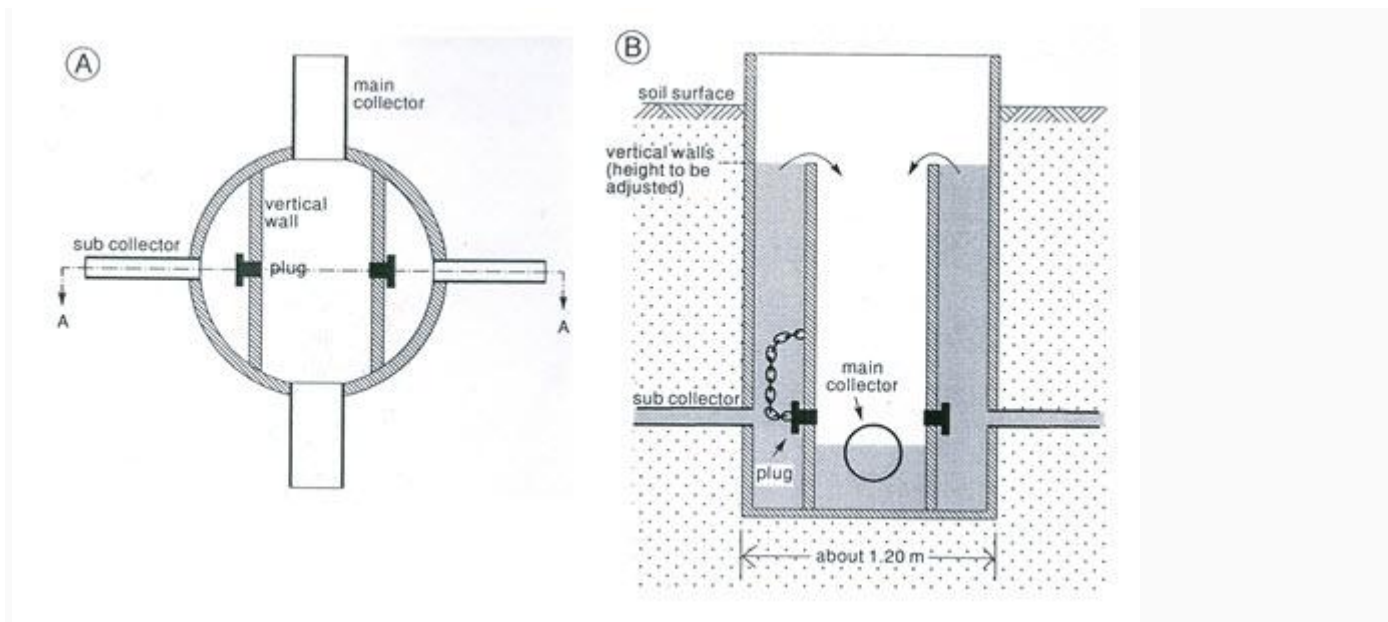


Fig. 4.9. Prototype of a closing device in a manhole: (A) Top view; (B) Section A-A.

(Source: Cavelaars et al., 1994)

## (1) Drain Bridges

Where a pipe drain crosses an unstable strip of soil (e.g., a recently filled-in ditch), it may get out of line or become damaged as a result of the soil setting. As a precaution, the drain can be supported by a rigid bridge across the unstable strip. This bridge can be made of wood or of a steel pipe around the pipe drain.

## (2) Surface-Water Inlets

Surface-water inlets can be built into the drain in places where surface water is likely to accumulate. Two possible types are **blind inlets** and **open inlets**. Considering the sedimentation risk involved, surface water inlets are not very common. Surface water should preferably be evacuated through a network of open drains. Blind inlets consist of a cover of stones and gravel extending from the ground surface to the drain pipe (Fig. 4.10). These inlets by nature are susceptible to clogging by soil particles at the ground surface.

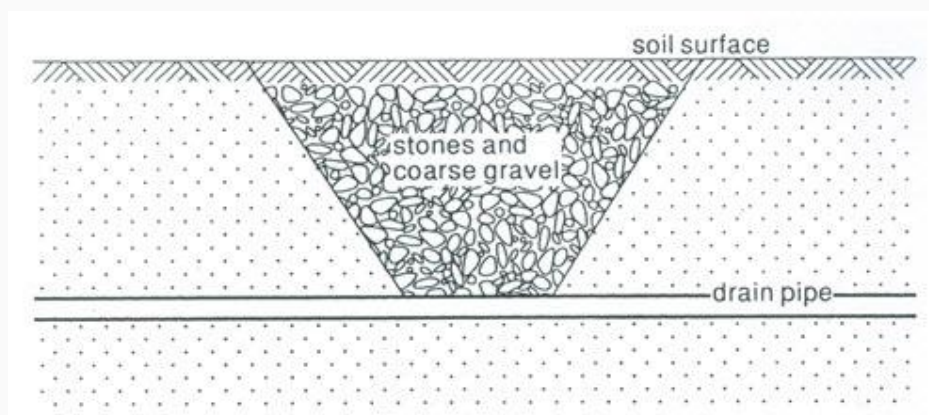
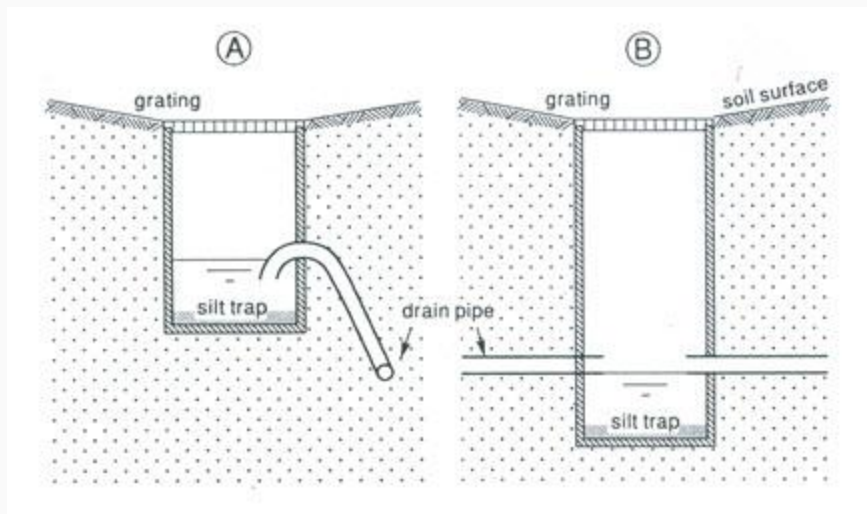


Fig. 4.10. Blind inlet for surface water into a pipe drain. (Source: SCS, 1971)

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Open inlets (Fig. 4.11) are positioned preferably at the upstream end of the drain pipe in order to reduce the chance of the pipe being blocked by sedimentation. These structures should always be provided with a silt trap. At the soil surface, they should be protected by some form of grating. The silt trap must be regularly checked and cleaned.



**Fig. 4.11. Open inlets for surface water into a pipe drain: (A) Built beside the drain line; (B) Built in the drain line. (Source: Cavelaars et al., 1994)**

### 4.3.4 Depth and Spacing of Field Drains

Ideally, the depth and spacing of field drains are determined with the help of drainage equations discussed in Lessons 6 and 7. Drainage criteria are formulated in terms of the parameters that fit in these equations. The parameters, characterizing soil hydraulic properties, are obtained from field investigations. The results of this approach are an infinite number of possible combinations of depth and spacing. However, in practice, depth can seldom be selected freely, thereby restricting the spacing options (Cavelaars et al., 1994). Depth-limiting factors are: 'drainage base', 'presence of unsuitable layers in the soil profile', and the 'available machinery'.

#### (1) Drainage Base

The drainage base can be defined as the water level at the outlet. It determines the hydraulic head available for drainage flow. The outlet is different for different points of a drainage area. For groundwater, the drainage base is the water level or the hydraulic head in the field drains, whether they are pipes or open drains. For the pipe drainage system, the drainage base is the water level that can be maintained in the recipient main drains. For a gravity-flow main drainage system, the drainage base consists of the water level prevailing critical periods, below the main outlet structure.

For pipe drains, we must ensure that they have a free outflow, meaning a pipe invert level at least about 0.10 m above the water level in the recipient drain. This holds for field drains discharging into a collector as well as for collectors discharging into an open main drain. Occasional submergence of short duration (e.g., 1 to 2 days or 2 to 3 times per season) is, however, usually permissible (Cavelaars et al., 1994).



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As ideal conditions (i.e., flat) are rare, the drainage base may be too high in parts of the area. It is then often a matter of professional judgement to find a compromise between insufficient drainage in a limited area and high costs for over-draining the majority of the area (e.g., by including pumping). In some cases, the local effect of insufficient drainage can be offset by other measures such as adding extra nitrogen to compensate for insufficient soil aeration in the winter season in temperate regions, or, in arid areas with saline seepage, by giving an extra leaching irrigation after the fallow period (Cavelaars et al., 1994).

### (2) Unsuitable Soil Layers

Certain soil textures are unsuitable for the installation of pipe drains. When a layer of such a soil texture occurs in the soil profile, the pipe drains should be installed above or below that layer (Cavelaars et al., 1994). Examples of such risky layers are quick-sand layers and slowly-permeable clay layers. Quick-sand layers are sandy layers that develop sloughing when saturated, and they pose a great risk of rapid sedimentation and of misalignment of the pipeline. Clay layers of very low permeability would lead to very narrow drain spacings, and hence high costs.

A typical example is a three-layered soil profile that can be found in alluvial soils. It consists of a root zone of good permeability, overlying a slowly-permeable clay horizon, followed by a permeable subsoil of coarse-textured soil or well-structured clay. If the permeable third layer is not too deep, the drains should preferably be installed in that layer. In this case, the pattern of groundwater flow will be: a short distance of vertical flow through the slowly-permeable second layer, and horizontal and radial flow in the permeable third layer. If the third layer consists of unstable sand, one should be aware of construction problems.

Moreover, in the case of a two-layered profile, with a permeable top soil underlain by a deep slowly-permeable substratum, the drains should be installed in the upper layer (e.g., just above the second layer). If the upper soil layer is very shallow, pipe drainage is not likely to be appropriate at all. In this case, mole drainage or surface drainage might be better alternatives.

### (3) Drain Spacing

Calculated drain spacings for a project area are likely to show considerable variations due to a natural variation in soil hydraulic conductivity over a field. If the variation in soil hydraulic conductivity is significant, the area to be drained should be divided into sub-areas or 'blocks' of a suitable size, and for each of which a uniform and representative drain spacing is selected (Cavelaars et al., 1994). For example, a suitable size could be the area served by one collector.

After considering the depth of the drainage base and the presence of unsuitable soil layers, one normally arrives at a range of possible drain spacings. Within this range, a number of standard spacings should be selected beforehand, each standard differing from the next one by a factor of 1.25 to 1.5 (Cavelaars et al., 1994). It makes little sense to make the increments too small in view of the many inaccuracies and uncertainties in the entire process of determining drain spacings. As an example, let's assume that the calculated drain spacings in a project area vary from 18 to 85 m (after ignoring a few extreme values). In this case, practical sets of standard drain spacings could be: 20-25-30-40-50-60-80 m, or 20-30-45-60-80 m (Cavelaars et al., 1994).

### 4.3.5 Pipe Diameter and Gradient

This section deals with two important factors viz., pipe slope and drainage coefficient which decide the size of a drain pipe and its gradient. The hydraulic design of a drain pipe (i.e., selection of slope and diameter) is based on the value of drainage coefficient ( $q$ ). The value of drainage coefficient is not always the same as the drainage coefficient used to calculate drain spacing. The steady-state criterion for the calculation of the drain spacing, often expressed as the ratio  $q/h$  (i.e., drainage coefficient divided by the hydraulic head midway between the drains), is generally based on average monthly or seasonal values and the design discharges for the hydraulics of drainage pipes on higher, less frequent, peak discharges as may occur during a shorter period, e.g., 10 days (Cavelaars et al., 1994). Furthermore, it is inherent in the steady-state approach that the water table may be incidentally higher than the designed value. This also means that drain discharges will be higher. In very general terms, one tries to avoid the design discharge being exceeded more than 'only a few times' during the main drainage season.

Nevertheless, especially in areas with a very uneven topography, the permissible maximum slope may be an additional matter of concern. This slope is dictated by the maximum permissible flow velocity, for which German standards suggest 1.5 m/s for concrete pipes (Cavelaars et al., 1994). Maximum slopes are of practical significance only for collectors. If the topography necessitates steeper slopes, drop structures should be built into the pipeline, which are normally incorporated in manholes. Special caution is needed if a steep slope changes to a flatter slope; high pressures may develop at the transition point unless the flow velocity on the upstream side is properly controlled and the downstream (flatter) reach of the pipeline has a sufficient capacity.

### 4.4 Computer Modeling for Drainage Design

Modern computers simplify the design of a subsurface drainage system and make possible the incorporation of other variables such as climate and plant growth factors so as to predict relative crop yields. Several computer software packages have been developed, out of which most popular software package is **DRAINMOD** (Skaggs, 1980). DRAINMOD has the capability of handling hourly and daily weather data, soil properties, crop characteristics, soil water distribution, and other related factors. It has been widely adopted in the eastern United States and a user's manual and computer program are available. This software is accessible in state SCS offices and has been accepted by many extension and research engineers in the humid states (Schwab et al., 2005).

DRAINMOD generates the number of working days for tillage operations, a quantitative evaluation of excess wetness conditions, the number of dry days with deficient soil water, and the yield effects of these stresses. It can also evaluate drainage system design for wastewater treatment. DRAINMOD can simulate the performance of a given drainage system for as many years of climatic record as desired. It can predict relative crop yields for the period of record from which economic probability analysis can be made. Surface drainage inputs can be evaluated, together with the effect of subirrigation through the existing drainage system. One of DRAINMOD's greatest merits is its ability to predict crop response to the changes in drainage or subirrigation system design. One or more design parameters can be changed without affecting others.



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Moreover, an indigenous and user-friendly software package named **DrainSolver** has been developed by Prof. Madan Kumar Jha of IIT Kharagpur (developer of this course) which facilitates computer-aided design of surface and subsurface drainage systems, simulation of subsurface flow to drains, computation of design drain discharge and leaching requirements, economic analysis of drainage systems, and the analysis of special drainage problems.



### Lesson 5 Investigation of Drainage Design Parameters

#### 5.1 Drainage Coefficient and Its Determination

##### 5.1.1 Concept of Drainage Coefficient

The concept of drainage coefficient is used for the design of drainage systems for agricultural lands; it is the key parameter needed for the hydraulic design of drainage systems. In agriculture lands, open ditches or drains are the most commonly used surface drainage structures. The rate at which the open drains should remove water from a drainage area depends on: (i) rainfall, (ii) size of the drainage area, (iii) characteristics of the drainage area, and (iv) nature of the crops grown and the degree of protection required for them from water logging.

Drainage coefficient is defined as the amount of surplus water to be removed from the agricultural land in 24 hours so that the plants are not stressed due to surplus water. Alternatively, it is also defined as the depth of water to be removed in 24 hours from the entire drainage area. A commonly used unit of drainage coefficient is cm/day or mm/day. It is also expressed as the flow rate per unit area, i.e., m<sup>3</sup>/s per km<sup>2</sup> or L/s per hectare (Lps/ha). Thus, for a 100 ha agricultural watershed, a drainage coefficient of 1 mm/day would lead to a discharge of  $100 \times 0.116 = 11.6$  L/s at the outlet of the watershed (because 1 mm/day = 0.116 Lps/ha).

Drainage coefficient for an agricultural land is decided such that no appreciable damage is caused to the crops to be grown in that land. The intensity of rain and its duration are inversely proportional to the time allowed for removal of water (which depends upon the type of crop). In deciding the drainage coefficient of an area past experience with similar soils, climatic conditions and crops is very useful. For open ditches for small agricultural areas, the value of drainage coefficient ranges from 0.6 to 2.5 cm, and in extreme cases up to 10 cm. Note that the drainage coefficient is an average rate and it does not take into consideration the runoff distribution with time. Conceptually, the drainage coefficient represents a flow rate lower than the peak of the hydrograph (as calculated by the rational formula). The flow rate corresponding to the drainage coefficient should be adjusted in such a way that the volume of water represented by the area of the direct runoff hydrograph above the drainage coefficient is able to flow out of the watershed within a duration during which it is not harmful for the plants.

**Example Problem** (Murty and Jha, 2009): A watershed of 1500 hectares is discharging through a drain at an average ratio of 2.5 m<sup>3</sup>/s. Calculate the drainage coefficient. If the drainage coefficient is 3 cm, what would be the discharge through the drain?

**Solution:**

Drain discharge in 24 hours =  $2.5 \times 60 \times 60 \times 24$  m<sup>3</sup>/day.

$$\therefore \text{Drainage Coefficient} = \frac{2.5 \times 60 \times 60 \times 24}{1500 \times 10^4}$$

## Drainage Engineering

= 0.0144 m per day = 1.44 cm/day, **Ans.**

If the drainage coefficient is 3 cm, the rate of flow through the drain (Q) will be:

$$Q = \frac{3}{100} \times \frac{1500 \times 10000}{24 \times 60 \times 60} = 5.21 \text{ m}^3/\text{s}, \text{ Ans.}$$

### 5.1.2 Determination of Drainage Coefficient

#### 5.1.2.1 Basic Approaches

In watersheds with average land slopes greater than 1 to 2%, the peak runoff rate is calculated by runoff estimation methods such as rational method, SCS triangular hydrograph method and empirical formula. However, in flat areas (land slopes less than 1%), it is essential to consider the time interval for removing a certain volume of excess surface water (surface water logging) occurring with a certain probability. The runoff for the design of open ditches is expressed as drainage coefficient.

A design drainage coefficient is obtained by considering the runoff from a design rainfall. A design rainfall may be considered as the rainfall of a given duration with a given recurrence interval. For example, one may determine a drainage coefficient for a 5-year 1-day rainfall. There are two basic approaches for determining drainage coefficient. In the **first approach**, the estimated runoff from the design rainfall is distributed over time by following a certain calculation procedure. The result is a hydrograph of flow with a peak. Under this approach, design drainage rate can also be estimated by using some empirical relations. The drainage channel capacity is determined to carry the peak flow as obtained from the above analysis. Such a procedure will result in two large dimensions of drainage channel cross-section which is not required and will be expensive. In the **second approach**, for designing the capacity of a drainage channel, a certain time is assumed as the time within which the excess runoff has to be removed. A safe excess water removal period may be considered as 2 days. This is based on the assumption that if the excess water is removed from the field within 2 days, there may not be any irreversible adverse effect on the plant, and hence on the crop yield. Therefore, it would be appropriate to consider a 2-day rainfall of a desired recurrence interval as the design rainfall, determine the corresponding direct runoff, and divide this by the stipulated period of excess water removal to get the value of design drainage coefficient.

Both the above approaches are indirect estimation of drainage coefficient, and are often used by drainage engineers. However, a more appropriate approach could be to monitor the performance of crops grown under varying drainage conditions or under imposed drainage treatments and work out the most appropriate rate of water removal that leads to an economic design of the drainage systems. An economic drainage system is one which may lead to the desired benefit from drainage (e.g., production at a pre-determined level) at a minimum cost. It is often difficult to quantify the benefits from drainage other than the increase in crop production due to good drainage. Such benefit components are: better trafficability, more field working days, lesser insect-pest attack, and so on. They ultimately help in increasing crop yields.

### 5.1.2.2 Methods for Determining Drainage Coefficient

The methods commonly used for determining drainage coefficient (i.e., design capacity of open ditches for drainage) are: (i) Cypress Creek formula, (ii) Boston Society formula, and (iii) Simplified Hydrologic Accounting method. These methods are briefly described below.

#### (1) Cypress Creek Formula

An empirical relationship relating design drainage rate at the outlet of a watershed and the watershed area was developed in the USA based on the data from a large number of watersheds. This relationship is popularly known as the Cypress Creek formula and is considered valid for a mean watershed slope of 0.45%. This relationship was developed based on the fact and observations that the unit drainage rate (discharge per unit area) reduces as the watershed area increases. Accordingly, an equation relating the runoff rate with the watershed area was obtained as follows:

$$Q = C \times A^p \quad (5.1)$$

Where,  $Q$  = runoff rate ( $\text{m}^3/\text{s}$ ),  $A$  = area of the watershed or agricultural land ( $\text{km}^2$ ),  $p = 5/6$  (Approximate average value), and  $C = (0.2098 + 0.0074Y)$ , where  $Y$  is the direct runoff volume (mm) estimated by the CN method.

This formula is entirely empirical and has been derived upon a large number of observations carried out in the USA. The value of  $Q$  is not the same as peak discharge, and it may so happen that its value will be much less than the peak discharge as certain amount of flooding is allowed before the water is drained.

Since the value of  $p$  in Eqn. (5.1) is less than 1, the rate of increase in the estimated design discharge will not be proportional to the increase in the drainage (watershed) area. This equation makes use of the CN-estimated runoff which is reflected in the coefficient ' $C$ '. The value of  $p$  as  $5/6$  was standardised based on the analysis of the runoff data from the watershed of different sizes.

Assuming that Eqn. (5.1) is applicable to the climatic conditions of India, a few average values of  $C$  in the equation for estimating a 5-year return period (recurrence interval)  $Q$  are given in Table 5.1. For obtaining the design runoff for a 2-year return period, the values of  $Q$ , calculated using Eqn. (5.1) for the  $C$  values listed in Table 5.1, are to be multiplied by a factor varying between 0.79 and 0.84 for different regions of India. These values have been obtained from the drainage area-design discharge curves for different regions of India and for three major groups of crops as developed by Gupta et al. (1971). The design discharge was calculated based on the volume of runoff estimated by the CN method for a constant  $I_a$  versus  $S$  relation of  $I_a = 0.2S$ . Eqn. (5.1) is further used to proportion the design discharge based on the size of the contributing segments of a watershed at a given junction of two drains. Based on the field studies, it has been found that the Cypress Creek formula considerably over estimates the drainage coefficient for watershed areas up to about  $100 \text{ km}^2$ .

Table 5.1. Average values of the coefficient (C) appearing in the Cypress Creek formula (Gupta et al., 1971)

Sl. No.	Region	Values of 'C' for Different Crops		
		Vegetable Crops	Grain Crops	Rice
1	Punjab and Haryana Alluvial Soils	1.414	0.354	0.071
2	Indo-Gangetic Alluvial Soil (North)	3.084	1.050	0.421
3	Indo-Gangetic Alluvial Soil (South)	2.375	0.668	0.260
4	Indo-Gangetic Alluvial Soil (Central)	2.820	0.816	0.185
5	Black Soil (sub-humid)	4.454	1.113	0.890
6	Black Soil (arid and semi-arid)	2.970	0.519	0.372
7	Eastern Red Soils	3.396	1.050	0.734
8	Southern Red Soils	2.262	0.565	0.356
9	Assam Valley	2.970	0.927	0.446

**(2) Boston Society Formula**

Peak discharge for the design of surface drains suggested by the Boston Society of Civil Engineers is given as:

$$Q = C \times A^{0.5} \tag{5.2}$$

Where, Q = peak discharge in cusec (ft<sup>3</sup>/s), C = coefficient, and A = peak catchment area in square miles. Uppal and Sehgal (1965) reported the values of C (Table 5.2) appearing in Eqn. (5.2). These proposed values are mainly applicable for the catchments in different parts of Punjab and Haryana states.

**Table 5.2. Values of coefficient (C) appearing in the Boston Society formula (Uppal and Sehgal, 1965)**

Sl. No.	Catchment Area (Square miles)	Values of 'C' for Different Rainfalls		
		For Rainfall less than 20 inches	For Rainfall between 20 and 30 inches	For Rainfall between 30 and 40 inches
1	0-25	20	50	100
2	25-100	50	100	250
3	100-250	100	200	450
4	Above 250	200	400	600

**Note:** For rainfall above 40 inches, a value of C of 2500 irrespective of the catchment area is suggested.

In order to economise the construction of drainage systems, the surface drains are sometimes designed for a discharge ranging from 1/4 to 1/12 of the calculated peak discharge (Dhruvanaryana, 1980). The practical consideration is to remove the excess water due to heavy storms from the cropped fields within seven days. The drainage systems on Sarda Canal Project in Uttar Pradesh, India were designed for a capacity of 0.11 m<sup>3</sup>/s per km<sup>2</sup> of the catchment, whereas the drainage systems in Punjab were designed for a capacity of only 0.04 m<sup>3</sup>/s per km<sup>2</sup> of the catchment.

**(3) Simplified Hydrologic Accounting Method**

The method given by Raadsma and Schulze (1974) consists of analyzing the rainfall data and estimating the number of hours required to remove the excess water using the information about crop tolerance.

The rainfall data are analyzed for duration-frequency. As drainage is planned taking crop into consideration, the rainfall duration-frequency for a particular crop season is considered. The rainfall excess is calculated and allowance is made for channel storage. Knowing the drainage coefficient, i.e., the depth of water to be removed in 24 hours, the capacity of the drainage system required can be obtained. The example presented below illustrates the application of this method using hypothetical data (Murty and Jha, 2009).

**Table 5.3. Example rainfall data for drainage design (Source: Murty and Jha, 2009)**



Sl. No.	Return Period	Type of Rainfall	Duration of Rainfall			
			90 min	24 h	48 h	72 h
1	1 ' 2 year	Annual	40	65	95	105
		Seasonal	30	55	78	93
		Excess (1)	16	30	52	66
		Excess (2)	6	20	42	56
2	1 ' 5 year	Annual	50	86	120	140
		Seasonal	40	72	85	120
		Excess (1)	25	48	58	90
		Excess (2)	15	38	48	80
3	1 ' 10 year	Annual	60	105	140	165
		Seasonal	50	85	120	150
		Excess (1)	35	55	90	120
		Excess (2)	25	45	80	110

In this example, storage of 10 mm is uniformly assumed in the surface channels. The information given in Table 5.3 is plotted as shown in Fig. 5.1. In addition, drainage capacities are plotted. These graphs can be used to determine the drainage capacity or for a given drainage capacity, the number of hours required to remove excess surface water. For instance, with a drainage capacity of 30 mm/24 hours, a rainfall excess occurring once in 5 years can be drained in about 40 hours (Fig. 5.1). This method is useful when a single crop is involved and its drainage coefficient is known. However, if more crops are involved, the calculation should be done for individual crops.

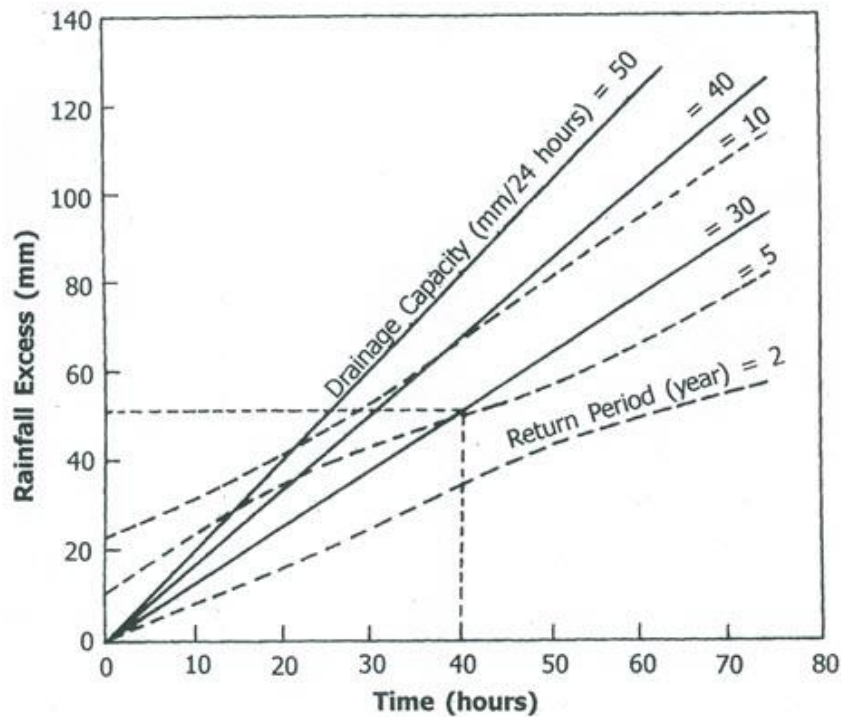


Fig. 5.1. Number of hours required to remove excess surface water.

(Source: Murty and Jha, 2009)

Pai and Hukkeri (1979) recommended that the drains should be designed for 1-day average of 3-day maximum rainfall of 5-year return period with a runoff percentage, calculated after taking into account infiltration rate, evaporation and permissible water storage in the fields or calculated by rainfall-runoff observations. If no field data are available for the area under study, the runoff percentage for different types of soils and for varying intensity of vegetation as given in Table 5.4 can be adopted. The period of disposal of rainfall depends on the type of crops and their growth stages. The values of drainage periods recommended by Pai and Hukkeri (1979) are summarized in Table 5.5.

Table 5.4. Recommended runoff percentage for different soils and vegetation intensities  
(Source: Murty and Jha, 2009)

Sl. No.	Type of Soil	Runoff (%)
1	Sandy soils	20
2	Loamy soils (largely cultivated)	30
3	Loamy soils (lightly covered by crops)	40
4	Gardens and cultivated areas	5 to 25

**Table 5.5. Recommended drainage periods for selected crops (Source: Pai and Hukkeri, 1979)**

Sl. No.	Type of Crop	Drainage Period	Remarks
1	Paddy and Sugarcane	7 days	Panicles in the case of paddy not to get sub-merged and depth of ponding for temporary period not to be more than 0.5 m.
2	Pearl Millet and Cotton	3 days	3 day rainfall to be drained in 3 days.
3	Sorghum and Maize	2 days	2 day rainfall to be drained in 2 days.
4	Vegetables	1 day	24 hour rainfall to be drained in 24 hours.

### 5.2 Determination of Hydraulic Conductivity

To determine a representative value of hydraulic conductivity ( $K$ ), the drainage surveyor must have a theoretical knowledge of the relationships between the kind of drainage system envisaged and the drainage conditions prevailing in the survey area. For example, the surveyor should have some idea about the relationship between effectiveness of drainage and such information as: (i) drain depth and the value of  $K$  at this depth, (ii) depth of groundwater flow and the type of aquifer, (iii) variation in hydraulic conductivity with depth, and (iv) the anisotropy of the soil. A variety of laboratory and field methods exist to determine soil hydraulic conductivity, with varying degrees of accuracy. The pros and cons of different methods of hydraulic conductivity determination are succinctly described below.

#### 5.2.1 Methods for Determining Hydraulic Conductivity

The methods for determining hydraulic conductivity ( $K$ ) of a soil can be classified into two broad groups: (1) correlation methods, and (2) hydraulic methods. Hydraulic methods of  $K$  determination can be further divided into two groups: laboratory methods and field methods. An overview of these methods is presented below.

##### 5.2.1.1 Correlation Methods

Correlation methods are based on predetermined relationships between an easily determined soil property (e.g., texture, pore-size distribution, grain-size distribution, etc.) and the hydraulic conductivity ( $K$ ). A variety of empirical formulae are available which relate  $K$  with content of sand, silt and clay;  $K$  with grain diameter (mean or effective grain diameter);  $K$  with grain-diameter and porosity;  $K$  with grain-size distribution; and  $K$  with soil series (Oosterbaan and Nijland, 1994; Domenico and Schwartz, 1998), and they can be used in the absence of field or laboratory values of hydraulic conductivity. For example, Smedema and Rycroft (1983) provided

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a generalized table with ranges of K-values for certain soil textures as shown in Table 5.6. However, such tables should be handled with care. Smedema and Rycroft (1983) warn that: "Soils with identical texture may have quite different K-values due to differences in structure and some heavy clay soils have well-developed structures and much higher K-values than those indicated in the table".

**Table 5.6. Values of K by soil texture (Smedema and Rycroft, 1983)**

Sl. No.	Soil Texture	Range of K (m/day)
1	Gravelly coarse sand	10 - 50
2	Medium sand	1 - 5
3	Sandy loam, fine sand	1 - 3
4	Loam, clay loam, clay (well structured)	0.5 - 2
5	Very fine sandy loam	0.2 - 0.5
6	Clay loam, clay (poorly structured)	0.002 - 0.2
7	Dense clay (no cracks, pores)	<0.002

Of the various empirical formulae, the Hazen formula is a simple relationship between the hydraulic conductivity and the effective grain diameter, and it is often used for the estimation of hydraulic conductivity from grain-size distribution data. It is expressed as (Freeze and Cherry, 1979):

$$K = A \times d_{10}^2 \quad (5.3)$$

Where, K = hydraulic conductivity, (cm/s);  $d_{10}$  = effective grain diameter, (mm) which is determined from the grain-size distribution curve; and A = constant, which is usually taken as 1.0 (Freeze and Cherry, 1979).

The advantage of the correlation methods is that an estimate of the K value is often simpler and faster than its direct determination. However, the major drawback of these methods is that the empirical relationship may not be accurate in all cases, and hence may be subject to random errors.

### 5.2.1.2 Hydraulic Methods

Hydraulic methods are based on imposing certain flow conditions in the soil and applying an appropriate formula based on the Darcy's law and the boundary conditions of the flow. The value of  $K$  is calculated from the formula using the values of hydraulic head and discharge observed under the imposed conditions. Hydraulic methods can be classified into two groups: **laboratory methods** and **field (in situ) methods**.

The **hydraulic laboratory methods** are applied to core samples (undisturbed samples) of the soil and saturated hydraulic conductivity can be determined by using constant head method or falling head method; the details about this method can be found in standard textbooks on irrigation or drainage (e.g., Murty and Jha, 2009; Smedema and Rycroft, 1983). Although hydraulic laboratory methods are more laborious than the correlation methods, they are still relatively fast and cheap, and they eliminate the uncertainties involved in relating certain soil properties to the hydraulic conductivity of the soil. However, regarding variability and representativeness, they have similar drawbacks as the correlation methods (Oosterbaan and Nijland, 1994). Owing to the small-size of core samples, one must obtain a large number of core samples for obtaining a representative value of  $K$ . Also, if used on a large scale, hydraulic laboratory methods are very laborious and time consuming.

In contrast to the hydraulic laboratory methods, which determine  $K$  inside a core with fixed edges, the **field or in situ methods** usually determine  $K$  around a hole made in the soil so that the outer boundary of the soil mass investigated is often not exactly known. The **hydraulic field methods** can be divided into two groups: small-scale methods and large-scale methods. The small-scale field methods are designed for rapid testing at many locations. They impose simple flow conditions to avoid complexity so that the measurements can be made relatively quick and cheap. The field methods usually represent the  $K$ -value of larger soil mass than the laboratory methods, and hence the variability in the results is relatively less, but can often still be considerable. A drawback of the small-scale field methods is that the imposed flow conditions are often not representative of the flow conditions corresponding to the drainage systems to be designed or evaluated. On the other hand, the large-scale field methods are designed to obtain a representative  $K$ -value of a large soil mass, whereby the problem of variation is eliminated to a greater extent. These methods are very reliable, but are more expensive and time consuming than the methods mentioned above.

#### (1) Small-Scale Field Methods

Various small-scale field methods for the determination of hydraulic conductivity are available (Bouwer and Jackson, 1974). The methods fall into two groups: (a) methods used to determine  $K$  above the water table (unsaturated zone), which are known as infiltration methods, and (b) the methods used to determine  $K$  below the water table (saturated zone/aquifer), which are known as extraction methods. Note that the small-scale in situ methods are not applicable to large depths, and hence their results are not representative for deep aquifers (Oosterbaan and Nijland, 1994). Thus, the results of small-scale methods are more valuable in shallow aquifers than in deep aquifers.

- **Infiltration Methods:** To measure the saturated hydraulic conductivity of a soil (i.e.,  $K$  above the water table), one has to apply sufficient water to obtain near-saturated (or field-

saturated) conditions. These methods are called infiltration methods and use the relationship between the measured infiltration rate and hydraulic head to calculate  $K$ . The equation describing this relationship is selected according to the boundary conditions induced (Oosterbaan and Nijland, 1994). The infiltration methods can be divided into steady-state methods and unsteady-state methods. Steady-state methods are based on the continuous application of water in the hole so that the water level is maintained constant, i.e., the infiltration rate becomes constant. An example of a steady-state infiltration method is 'shallow well pump-in method' (Bouwer and Jackson, 1974). A modified form of the shallow well pump-in method is the 'Guelph permeameter method', which uses a specially developed apparatus and is based on both saturated and unsaturated flow theory (Reynolds and Elrick, 1985). Interested readers are referred to Bouwer and Jackson (1974), Oosterbaan and Nijland (1994), and Reynolds and Elrick (1985) for the detailed methodology of these steady-state infiltration methods.

In contrast, unsteady-state methods are based on observing the rate of fall of the water level below which the infiltration occurs, after the application of water has been stopped. This measurement can start only after sufficient water has been applied to ensure the saturation of a large enough part of the soil around and below the place of measurement. Bouwer and Jackson (1974) present a number of unsteady-state methods, of which the 'double-tube method' is commonly used. Another unsteady-state method is called 'inversed auger-hole method' (Oosterbaan and Nijland, 1994), wherein an uncased hole is used. The detailed procedures for using these methods can be found in Bouwer and Jackson (1974), and Oosterbaan and Nijland (1994).

In general, the infiltration methods measure  $K$  in the vicinity of the infiltration surface. Hence, it is not easy to obtain  $K$  values at greater depths in the soil. Depending on the dimensions of the infiltrating surface, the infiltration methods yield either horizontal  $K$  values ( $K_h$ ), vertical  $K$  values ( $K_v$ ), or  $K$  values in an intermediate direction (Oosterbaan and Nijland, 1994). The infiltration methods are more often used for specific research purposes than for routine measurements on a large scale.

- **Extraction Methods:** To measure the saturated hydraulic conductivity of a soil below the water table, one has to remove water from the soil (because the soil is saturated), create a sink, and then observe the flow rate of water into the sink together with the hydraulic head induced. These methods are called extraction methods and use the equation fitting to the boundary conditions to calculate  $K$ . The most frequently used extraction method for irrigation and drainage purposes is the 'auger-hole method', which is based on the principle of unsteady-state flow (Oosterbaan and Nijland, 1994). Another well-known extraction method is 'piezometer method' (Bouwer and Jackson, 1974), which is based on the same principle as the auger-hole method, except that a tube is inserted into the hole, thereby leaving a cavity of limited height at the hole bottom.

As the depth of the hole made for water extraction is large compared to its radius, the flow of groundwater to the hole is mainly horizontal, and hence the extraction methods predominantly yield horizontal  $K$  ( $K_h$ ) values. The extraction methods measure  $K$  for a larger soil volume (0.1 to 0.3 m<sup>3</sup>) than the laboratory methods, and therefore the values of  $K$  obtained by these methods are more reliable.



### (2) Large-Scale Field Methods

Large-scale field methods are designed for determining hydraulic conductivity below the water table (i.e.,  $K$  of the saturated zone). The methods available for large-scale  $K$  determination are of two types (Oosterbaan and Nijland, 1994): (a) the method that uses pumping from wells (known as 'pumping test'), and (b) the method that uses pumping or gravity flow from horizontal drains (known as 'parallel drains method'). The pumping test is the standard and most accurate method for determining 'hydraulic conductivity' and 'storage coefficient' of saturated zones (aquifers). The detailed methodology for determining  $K$  by the pumping test can be found in Groundwater Hydrology books such as Todd (1980), Raghunath (2007), or Fetter (2000).

Using the parallel drains method, hydraulic conductivity ( $K$ ) can be determined from the functioning of drains in experimental fields, pilot areas, or on existing drains (Oosterbaan and Nijland, 1994), and thus this method is very suitable for drainage. This method uses observations on drain discharges and corresponding elevations of the water table in the soil at some distance from the drains. From these observed data, the value of  $K$  can be calculated using a drainage formula (either steady-state or unsteady-state formula) appropriate for the conditions under which the drains are functioning. Since random deviations of the observations from the theoretical relationship frequently occur, a statistical confidence analysis is necessary (Oosterbaan and Nijland, 1994). Note that the analysis of functioning of existing drains under unsteady-state conditions offers an additional possibility of determining another important hydraulic parameter namely 'drainable porosity' (discussed in the subsequent section).

The advantage of large-scale determination is that the flow paths of the groundwater and the natural irregularities of the  $K$  values along these paths are automatically taken into account in the overall  $K$  value found by the method. Therefore, it is not necessary to determine the variation in  $K$  values from place to place as well as in horizontal and vertical directions, and the overall  $K$  value found can be used directly as an input to the drainage formulae (Oosterbaan and Nijland, 1994). A second advantage is that the variation in  $K$  values found is considerably less than those found with small-scale field methods.

### 5.3 Concept and Determination of Drainable Porosity

#### 5.3.1 Concept of Drainable Porosity

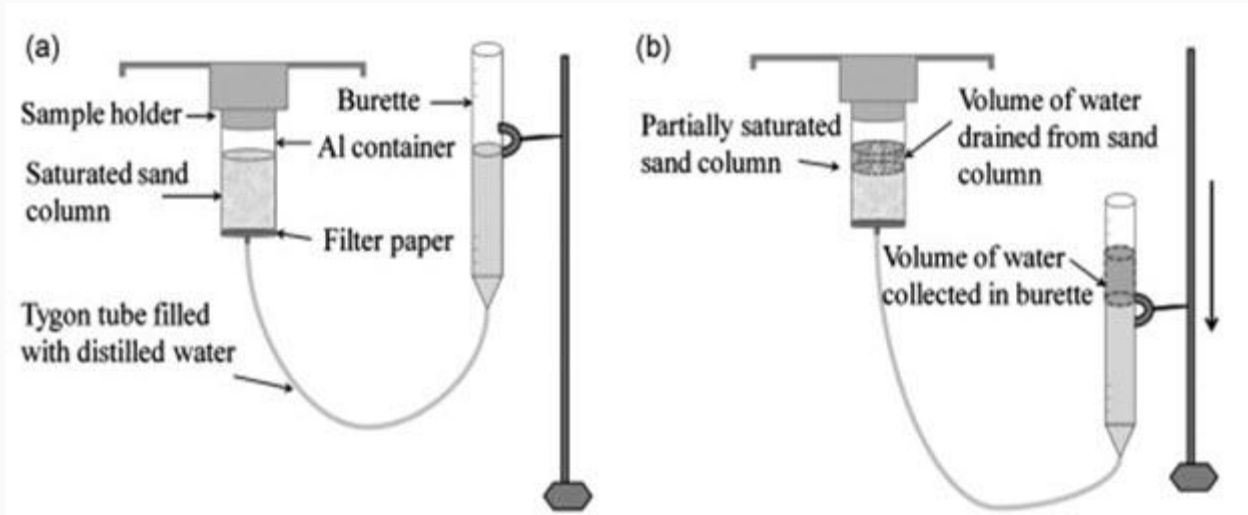
The concept of 'drainable porosity' is applicable for saturated soils and is very important for the analysis of unsteady flow to drains and for estimating groundwater recharge. When a saturated soil is allowed to drain under gravity, some of the water will drain out. The amount of water drained depends on the size of the pores present in the soil. The large-size pores will drain rapidly followed by medium-size pores and the small-size pores drain very slowly. The volume of water drained under gravity by the coarse-textured soils is more than that by the fine-textured soils. This is due to the fact that coarse-textured soils have greater percentage of large-size pores, while fine-textured soils have greater percentage of small and narrow pores.

The term 'drainable porosity' is defined as "the volume of water drained by gravity per unit volume of the saturated soil". It is also called 'effective porosity' or 'specific yield' or 'storage coefficient', especially in groundwater hydrology or hydrogeology. Since the release of water from a saturated soil under gravity is not instantaneous rather a slow process, the drainable

porosity is a function of time and water table depth. However, most drain design methods adopt an average and constant value of drainable porosity because of simplicity in design computations.

### 5.3.2 Determination of Drainable Porosity

Drainable porosity can be measured in the laboratory or in the field. In the laboratory, drainable porosity can be measured using Hanging Water-Column apparatus (Fig. 5.2) which is suitable for a tension range of 0-150 cm. Hanging Water-Column apparatus consists of a glass funnel with a porous plate, a burette, and a flexible transparent tube connecting the glass funnel and the burette.



**Fig. 5.2. Hanging-Water Column apparatus: (a) Initial saturated sand column; (b) Lowered burette.**

(Source: Kang et al., 2012)

Undisturbed soil sample is taken from the field and it is saturated in the laboratory with the help of Hanging Water-Column apparatus (Fig. 5.2a). The saturation may take 24 hours or more depending on the soil type. The water level in the burette is maintained at the same level as the top of the porous plate. Thereafter, the burette is lowered by a certain distance (usually in steps of 10 cm), which imparts a suction to the saturated soil sample, and hence water starts draining slowly (Fig. 5.2b). The drained water raises the water level in the burette. At a given suction, this rise in water level is adjusted by readjusting the burette height such that the originally applied suction is closely maintained. When there is no further rise in water level in the burette, the elevation difference between the top of the porous plate and the water level in the burette are noted down, which gives the value of average suction applied to the soil sample. The difference between the initial and the final burette readings gives the volume of water drained from the soil sample due to the applied suction. This process is repeated by lowering the burette in steps of 10 cm initially and more lately until the desired suction (corresponding to the maximum possible depth of the subsurface drain or any other criteria) is obtained. Generally, applying a suction of greater than 2 m is not required for drainage related studies. Based on the cumulative volume of water drained, drainable porosity is calculated by dividing the volume of water drained with the volume of the soil sample. Note that the Hanging Water-Column apparatus facilitates the

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determination of drainable porosity of a soil at small and closer suction values that usually occur under subsurface drainage.

Moreover, the drainable porosity can be measured in the field by observing the subsurface drain discharge and the water table recession over a period when the evaporation is insignificant. Generally, the field method provides more accurate values of drainable porosity than the laboratory method.

In practice, drainable porosity is considered as a static soil hydraulic parameter, which represents the average change in the water content of the soil profile when the level of water table changes with a discrete step. Its value depends on soil texture and structure, and the depth of water table. To calculate a practical mean value of the drainable porosity for an area, it should be calculated for the major soil series and for several depths of the water table. If the water retention characteristic of the soil is known and if the pressure-head profile is known for two different levels of water table, the drainable porosity ( $\mu$ ) can be calculated from the following equation:

$$\mu = \frac{\int_0^{z_2} \theta_2(z) dz - \int_0^{z_1} \theta_1(z) dz}{z_2 - z_1} \quad (5.4)$$

Where,  $z_1$  = water table depth (m) for Stage 1 (say at  $t = t_1$ ),  $z_2$  = water table depth (m) for Stage 2 (say at  $t = t_2$ ),  $q_1(z)$  = soil-water content as a function of soil depth for the water-table position at  $t_1$ , and  $q_2(z)$  = soil-water content as a function of soil depth for the water-table position at  $t_2$ .

Thus, 'drainable porosity' can also be defined as "the ratio of the change in soil-water content in the soil profile above the water table to the corresponding rise/fall of the water table in the absence of evaporation".

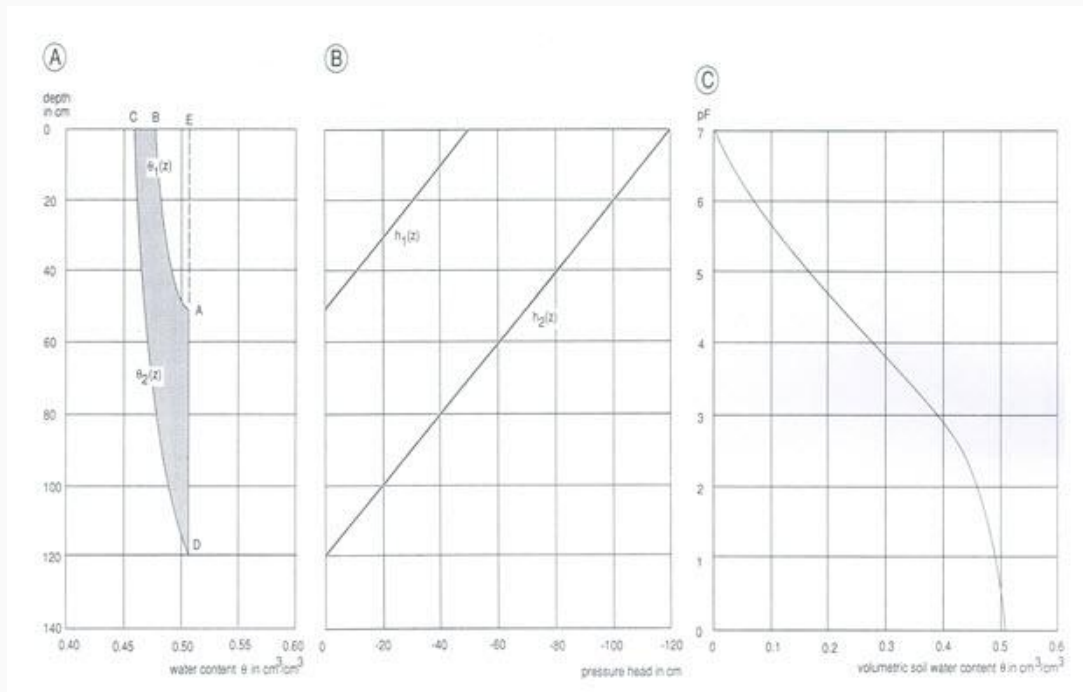
The above definition of drainable porosity is illustrated in Fig. 5.3A. In this figure, the soil-water content of a silty clay soil is shown by the line A-B for a water table depth of 0.50 m, and by the line C-D for a water table depth of 1.20 m. The drainable porosity in this case is represented by the enclosed area ABCD (representing the change in soil-water content) divided by the change in water table depth AD. That is,

$$\mu = \frac{ABCD}{AD} \quad (5.5)$$

Usually, the drainable pore space is calculated for equilibrium conditions between soil-water content and water table depth. Note that the drainable porosity for a given soil is not a constant for the entire soil profile; rather it depends on the depth of the water table. Generally, drainable porosity increases with increasing water table depths. The capillary reach in which equilibrium conditions exist is only active where the soil surface is nearby and when soil water is occasionally removed by evaporation. For a depth greater than a certain critical value (which

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depends on the soil type), the drainable porosity can be approximated by the difference in soil moisture ( $q$ ) between field capacity and saturation.



**Fig. 5.3. (A) Soil-water profiles for equilibrium conditions with the water table at 0.50 m [ $q_1(z)$ ] and at 1.20 m [ $q_2(z)$ ].**

The area enclosed by  $q_1(z)$ ,  $q_2(z)$ , the soil surface, and AD represents drainable porosity;

**(B) Equilibrium pressure-head profiles for water tables at 0.50 and 1.20 m;**

**(C) Soil-water retention curve for a silty clay soil. (Source: Kabat and Beekma, 1994)**

Typical values of drainable porosity ( $m$ ) for field soils vary from 2 to 10% (Smedema and Rycroft, 1983). A  $m$ -value of 5% indicates that the water table falls or rises by 10 cm for each 5 mm of water extracted from or added to the groundwater, respectively. If the values of  $m$  are small, the response of water table to the extraction or addition of water is large, and the reverse is true for large  $m$ -values. Table 5.7 summarizes representative values of drainable porosity for salient soils.

**Table 5.7. Drainable porosity for different soils (Smedema and Rycroft, 1983)**

Sl. No.	Soil Type	Drainable Porosity (%)
1	Dense Clay	1 to 2
2	Well Structured Loams, Clay Loams and Clays	4 to 8
3	Fine Sand	15 to 20
4	Coarse Sand	25 to 35

**Example Problem on Drainable Porosity** (Bhattacharya and Michael, 2003): In a subsurface drainage network, 10 lateral drains laid at a spacing of 40 m and each 150 m long, join a collector drain. The average discharge at the outlet of the collector drain was 10 L/s when the water table dropped from ground surface to 40 cm below the ground surface in 3 days. Find the average drainable porosity of the soil.

**Solution:**

Total area drained =  $10 \times 150 \times 40 = 60,000 \text{ m}^2$

Volume of soil drained =  $60,000 \times 0.4 = 24,000 \text{ m}^3$

Volume of water drained in 3 days =  $10 \times 3600 \times 24 \times 3/1000 = 2592 \text{ m}^3$ .

There for, Drainable Porosity =  $2592 \div 24000 = 0.108$  or 10.8%, **Ans.**

The above calculated value of drainable porosity is the average of the top 40 cm soil layer and also an average over the time period of 3 days. As the water table is gradually declining, the discharge rate will also gradually decline. If the information on the discharge for shorter durations and the corresponding water table decline were available, the drainable porosity calculated for the shorter duration would have been different. Furthermore, the computed value of drainable porosity is also approximate as the entire depth of 40 cm of the soil has been assumed to have experienced a uniform water table decline of 40 cm. However, in a subsurface drained field, the water table is curved between the adjacent parallel drains. Therefore, the drained soil volume is not uniform throughout the drained field.



### *Module 3: Subsurface Flow to Drains and Drainage Equations*

#### **Lesson 6 Steady-State Flow to Drains**

##### **6.1 Introduction**

In subsurface drainage, field drains are used to control the depth of the water table and the level of salinity in the rootzone by removing excess groundwater. In this module, we will discuss the flow of groundwater towards field drains. The discussion will be restricted to parallel drains, which may be either open ditches or pipe drains. Relationships will be derived between the drain properties (diameter, depth, and spacing), the soil characteristics (profile and hydraulic conductivity), the depth of the water table, and the corresponding discharge. To derive these relationships, several assumptions are to be made. Note that all the solutions are approximations. However, their accuracy is such that their application in practice is fully justified (Ritzema, 1994).

First of all, steady-state drainage equations will be discussed. These equations are based on the assumption that the drain discharge equals the recharge to the groundwater, and hence, the water table does not change with time. In irrigated areas or areas with highly variable rainfall, these assumptions are not met and unsteady-state equations are sometimes more appropriate. Unsteady-state equations will be discussed in Lesson 7.

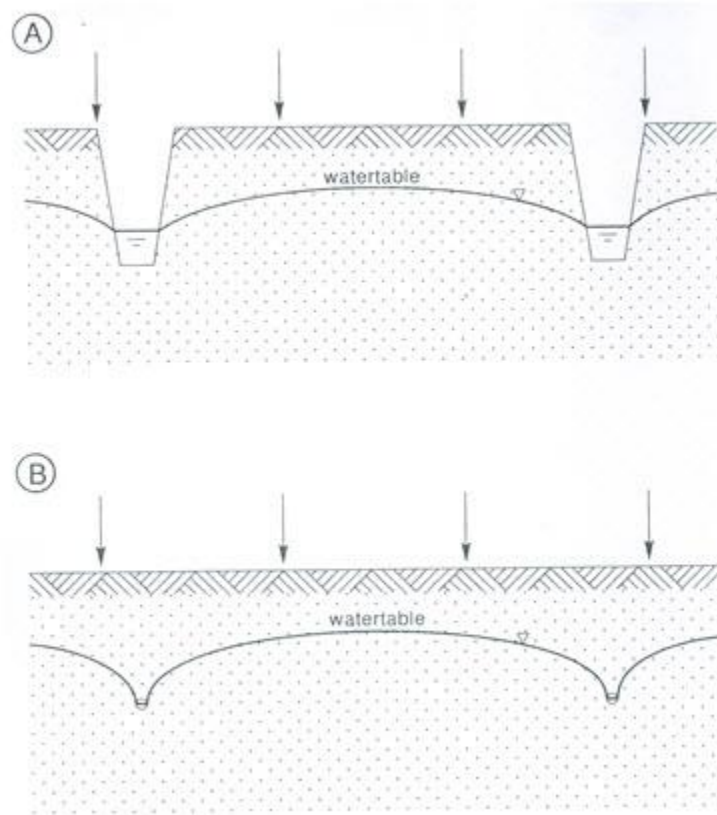
##### **6.2 Steady-State Drainage Equations**

###### **6.2.1 Problem Definition and Assumptions**

This section deals with the flow of groundwater to parallel field drains under steady-state conditions. This is a typical situation in areas with a humid climate and prolonged periods of fairly uniform, medium-intensity rainfall. The steady-state theory is based on the assumption that the rate of recharge to the aquifer is steady and that it equals the discharge of the drain. Thus, under steady-state conditions the water table position does not change as long as the recharge continues.

Fig. 6.1 shows two typical cross-sections of a drainage system under steady-state conditions. In this figure, since the aquifer receives recharge from excess rainfall, excess irrigation, or upward seepage, the water table is curved and its elevation is the highest at mid-drain spacing. For analysis, we assume the symmetry of the flow system, and hence we will consider only one half of the figure.





**Fig. 6.1. Cross-sections of open field drains (A) and pipe drains (B), showing a curved water table under recharge.**

**(Source: Ritzema, 1994)**

To analyze the flow of groundwater to the drainage systems, the following assumptions are made in order to simplify the complex flow process so as to apply analytical techniques:

- Subsurface flow is two-dimensional. This means that the flow is considered to be identical in any cross-section perpendicular to the drains; this is true only for infinitely long drains.
- The recharge is uniformly distributed.
- Soils are homogeneous and isotropic. Thus, spatial variation of the hydraulic conductivity within a soil layer is ignored; through soil profiles consisting of two or more layers can be handled.

Most drainage equations are based on the Dupuit-Forchheimer assumptions. These assumptions state that the streamlines in a vertical plane under study are horizontal and that the flow velocity in the plane at all depths is proportional to the slope of the water table. Based on these assumptions, the two-dimensional flow can be reduced to a one dimensional flow. Such a flow pattern is possible when the impervious layer is close to the drain. The Hooghoudt Equation (described later) is based on these conditions. If the impervious layer does not coincide with the bottom of the drain, the flow in the vicinity of the drains will be radial and the Dupuit-Forchheimer assumptions cannot be applied. Hooghoudt solved this problem by introducing an imaginary impervious layer to take into account the extra head loss caused by the radial flow.

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Other approximate analytical solutions were derived by Kirkham and Dagan. Kirkham (1958) presented a solution based on the potential flow theory, which takes both the flow above and below drain level into account. Dagan (1964) considered radial flow close to the drain and horizontal flow further away from it. Ernst derived a solution for a soil profile consisting of more than one soil layer.

Of the above-mentioned equations, Hooghoudt's gives the best results (Lovell and Youngs, 1984). Also, whichever equations are used to calculate drain spacings, the difference in the results will be minor in comparison with the accuracy of the input data (e.g., data on the hydraulic conductivity). Therefore, in this lesson, the Hooghoudt equation and the Ernst equation are described.

### 6.2.1 Hooghoudt Equation

Consider a steady-state flow to vertically-walled open drains reaching an impervious layer (Fig. 6.2). According to the Dupuit-Forchheimer assumptions, Darcy's equation can be applied to describe the flow of groundwater ( $q_x$ ) through a vertical plane ( $y$ ) at a distance ( $x$ ) from the drainage ditch, which yields the following:

$$q_x = K y \frac{dy}{dx} \quad (6.1)$$

Where,  $q_x$  = unit flow rate in the x-direction (m<sup>2</sup>/day),  $K$  = hydraulic conductivity of the soil (m/day),  $y$  = height of the water table at  $x$  (m), and  $\frac{dy}{dx}$  = hydraulic gradient at  $x$  (dimensionless).

According to the law of conservation of mass, all the water entering the soil in the surface area midway between the drains and the vertical plane ( $y$ ) at distance ( $x$ ) must pass through this plane on its way to the drain. If  $R$  is the rate of recharge per unit area, then the rate of flow through the plane ( $y$ ) is given as:

$$q_x = R \left( \frac{1}{2} L - x \right) \quad (6.2)$$

Where,  $R$  = rate of recharge per unit surface area [L/T], and  $L$  = drain spacing [L].

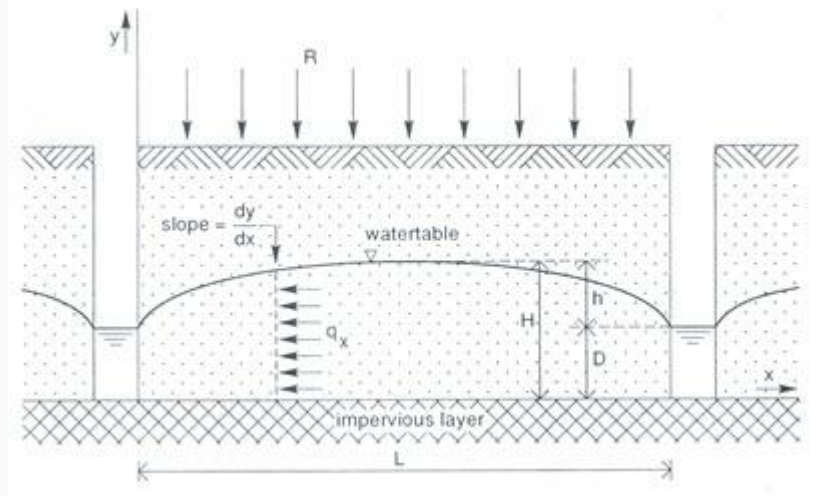


Fig. 6.2. Flow to vertically-walled drains reaching the impervious layer. (Source: Ritzema, 1994)

Since the flow in the two cases must be equal, we can equate the right sides of Eqns. (6.1) and (6.2) as follows:

$$K y \frac{dy}{dx} = R \left( \frac{1}{2} L - x \right)$$

$$\Rightarrow K y dy = R \left( \frac{1}{2} L - x \right) dx \quad (6.3)$$

Integrating this differential equation [Eqn. (6.3)] with the lower and upper limits of  $x$  and  $y$ , we have:

$$\text{at } x = 0, y = D; \text{ and at } x = \frac{L}{2}, y = H$$

Integrating Eqn. (6.3) within these limits, we have:

$$L^2 = \frac{4K(H^2 - D^2)}{R}$$

$$\text{or, } q = R = \frac{4K(H^2 - D^2)}{L^2} \quad (6.4)$$

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Where,  $D$  = elevation of the water level in the drain [L],  $H$  = elevation of the water table midway between the drains [L],  $q$  = drain discharge [L/T], and the remaining symbols have the same meaning as defined earlier.

Eqn. (6.4), which was derived by Hooghoudt in 1936, is also known as the Donnan Equation (Donnan, 1946). Hooghoudt derived this equation by assuming constant and uniform rate of recharge and horizontal flow to vertical ditches. The Hooghoudt's theory also assumes that the drains (pipe or open drains) run half full and that the drains have no entrance resistance. The second assumption (no entrance resistance) suggests that the drain is ideal. To be an ideal drain, the hydraulic conductivity of the surround (drain trench) should be at least 10 times higher than that of the undisturbed soil outside the trench (Smedema and Rycroft, 1983). If the hydraulic conductivity of the surround is less, an envelope material can be used to minimize the entrance resistance, so that a greater part of the total head could be available for flow through the soil. In case, it is not possible to use an envelope material, the entrance resistance should be introduced into the Hooghoudt equations by replacing  $h$  with  $(h - h_e)$ , wherein  $h_e$  is the entrance head loss in metres. Hence, the validity of Eqn. (6.4) becomes better when the drains are of negligible width as compared to the drain spacing, shallow, fully penetrating and with a small difference between  $H$  and  $D$  such that the assumption of parallel flow is applicable. Also, homogeneous soil (constant hydraulic conductivity) is also an important pre-condition for the validity of Eqn. (6.4). Equation (6.4) can be rewritten as:

$$q = \frac{4K(H + D)(H - D)}{L^2}$$

From Fig. 6.2, it is clear that  $H - D = h$ , and hence  $H + D = 2D + h$ , where  $h$  is the height of the water table above the water level in the drain. Consequently, Equation (6.4) can be written as follows:

$$q = \frac{8K D h + 4 K h^2}{L^2} \quad (6.5)$$

If the water level in the drain is negligible (i.e.,  $D \gg 0$ ), Eqn. (6.5) reduces to:

$$q = \frac{4 K h^2}{L^2} \quad (6.6)$$

Equation (6.6) describes the flow above the drainage base (drain level)

If the impervious layer is far below drain level ( $D \gg h$ ), the second term in the numerator of Eqn. (6.5) can be neglected, yielding:

$$q = \frac{8 K D h}{L^2} \quad (6.7)$$

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Eqn. (6.7) describes the flow below the drain level.

Thus, if the soil above drainage base has a different hydraulic conductivity (say  $K_1$ ) than the hydraulic conductivity of the soil below drainage base (say  $K_2$ ), and the drain level is at the interface between the two soil layers, Eqn. (6.5) can be written as:

$$q = \frac{8K_2 D h + 4 K_1 h^2}{L^2} \quad (6.8)$$

The situation of layered or stratified soil is quite common in the field. The soil above the drain level is often more permeable than that below the drain level because the soil structure above drain level gets improved by the periodic wetting and drying of the soil (resulting in the formation of cracks), and the presence of roots, micro-organisms, micro-fauna, etc.

### Concept of Equivalent Depth

If the pipe or open drains do not reach the impervious layer, the flow lines will converge towards the drain and will thus no longer be horizontal (Fig. 6.3A). Consequently, the flow lines are longer (elongated) and extra head loss is required to have the same volume of water flowing into the drains. This extra head loss results in a higher water table.

Hooghoudt (1940) introduced following two simplifications in his theory to account for the extra head loss due to radial flow to the drains:

- He assumed an imaginary impervious layer above the real one, which decreases the thickness of the layer through which the water flows towards the drains.
- He treated horizontal and radial flow to pipe/tile drains as an equivalent flow to imaginary ditches with their bottoms on an imaginary impervious layer at a reduced depth.

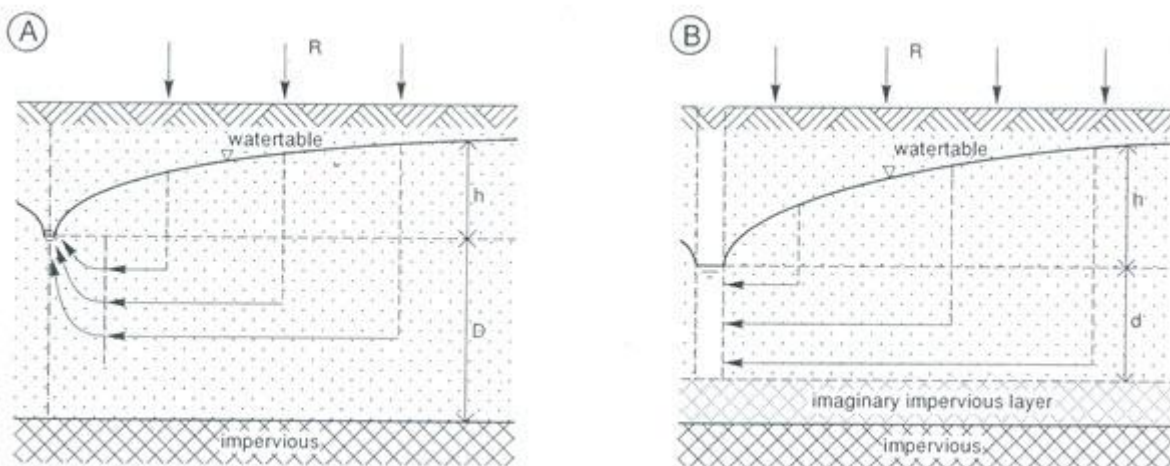


Fig. 6.3. The concept of the equivalent depth ( $d$ ) to transform a combination of horizontal and radial flow shown in

(A) into an equivalent horizontal flow shown in (B). (Source: Ritzema, 1994)

Under these assumptions (Fig. 6.3B), the equivalent flow is essential horizontal, and hence Eqn. 6.5 can be used to express the flow towards the drains, by replacing the actual depth to the impervious layer ( $D$ ) with an equivalent depth ( $d$ ), which is smaller than  $D$ . The equivalent depth ( $d$ ) represents an imaginary thinner soil layer through which the same amount of water will flow per unit time as in the actual situation. This higher flow per unit area introduces an extra head loss, which accounts for the head loss caused by the converging flow lines. Thus, Eqn. (6.5) can be modified as follows:

$$q = \frac{8KDh + 4Kh^2}{L^2} \quad (6.9)$$

Now, the only problem that remains is to find a value for the equivalent depth ( $d$ ). On the basis of the method of 'mirror images', Hooghoudt derived a relationship between the equivalent depth ( $d$ ) and, respectively, the spacing ( $L$ ), the depth to the impervious layer ( $D$ ), and the radius of the drain ( $r_0$ ). This relationship, which is in the form of infinite series, is complex, and hence Hooghoudt prepared tables for the most common sizes of drain pipes, from which the equivalent depth ( $d$ ) can be read directly. Table 6.1 (for  $r_0 = 0.1$  m) is one such table. It is obvious from this table that the value of  $d$  increases with  $D$  until  $D \gg \frac{1}{4}L$ . If the impervious layer is even deeper, the equivalent depth remains approximately constant; apparently the flow pattern is then no longer affected by the depth of the impervious layer.

Since the drain spacing  $L$  depends on the equivalent depth  $d$ , which in turn is a function of  $L$ , Eqn. (6.9) can only be solved by iteration. As this calculation method with the use of tables is somewhat time-consuming, Van Beers (1979) prepared nomographs from which  $d$  can be read easily.

With the readily availability of computers these days, the Hooghoudt's approximation method for calculating the equivalent depth can be replaced by exact solutions. As given below (Smedema and Rycroft, 1983):

- For  $D < L/4$ :  $d = \frac{D}{\frac{8D}{\pi L} \ln \frac{D}{u} + 1}$  (6.10)

- For  $D > L/4$ :  $d = \frac{\pi L}{8 \ln \frac{L}{u}}$  (6.11)

In situations where there is no distinct impermeable layer, the depth  $D$  may be equal to the depth at which the  $K$ -value has decreased to  $1/10$  of the (average)  $K$ -value of the layer(s) above, provided no highly permeable layer occurs within 1-2 m below this depth (Smedema and Rycroft, 1983).



Table 6.1.Values for the equivalent depth (d) of Hooghoudt for  $r_0 = 0.1$  m, D and L in m (after Hooghoudt, 1940)

L®	5m	7.5	10	15	20	25	30	35	40	45	50	L®	50	75	80	85	90	100	150	200	250	
D												D										
0.5 m	0.47	0.4 8	0.49	0.49	0.49	0.50	0.50	0.50	0.50	0.50	0.50	0.5	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
0.75	0.60	0.6 5	0.69	0.71	0.73	0.74	0.75	0.75	0.75	0.76	0.76	1	0.96	0.97	0.97	0.97	0.98	0.98	0.90	0.99	0.99	0.99
1.00	0.67	0.7 5	0.80	0.86	0.89	0.91	0.93	0.94	0.96	0.96	0.96	2	1.72	1.80	1.82	1.82	1.83	1.85	1.00	1.92	1.94	1.94
1.25	0.70	0.8 2	0.89	1.00	1.05	1.09	1.12	1.13	1.14	1.14	1.15	3	2.29	2.49	2.52	2.54	2.56	2.60	2.72	2.70	2.83	2.83
1.50	0.70	0.8 8	0.97	1.11	1.19	1.25	1.28	1.31	1.34	1.35	1.36	4	2.71	3.04	3.08	3.12	3.16	3.24	3.46	3.58	3.66	3.66
1.75	0.70	0.9 1	1.02	1.20	1.30	1.39	1.45	1.49	1.52	1.55	1.57	5	3.02	3.49	3.55	3.61	3.67	3.78	4.12	4.31	4.43	4.43
2.00	0.70	0.9 1	1.13	1.28	1.41	1.50	1.57	1.62	1.66	1.70	1.72	6	3.23	3.85	3.93	4.00	4.08	4.23	4.70	4.97	5.15	5.15

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2.25	0.70	0.9 1	1.13	1.34	1.50	1.69	1.69	1.76	1.81	1.84	1.86	7	3.43	4.14	4.23	4.33	4.42	4.62	5.22	5.57	5.81
2.50	0.70	0.9 1	1.13	1.38	1.57	1.69	1.79	1.87	1.94	1.99	2.02	8	3.56	4.38	4.49	4.61	4.72	4.95	5.68	6.13	6.43
2.75	0.70	0.9 1	1.13	1.42	1.63	1.76	1.88	1.98	2.05	2.12	2.18	9	3.66	4.57	4.70	4.82	4.95	5.23	6.09	6.63	7.00
3.00	0.70	0.9 1	1.13	1.45	1.67	1.83	1.97	2.08	2.16	2.23	2.29	10	3.74	4.74	4.89	5.04	5.18	5.47	6.45	7.09	7.53
3.25	0.70	0.9 1	1.13	1.48	1.71	1.88	2.04	2.16	2.26	2.35	2.42	12.5	3.74	5.02	5.20	5.38	5.56	5.92	7.20	8.06	8.68
3.50	0.70	0.9 1	1.13	1.50	1.75	1.93	2.11	2.24	2.35	2.45	2.54	15	3.74	5.20	5.40	5.60	5.80	6.25	7.77	8.84	9.64
3.75	0.70	0.9 1	1.13	1.52	1.78	1.97	2.17	2.31	2.44	2.54	2.64	17.5	3.74	5.30	5.53	5.76	5.99	6.44	8.20	9.47	10.4
4.00	0.70	0.9 1	1.13	1.52	1.81	2.02	2.22	2.37	2.51	2.62	2.71	20	3.74	5.30	5.62	5.87	6.12	6.60	8.54	9.97	11.1
4.50	0.70	0.9 1	1.13	1.52	1.85	2.08	2.31	2.50	2.63	2.76	2.87	25	3.74	5.30	5.74	5.96	6.20	6.79	8.99	10.7	12.1

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5.00	0.70	0.9 1	1.13	1.52	1.88	2.15	2.38	2.58	2.75	2.89	3.02	30	3.74	5.30	5.74	5.96	6.20	6.79	9.27	11.3	12.9
5.50	0.70	0.9 1	1.13	1.52	1.88	2.20	2.43	2.65	2.84	3.00	3.15	35	3.74	5.30	5.74	5.96	6.20	6.79	9.44	11.6	13.4
6.00	0.70	0.9 1	1.13	1.52	1.88	2.20	2.48	2.70	2.92	3.09	3.26	40	3.74	5.30	5.74	5.96	6.20	6.79	9.44	11.8	13.8
7.00	0.70	0.9 1	1.13	1.52	1.88	2.20	2.54	2.81	3.03	3.24	3.43	45	3.74	5.30	5.74	5.96	6.20	6.79	9.44	12.0	13.8
8.00	0.70	0.9 1	1.13	1.52	1.88	2.20	2.57	2.85	3.13	3.35	3.56	50	3.74	5.30	5.74	5.96	6.20	6.79	9.44	12.1	14.3
9.00	0.70	0.9 1	1.13	1.52	1.88	2.20	2.57	2.89	3.18	3.43	3.66	60	3.74	5.30	5.74	5.96	6.20	6.79	9.44	12.1	14.6
10.00	0.70	0.9 1	1.13	1.52	1.88	2.20	2.57	2.89	3.23	3.48	3.74	¥	3.88	5.38	5.76	6.00	6.26	6.82	9.55	12.2	14.7
¥	0.71	0.9 3	1.14	1.53	1.89	2.24	2.58	2.91	3.24	3.56	3.88										

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In the above equation,  $u$  is the entrance area, which is equal to the wetted perimeter of a semi-circle (i.e.,  $\pi r_0$ ). That is,

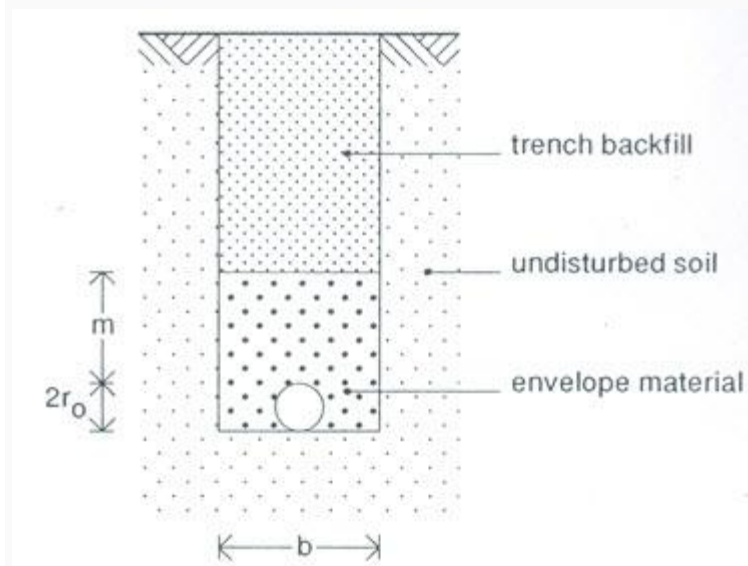
$$u = \pi r_0$$
$$\Rightarrow r_0 = \frac{u}{\pi} \quad (6.12)$$

Where,  $r_0$  = radius of the drain [L], and  $u$  = wetted perimeter of the drain [L].

For open drains, the equivalent radius ( $r_0$ ) can be calculated by substituting the wetted perimeter of the open drain for  $u$  in Eqn. (6.12). For pipe drains laid in trenches, the wetted perimeter is computed as:

$$u = b + 2r_0 \quad (6.13)$$

Where,  $b$  is the width of the trench [L].



**Fig. 6.4. Drain pipe with gravel envelope in the drain trench.**

**(Source: Ritzema, 1994)**

If an envelope material is used around the pipe drain (Fig. 6.4), Eqn. (6.13) becomes:

$$u = b + 2(2r_0 + m) \quad (6.14)$$

Where,  $m$  is the height of the envelope above the drain [L], and the remaining symbols have the same meaning as defined earlier.

### 6.2.3 Ernst Equation

The Hooghoudt Equation can be applied for a homogeneous soil profile or for a two-layered soil profile provided that the interface between the two layers coincides with the drain level. In contrast, the Ernst Equation is applicable to any type of two-layered soil profile. It has an advantage over the Hooghoudt Equation that the interface between the two layers can be either above or below drain level. It is especially useful when the top soil layer has a considerably lower hydraulic conductivity than the bottom soil layer.

To obtain a generally applicable solution for soil profiles consisting of layers with different hydraulic conductivities, Ernst (1956; 1962) divided the flow to the drains into vertical, horizontal, and radial components (Fig. 6.5). The extent of the three flow zones differs from case to case, depending mainly on the relative magnitude of  $h$ ,  $L$  and  $D$ . Consequently, the total available head ( $h$ ) can be visualized as being made up of the head loss due to vertical flow ( $h_v$ ), horizontal flow ( $h_h$ ), radial flow ( $h_r$ ), and entry flow ( $h_e$ ):

$$h = h_v + h_h + h_r + h_e \quad (6.15)$$

Generally,  $h_e$  is assumed to be zero (ideal drains).

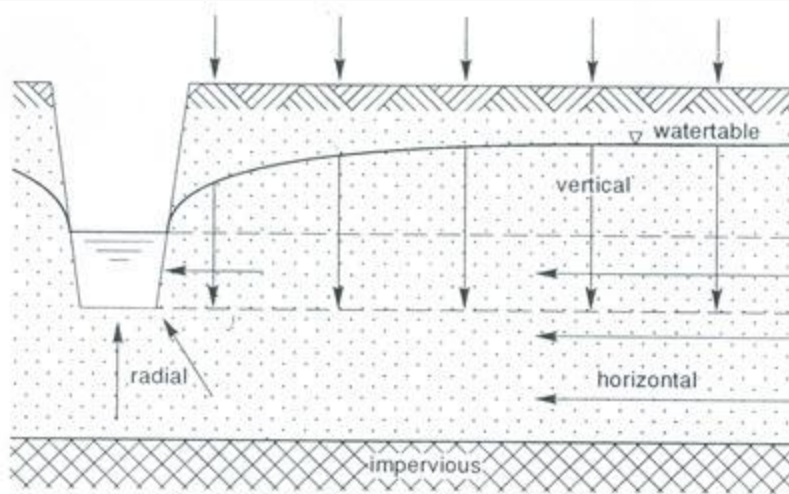


Fig. 6.5. Geometry of two-dimensional flow towards drains according to Ernst.

(Source: Ritzema, 1994)

#### (i) Vertical Flow

Vertical flow is usually assumed to take place in the zone between the water table and the drain level (Fig. 6.5); though in reality it often goes deeper. The head loss due to a vertical flow of  $q$  through a soil layer of thickness  $D_v$  and a vertical hydraulic conductivity of  $K_v$  can be calculated by applying Darcy's Law:

$$q = K_v \frac{h_v}{D_v}$$
$$\therefore h_v = \frac{qD_v}{K_v} \quad (6.16)$$

Where,  $h_v$  = head loss due to vertical flow [L].

As the vertical hydraulic conductivity is difficult to measure under field conditions, it is often replaced with the horizontal hydraulic conductivity, which is rather easy to measure by the auger-hole method. In principle, this is not correct, especially not in the alluvial soils where big differences between horizontal and vertical conductivity may occur. The vertical head loss, however, is generally small compared to the horizontal and radial head losses. Therefore, the error caused by replacement of  $K_v$  with  $K_h$  can be neglected.

### (ii) Horizontal Flow

The horizontal flow is assumed to take place below drain level (Fig. 6.5). Analogous to Eqn. (6.7), the horizontal head loss ( $h_h$ ) can be expressed as:

$$h_h = \frac{qL^2}{8 K_h D_h} \quad (6.17)$$

Where,  $K_h D_h$  = transmissivity of the soil layers through which the water flows horizontally [ $L^2/T$ ], and the remaining symbols have the same meaning as defined earlier.

If the impervious layer is very deep, the value of  $K_h D_h$  increases to infinity and hence the horizontal head loss decreases to zero. To avoid this situation, the maximum thickness of the soil layer below the drain level through which horizontal flow is considered ( $D_h$ ) is restricted to  $\frac{1}{4} L$  (i.e.,  $D_h < \frac{1}{4} L$ ).

### (iii) Radial Flow

The radial flow is also assumed to take place below drain level (Fig. 6.5), because towards the end of its path the flow converges radially onto the drain. The head loss caused by the radial flow can be expressed as:

$$h_r = \frac{qL}{\pi K_r} \ln \frac{aD_r}{u} \quad (6.18)$$

Where,  $K_r$  = radial hydraulic conductivity [ $L/T$ ],  $a$  = geometry factor of the radial resistance (dimensionless),  $D_r$  = thickness of the layer in which the radial flow is considered [L], and  $u$  = wetted perimeter of the drain [L], and the remaining symbols have the same meaning as defined earlier.



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Equation (6.18) has the same restriction for the depth of the impervious layer as the equation for horizontal flow (i.e.,  $D_r < \frac{1}{4} L$ ).

The geometry factor ( $a$ ) depends on the soil profile and the position of the drain. In a homogeneous soil profile, the geometry factor equals one; in a layered soil, the geometry factor depends on whether the drains are in the top or bottom soil layer. If the drains are in the bottom layer, the radial flow is assumed to be restricted to this layer, and again  $a = 1$ . If the drains are in the top layer, the value of ' $a$ ' depends on the ratio of the hydraulic conductivity of the bottom ( $K_b$ ) and top ( $K_t$ ) layer. Using the relaxation method, Ernst (1962) distinguished the following situations:

- Case when  $\frac{K_b}{K_t} < 0.1$ : The bottom layer can be considered impervious and the case is reduced to a homogeneous soil profile and the value of ' $a$ ' is 1.
- Case when  $0.1 < \frac{K_b}{K_t} < 50$ : The value of ' $a$ ' depends on the ratios  $\frac{K_b}{K_t}$  and  $\frac{D_b}{D_t}$  as given in Table 6.2.
- Case when  $\frac{K_b}{K_t} > 50$ : The value of ' $a$ ' is taken as 4.

Now, the equations for the vertical head loss [Eqn. (6.16)], horizontal head loss [Eqn. (6.17)], and the radial head loss [Eqn. (6.18)] can be substitute into Eqn. (6.15) to obtain the total head loss:

$$h = \frac{qD_v}{K_v} + \frac{qL^2}{8K_h D_h} + \frac{qL}{\pi K_r} \ln \frac{aD_r}{u}$$

or,

$$h = q \left( \frac{D_v}{K_v} + \frac{L^2}{8K_h D_h} + \frac{L}{\pi K_r} \ln \frac{aD_r}{u} \right) \quad (6.19)$$

Table 6.2. The Geometry factor (a) obtained by the relaxation method (after Van Beers, 1979)

Sl. No.	$\frac{K_b}{K_t}$ Ratio	Value of 'a' for different $\frac{D_b}{D_t}$ Ratios					
		1	2	4	8	16	32
1	1	2.0	3.0	5.0	9.0	15.0	30.0
2	2	2.4	3.2	4.6	6.2	8.0	10.0
3	3	2.6	3.3	4.5	5.5	6.8	8.0
4	5	2.8	3.5	4.4	4.8	5.6	6.2
5	10	3.2	3.6	4.2	4.5	4.8	5.0
6	20	3.6	3.7	4.0	4.2	4.4	4.6
7	50	3.8	4.0	4.0	4.0	4.2	4.6

Equation (6.19) is commonly known as the Ernst Equation. If the design discharge rate (q) and the total hydraulic head (h) are known, this quadratic equation for the drain spacing (L) can be solved directly.

Note that because of the restriction on the depth of the impervious layer in the Ernst Equation, the drain spacings calculated by this equation for deeper impervious layers are usually too small.

### 6.3 Selection of Suitable Steady-State Drainage Equations

It is clear from the above discussion that two important factors to be considered for selecting the most appropriate steady-state equation are the soil profile and the relative position of the drains in the profile. Table 6.3 summarizes some of the more common field situations and appropriate equation for each of them. In all the cases, the lower boundary is formed by an impervious layer. Detailed discussion about these field situations is given in Ritzema (1994).

Table 6.3. Summary of the steady-state equations (Source: Ritzema, 1994)

Sl. No.	Soil Profile	Location of Drain	Equation
1	Homogeneous	On the top of the impervious layer	Hooghoudt/Donnan Equation: $q = \frac{4K(H^2 - D^2)}{L^2}$
2	Homogeneous	Above the impervious layer	Hooghoudt Equation with equivalent depth: $q = \frac{8Kdh + 4Kh^2}{L^2}$
3	Two layers	An interface of the two soil layers	Hooghoudt Equation: $q = \frac{8K_b dh + 4K_t h^2}{L^2}$
4	Two layers ( $K_t < K_b$ )	In the bottom layer	Ernst Equation: $h = q \left( \frac{D_v}{K_t} + \frac{L^2}{8K_b D_b} + \frac{L}{\pi K_b} \ln \frac{D_r}{u} \right)$
5	Two layers ( $K_t < K_b$ )	In the top layer	Ernst Equation: $h = q \left( \frac{D_v}{K_t} + \frac{L^2}{8(K_b D_b + K_t D_t)} + \frac{L}{\pi K_t} \ln \frac{aD_r}{u} \right)$ Where, $D_t = D_r + \frac{1}{2} h$ , and $D_v = h$ .

#### 6.4 Application of Steady-State Drainage Equations

To calculate the drain spacing with steady-state equations, we must have information on the soil characteristics, the agricultural design criteria, and the technical criteria. The required soil data

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include a description of the soil profile, the depth of the impervious layer, and the hydraulic conductivity.

The agricultural design criteria are the required depth of the water table ( $h$ ) and the corresponding design discharge ( $q$ ). They depend on many factors (e.g., type of crop, and climate). The ratio  $q/h$  is sometimes called the drainage criterion or drainage intensity. The higher the  $q/h$  ratio, the more safety is built into the drainage system to prevent high water tables. The use of the steady-state equations discussed in the previous section is demonstrated through one example given below.

### 6.4.1 Example Problem (after Ritzema, 1994)

In an agricultural area, high water table condition occurs. A subsurface drainage system is to be installed to control the water table under the following conditions:

#### (1) Agricultural drainage criteria:

- Design discharge rate is 1 mm/day
- The depth of the water table midway between the drains is to be kept at 1.0 m below the soil surface.

#### (2) Technical criteria:

- Drains will be installed at a depth of 2 m;
- PVC drain pipes with a radius of 0.10 m will be used.

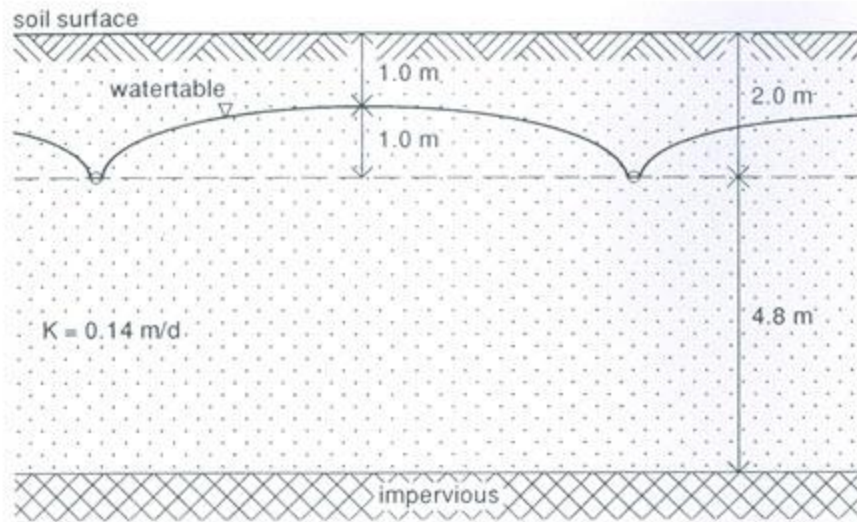


Fig. 6.6. Calculation of drain spacing in a one-layered soil profile.

(Source: Ritzema, 1994)

Field investigation revealed that there is a layer of low conductivity at 6.8 m depth, which can be regarded as the base of the flow region (Fig. 6.6). Auger-hole method was used to calculate the

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hydraulic conductivity of the soil above the impervious layer and its average value was found to be 0.14 m/day. Calculate the spacing of pipe drains.

### Solution:

If we assume a homogeneous soil profile, we can use the Hooghoudt formula [Eqn. (6.9)] to calculate the drain spacing. We have the following data:

$$q = 1 \text{ mm/day} = 0.001 \text{ m/day,}$$

$$h = 2.0 - 1.0 = 1.0 \text{ m,}$$

$$r_0 = 0.10 \text{ m,}$$

$$K = 0.14 \text{ m/day, and}$$

$$D = 6.8 - 2.0 = 4.8 \text{ m}$$

Substitution of the above values into Equation (6.9) yields:

$$L^2 = \frac{8 K d h + 4 K h^2}{q} = \frac{8 \times 0.14 \times d \times 1.0 + 4 \times 0.14 \times 1.0^2}{0.001}$$

$$\Rightarrow L^2 = 1120 d + 560$$

As the equivalent depth, (d) is a function of L (among other factors), we can solve this quadratic equation for L by the trial-and-error method.

**First Trial:** Assume  $L = 75 \text{ m}$ . We can read the equivalent depth, (d) from Table 6.1.

$$d_{75} = 3.04 + \frac{8}{10}(3.49 - 3.04) = 3.40 \text{ m}$$

Thus,  $L^2 = 1120 \times 3.40 + 560 = 4368 \text{ m}^2$ . This is not in agreement with the assumed value of L, because  $L^2 = 75^2 = 5625 \text{ m}^2$ . Apparently, the drain spacing of 75 m is too wide.

**Second Trial:** Assume  $L = 50 \text{ m}$ . In this case, d is obtained from Table 6.1 as:

$$d_{50} = 2.71 + \frac{8}{10}(3.02 - 2.71) = 2.96 \text{ m}$$

Thus,  $L^2 = 1120 \times 2.96 + 560 = 3875 \text{ m}^2$ . Again, this is not in agreement with the assumed value of L, because  $L^2 = 50^2 = 2500 \text{ m}^2$ . Thus, a drain spacing of 50 m is very narrow.

**Third Trial:** Assume  $L = 65 \text{ m}$ . In this case d is obtained as:

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$$d_{65} = d_{50} + \frac{15}{25}(d_{75} - d_{50}) = 2.96 + \frac{15}{25}(3.40 - 2.96) = 3.22 \text{ m}$$

Thus,  $L^2 = 1120 \cdot 3.22 + 560 = 4166 \text{ m}^2$ . This is reasonably close to the assumed value of  $L$  because  $L^2 = 65^2 = 4225 \text{ m}^2$ . Therefore, a drain spacing of 65 m can be selected, **Ans.**





### Lesson 7 Unsteady-State Flow to Drains

#### 7.1 Introduction

The steady-state approach to the flow into drains only describes a simplified, constant relationship between the water table and the drain discharge. In reality, however, the recharge to groundwater varies with time and hence the flow of groundwater towards the drains is not steady. To describe the fluctuation of the water table as a function of time, we should use unsteady-state approach for analyzing flow into the drains. Both the unsteady-state and the steady-state approaches are based on the Dupuit-Forchheimer assumptions. The only difference is the recharge, which varies with time in the unsteady-state approach. In this lesson, two widely used unsteady-state equations are discussed.

The **Glover-Dumm Equation** is used to describe a falling water table after its sudden rise due to an instantaneous recharge. This is a typical situation in irrigated areas where the shallow water table often rises sharply during the application of irrigation water and then recedes more slowly. On the other hand, the **De Zeeuw-Hellinga Equation** is used to describe a fluctuating water table. In this approach, a non-uniform recharge is divided into shorter time periods in which the recharge to groundwater can be assumed to be constant. This is a typical situation in humid areas with high-intensity rainfall concentrated in discrete storms.

#### 7.2 Unsteady-State Drainage Equations

##### 7.2.1 Glover-Dumm Equation

In the case of unsteady/transient flow, the flow is not constant, rather it changes with time as water is stored in or released from the soil. The change in storage is reflected either in a rise or a fall of the water table. The Dupuit-Forchheimer approach is used to derive a differential equation of unsteady flow in the waterlogged soil. Let's consider a soil column which is bounded by the water table at the top and by an impervious layer at the bottom. If there is no recharge to the groundwater, the change in storage in the soil profile is given as (Fig. 7.1):

$$\Delta S = \mu \Delta h dx dy \quad (7.1)$$

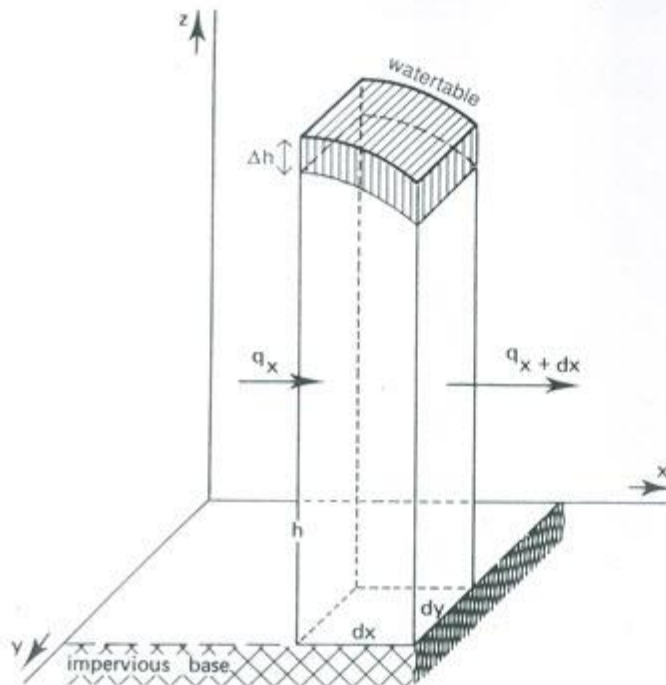


Fig. 7.1. Change in storage in a soil column under a falling water table. (Source: Ritzema, 1994)

Where,  $DS$  = change in water storage per unit surface area over a given time [L],  $m$  = drainable porosity (dimensionless), and  $Dh$  = change in the water table over a given time [L].

Equation (7.1) can be written as follows if the change in storage is considered over an infinitely small period of time ( $dt$ ):

$$dS = \mu \frac{\partial h}{\partial t} dx dy \quad (7.2)$$

From the continuity principle, the net inflow or outflow in x-and y-directions is equal to the change in storage. Therefore, using the Darcy's law the differential form of the two dimensional continuity equation for a homogeneous and isotropic soil profile can be written as:

$$-K \left[ \frac{\partial}{\partial x} \left( h \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( h \frac{\partial h}{\partial y} \right) \right] dx dy = \mu \frac{\partial h}{\partial t} dx dy \quad (7.3)$$

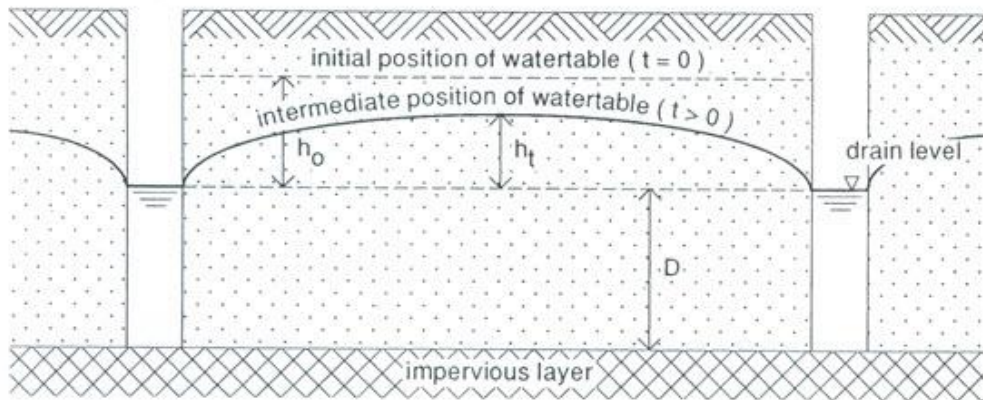
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Equation (7.3) is known as the Boussinesq equation which describes the position of the water table under unsteady recharge. It is a non-linear equation, which can be linearized by assuming that initial saturated thickness of the water transmitting layer is ( $D$ ) large compared to the changes in the water table. Hence,  $h$  can be taken as a constant (average thickness of the water-transmitting layer). Further, in drainage, we deal with only one dimensional flow and hence, Eqn. (7.3) reduces to:

$$KD \frac{\partial^2 h}{\partial x^2} = \mu \frac{\partial h}{\partial t} \quad (7.4)$$

Dumm (1954) used this differential equation to describe the fall of the water table after it had risen instantaneously to a height  $h_0$  above the drain level (Fig. 7.2). His solution, which is based on a formula developed by Glover, describes the lowering of an initially horizontal water table as a function of time, place, drain spacing, and soil properties. It is expressed as follows:

$$h(x,t) = \frac{4h_0}{\pi} \sum_{n=1,3,5}^{\infty} \frac{1}{n} e^{-n^2 \alpha t} \sin \frac{n\pi x}{L} \quad (7.5)$$



**Fig. 7.2. Boundary conditions for the Glover-Dumm equation with an initially horizontal water table. (Source: Ritzema, 1994)**

Where,

$$\alpha = \frac{\pi^2 K d}{\mu L^2} \quad (7.6)$$

$h(x, t)$  = height of the water table at distance  $x$  at time  $t$  [L],  $h_0$  = initial height of the water table at  $t = 0$  [L],  $a$  = reaction factor [ $T^{-1}$ ],  $K$  = hydraulic conductivity of the soil layer [L/T],  $d$  = equivalent depth of the soil layer below the drain level [L],  $m$  = drainable porosity of the soil layer (dimensionless),  $L$  = drain spacing [L], and  $t$  = time for water table to drop after the instantaneous rise of the water table [T].

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The height of the water table at the mid spacing of the drains can be obtained by substituting  $x = \frac{1}{2} L$  into Eqn. (7.5) as:

$$h_t \left( \text{at } x = \frac{L}{2} \right) = \frac{4}{\pi} h_0 \sum_{n=1,3,5}^{\infty} \frac{1}{n} e^{-n^2 \alpha t} \quad (7.7)$$

Where,  $h_t$  is the height of the water table at the mid-spacing of the drains at  $t > 0$  [L].

If  $\alpha t > 0.2$ , the second and subsequent terms of Eqn. (7.7) become small, and hence they can be neglected. Hence, Eqn. (7.7) reduces to:

$$h_t = \frac{4}{\pi} h_0 e^{-\alpha t} = 1.27 h_0 e^{-\alpha t} \quad (7.8)$$

If the initial water table has the shape of a fourth-degree parabola (not horizontal), Eqn. (7.8) becomes (Dumm, 1960):

$$h_t = 1.16 h_0 e^{-\alpha t} \quad (7.9)$$

Now, the substitution of Eqn. (7.6) into Eqn. (7.9) yields an expression for the drain spacing [L] as follows:

$$L = \pi \left( \frac{K d t}{\mu} \right)^{\frac{1}{2}} \left( \ln 1.16 \frac{h_0}{h_t} \right)^{-\frac{1}{2}} \quad (7.10)$$

Equation (7.10) is called Glover-Dumm drainage formula, which is recommended for design purposes as illustrated by an example presented later on in this lesson.

Moreover, the drain discharge per unit surface area at any time ( $t$ ) can be obtained from the Darcy's law as:

$$q_t = - \frac{2Kd}{L} \left[ \frac{dh_t}{dx} \right]_{x=0} \quad (7.11)$$

Where,  $q_t$  is the drain discharge per unit surface area at  $t > 0$  (m/day), and the remaining symbols have the same meaning as defined earlier.

Differentiating Eqn. (7.5) with respect to  $x$  as well as neglecting all the terms  $n > 1$ , substituting  $x = 0$ , and combining with Eqn. (7.11) we obtain:

$$q_t = \frac{8Kd}{L^2} h_0 e^{-\alpha t} \quad (7.12)$$

Equation (7.12) can also be written in terms of  $h_t$  by substituting Eqn. (7.8). That is,

$$q_t = \frac{2\pi Kd}{L^2} h_t \quad (7.13)$$

Eqn. (7.13) is similar to the Hooghoudt Equation describing the flow below the drain level, except that the factor 8 is replaced with  $2\pi$ . Note that for the 4<sup>th</sup> degree parabola,  $2\pi$  becomes 6.89. It can be seen that the drain discharge ( $q_t$ ) is directly related to the depth of the water table ( $h_t$ ). This is important when the data from an experimental field are being analyzed, for example, to determine reaction factor ( $\alpha$ ).

The original Glover-Dumm Equation is based on horizontal flow only and hence it ignores the radial resistance resulting from the convergence of the flow lines near the drains not reaching the impervious layer. However, similar to the steady-state approach, by introducing the Hooghoudt's concept of the equivalent depth ( $d$ ) into Eqns. (7.6) and (7.10), the extra resistance caused by the converging flow towards the drains is taken into account by the Glover-Dumm Equation.

### 7.2.2 De Zeeuw-Hellinga Equation

To simulate the drain discharge over a time period with a non-uniform distribution of recharge, the time period is divided into time intervals of equal length during which recharge ( $R$ ) is assumed to be constant. The length of the time interval should be such that changes occurring during the time interval could be described sufficiently accurately by the existing steady-state drainage equations, using as input average rates during the interval. This requirement can generally be fulfilled by adopting time intervals ( $Dt$ ) of length 1 day. De Zeeuw and Hellinga (1958) found that, if the recharge ( $R$ ) in each time period is assumed to be constant, the change in drain discharge ( $q$ ) is proportional to the excess recharge ( $R - q$ ), which is mathematically expressed as:

$$\begin{aligned} \frac{dq}{dt} &\propto R - q \\ \Rightarrow \frac{dq}{dt} &= \alpha(R - q) \end{aligned} \quad (7.14)$$

Where,  $\alpha$  is the proportionality constant and is known as 'reaction factor'. Integration of Eqn. (7.14) between the limits  $t = t$ ;  $q = q_t$  and  $t = t-1$ ;  $q_{t-1}$  yields:

$$q_t = q_{t-1}e^{-\alpha\Delta t} + R_{\Delta t}(1 - e^{-\alpha\Delta t}) \quad (7.15)$$

Where,  $\Delta t = t - (t - 1)$ , the time interval over which the recharge  $R_{\Delta t}$  is assumed to be constant (i.e.,  $R_{\Delta t}$  is the mean value of  $R$  during the time interval  $t-1$  to  $t$ ).

We can simulate the depth of the water table by considering the simplified Hooghoudt Equation, which neglects the flow above the drain level and is given as:

$$q = \frac{8Kd}{L^2}h$$

The above equation shows the linear relationship between  $q$  and  $h$ . By using Eqn. (7.6), we can

replace the quotient  $\frac{Kd}{L^2}$  of simplified Hooghoudt's Equation with  $\frac{\mu\alpha}{\pi^2}$ . Thus, we have:

$$q = \frac{8Kd}{L^2}h = \frac{8\mu\alpha}{\pi^2}h \approx 0.8\mu\alpha h$$

Substituting the latter into Eqn. (7.15) yields:

$$h_t = h_{t-1}e^{-\alpha\Delta t} + \frac{R_{\Delta t}}{0.8\mu\alpha}(1 - e^{-\alpha\Delta t}) \quad (7.16)$$

Equations (7.15) and (7.16) are called De Zeeuw-Hellinga Equations, which can be used to simulate drain discharge and water table fluctuations on the basis of historical water records, provided that the value of the reaction factor ( $\alpha$ ) is known.

### 7.2.3 Reaction Factor ( $\alpha$ )

The reaction factor  $(\alpha = \frac{10Kd}{\mu L^2})$  is a direct index of the intensity with which the drain discharge responds to changes in the recharge. According to Smedema and Rycroft (1983), the values of reaction factor generally vary from  $\alpha = 0.1-0.3$  for land with a slow response (low  $KD$  values, wide drain spacing, high drainable pore space) to  $\alpha = 2.0-5.0$  for rapidly responsive land (high  $KD$  value, narrow drain spacing, low drainable pore space). It may be calculated using Eqn. (7.6) if the values of  $KD$ ,  $L$  and  $m$  are known. However, since the  $m$ -value is generally difficult to determine, best estimates of  $\alpha$  are obtained by observing the actual response of a drainage system in the field (Smedema and Rycroft, 1983). From Eqns. (7.15) and (7.16), it follows that in periods during which there is no recharge ( $R = 0$ ), the reaction factor ( $\alpha$ ) can be expressed as follows (Smedema and Rycroft, 1983):



$$\alpha = \frac{\ln q_{t-1} - \ln q_t}{\Delta t} = 2.30 \frac{\log q_{t-1} - \log q_t}{\Delta t} \quad (7.17)$$

$$\text{Or,} \quad \alpha = \frac{\ln h_{t-1} - \ln h_t}{\Delta t} = 2.30 \frac{\log h_{t-1} - \log h_t}{\Delta t} \quad (7.18)$$

Observed  $q_t$  or  $h_t$  values can be plotted on the log normal paper. If the system obeys the assumptions underlying the basic equations, the observed values more or less fit to a straight line with a slope equal to  $\alpha$ . Observations are best made during periods of low evaporation shortly after the end of a few good rainy days when the recharge to groundwater has ceased and the water table starts receding (the recession sections of the water table or drainflow versus time graphs can be used to estimate  $\alpha$ ).

### 7.2.4 Remarks on Unsteady-State Drainage Equations

At first sight, the unsteady-state approach offers major advantages compared to the steady-state approach, but various assumptions restrict the use of the unsteady-state equations. **Firstly**, both the Glover-Dumm and the De Zeeuw-Hellinga equations can only be applied in soil with a homogeneous profile. **Secondly**, the flow in the region above the drains is not taken into account. When the depth of the water table above drain level ( $h$ ) is large compared to the depth of the impervious layer ( $D$ ), an error may be introduced. However, **the biggest restriction** is the introduction of drainable pore space into the equations. Besides the fact that this soil property is very difficult to measure, it also varies spatially. Therefore, introducing a constant value for the drainable pore space could result in considerable errors. As a result, the unsteady-state equations are hardly ever used directly in the design of subsurface drainage systems. Instead, it is used in combination with steady-state equations. The benefits of this combined approach are discussed in Section 7.4. Nevertheless, unsteady-state equations are very useful tools when the goal is to study temporal variation of the parameters such as the water table depth or elevation and the drain discharge due to rainfall or irrigation.

### 7.3 Application of Unsteady-State Drainage Equations

Like the steady-state equations, the unsteady-state equations require data on soil properties and agriculture and technical design criteria. The main differences are that an additional soil property (i.e., drainable pore space) is required and that, instead of the  $q/h$  ratio, a water table drawdown ratio  $h_0/h_t$  is required.

**Example Problem** (Ritzeman, 1994): In an irrigated area, a drainage system is needed to control the water table under the following conditions (Fig. 7.3):

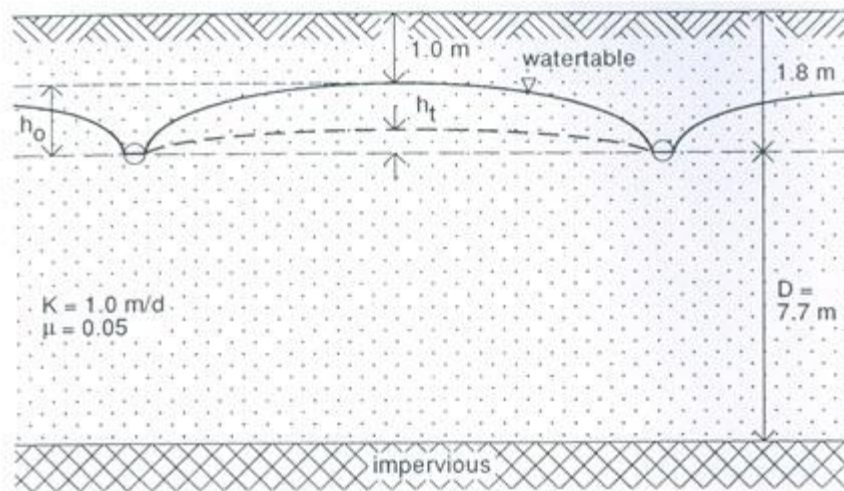


Fig. 7.3. Calculation of drain spacing under unsteady-state conditions. (Source: Ritzeman, 1994)

### (1) Agricultural drainage criteria:

- The maximum permissible height of the water table is 1 m below the soil surface; and
- Irrigation water is applied every 10 days, and the field application losses percolating to the water table are 25 mm for each irrigation.

### (2) Technical design criteria:

- Drains are installed at a depth of 1.8 m; and
- PVC drain pipes with a radius of 0.10 m are used.

### (3) Soil data:

- The depth of the impervious layer is 9.5 m below the soil surface; and
- The average hydraulic conductivity of the soil is 1.0 m/day and the drainable porosity is 0.05.

### Solution:

If we assume that the field application losses can be regarded as an instantaneous recharge,  $R_i = 0.025 \text{ m}$ , the rise of the water table computed as:

$$\Delta h = \frac{R_i}{\mu} = \frac{0.025}{0.05} = 0.5 \text{ m.}$$

If we assume that, after irrigation, the water table rose to its maximum permissible height, we know

## Drainage Engineering

$$h_0 = 1.8 - 1.0 = 0.8 \text{ m}$$

Thus, we have the following data:

$K = 1.0 \text{ m/day}$ ,  $m = 0.05$ ,  $D = (9.5 - 1.8) \text{ m} = 7.7 \text{ m}$ ,  $r_0 = 0.10 \text{ m}$ ,  $h_0 = 0.8 \text{ m}$ ,  $h_{10} = 0.3 \text{ m}$ , and  $t = 10 \text{ days}$

Substituting the above values into the Glover-Dumm drainage equation

$$L = \pi \left( \frac{Kdt}{\mu} \right)^{\frac{1}{2}} \left( \ln 1.16 \frac{h_0}{h_t} \right)^{-\frac{1}{2}}, \text{ we have:}$$

$$L = \pi \left( \frac{1.0 \times d \times 10}{0.05} \right)^{\frac{1}{2}} \left( \ln \frac{1.16 \times 0.8}{0.3} \right)^{-\frac{1}{2}}$$

$$\Rightarrow L = 41.8 \sqrt{d} \text{ m}$$

As we know with the help of  $D$ ,  $r_0$  and  $L$ , we can obtain the equivalent depth  $d$  from Table 6.1 (Lesson 6). Thereafter,  $L$  can be computed by the trial-and-error method:

**First Trial:** Assume  $L = 80 \text{ m}$ , and with  $D = 7.7 \text{ m}$ ,  $d$  is found from Table 6.1 (Lesson 6) as:

$$d = 4.23 + \frac{7}{10}(4.49 - 4.23) = 4.41 \text{ m.}$$

$$\therefore L = 41.8 \sqrt{d} = 41.8 \sqrt{4.41} = 88 \text{ m}$$

which is more than 80 m (assumed value of  $L$ ), and hence the spacing is too large.

**Second Trial:** Assume  $L = 90 \text{ m}$ , and with  $D = 7.7 \text{ m}$ ,  $d$  is found from Table 6.1 as:

$$d = 4.42 + \frac{7}{10}(4.72 - 4.42) = 4.63 \text{ m}$$

$$\therefore L = 41.8 \sqrt{4.63} = 89.94 \text{ m, which is acceptable, Ans.}$$

### 7.4 Comparison of Steady-State and Unsteady-State Equations

The question of whether to use the steady-state or the unsteady-state approach to calculate the required drain spacing depends mainly on the availability of data (Ritzema, 1994). Table 7.1 summarizes the input data required for the steady-state and unsteady-state equations.

**Table 7.1. Input data for steady-state and unsteady-state drainage equations (after Ritzema, 1994)**

Input Data	Steady-State Equations	Unsteady-State Equations
<b>(i) Soil Data:</b> <ul style="list-style-type: none"> <li>• Profile description</li> <li>• Hydraulic conductivity</li> <li>• Drainable porosity</li> </ul>	<p style="text-align: center;">Yes</p> <p style="text-align: center;">Yes</p> <p style="text-align: center;">No</p>	<p style="text-align: center;">Yes</p> <p style="text-align: center;">Yes</p> <p style="text-align: center;">Yes</p>
<b>(ii) Agricultural Criteria:</b> <ul style="list-style-type: none"> <li>• <math>q/h</math> ratio</li> <li>• <math>h_0/h_t</math> ratio</li> </ul>	<p style="text-align: center;">Yes</p> <p style="text-align: center;">No</p>	<p style="text-align: center;">No</p> <p style="text-align: center;">Yes</p>
<b>(iii) Technical Criteria:</b> <ul style="list-style-type: none"> <li>• Drain depth, pipe size, etc.</li> </ul>	<p style="text-align: center;">Yes</p>	<p style="text-align: center;">Yes</p>

To apply the drainage equations, we have to simplify the soil profile. We have already mentioned that unsteady-state equations can only be applied if a homogeneous soil profile is assumed; for a layered soil profile, steady-state equations have to be used. In both the cases, the hydraulic conductivity which is considered to be constant within each soil layer should be known. On the other hand, for unsteady-state equations, the drainable porosity is also required. As it is even more complicated to measure the drainable porosity than the hydraulic conductivity, the applicability of unsteady-state equation is somewhat limited.

In the unsteady-state approach, the agricultural criterion is based on the rate of water table drawdown ( $h_0/h_t$ ) instead of a water table discharge criterion ( $q/h$ ) as in the steady-state approach. The agricultural criteria are often based on relationships that only take the variation in depth of the water table into consideration. Thus, it can be concluded that, on the one hand, steady-state equations are preferred because relatively less soil data are required, but, on the other hand, the agricultural criteria are often based on the variation in the depth of the water table. Fortunately, it is possible to combine the two approaches because the corresponding criteria can be converted into one another (Ritzema, 1994).

Let's consider the following Hooghoudt Equation which assumes flow below the drain level only:

$$q = \frac{8 K d h}{L^2}$$

In the unsteady-state equations, the design criteria are expressed in the reaction factor ( $\alpha$ ) as:

$$\alpha = \frac{\pi^2 K d}{\mu L^2}$$

Combining these two equations by eliminating  $L$  yields the following equation

$$\frac{h}{q} = \frac{\pi^2}{8\mu\alpha} \quad (7.19)$$

Where, all symbols have the same meaning as defined earlier.

Using Eqn. (7.19), it is possible to establish the unsteady state criteria (i.e., the regard drawdown of the water table in a certain period of time) in experiments on a pilot scale. These unsteady-state criteria can be converted into steady-state criteria, which can be applied on a project scale. In this way, it is not necessary to measure the drainable porosity on a project scale, which is virtually impossible in practice.

**Illustrative Example** (Ritzema, 1994): We can also solve Example Problem 1 in an indirect way by converting the unsteady-state drainage criterion  $h_0/h_t$  into a steady-state criterion  $q/h$ . We know the rate of drawdown of the water table over a period of 10 days. Therefore, we can calculate the reaction factor using Eqn. (7.9) as:

$$h_t = 1.16 h_0 e^{-\alpha t} \Rightarrow \alpha t = -\ln \frac{h_t}{1.16 h_0}$$

$$\Rightarrow \alpha t = -\ln \frac{0.3}{1.16 \times 0.8} = 1.13$$

$$\therefore \alpha = \frac{1.13}{10} = 0.113.$$

By applying Eqn. (7.19), we can convert this unsteady-state criterion into a steady-state criterion as follows:

$$\frac{h}{q} = \frac{\pi^2}{8\mu\alpha} = \frac{\pi^2}{8 \times 0.05 \times 0.113} = 218.35 \text{ d}^{-1}$$

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Neglecting the flow above the drain level, we can now calculate the drain spacing by using the simplified Hooghoudt Equation:

$$L^2 = 8 K d \frac{h}{q} = 8 \times 1.0 \times d \times 218 = 1746.83 \times d \text{ m}^2$$

which can be solved by the trial-and-error method.

**First Trial:** Assume  $L = 90 \text{ m}$ , and we have  $D = 7.7 \text{ m}$ ,  $d = 4.63 \text{ m}$  (from Example Problem 1). Thus,

$$L^2 = 1746.83 \times 4.63 = 8087.84 \text{ m}^2$$

$L = 89.93 \text{ m}$ , which is acceptable.

**Note:** The reaction factor ( $a$ ) is a function of the parameters  $L$ ,  $K$ ,  $d$ , and  $m$  (Equation 7.6). Except for the drain spacing ( $L$ ), these parameters are difficult to establish. The above example shows that an alternative way of obtaining  $a$  is by monitoring the drawdown of the water table after a sudden rise (e.g., caused by irrigation or heavy rainfall). In this example,  $a$  was calculated only from the water table level at  $t = 0$  and  $t = 10$  days. If more data are available,  $a$  can be found by an exponential regression (Ritzema, 1994).

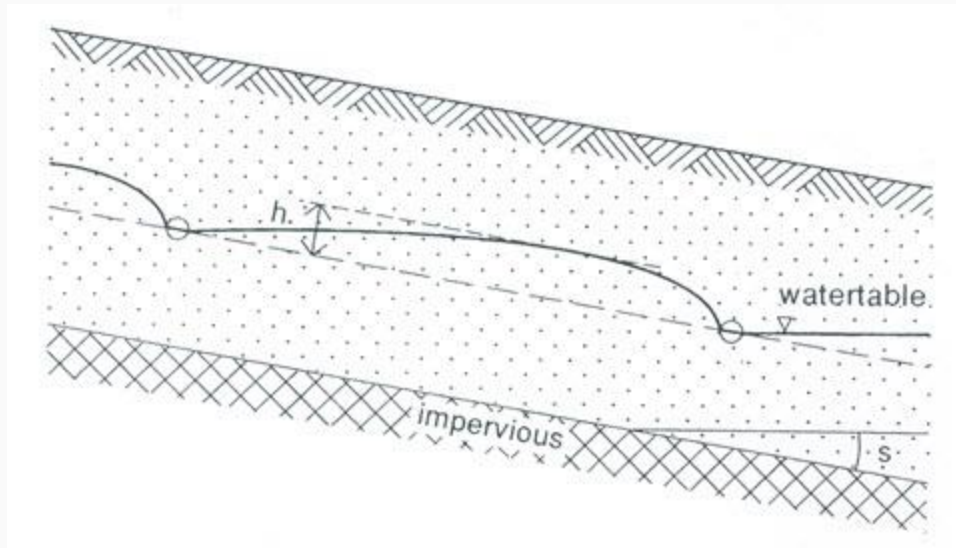




## Lesson 8 Special Drainage Situations

### 8.1 Drainage of Sloping Land

In earlier lessons, we only considered drainage problems in flat lands. However, some agricultural areas are sloping. Hence, the question arises: can equations for flat lands be applied to sloping lands? When a hillside is drained by a series of parallel drains, the situation is as shown in Fig. 8.1 (Ritzema, 1994). The highest water table height ( $h$ ), above the drain level is now not midway between the drains, but is closer to the downslope drain.



**Fig. 8.1. Flow to parallel drains in a homogenous soil overlying a sloping impervious layer. (Source: Ritzema, 1994)**

Schmidt and Luthin (1964) solved the hillside seepage problem of steady vertical recharge to parallel ditches penetrating to a sloping impervious layer. The resulting drain spacings for gently sloping areas (slope  $< 0.1$ ) do not differ much from the drain spacings for flat lands. This is in agreement with the results of Bouwer (1955), who conducted a series of tests in sand-tank models, and the numerical simulations done by Fipps and Skaggs (1989). Because a vast majority of agricultural land will not have slopes more than 0.1, we can apply the solutions obtained for flat lands to sloping lands without any modification as long as the slope is not steeper than 0.1 (Ritzema, 1994).

The above conclusion implies that we assume no difference in efficiency between drains laid parallel or perpendicular to the slope. Where the hydraulic conductivity of the soil is low, it could be advisable to lay the drains parallel to the contour lines, and hence perpendicular to the slope. As the backfilled trenches have and retain a higher permeability than the original soil profile, any surface runoff may possibly be intercepted by the trenches. Further discussion on the layout of subsurface drainage systems in sloping areas is given in Cavelaars et al. (1994).

## 8.2 Interceptor Drains

Interceptor drains intercept (cutoff) the surface or subsurface flow from higher reaches before such water can encroach upon the cultivated lands and create water logging problem. They are also called 'relief drains'. They can be of open type or buried pipe type. In general, interceptor drains are used for two different purposes (Ritzema, 1994): (a) to intercept seepage water from neighbouring irrigation canals, and (b) to intercept foreign water that seeps down a hill.

The **first type of interceptor drains** are often installed in irrigated areas parallel to and a short distance away from conveyance canals. To drain such areas, the interceptor drain is frequently installed on both sides of the waterway. Typical interceptor drains in humid areas (Fig. 8.2d) are located above the seepage area where seepage is caused by the shallow depth or outcropping of the impervious layer on the surface. In irrigated regions, the seepage from an

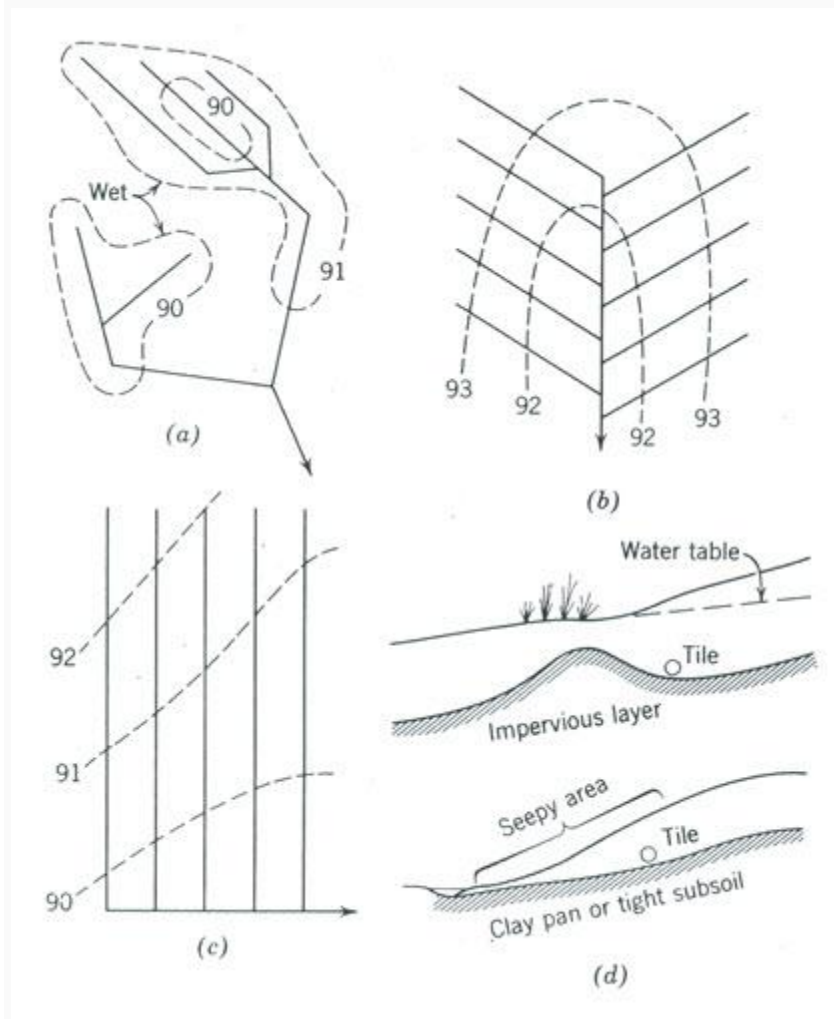
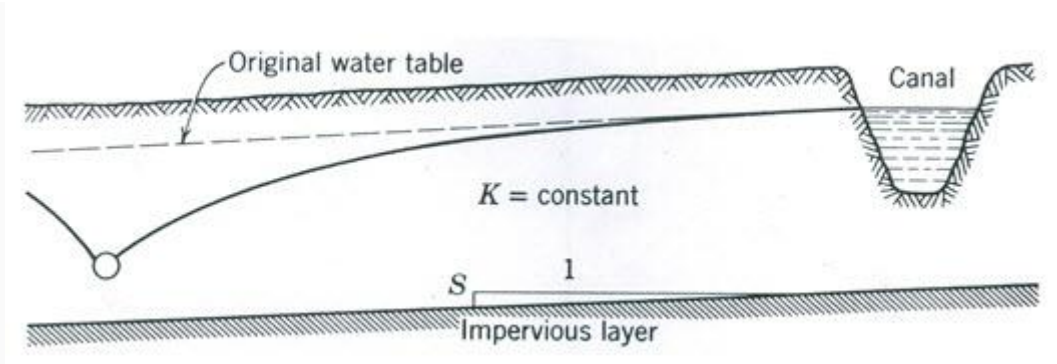


Fig. 8.2. Common types of pipe drainage systems: (a) Natural or random; (b) Herringbone; (c) Gridiron; (d) Cutoff or Interceptor.

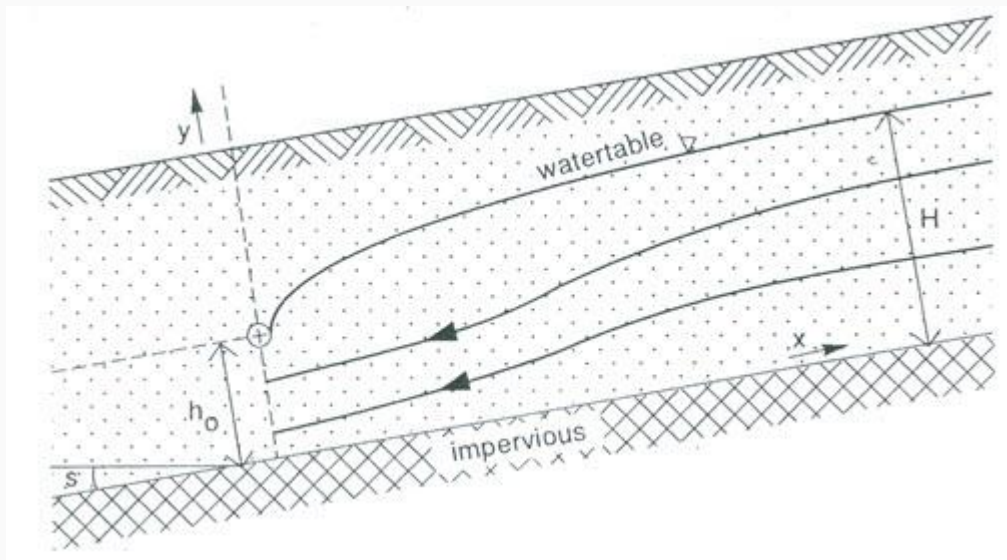
(Schwab et al., 2005)



**Fig. 8.3 Water table drawdown from an interceptor drain below a canal. (Source: Schwab et al., 2005)**

unlined canal, shown in Fig. 8.3, often causes wetness and damage to crops below. The flow towards such a drain is similar to the flow between drains with different water levels. If we assume that there is no recharge from precipitation, we can use the Dupuit Equation to calculate the flow per unit length.

The distance of the first pipe drain below the ditch or canal can be determined by the procedures described by SCS (1973) and USBR (1978). Spacing of drains below the first one are computed from earlier drainage equations, where the land slope is less than 10%. Problems of this type with special boundary conditions can be solved by using computers (Schwab et al., 2005).



**Fig. 8.4. Flow towards an interceptor drain through a homogenous soil overlying a uniformly sloping layer. (Source: Ritzema, 1994)**

The **second type of interceptor (or hill-side) drainage** is shown in Fig. 8.4. Donnan (1959) presented a solution for this type of drainage. He assumed a homogeneous uniform soil layer on top of an impervious layer with a slope. Without an interceptor drain, the slope of the water table will be parallel to the slope of the impervious layer, and hence the amount of seepage water flowing downhill can be calculated by Darcy's Equation as follows:

$$q = K \times H \times s \quad (8.1)$$

Where,  $q$  = flow rate per unit width [ $L^2/T$ ],  $K$  = hydraulic conductivity of the top layer [ $L/T$ ],  $H$  = height of the water table above the impervious layer before the installation of the interceptor drain [ $L$ ], and  $s$  = slope of the impervious layer (dimensionless).

If an interceptor drain is constructed at the bottom of the hill at a height  $h_0$  above the impervious layer, the slope of the water table in the vicinity of the drain will no longer be parallel to the impervious layer, but will curve towards the drain. With a coordinate system as shown in Fig. 8.4, we can assume that the slope is approximately  $s + dh/dx$ . Hence, the amounts of seepage flow through a cross-section at a distance  $x$  uphill from the drain is given as (Ritzema, 1994):

$$q = K y \left( s + \frac{dy}{dx} \right) \quad (8.2)$$

Where,  $y$  = height of the water table above the impervious layer at distance  $x$  [ $L$ ], and  $\frac{dy}{dx}$  = hydraulic gradient at  $x$  (dimensionless), and the remaining symbols have the same meaning as defined earlier.

Because of continuity, the flow with or without the interceptor drain must be equal. That is,

$$K H s = K y \left( s + \frac{dy}{dx} \right) \quad (8.3)$$

Integrating with  $y = h_0$  at  $x = 0$  yields (Donnan, 1959):

$$x = \frac{1}{s} \left[ 2.3 H \log \frac{H - h_0}{H - y} - (y - h_0) \right] \quad (8.4)$$

Where,  $x$  is the distance uphill from the interceptor drain [ $L$ ], and the remaining symbols have the same meaning as defined earlier.

Equation (8.4) can be used to calculate the height of the water table at any distance,  $x$  uphill from the interceptor drain. Theoretically,  $y = H$  is only reached at  $x = \infty$ .

**Example Problem** (Ritzema, 1994): An irrigation scheme (500 m  $\times$  1000 m) is located in a sloping area (Fig. 8.5). The deep percolation losses are 1 mm/day. The soil consists of a permeable layer, 6 m thick and has a hydraulic conductivity of 2.5 m/day, on top of an impervious layer with a slope of  $s = 0.04$ . To control the water table in the area downhill from the irrigated area at a level of 2 m below the soil surface, an interceptor drain will be constructed. Calculate the required

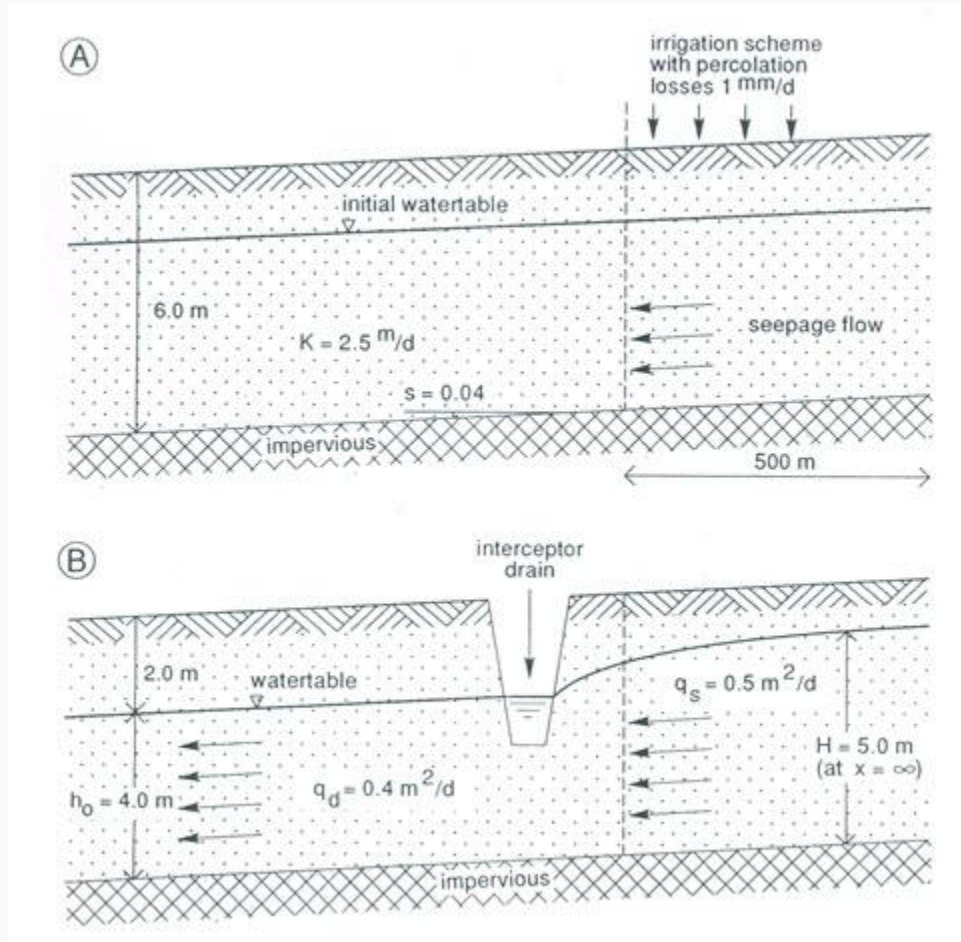


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depth and capacity of the interceptor drain and the uphill elevation of the water table after the construction of the interceptor drain.

**Solution:** To control the water table at 2 m below the soil surface, the height of the interceptor drain above the impervious layer ( $h_0$ ) has to be,

$$h_0 = 6.0 - 2.0 = 4.0 \text{ m.}$$



**Fig. 8.5. Calculation of an interceptor drain in a sloping area: (A) Before construction; (B) After construction. (Source: Ritzema, 1994)**

The percolation losses result in a seepage flow per meter width, which is:

$$q_s = 500 \times 0.001 = 0.5 \text{ m}^2/\text{day.}$$

The elevation of the water table above the impervious layer before the construction of the interceptor drain can be calculated with using Eqn. (8.1) as:

$$H = \frac{q_s}{Ks} = \frac{0.5}{2.5 \times 0.04} = 5.0 \text{ m.}$$

After the interceptor drain has been constructed, the seepage flow downhill from the drain will be:

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$$q_d = K h_0 s = 2.5 \times 4.0 \times 0.04 = 0.4 \text{ m}^2/\text{day}.$$

Thus, the required capacity of the interceptor drain per meter length ( $q_i$ ) will be:

$$q_i = q_s - q_d = 0.5 - 0.4 = 0.1 \text{ m}^2/\text{day}.$$

In other words, 20% of the percolating water will be intercepted. As the irrigation scheme is 1000 m long, the discharge at the outlet of the interceptor drain ( $Q_i$ ) will be:

$$Q_i = 1000 \times q_i = 1000 \times 0.1 = 100 \text{ m}^3/\text{day} = 1.16 \text{ L/s}.$$

Now, the elevation of the water table uphill from the interceptor drain can be calculated using Eqn. (8.4) as follows:

$$x = \frac{1}{s} \left[ 2.3H \log \frac{H - h_0}{H - y} - (y - h_0) \right]$$

$$\Rightarrow x = \frac{1}{0.04} \left[ 2.3 \times 5.0 \log \frac{5.0 - 4.0}{5.0 - y} - (y - 4.0) \right]$$

$$\Rightarrow x = 287.5 \log \frac{1.0}{5.0 - y} - 25 \times (y - 4.0)$$

From the above expression, we have:

At  $x = 0$  m,  $y = 4.0$  m,

At  $x = 23$  m,  $y = 4.2$  m,

At  $x = 54$  m,  $y = 4.4$  m,

At  $x = 99$  m,  $y = 4.6$  m,

At  $x = 181$  m,  $y = 4.8$  m, and

At  $x = 265$  m,  $y = 4.9$  m.

### 8.3 Artesian Relief Wells

Where artesian aquifers are the main cause of drainage problems, wells may be drilled into the aquifer to reduce the hydrostatic pressure and to lower the water table (Schwab et al., 2005). Sometimes these wells are connected directly into a subsurface drain, thereby allowing the groundwater to flow by gravity rather than by pumping. Water table contour maps or piezometric level contour maps are often required prior to designing such a drainage system.



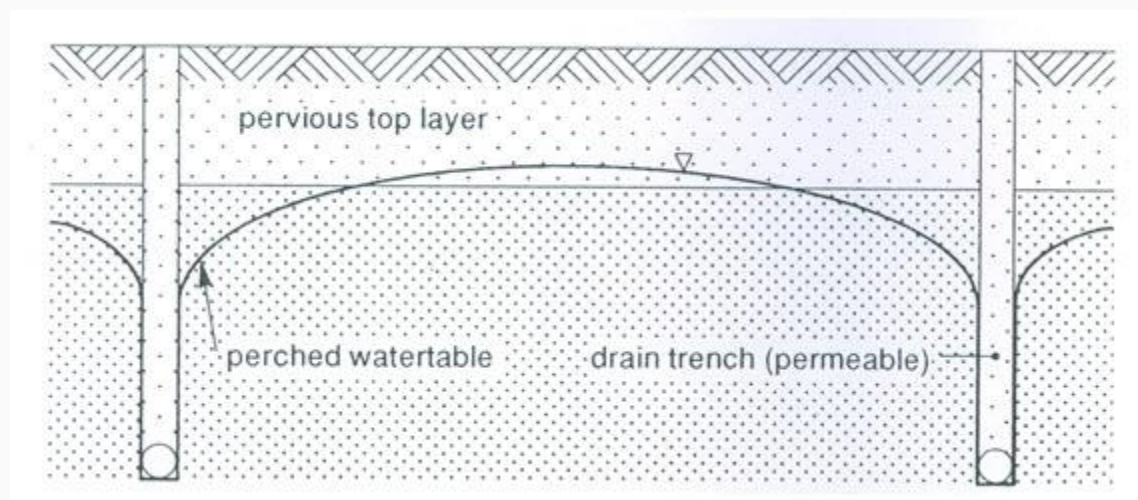
### 8.4 Drainage of Heavy Clay Soils

#### 8.4.1 Drainability of Heavy Clay Soils

Heavy clay soils often have such a low hydraulic conductivity that they need very narrow drain spacings. The narrowest spacing applicable in practice is a matter of economics (e.g., crops to be grown, prices of products). The hydraulic conductivity may be so low that no subsurface drainage with economically justifiable spacing is possible. Under such conditions, we should use a surface drainage system of furrows and small ditches, possibly combined with bedding of the soil (Ritzema, 1994).

For moderate soil hydraulic conductivity, it may happen that the infiltration rate is too low for the water to enter the soil so that frequent surface ponding will occur. A suggested limit for the installation of a subsurface drainage system is that the infiltration rate of the soil must be such that the rainfall to be expected in two or three subsequent days must easily infiltrate during that time. If not, a subsurface drainage system will not work satisfactorily and one has to resort to a surface drainage system (Ritzema, 1994).

Heavy clay soils of low hydraulic conductivity often have a top layer with a surprisingly high hydraulic conductivity because of the activity of plant roots or the presence of a tilled layer. In such cases, rainfall will build up a perched water table on the layer just below the top layer (Fig. 8.6). Under such conditions, a subsurface drainage system can be effective because of the interflow in the permeable top layer, but it will only work as long as the backfilled trench remains more permeable than the original soil.



**Fig. 8.6. Perched water table built up in heavy clay soil, just below the top layer with a higher hydraulic conductivity. (Source: Ritzema, 1994)**

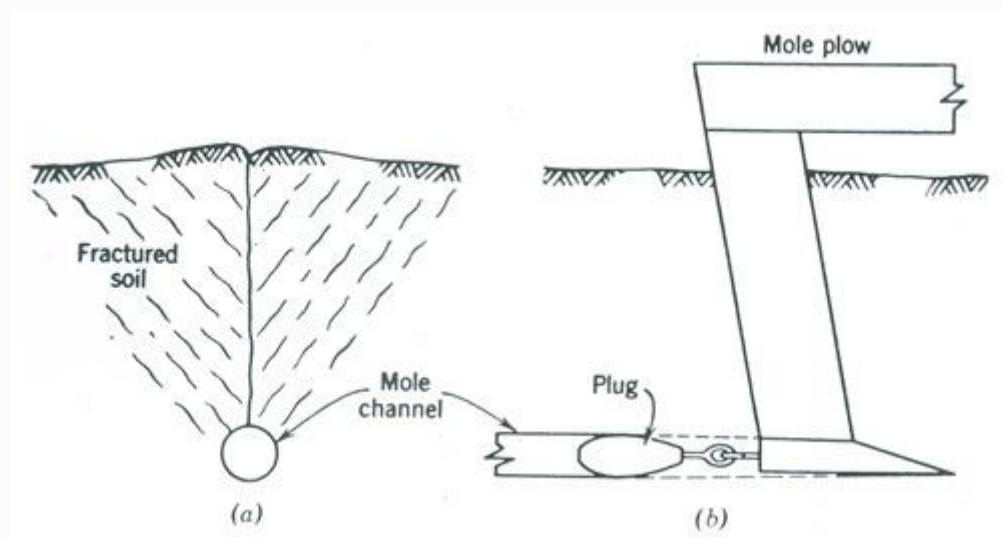
Unless one can expect the hydraulic conductivity of the subsoil to increase with time (e.g., because of the soil ripening process), it makes no sense to install a drainage system at a great depth (Ritzema, 1994). In fact, a system reaching just below the top layer should be sufficient. The system can be improved by filling the trench with coarse material or adding material like lime. Further improvement can be sought in mole drainage, perpendicular to the subsurface lines.

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In none of the cases discussed above, it is possible to apply a drainage theory, because the exact flow paths of water are not known (Ritzema, 1994). Also, these heavy soils often have a seasonal variation in hydraulic conductivity because of swelling and shrinking.

### 8.4.2 Mole Drain: A Promising Solution

Mole drain (Fig. 8.7a) is a temporary method of drainage for heavy clay soils. It is also known as a pipeless drain. Where soil conditions are favorable, mole drains function efficiently for the first few years and then gradually deteriorate. Mole drains have been successful in England, New Zealand, and several European countries. Their maximum life is 10 to 30 years (Schwab et al., 2005). Mole drains are unlined cylindrical channels of about 10 cm (normal range is 5 to 10 cm) in diameter, which are artificially created in the subsoil without digging a trench from the surface. They are constructed at a depth shallower than one meter (usually 40 to 60 cm) to work as a subsurface drain by intercepting gravitational soil-water and conveying it towards the drain outlet. The mole drain outlets are protected by installing a rigid pipe for the last about 2 m length of the mole drain, protruding out sufficiently to permit a clear overfall of drainage effluent without disturbing the soil around the downstream end of the mole drain. Mole drains are constructed using a mole plough (Fig. 8.7b) which is comprised of a rigid vertical bar of thin front edge to reduce resistance to soil shearing when it is pulled by a tractor, a plough fitted to the lower end of the vertical bar, and a conduit opener in the shape of a bullet. The bullet is attached to the plough and creates a cylindrical channel as the mole plough is pulled forward by a tractor. In order to have stable mole drains, the soil must be cohesive, with a greater percentage of clay (Jha and Koga, 2002).



**Fig. 8.7(a,b). Schematic diagram of mole drainage: (a) Cross-section of a mole channel showing cracks around it; (b) Profile of a mole plough.(Source: Schwab et al., 2005)**

If mole drains are constructed at suitable soil moisture content, the shearing effect on the soil in the vicinity of the rigid bar and the mole plough extends one to two meters on either side, forming cracks around mole channels (Fig. 8.7a) which facilitate gravitational water movement towards the mole channels. The soil moisture content at the time of moling plays an important role in crack formation, mole channel stability, and power requirement to pull the mole plough. If the soil is too wet, cracks may not develop properly, the internal mole surface will get smeared

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and will not permit adequate transfer of gravitational water in the soil profile across the mole surface, and the mole channel may collapse rapidly. On the other hand, if the soil is too dry, cracks will develop but the power requirement will be too large and the mole may also collapse due to the dislodgement of relatively drier soil particles at the inner mole surface. The appropriate moisture content to construct mole drains is judged from experience. A general guideline in this respect is that the soil moisture content should be between the Liquid Limit and the Plastic Limit (Bhattacharya and Michael, 2003). Besides the moisture content, the bulk density of the soil is also an important factor governing the power requirement and the crack formation during moling. If the soil above the mole drain is less pervious, subsoiling helps in developing wider path for the shallow soil water to flow towards the mole drain.

In India, there is more than 76 Mha of heavy clay/clay soils, of which about 69 Mha is distributed (in decreasing order of the area) in the states of Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh and Karnataka, and about 7 Mha is distributed (in decreasing order of the area) in the states of Tamil Nadu, Rajasthan, Orissa and Bihar (Bhattacharya and Michael, 2003). Some of these soils are suitable for mole drainage. An excellent review of the theory and practice of mole drainage is presented by Jha and Koga (2002), while a case study on the performance evaluation of mole drainage in Bangkok clay soils is reported in Jha and Koga (1995).



#### **Lesson 9 Materials for Pipe Drainage Systems**

##### **9.1 Materials for Drain Pipe**

The materials used for manufacturing drain pipes are clay, concrete, and plastics. Important criteria for pipe quality and for selecting the most suitable type of pipes are: resistance to mechanical and chemical damage, longevity, and costs (Cavelaars et al., 1994). Mechanical damage and chemical deterioration may occur during transport and handling, or after the pipe has been installed. In addition, the lifetime of the pipes should not be excessively shortened by deterioration in mechanical or chemical properties in the course of time. The costs are the total costs for purchase, transport, handling, and installation.

##### **9.1.1 Clay Tiles**

Clay tiles used to be predominant type of drain pipes in Europe, from the first introduction of pipe drainage (before 1850), to about 1960-1970 (Cavelaars et al., 1994). Clay tiles were made from clay, shale, fireclay or mixture thereof and burnt (IS, 1983). These clay tiles had common diameters of 0.05 to 0.15 m, and came in lengths of 0.30 to 0.33 m. Their ends were either straight or had a collar, with a less-than-perfect fit so that the water could enter through the joints. The chemical stability and longevity of good-quality pipes are excellent.

Criteria for testing the quality of clay pipes are (Cavelaars et al., 1994): shape (they should be straight, with straight-cut ends), absence of fissures and cracks (which can be judged by the sound when the pipe is hit), and mechanical strength (breaking strength). Moreover, the tiles should be uniformly burnt and should be free from minerals and chemicals that are known to cause slaking or disintegration of tiles (IS, 1983). The manufacture of good-quality pipes requires considerable skill and a fairly large well-equipped production unit.

##### **9.1.2 Concrete Pipes**

Concrete pipes were used as field drains like clay tiles in various countries, until they virtually became obsolete with the introduction of plastic pipes (Cavelaars et al., 1994). In larger diameters, concrete pipes are still commonly used as collectors. Concrete pipes (Fig. 9.1) can be manufactured in comparatively simple (mobile) production units that can easily be erected in the project area. There is practically no limit to their diameter, although for large diameters (i.e., >0.4 m), the concrete must be reinforced (Cavelaars et al., 1994). Pipe ends are either straight, have a collar, or a spigot-and-groove. Water entry is almost exclusively through the joints between pipe sections. For larger diameters, openings at the joints may become rather large; this is the reason that some manufacturers supply rubber sealing rings.



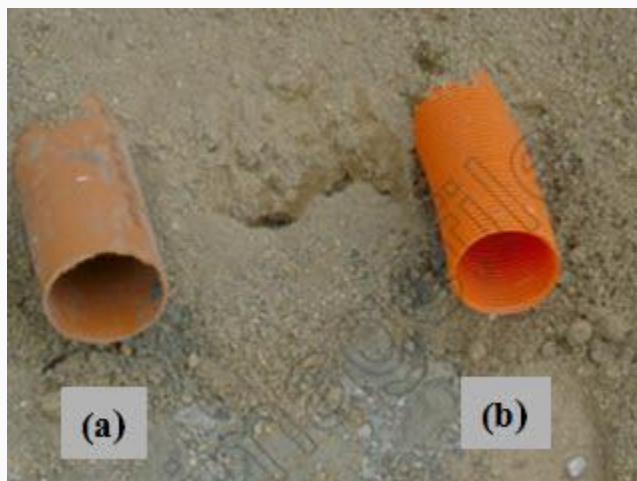


**Fig. 9.1. Reinforced concrete drain pipes.**

Possible disadvantages of concrete pipes are their susceptibility to acidity and sulphate, which may be present in the soil. This susceptibility can be reduced to some extent with the use of sulphate-resistant cement, and by producing to a high manufacturing standard so that high-density concrete is formed which seals off the concrete from attack by soil chemicals (Cavelaars et al., 1994).

### 9.1.3 Plastic Pipes

The introduction of plastic pipes for drainage started around 1960. Initially, straight-walled smooth pipes (Fig. 9.2a) were used. Around 1970, corrugated pipes (Fig. 9.2b) were introduced, which soon replaced the smooth pipes (Cavelaars et al., 1994). The major advantages of plastic over clay or concrete are the much lower weight per meter of pipe, and the greater length of pipe (at least several meters). This makes transporting and handling the pipes a lot easier and cheaper, and it enables higher installation rates. A disadvantage is the environmental pollution caused by the raw material (resin). Ex-factory prices of plastic pipes may be higher than that for clay or concrete pipes, but the total costs may be lower because of a saving in the costs of transport, handling and installation.



**Fig. 9.2. Plastic drain pipes: (a) Smooth pipe; (b) Corrugated pipe.**

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The three predominant materials for plastic pipes are (Cavelaars et al., 1994): polyvinyl chloride (PVC), high-density polyethylene (HDPE) (Fig. 9.3), and, to a minor extent, polypropylene (PP). When comparing PVC and HDPE, one can find that the dark-colored HDPE is more affected by high temperatures than the light-colored PVC. Consequently, the risk of deformation for HDPE pipes is greater than for PVC pipes.



**Fig. 9.3. High-density polyethylene (HDPE) drain pipes.**

On the other hand, PVC, being more sensitive to low temperatures, becomes brittle when exposed to temperatures below freezing point. In addition, PVC is more sensitive to ultra-violet radiation (sunshine), which may cause irreversible deterioration of mechanical properties (brittleness). Therefore, PVC pipes should not be stored in bright sunlight. PVC has some environmental disadvantages also because it forms hydrochloric acid when burnt (FAO, 2005). Note that plastic pipes (PVC, HDPE, or PP) are resistant to all chemicals that may occur in agricultural soils.

### 9.2 Drain Envelopes

When a subsurface drain is installed, some soils may require measures to protect the drain pipe from soil particle entry. Due to the drag force of the water, soil particles or aggregates may be carried into the pipe through the perforations in the pipe wall. This process can never be prevented completely, but it may substantially be slowed down or partially stopped by the use of external porous material around the drain pipe. The porous material designed to do this job is called 'drain envelope' (FAO, 2005). A variety of terms are used for drain envelopes, reflecting its purpose and method of application. Commonly used terms are: filter, cover material, and permeable fill. However, the term 'drain envelope' has often erroneously been referred to as a 'drain filter' (FAO, 2005).

In the subsequent sub-sections, the discussion on drain envelopes is provided in terms of their requirement, functions, design criteria, and construction materials.

#### 9.2.1 Requirement of Drain Envelopes

Qualitative guidelines for designing drain envelopes mainly consider soil texture. Straightforward rules can be given for fine-textured and coarse-textured soils. However, for soils in the intermediate texture classes, there is a considerable uncertainty.



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Fine-textured soils with a clay content of more than about 0.25 to 0.30 are characterized by a high structural stability, even if being worked under wet conditions (Cavelaars et al., 1994). Thus, with trencher-installed pipe drains, no problems are to be expected and a drain envelope is not required. However, with trenchless drainage, one can easily work below the critical depth, especially in wet conditions, resulting in a high entrance resistance. A drain envelope is not likely to be of any help. Clogging of the pipe is not to be expected.

On the other hand, coarse-textured soils free of silt and clay are permanently unstable, even if undisturbed. Thus, soil particles are likely to wash into the pipe, both from the trench backfill and from the undisturbed soil below the pipe. There is a need for a permanent drain envelope, completely surrounding the pipe, only as an effective filter, because there is no high entrance resistance. In this case, a thin geotextile envelope is probably the best solution (Cavelaars et al., 1994).

Soils of intermediate texture are not so simple. In the finer-textured soils of this category (clay contents less than 0.25 to 0.30, but more than say 0.10 to 0.15), the trench backfill will remain stable and of good permeability, provided that pipe installation is done under dry conditions and in irrigated land, provided that the trench backfill is properly compacted (Cavelaars et al., 1994). In these cases, even without an envelope, no problems will arise. However, if the pipes are installed under wet conditions, both drain sedimentation and a high entrance resistance can follow. Hence, a drain envelope is required in this case. A commonly applied guideline in The Netherlands is that the drain envelope should be 'voluminous' in order to fulfill its hydraulic function. Nevertheless, a thin filter sheet wrapped around a corrugated pipe will do the job equally well, because it ensures that water is conveyed towards the perforations (Cavelaars et al., 1994). It should be noted that a drain envelope, in spite of its general positive effect, is no guarantee against poor drain-line performance, especially when the pipes are installed under wet conditions.

### 9.2.2 Functions of Drain Envelopes

A drain envelope is defined as the material placed around pipe drains to perform one or more of the following functions (Cavelaars et al., 1994):

- **Filter function:** to prevent or restrict soil particles from entering the pipe where they may settle and eventually clog the pipe;
- **Hydraulic function:** to constitute a medium of good permeability around the pipe and thus reduce entrance resistance;
- **Bedding function:** to provide-all-round support to the pipe in order to prevent damage due to the soil load. Note that large diameter plastic pipes are embedded in gravel especially for this purpose.

The first two functions provide a safeguard against the two main hazards of poor drain-line performance, viz., siltation and high flow resistance in the vicinity of drains.

### 9.2.3 Design Criteria

In view of drain-envelope functions, ideally, the drain envelope should be designed in such a way that it prevents the entry of soil particles into the pipe, though a limited flow of clay particles will do little harm, because they mainly leave the pipe in suspension. The filtering effect, however, should not be such that the envelope, while keeping the pipe free from sediment, itself becomes clogged. If this happens, the hydraulic function of the drain envelope is severely affected. Besides these conflicting filtering and hydraulic functions, the formulation of functional criteria for the design of envelopes is complicated by a dependence on soil characteristics (mainly soil texture) and drain installation conditions as mentioned earlier. In spite of considerable research efforts, firm quantitative criteria are still far from established. Instead, to a large extent, drainage practice works with qualitative, empirical guidelines (Cavelaars et al., 1994).

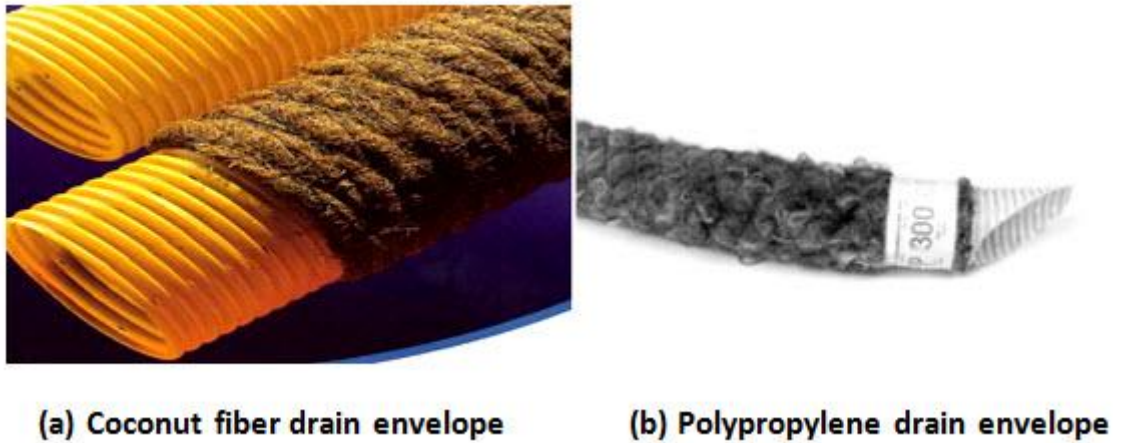
The standard procedure for the design of gravel envelopes is to match the particle-size distribution of the soil with the particle-size distribution of the gravel. Several sets of design criteria to prevent base soil invasion into the drain envelope and the drain pipe have been developed such as Soil Conservation Services (SCS) and United States Bureau of Reclamation (USBR) criteria (Cavelaars et al., 1994). In these standards, the underlying requirements are that the drain envelope should fulfill both the filter and the hydraulic function, that particles from the drain envelope itself should not move through the perforations into the drain in significant amounts, and that the drain envelope should not contain very coarse particles which could possibly damage the pipe during placement. The general procedure for designing a gravel envelope for a given soil is as follows (FAO, 2005):

- (1) Make a particle-size analysis of both the soil and the proposed gravel envelope;
- (2) Compare the two particle-size distribution curves; and
- (3) Decide, by some design criterion, whether the proposed gravel envelope material is suitable.

Gravel is available in many countries and has proven to be a suitable drain envelope if properly installed. Nevertheless, although modern drainage machinery has facilities to install gravel automatically under and around the pipe, it remains a costly and difficult operation (Cavelaars et al., 1994).

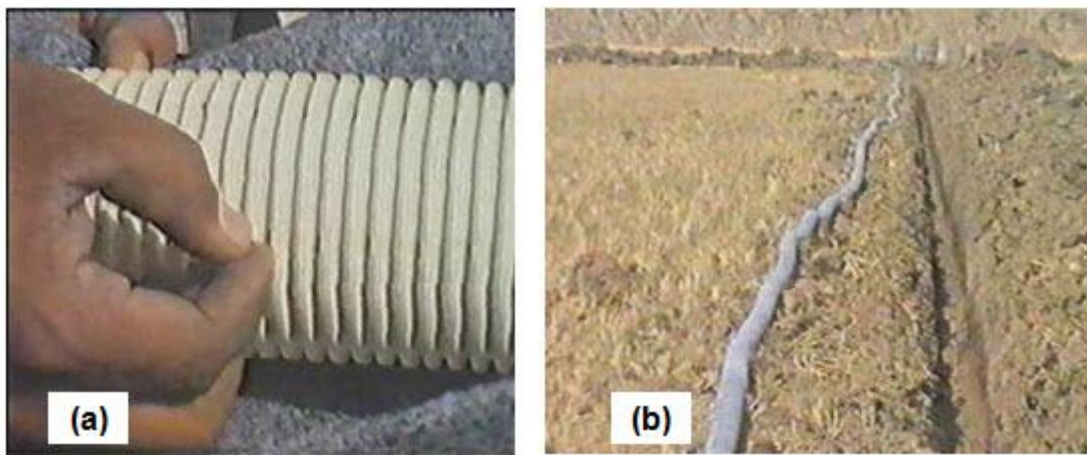
### 9.2.4 Envelope Materials

A wide variety of materials are used as envelopes for drain pipes ranging from organic and mineral material to synthetic material and mineral fibers (Cavelaars et al., 1994). **Organic material** is mostly fibrous, and includes peat (the classical material used in Western Europe), coconut fiber (Fig. 9.4a), and various organic waste products like straw, chaff, heather, and sawdust. **Mineral materials** are mostly used in a granular form; they may be gravel, slag of various kinds (industrial waste products), or fired clay granules. **Synthetic materials** may be in a granular form (e.g., polystyrene) or in a fibrous form [e.g., nylon, acryl, and polypropylene (Fig. 9.4b)]. **Mineral fibers** such as glass fiber, glass wool, and rock wool, are also used.



**Fig. 9.4. Drain-envelope materials: (a) Coconut fiber; (b) Polypropylene. (Source: FAO, 2005)**

Envelope materials are applied in bulk, as thin sheets (Fig. 9.5), or as more voluminous 'mats' (Cavelaars et al., 1994). Bulk application is common for gravel, peat litter, various slags, and granules. The classical method is to spread the material after the pipe has been laid in the trench so that the material will protect the top and the sides of the pipe. A complete surround (e.g., with gravel) is achieved by first spreading gravel on the trench bottom, then laying the pipe, and again spreading gravel.



**Fig. 9.5. Application of geo-textile envelope material: (a) Corrugated perforated PVC pipe being wrapped with geo-textile envelope material; (b) Lateral drain pipe wrapped with geo-textile envelope material is ready for installation. (Source: Indo-Dutch/APWAM Project, ANGRAU)**

Many of the drawbacks of gravel envelopes can be overcome with the use of synthetic envelopes. Thin sheets are commonly used with corrugated plastic pipe as a pre-wrapped envelope. They may consist of glass fibre or synthetic fibres, which are also known as geotextiles. More voluminous mats of up to about 10 mm thick normally consist of fibrous materials, whether they are organic materials, synthetic fiber, or mineral fiber (Cavelaars et al., 1994). These mats are often used as pre-wrapped envelopes with plastic pipes, but they can also be used in the form of strips. One such a strip may be placed only on top of the pipe, or another strip may be placed

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below the pipe, thereby making it suitable in combination with any type of pipe (clay, concrete, or plastic).



### Lesson 10 Layout and Installation of Pipe Drains

#### 10.1 Introduction

Although a subsurface drainage system is adequately designed and is staked out according to plan, it will not function satisfactorily unless properly installed and maintained. The trench should be dug to the specified grade, the bedding condition and width of the trench should be such as to prevent overloading of the pipe, good workmanship should be secured in laying the pipe and in making junctions, the cost of installation should be reasonable, and the drainage system should be mapped and properly recorded.

The classical method of pipe installation comprises marking the alignment and grade, excavating trenches, placing the pipes and envelope material, and backfilling the trenches. Field drains are now installed by drainage machines, either by trenchers or by trenchless machines, whereas concrete collectors are often installed with excavators. In addition to the mechanics of installation, the work planning, working conditions, and the supervision and inspection are also important (Cavelaars et al., 1994).

A variety of adverse field conditions may jeopardize the pipe drainage system if no special precautions are taken. Most of these hazardous conditions can be grouped as wet conditions. Examples are a high watertable, a high water level in the open main drain, a waterlogged top soil due to recent irrigation or rainfall, and a pipe drain crossing an irrigation canal. Sometimes, an appropriate choice of season may overcome many of these problems. The hazards of wet conditions include:

- The internal erosion of soil resulting in siltation of the pipe;
- The formation of a puddled soil around the pipe, with a low permeability and a high entrance resistance;
- The dislocation of pipe and envelope material in the case of sloughing conditions.

A general principle of drain installation is to start at the downstream end so that any free water can drain away immediately. Thus a good drainage base should be secured, which implies that the collector should be in place and should be functioning before the start of the field drain installation. Also, the water level in the open drain should be below the pipe outlets, and the connection with the collector should be made before a field drain is installed.

#### 10.2 Alignment and Grade

Experience is desirable in the proper location of pipe drains, but there are a few general rules (Schwab et al., 2005): (i) place the outlet at the best possible location; (ii) provide as few outlets as possible; (iii) layout the system with short mains and long laterals; (iv) use the available slope to best advantage, especially on flat land; (v) follow the general direction of natural water ways, particularly with mains and submains on land with considerable slope; (vi) avoid routes that



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result in excessive cuts; (vii) avoid crossing waterways except at an angle of  $45^\circ$  or greater; and (viii) avoid soil conditions that increase installation and maintenance costs.

The classical method of marking alignment and grade is by placing stakes in the soil at both ends of the drain line, with the top of the stakes at a fixed height above the future trench bed. The slope of the drain line is thereby implicitly indicated. A row of boning rods is placed in line (both vertically and horizontally) between the stakes, with an extension at the upstream end of the drain line, where the run of the drainage machine ends (Fig. 10.1). The boning rods are thus in a line parallel to the trench bed, and grade control can be

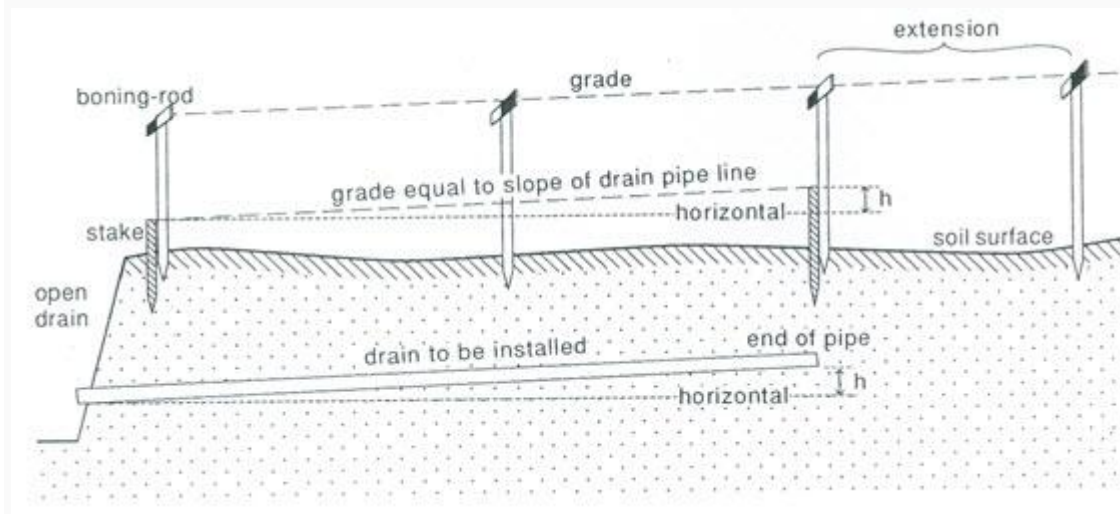


Fig. 10.1. Staking out for grade control of drain pipeline. (Source: Cavelaars et al., 1994)

achieved through sighting by the driver of the drainage machine (Fig. 10.2). The same principle can be applied when drains are installed manually.

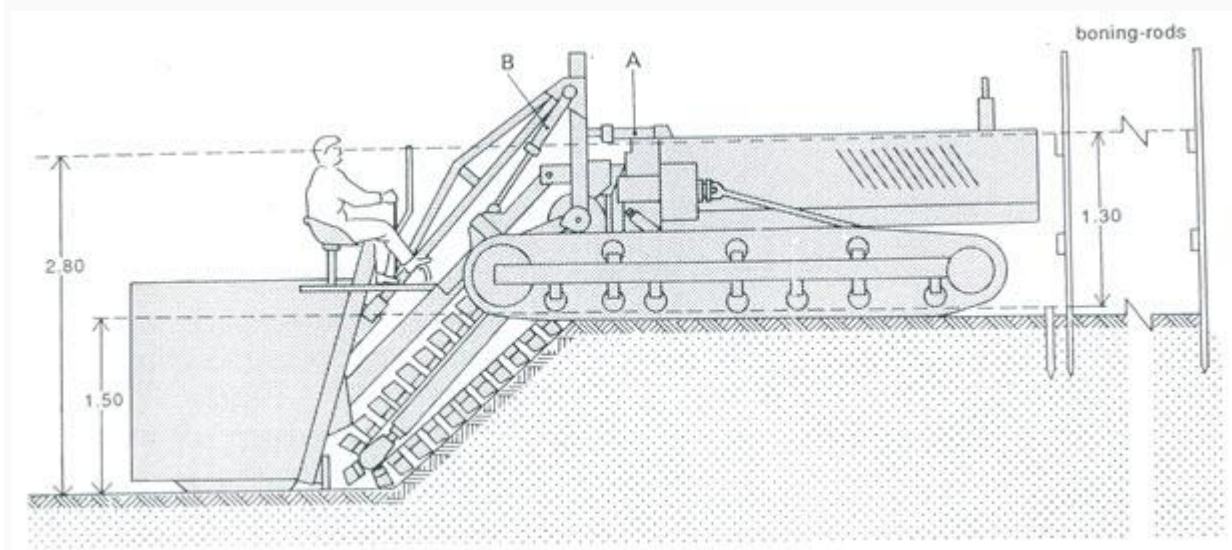


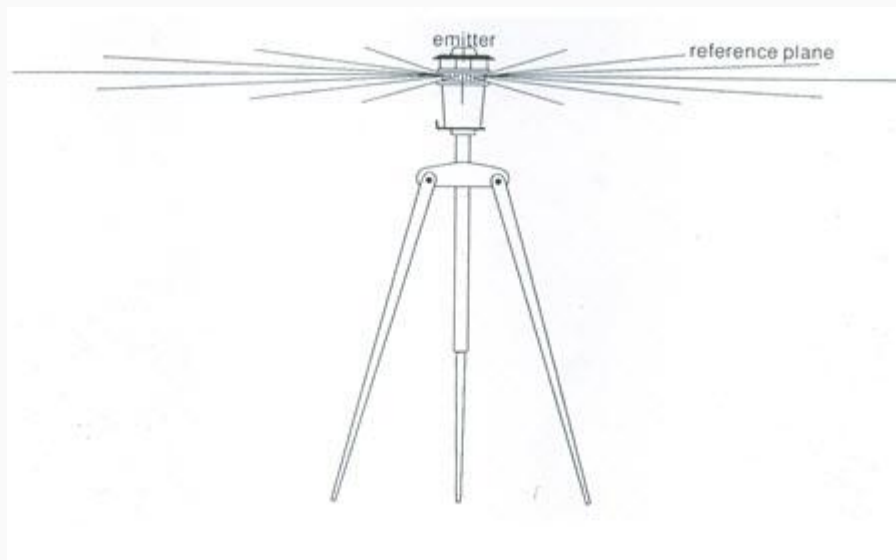
Fig. 10.2. Grade control by the operator. (Source: Cavelaars et al., 1994)

These days, most drainage machines have grade control by laser. An emitter, placed on a tripod near the edge of the field, establishes an adjustable reference plane over the field by means of a rotating laser beam (Fig. 10.3). A receiver, mounted on the digging part of the drainage machine,



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picks up the signal (Fig. 10.4). The control system of the machine continuously keeps a fixed mark in the laser plane. One position of the emitter can serve the installation of a fairly large number of drains.



**Fig. 10.3. Laser emitter establishes a reference plane. (Source: Cavelaars et al., 1994)**

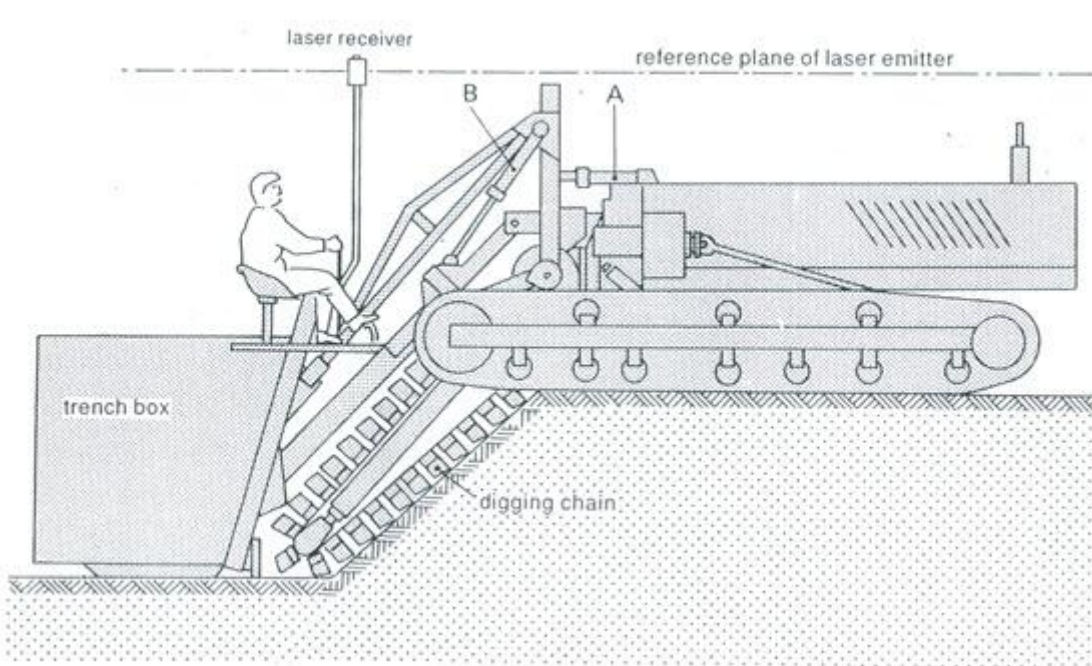
### 10.3 Drainage Machinery

The most common types of machines for installing field drains can be classified into two major types (Cavelaars et al., 1994): trenchers and trenchless machines.

#### 10.3.1 Trenchers

Trench-excavating drainage machines vary from attachments to a wheel tractor, suitable for installation depths of up to 1 m, to heavy-duty machines, suitable for installing large-diameter collector pipes to a depth of about 3.5 m.

Most machines move on tracks, but especially the lighter ones may have rubber tyres. The digging implement is commonly a continuous chain with knives (Figs. 10.2 and 10.4). The excavation depth and trench width of a machine can be varied through interchanging digging attachments. The maximum depth of a trencher is somewhere between 1 and 3.5 m. The trench width varies roughly between 0.12 and 0.65 m, a standard width for field drains being 0.20 to 0.25 m. The engine power ranges from 75 to 300 kW (100 to 400 hp), and one machine weighs between 10 and 50 tons. The grade-control system is optional for most machines: either by the driver or by laser.



**Fig. 10.4. Trencher equipped with laser-grade control. (Source: Cavelaars et al., 1994)**

The corrugated plastic pipe for small-diameter field drains is carried on the machine on a reel and is fed into the trench. Larger-diameter corrugated pipes (e.g., for collectors) are usually laid out and coupled in the field beforehand. The continuous tube is subsequently picked up by the machine as it moves along. Clay tiles and concrete pipes move down a chute behind the digging chain. Synthetic and organic envelopes are usually pre-wrapped around the corrugated pipe. For gravel envelopes, a hopper can be fitted into which the gravel is fed from a trailer moving alongside the drainage machine. For a complete gravel surround, two gravel hoppers can be installed: one before and one after the point where the pipe is fed in.

Special trencher-machine attachments are water tank with a spraying nozzle to wet the chain (in sticky clay), and a scratcher at the back of the machine for blinding the pipe with soil from pre-selected layer (mostly well-structured top soil).

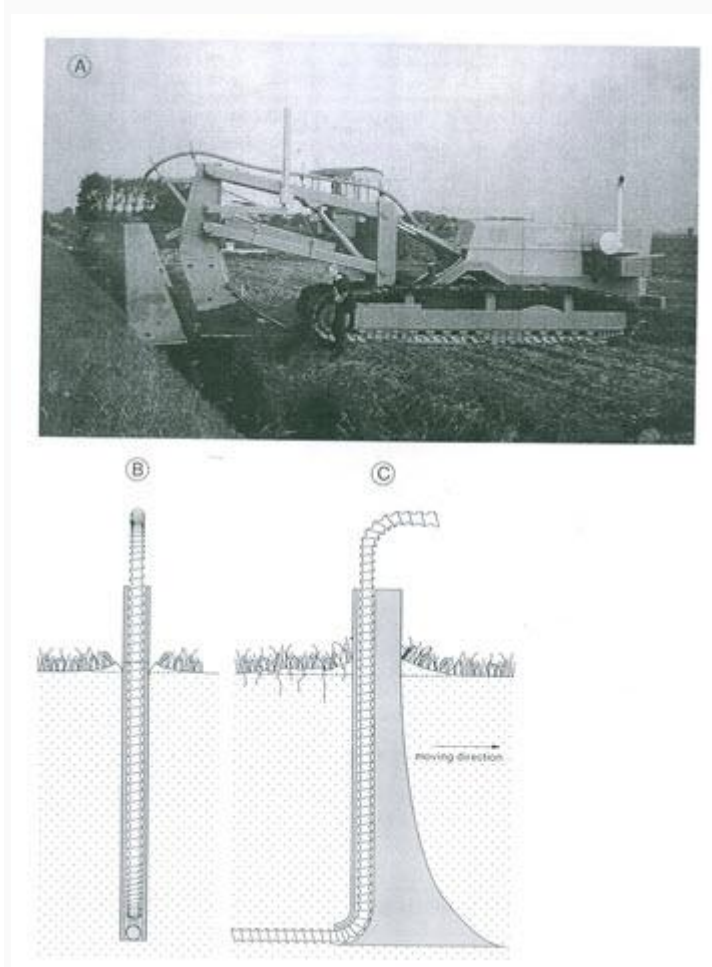
### 10.3.2 Trenchless Drainage Machines

Trenchless drainage machines have been used since about 1965, after flexible corrugated plastic pipe appeared on the market. Two main types of trenchless devices are: vertical plough (Fig. 10.5) and V-plough (Fig. 10.6).

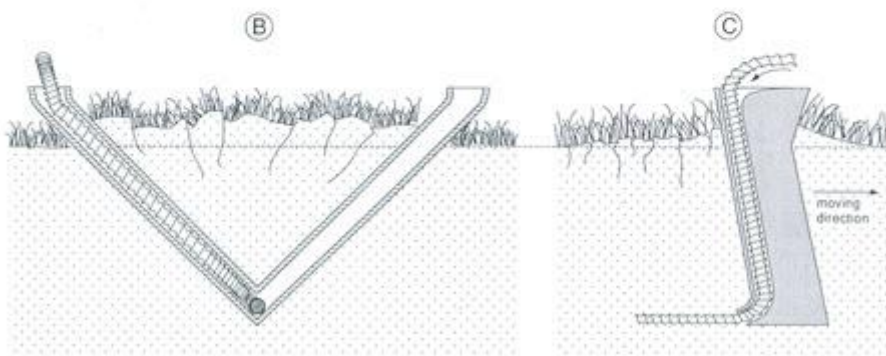
A **vertical plough** acts as a subsoiler: the soil is lifted and large fissures and cracks are formed. If these extend down to the drain depth, the increased permeability leads to a low entrance resistance and an enhanced inflow of water into the pipe. Beyond a certain critical depth, however, the soil is pushed aside by the plough blade, instead of being lifted and fissured. This results in smearing, compaction and a destruction of macropores, so that the permeability is reduced and the entrance resistance is increased. The critical depth depends mainly on the soil texture and on the water content during pipe installation.

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The **V-plough**, which lifts a triangular 'beam' of soil while the drain pipe is being installed, has a hazard of deforming the corrugated pipe under the weight of the soil beam. The problem was found to occur in heavy alluvial clay soil in The Netherlands, but it can be solved by simple adjustments to the plough.



**Fig. 10.5. Trenchless pipe drain installation: (A) Machine equipped with a vertical plough; (B) Rear view; (C) Side view. (Source: Cavelaars et al., 1994)**



**Fig. 10.6. Trenchless pipe drain installation: (A) Machine equipped with a V-shaped plough; (B) Rear view; (C) Side view. (Source: Cavelaars et al., 1994)**

Corrugated plastic pipes are the only feasible pipes for trenchless machines. The V-plough can handle a maximum outside pipe diameter, including the envelope, of 0.10 to 0.125 m (Cavelaars et al., 1994). The vertical plough can handle much larger diameters. Although gravel envelopes would be possible with

trenchless drainage, it is not recommended because of the risk of a clogged funnel and because of the difficulty of supplying gravel to a comparatively fast-moving machine. The only practical option is to use pre-wrapped envelopes.

**Table 10.1. Example of the capacity of a trencher (160 kW) and a trenchless machine with a V-shaped plough (200 kW) for the installation of field drains in singular systems in The Netherlands (Source: Van Zeijts and Naarding, 1990)**

Sl. No.	Soil Type	Drain Depth (m)	Capacity (m/h)		Ratio Trenchless/Trencher
			Trencher	Trenchless	
1	Sand	1.00	700	840	1.2
2		1.30	600	600	1.0
3		1.60	520	430	0.8
4		1.90	475	-	-
5	Clay loam and clay	1.00	620	1150	1.9
6		1.30	540	1050	1.9
7		1.60	470	800	1.7
8		1.90	420	-	-

Because of the high speed, depth regulation by laser is the only practical method for trenchless machines. Furthermore, visual inspection is impossible due to the absence of an open trench. The advantage of trenchless installation decreases rapidly with greater drain depth and with higher soil resistance.

### 10.4 Backfilling

Backfilling of the trench can be accomplished with many machines such as bulldozers, hoes, motor graders, manure loaders, and blades on small tractors. All soil should be replaced and heaped up so that after settlement the trench can be crossed with tillage equipment. If the soil is dry or contains stones, extreme care should be taken to prevent breakage of the tile or crushing of the plastic tubing.

### 10.5 Installation of Collector Drain

Concrete pipes are installed either by trencher or by hydraulic excavator (backhoe). As a safeguard against siltation, the collector is commonly constructed as a closed conduit. Thus, the joints between pipe sections are sealed with either mortar or close-fitting rubber rings.

The larger corrugated plastic pipes (>0.20 m diameter) need to be embedded in gravel as a protection against deformation, and are comparatively expensive, although their use is increasing. They are the only alternative if a de-watering collector is needed. The installation of such a collector is commonly done by a trencher. The gravel bed also has a hydraulic function as well as a filter function.

Installing a deep collector in an unstable soil well below the water is a difficult job, because of the sloughing conditions during pipe installation. Installing concrete pipes is then only possible after the soil has been de-watered (i.e., by lowering the water table to below the installation depth of the collector). This can be achieved by the classical well-pointing technique or, alternatively, by horizontal dewatering (Cavelaars et al., 1994).

### 10.6 Operation and Maintenance

Once a drainage system has been installed, we have to ensure that it will function properly for a long time. Technically, this requires that a good drainage base is maintained, that the system is inspected regularly, and that repairs and cleaning are done when necessary. Administratively, responsibilities for operation and maintenance must be well-defined, and an adequate budget must be available. In large drainage projects, it is common that upon completion of the drainage works, the responsibility for the system is transferred from a construction agency to an operation or maintenance agency.





#### Lesson 11 Drainage of Irrigated, Humid and Coastal Regions

##### 11.1 Introduction

Besides forming the mineral constituents of various size ranges, the weathering and the chemical composition of the parent rock decide the chemical characteristics (neutral, acidic or alkaline) of a soil mass. These fundamental soil chemical properties undergo major changes, particularly at the surface and in shallower depths during various soil treatments through human intervention and the influence of climatic factors such as evaporation and high rainfall. Thus, a neutral soil may become saline or alkaline over a time period. On the other hand, rainfall infiltration during the monsoon washes out and also leaches down the salts, causing a temporary reduction in salt concentration on the land surface and at shallow depths. Organic matter and its decomposition, oxidation of sulphur compounds in the soil, washing out of cations present in the soil in high rainfall regions and irrigation using acidic water may turn the soil acidic (Bhattacharya and Michael, 2003).

The chemical behavior of the soil and the various reactions that may take place between soil, various chemicals present in the soil water and the chemicals that may be added to it from outside the soil system, are governed by the surface properties of the soil particles. The larger is the surface area per unit mass of the soil, the more chemically active the soil will be (Bhattacharya and Michael, 2003). The total surface area of clay per unit mass is much greater than that of sand, and hence clay is highly active chemically. Such chemical activity and the resulting chemical changes in the clay component of the soil have profound influence on the physical behavior of the soil. However, the chemical activity involving sand and silt are practically of no major consequence on the physical behavior of the soil (Bhattacharya and Michael, 2003).

Soil is the natural base for all biological activities, including agriculture. Many of the chemical problems of soils are found in the irrigated areas of the world (including India). Maintaining a favorable chemical regime in the soil is very important for a successful and sustainable agriculture. Broad groups of Indian soils and their brief description are presented in Table 11.1.

Table 11.1. Major soil groups in India (Bhattacharya and Michael, 2003)

Sl. No.	Soil Type	Area (Mha)	Soil Taxonomic Group	Major Places of Occurrence	Properties and Suitability
1	Alluvium Soils	50	Entisol, Alfisol, Inceptisol, Aridisol.	Punjab, Haryana, Uttar Pradesh, Madhya Pradesh, Bihar, West Bengal, Assam, Coastal regions.	Coarse to fine, permeable, can support most agricultural crops, slightly alkaline. In Assam, it is slightly acidic due to high rainfall.
2	Black Soils	54	Vertisol, Entisol.	Maharastra, Madhya Pradesh, Gujarat, Rajasthan, Andhra Pradesh, Tamil Nadu.	Fine texture, slow in water transmission, cracks when dry, poor workability, supports cotton, sorghum, millet, wheat, soybean, sugarcane.
3	Desert Soils	29	Calciorthids, Lithic Entisols, Psamments	Rajasthan, Haryana, Punjab.	Fine to medium texture, alkaline, saline, can support crop with irrigation.
4	Forest and Hill Soils	55	Aridisol and Entisol	Sikkim, Himachal Pradesh, Kashmir.	Coarse to fine, permeable, slightly acidic, supports maize and wheat.
5	Laterites and Lateritic Soils	24.8	Oxisol, Ultisol, Alfisol	Orissa, Maharastra, Tripura, West Bengal, Karnataka, Andhra Pradesh, Bihar.	Coarse to medium texture, varying water transmission rate, slightly acidic, hard when dry, supports tea, cardamom, rubber, paddy, arecanut.
6	Peat and Marshy Soils	0.015	Histosol	Kerala	High water holding capacity, acidic, supports rice, coconut.
7	Red Soils	55	Alfisol, Ultisol	Tamil Nadu, Karnataka, Maharastra, Andhra Pradesh, Goa, Pondichery, Bihar, West Bengal, Assam, Uttar Pradesh, Rajasthan.	Generally loam to clay loam, slightly acidic to slightly alkaline, good water transmission property, supports a large variety of field crops and cash crops.

### 11.2 Problematic Soils and Salient Terminologies

#### 11.2.1 Overview of Problematic Soils

All soils contain some amount of salts. Salinization of soil refers to further increase in the natural salt concentration in the soil. Soil salinization has been identified as a major process of land degradation (FAO, 2000). The greatest technical causes of decreasing production in many irrigation command areas, particularly in the arid and semi-arid regions, or failure of large rainfed agricultural areas are water logging, salinization, and development of alkali lands. Management of salt-affected soils requires a combination of engineering and agronomic measures based on a careful analysis of the causes of salt problem, behaviour of different crop plants under saline environment, the current and desired production level from the land, the alternate technologies available to tackle the salt problem and the costs and benefits expected in the adoption of a certain technology package (Bhattacharya and Michael, 2003). Note that all types of salt-affected soils may not be subjected to reclamation, which may prove to be quite expensive.

From the agricultural viewpoint, a soil is called salt affected when its salt concentration starts adversely affecting seed germination, plant growth, and crop yield. The extent of adverse effects varies with the type of soil, plant species, stage of plant growth, and the type of salt present in the soil. There is a large inter-seasonal variability of the concentration of salt in the soil profile and groundwater due to temporal variation in rainfall and evaporation. Despite all these variations, it is desirable to classify the soils chemically. The salt-affected soils can be grouped into three classes: **(a)** saline soil, **(b)** alkali or sodic soil, and **(c)** saline-alkali soil. Acid soils belong to a different class and may or may not be saline.

In India, the salt-affected soils are found in the irrigated semi-arid regions, arid and semi-arid western part of the country and in several places in southern India (Bhattacharya and Michael, 2003). In addition, the soils in the large coastal belt suffer from coastal salinity. Acidic soils are found in the high rainfall zones of north-eastern India. Highly acidic soils are found in the south-western state of Kerala. The details about the classification of salt-affected soils and their occurrence in India are given in Lesson 14.

#### 11.2.2 Salient Terminologies

The terminologies characterizing the chemical properties of soil and water are briefly described in this section.

##### (1) Electrical Conductivity (EC)

Soil water (i.e., water present in soil pores) is a solution of different salts, mainly Chlorides, Sulphates, Carbonates, and the Bicarbonates of Sodium, Potassium, Calcium and Magnesium. Therefore, the soil water is a conductor of electricity. There may be many other salts also in solution in the soil water, but their proportions are much smaller than the above-mentioned constituents. Since the salt concentration in the soil water has a direct bearing on the performance of plant, electrical conductivity (EC) of the soil solution, usually denoted as  $EC_e$  (EC of soil saturation extract), is a widely used soil chemical parameter to describe the salinity status of the soil and its influence on plant growth.

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The usually adopted units for expressing electrical conductivity are mmhos/cm (millimhos per centimetre), mmho/cm (micromhos per centimetre) and dS/m (deciSiemens per metre); the last one is most widely used these days. Numerically, 1 mmhos/cm = 1 deciSiemens per metre. The salt concentration of the soil solution is also expressed as total dissolved solids (TDS) in units such as in parts per million (ppm), milligram per litre (mg/L), milliequivalent per litre (meq/L or me/L), or in parts per hundred (percent). The average and approximate interrelation (adequate for drainage studies) between EC and TDS is as follows (Bhattacharya and Michael, 2003): EC of 1 dS/m = 640 mg/L of TDS = 640 ppm = 10 meq/L. Also, note that EC of 1 dS/m = 1 mmhos/cm = 1000 mmhos/cm.

The above interrelation is approximate and is valid for a mixed salt solution and up to an electrical conductivity of 5 dS/m (Bhattacharya and Michael, 2003). For the solution of individual salts, the salt concentration in mg/L divided by the equivalent weight gives the salinity in meq/L. Thus, if 1000 mg of NaCl is dissolved in 1 L of pure water, the NaCl concentration will be 1000 mg/L or 1000 ppm or  $1000/23 = 43.48$  meq/L. The EC of this solution will be close to 5 dS/m or 5 mmhos/cm or 5000 mmhos/cm. The relation between the concentration of individual salts and the corresponding electrical conductivity is given for a number of commonly occurring and major salt components of soil in USDA (1954). Most plants grow best under a non-saline soil environment. However, every plant has a certain capacity to withstand saline soil condition to some extent. For most food crops, the upper limit of this tolerance is considered as an EC of 4 dS/m (Bhattacharya and Michael, 2003). If the EC of the soil solution exceeds this value, the plant may suffer irreversibly, thereby reducing crop yield. Electrical conductivity is an important parameter for describing the salinity status of water when such water is used for irrigation. It is equally important in drainage, because leaching of salt solutions by drainage reduces EC of the soil solution and makes the soil environment more conducive for plant growth. Electrical conductivity measurement and interpretation of the measured EC data are described in FAO Irrigation and Drainage Paper 57 (Rhoades et al., 1999). A useful and concise description is also given by van Hoorn and van Alphen (1994).

### (2) pH

The soil reaction such as acidic, alkaline or neutral is expressed through pH. This notation stands for 'power of Hydrogen'. Numerically, pH is defined as the logarithm of the reciprocal of the hydrogen ion concentration in the solution under consideration (i.e., soil solution). **Acids** are those which are the sources of  $H^+$  or  $H_3O^+$  ions in aqueous solution, which can donate proton and which can accept pair of electrons. The **bases (alkali)** are those which are the sources of  $OH^-$  in aqueous solution, which can accept proton and which can donate pair of electrons (Mishra and Mishra, 1996). In pure water, the concentrations of  $H_3O^+$  or  $H^+$  and  $OH^-$  ions are equal and is  $1 \times 10^{-7}$  moles per liter at 295 K (i.e., at 22 °C). Accordingly, the pH of pure water is  $\log (1/10^{-7}) = \log 10^7 = 7$ .

A pH less than 7 represents an **acidic soil solution** and a pH greater than 7 represents an **alkaline soil solution**. The upper limit of pH is 14 [ $\log (1/10^{-14}) = 14$ ] and the lower limit of pH is zero [ $\log (1/10^0) = 0$ ]. Though a pH of 7 is generally considered ideal for plant growth, most plants grow and yield quite well under a soil-water environment ranging from slightly acidic to slightly alkaline. Some plants (e.g., tea) prefer a slightly acidic soil condition than neutral, which is due to specific plant characteristics. If the chemical condition of a soil is beyond the tolerance capacity of a plant, remedial measures are required for improved plant growth and

crop yield. The most important and widely adopted remedial measure is to add chemical amendment to the soil (e.g., lime to neutralize acidity and gypsum to neutralize the alkalinity) in presence of water and remove the resulting chemical products of the reaction from the soil-water-plant root system by leaching through drainage.

### (3) Sodium Adsorption Ratio and Exchangeable Sodium Percent

For diagnosing, if a soil is seriously alkaline, one may adopt the soil quality parameter pH. Its measurement is done using a simple instrument or by titration method in the laboratory, or by a portable instrument in the field. Since alkalinity of a soil could be due to the presence of several bases in soil solution, all of which are not as harmful to the plants as Sodium, determination of sodium hazard becomes necessary. If the concentration of Sodium in the soil solution is more than the concentration of other major bases, then such a soil is usually not good for normal plant growth, and hence the excess Sodium has to be removed. A soil which is alkaline due to high presence of Sodium is also termed 'Sodic Soil'. The proportion of sodium in relation to two other important bases, i.e., Calcium and Magnesium is expressed by the parameter known as **Sodium Adsorption Ratio (SAR)**. SAR is defined as:

$$SAR = \frac{Na^+}{\left[ \frac{(Ca^{2+} + Mg^{2+})}{2} \right]^{1/2}} \quad (11.1)$$

Where, SAR = Sodium Adsorption Ratio (meq/L)<sup>1/2</sup>, and Na<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup> are concentrations of Sodium, Calcium and Magnesium cations in the saturation extract of the soil in meq/L.

**Exchangeable Sodium Percent (ESP)** is calculated by an approximate empirical relation, which is given as follows (USDA, 1954):

$$\begin{aligned} ESP &= \frac{(-0.0126 + 0.01475 SAR)}{\{1 + (-0.0126 + 0.01475 SAR)\}} \times 100 \\ &= \frac{(-0.0126 + 0.01475 SAR)}{(0.9874 + 0.01475 SAR)} \times 100 \end{aligned} \quad (11.2)$$

The above empirical relation between ESP and SAR is valid for a lower limit of SAR of 0.8542 (meq/L)<sup>1/2</sup>. At this value of SAR, the ESP becomes zero. At a value of SAR lower than this, the ESP becomes negative. Another important feature of the above relation is that for SAR values between 5 and 30, the estimated values of ESP do not differ much from the SAR values as shown in Table 11.2.

**Table 11.2. Numerical correspondence between SAR and ESP values (Bhattacharya and Michael, 2003)**

<b>SAR (meq/L)<sup>1/2</sup></b>	1	5	10	15	20	25	30	35	40	45	50
<b>ESP (%)</b>	0.2	5.8	12.0	17.3	22.3	26.5	30.4	33.4	36.9	39.8	42.4

The relation [Eqn. (11.2)] is not universal, as is the case for any empirical relation. This is due to the fact that the exchangeable Sodium is not necessarily the function of the relative proportions of Calcium, Magnesium and Sodium only (i.e., SAR) in the soil. Therefore, in a strict sense, the exchangeable Sodium percentage (ESP) is a ratio of exchangeable Sodium to the exchangeable total cations (i.e., Cation Exchange Capacity, CEC). To express in percentage, the ratio is multiplied by 100 to obtain ESP.

Note that for alkali soil characterization in drainage studies, the ESP, as defined in terms of SAR is normally sufficient (Bhattacharya and Michael, 2003). Moreover, in alkali soils, the interplay between Sodium, Calcium and Magnesium are generally more dominant. Therefore, to reduce Sodium hazard, the exchangeability of Sodium by the other two cations (mainly by Calcium) is a more important consideration. Nevertheless, the use of CEC is made while estimating the gypsum requirement for the reclamation of alkali soils.

In the semi-arid and arid regions, the rainfall is scarce and uncertain. The evapotranspirative demand of the atmosphere is, however, constantly very high due to high temperature and wind velocity. This mismatch between the demand and the supply of the water does not permit a favourable salt and water balance to develop in the soil. The soil solution is drawn towards the surface and the salts in it are precipitated in the surface soil layers when the water evaporates, turning the surface soil highly saline. In arid regions, Sodium, Magnesium, and Calcium salts are concentrated mainly in Chloride and Sulphate forms. In less arid regions, salt concentration is less and Sodium is found predominantly in Carbonate and Bi-carbonate forms. Such forms of Sodium favour the formation of sodic soils (Bhattacharya and Michael, 2003). Soil sodifies when the Sodium is adsorbed in the exchange complex. Since clay soil has much larger surface area per unit mass as compared to sandy soil, the former is more prone to sodification. The process of **soil sodification** includes desalinization in absence of enough divalent cations and with insufficient drainage, evaporation from the capillary rise of groundwater rich in  $\text{NaHCO}_3$  and  $\text{Na}_2\text{CO}_3$ , decomposition of Sodium Alumino Silicates, denitrification and sulphate reduction under anaerobic condition (e.g., in rice fields or waterlogged lands), irrigation with water of low salinity but with dominant  $\text{HCO}_3$  anions, and migration and accumulation of sodic salts in arid climate (Bhattacharya and Michael, 2003). Desalinization (reclamation of saline soil by leaching) in absence of enough divalent cations and with insufficient drainage also turns a land sodic (FAO, 2000).

### 11.3 Drainage of Irrigated Regions

#### 11.3.1 Irrigation Water Quality vis-à-vis Soil salinity

In irrigated areas, soil salinization is mostly a post-irrigation development caused by seepage through unlined water conveyance network and adoption of faulty irrigation practices. Addition



of salts through the application of poor quality irrigation water and a lack of proper drainage to dispose runoff during monsoon and control water table are the other factors causing soil salinity. Such risks are more in the semi-arid and arid regions of the world.

When water is used for irrigation, its chemical composition has a direct influence on the resulting chemical composition of the soil. Rainwater is the purest source of water and when used for irrigation, it does not produce chemical hazard (except the washing away and leaching of cations, which is a slow process). Other waters, i.e., canal water and groundwater contain salts in varying degree. Such water may be saline, with or without Sodium hazard. Accordingly, use of such waters in irrigation, turns the agricultural land saline or alkaline. As a thumb rule, most irrigated crops will tolerate dissolved salts in the irrigation water below 600 ppm (Bhattacharya and Michael, 2003). With the provision of drainage and leaching, most crops can tolerate irrigation water salinity up to 1500 ppm of dissolved salts (FAO, 2000). The groundwater quality also varies to a very great extent in different parts of India. Saline or high Sodium content groundwater is a major problem facing the irrigators in several states such as Punjab, Haryana, Rajasthan and Gujarat, to name a few important ones (Bhattacharya and Michael, 2003).

Acidic water in the natural water sources such as in rivers and streams is a local phenomenon. It happens over some specific reaches of these sources that pass through coal mine regions, as in the state of Meghalaya and parts of Bihar (Bhattacharya and Michael, 2003). The major cause of such occurrences is unplanned and unscientific human activities. This problem is common in the non-monsoon months when the river flow is low. However, if these waters are used for irrigation, it makes the soil acidic. Comprehensive descriptions of the methods of determination of important cations and anions in soil solutions can be found in USDA (1954), van Hoorn and van Alphen (1994), Rhoades et al. (1999) and Singh et al. (1999).

### 11.3.2 Salinity of Irrigation Water Sources: Indian Scenario

All irrigation water contains some dissolved salts from as low as 100 ppm to as high as 7500 ppm (Paliwal, 1972; Rhoades, 1974). The canal water qualities are generally the same as the waters of their parent rivers, unless it is contaminated while passing through a salt-affected area. River water with a salt concentration of 100 ppm contains 0.1 kg of salt in 1 m<sup>3</sup> of water. A 30 cm water application to 1 ha of wheat field with such water will add 300 kg of salt in one hectare in one irrigation season. Table 11.3 presents the quantities of salt added to the soil by irrigating with waters of different salinity levels. Due to low surface irrigation efficiency, one has to apply water more than the irrigation requirement. Some excess water application is also needed to leach down the salts below the root zone, which is known as 'leaching requirement'. This causes addition of more salt than the amount mentioned in Table 11.3.

**Table 11.3. Salt addition to 1 ha of land due to application of 1 ha-cm irrigation water of different salinity levels**

(Bhattacharya and Michael, 2003)

Sl. No.	Salinity of Irrigation Water		Salt Added (kg)
	TDS (mg/L)	EC (dS/m)	
1	100 (Freshwater)	0.156	10
2	500 (Freshwater)	0.781	50
3	1000 (Marginal water)	1.563	100
4	1500 (Marginal water)	2.344	150
5	2000 (Brackish water)	3.125	200
6	3000 (Brackish water)	4.688	300
7	5000 (Brackish water)	7.813	500
8	7000 (Saline water)	10.938	700
9	10,000 (Saline water)	15.625	1000

The water quality of the Indian rivers is generally good, except in the dry season in some of the rivers and when the river water gets contaminated by polluting water from different sources. Salient information on the quality of water of some of the Indian rivers is provided in Table 11.4. Note that the salt load due to irrigation will be over and above the salts already present in the soil. The salinity of the waters in canals fed from the rivers such as Ganga, Yamuna and Kosi ranges from 0.2 to 0.44 dS/m (128-282 ppm). In West Bengal, the canal water in 24 Parganas has salinity of 2.2 dS/m (1408 ppm) and in Howrah, the canal water salinity becomes as high as 12.6 dS/m (8064 ppm) when it gets mixed with tidal water (Bhattacharya and Michael, 2003).

Table 11.4. Salinity of water of some of the Indian rivers (Paliwal, 1972)

Sl. No.	River	Salinity of Water		River	Salinity of Water	
		EC (dS/m)	TDS (mg/L)		EC (dS/m)	TDS (mg/L)
1	Beas	0.26	166	Kankawati	1.70	1088
2	Brahmaputra	0.18	115	Kosi	0.14	90
3	Cauvery	0.27	173	Krishna	1.39	890
4	Chambal	0.45	288	Mathal	2.19	1402
5	Chandrabhaga	3.54	2266	Narmada	0.34	218
6	Gandak	0.25	160	Rupen	6.78	4339
7	Ganga	0.27	173	Satlej	0.33	211
8	Hagari	1.64	1050	Sengar	1.05	672
9	Hansthal	0.60	384	Tapti	0.55	352
10	Jangadia	7.42	4749	Umai	4.27	2733
11	Kali Nadi	0.66	422	Yamuna	0.65	416

Moreover, groundwater and runoff water stored in tanks which are used for irrigation have a great variation in their salinity and in many cases they are more saline than the river water or canal water. Salinity of runoff water collected in tanks in Uttar Pradesh varies from 1 to 6 dS/m. The well waters in most of the districts of Rajasthan have salinity greater than 3 dS/m and going up to 14 dS/m. The well waters in northern Gujarat have salinity ranging from 1 to 15 dS/m. These are in contrast to the groundwater salinity of less than 1 to 2 dS/m over most of Uttar Pradesh, except in Agra and Mathura regions where it is as high as 21 dS/m (Paliwal, 1972).

### 11.4 Drainage of Humid Regions

Humid regions receive annual rainfall in excess of 1000 mm, much of which occurs as heavy rains in short spells. About 80% of the annual rainfalls are received in less than 3 months and 80% of this occurs in about 8 to 10 rainfall events (Bhattacharya and Michael, 2003). In a region receiving 1500 mm annual rainfall, one may expect a rainfall of about 100 mm in one day and a major portion of this may occur in a few hours. The infiltration capacity of soils varies from 4 mm/h in clay loam soils to 40 mm/h in sandy soils (Bhattacharya and Michael, 2003). Under monsoon climatic conditions, the intensity of rainfall is usually much higher than the infiltration capacity of soils. Therefore, runoff is quite common in monsoon dominated regions. Drainage of humid regions is expected to dispose runoff from agricultural lands.

### 11.5 Drainage of Coastal Regions

While discussing the drainage problems in arid, semi-arid and humid regions, it is also important to discuss the drainage problems of coastal regions which call for a special attention. In India, the arable coastal land lies adjoining over 7000 km long coast line covering eight states, from West Bengal in the east to Gujarat in the west (Bhattacharya and Michael, 2003). Coastal tracts are often considered similar in terms of the constraints to agricultural production that is low. Perhaps, cultivation of rice and its low productivity are the only common features in the coastal regions. The determinants of agricultural production such as soil, rainfall, climate, rice varieties, cultural practices, and the nature and severity of drainage problems vary from place to place in coastal regions. Annual rainfall varies from 800 mm to more than 2700 mm. Soil texture ranges from medium to heavy. The soil-water pH varies from 3.5 in acid sulphate soils to 9.5 in saline sodic soils. The EC of soil extracts varies from 3 to 30 dS/m. The hydraulic conductivity varies from practically zero to 1.5 m/day and the infiltration rate varies from 0.1 to 20 mm/h (Bhattacharya and Michael, 2003).

Land drainage problems in the coastal regions arise due to restricted natural outflow in a flat land, silted and weed-infested drains, and higher downstream water level during high tides. A unique case is the low-lying paddy lands in acid-sulphate soils of coastal Kerala where the land elevation is 1-2 m below the mean sea level (Bhattacharya and Michael, 2003). The protective bunds built around the cultivated fields frequently breach, causing inflow of huge quantities of outside water to the paddy fields that must be drained. Also, lands are purposely kept under water fallow during the non-cultivated season to reduce acidity hazard. This water needs to be drained before the start of cultivation.

In general, the elevation of most of the coastal agricultural lands is only marginally higher than the sea level. When they suddenly receive a large quantity of water, which may be due to cyclonic storms (an annual event over much of the east coast), water release from upstream reservoirs or accumulation of runoff from higher reaches -- all of which are uncontrollable to a great extent, the water stagnates over the land (Bhattacharya and Michael, 2003). Quite often, water inundates the paddy plants completely and the situation may prolong which destroys the crop. Monsoon (kharif) cultivation in these areas becomes risky and can succeed only in some years when the magnitude of the incoming water from different sources is small. Seawater backflow during high tides is a recurring phenomenon in the coastal areas. This brings in large amount of dissolved salts, contaminating the local water bodies and the low-lying lands. Therefore, water logging and salinity are the two major problems faced by the farmers of the

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coastal regions (Bhattacharya and Michael, 2003). The dilution effect of the large volume of incoming freshwater during the monsoon season considerably reduces the salinity hazard in this season. Salinity problem is dominant during dry seasons due to high evapotranspiration, contaminated water in the local water bodies and the lack of adequate fresh surface water or groundwater. Thus, rice cultivation suffers during both monsoon (kharif) and winter (rabi) seasons.



### Lesson 12 Vertical Drainage and Biodrainage Systems

#### 12.1 Introduction

Non-conventional drainage methods are adopted when the conventional surface drainage or subsurface drainage methods are not suitable due to technical or economic reasons. Vertical drainage using shallow or deep wells or a shallow multiple well-point system, biodrainage, pump drainage and mole drainage are some of the non-conventional drainage methods (Bhattacharya and Michael, 2003). Construction of ring bunds to protect agricultural lands from inundation by flood water (widely adopted in Kerala), washing out the dry season surface accumulated salts in the saline land by using the water from the initial monsoon rains, and reducing the depth of accumulated runoff by recharging it into groundwater are some of the other non-conventional methods (Bhattacharya and Michael, 2003). The function of the non-conventional drainage methods is to achieve the same goals as those of the conventional drainage methods, i.e., control of excess water and excess salts in agricultural lands. However, their scope, working principle and design methods are different.

In lowland regions, the natural drainage network is usually found non-functional due to either siltation or higher water level in the drains than in the field. This situation does not permit to use gravity drainage through a conventional surface drainage network in the waterlogged fields. Renovation of the silted natural drains may be highly expensive, and hence a feasible option in such situations is to construct a dyke and adopt pump drainage to pump out the accumulated runoff from the cultivated land upstream to the dyke and dispose it through shallow carrier drains towards the natural drain or directly into the natural drain (Bhattacharya and Michael, 2003). On the other hand, pumping of groundwater in canal commands not only augments the surface water supply but also helps in controlling the rise of water table due to continuous irrigation.

Low-cost and environment-friendly drainage method like biodrainage provides several advantages over conventional drainage systems. It is described in **Section 12.3**. In heavy soils (soils having very high clay content, which are also known 'black cotton soils' in India), conventional subsurface drainage by pipe or tile drains is usually expensive. Hence, mole drainage system alone or in combination with subsoiling proves to be effective and less expensive in heavy soils. Mole drainage has already been discussed in Lesson 8. In this lesson, different types of vertical drainage systems as well as one environment-friendly drainage technique known as 'biodrainage' are succinctly discussed.

#### 12.2 Vertical Drainage System

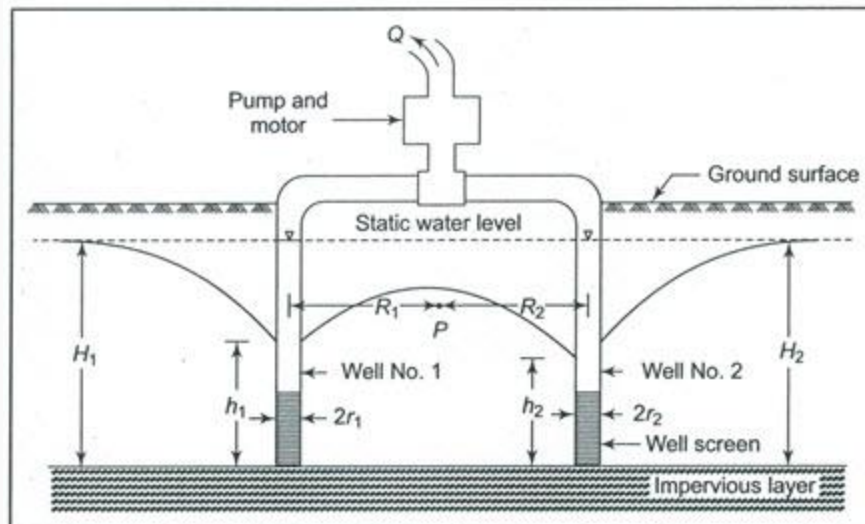
In conventional horizontal pipe subsurface drainage systems, the flow of water through the soil profile is a combination of horizontal and radial flow. For most part of the flow domain, from the mid-spacing up to the drain, the direction of flow remains essentially horizontal. In the radial flow zone, in the vicinity of the drain, there is a vertical component of the flow velocity. The drawdown in the case of horizontal pipe subsurface drainage system is limited to a maximum of



depth of the drain from the soil surface, which seldom exceeds 2 m. Consequently, the vertical flow component is small (negligible). Once the excess water is collected in the drain, its outward flow takes place at a low gradient (normally not more than 0.2%) to limit the depth of installation and to permit gravity outfall (Bhattacharya and Michael, 2003). In contrast, a tubewell dewateres the soil profile from much greater depths. The outflow through a tubewell is directed vertically upwards, and if the drawdown is large and the cone of depression is evenly spread (as in uniform coarse soils), there is a substantial component of vertical flow even within the soil profile. Therefore, drainage by tubewells is known as **vertical drainage**. Another case of vertical drainage is when excess accumulated surface runoff water is to be disposed by recharging it into deeper aquifers through a tubewell (i.e., recharge well), wherein the flow through the recharge well is vertically downward.

### 12.2.1 Vertical Drainage using Tubewells

**Tubewell drainage** is a technique of controlling water table and salinity in agricultural areas. It consists of pumping an amount of groundwater equal to the drainable surplus using a series of wells (Fig. 12.1). Tubewell drainage is not new, but it has not been widely used. Early attempts to use a series of pumped wells for land drainage and salinity control were made in the U.S.A. and the former U.S.S.R. more than half a century ago (Boehmer and Boonstra, 1994).



**Fig. 12.1. Schematic of tubewell drainage technique: Two wells tapping an unconfined aquifer in series. (Source: Michael et al., 2008)**

A review of studies and experiences with tubewell drainage in various countries shows that this technique cannot simply be regarded as a substitute for the conventional technique of subsurface drainage (Boehmer and Boonstra, 1994). The success of tubewell drainage depends on many factors, including the hydrogeological conditions of the area, physical properties of the aquifer to be pumped, and the physical properties of the overlying fine-textured layers. Another important factor is that skilled personnel are needed to operate and maintain tubewells, and to monitor water tables and the quality of the pumped water.

Tubewells may be shallow or deep. A **shallow tubewell** is that which draws groundwater from the top unconfined aquifer. The depth of such an aquifer is highly variable from one region to

another, but it usually ranges from a few metres to 30 or 60 m. **Deep tubewells** are those which draw water from a deep confined aquifer or from multiple aquifers. When the top unconfined aquifer is pumped, its effect on water table decline is clearly visible in the upper soil layer within a short period of pumping. If a deep tubewell is pumped, its effect on water table decline in the upper soil layer will be slow and will be visible if the pumped aquifers have hydraulic connection with the upper soil layers. If the pumped aquifer is fully confined, pumping from it may not have any effect on the water table in the overlying unconfined soil system. It is worth mentioning that in most cases, the planned tubewell constructions have been for the purposes other than drainage, i.e., to supply water for irrigation, domestic and industrial purposes.

Today, the groundwater scenario is that excessive groundwater pumping has resulted in an alarming decline of groundwater levels in several states of India due to the fact that annual groundwater withdrawal is much higher than the naturally occurring annual groundwater recharge (Bhattacharya and Michael, 2003). It is also a fact that groundwater withdrawal in the command areas of purely surface irrigation projects (e.g., Kosi and Gandak projects in Bihar) has benefitted the command area by lowering the water table and saving land from water logging and from possible chemical degradation (Prasad and Prasad, 1996). In these two projects, groundwater withdrawal, even for irrigation, was not a planned activity. However, plentiful availability of groundwater at low lift and a generally inefficient functioning of the irrigation projects led the enterprising and surface water deprived farmers to sink and operate a large number of shallow tubewells. This gave the desired drainage effect by lowering the water table, simultaneously ensuring availability of irrigation on demand by the farmers.

A case study of planned groundwater withdrawal and its effect on water table behavior in the irrigation command (Hisar district in Haryana) of the Fatehabad branch of the Bhakra canal system has been reported by Dua and Puri (1996). Along the branch canal, 50 strainer type and gravel packed tubewells of depth varying between 27 and 38 m were commissioned at a spacing of 120 m. The tubewell discharge varied between 10-15 L/s. The pumped water was fed into the branch canal for augmenting water supply. Tubewell spacing, depth and the pumping rate were fixed keeping in mind the aquifer characteristics, presence of saline water at deeper depths and for avoiding upconing of the saline water zone into the fresh water zone during pumping, respectively. Initial and subsequent (after more than a year, from July 1995 to October 1996) water table observations were taken in a number of piezometers installed perpendicular to the branch canal at several locations. The quality of the pumped water was also monitored. These observations revealed a decline in the water table varying between 0.32 m and 3.09 m (average = 2.13 m, for 12 locations, covering a maximum distance of 600 m from the branch canal). The increase in the electrical conductivity (EC) of the pumped water after more than a year was small (0.1 dS/m).

The above-mentioned facts confirm a close linkage between groundwater pumping and water table decline both on a short-term and a long-term basis. Therefore, it follows that a planned groundwater pumping in shallow water table regions will provide water supply for certain purposes and at the same time, will ensure a favourable soil water regime in the root zone through water table management. Generally, the availability of good-quality groundwater is a prerequisite for the success of such an endeavor (Bhattacharya and Michael, 2003). However, if an irrigated area receives water from good-quality surface water sources, the poor-quality groundwater can be pumped and mixed with the good-quality surface water in a suitable

proportion to meet the irrigation water demand. This is one feasible conjunctive use technique to control the rise of water table in the regions having poor-quality groundwater.

The discharge capacity of a tubewell is governed by the aquifer properties namely, transmissivity and storage coefficient or specific yield. The actual discharge determines the extent of drawdown. The discharge and the aquifer properties together, govern the shape and the spread of the cone of depression (i.e., the volume of soil being drained). The pumping schedule, non-pumping hours and the density of tubewell network determine the residuals drawdown after selected intervals of time and its cumulative effect over the years in a certain region. It is theoretically possible to predict the combined effect of the above factors on the water-table scenario of a region. However, the best method is to regularly monitor water table in a network of observation wells over a region and analyze the data to enable proper interpretation in terms of future possibilities of water-table rise or fall. In India, the Central Groundwater Board (CGWB) and the State agencies collect pre- and the post-monsoon groundwater-level data in different basins or sub-basins. These data should be analyzed along with the data of past developments in the region in terms of agriculture, urbanization and industrialization in order to obtain a clear picture of the possible future scenarios of water table behavior. Also, suitable theoretical analyses are necessary to estimate a proper tubewell density and a desirable rate of groundwater pumping to maintain a favourable groundwater balance. The interested readers should refer to the standard textbooks on groundwater hydrology for the detailed information about well hydraulics.

### 12.2.2 Vertical Drainage using Multiple Well-Point System

A **multiple well-point system** consists of a network of closely spaced shallow tubewells to dewater a waterlogged area where the water table is close to the groundwater or very close to the root zone and pumping by a single or a few scattered deeper tubewells are not adequate to lower the water table. It is also suitable when the deep well pumping or pumping at a high rate from a single tubewell may be hazardous due to the presence of poor-quality water at deeper depths (Bhattacharya and Michael, 2003). Thus, a multiple well-point system of groundwater pumping is essentially a drainage method. In this system, shallow tubewells are closely spaced to produce interference effect when they are simultaneously pumped. Khepar et al. (1971) reported that a battery of two tubewells, spaced at an interval of 3 m can achieve a drawdown of 1.74 m at the mid-point due to well interference between the two, whereas the drawdown effect on the outer region was the same as if the single well were being pumped. Therefore, to cause an effective drawdown over a larger waterlogged area, there should be several tubewells located within their radii of influence. Note that well interference is not desirable for the tubewells constructed for water supply purposes.

The result of operating a **multiple well-point system** will be that all the individual cones of depression will superimpose on one another, giving a larger overall water table decline during pumping over a larger area. Pumping from such a network can be accomplished using a single pump installed on the main line after joining all the well points by pipes having air-tight joints (Bhattacharya and Michael, 2003). Alternatively, individual rows of the well points can be joined by a pipe which delivers water in a common sump well. By using bends, the delivery points of these pipes are kept sufficiently deep in the sump well. A single pump draws water from the sump well causing a drawdown in it, adequately below the surrounding water table. This enables the pipelines connected to the well points draw groundwater and deliver it into the

sump well. A specific situation where such a system is useful is when the water table is shallow and the soil is fine textured and non-cohesive (Bhattacharya and Michael, 2003). Under these conditions, making stable open drains or trenches for installation of a pipe subsurface drainage system become a difficult task due to immediate collapse of the drains or the trenches. Further, to take the full advantage of the system, the groundwater quality should be such that it can be used for irrigation or other purposes.

In **brackish (saline) groundwater regions**, the extraction of groundwater is low as the water cannot be used for irrigation. Use of only surface water for irrigation causes a gradual rise of the poor-quality groundwater. **Conjunctive use of surface water and groundwater** can be adopted in such places for controlling water table as well as for increasing irrigation water availability. Gupta et al. (1987) studied this aspect in the Faridkot region of south-west Punjab where the EC of the groundwater was about 8 dS/m and the land had turned waterlogged and saline due to prolonged irrigation with surface water only. This study revealed that of the total water applied in irrigation, the groundwater and the surface water mixed in the proportion of 40:60 resulted in a maximum return from irrigation. Obviously, the water table would decline when 40% of the irrigation water is withdrawn from the aquifer rather than irrigating with only surface water.

Shakya et al. (1995a,b) conducted an experiment with a multiple well-point system in a 16 ha area near Golewala village in south-west Punjab. The discharge from each of the well points was approximately 3 L/s. The system was operated intermittently with 8 hours of pumping followed by 16 hours of recovery in 24 hours and continued for at least a week at a time. The residual drawdown at the end of pumping was 24 cm near a well point, but only a few centimetres at the farther point, i.e., at the intersection of the diagonals of a rectangle formed by joining the locations of four adjacent well points. The longer was the total duration of pumping, the more was the residual drawdown. This study was carried out in a small area (16 ha) within a vast expanse of a shallow water-table region. Therefore, the temporary drawdown during and immediately after pumping was recovered soon due to the inflow of groundwater from the surrounding area. The major conclusion of their study was that the multiple well-point system could be used for the control of water table, and hence for the drainage of waterlogged areas. However, for effective and long lasting drainage effects, such a system is to be adopted over a relatively larger area. The functioning and the results of this study were demonstrated to the local villagers. A large number of the villagers having their own tubewells but of low discharge to avoid upconing of saline groundwater from deeper depths adopted the system with a minimum of two well points to a maximum of 12 well points, depending on the size of their farm holdings.

### 12.2.3 Vertical Drainage using Dug Well

Dug wells tap shallow unconfined aquifers. Therefore, pumping from dug wells has an immediate effect on the shallow water table. However, since the dug wells are shallow, have small discharge capacity, and have a small zone of influence, the effect of water table decline is limited to a small area surrounding the wells. The constraints of low discharge can be partially avoided by withdrawing water at a high rate to cause adequate drawdown within a short period and stop pumping thereafter to allow recovery (Bhattacharya and Michael, 2003). If the rate of recovery is very slow, as in the situations where the surrounding soil/porous medium has a low saturated hydraulic conductivity, the drawdown effect in the close vicinity of the well lasts longer. This period can be farther lengthened by pumping a number of times in a day. The water



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so pumped can be used for irrigation in lieu of using the canal water, if the area is canal irrigated.

Sharma (1999) studied the effect in terms of vertical drainage and improvement in crop yield by pumping from a dug well in a shallow water table farm holding in the Barna Command area of Madhya Pradesh. The crops were soybean in kharif and wheat in rabi. It was found that the temporary water table decline due to pumping from dug well and using the water for irrigation, instead of the available canal water, could give a 14.6% and 27.3% increase in yield, respectively for the kharif soybean and rabi wheat as compared to the area where the irrigation was only by canal water. In the rabi season, the unpumped dug wells in the canal irrigated region recorded a rise in water table by 2 cm, whereas the pumped dug wells recorded a decline in water table by 15 cm from the start to the closure of the canal during the rabi season. For the pumped dug well, the well water was used for irrigation, not the canal water. Water table observations made in a number of auger holes, in the areas under canal irrigation and under well irrigation, revealed a reduction in the  $SEW_{100}$  (number of days when the water table were shallower than 100 cm) values in the rabi season from 76 in the canal irrigated region to 24 in the dug well irrigated region.

Based on the above information and discussion, it can be concluded that vertical drainage has many advantages. It is a means of controlling water table in the unconfined aquifer and leaky aquifer regions as well as it is a vital component of conjunctive use of surface water and groundwater which is considered an appropriate mechanism of land and water management against degradation, especially in canal command areas (Bhattacharya and Michael, 2003). Thus, it augments surface water supply and the additional water irrigates more area or makes more water available for irrigation in a given area. Also, with a proper mixing of surface water and groundwater, it is useful in irrigation even in the poor-quality groundwater regions. A constraint, perhaps in several countries, in adopting vertical drainage at all the places where it is needed is that it requires an assured supply of additional energy to operate a pumping system. In fact, the availability and cost of energy and the timely replacement of pumps and engines after their economic lifetime are the key determinants in the selection of vertical drainage.

### 12.3 Biodrainage System

#### 12.3.1 Concept of Biodrainage

All living plants transpire water. The source of the water is either irrigation water or groundwater. The transpiration capacity of a plant depends on its species root depth and spread, canopy area, leaf area and leaf structure. When the transpiration is met primarily by withdrawing groundwater, the process is known as biodrainage in the field of drainage engineering. The total water transpired from the groundwater reservoir in a region, and hence its drainage effect (i.e., effect on water table decline) in a region is a function of plant density and other plant factors. Rice plants transpire quite heavily but the process is not called biodrainage because the rice root system are shallow (30-40 cm deep) (Bhattacharya and Michael, 2003).

Medium to deep rooted plants in a shallow water table region may act as small capacity tubewells, constantly pumping groundwater to maintain their transpiration rates (FAO, 2002; Bhattacharya and Michael, 2003). The difference between the two is that in case of tubewell drainage, the area encompassed by the tubewell network is available for normal crop production

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but in the case of biodrainage by a cluster of plants, the area within the cluster cannot be used for normal crop production.

Use of plants to supplement the drainage effect of conventional drainage systems in reclaiming polders in the Netherlands has been reported by Raadsma (1974). Weed of a certain species were aerially sown over the area to be reclaimed from water logging, besides providing shallow trenches. Figures 12.2(a,b) illustrate the application of biodrainage systems in controlling water logging in the canal command of Indira Gandhi Nahar Project (IGNP), Rajasthan, India. Besides canal commands, the prospective sites for tree plantations for the purpose of biodrainage are government lands and fallow lands with low productivity (Bhattacharya and Michael, 2003).



**Fig. 12.2. (a) Inundated area caused by leakage alongside IGNP main irrigation canal; (b) Trees in background are the biodrainage system that dried-up the inundated areas along the main canal. (Source: FAO, 2002)**

### 12.3.2 Advantages and Disadvantages of Biodrainage

Kapoor (1998) and FAO (2002) have reported several advantages of biodrainage in comparison to the conventional drainage methods. The major advantages are that biodrainage is a low-cost measure, does not require gravity outlet and hence no physiographic constraint, operation and maintenance are required only at the plant establishment stage, no requirement of energy for operation and supply of fuel and fodder materials. Kapoor (1998) compared a row of trees, separated from another row at a distance, to a system of parallel subsurface drainage and suggested the use of one of the steady-state drainage design approaches for the determination of a suitable spacing between the tree rows when the water withdrawal rate from the tree row is known or can be estimated and is substituted for drainage coefficient in the design equation.

The disadvantages of biodrainage are that some area is required for growing the plants, which cannot be available for crop cultivation and that good-quality water should be available for plant establishment. According to Kapoor (1998), despite the advantages outweighing the disadvantages, it is not yet a recognized drainage method and it is necessary to conduct field studies on the evapotranspiration from afforested areas, chemical properties changes in the soil under the plants established for biodrainage, and the drainage effect within and outside the plantation area.



Other than providing drainage effect, which remains yet to be properly quantified in terms of the magnitude of water table decline under a specified tree density, certain tree species have been shown to improve soil chemical condition in the top 0-30 cm soil depth. Mishra et al. (2000) have reported changes in the chemical properties of the 0-30 cm soil under plantation densities of 5,000 to 20,000 trees per hectare after 10 years of plant establishment and have compared those with the corresponding chemical parameters in the unplanted area. The study was conducted at Dhaulakuan in Himachal Pradesh, India where the soils texture varies from sandy loam to loamy sand and the annual rainfall is 1600 mm. On average, in the top 15 cm soil of the planted area, the pH and EC registered declines varying from 4 to 9% (in the existing acidic range) and from 12 to 28%, respectively as compared to those of the unplanted area. For the 15-30 cm soil, the decrease in EC and pH varied from 2 to 39%. Other properties such as organic carbon, available N, P and K and exchangeable calcium and magnesium were reported to increase under the planted area varying from 14 to 60% in the top 15 cm of the soil and from 12 to 75% in the 15-30 cm soil.

### 12.3.3 Concluding Remarks

Research conducted in different parts of the world indicated that biodrainage is a viable non-conventional drainage technique (FAO, 2002). Much research on biodrainage has been completed, but more is required. Not all questions have been answered concerning the precise design of biodrainage systems, even in those areas where biodrainage systems have been found to be adequate in integrated water management of irrigation and drainage systems. Examples from several countries are available where vegetation, particularly trees and salt-tolerant plants, has been used to attain environmentally safe, and effective drainage and disposal systems (FAO, 2002).

More research on biodrainage is necessary to quantify the groundwater withdrawal rates by different tree species, their effect on water-table decline, their tolerance to water logging, irrigation water requirement at the time of their establishment and afterward, salt tolerance of the highly transpiring deep-rooted trees, salt balance in the soil under tree plantation, impact of the trees on the local environment (it has been found that the vegetation growth is usually poor under a eucalyptus tree), and the economics of biodrainage systems (FAO, 2002; Bhattacharya and Michael, 2003). Considering the capability of certain plants to grow satisfactorily under adverse soil and water environment, tree plantation may be a feasible alternative to yield remunerative products, especially in the chemically degraded and waterlogged soils where normal crop production is not possible. According to FAO (2002): "Drainage engineers should no longer ignore the opportunities that biodrainage systems can offer. When planning for projects, the agricultural sector increasingly feels pressure from other users of the environment. For example, it is becoming increasingly unacceptable to set aside land exclusively for routinely designed irrigation and drainage projects. This illustrates the possible advantages of biodrainage systems".



### Lesson 13 Salt Balance of Irrigated Land

#### 13.1 Introduction

All soils contain some salt, which originate from parent rocks as they weather into the soil. In this process, the salts are carried downwards with the percolating water (known as '**leaching**') where they may either precipitate or continue to be transported in solution, ultimately ending up in the sea. In exceptional case, a high salt-content in the soil may be directly related to the soil's parent material; this type of soil salinity is termed **primary salinity or residual salinity**. The salinity of marine soils is a special case of residual salinity. Marine deposits may remain saline from past geological periods up to the present time in situations where there is very little leaching (e.g., arid climates and poor drainage).

Undoubtedly, the most common cause of high soil salinity is **salinisation**, which is broadly defined as the process of accumulation of salts in the upper soil layers from some outside source. Frequently, salinisation involves a reverse of the leaching process, i.e., the return of the leached salts into upper soil layers, usually carried by water. Therefore, salinisation is often termed **secondary salinity**. A great deal of present-day salinisation is caused by human activities, especially by wrong irrigation practices. For example, poor quality of irrigation water can pose salinisation and/or **sodification** hazards. Hence, prior analysis and evaluation of the water to be used for irrigation is essential to avoid these hazards. As to salt problem in agricultural lands, three types of hazards can be distinguished (Smedema and Rycroft, 1983): **(i)** salinity hazard (danger that the use of irrigation water will lead to osmotic problems in the soil/plants), **(ii)** sodicity hazard (danger that the use of irrigation water will lead to sodic problems), and **(iii)** toxicity hazard (danger that the use of irrigation water will lead to toxic problems). **Salinity hazard** can be diagnosed on the basis of the EC value of the irrigation water. The **sodicity hazard** can be diagnosed on the basis of  $EC_i$  [EC of the irrigation water and  $SAR_i$  (SAR of the irrigation water)]. **Toxicity hazards** are: Na-toxicity, Cl-toxicity and Boron-toxicity.

The occurrence of salty soils, although not restricted to hot, dry climates, is much more prevalent under these conditions than in the temperate, humid climates. In temperate climates, there is usually sufficient excess water percolating downwards through the soil to maintain low salt levels in the upper soil layers. However, soil and drainage conditions also have a great influence because they largely determine the physical possibilities for leaching and for the removal of excess salts from the land. Salts occur in the soil in one of the following three forms (Smedema and Rycroft, 1983): **(a)** salt ions dissolved in the soil water (i.e., soil solution), **(b)** cations adsorbed on the negatively charged surfaces of the soil particles (adsorption complex), and **(c)** precipitation salts. Dynamic exchange equilibriums exist between the cations in the soil solution and those adsorbed on the complex, and also between dissolved and precipitated salts.

Note that the salt composition in a soil is generally a reflection of the salt composition at its source of origin (i.e., parent-rock material, groundwater seawater, etc.). However, various

desalinisation-resalinisation cycles over the time may produce considerable changes in the original salt composition.

### 13.2 Salinisation and Akalisation Problems

**Soil salinisation** generally refers to the development of salinity in non-salty soil, especially to the development of a non-saline soil into a saline soil. It involves an increase of the soluble salt content of the soil, resulting in an increase of salt concentration of the soil solution. Depending on the salt composition, the ESP may also increase and sodic soils may develop. **Sodification** almost never occurs in isolation, rather it is usually triggered off by salinisation (Smedema and Rycroft, 1983). Note that salinisation is the basic process underlying the development of almost all salty soils, whether saline or sodic. The problems caused by soil salinity can be grouped into three classes as follows, each class of problem being related to a particular aspect of soil salinity (Smedema and Rycroft, 1983):

**(i) Osmotic Problems:** They are caused by a high total salt concentration of the soil solution, which raises the osmotic pressure that can be exerted by the soil solution. This makes it more difficult for the plant roots to uptake water from the soil.

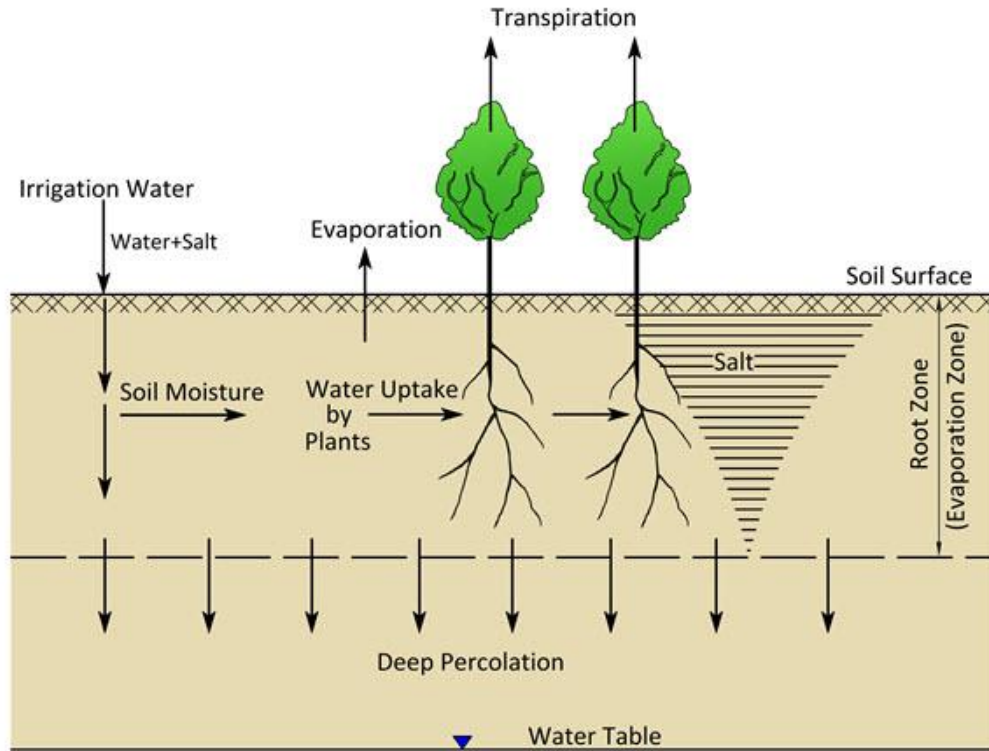
**(ii) Toxic Problems:** They are caused by a high concentration of some particular ion in the soil solution or by the imbalance between two or more ions. They severely harm plant growth.

**(iii) Dispersion Problems:** They are caused by relatively high percentage occupancy of the soil exchange complex by  $\text{Na}^+$ , which results in poor soil structure due to easy dispersion of the colloids in the soil. They also produce detrimental effects on plant growth.

The detailed discussion of the above salinity problems can be found in Smedema and Rycroft (1983). Salinisation processes discussed in this lesson are those leading to high salinity in the upper soil layers and specifically in the root zone (root-zone salinisation). Two main processes viz., salinisation by irrigation and salinisation by groundwater evaporation are discussed which are related to irrigation, thereby emphasizing the fact that most serious salinisation problems occur in irrigated areas (Smedema and Rycroft, 1983).

#### 13.2.1 Direct Salinisation by Irrigation

All water for irrigation contains some salts. Most irrigation water originates as rainfall which percolates through the soil towards the groundwater and onwards towards the rivers, collecting salts on its way. The use of groundwater for irrigation poses special problems because this water in particular may contain a considerable salt load. This is especially true for arid climates where groundwater is not refreshed so frequently as in humid climates due to low rainfall and high evaporation, and hence salts tend to become more concentrated. Rivers often have a higher salt content during low-flow seasons than during flood seasons. Also, salt conditions may also vary along the course of a river.



**Fig. 13.1. Schematic of direct salinisation by irrigation. (Source: Modified from Smedema and Rycroft, 1983)**

Every irrigation event brings a certain amount of salt into the root zone. As the water is lost by evapotranspiration, the salts remain behind in the root zone/evaporation zone (Fig. 13.1) where they will accumulate as is brought in by the irrigation water (salt balance concept) unless an equivalent amount of salt is removed from this zone. The salt uptake by crops is small, salt removal depending almost completely on leaching by deep percolation (i.e., washing out of salt by water percolating through the soil to the depth below the root zone). This type of salinisation is most likely to occur under conditions where the salt influx to the root zone is high and/or the salt outflux from the root zone is low.

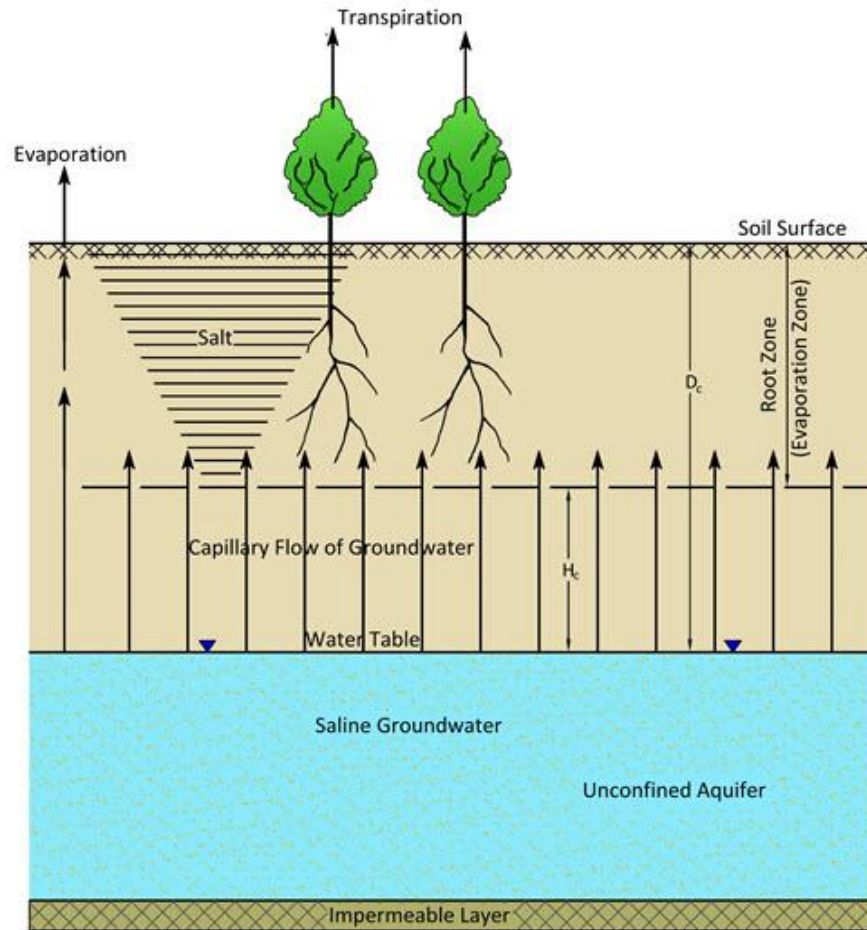
High salt influx conditions prevail when the climate is hot and dry (high irrigation water requirements), and the water is saline. On the other hand, low salt outflux conditions prevail when:

- The climate is hot and dry. That is, there are low rainfall and high evaporation, and hence little excess rain goes into deep percolation.
- Minimum irrigation practices are followed, i.e., just enough water is applied to meet the crop evapotranspiration, leaving no excess for deep percolation (i.e., under-irrigation).
- Drainage conditions are poor, which result in insufficient percolation and drainage discharge.

### 13.2.2 Salinisation by Groundwater Evaporation

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Evaporation of saline groundwater from the soil is a common cause of soil salinisation. The groundwater may evaporate directly from the water table when the latter occurs within the evaporation zone, or it may be drawn from deeper down as the evaporation itself will create a gradient for upward capillary flow from the water table into the evaporation zone. It is also known as **capillary salinisation**. As the water evaporates, the salts remain behind in the evaporation zone (Fig. 13.2). Hence, this type of salinisation takes place only when saline groundwater occurs within such a depth that upward capillary flow is able to reach the evaporation zone.



**Fig. 13.2. Schematic of capillary salinisation. (Source: Modified from Smedema and Rycroft, 1983)**

A great deal of irrigated land is underlain at shallow depth by saline groundwater. Prior to the introduction of irrigation, groundwater recharge is usually low, consisting only of deep percolation due to rainfall which is also low under the arid climatic setting of a typical irrigation scheme. In general, the natural groundwater discharge can easily cope with such a low recharge, even with deep water tables (low head). The deep percolation component of the irrigation can in some cases (permeable soil, poor irrigation practices and management) amount to 20-30% of the irrigation water supplied and recharge under irrigation can easily rise to a multiple of the original recharge. Water tables will rise up to a level which produces sufficient hydraulic head for the required higher discharge. There are numerous irrigation projects where this has happened with water tables rising from 20-30 m depth to 1-2 m depth below the soil surface during a period of 10-15 years the start of the project (Smedema and Rycroft, 1983).

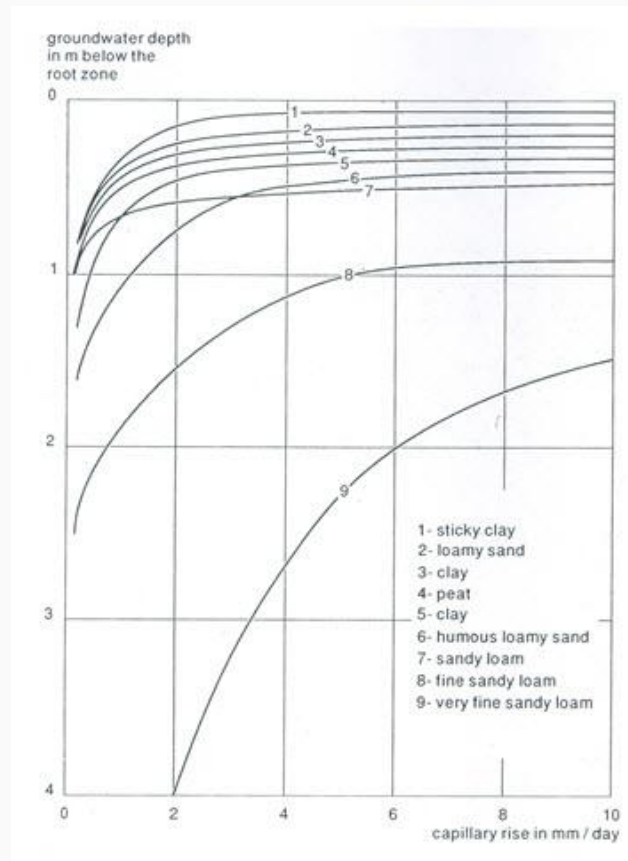


### 13.2.3 Critical Water Table Depth

Capillary flow upwards from a water table can reach to great heights but the rate of flow generally decreases with increasing height above the water table. So the rate of upward salt movement, being proportional to the rate of upward flow, also decreases as the distance between the evaporation zone and the water table increases (Fig. 13.3). The distance at which the upward capillary flow becomes too small for any significant upward salt movement is called **critical capillary height ( $H_c$ )**. Its value depends on following two factors (Smedema and Rycroft, 1983):

(a) **Soil type:** Soils with a large proportion of their pores of a small size, have large  $H_c$  values (e.g., fine sandy loam, silty loam). Coarse sand has a small  $H_c$  value, whereas well structured medium to fine soils have intermediate values (Fig. 13.3).

(b) **Salt concentration of groundwater:** Upward salt movement is the product of 'Flow rate' × 'Salt concentration'. Therefore,  $H_c$  values should increase with increasing groundwater salinity (Fig. 13.4). In general, very little capillary salinisation will occur provided the salt concentration in the upper groundwater layer remains <1000 mg/L (EC £ 1.5 mmhos/cm).



**Fig. 13.3. Capillary rise of groundwater to the root zone for different groundwater depths and soil textures under moist conditions (soil water tension in the root zone  $\gg$  5 m). (Source: Doorenbos and Pruitt, 1977)**

In situations where the groundwater inflow or outflow in the area is insignificant, the **critical water table depth ( $D_c$ )** may be estimated as the depth to which the water table falls towards the end of a long dry period. Some indicative values for  $H_c$  are given in Table 13.1 (Smedema and Rycroft, 1983):



Table 13.1. Indicative values of critical capillary heights for selected soils

Sl. No.	Type of Soil	Critical Capillary Height ( $H_c$ )
1	Sand (Coarse @ Fine)	$H_c = 50 @ 75$ cm
2	Loamy Sand, Sandy Loam	$H_c = 100-150$ cm
3	Fine Sandy Loam, Silt Loam	$H_c = 150-200$ cm
4	Loam, Clay Loam, Clay	$H_c = 100-150$ cm

The values given in Table 13.1 apply to uniform soil profiles. The stratification of soils generally reduces the high values, but it may increase the low values.

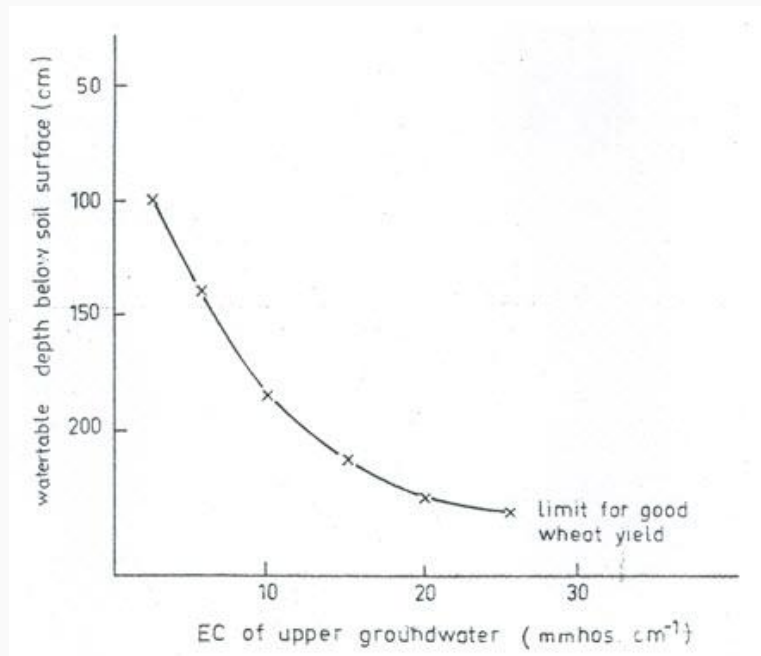


Fig. 13.4. Interaction between critical water table depth and salt concentration of groundwater in Lower Indus, Pakistan. (Source: Smedema and Rycroft, 1983)

### 13.2.4 Sodification

**Sodification** (also known as 'Alkalisiation') involves the replacement of other cations on the adsorption complex by sodium. Significant replacement only occurs when  $Na^+$  becomes the dominant soluble cation in the soil solution (high SAR-value). This may occur when the salinizing source is  $Na^+$  rich, when the soil solution becomes more concentrated or when for other reasons the salinisation processes favour the accumulation of  $Na^+$ . The presence of  $CO_2^{--}$  and  $HCO_2^-$  in the soil solution is especially important. These anions form salts with  $Ca^{++}$  which are only slightly soluble while the corresponding  $Na^+$  salts are highly soluble. Their presence

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thus leads to a relative enrichment of the soil solution with  $\text{Na}^+$  as the overall salt concentration increases because the  $\text{Ca}^{++}$  salts precipitate.

Sodic soils, having a low concentration of salts in the soil solution but a high  $\text{Na}^+$  occupancy on the complex also occur. The high values of ESP that these soils exhibit are unlikely to have developed under conditions of low salinity. In fact, these soils almost always develop from saline-sodic soils by a leaching process in which the soluble salt concentration of the soil decreases more rapidly than the  $\text{Na}^+$  occupancy on the complex.

### 13.3 Salt Balance of Irrigated Land

#### 13.3.1 Dynamic Salt Balance Equation

The salt balance for a root zone under irrigation (Fig. 13.5) can be expressed as:

$$I \times C_i + P_e \times C_p + GW \times C_{gw} = DP \times C_{dp} + \Delta S \quad (13.1)$$

Where,  $I$  = irrigation water entering the root zone,  $C_i$  = salt concentration of the irrigation water,  $P_e$  = effective precipitation (i.e., precipitation entering the root zone),  $C_p$  = salt concentration of the rainwater,  $GW$  = groundwater inflow into the root zone (i.e., capillary flow into the root zone),  $C_{gw}$  = salt concentration of the groundwater,  $DP$  = deep percolation from the root zone,  $C_{dp}$  = salt concentration of the deep percolated water, and  $\Delta S$  = change in salt content of the soil solution in the root zone.

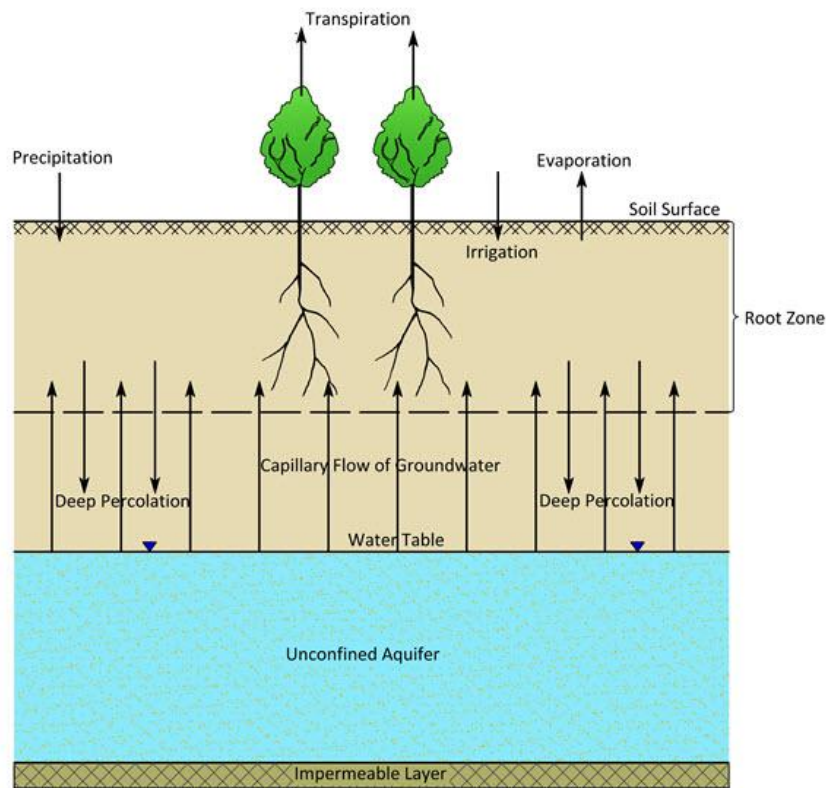


Fig. 13.5. Water balance of an irrigated land. (Source: Modified from Smedema and Rycroft, 1983)

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I, P, GW and DP may be expressed in various units although mm/period is most convenient (e.g., mm/month, mm/season, etc). The correct unit for salt concentration is mg/L, but since C and EC are linearly related mhos/cm may also be used. Note that Eqn. (13.1) applies to the soluble salts only. It should also be noted that this equation ignores some of the components of the more detailed salt balance relation given by Rhoades (1974). The salt balance components which have been ignored are: the salt input due to weathering of soil mineral, salt input through fertilisers and amendments, temporarily precipitated salt input from irrigation water that may re-dissolve, and the salt output through uptake by the plants. All these salt balance components are much smaller than the other components and their elimination from the detailed salt balance relation is justified for field works on drainage and land reclamation. For example, the salt uptake by common crops can be either neglected or assumed to be offset by the fertilizer application (Smedema and Rycroft, 1983).

### 13.3.2 Leaching Requirement

Equation (13.1) reduces to Eqn. (13.2) under the following conditions (Smedema and Rycroft, 1983):

- (i)  $C_p$  is negligible small as is the case for normal rainwater which has an EC-value of 0.02-0.05 mmhos/cm; close to the seawater, however, the salt content of the rainwater may rise to EC = 0.20-0.30 mmhos/cm.
- (ii)  $C_{gw} = C_{dp}$ , a reasonable assumption for averages over annual periods; less valid for short time periods.
- (iii)  $DS = 0$ , i.e., the salt balance is in equilibrium (i.e., salt contents in the root zone at the beginning of the period and at end are equal).

The assumption of  $DS = 0$  means that there is no change in the salt content of the soil solution from what it was at the beginning of the period under consideration to what it is at the end of the period. If the period considered is one irrigation season, it implies that inter-seasonally, there is neither a cumulative salt build up nor a cumulative salt depletion from the soil depth (root zone) under consideration. This assumption tends to be more justified over a long period such as a season or a year. The assumption of equality of the salt concentration of the groundwater and deep percolated water is also reasonably valid in terms of their average values over a long period. However, the above assumptions are grossly violated during short time periods such as day or week.

$$I \times C_i = (DP - GW) \times C_{dp} = LR \times C_{dp} \quad (13.2a)$$

Or,

$$I \times EC_i = (DP - GW) \times EC_{dp} = LR \times EC_{dp} \quad (13.2b)$$

Where, LR = leaching requirement, which is the excess of deep percolation over groundwater inflow into the root zone (GW).

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Note that when a water quantity LR satisfying Eqn. (13.2) is drained from the root zone, as much salt is leached from the root zone as is brought in by the irrigation. Eqn. (13.2b) can be rewritten as follows:

$$LR = \left( \frac{EC_i}{EC_{dp}} \right) \times I \quad (13.3)$$

Equation (13.3) expresses LR as a fraction of I, i.e., the fraction of the infiltrated irrigation water that must go into deep percolation in order to maintain a salt balance in the root zone. Thus, **leaching requirement (LR)** is a fraction of the amount of irrigation water and the fraction is the ratio of the salinity of the irrigation water to the salinity of the deep percolated (drained)

water. The fractional factor  $\frac{EC_i}{EC_{dp}}$  is called the leaching fraction or leaching percentage when

expressed as  $\frac{EC_i}{EC_{dp}} \times 100$ .

It is obvious from Eqn. (13.3) that for a given irrigation water quality ( $EC_i$ ), the leaching requirement will increase if the deep percolated water electrical conductivity ( $EC_{dp}$ ) is to be decreased. Under real-world conditions,  $EC_i$  is always less than  $EC_{dp}$ . Hence, their ratio is always less than 1. In a hypothetical situation, when there is no salts present in the soil solution in the excess of the salt concentration of the irrigation water, LR and I becomes equal. This means that there is no requirement of water in excess of irrigation requirement for the purpose of leaching. However, in the actual field situation, since the salt concentration of the soil solution is higher than the salt concentration of irrigation water, the actual quantity of water to be applied for both irrigation and leaching will be the sum of LR and the irrigation water requirement (I), i.e.,

$$\left[ \left( \frac{EC_i}{EC_{dp}} \right) \times I + I \right].$$

Moreover, in an equilibrium situation, the following water balance also holds (Fig. 13.5):

$$I = (ET - P_e) + (DP - GW) \quad (13.4)$$

In this equation,  $(ET - P_e)$  is the rainfall deficit (i.e., Net crop irrigation requirement, designated as  $I_c$ ), while the difference  $(DP - GW)$  represents the leaching requirement (LR). Thus, Eqn. (13.4) can be written as:

$$I = I_c + LR \quad (13.5)$$

Where, I is called total irrigation requirement (i.e., Net crop irrigation requirement + Leaching requirement). Combining Eqns. (13.3) and (13.5) yields:

$$LR = \frac{EC_i}{EC_{dp} - EC_i} \times I_c \quad (13.6)$$

The required LR can be calculated using Eqn. (13.6), if the values of  $EC_i$  and  $I_c$  are known and a value of  $EC_{dp}$  is selected on the basis of an acceptable level of salinity in the root zone.

### 13.3.3 Computation of Leaching Requirement

Values for  $EC_{dp}$  should be determined experimentally by sampling the soil below the root zone (the upper groundwater or the drain water). In planning, the values of  $EC_{dp}$  are usually set equal to the maximum salinity which can be tolerated in the root zone. On the basis of certain considerations to deal with complex flow and salt transport in the root zone, the values for  $EC_{dp}$  in Eqn. (13.6) are often taken as (Rhoades, 1974):

- $EC_{dp} = 2EC_e25\%$  in cases where crops are mostly sensitive, or rather low leaching efficiencies are to be expected or where a high standard of salinity control is desirable.
- $EC_{dp} = 2EC_e50\%$  in cases where crops are more tolerant to salinity, or high leaching efficiencies are to be expected or a somewhat lower salinity control is considered acceptable.

The value of  $EC_e25\%$  and  $EC_e50\%$  can be obtained from the standard table given in FAO (1976).

**Example Problem:** Calculate LR, total irrigation requirement (I) and leaching percentage (LP) for the following data (Smedema and Rycroft, 1983):

$EC_i = 1.2$  mmhos/cm,  $EC_{dp} = 12.0$  mmhos/cm (= 2  $\times$   $EC_e50\%$  for the crop to be grown), and  $I_c = 6$  mm/day.

**Solution:**

We know that

$$LR = \frac{EC_i}{EC_{dp} - EC_i} \times I_c = \frac{1.2}{12.0 - 1.2} \times 6.0 = 0.7 \text{ mm/day.}$$

$$I = I_c + LR = 6.0 + 0.7 = 6.7 \text{ mm/day.}$$

$$\text{Leaching Percentage} = \frac{EC_i}{EC_{dp}} \times 100 \% = \frac{LR}{I} \times 100 \% = \frac{0.7}{6.7} \times 100 \% = 10\%, \text{ Ans.}$$

This example shows the salt balance in the root zone is maintained when a minimum of 10% of the infiltrated irrigation water goes as deep percolation. A deep percolation loss of this order or

even higher is quite common under surface irrigation methods, and hence there is generally no need to over-irrigate to satisfy the leaching requirement (Smedema and Rycroft, 1983).

### 13.3.4 Regional Salt Balance

The basic principle of the salt balance discussed above can also be applied regionally as follows:

Salt Influx in a Region - Salt Outflux from the Region = Change in Salt Storage in the Region  
(13.7)

The salt influx or outflux can be calculated as: Water flux  $\times$  Salt concentration  $\times$  Time. Both the water flux and the salt concentration vary during the year. Therefore, annual fluxes have to be determined by summing the assumed uniform salt fluxes occurring during shorter periods of time. Dimensional units could be  $\text{m}^3/\text{s}$  or  $\text{mm}/\text{day}$  for the water flux and  $\text{g}/\text{L}$ ,  $\text{ppm}$  or  $\text{mmhos}/\text{cm}$  for the salt concentration.

The water fluxes in a region, especially those due to groundwater, are very difficult to quantify. Hence, we often have to rely on estimates (Smedema and Rycroft, 1983). If water inflows into and outflows from regions are denoted by  $Q_i$  and  $Q_d$ , respectively and their salt concentrations are denoted by  $C_i$  and  $C_d$ , the regional salt balance equation can be written as follows:

$$\sum Q_i \times C_i - \sum Q_d \times C_d = \Delta S \quad (13.8)$$

Equation (13.8) can be used to examine whether in the long term salts are likely to accumulate in a region (e.g., irrigated area).





### Lesson 14 Reclamation of Chemically Degraded Soils

#### 14.1 Overview of Salt-Affected Soils and Acid Soils

##### 14.1.1 Classification of Salt-Affected Soils

Salt-affected soils are generally classified as saline, alkali or saline-alkali, based on the values of EC, ESP and pH of the soil saturation extract. These classes are defined as follows (Bhattacharya and Michael, 2003):

(i) **Saline Soil:**  $EC_e > 4$  dS/m,  $ESP < 15\%$  and  $pH < 8.5$ .

(ii) **Alkali Soil:**  $EC_e < 4$  dS/m,  $ESP > 15\%$  and  $pH > 8.5$ .

(iii) **Saline-Alkali Soil:**  $EC_e > 4$  dS/m,  $ESP > 15\%$  and  $pH = 8.5$  or slightly higher.

The above classification of salt-affected soils help to identify whether salinity is the major constraint to agriculture or soil alkali condition or both salinity and alkali condition which are adversely affecting the plant growth and crop yield. Based on such understanding, appropriate remedial measures can be selected for the reclamation of lands having above types of soils or for the selection of crops which can survive and yield reasonably well even under such adverse soil conditions.

In general terms, and from agricultural viewpoint, the soils of all the above classes can be considered as chemically degraded because of poorer crop performance in such soils compared to that in the normal soils (Bhattacharya and Michael, 2003). Other types of chemically degraded soils are those which have too poor soil fertility to support plant growth and which are polluted by human activities such as dumping of untreated industrial and mine wastes containing toxic chemicals in streams or on the land. Nutrient availability to the plant is dependent upon the degree of salt problem. Usually, salt-affected soils need higher doses of fertilisers to meet the plant requirement. Plant roots experience difficulty in extracting water from the soil if the concentration of the dissolved salts in the soil solution is high, which raising its osmotic pressure. This is why, in highly saline soils, despite having adequate soil moisture, plants may show wilting symptom similar to the situation when there is a lack of adequate soil moisture (Bhattacharya and Michael, 2003). Intensive agriculture, supported by irrigation may also lead to chemical degradation of soil through the depletion of nutrients and the rise of water table (water logging).

##### 14.1.2 Acid Soils

Apart from salt-affected soils, a special type of degraded soil is **acid soil**. Acid soil is defined as a soil having pH of its saturation extract less than 7. Acid soils are also considered degraded because plant growth and crop production are directly and seriously hampered under low pH conditions of the soil solution and indirectly through lower nutrient uptake capability of the plants in the acidic root zone environment. Fortunately, the severely acidic soils occupy much

smaller area in India as compared to the severely salt-affected soils (Bhattacharya and Michael, 2003). Also, unlike alkali soils, a highly acidic soil does not remain so throughout the year because the rains during the rainy season dilute the acids considerably. This is particularly true in monsoon-dominated climatic regions.

An important reason of soil acidity is the oxidation of Sulphur compounds in the soil under the action of atmospheric Oxygen and eventual conversion of the  $\text{SO}_2$  into  $\text{H}_2\text{SO}_4$  with the addition of water. Sulphur and its compounds may be present in the soil or may have been dumped along with the wastes while extracting metal ores from mines (ores of Copper, Lead, Iron and Zinc mainly occur in their Sulphide form) or may have come due to land inundation (as in the case of the coastal Kerala) by seawater which contains  $\text{H}_2\text{S}$  (Bhattacharya and Michael, 2003). Under this situation, the acidity may be very severe having soil pH as low as 4 or even lower.

Acid soils are also found in the lateritic regions of India such as in West Bengal, Bihar, Odisha, Goa and Karnataka. Acidity due to high rainfall as the major factor is not severe because pH is normally above 5, with some exceptional locations where it may be lower than this. Besides the causative factors of the oxidation of Sulphur compounds and local rainfall behaviour, soil acidity is also caused due to the acidic nature of some of the constituents of the parent material of the soil. In general, acid soils are found in the north, north-east, east (including the coastal region), south and west coastal regions of India (Bhattacharya and Michael, 2003). The most severely acidic soils are found in the low-lying (below sea level) bunded rice fields in the Kuttanand region of Kerala, where pH as low as 3.2 has been reported (Mathew et al., 1993). The states like Punjab, Uttar Pradesh, major parts of Bihar and Madhya Pradesh, Rajasthan, Gujarat and Maharashtra do not suffer from the problem of soil acidity. A comprehensive discussion on the occurrence, genesis, nutrient status, crop response and management of acid soils of India is given in Anonymous (1976). A brief description of the reasons for forming acid soils, their types and the economic feasibility of acidity amelioration is presented by Panda et al. (1996).

The commonly used method of neutralizing soil acidity is the application of lime. This is routinely practiced by the rice farmers of the Kuttanand region in Kerala. Such chemical amendment, supplemented by subsurface drainage and application of suitable doses of nutrients, has been found to improve rice productivity to a large extent.

### 14.1.3 Distribution of Chemically Degraded Soils in India

Abrol and Gupta (1991) provided an estimate of total salt-affected soils in India, as shown in Table 14.1. This table shows that the total estimate of salt-affected soils is 7.044 Mha. The geographical distribution of sodic soils, inland saline soils and coastal saline soils in the Indian mainland is shown in Fig. 14.1 (Abrol and Gupta, 1991).

Table 14.1. Distribution of salt-affected soils in the Indian mainland (Source: Abrol and Gupta, 1991)

Sl. No.	Category	States	Area (Mha)
1	Arid and Semi-Arid Regions	Gujarat, Haryana, Punjab, Rajasthan, Uttar Pradesh	1.0
2	Indo-Gangetic Plains	Bihar, Haryana, Madhya Pradesh, Punjab, Rajasthan, Uttar Pradesh	2.5
3	Medium and Deep Black Soil Regions	Andhra Pradesh, Gujarat, Karnataka, Madhya Pradesh, Maharashtra	1.42
4	Coastal Regions:		
	• Arid	Gujarat	0.714
	• Deltaic and Humid	Andhra Pradesh, Odisha, Tamil Nadu, West Bengal	1.394
	• Acidic	Kerala	0.016
<b>Total = 7.044</b>			

A relatively recent report (Singh, 1994) mentions the salt-affected area in India as about 8.57 Mha, comprising about 3.47 Mha in various canal command areas, 3.03 Mha in non-canal command areas and 2.07 Mha in the coastal regions. This report also mentions that the area under acid soil having pH < 6.5 is 49 Mha, of which the area having pH < 5.5 is 26 Mha. Another study (Suraj Bhan, 1995) reports the total salt-affected soils (including coastal saline soil) as

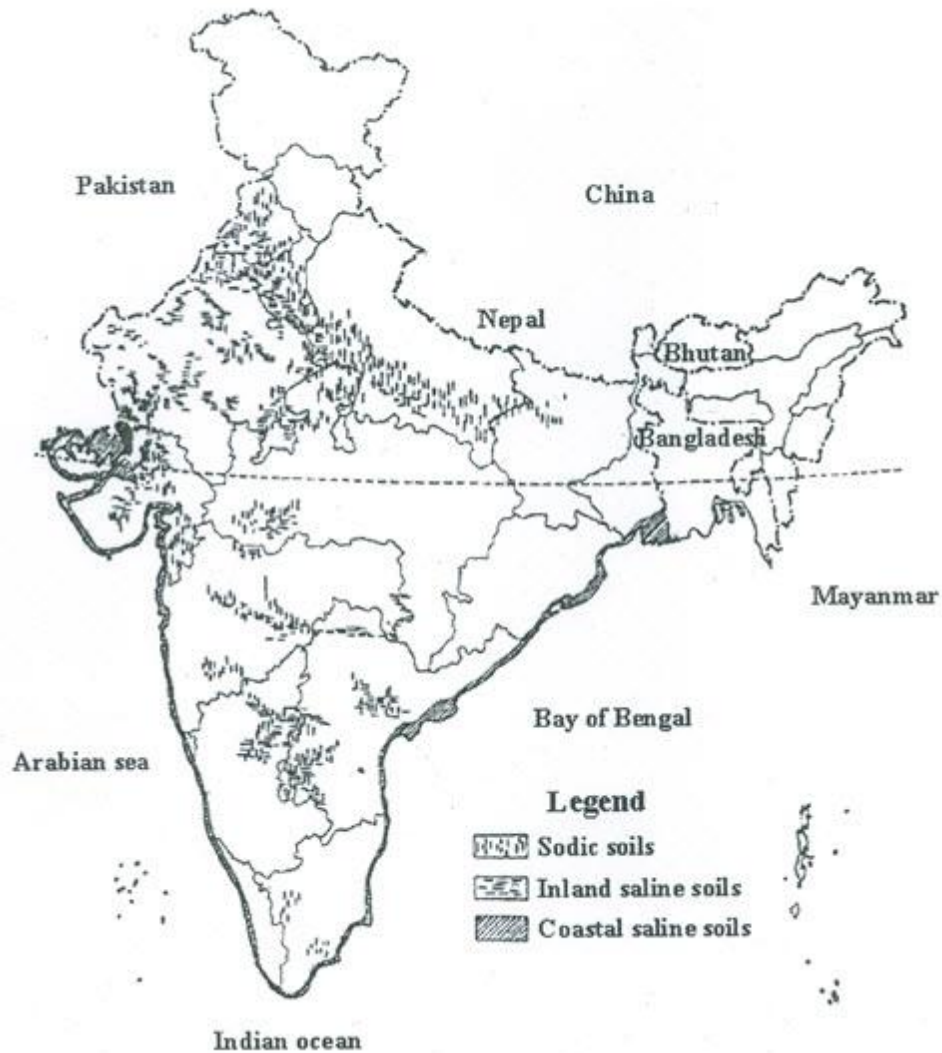


Fig. 14.1. Approximate distribution of salt-affected soils in India. (Source: Abrol and Gupta, 1991)

7.028 Mha and acid soils as 0.016 Mha. It should be mentioned that soil acidity gets diluted during rainy seasons. With the addition of chemical amendments and drainage, such soils are capable of giving good rice yield in high rainfall regions where rice is a preferred crop. In addition, certain plantation crops, especially tea, prefers an acidic soil environment with a pH 4.5 and 5.8 (Rehman, 1991). Such lands, though degraded based on the pH level, are not constraints to agricultural production.

## 14.2 Reclamation of Saline Soils

### 14.2.1 Introduction

Reclamation of chemically degraded soils is based on the concept of removal (leaching) of dissolved salt solutions from the root zone. In case of saline soils, addition of adequate quantity of water and its percolation through the soil dilutes the soil water in the soil profile and pushes them downward; this process is called **leaching**. If water table is shallow or natural subsurface drainage is restricted, the percolated soil solutions are to be removed by installing a subsurface

drainage system. Even so, the permanent reclamation may be difficult because the hot and dry weather prevailing over several months (particularly in the monsoon climate as in India) resalinizes the soil profile. In the coastal region, there may be considerable upward flux of saline groundwater from below and that would also require long-term functioning of the subsurface drainage system to continuously remove salts through leaching. Fortunately, a well-designed and executed subsurface drainage system has a long life and the leaching requirement is automatically taken care as long as freshwater is used for irrigation and leaching is practiced (if necessary).

### 14.2.2 Estimation of Leaching Requirement

#### (1) Theoretical Estimation

In the most simple way, leaching requirement (LR) is the difference between the deep percolation from the root zone and the capillary flow from groundwater to the root zone, both expressed in units of depth of water over a certain period (e.g., mm/day, mm/month and so on). Under irrigation or rainfall, the outflow from the root zone is always greater than the inflow into the root zone due to upward capillary movement of water from deeper layers. Hence, LR is a positive quantity. As mentioned in Lesson 13, LR can also be expressed as a fraction of irrigation water that must be deep percolated to maintain a desirable salt concentration in the root zone (i.e., neither depletion nor build up of salt). For the reclamation of saline soils, the salt content of the root zone should be depleted. Therefore, conceptually the **LR** can be defined as the amount of water that has to move down beyond the root zone to maintain a favorable salt balance in the root zone.

Hypothetically, if one assumes that the applied irrigation water has negligible EC and further assumes that the added irrigation water act like a piston in pushing down the saline water in a saturated soil, then the leaching requirement becomes simply the depth of water required to saturate the soil to a given depth. If this happens, then a saline soil could be reclaimed by leaching with minimum possible quantity of added irrigation water and the existing soil salinity would reduce to zero or to a negligible value due to such a hypothetical leaching. In reality, however, such type of irrigation water quality is not available in practice; even rainwater has a measurable EC in the range of 0.1 to 0.2 dS/m. Moreover, a piston like water movement does not take place through the soil profile. While some of the added water first saturates the soil, some portion moves down faster through larger capillary pores and cracks, particularly in unsaturated soil comprising swelling and shrinking type of clays. The water that moves down faster, does not get an opportunity to thoroughly dilute the salt solutions in the soil pores, and hence does not perform proper leaching. The part of the added water that moves through the soil pores mixes with the saline soil water and the solution moves down under gravity. The phenomenon of leaching and the concept of leaching requirement can be better described through a general and fundamental salt balance relationship. Such a relationship, containing all the possible input and output components has been described by Rhoades (1974). Since many of the components considered by him may have insignificant contribution to the overall salt balance, a simpler salt balance model is sufficient to understand the leaching requirement. The simple salt balance model for irrigated lands can be written in words as:

Mass of Salt Added to the Soil = Mass of Salt Extracted from the Soil + Change in the Salt Content of the Soil.

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The above statement can be mathematically expressed as Eqn. (13.1) of Lesson 13. The salt addition to the soil is through irrigation water and through the capillary rise of groundwater. The salt extraction takes place through the water that deep percolates beyond the root zone.

For using Eqn. (13.3) of Lesson 13, let's consider that the irrigation requirement for a three-month cropping season is 275 mm and the electrical conductivities of irrigation water and deep percolated water are 1 and 6 dS/m, respectively (Bhattacharya and Michael, 2003). Therefore, leaching requirement (LR) from Eqn. (13.3) will be:

$$LR = \frac{1}{6} \times 275 \approx 46 \text{ mm for three months.}$$

The total water needed to satisfy both irrigation and leaching requirement is 321 mm. Since, irrigation application efficiency is less than 10%, actually more than the above quantity of water is to be applied. For example, if the irrigation application efficiency is 75%, the total amount of

water to be applied to satisfy crop water requirement is  $\left(\frac{275}{0.75}\right) \approx 367$  mm in three months, which is more than the sum of the net irrigation requirement (275 mm) and the leaching requirement (46 mm). The excess water application due to lower than 100% application efficiency will eventually deep percolate beyond the root zone. Therefore, the application of a total of 367 mm water in three months will take care of both the irrigation and leaching requirements.

### (2) Leaching Efficiency

Recall Eqn. (13.6) which is given as:

$$LR = \frac{EC_i}{EC_{\phi} - EC_i} \times I_c$$

Note that  $EC_{dp}$  is the electrical conductivity of the deep percolated water beyond the root zone. This water may be considered as the subsurface drainage effluent, if there is a subsurface drainage system to intercept the water deep percolating beyond the root zone. Gravitational water movement starts when the soil moisture content exceeds the field capacity. Therefore, the electrical conductivity (EC) of the deep percolated water may be roughly assumed to be the same as the electrical conductivity of the soil solution at field capacity ( $EC_{fc}$ ), i.e.,  $EC_{dp} = EC_{fc}$ . This will be the case when all of the deep percolated water actually travels through the soil pores before leaving the root zone. However, the water added at the soil surface for the leaching of salts does not move in such a fashion. Normally, a fraction of the added water will deep percolate beyond the root zone faster without mixing with the soil water and the remaining fraction will mix with the soil water and the mixture will move down. If  $L_e$  is the fraction of added water that moves down after mixing, then  $(1-L_e)$  is the fraction that moves without mixing. Considering that the added water is the irrigation water (I) with electrical conductivity of  $EC_i$  and  $EC_{dp}$  is the overall electrical conductivity of the deep percolated water (including both the above-mentioned fractions), then more correct expression for  $EC_{dp}$  will be:



$$EC_{dp} = L_e \times EC_{fc} + (1 + L_e) \times EC_i \quad (14.1)$$

Substituting the above value of  $EC_{dp}$  in Eqn. (13.6) of Lesson 13, we have:

$$LR = \frac{(ET - P_e) \times EC_i}{[L_e \times EC_{fc} + (1 - L_e) \times EC_i - EC_i]}$$

$$= \frac{(ET - P_e) \times EC_i}{[L_e \times (EC_{fc} - EC_i)]} \quad (14.2)$$

The term  $L_e$  in Eqn. (14.2) is known as '**leaching efficiency**' or '**leaching efficiency fraction**' or '**leaching efficiency factor**' and its theoretical limits vary from 0 to 1. In using Eqn. (14.2), a maximum permissible value of  $EC_{fc}$  is to be assigned. Also, Eqn. (14.2) is valid for the dry season when ET exceeds effective precipitation ( $P_e$ ). In the wet season, the rainfall is assumed to take care of leaching. The EC of the irrigation should be known. The total water to be applied is the sum of the irrigation requirement and the leaching requirement. For the low-level of salinity hazard, it may not be necessary to estimate leaching requirement separately as the efficiency of water application in the surface methods of irrigation (e.g., border, check basin, and furrow) is generally low. This means that more water is invariably applied on the cropped land than is utilized by the plants. This excess water application satisfies the leaching requirement. The leaching efficiency is low (0.2 to 0.5) for fine-textured soils and is relatively high (>0.5) for coarse-textured soils. The leaching operation becomes more efficient, if the calculated leaching requirement is given in split applications rather than dumping the entire water on the soil surface at one time (Bhattacharya and Michael, 2003). For an effective leaching, the field should be banded in small units and levelled such that there is no runoff loss and the water spread is of uniform depth on each land unit to be leached.

To demonstrate the use of Eqn. (14.2), let the ET for a cropping season of 3 months is 300 mm, the effective rainfall during this period is 25 mm, the EC of the irrigation water is 1 dS/m, the maximum permissible average electrical conductivity of the deep percolated water ( $EC_{fc}$ ) is 6 dS/m and the leaching efficiency is 0.4. Substituting these values in Eqn. (14.2) yields:

$$LR = \frac{(300 - 25) \times (1)}{[0.4 \times (6 - 1)]} = 137.5 \text{ mm in 90 days} \approx 1.5 \text{ mm/day.}$$

If the above calculation pertains to a wheat field, the net irrigation requirement is the difference between ET and  $P_e$  which, in this case is  $300 - 25 = 275$  mm in 90 days. If the irrigation application efficiency is 75%, the gross amount of water needed at the field head to satisfy the crop water requirement and the leaching requirement is  $275 + 137.5 = 412.5$  mm in 90 days  $\approx 4.6$  mm/day. Since this is greater than the gross irrigation requirement of 367 mm, and gross irrigation requirement comprises the extra water that will eventually percolate beyond the root zone, a total water application of 412.5 mm will be enough. If the irrigation interval is 15 days, the amount of water to be applied at each irrigation (to satisfy both the irrigation requirement and

leaching requirement) is » 69 mm. Wheat in many regions of India is given 4 to 5 irrigations. If at the location under consideration the number of irrigations is less than 6, the balance water between the actual number of irrigations and 6 irrigations is to be distributed among the actual number of irrigations to meet the leaching requirement.

An important point that emerges is that the excess water application during irrigation (due to less than 100% irrigation application efficiency) has a beneficial effect in terms of leaching of salts. This benefit will exist as long as there is a provision of evacuating the deep percolated water by a suitable drainage system. Otherwise, the deep percolated water will gradually accumulate over years of irrigation and will result into a shallow water table situation with poor-quality soil water, which will be instrumental in creating salinity hazard in the root zone due to capillary rise (Bhattacharya and Michael, 2003).

### (3) Field Estimation

The various assumptions made for the theoretical development of the concept of leaching and the estimation of leaching requirement limit the applicability of the result as a guideline only (Bhattacharya and Michael, 2003). Better estimates of leaching requirement, or the consequence of leaching by different amounts and qualities of the water on the soil salinity reduction, are obtained by field experiment in subsurface drained saline lands. Experiments are conducted by actually undertaking leaching operation and monitoring the changes in the drainage effluent salinity or the average root zone salinity over the period of leaching. The leaching curve, with the ratio of final and initial electrical conductivities of the saturation extract of the root zone soil on the Y axis and the amount of leaching water applied (in depth unit) on the X axis, is a declining curve similar to the infiltration rate curve. As the amount of leaching water increases, the above-mentioned electrical conductivity ratio decreases, assuming an almost constant value beyond a certain depth of applied leaching water. Such curves can be developed for different soil depths to be reclaimed (i.e., excess salts removed). When conducted as a pilot study, the result is applicable over the larger project area having similar soil salinity feature. Although this method gives a reliable result, it is time consuming and requires a subsurface drainage facility in the pilot experimental area (Bhattacharya and Michael, 2003). Also, the applicability of the results of such pilot experiments remain restricted to the area which is represented by the pilot experimental area. Nevertheless, the results are much superior to those obtained by the theoretical estimation procedures. Another field method for estimating leaching requirement is 'infiltration test', which is less expensive and less time consuming. The leaching requirement obtained by infiltration tests and that obtained by leaching trials in pilot experimental plots having subsurface drainage facility have been found to be in agreement (Dieleman, 1972). Details about infiltration tests for estimating leaching requirement can be found in Bhattacharya and Michael (2003).

### 14.2.3 Final Remarks

Leaching is an effective process for removing salts from the root zone. In coarse-textured soils and when the water table is deep, the chance of the deeper and saline groundwater rising up and resalinizing the root zone is less. In this situation, the reclamation effect due to leaching may last for several years, provided there is no water table rise. In the shallow water table region and in fine-textured soils in which the leaching of salt solutions to greater depths may be very slow, subsurface drainage at an appropriate depth facilitates the removal of the salt-concentrated water that is leaching downward. This may help in permanent reclamation of the topsoil.

However, due to prolonged dry season in monsoon climatic regions (e.g., India) and since leaching is seldom complete, the chance of resalinization of the root zone exists due to upward capillary flux of saline groundwater, if the drainage system operation is discontinued. Discontinuity of the subsurface drainage system operation occurs when the drainage effluent collection sump is not evacuated by continuing pumping operation in a pumped subsurface drainage scheme. Discontinuity may also occur in a gravity subsurface drainage scheme if the subsurface drain outlets and the open outlet drains are blocked because of inadequate maintenance. This possibility of resalinization of the root zone under the above situations is strong (Bhattacharya and Michael, 2003).

### 14.3 Reclamation of Alkali Soils

#### 14.3.1 Introduction

In alkali and acid soils, chemical amendments are required for neutralizing alkali and acid first. Subsurface drainage removes the reaction products of neutralization and restores the soil health. In the case of alkali soils, since the alkali hazard is mostly due to the presence of excess of Sodium, the additive chemical should be able to replace the absorbed Sodium from the soil surface. Gypsum (hydrated Calcium Sulphate) is the most widely used chemical additive for the replacement of Sodium.

#### 14.3.2 Gypsum Requirement for Reclaiming Alkali Soils

Gypsum (powdered hydrated Calcium Sulphate -  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) is a commonly used chemical amendment to the alkali soil for replacing the absorbed Sodium by Calcium. The replaced Sodium, in the form of aqueous solution of Sodium Sulphate, is to be removed from the soil profile through drainage so that it may not again get attached to the soil when Calcium is eventually depleted and the Sodium ion concentration becomes more than the Calcium ion concentration in the soil. The amount of gypsum to be added to the alkali soil for its reclamation is a function of the amount of exchangeable Sodium or more correctly, it depends upon how much of the exchangeable Sodium is to be replaced by Calcium. It also depends upon how much mass of the alkali soil is to be reclaimed (i.e., subjected to replacement of Sodium by Calcium). The calculation of gypsum requirement is explained below through an example.

In the 0-60 cm soil profile at a location in the village Olak, in Taluka Lakhtar of Surendranager district in Gujarat, the average exchangeable cations are as follows (Yadav, 1981):

$\text{Ca}^{2+}$ : 7.5 meq/100 g,  $\text{Mg}^{2+}$ : 6.6 meq/100 g,  $\text{Na}^+$ : 12.3 meq/100 g, and  $\text{K}^+$ : 1.2 meq/100 g.

Assuming that the other exchangeable cations are present in negligible quantities, the cation exchange capacity (CES) is the sum of the above, i.e., 27.6 meq/100 g. The exchangeable Sodium

percentage (ESP) is  $100 \times \frac{12.3}{27.6} = 44.6\%$ . According to the classification of salt-affected soils described in Section 14.1, this soil is highly sodic. If the ESP is to be reduced to below 15%, one has to replace enough Sodium by Calcium (of gypsum) such that the exchangeable Sodium

comes down to about 4 meq/100 g; note that  $100 \times \frac{4}{27.6} = 14.5\%$ . Thus, Sodium to the extent of

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(12.3-4) = 8.3 meq/100 g of soil is to be replaced by Calcium. In other words, the Calcium application should be at the rate of 8.3 meq/100 g of soil.

The equivalent weight of Calcium Sulphate ( $\text{CaSO}_4, 2\text{H}_2\text{O}$ ) is its molecular weight divided by the valency of the basic element present in it. Hence, one equivalent weight of  $\text{CaSO}_4, 2\text{H}_2\text{O}$

$$\frac{(40 + 32 + 4 \times 16 + 2 \times 2 + 2 \times 16)}{2} = 86$$

contains 86 g of Calcium Sulphate. The equivalent

weight of Calcium in gypsum is its atomic weight divided by the valency  $= \frac{40}{2} = 20$  g. Thus, 86 g of gypsum contains 20 g of calcium.

The amount of Calcium required in milligramme is the amount in milliequivalent times the equivalent weight. Hence, mg of Calcium required is  $8.3 \times 20 = 166$  mg/100 g of soil. The

corresponding amount of gypsum required is  $166 \times \frac{86}{20} = 713.8$  mg/100 g of soil.

In the usual process of reclamation of alkali soils through the application of gypsum, a small topsoil layer of 15 to 30 cm depth is considered for reclamation. It is presumed that once this top layer is reclaimed, it will promote good seed germination and enough plant growth. Reclamation of deeper layers by further application of amendment may be taken up later if there is a need felt to do so (Bhattacharya and Michael, 2003). Therefore, in this example, we shall find the gypsum requirement to reduce ESP from the exiting value of 44.6 to 14.5% in top 15 cm of the soil. Assuming an average dry bulk density of the top 15 cm soil as  $1.3 \text{ g/cm}^3$  (or,  $1300 \text{ kg/m}^3$ ), the mass of soil in 15 cm depth of 1 ha land is 19,50,000 kg or 1950 tonne (t). Earlier, we have found that gypsum is to be applied at the rate of 713.8 mg/100 g of soil which equals to 0.007138 kg of gypsum per kg of soil. Hence, the gypsum requirement for reclaiming the top 15 cm soil in 1 ha area is:  $0.007138 \times 1950000 \text{ kg} = 13919.1 \text{ kg} \gg 13.9 \text{ t/ha}$ .

Note that the actual gypsum requirement will be more than the above calculated value due to three reasons (Bhattacharya and Michael, 2003). **Firstly**, during reclamation, one-to-one replacement of Sodium by Calcium does not take place. **Secondly**, the whole of gypsum may not come in solution if the amount of water added is not adequate. The average value of solubility of gypsum is 0.25% (i.e., 0.0025 kg in 1 liter of water). Addition of such a high quantity of water in one application will invariably cause percolation loss of water without fully dissolving some of the applied gypsum. **Thirdly**, the commercially available gypsum is not 100% pure.

For the first reason, it is recommended that the actual gypsum application may be 1.25 times the value calculated above (USDA, 1954). To take care of the second reason, gypsum should be applied in split doses with lower quantity of water applied each time. To compensate for the impurity, the result of gypsum calculation should be divided by the purity expressed in fraction.



From the above details of calculating gypsum requirement, one can find the quantity of gypsum to be added under different situations. If all other conditions remain the same, then for a Sodium replacement of 4 meq/100 g of soil, the gypsum requirement will be  $\frac{4}{8.3} \times 13.9 = 6.7$  t/ha. To account for a lack of one-to-one replacement of Sodium by Calcium, one would require  $1.25 \times 6.7 = 8.4$  t/ha of gypsum. If the purity of commercially available gypsum is 85%, the actual quantity of gypsum needed will be  $\frac{8.4}{0.85} \approx 9.9$  t/ha. If a 30-cm soil depth is to be reclaimed instead of 15 cm, then the gypsum requirement will be  $\frac{30}{15} \times 9.9 = 19.8$  t/ha. If the dry density of soil is 1.2 g/cm<sup>3</sup> instead of 1.3 g/cm<sup>3</sup>, then the gypsum requirement will be  $\frac{1.2}{1.3} \times 19.8 \approx 18.3$  t/ha for a 30-cm soil depth reclamation. For a practicing drainage engineer engaged in alkali land reclamation, it will be useful to develop a table or a graph, in the form of a ready reckoner, to estimate gypsum requirement for various desired levels of reduction of milliequivalents of Sodium, for various depths of soil reclamation

and for various dry densities of soil. The value obtained from the ready reckoner can be suitably adjusted for the lack of one-to-one correspondence between Calcium applied and Sodium removed and for the purity level of the available gypsum. A condensed sample table of gypsum requirement for selected values of milliequivalents of Sodium replacement and for three dry densities of field soil is shown as Table 14.2.

**Table 14.2. Gypsum requirement using pure gypsum, one-to-one replacement of Sodium by Calcium and complete dissolution and mixing of gypsum (Source: Bhattacharya and Michael, 2003)**

Sodium Replacement (meq/100 g of Soil)	Gypsum Requirement (t/ha) for Reclaiming 15 cm Field Soil at Different Dry Densities		
	1.2 g/cm <sup>3</sup>	1.4 g/cm <sup>3</sup>	1.6 g/cm <sup>3</sup>
2	3.1	3.6	4.1
4	6.2	7.2	8.3

6	9.3	10.9	12.4
8	12.4	14.5	16.5
10	15.5	18.1	20.7

**Note:** All values are rounded off to one place after decimal. For field application, multiply table values by 1.25 and divide by the purity of gypsum in fraction. To estimate Gypsum requirement for other values of Sodium replacement, soil depth and average bulk density, use linear interpolation/extrapolation.

For getting best results from the field application of gypsum, the soluble salts should first be leached out of the soil as much as practicable. This enhances the efficiency of utilization of the Calcium present in gypsum for replacing the adsorbed Sodium in the soil (Bhattacharya and Michael, 2003). However, this step may not be feasible to follow if the soil particles are so dispersed in an alkali soil of fine texture that the soil pores are blocked to permit water movement and leaching. Gypsum in a powdered form is usually broadcast on the field and then mixed with the top soil layer using a suitable implement (e.g., a disc plough). After broadcast and mixing, adequate water is added to the field to dissolve the gypsum. The replacement reaction of Sodium by Calcium takes place in the solution phase. It is highly desirable to facilitate leaching out the reaction product in solution from the soil through a subsurface drainage system to get rid of the harmful Sodium.

### 14.3.3 Final Remarks

Gypsum is one of the several chemical amendments that can be applied for alkali land reclamation. Some of the other chemical amendments are: Sulphur, Sulphuric acid ( $H_2SO_4$ ), Iron Sulphate ( $FeSO_4 \cdot 7H_2O$ ), Calcium Chloride ( $CaCl_2$ ), Calcium Carbonate ( $CaCO_3$ ) and Aluminium Sulphate ( $Al_2(SO_4)_3 \cdot 18H_2O$ ). The quantities of the above chemical amendments equivalent to 1 unit of gypsum is obtained by multiplying the gypsum quantity with the ratio of the equivalent weights of the amendment and the equivalent weight of gypsum. Accordingly, the following equivalent quantities are obtained for different amendments corresponding to 1 unit of gypsum (Bhattacharya and Michael, 2003):



$$\begin{aligned}1 \text{ unit of Gypsum} &= 1 \times \frac{16}{86} = 0.186 \text{ unit of S} \\ &= 1 \times \frac{49}{86} = 0.569 \text{ unit of H}_2\text{SO}_4 \\ &= 1 \times \frac{139}{86} = 1.615 \text{ units of FeSO}_4, 7\text{H}_2\text{O} \\ &= 1 \times \frac{55}{86} = 0.64 \text{ unit of CaCl}_2 \\ &= 1 \times \frac{50}{86} = 0.581 \text{ unit of CaCO}_3 \\ &= 1 \times \frac{111}{86} = 1.29 \text{ units of Al}_2(\text{SO}_4)_3, 18\text{H}_2\text{O}\end{aligned}$$

The unit in all the cases is the same, for example, tonnes per hectare (t/ha).

It should be noted that in the amendments which do not contain Calcium, the reaction with water first produces Sulphuric acid which then reacts with available Calcium Carbonate in the soil to produce Calcium Sulphate, the Calcium of which replaces the Sodium. In India, gypsum is preferred and is the most commonly used chemical amendment for alkali land reclamation because of its easy availability and low cost (Bhattacharya and Michael, 2003).

### 14.4 Reclamation of Acid Soils

#### 14.4.1 Lime Requirement for Reclaiming Acid Soils

Lime is the most commonly used chemical additive in acid soils to neutralize the soil acidity. As gypsum requirement for the reclamation of alkali soil is determined on the basis of desired replacement of Sodium from the soil complex, in principle, the lime requirement is determined based on the requirement of raising soil pH from less than 6 to a desirable higher value (Bhattacharya and Michael, 2003). Theoretically, the lime requirement depends on the extent by which the exchangeable H is to be replaced by the Calcium present in the lime. Calculation of lime requirement through pH determination of the soil has several procedures and they give widely varying results (Peech, 1965). The one that is recommended in India (Singh et al., 1999) is based on the procedure suggested by Shoemaker et al. (1961). In this procedure, a known mass of soil is treated with a buffer solution of known pH and the resulting pH of the suspension is measured with a pH Meter after standardizing it with buffer solutions of known pH. The lime requirement for the original soil (from which the sample was taken) is read from a ready reckoner table, which gives the lime requirement of the soil to raise its pH from the known lower value to a desired higher value. For example, if the pH of the soil sample prepared in the above fashion is 5.0 and it is to be raised to 6.0, the theoretical lime requirement will be close to 20 t/ha. The actual lime requirement is determined by dividing the theoretical requirement by the purity of lime (in fraction). The calculated lime quantity is for increasing the soil pH of the plough layer, which is generally considered as 15 cm.

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From the above discussion, it is apparent that the calculated lime requirement is huge, particularly if a greater depth of soil is considered for raising pH or if the pH is to be raised by a greater extent. However, in practice much lesser lime application rate has been found to achieve the goal of increasing agricultural production in acid soils. The phenomenon responsible for this is not well understood (Bhattacharya and Michael, 2003). For instance, Panda et al. (1996) reported that by reducing lime application from full dose once at the beginning of a six-year field experiment to one-twentieth of the full dose at the sowing time every year, the reduction in yield of green gram, groundnut, black gram, soybean, lentil and pea varied between 8 and 11%. With lime application every year at the time of sowing at one-fifteenth of the lime requirement, the yield reduction of the above crops were less than 8% as compared to when the lime was applied at full dose once at the beginning of the six-year experiment. In the acid sulphate soils of Kerala, the farmers' conventional practice is to apply about 600 kg of lime (CaO) at the time of preparation of rice fields every year. There are several other sources in the literature, which also show that the lime applied at much lesser than the calculated dose considerably increases the production of various crops in acid soils.

### 14.5 Concluding Remarks

In a nutshell, for the reclamation of chemically degraded soils, usually one has to determine the leaching requirement for saline soils, gypsum requirement for alkali soils and the lime requirement for acid soils. In general, salinity can be controlled by natural leaching if the water table is deep, salt washing from the land surface by runoff or by additional good-quality water, or by subsurface drainage. Control of alkali and acidity is best achieved by adopting drainage and using suitable chemical amendments. Under alkali conditions, particularly in fine-textured soils, the application of chemical amendment is necessary to improve the water transmission characteristics through the soil. Simultaneous adoption of subsurface drainage removes the reaction products from the soil system. Due to arid and semi-arid climate over several parts of India, there are chances of resalinization and reconversion to alkali condition. Therefore, subsurface drainage operation should not be discontinued even the soil has been fully reclaimed (Bhattacharya and Michael, 2003).



### Lesson 15 Salient Case Studies on Drainage and Salt Management

#### 15.1 Introduction

Detailed descriptions about selected cases of drainage and reclamation works carried out during the second half of the 20<sup>th</sup> century in India are given in Bhattacharya and Michael (2003). They are:

- Drainage and reclamation of the low-lying waterlogged areas of the Punjab Agricultural University Farm at Ludhiana, Punjab in the semi-arid alluvial region.
- Drainage works in the Mahi Right Bank Canal Command Area in the semi-arid Kheda district of Gujarat in West India.
- Drainage for efficient land and water management in the Chambal Canal Command Area located in the Kota region of Rajasthan in North India.
- Selected pilot projects on drainage and reclamation of waterlogged, saline and alkali lands in the state of Haryana in the semi-arid region of North India.

In this lesson, two major case studies are succinctly presented: one on 'Drainage for efficient land and water management in the Chambal Canal Command Area located in the Kota region of Rajasthan (North India)' and another on 'Drainage and reclamation of waterlogged, saline and alkali lands in the state of Haryana in the semi-arid region of North India'.

#### 15.2 Conjunctive Use of Surface Water and Groundwater

Conjunctive use of surface water and groundwater is of great importance because it can enhance canal water supplies, combat water logging, and facilitate irrigation with poor-quality groundwater. Thus, the conjunctive use of surface water and groundwater can be planned in various ways. It can take the form of enhancing canal water supplies by direct pumping of groundwater through augmentation wells or the direct use of groundwater during low canal supplies or during canal closures. It can also take the form of irrigating part of the canal command area with groundwater only. Conjunctive use has been in practice in India to a limited extent (Michael et al., 2008). It has been prevalent in the Kaveri delta of Tamil Nadu, the Godavari and Pravara canal systems in Maharashtra, the Ganga Canal in Uttar Pradesh and the Western Yamuna Canal in Haryana and in parts of Punjab. In Israel and the USA, saline groundwater has been used for irrigation to a limited extent after diluting it with good-quality surface water. There is a scope for adopting such practice in some areas of Gujarat, Punjab, and Rajasthan where groundwater is brackish (Michael et al., 2008).

Vertical drainage as a component of conjunctive water use appears to be more attractive option as the water pumped at a cost can be used to reap the benefit from irrigation by utilizing the pumped groundwater and the surface water thus saved can be diverted to water deficit regions in a command. Rao and Prasad (1998) studied the effect of operating 33 wells in the Chelgal village under the Sri Ram Sagar irrigation project in Andhra Pradesh. The pumped water was used for irrigation and the canal water input was so reduced as to make the total of canal and

groundwater adequate to meet the crop irrigation requirement. The system was operated for two years and the positive result was that the reducing crop yield due to water logging condition developed after five years of starting canal irrigation picked up due to a better soil environment caused by the declined water table after two years of groundwater use.

Hooja et al. (1996) reported the result of operating a battery of five skimming wells (dug wells of 3 m in diameter) in the village Lunio ki Dhani, under the phase I of the Indira Gandhi Nahar Pariyojana (IGNP) in Rajasthan. Skimming wells are those from which the relatively better quality groundwater in the upper aquifer is tapped at a low rate to avoid pumping of deeper but poor quality groundwater. It also avoids excessive upcoming of the interface between the good and poor water quality ground waters, which may result in pumping out poor quality water or mixing of the two waters, deteriorating the quality of the relatively fresh groundwater of the upper region of the aquifer. In Lunio ki Dhani, the groundwater was pumped at a rate of 0.4 L/s from each of the five wells for 30 minutes in the morning and 30 minutes in the evening. The pumped groundwater had a salinity of 10 dS/m. The pumped water was blended with the water flowing in the IGNP main canal at a rate of about 143 m<sup>3</sup>/s, having an EC of 0.3 dS/m. Due to a large difference between the canal flow rate and the pumping rate of the groundwater which was blended with the canal water, there was no significant change in the canal water quality after blending. At 10 to 15 m downstream from the point of blending, there was practically no difference in the quality of the blended and non-blended canal water. Operation of the skimming wells for six months caused a decline in the groundwater table by 1 m within the region of pumping. Similarly, in another village Masitawali in the IGNP area, a battery of five tubewells 20 to 30 m deep were attempted and the pooled pumped water was blended with the water in the IGNP main canal. These measures, however, were found to be costly.

### 15.3 Rajasthan Agricultural Drainage (RAJAD) Research Project

#### 15.3.1 Overview of Project Area

The Chambal Irrigation and Power project is a joint venture of the Governments of Rajasthan and Madhya Pradesh in India to harness the water of the Chambal river. Its main storage dam Gandhi Sagar, the Kota diversion barrage and the main canal system were completed by 1960. Two more dams, the Ram Pratap Sagar and the Jawahar Sagar were added to the system between late sixties and mid seventies (Fig. 15.1). The Chambal Irrigation project has a gross command area of 566,000 ha, of which about 385,000 ha is in Rajasthan and the rest is in Madhya Pradesh. The canal command area in Rajasthan is spread over four Panchayet Samities of Kota and Baran districts and two Panchayet Samities of Bundi district. The command area lies between 25° and 26° N latitude and 75° 30' and 76° 6' E longitude, in the south-eastern part of Rajasthan (Fig. 15.1). The Kota barrage serves two main canal systems, the Right Main Canal (RMC) and the Left Main Canal (LMC). The LMC system, comprising 274 km long main canal with a design capacity of 42 m<sup>3</sup>/s and 966 km of distributaries and minors, is wholly in the state of Rajasthan. The RMC within Rajasthan is 124 km long with 1367 km of branches, distributaries and minors (Fig. 15.2).

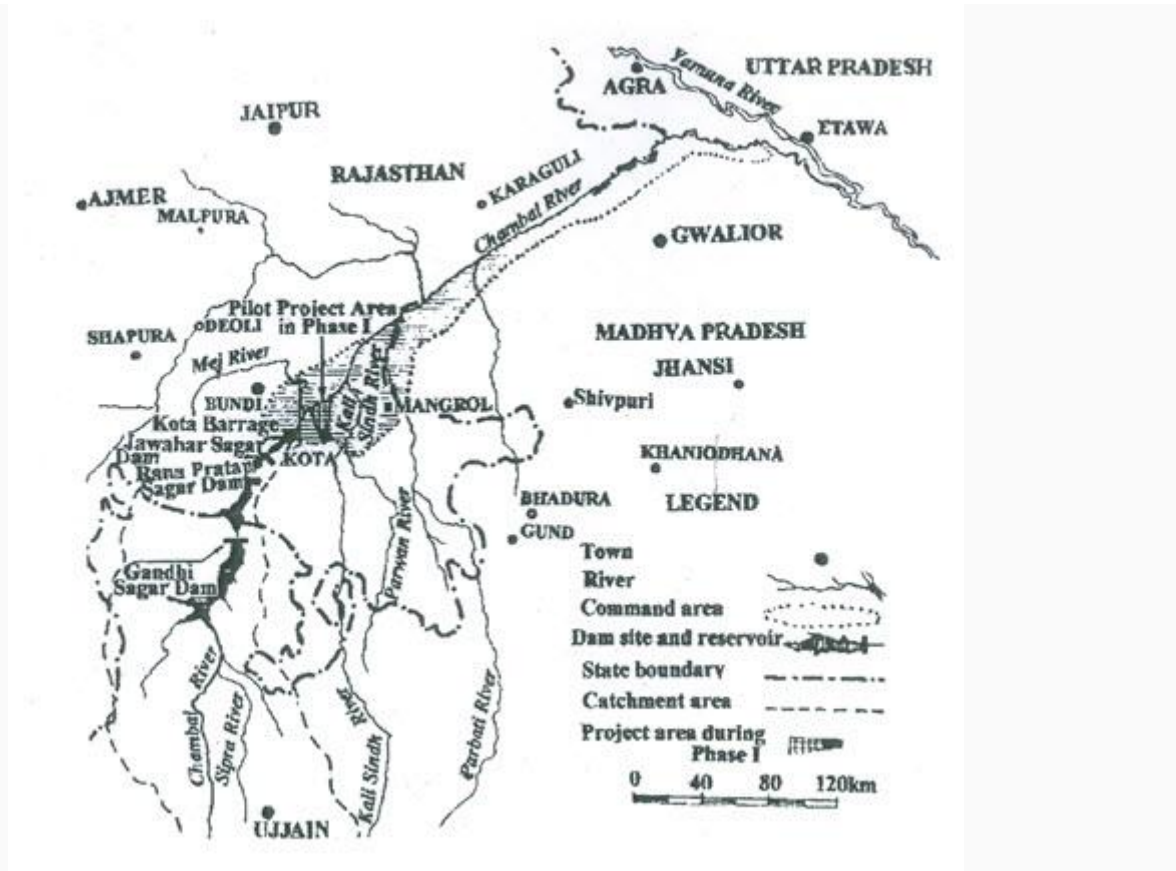


Fig. 15.1. Location map of Chambal Canal Command Area, Rajasthan. (Source: UNDP, 1971)

The quality of water in the canals is good. The climate of the project area is sub-tropical and semi-arid. The average annual rainfall is 850 mm and has substantial inter-year and spatial variation. About 90 per cent of annual rainfall is received during the monsoon period (July to September). The summer temperature occasionally rises to as high as 49°C during May-June and the winter temperature falls to as low as 4°C during December-January. The mean annual potential evaporation is 2650 mm, far exceeding the mean annual rainfall.

The elevation of the command area ranges from 170 m to 260 m above mean sea level. The irrigated land is flat with an average slope of 0.08%. There are several rivers and meandering streams (nallas) passing through the area. The Chambal river runs in the centre of the command area, with three major perennial rivers, namely the Maj, the Kalisindh and the Parbati, joining it. Also, there are some smaller perennial rivers and numerous non-perennial tributaries in the Chambal river system. Deep alluvial to exposed or thinly covered shale, limestone and sandstone comprise the main geologic formations of the command area. Further details of the Chambal Command Area can be found in Bhattacharya and Michael (2003).



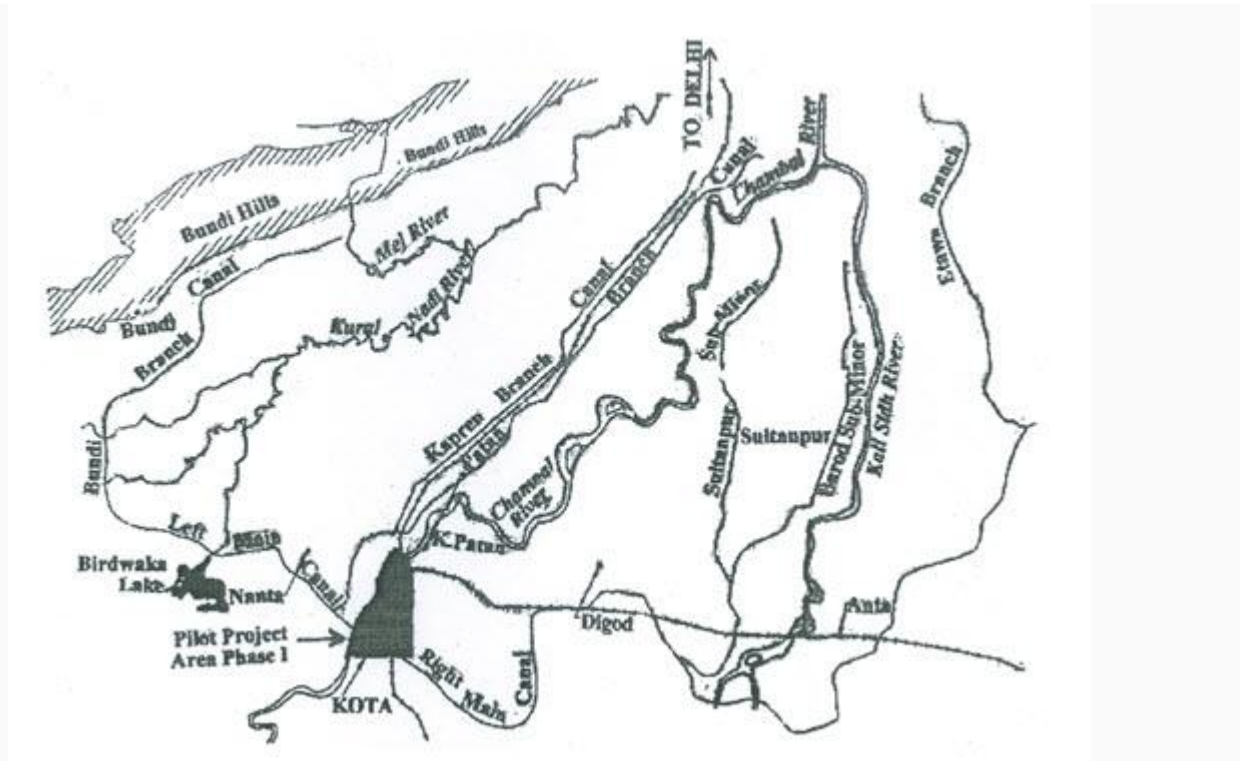


Fig. 15.2. Layout map of Chambal Command Area, Rajasthan. (Source: Anonymous, 1995)

### 15.3.2 Genesis of RAJAD Project

Before introducing canal irrigation in the command area in 1960, it was under rain-fed agriculture and there was no significant water logging problem then (Mehta, 1958). Soon after canal irrigation started, the groundwater table began to rise and water logging and salinity problems occurred. According to the Preparatory Mission Report of FAO (1966), "By 1965, of the 32,000 ha estimated under irrigation about 16,000 ha had water table within 1.5 m bgl and were to varying degrees, affected by salinity." During the initial phase of irrigation, there was a major gap between the development of irrigation potential and water utilization. With the increase in irrigation development there was rapid rise of water table and salt problems in the command area. By the 1970s about 161,000 ha of land had water logging problem (water table within 3 m of the soil surface), and about 25,000 ha were affected by salinity.

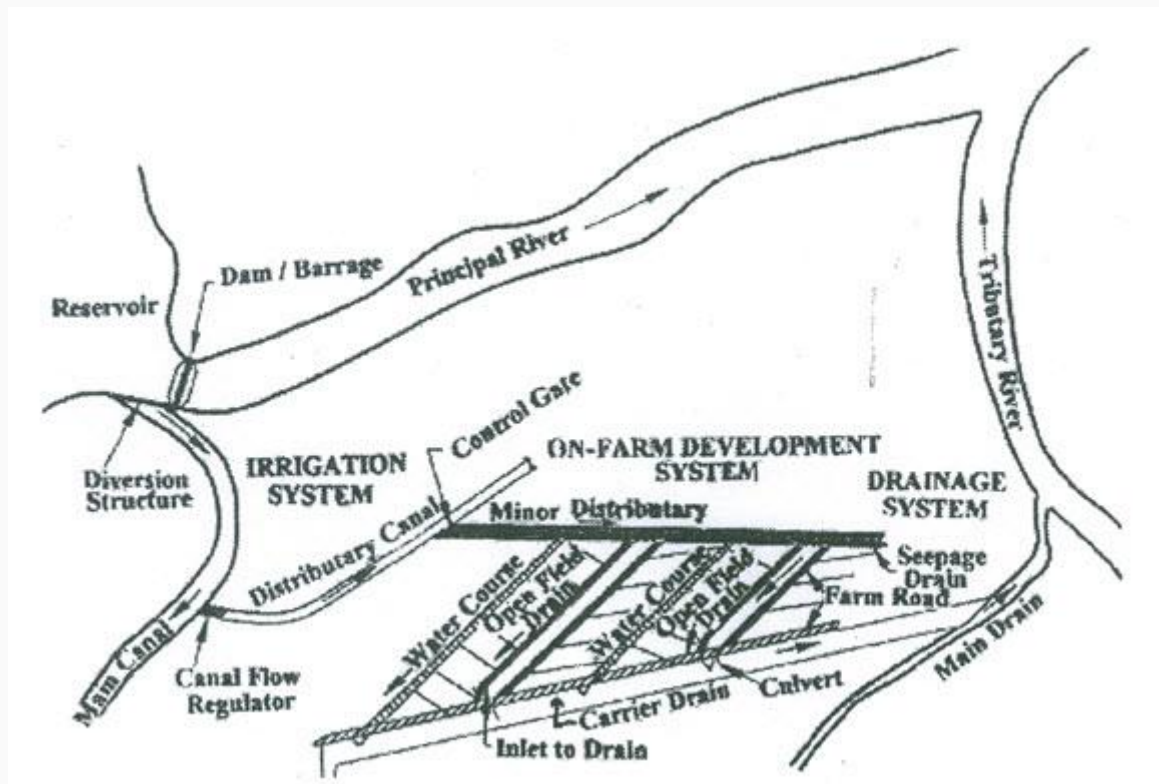
Considering the importance of the Chambal Irrigation Project and the magnitude of the problems involved, the Government of India requested for the assistance of the United Nations Development Programme (UNDP). The UN assisted project: "Land and Water Use Management in the Chambal Command Area, Rajasthan" became operational in March 1968 (UNDP, 1971). Besides UNDP, the Governments of Rajasthan and India and the FAO of the United Nations were also involved in the project. The project envisaged evolving solutions to the soil and water management problems in the irrigated area by implementing a pilot development scheme in the Rajasthan part of the canal command area. The drainage related objectives were: (a) control of water logging and salinity, (b) proper distribution of the irrigation water and control of weeds in canals, and (c) improvement in irrigation, drainage and farm practices in the farmers' fields. By the end of 1970, a land development system evolved. It was named On-Farm Development (OFD). This was subsequently supported by the World Bank. Some of the components of the OFD programme were realignment of the field boundaries to facilitate proper layout of



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irrigation, drainage and road systems, land shaping for efficient irrigation water distribution and better surface drainage, and construction of irrigation and drainage channels with necessary structures to serve each farm.

The watershed concept was adopted for the OFD work. A typical sub-watershed size was between 1000 and 10,000 ha of irrigated area. Field drains (lateral drains) at about 500 m apart either joined a sub-main, or depending on the topography and main drain layout, were directly connected to the main drain. Interceptor drains were provided adjacent to the canals to arrest the seepage flow before it could cause water logging and salinity problems in the adjoining area. Fig. 15.3 shows a sketch of the irrigation and surface drainage systems.



**Fig. 15.3. Schematic sketch illustrating on-farm development system (OFD) in Chambal Canal Command Area, Rajasthan. (Source: Anonymous, 1995)**

Based on the initial success of the watershed based OFD works in the irrigated areas, a Command Area Integrated Development Programme was launched as a follow up by the World Bank and the Government of India. Under this programme, surface drainage works in 167,000 ha and OFD works in 55,000 ha were completed during 1977-1990.

Although a surface drainage network was developed in the Chambal Command Area, its poor maintenance caused serious problems of water logging, soil salinity and silting of many of the drains (Figs. 15.4 and 15.5). It became evident that subsurface drainage was essential to reclaim saline and waterlogged lands and also to prevent further development of salinity and water logging. The Rajasthan Agricultural Drainage Research Project (RAJAD Project) took up subsurface drainage work on a relatively much larger scale than elsewhere in India. Under this project, the earlier executed surface drainage network was also renovated and used for gravity flow of subsurface drained water into and through them.



**Fig. 15.4. A view of surface water standing in a crop field in the Left Main Canal Command Area, Chambal Project, Rajasthan. (Source: Anonymous, 1995)**



**Fig. 15.5. Salinity affected cracked soil surface in a test plot in the Left Main Canal Command Area, Chambal Project, Rajasthan. (Source: Anonymous, 1995)**

### 15.3.3 Introduction to RAJAD Project

On farm irrigation efficiencies and surface drainage improved substantially in the Chambal Canal Command area through the various developmental activities undertaken during the Phase-I and Phase-II projects. However, salinity and water logging problems continued to exist. Towards finding a comprehensive solution to these problems, the Rajasthan Agricultural Drainage Research Project (RAJAD) was started in 1991, initially for a 7-years period. It was undertaken jointly by the Governments of India, the State of Rajasthan and Canada. The main focus of the project was on establishing horizontal gravity based subsurface drainage system in a target area of about 20,000 ha area, preceded by a pilot research project in about 10 percent of the

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target area to determine various parameters of the design to be followed for the larger area. The objectives of the project were to reclaim saline and waterlogged irrigated lands, to prevent development of salinity and water logging, and to improve agricultural productivity of the farmers of the Chambal Command Area. The project had utilized some of the surface drainage infrastructure built earlier under the UNDP programme of OFD after making suitable renovations. It was a large-scale applied research project focusing on the design and execution of horizontal subsurface drainage system and adopting complementary land and water management measures for water logging and salinity control and for enhancing the agricultural production in irrigated agricultural lands in the semi-arid region. The commissioning of the subsurface drainage systems and construction/renovation of outlet drains and structures were completed by 2000. Presently, the executed system is monitored by the Chambal Command Area Development Authority.

For the first few initial years, the RAJAD project made an in-depth study of drainage and irrigation water management in the Chambal Command area and the following findings were obtained:

- Heavy soil with poor internal drainage, seepage from the irrigation canals, excessive irrigation and a lack of properly functional drainage system due to weed growth and sloughing of the banks were the major causes of water logging and salinity in the command area.
- Deterioration of the canal infrastructure constructed in early 1960s had been so widespread that their rehabilitation would be expensive and even if done, it might not help in solving the problem.
- The existing irrigation practices are wasteful, and hence they need to be improved.
- Surface drains constructed during the OFD works were unable to control water logging due to lack of maintenance and unauthorised construction of checks across the drains.
- Despite the existence and operation of several thousands shallow tube wells in the Chambal Command area, the concept of conjunctive use of surface and groundwater for controlling the rise of water table did not materialise.
- Considering the alarming spread of water logging and salinity, horizontal subsurface drainage, supplemented by land shaping and surface drainage appeared to be the best alternative for enhancing and sustaining soil health and agricultural productivity in the command area.

Out of the 285,000 ha Rajasthan portion of the Chambal Command area, with several saline and waterlogged patches, the RAJAD project area was selected based on a careful data collection and analysis of the type and severity of the problem, suitability of the subsurface drainage technology as a major remedial measure and the site feasibility of adopting a gravity flow based subsurface drainage system.

### 15.3.4 Pilot Studies in RAJAD Project

Before taking up the large scale subsurface drainage installation, a number of smaller representative areas, 50 to 180 ha in size were identified to conduct pilot experiments in order to develop design criteria and identify suitable installation technology. The total pilot experimental area was 1400 ha distributed in ten locations. The results of the pilot study were monitored in terms of the effect of drain depth and spacing on water table decline salt removal, drain discharge, trafficability and crop production. In addition, the other post-pilot investigations and monitoring were sediment outflow through the drainage effluent and consequent decision on the filter type and quality, impact of subsurface drainage water disposal in the open drainage system in changing the water quality and its environmental implications, changes in soil physical properties due to the functioning of subsurface drainage technology.

The important findings and conclusions from the pilot studies in the ten research areas under the RAJAD project are as follows:

- Saturated hydraulic conductivity calculated from drain discharge versus hydraulic head data varied from 0.25 to 0.55 m/day in the top 1 metre depth; 0.02 to 0.2 m/day in the 1 to 1.5 m depth and 0.75 m/day below 1.5 m depth. The drainable porosity varied from 2 to 5%.
- The transient drainage design equation of Glover-Dumm was found appropriate than the steady-state equation of Hooghoudt.
- A crop tolerance period of 3 days was found acceptable for drainage design.
- A drainage coefficient of 1 to 4 mm/day or a water table decline of 20 to 40 cm below the ground level within 3 to 4 days (later standardized to 20 cm in three days) were found adequate for water table control and salt leaching.
- An average drain depth of 1.2 m, with a range from 1 to 1.5 m was found adoptable considering the gravity drainage requirement and flat land.
- Drain spacing of 30 m was found necessary for the control of salinity and water logging, whereas it was 60 m for the control of salinity only.
- Synthetic filter was found to be suitable for large scale subsurface drainage installation work.
- Performance analysis of the pilot study indicated an anticipated average Benefit-Cost (B-C) ratio of 2.4 for the subsurface drainage technology.

The results from all the pilot study sites were synthesized for undertaking the subsurface drainage work in the remaining area of the RAJAD project. Different drainage machinery, filter types (without filter as well) drain depth and spacing and layouts were used, and adopted to complete the installation by the year 2000. The installation programme included providing suitable structures, outlets, deepening and re-sectioning of the existing open drain network, providing new open drains and some other constructional activities. Presently, Chambal Canal Command Area Development Authority is maintaining the executed system.



### 15.3.5 Irrigated Water Management Pilot Projects

Since, drainage is an important but just one of the several requirements for efficient water management to reclaim land and enhance agricultural productivity. Therefore, the concept of Integrated Water Management (IWM) was introduced in RAJAD as a pilot programme in 1994. Due to the multidisciplinary input requirement towards achieving the desired goal through IWM, there has been an effort to ensure effective cooperation and involvement of various agencies working on the problem of land and water management in the Chambal Command area to ensure their effective and complementary functioning towards the common goal of increasing agricultural production per unit of land and water.

The IWM program had the following specific objectives:

- (i) Adopt a multidisciplinary approach in irrigation management.
- (ii) Ensure effectiveness of water supply to the fields and improved water application efficiency.
- (iii) Establish pilot-scale demonstrations of effective water delivery and control systems.
- (iv) Ensure adequate and timely supply of crop production inputs.
- (v) Assist in the introduction of rotational water delivery in selected blocks.
- (vi) Improve farmers' awareness and ensure their participation through Water User's Associations (WUAs).

The IWM pilot project, with the above objectives was introduced in three blocks, IWM-1, IWM-2 and IWM-3, all of which were served by the Chitawa distributary on the LMC of the Chambal canal system. The block IWM-1 with an area of 22 ha was non-saline and without subsurface drainage, had clay loam soil and grew soybean and paddy in the kharif season and wheat mustard and berseem in the rabi season. The block IWM-2 with an area of 40 ha was saline and having subsurface drainage, had clay to clay loam soil and with similar cropping pattern as of IWM-1. The block IWM-3 with an area of 19 ha had highly saline and uncultivable patches, sandy loam soil and was proposed to be equipped with a subsurface drainage system under the pilot project (Gaur et al., 1996).

Baseline surveys on socio-economic status of the farmers of the IWM blocks as well as on the cropping system followed were conducted. Major constraints in the irrigation supply system, water application methods, drainage system, agronomic practices and information dissemination in the IWM blocks were identified. Also, necessary field investigations were conducted in all the three IWM blocks in order to minimize water and fertilizer losses. WUAs were also formed and trained for their active participation in local water management activities.

### 15.3.6 Concluding Remarks

Proper planning and implementation of the command area development program in the Chambal Command Area of Rajasthan, in different phases could combat satisfactorily the severe problems of water logging and salinity. The programme comprised lining of canal water

conveyance and distribution system, land levelling, provision of drainage disposal network, on-farm surface drainage and subsurface drainage in selected areas and provision of access roads to farms. The development and adoption of suitable cropping patterns and crop management practices formed an important activity. Appropriate models for the effective maintenance of irrigation and drainage systems could be established in the IWM blocks and some other locations. However, the comparatively slow pace of development is directly attributed to the lack of direct involvement of the farmers in the development project and farmers' participation in the extension training programmes. There is a need for active participation of the farmers in these areas. The farmers could be helped, advised and educated on modern and efficient land and water management methods through WUAs.

The RAJAD project has been able to develop valuable information on various water management and essential complementary practices such as irrigation, drainage, land development, suitable cropping system and crop husbandry and farmers' participation. The multi-disciplinary approach to combat the problem and the involvement of various agencies at the State and the Central Government levels, including the State Agricultural University, the Central Soil Salinity Research Institute and the substantial involvement and support of international agencies like the UNDP, World Bank and Canadian International Development Agency have been commendable. Now, there is a need to extend the benefits of the technology to the entire command area and other major and medium irrigation projects with comparable agro-climatic and socio-economic situations. There is also a need to continuously monitor the performance of irrigation and drainage systems in an irrigation command area. Appropriate and timely actions are essential to prevent the occurrence of water logging and salinity problems as well as to find suitable remedial measures for their control in case these problems occur.

### 15.4 Pilot Projects on Land Reclamation and Management of Salt-Affected Soils in Haryana

#### 15.4.1 Overview of Project Area

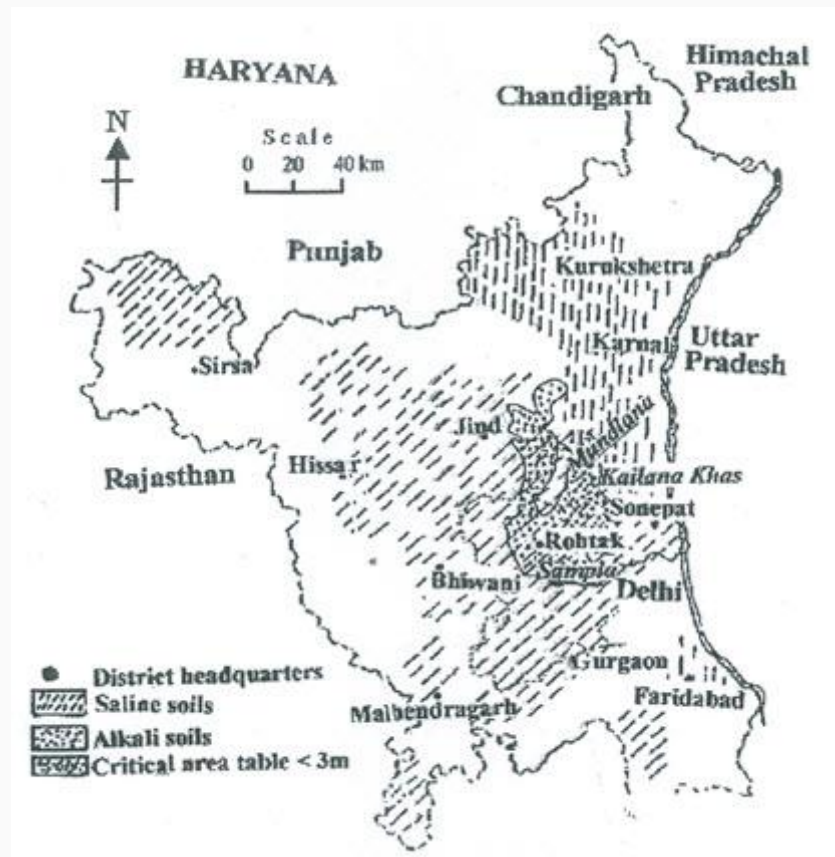
The state of Haryana is situated between 27°35' to 31°55' 30" N latitude and 74° 22' 48" and 77° 35' 36" E longitude. The south-western boundary of the state merges with the Thar desert. It is an agriculturally advanced state in the Indo-Gangetic plain and is an important segment of the rice-wheat belt in India. The state is characterized by a sub-tropical semi-arid climate with a relatively short but distinct monsoon season of about three months (July to September), receiving about 83% of the annual rainfall. Most of the remaining part of the year experiences a dry climate with high evaporation rates. The average annual rainfall varies from 800 mm in the north to 300 mm in the west. Maximum temperature of 41°C is recorded in the months of May-June and the minimum temperature of 5°C is recorded during December-January.

There are two river basins, namely, the Yamuna basin (16,330 km<sup>2</sup>) and the Ghaggar basin (10,675 km<sup>2</sup>). There is also an internal basin (17,207 km<sup>2</sup>), which is physiographically depressed. In the absence of any natural drainage outlet, the internal basin has serious water logging and salinity problems. Irrigation water of 1.05 million hectare metres (Mha.m) from the two major canal systems, namely the Western Yamuna and the Bhakra and about 0.85 Mha.m of good-quality groundwater provide irrigation to about 1.2 Mha land in the state.



### 15.4.2 Need for Salt Management and Initiation of Pilot Projects

Haryana state has been facing serious problems of water logging, soil salinity and alkali condition. Significant rise in water table has occurred in a major part of its arable irrigated. Groundwaters in the regions of rising water table are generally brackish. About 77% of the area of the Yamuna and the internal depressed basins has brackish groundwater. Due to semi-arid climate, salt accumulate in the shallow depths, arising out of evaporation from shallow and brackish groundwater table. Additionally, considerable salt is also added to the irrigated lands by the irrigation water delivered by the canal system. Non-exploitation of the saline groundwater and recharge from the canal irrigated area have aggravated the water table rise and groundwater salinity problems in these two basin areas (Figs. 15.6 and 15.7).



**Fig. 15.6. Distribution of saline and alkali soils in Haryana and the location of pilot projects on the reclamation of saline soils undertaken by CSSRI under the Operational Research Project Scheme. (Source: Rao et al., 1986)**



**Fig. 15.7. Extensive saline barren land in the Pilot Project area of CSSRI in Haryana, prior to reclamation. (Source: Bhattacharya and Michael, 2003)**

The Indian Council of Agricultural Research (ICAR) had established the Central Soil Salinity Research Institute (CSSRI) in 1969 at Karnal township in the Karnal district in Haryana. After about five years of research, the institute developed some tentative technologies for the reclamation of salt affected soils. In 1974, the ICAR sanctioned an operational research project (ORP) to the CSSRI for the reclamation of alkali soils of the Karnal district. This project had the following objectives: (i) to test and demonstrate available technologies of alkali soil reclamation to make such lands productive, (ii) to promote technology transfer, (iii) to monitor changes in the soil properties after adopting reclamation measures, (iv) to study the economic implications of the adoption of reclamation measures, and (v) to improve the standard of living of the farming community. Subsequently in 1979, the institute started pilot projects for reclaiming waterlogged saline lands with identical concepts as in the earlier ORP. Initially, the pilot projects were established in selected problem areas in Haryana state. Later, similar projects were undertaken by the institute in other states facing similar problems of water logging, soil salinity and alkali. The two case studies reported in subsequent sub-sections are based on the pilot projects undertaken by the CSSRI, Haryana.

### **15.4.3 Case Study on the Reclamation of Saline Soils of Sampla Experimental Farm**

#### **(1) Introduction**

The pilot project on reclamation of saline soil was the first major project of its type and was taken up in the Panchayet (a village Panchayet is a local body elected by the villagers) land in the village Sampla in Rohtak district of the Haryana state (Gupta et al., 1998). The project area is located in the Western Yamuna Canal Command Area and is a part of the depressed internal basin, which has no natural outlet even for surface drainage. Hence, runoff water disposal is through a pump drainage scheme of  $1.5 \text{ m}^3/\text{s}$  capacity. The pumped water is led to an irrigation distributary (Dulehra) of  $10 \text{ m}^3/\text{s}$  capacity. The project site is around the central region of the basin with a bi-directional slope of 0.2% along south-west to north-east direction and 0.1% from west to east.

The initial small-scale experiment on open drains spaced 25 m apart and buried subsurface drains spaced 50 m apart were operated successfully, but the latter drainage technique was suggested as the more acceptable solution for large-scale saline land reclamation work because of several reasons such as the loss of area, frequent maintenance, and incompatibility with mechanized farming in the case of open drains.

### (2) Characteristics of the Pilot Project Area

The area is characterized by 650 mm average annual rainfall and 2000 mm annual evapotranspiration. The water table fluctuates from surface in the monsoon season to 1.8 m below the surface in the summer season. The soil texture is sandy loam in 0 - 1.8 m depth; sand to loamy sand for a variable depth of 0.7 to 1.7 m thereafter and sandy loam again beyond that at depths varying from 2.5 to 3.5 m and down below. This layer being located below a relatively more previous layer, it was treated as the impervious layer for drainage design purpose. The saturated hydraulic conductivity at the upper 1.1 m soil was 1.15 m/day, for the soil layer from 1.1 to 1.8 m it was 0.85 m/day and from 1.8 to 3 m, it was 7.5 m/day. The bulk density of the 0-20 cm surface soils was unusually high (1.67 to 1.83 g/cm<sup>3</sup>). Steady-state infiltration rate was low (4.8 cm/day). The soil salinity in the 0-15 cm soil layer had a high spatial variability (20 to 150 dS/m). It varied from 50 to 75 dS/m in the 15-30 cm soil layer and remained fairly constant at 30 dS/m at deeper depths. The high soil salinity at or near the surface was caused by high evaporation from the shallow water table of poor quality. Temporally, the salinity was higher during the period from January to June.

### (3) Design of Subsurface Drainage System

For designing a drainage system, the first requirement was to find the drain depth. Due to the need of leaching of salts and avoid salinization due to capillary rise in the compacted surface soil layers, the drain depth was kept at an average of 1.75 m from the ground surface. With a hydraulic head of 50 cm, this would restrict the water table to a depth of 1.25 m from the ground surface. The relatively coarse sandy loam soil (except the top 20 cm, where the soil was compact) would restrict upward capillary movement of water. The water table depth of 1.25 m was considered adequate for growing pearl millet and sorghum in the monsoon season. Having decided on the depth, based on the specific crop requirement and soil features, the lateral drain spacing was determined using Ernst equation. The calculated drain spacing was 50 m. As the pilot project was to develop suitable drainage design criteria applicable in similar conditions elsewhere, and all drainage design equations are based on certain assumptions, which are only partially valid in the field, two other spacings were adopted. One was 50 per cent higher and the other was 50 per cent lower than the drain spacing calculated by Ernst equation. Mineral envelope was used around the lateral drains to a thickness of 7.5 cm. The envelope was needed as the soil had more than 70% of fine sand. The drain envelope was designed based on the study by Kamra and Rao (1984). River bed material was sieved to get the envelope according to the design. The lateral drains were made of 30 cm long cement concrete pipes with straight edges placed end to end. The collector drains were made of 2 m long straight edged reinforced cement concrete pipes with collar joints. The trench for laying the drain pipes had a trapezoidal shape from surface down to 1.5 m and a narrow 30 cm × 30 cm section below to reduce the earthwork and also to reduce the unnecessary spread and waste of envelope material. The drain slope closely followed the topography to avoid the drains being too shallow or too deep at places with respect to the local ground level. The system was commissioned in the summer of 1984 when the water table

## Drainage Engineering

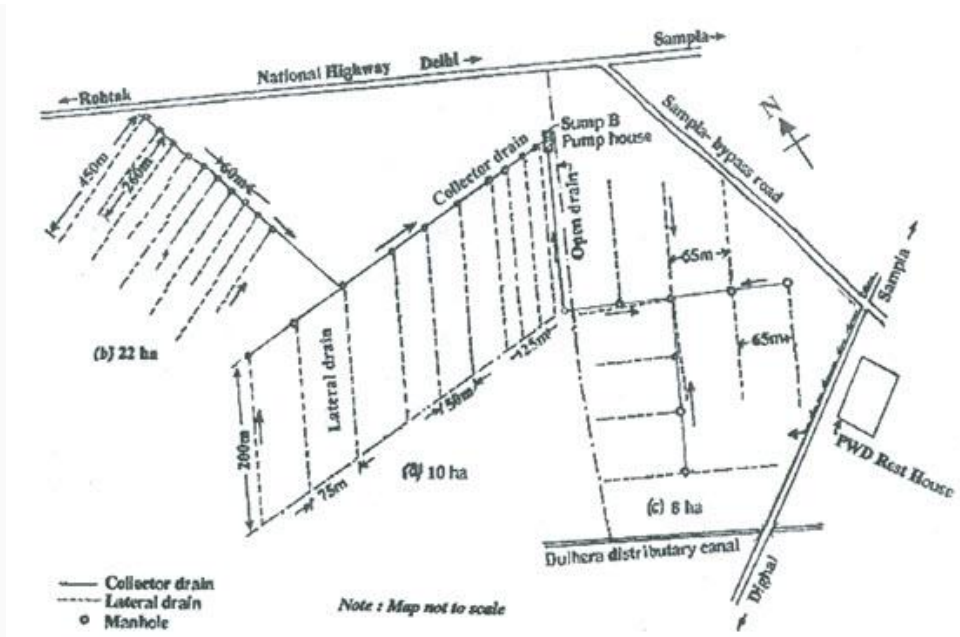
was at the lowest level during the year. The complete design information of the subsurface drainage system is summarized in Table 15.1.

**Table 15.1. Specifications of the subsurface drainage system at the Sampla pilot experimental farm (Source: Gupta et al., 1998)**

Sl. No.	Particulars	Design Description
1	Lateral drain depth	1.75 m
2	Lateral drain spacing	25, 50, 75 m
3	Lateral drain slope	0.2%
4	Collector drain slope	0.1%
5	Maximum lateral drain length	300 m
6	Lateral drain diameter	10 m
7	Collector drain diameter	20 cm
8	Material of lateral and collector drains	Cement concrete
9	Type of envelope	Mineral
10	Type of outlet	Pumped

The drainage system was installed manually in a 10 ha area initially, which was later extended to another 40 ha to test other design alternatives in terms of depth and spacing of the drains and drainage material (Fig. 15.8).





**Fig. 15.8. Layout of subsurface drainage experimental system at the Sampla Drainage Experimental Station, Rohtak district, Haryana. (Source: Anonymous, 1998)**

Observation wells were provided at a regular interval in the drained area to monitor hydraulic head distribution and inspection chambers were provided at the end of the lateral drains to allow sampling of the drainage effluent for laboratory analysis. In absence of a gravity outlet, a large diameter and deep sump well was constructed to have sufficient storage capacity for the drainage effluent, which was pumped out and into a shallow surface drain from where, the water could be pumped into the Dulhera distributory (Fig. 15.9). An alternative arrangement was also made to dispose the drainage effluent by constructing an evaporation pond to collect the drainage effluent, when for some reason; the distributory cannot be used for effluent disposal. Commissioning of the drainage system was followed up by crop cultivation on land by adopting all the scientific methods of crop husbandry, and irrigation water and fertilizer management practices.



**Fig. 15.9. Fifth year of reclamation of Sampla Experimental Farm, Rohtak district, Haryana. Note the subsurface drainage water discharges into a small tank, the sump well and the rich crop land of the project area in the background. (Source: Bhattacharya and Michael, 2003)**



### (4) Evaluation of Drainage System

Drainage system was evaluated by monitoring the rate of drainage effluent flow, its quality and crop yield. From the base level of no crop production prior to reclamation, the average yield of wheat over 10 years of the post-reclamation period was 4.5 tones/ha in the project area. During the monsoon season, the drain discharges were equivalent to the drainage coefficients varying between 1.7 to 8.1 mm/day. However, during the winter season, when the source of water was only irrigation, there was a decline in drain discharges.

The monitored water quality parameters for drainage effluent, groundwater and canal water were electrical conductivity (EC), concentrations of sodium, calcium, magnesium, bicarbonate and chloride, and the sodium adsorption ratio (SAR). The canal water quality was found to be the best with EC of 0.7 dS/m; SAR of 0.8 (meq/L)<sup>1/2</sup>; and (calcium + magnesium), sodium, bicarbonate and chloride concentrations respectively as 2, 0.8, 2 and 0.8 meq/L. The quality of groundwater (sampled from 20 m depth) was the poorest with EC as high as 32.5 dS/m and high values of all the other constituents. The drainage effluent properties were in between the properties of the canal water and the groundwater, with all the parameter values gradually reducing over the years. Although the SAR of the drainage effluent was reducing over the years, it was always higher than that of the groundwater.

### (5) Lessons from Sampla Pilot Experiment on Saline Land Reclamation

The sample pilot experiment indicated that the practice of only land drainage for saline land reclamation is not enough; rather it should be one component of a package of practices for crop production. Such a package should consist of land grading and shaping, field dyking (for impounding water for a comprehensive leaching of salts), surface drainage system selection of suitable crops and cropping sequences, and adoption of improved cultural practices, together with the subsurface drainage system (especially for removing the concentrated water from the soil).

According to the Sampla experience, the crops (and their salt tolerant varieties) that may well adapt themselves to the condition at the initial years of reclamation (subject to availability of irrigation water) are paddy, barley, wheat, mustard, cotton, sorghum, cluster bean and pearl millet. As to the cultural practices, it was experienced that a 25% more seed rate for the seeded crops and 25% more plants per unit area for transplanted crops, as compared to the seed rate and transplanting density in normal (non-salient) soils would provide desired plant population in saline soils at the initial period of reclamation. This is needed to compensate for the mortality of seedlings and poor tillering in saline soils. Crops grown in saline soils respond well to the added doses of Nitrogen and Phosphorus fertilizers over the doses in normal soils. Application of Farm Yard Manure (FYM) with Phosphorous reduces salt injury to the plants. The generally high quantity presence of Potassium in saline soil gets depleted under excessive leaching during reclamation, in which case, Potassium fertilizer should also be added in quantity decided on the soil test result. Soils with shallow water table are prone to salinisation if left fallow, particularly during dry period. Subsurface drainage reduces soil water salinity and under shallow water table condition, plants are able to uptake this water thereby reducing irrigation requirement. In the Sample experiment, plant uptake of groundwater with salinity between 3 to 5.5 dS/m could reduce surface irrigation water application by 50%, still achieving good crop yield comparable to normal conditions. Subsurface drains reduced salinization considerably and whatever salts

accumulated at or near the soil surface those were leached or washed out during the monsoon season.

Finally, to manage drainage effluent, it was found that it is possible to blend the drainage effluent with other available water of good quality and still get a salinity of the blended water which is within the permissible limit of irrigation water quality for a given soil, water table depth and crop conditions. The Sample experiment revealed that for wheat, after giving a pre-sowing irrigation with canal water of EC 0.5 dS/m, subsequent irrigations using blended water with an EC range of 6 to 12 dS/m gave 97 to 83% yields, respectively as compared to the yield obtained by canal water irrigation alone. On the other hand, irrigation of mustered with blended water of EC 8 dS/m gave higher yield compared to the yields obtained by irrigation with canal water and blended water of EC 15 dS/m (Sharma et al., 1995). This study also revealed that cyclic use of canal and blended water was possible.

In the reclamation of saline land, there are two essential steps. **Firstly**, leaching of salts to reduce the soil salinity to a level that is not harmful to the crops to be grown. **Secondly**, following scientific land, water and crop management practices to sustain the beneficial effect of salt removal by leaching. As the package of practices are formulated based on the relevant data collected from a site, the specific details of the salt management technology of a region may not be directly applicable to other regions.

### 15.4.4 Case Studies on Alkali Land Reclamation

#### (1) Overview of Project Area

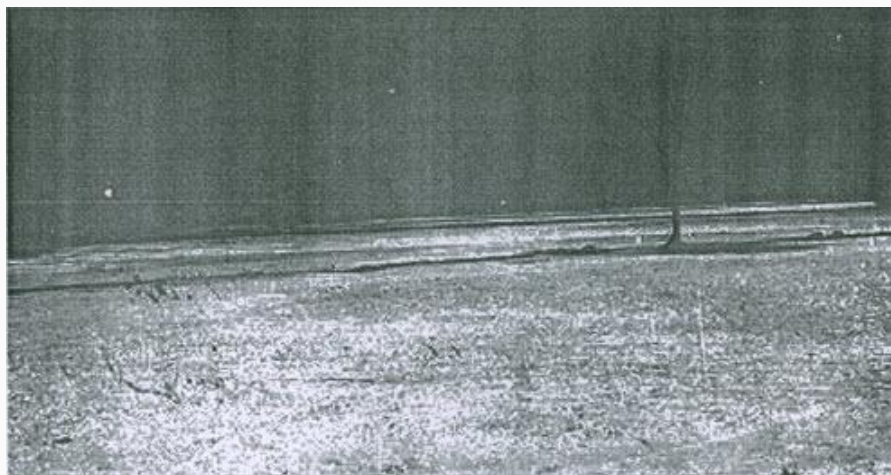
Alkali lands are found over large regions in the state of Haryana. Under the earlier mentioned Operational Research Project (ORP) of CSSRI, Karnal (Haryana), developing methodologies for alkali land reclamation was a main mandate. Pilot projects on alkali land reclamation were initiated in the mid 1970s in two clusters of seven villages, where the alkali problem was acute in large areas (Fig. 15.10).

There were four villages namely Kachhwa, Sagga, Sambhi and Birnaraina in the first cluster with a total area of about 6000 ha which about 1952 ha (32.5%) area were suffering from alkalisation problem. The second cluster consisted of three villages namely, Gudda, Begampur and Dadlana with a total area of 2500 ha of which, 500 ha (20%) affected with alkali problem (Bhattacharya and Michael, 2003). Important common soil topography and hydrometeorologic feature of these villages are described below.



**Fig. 15.10.** Location of the first cluster of villages along the Karnal-Sitamai road lying between 6 and 26 km from Karnal in which the Pilot Projects on the reclamation of alkali soils were undertaken by the CSSRI, commencing in 1975. (Source: Mehta and Mondal, 1988)

The alkali-affected areas were distributed over several patches, large and small, interspersed with normal soil regions. The pH of the surface soils was high (10.1). It was only marginally lower below the surface with a slightly reducing trend with increasing depth within the root zone (Bhattacharya and Michael, 2003). Besides high pH, the alkali soils had dominant cation Sodium and the dominant anions of Carbonates and Bi-Carbonates of Sodium. There were concretions at the root zone and below it. The salinity was also high ( $EC_e$  of the surface soils being 8 dS/m), going down with depth to 4.8 dS/m at 90 cm below the soil surface. The soil texture is sandy loam, with clay content varying from 16 to 27%. The infiltration rate was very low at 3 mm/day. Crop activity was practically non-existent in the alkali lands (Figs. 15.11 and 15.12). Even rice could not grow well due to the presence of high Sodium in the soil with an ESP of 62 to 95%. The 12-year (1975 to 1986) average annual rainfall recorded at the CSSRI observatory, located close to the project site, was 730 mm.



**Fig. 15.11.** A view of an extensive area of alkali land in the CSSRI Pilot Project area prior to reclamation. (Source: Bhattacharya and Michael, 2003)

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Long dry spells in the monsoon season were quite common and a major part of the monsoon rainfall was received in a few storms in some of the years. Due to poor infiltration, most of the runoff water was going waste and causing soil erosion, whereas the remaining water was stagnating on the land for long durations. The water table fluctuation ranged from 2 to 3 m. The water quality of a few tubewells was good with EC of 0.6 dS/m and was free from Sodium hazard. The annual pan evaporation was about 1640 mm.



**Fig. 15.12. An extensive stretch of alkali land in the Pilot Project area of CSSRI in Haryana prior to reclamation. Source: Bhattacharya and Michael, 2003)**

### (2) Project Activities

The operational research projects were taken up with full participation of the Institute (CSSRI), the village body, the district administration and the farmers. In addition, collaboration of the Haryana Land Development Corporation and financial institutions ensured timely supply of the necessary inputs such as gypsum and fertilizer, and completion of activities of land levelling and installation of tubewells for the farmers.

- **Land Levelling and Bunding:** Land levelling suited to the desired irrigation and drainage and bunding for the leaching of Sodium by rainfall or applied water, after converting Sodium Bicarbonate and Carbonate into Sodium Sulphate form by applying Calcium Sulphate (gypsum), are the two important field constructional activities for the reclamation of the alkali lands. The bunded fields when reclaimed from the alkali problem are suitable for rice cultivation. The alkali lands in the project area were levelled using a scraper, giving a gentle slope of 0.1%. Strong bunds of 35 to 40 cm height were constructed surrounding large areas, which were subdivided into 0.4 ha blocks by constructing smaller bunds around them.
- **Irrigation and Drainage:** Shallow tubewells were constructed for irrigation and for meeting leaching requirement. Groundwater pumping also helped in lowering the water table. The discharge of a 10 cm diameter tubewell was about 10 Lps, which could irrigate 4 to 5 ha of land. For the bunded rice fields, the need of surface drainage was considerably reduced, but not completely eliminated due to the occurrence of a few heavy rains in the



monsoon season. In the initial stages of reclamation of alkali lands, subsurface drainage did not work due to sealing of the pores of surface soil by the dispersed clay particles and poor water transmission characteristics through the soil below the surface. This is why, groundwater pumping was adopted for irrigation and for controlling water table, and surface drainage for evacuating excess rainfall in some of the ORP villages.

- **Application of Amendment:** The most commonly used amendment for the reclamation of alkali soils is gypsum. In the ORP villages, the pH of the surface soils varied from 9.8 to 10.6. Gypsum powder was applied to the ploughed and levelled land at a rate of 12.5 tonnes/ha and mixed with the topsoil using a plough. It was applied 15 to 20 days before paddy transplantation in June-July so as to take advantage of the monsoon rainfall in dissolving gypsum and percolating the solution down the soil profile. Addition of gypsum displaced Sodium from the exchange complex by Calcium, which improved the soil permeability thereby facilitating natural leaching of Sodium Sulphate (a reaction product).
- **Cropping Pattern:** During the initial phase of reclamation for a few years rice varieties IR-8 and Jaya were grown. Later fine and super-fine varieties such as PR-106, PR-107, Basmati (B-370), Pb. No. 1, Basmati, CSR-1, CSR-27, Pusa 150 and Pusa 169, were tested and popularised because they provided more economic returns. Where well irrigation water was available, green manuring crop was grown prior to initiating paddy cultivation. Nitrogen was applied at a rate of 150 kg/ha in four equal splits (one essentially at the time of transplanting) and Zinc Sulphate was applied at a rate of 25 kg/ha. Neither Phosphorus nor Potassium was necessary for first 4-5 years of cropping after starting the reclamation by the conjunctive use of amendment and leaching. After harvesting the kharif paddy during the first week of October, the land was ploughed and allowed to dry for about a week for the cultivation of rabi crops. Normal (HD 2009, WH 711, HD 1982, KRL 19) or late (HD 1553) varieties of wheat were selected depending on the time when a favourable sowing condition arrived. Nitrogen was applied at a rate of 130-135 kg/ha with 50% as the basal dose and 25% each at tillering and pre-flowering stages. Five to six irrigations were given to wheat; the first irrigation was given four weeks after sowing.

Though the most common winter crop of the region was wheat, berseem (*Trifolium alexandrinum*) and shaftal (*Trifolium resumpinatum*) were also grown to meet the requirement of the farmers. In addition, different trees were grown after reclaiming alkali soils.

- **Tree Plantation in the Reclaimed Land:** Different trees were planted on alkali soils after reclamation and growing crops for a limited period. A new approach for tree plantation was evolved which aimed at solubilization of native calcium carbonate for the reclamation of alkali soil and providing suitable soil condition for the growth of roots. (Figs. 15.13 to 15.15). It led to a large-scale and successful plantation of useful trees with intercrops.





**Fig. 15.13. Drilling of hole with a mechanically operated auger to break the hard layer formed by kankar layer about 1 m below the land surface in the CSSRI Pilot Project area for tree plantation. (Source: Bhattacharya and Michael, 2003)**



**Fig. 15.14. Soil profile showing the root development of a one-year old eucalyptus sapling planted using a mechanically operated soil auger. (Source: Bhattacharya and Michael, 2003)**



**Fig. 15.15. Afforestation of the salt-affected area. Trees are planted in the irrigation furrows. Note the salt accumulation on either side of the rows of trees. (Source: Bhattacharya and Michael, 2003)**

### **(3) Lessons from Pilot Experiments on Alkali Land Reclamation**

- **Need for Technology Demonstration:** During 1975-1986, small demonstration plots measuring 0.2 to 0.4 ha were set up in some of the worst alkali affected farmers lands. The total number of such demonstration was more than 600 in the seven ORP villages. These demonstrations served as the eye-openers for the alkali affected cultivators by convincing them that their bad and unproductive/less productive lands can be made productive with remunerative crop yields by applying amendments and by following simple cultural practices.
- **Farmers' Participation:** Through the initial demonstration of the techniques of alkali land reclamation, the farmers' participation in learning and applying the technology could be ensured. This was the most important factor, which was responsible for reclaiming almost the entire alkali land of the affected villages by the initiative, effort and input of the farmers themselves. Out of the total alkali affected are of about 2500 ha in the seven ORP villages, about 160 ha was reclaimed under the demonstration program and the farmers themselves reclaimed an additional alkali land of 2200 ha at their own costs. The increase in grain yields of about 1 tonne/ha from the demonstration plots compared to the farmers' fields were considerably reduced when the farmers mastered the art of the technology application and followed desirable cultural practices.
- **Cultural Practices:** Besides the reclamation technology a suitable package of cultural practices are required to be followed in the alkali lands during and after reclamation. The package comprises proper water management, weed management, green manuring, application of FYM, fertilization through mineral fertilizers (mainly Nitrogen), maintaining timelines in field activities and the use of good quality seeds. In the reclaimed alkali land, crop diversification is possible within and outside the rice-wheat rotation. In the ORP villages, these were fodder sorghum, mustard, green gram and vegetables such as onion, garlic, radish, potato, tomato, brinjal and spinach. Alkali tolerant varieties (if

available) should be used in under-reclamation and fully reclaimed alkali lands to take care of the eventual re-alkalised soil with gradual calcium uptake by the plants.

- **Alternative Amendment:** Besides gypsum, there are other agents for reclaiming alkali lands such as pyrites (iron ore containing Sulphur) and rice husk, available as a by-product from rice mills. In a small scale in the ORP villages, application of pyrite with 15% Sulphur content at a rate of 14.2 tonnes/ha could produce significantly increased yields of rice and wheat. Also, in a few small areas of the ORP villages, the application of rice husk at a rate of 30 tonnes/ha, together with gypsum at a rate of 4.2 tonnes/ha produced the same crop yield as was obtained by applying only gypsum at the rate of 12.5 tonnes/ha.
- **Improvement in Soil Properties:** Application of amendment, leaching and cropping activities improved the soil chemical and physical parameters gradually. The pH and EC of the soils at various depths revealed a continuous declining trend.

Infiltration rate increased from 3 mm/day in the unreclaimed soil to 9 mm/day after one year of reclamation and to 25 mm/day after 5 years. Water holding capacity and hydraulic conductivity of the soil also increased. With increased infiltration and hydraulic conductivity, application of more water became necessary, which proved to be expensive. Therefore, it was recommended to transplant rice seedlings after 2-3 days of gypsum application and impounding water for leaching. This saved water and time, and did not have any adverse effect on the paddy plants. However, this recommendation was not valid if pyrites were used as the amendment.

#### (4) Concluding Remarks

The pilot project undertaken by the Central Soil Salinity Research Institute yielded useful technologies for the reclamation and management of saline and alkali soils, particularly in the arid and semi-arid regions. The case studies presented in Section 15.4 are based on the two pilot projects in Haryana. Similar projects were subsequently taken up at selected sites within the Haryana state and in some other states such as in Gujarat and Rajasthan. The success of the projects reported under the case studies has been due to the holistic approach to planning, well integrated multi-disciplinary and multi-sectoral involvement, adoption of appropriate technology, and effective participation of the farmers. The technological breakthrough brought about by the projects and ancillary programmes of the Institute attracted global attention and resulted in a significant collaboration and involvement of some international agencies.

Considering the success of earlier irrigation and drainage projects, it is necessary that such efforts should be taken in other parts of the country to solve water logging salinity problems, together with the experiences and ideas for avoiding these problems. In addition, the irrigation and drainage technologies are being continuously upgraded and we must take the advantage of the updated and improved global information concerning drainage and reclamation of agricultural lands. Such an approach to land and water management is the need of the hour in order to ensure sustainable agricultural production in the country.



### Lesson 16 Economic Evaluation of Drainage Projects

#### 16.1 Introduction

Land drainage is generally undertaken either to bring land into production or to increase the productivity of existing cultivable land. It represents a capital investment intended to result in future benefits and the viability of the drainage project should be assessed like any other investment on the basis of sound economic analysis. Economic evaluation of any projects/schemes calls for the comparison of benefits and costs. However, which items should be regarded as benefits and costs and how they should be valued depends at least partly on the outcome of planning process in other strata of the economy (Smedema and Rycroft, 1983). Thus, a proper identification of costs and benefits is the key to any economic analysis.

The costs of a drainage project can conveniently be grouped under the following heads (ILRI, 1974):

- Initial or capital investments: Examples of capital investments are: canals, control works, ditches, pipes, pumps, land leveling, land clearing, farm roads, reallocation of existing structures, etc.
- Replacement investments: They are required in the future when capital goods come to the end of their technical or economic lifetime and have to be replaced.
- Loss of existing property.
- Recurrent costs of the maintenance works.
- Recurrent costs of the operation and management of a scheme.
- Other associated costs.

The benefits of land drainage may be divided into following two major heads:

- Tangible benefits: Examples of tangible benefits are: enhanced agricultural production, water supply for domestic or industrial use, etc.
- Intangible benefits: Examples of intangible benefits are: improvement in local environment, improved hygiene, better trafficability, etc.

### 16.2 Computation of Costs and Benefits for Economic Analysis

#### 16.2.1 Computation of Discounting Factor

The costs and the benefits of a land drainage project occur at different times during the project period; the main cost occurring mostly during the construction phase and the benefits after the project has reached maturity. Hence, there is a need for some device to bring the benefits and costs occurring at different points of time on to a common base; otherwise no comparisons are possible. This device is called discounting. Numerically, discounting is the inverse of charging compound interest. It is calculated using the following equation (Finkel, 1983):

$$DF = \sum_{i=1}^{PL} \frac{1}{(1 + RI)^i} \quad (16.1)$$

Where, DF = discounting factor, PL = life of the drainage project (years), and RI = rate of interest (fraction).

#### 16.2.2 Computation of Annual Repayment

The annual repayment on the initial loan at a rate of interest and over a repayment period is calculated as (Finkel, 1983):

$$F = \frac{IC}{PWF} \quad (16.2)$$

Here, PWF (present worth factor) is equal to:

$$PWF = \frac{[(1 + RI)^{RP} - 1]}{RI(1 + RI)^{RP}} \quad (16.3)$$

Where, F = annual repayment (Rs.), IC = initial investment (Rs.), RP = repayment period (years), and the remaining symbols have the same meaning as defined earlier.

#### 16.2.3 Inflation Factor Computation

Rate of the money can increase the future costs and benefits are increased in value to take account of an assumed rate of inflation. Yearly inflation factor is calculated by:

$$IF = (1 + IR)^{PL} \quad (16.4)$$

Where, IF = inflation factor, IR = inflation rate (fraction), and the remaining symbols have the same meaning as defined earlier.



### 16.3 Indices for Economic Evaluation

In practice, three principal indices are used in an economic analysis: (i) net present value (NPV), (ii) benefit-cost ratio (B-C ratio), and (iii) internal rate of return (IRR). A brief description about these economic indices is given below.

#### 16.3.1 Net Present Value (NPV)

Net Present Value (NPV) is the difference between the present value of benefits and costs. It also known as Net Present Worth (NPW). Clearly, a positive value of NPV (or NPW) is desirable (Smedema and Rycroft, 1983). The formula for the computation of NPV is (ILRI, 1974; Brooks et al., 1997):

$$NPV = \sum_{i=1}^{PL} \frac{(B_i - C_i)}{(1 + RI)^i} \quad (16.5)$$

Where,  $B_i$  = benefits in the  $i^{\text{th}}$  year (Rs.),  $C_i$  = cost in the  $i^{\text{th}}$  year (Rs.), and the remaining symbols have the same meaning as defined earlier.

#### 16.3.2 Benefit-Cost Ratio (B-C Ratio)

Benefit-Cost Ratio (B-C Ratio) is the present value of benefits divided by present value of costs. For a project to be economically viable, the B-C ratio should be greater than one (Smedema and Rycroft, 1983). The benefit-cost ratio is computed as (Brooks et al., 1997):

$$B - C \text{ Ratio} = \frac{\sum_{i=1}^{PL} \left[ \frac{B_i}{(1 + RI)^i} \right]}{\sum_{i=1}^{PL} \left[ \frac{C_i}{(1 + RI)^i} \right]} \quad (16.6)$$

#### 16.3.3 Internal Rate of Return (IRR)

Internal Rate of Return (IRR) is often used for large public projects (Smedema and Rycroft, 1983). Unlike the NPV or B-C ratio, the IRR does not use a predetermined discount rate. Rather, IRR is the discount rate that sets the present value of benefits equal to the present value of costs. That is (Brooks et al., 1997),

$$\sum_{i=1}^{PL} \frac{B_i}{(1 + RI)^i} = \sum_{i=1}^{PL} \frac{C_i}{(1 + RI)^i} \quad (16.7)$$

$$\text{Or,} \quad \sum_{i=1}^{PL} \frac{(B_i - C_i)}{(1 + RI)^i} = 0 \quad (16.8)$$

### 16.3.4 Capital Recovery Factor (CRF)

A more precise method for computing the annual amortized fixed cost is to take into account the expected service life of the project/item and the interest rate. In this method, the fixed cost is based on the present worth multiplied by the 'capital recovery factor'. **Capital Recovery Factor (CRF)** is defined as the ratio of a constant annuity to the present value of receiving that annuity for a given time period. It is mathematically expressed as (James and Lee, 1971):

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (16.9)$$

Where,  $i$  = rate of interest (fraction), and  $n$  = anticipated service life of the drainage project (years).

### 16.3.5 Selection of Suitable Economics Indices

All three economic measures viz., NPV, B-C Ratio and IRR are calculated using the same benefit and cost data and assumptions, and have symmetry in their results. It is possible that when a set of alternative projects is examined, the use of different evaluation indices will give different project ranking. This raises the question as to which economic indices to use. A comparative analysis of these three economic indices is presented in Table 16.1, which can help drainage engineers during economic analysis of drainage projects.

**Table 16.1. Comparison between three widely used economic indices (Brooks et al., 1997)**

Project Condition	NPV	IRR	B-C Ratio
1. Independent Projects (no constraint on costs)	Select all project with NPV>0; project ranking not required	Select all projects with IRR greater than cutoff rate of return; project ranking not required	Select all projects with B-C ratio>1; project ranking not required.
2. Constraint on Costs	Not suitable for ranking projects	Ranking all projects by IRR may yield incorrect solution	Rank all projects by B-C ratio where C is defined as constrained cost will always give correct ranking.
3. Mutually Exclusive Projects (within a given budget)	Select alternative with largest NPV	Selection of alternative with highest IRR may give incorrect result	Selection of alternative with highest B-C ratio may give incorrect result.

4. Discount Rate	Appropriate discount rate must be adopted	No discount rate required, but reference rate must be adopted	Appropriate discount rate must be adopted.
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### 16.4 Example Problem on Economic Analysis of Drainage Projects

**Problem:** The following data are given for land drainage systems (Smedema and Rycroft, 1983):

Total costs of drainage systems = 520 £/ha

Maintenance costs of drainage systems = 5 £/ha

Rate of interest = 10 % /year

Repayment period = 10 years

Inflation rate = 5 %

Life of drainage project = 20 years

Total benefits = 90 £/ha

**Solution:** The solution to the above problem is presented in Table 16.2.

Table 16.2. Results of the cost and benefit analysis of a drainage project

Year	Costs and Benefits at Actual Prices (£/ha)			Actual Future Costs and Benefits with 5% Inflation (£/ha)					Present Values of Future Sums (£/ha)		
	Loan	Mainten ance of Moling	Benefits	Inflation Factor	Loan	Moling Main- tenance	Benefits	Benefits - Costs	Discount Factor 10%	Benefits - Costs	NPV
1	84.60		90	1.05	84.60		94.50	9.90	0.91	9.00	9.00
2	84.60		90	1.10	84.60		99.00	14.40	0.83	12.00	21.00
3	84.60		90	1.16	84.60		104.40	19.80	0.75	14.90	35.90
4	84.60		90	1.22	84.60		109.80	25.20	0.68	17.10	53.00
5	84.60	15	90	1.28	84.60	19.20	115.20	11.40	0.62	7.10	60.00
6	84.60		90	1.34	84.60		120.60	36.00	0.56	20.20	80.30
7	84.60	20	90	1.41	84.60	28.20	126.90	14.10	0.51	7.20	87.50
8	84.60		90	1.48	84.60		133.20	48.60	0.47	22.80	110.30
9	84.60		90	1.55	84.60		139.50	54.90	0.42	23.10	133.40

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10	84.60	15	90	1.63	84.60	24.50	146.70	37.60	0.39	14.70	148.10
11			90	1.71			153.90	153.90	0.35	53.90	202.00
12			90	1.80			162.00	162.00	0.32	51.90	253.90
13			90	1.89			170.10	170.10	0.29	49.30	303.20
14		20	90	2.00		40.00	180.00	140.00	0.26	34.40	335.60
15		15	90	2.08		31.20	187.20	154.50	0.24	37.10	376.70
16			90	2.18			196.20	196.20	0.22	43.20	419.90
17			90	2.29			206.10	206.10	0.20	41.20	461.10
18			90	2.41			216.90	216.90	0.18	39.00	500.10
19			90	2.53			227.70	227.70	0.16	36.40	536.50
20		15	90	2.65		39.80	238.50	198.70	0.15	29.80	566.30

B-C ratio after 10 years is  $(555.44+148.10)/555.44 = 1.27$  while after 52 years is  $(566.30+581.90)/581.90 = 1.97$



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