17 Agricultural Drainage Criteria

R.J. Oosterbaan[1]

17.1 Introduction

'Agricultural drainage criteria' can be defined as criteria specifying the highest permissible levels of the watertable, on or in the soil, so that the agricultural benefits are not reduced by problems of waterlogging.

If the actual water levels are higher than specified by the criteria, an agricultural drainage system may have to be installed, or an already installed system may have to be improved, so that the waterlogging is eliminated. If, on the other hand, a drainage system has lowered water levels to a depth greater than specified by the criteria, we speak of an over-designed system.

Besides employing agricultural drainage criteria, we also employ technical drainage criteria (to minimize the costs of installing and operating the system, while maintaining the agricultural criteria), environmental drainage criteria (to minimize the environmental damage), and economic drainage criteria (to maximize the net benefits).

This chapter deals mainly with the agricultural criteria. The technical criteria will be discussed in Chapters 19 to 23, but some examples will be given in this chapter. Environmental aspects will be comprehensively treated in Chapter 25, but are also briefly discussed in this chapter.

A correct assessment of the agricultural drainage criteria requires:
- A knowledge of the various possible types of drainage systems;
- An appropriate index for the state of waterlogging;
- An adequate description of the agricultural objectives;
- Information on the relationship between index and objective.

In Sections 17.2 to 17.4, this chapter aims to bring the above subjects into perspective and to illustrate their relationships based on information derived from literature. Section 17.2 concentrates on the types of drainage systems, Section 17.3 on the formulation of drainage criteria, and Section 17.4 on the soil and water factors intermediate between engineering and agriculture. Section 17.5 gives some examples of agricultural and other drainage criteria developed and used in various agro-climatological regions of the world.

17.2 Types and Applications of Agricultural Drainage Systems

17.2.1 Definitions

'Agricultural drainage systems' are systems which make it easier for water to flow from the land, so that agriculture can benefit from the subsequently reduced water

[1] International Institute for Land Reclamation and Improvement

levels. The systems can be made to ease the flow of water over the soil surface or through the underground, which leads to a distinction between 'surface drainage systems' and 'subsurface drainage systems'. Both types of systems need an internal or 'field drainage system', which lowers the water level in the field, and an external or 'main drainage system', which transports the water to the outlet.

A surface drainage system is applied when the waterlogging occurs on the soil surface, whereas a subsurface drainage system is applied when the waterlogging occurs in the soil. Although subsurface drainage systems are sometimes installed to reduce surface waterlogging and vice versa, this practice is not recommended, with exceptions as illustrated in Section 17.2.3. Under certain conditions, combined surface/subsurface drainage systems are feasible (Chapter 21).

Agricultural drainage systems do not necessarily lead to increased peak discharges. Although this may occur, especially with surface drainage, the reduced waterlogging can lead to an increase in the storage of water on or in the soil during periods of peak rainfall, so that peak discharges are indeed reduced (Oosterbaan 1992). A drainage engineer should see to it that the flow of water from the soil occurs as steadily as possible instead of suddenly.

Sometimes (e.g. in irrigated, ponded rice fields), a form of temporary drainage is required whereby the drainage system is only allowed to function on certain occasions (e.g. during the harvest period). If allowed to function continuously, excessive quantities of water would be lost. Such a system is therefore called a 'checked drainage system'. More usually, however, the drainage system should function as regularly as possible to prevent undue waterlogging at any time. We then speak of a 'regular drainage system'. (In literature, this is sometimes also called 'relief drainage'.)

The above definition of agricultural drainage systems excludes drainage systems for cities, highways, sports fields, and other non-agricultural purposes. Further, it excludes natural drainage systems. Agricultural drainage systems are artificial and are only installed when the natural drainage is insufficient for a satisfactory form of agriculture. The definition also excludes such reclamation measures as 'hydraulic erosion control' (which aims rather at reducing the flow of water from the soil than enhancing it) and 'flood protection' (which does not enhance the flow of water from the soil, but aims rather at containing the water in watercourses). Nevertheless, flood protection and drainage systems are often simultaneous components of land reclamation projects. The reason is that installing drainage systems without flood protection in areas prone to inundation would be a waste of time and money. Areas with both flood protection and drainage systems are often called 'polders'. Sometimes, a flood-control project alone suffices to cure the waterlogging. Drainage systems are then not required.

In literature, one encounters the term 'interceptor drainage'. The interception and diversion of surface waters with catch canals is common practice in water-management projects, but it is a flood-protection measure rather than a drainage measure. The interception of groundwater flowing laterally through the soil is usually not effective, because of the low velocities of groundwater flow (seldom more than 1 m/d and often much less). In the presence of a shallow impermeable layer, subsurface interceptor drains catch very little water and generally do not relieve waterlogging in extensive agricultural areas. In the presence of a deep impermeable layer, the total flow of groundwater can be considerable, but then it passes almost entirely underneath the subsurface interceptor drain. The upward seepage of groundwater cannot be intercepted by a single interceptor drain: here, one needs a regular drainage system.

17.2.2 Classification

Figure 17.1 classifies the various types of drainage systems. It shows the field (or internal) drainage systems and the main (or external) systems. The function of the field drainage system is to control the watertable, whereas the function of the main drainage system is to collect, transport, and dispose of the water through an outfall or outlet.

In the figure, the field drainage systems are differentiated in surface and subsurface drainage systems. The surface systems are differentiated in regular systems and checked systems as defined in Section 17.1.

The regular surface drainage systems, which start functioning as soon as there is an excess of rainfall or irrigation, operate entirely by gravity. They consist of reshaped or reformed land surfaces (Chapter 20) and can be divided into:

- Bedding systems, used in flat lands for crops other than rice;
- Graded systems, used in sloping land for crops other than rice, which may or may not have ridges and furrows.

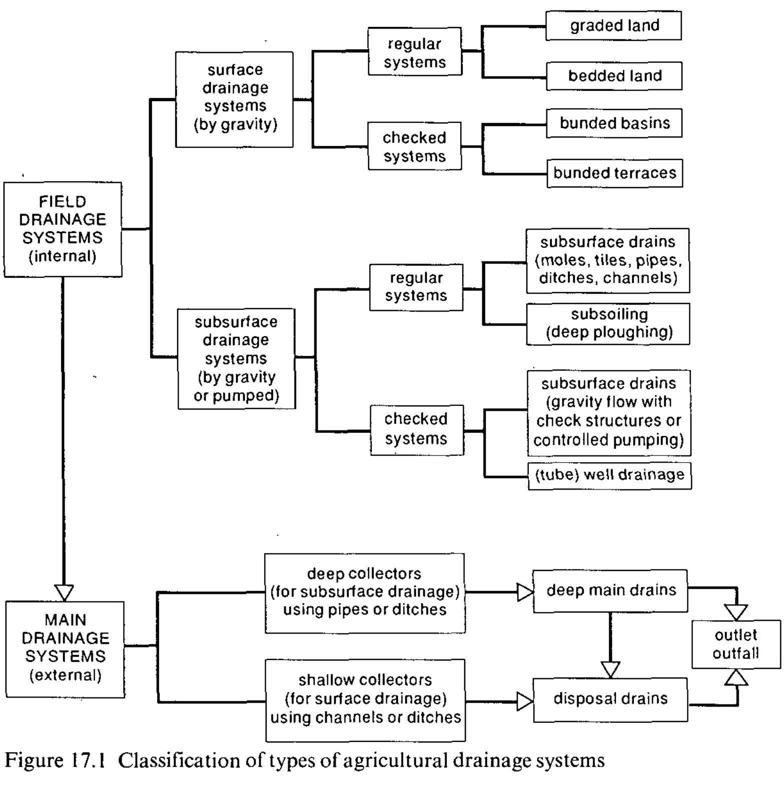


Figure 17.1 Classification of types of agricultural drainage systems

The checked surface drainage systems consist of check gates placed in the bunds surrounding flat basins, such as those used for rice fields in flat lands. These fields are usually submerged and only need to be drained on certain occasions (e.g. at harvest time). Checked surface drainage systems are also found in terraced lands used for rice (Oosterbaan et al. 1987).

In literature, not much information can be found on the relationship between the various regular surface field drainage systems, the reduction in the degree of waterlogging, and the agricultural or environmental effects. It is therefore difficult to develop sound agricultural criteria for the regular surface field drainage systems. Most of the known criteria for these systems concern the efficiency of the techniques of land levelling and earthmoving (Chapter 20). Similarly, agricultural criteria for checked surface drainage systems are not very well known.

Like the surface field drainage systems, the subsurface field drainage systems can also be differentiated in regular systems and checked systems (Figure 17.1). When the drain discharge takes place entirely by gravity, both types of subsurface systems have much in common, except that the checked systems have control gates that can be opened and closed according to need. They can save much irrigation water (Qorani et al. 1990). A checked drainage system also reduces the discharge through the main drainage system, thereby reducing construction costs.

When the discharge takes place by pumping, the drainage can be checked simply by not operating the pumps or by reducing the pumping time. In North-West India, this practice has increased the irrigation efficiency and reduced the quantity of irrigation water needed, and has not led to any undue salinization (Rao et al. 1992).

The subsurface field drainage systems consist of horizontal or slightly sloping channels made in the soil; they can be open ditches, buried pipe drains, or mole drains; they can also consist of a series of wells. The channels discharge their water into the collector or main system either by gravity or by pumping. The wells (which may be open dug wells or tubewells) have to be pumped, but sometimes they are connected to drains for discharge by gravity. In some instances, subsurface drainage can be achieved simply by breaking up slowly permeable soil layers by deep ploughing (subsoiling), provided that the underground has sufficient natural drainage. In other instances, a combination of subsoiling and subsurface drains may solve the problem.

Subsurface drainage by wells is often referred to as 'vertical drainage', and drainage by channels as 'horizontal drainage', but it is better to speak of 'field drainage by wells', or 'field drainage by ditches or pipes'.

The main drainage systems consist of deep or shallow collectors, and main drains or disposal drains (Figure 17.1). Deep collectors are required for subsurface field drainage systems, whereas shallow collectors are used for surface field drainage systems, but they can also be used for pumped subsurface systems. The terms deep and shallow collectors refer rather to the depth of the water level in the collector below the soil surface than to the depth of the bottom of the collector. The bottom depth is determined both by the depth of the water level and by the required discharge capacity.

The deep collectors may either discharge their water into deep main drains (which are drains that do not receive water directly from field drains, but only from collectors), or their water may be pumped into a 'disposal drain'. Disposal drains are main drains in which the depth of the water level below the soil surface is not bound to a minimum, and the water level may even be above the soil surface, provided that embankments are made to prevent inundations. Disposal drains can serve both subsurface and surface field drainage systems. Deep main drains can gradually become disposal drains if they are given a smaller gradient than the land slope along the drain. The final point of a main drainage system is the gravity outlet structure or the pumping station.

The technical criteria applicable to main drainage systems depend on the hydrological situation and on the type of system. These criteria will be discussed in Chapter 19, but some examples are given in Section 17.5.1 (for temperate humid zones) and in 17.5.4 (for tropical humid zones). Pumping stations will be discussed in Chapter 23 and gravity outlet structures in Chapter 24.

17.2.3 Applications

Surface drainage systems are usually applied in relatively flat lands that have soils with a low or medium infiltration capacity, or in lands with high-intensity rainfalls that exceed the normal infiltration capacity, so that frequent waterlogging occurs on the soil surface.

Subsurface drainage systems are used when the drainage problem is mainly that of shallow watertables. When both surface and subsurface waterlogging occur, a combined surface/subsurface drainage system is required. Sometimes, a subsurface drainage system installed in soils with a low infiltration capacity and a surface drainage problem improves the soil structure and the infiltration capacity so greatly that a surface drainage system is no longer required (De Jong 1979). On the other hand, it can also happen that a surface drainage system diminishes the recharge of the groundwater to such an extent that the subsurface drainage problem is considerably reduced or even eliminated.

The choice between a subsurface drainage system by pipes and ditches or by tubewells is more a matter of technical criteria and costs than of agricultural criteria, because both types of systems can be designed to meet the same agricultural criteria and achieve the same benefits. Usually, pipe drains or ditches are preferable to wells. However, when the soil consists of a poorly permeable top layer several metres thick, overlying a rapidly permeable and deep subsoil, wells may be a better option, because the drain spacing required for pipes or ditches would be very narrow whereas the well spacing can be very wide.

When the land needs a subsurface drainage system, but saline groundwater is present at great depth, it is better to employ a shallow, closely-spaced system of pipes or ditches instead of a deep, widely-spaced system. The reason is that the deeper systems produce a more salty effluent than the shallow systems. Environmental criteria may then prohibit the use of the deeper systems.

In some drainage projects, one may find that only main drainage systems are envisaged. The agricultural land is then still likely to suffer from field drainage problems. In other cases, one may find that field drainage systems are ineffective because there is no main drainage system. In either of these cases, the installation of an incomplete drainage system is not recommended.

17.3 Analysis of Agricultural Drainage Systems

17.3.1 Objectives and Effects

The objectives of agricultural drainage systems are to reclaim and conserve land for agriculture, to increase crop yields, to permit the cultivation of more valuable crops, to allow the cultivation of more than one crop a year, and/or to reduce the costs of crop production in otherwise waterlogged land. Such objectives are met through two direct effects and a large number of indirect effects.

The direct effects of installing a drainage system in waterlogged land are (Figure 17.2):

- A reduction in the average amount of water stored on or in the soil, inducing drier soil conditions and reducing waterlogging;
- A discharge of water through the system.

The direct effects are mainly determined by the hydrological conditions, the hydraulic properties of the soil, and the physical characteristics of the drainage system. The direct effects trigger a series of indirect effects. These are determined by climate, soil, crop, agricultural practices, and the social, economic, and environmental conditions. Assessing the indirect effects (including the extent to which the objectives are met) is therefore much more difficult, but not less important, than assessing the direct effects.

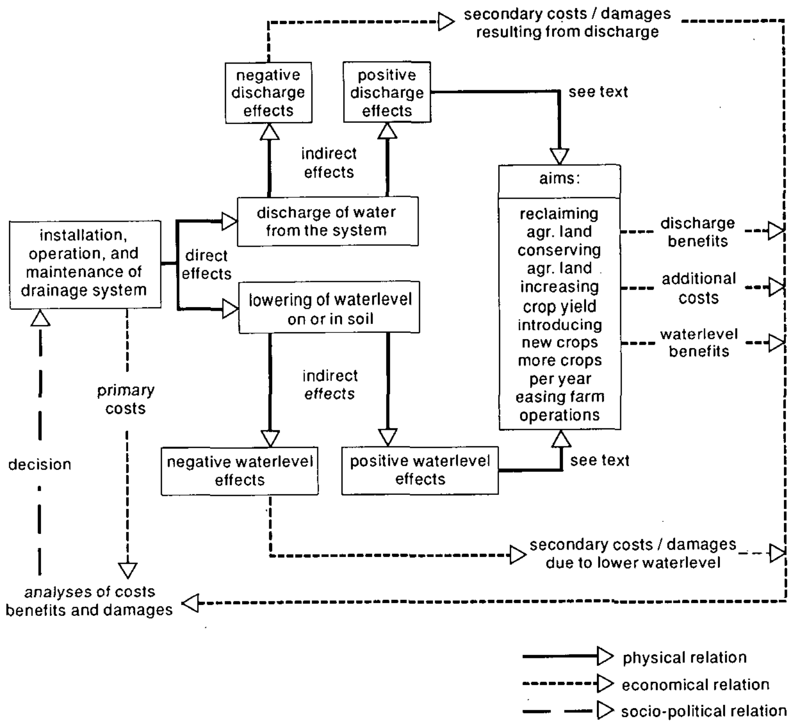


Figure 17.2 Diagram of the effects of drainage on agriculture and the economic evaluation

The indirect effects, which can be physical, chemical, biological, and/or hydrological, can be either positive or negative. Some examples are:

- Positive effects owing to the drier soil conditions: increased aeration of the soil; stabilized soil structure; higher availability of nitrogen in the soil; higher and more diversified crop production; better workability of the land; earlier planting dates; reduction of peak discharges by an increased temporary storage of water in the soil;
- Negative effects owing to the drier soil conditions: decomposition of organic matter; soil subsidence; acidification of potential acid sulphate soils; reduced irrigation efficiency; increased risk of drought; ecological damage;
- The indirect effects of drier soil conditions on weeds, pests, and plant diseases: these can be both positive and negative; the net result depends on the ecological conditions;
- Positive effects owing to the discharge: removal of salts or other harmful substances from the soil; availability of drainage water for various purposes;
- Negative effects owing to the discharge: excessive leaching of valuable nutrients from the soil; downstream environmental damage by salty or otherwise polluted drainage water; the presence of ditches, canals, and structures impeding accessibility and interfering with other infrastructural elements of the land.

Many of the indirect effects are mutually influenced and also exert their influence on the direct effects. For example, as a result of drainage, the following may happen:

- The more intensive agriculture increases the evapotranspiration and consequently may reduce the discharge, unless this leads to an increased irrigation intensity;
- The more stable soil structure may increase the infiltration and the subsurface drain discharge, and decrease the surface runoff.

Both of the above effects sometimes neutralize each other so that the drain discharge is not appreciably affected.

The above considerations illustrate that, in developing agricultural drainage criteria, one needs a clear conceptual framework and a systems approach. Rules of thumb may be useful in the initial stages of reclaiming land by drainage, but subsequently a systematic monitoring program is required to validate or improve the criteria used with the aim, in the future, of avoiding ineffective and inefficient drainage systems and of mitigating negative effects.

17.3.2 Agricultural Criterion Factors and Object Functions

In agricultural drainage, one is dealing with agricultural, environmental, engineering, economic, and social aspects.

The agricultural aspects concern 'object factors' and 'criterion factors'. Object factors represent the agricultural aims (Figure 17.2) that are to be achieved to the highest possible degree (maximization) through a process of optimization, yielding 'agricultural targets' (see the insert in Figure 17.3). Optimizing is done with criterion factors, which are factors that are affected by the drainage system and at the same time influence the object factors.

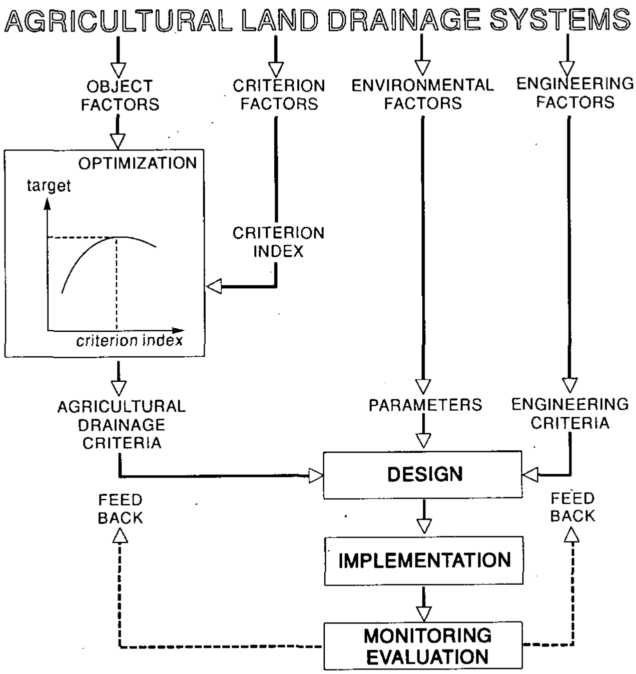


Figure 17.3 The role of agricultural, environmental, and engineering factors in the optimization, design, and evaluation of drainage systems

Examples of criterion factors are the degree of waterlogging, the dryness or wetness of the soil, and the soil salinity.

Owing to its variation in time and space, a criterion factor can be specified in different ways. A chosen specification can be called a 'criterion index'. Examples of such indices are:

- The average depth of the watertable during the cropping season;
- The average depth of the watertable during the off-season;
- The exceedance frequency of the watertable over a critically high level;
- Seasonal average salinity of the rootzone;
- Salinity of the topsoil at sowing time;
- Average, minimum, or maximum number of days that the soil is workable during a critical period.

The relationship between an object factor and an index can be called 'object function of the index' and is also known as 'response function' or 'production function'.

The optimization procedure through the object function leads to a tolerance, or even an optimum, value of the index, which can be called an 'agricultural drainage criterion'. It serves as an instruction to the designer of the drainage system because it stipulates the agricultural condition the system must meet to be effective (i.e. to fulfil its purpose). Also, the instruction can prevent the design and implementation of a system that is unnecessarily intensive, expensive, and even detrimental (Oosterbaan 1992).

‘Environmental factors’ are factors representing the given natural or hydrological conditions under which the system has to function. Examples of these factors are irrigation, rainfall, the soil’s hydraulic conductivity, natural surface or subsurface drainage, topography, and aquifer conditions.

For design purposes, the environmental factors must be specified as ‘environmental indices’, in the same way as the criterion factors are specified as criterion indices. Examples of environmental indices are the average seasonal rainfall, the extreme daily rainfall, the arithmetic or geometric mean of the hydraulic conductivity, and the variation in hydraulic conductivity with depth in the soil. Through a process of optimizing the engineering aspects, the environmental indices yield ‘environmental parameters’, which are fixed values of the indices, chosen as engineering or design criteria, in similarity to the agricultural criteria. Examples of such parameters are design values for rainfall, discharge, and hydraulic conductivity.

The engineering aspects include ‘engineering factors’ and ‘engineering objectives’. The objectives usually aim at minimizing the costs, and relate to the efficiency of the drainage system. A fully efficient drainage system fulfils the agricultural criteria at the lowest possible input level of materials and finances.

The engineering factors are factors representing the technical and material components of the drainage system (e.g. the layout, the longitudinal section and the cross-section of the drains, and the kind and quality of materials). The choice of the engineering factors is specified in the tender documents produced after the design has been completed.

Optimizing the engineering aspects results not only in environmental parameters, but also in ‘engineering criteria’. Both serve as instructions to the designer of the drainage system to secure an efficient design. The engineering criteria, which aim at minimizing costs, can also be called ‘efficiency criteria’, whereas the agricultural criteria, which aim at maximizing benefits can also be called ‘effectiveness criteria’. Engineering criteria will be discussed in Chapters 19-22.

After the design procedure has been completed, and before the drainage project can be offered for implementation, it has to be analyzed on costs, benefits, and side-effects. Through a survey of environmental factors, the agricultural criteria provide tools for an estimate of the drainage needs and the expected benefits. For example, with criteria specifying a minimum permissible depth of the watertable and a depth-to-watertable map, one can judge the extent of the drainage problems. With the response function, the expected benefits can also be estimated, assuming a drainage system is installed that meets the criteria. Examples of such an analysis are given by Nijland and El Guindy (1984) and Oosterbaan et al. (1990).

Summarizing, one can say that the role of agricultural criterion factors and indices, and their object (production) functions, is threefold:

- They serve to assess the magnitude of drainage problems in hitherto undrained lands and to predict the benefits of a drainage system;
- They serve to develop agricultural drainage criteria and instructions to the designer of the drainage system so that the system fulfils the agricultural objectives;
- They serve to check the (agricultural) effectiveness of a drainage system after its implementation and to assess the need for upgrading the system.

17.3.3 Watertable Indices for Drainage Design

Presented in this section are examples of how the depth of the watertable below the soil surface is used as a criterion factor for the development of watertable indices and agricultural criteria for the design of a subsurface drainage system.

The depth of the watertable is often used as a criterion factor because it can be related to crop production on the one hand, and to drain depth and spacing on the other. Since the watertable in the soil fluctuates with time, as illustrated in Figure 17.4, the behaviour of the watertable has to be characterized by an appropriate index. Various indices that feature the average depth and extremely shallow depths have been developed. The relevant question is: 'Which of the indices is better?' Before this question can be answered, a depth-duration-frequency analysis of the watertable has to be made.

Figure 17.5 shows a typical frequency distribution of the daily average depth of the watertable. The distribution is skew with mode > median > mean (Chapter 6). It has a considerable standard deviation, and the 10% and 1% extremely shallow depths deviate much from the mean, mode, and median.

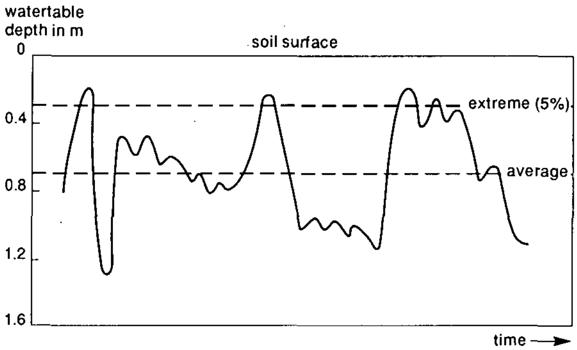


Figure 17.4 A fluctuating watertable with an indication of the average depth and an infrequent shallow depth of the watertable

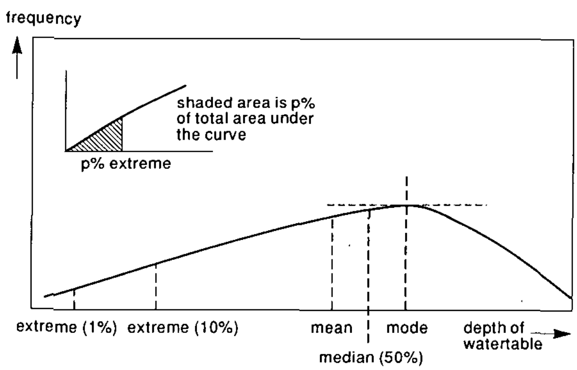


Figure 17.5 A frequency distribution of the daily average watertable depths with some of its characteristic values

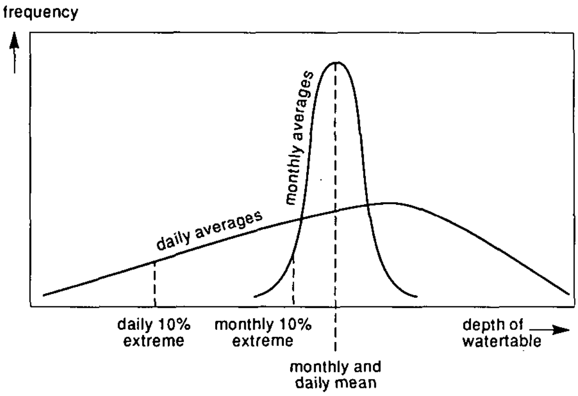


Figure 17.6 Frequency distributions of daily average and monthly average depths of the watertable

Figure 17.6 shows the same distribution together with the frequency distribution of the monthly averages. As can be seen, the mean values of the daily and monthly averages coincide, but the standard deviation of the monthly averages is much smaller than that of the daily averages, and the monthly extremes are much closer to the mean. Hence, the longer the duration that is taken, the better the mean value represents the frequency distribution. It depends on the crop-response function whether the mean value over a long duration can be used as a watertable index, or whether short-term extreme values, even though they occur infrequently, need to be considered.

Figure 17.7 shows the production of sugarcane as a function of the average depth of the watertable during the growing season from December to June (indicated by circles), and the number of days during which the watertable is shallower than 0.5 m below the soil surface in the same period (indicated by dots). The function shows that both indices give the same result, because the long-term average depth and the number of extremely shallow depths are apparently strongly correlated. This is logical because, when the average depth is great, a shallow depth is relatively infrequent, and vice versa. Therefore, if one employs either of these indices, the other will not provide any additional explanation of variations in yield. In this example, it is better to use the seasonal average depth as an index because it can be determined with a higher statistical certainty and it leads to a simpler design procedure than when the number of exceedances of a reference level needs to be taken into account.

If the yield data of Figure 17.7 represent random samples from an area, the figure also shows that a large part of the area has serious drainage problems and that, if a drainage project could ensure a seasonal average watertable depth of 0.75 m, or somewhat deeper, a large production increase could result. This increase can be calculated from the data by a segmented linear regression analysis (Chapter 6; Oosterbaan et al. 1990).

In literature, the following watertable indices have been used:

1) The depth of the watertable at harvest date (Oosterbaan 1982);
2) The average depth of the watertable during a season with rainfall excess (Figures 17.7 and 17.8);
3) The average depth of the watertable during the irrigation season (Figure 17.9; Nijland et al. 1984; Safwat Abdel-Dayem and Ritzema 1990);

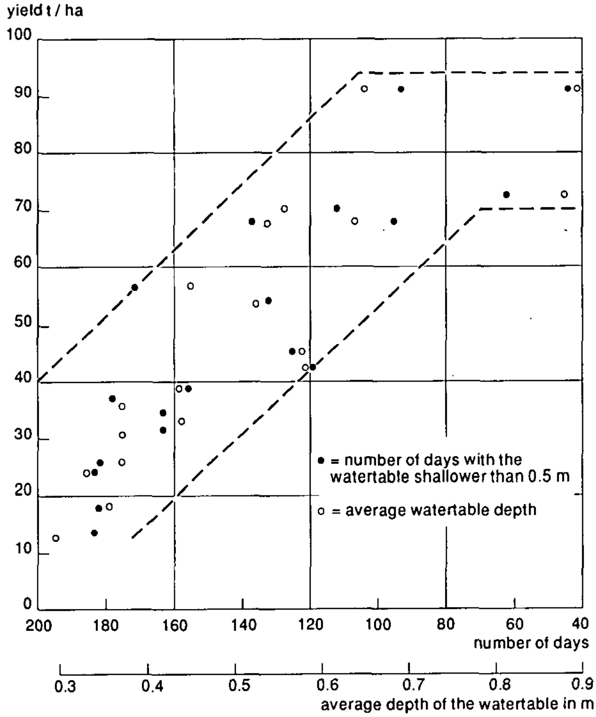


Figure 17.7 A plot of yield data of sugar cane versus average depth of the watertable and number of days with a watertable shallower than 0.5 m during the growing season from December to June in N. Queensland, Australia (Rudd and Chardon 1977)

4) The frequency or number of days during the growing season with a watertable shallower than a certain reference level (Figure 17.7; Doty et al. 1975);
5) The Sum of the Exceedances (SE_x) of daily watertables over a fixed reference level at x cm below the soil surface (Figure 17.10; Sieben 1965; Feddes and Van Wijk 1977);
6) The time it takes for the watertable to fall from a certain critically high level to a safe lower level (Figure 17.11).

The first index is easily determined. Although it is a once-only reading, it can sometimes be representative of the watertable regime. Nevertheless, literature does not provide much information on the value of this index and it will therefore not be further discussed.

The second index is useful in areas with a pronounced humid period. The example given in Figure 17.8 concerns an area in England. It illustrates the effect of off-season drainage, because in England the growing period is in summer whereas the data on the watertable depth were collected in winter. It appears that the depth in winter exerts a marked influence on the yield in summer, probably because a well-drained soil warms up faster in spring than a waterlogged soil, so that crop growth can start earlier. Also, waterlogging in spring may create unfavourable chemical or physical soil conditions. In summer, there is usually no drainage problem in England because the evapotranspiration is then much higher than in winter, and the watertables are therefore deep (> 1 m).

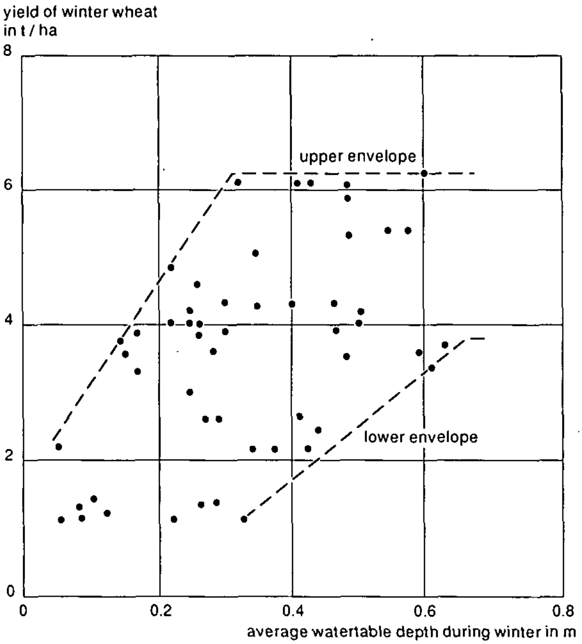


Figure 17.8 A plot of the yield of winter wheat versus average depth of the watertable in winter in a heavy clay soil; 5 years of observation (unpublished data, FDEU, Min. Agr., U.K.)

From the data of Figure 17.8, we can conclude that, if drainage could maintain the watertable in winter at an average depth of 0.50 m or more, a considerable yield benefit would result. This depth would be a good agricultural drainage criterion for the area in which the data were collected. The trend in the figure suggests that maintaining an average watertable deeper than 0.60 m would be excessive: the costs would be higher and there would be no additional crop response.

The data of Figure 17.8 also reveal that, under good agricultural conditions (represented by the upper envelope), the permissible average depth of the watertable (about 0.30 m) is shallower than the permissible depth (about 0.60 m) under poor agricultural conditions (represented by the lower envelope). It appears that, in this example, favourable agricultural conditions compensate for unfavourable watertable depths. Further, the data show that the relationship between crop production and depth of the watertable is subject to considerable scatter, which is logical because crop production is not determined exclusively by the depth of the watertable but by many other agricultural conditions. The data of Figure 17.8, which were collected in farmers' fields, are more representative of reality than data obtained under controlled conditions where only the drainage situation is varied and all other production factors are kept constant.

The third index, used in the example of Figure 17.9, shows that the critical value of the average seasonal depth of the watertable in irrigated cotton fields in the Nile Delta is about 0.90 m. This would be a good field drainage criterion. The figure shows that a small majority of the data (about 60%) are found in the range of watertable depths of over 0.90 m (the safe depth). This indicates that the yield increase of a

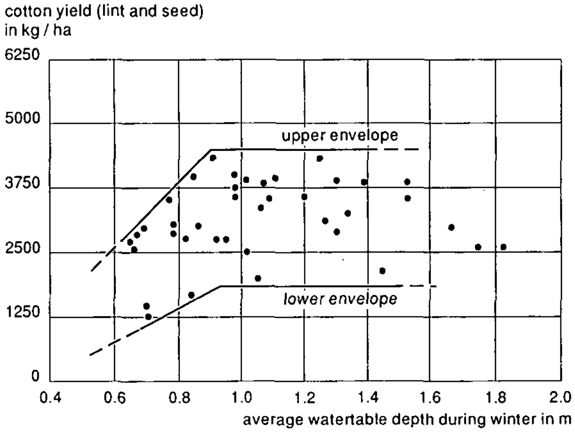


Figure 17.9 A plot of cotton yield (lint + seed) versus average depth of the watertable in the Nile Delta, Egypt (Nijland and El Guindy 1984)

drainage project would be less than in the example of Figure 17.8, where the vast majority of the data (about 90%) are below the safe depth. Unlike Figure 17.8, Figure 17.9 makes no distinction between the breakpoints of upper and lower envelope. For the rest, many of the conclusions drawn from Figure 17.8 are also applicable to Figure 17.9.

Together with the second index, the fourth index is shown in the example of Figure 17.7 and needs no further discussion.

The fifth index (the SE_x value; Figure 17.10) was developed by Sieben (1965). Figure 17.10, referring to the same cotton experiments as in Figure 17.9, reveals that the yield does not respond much to the SE_x index. Therefore, in the example given, the SE_x index has less value for the development of a drainage criterion than the second index used in Figure 17.9. It appears that short-term exceedances of the watertable over a shallow reference level are not harmful for irrigated cotton. This may be explained by the fact that irrigation supplies are usually much more regular in magnitude and time than rainfall is. In addition, the regular irrigation may be

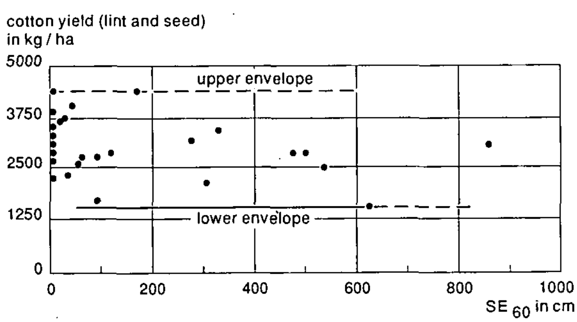


Figure 17.10 A plot of cotton yield (lint + seed) versus SE_{60} in farmers' fields in the Nile Delta (Advisory Panel 1982)

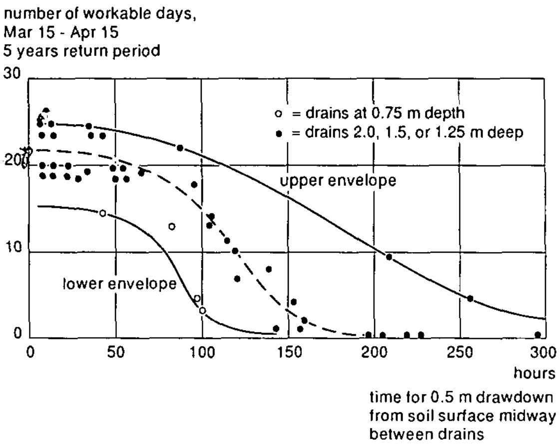


Figure 17.11 A plot of drawdown time of the watertable versus number of workable days for different drainage systems in North Carolina, U.S.A. (Skaggs 1980)

instrumental in expelling the noxious gasses formed in the soil by the plant roots, whereas the subsequent evaporation enhances the entry of fresh air into the soil. Only long-term shallow depths of the watertable appear to be damaging.

In literature, not many examples can be found of the sixth index for crop production. Therefore, instead of crop yield, the workability of land was chosen as an object factor as shown in Figure 17.11. This figure, like the previous ones, shows a large scatter of data. Yet it permits the conclusion that the longest permissible time of drawdown from the soil surface to a depth of 50 cm is about 75 hours or about 3 days. With a shorter drawdown time (i.e. with a faster drawdown rate), the number of workable days does not increase, and its maximum value is about 20 days a month.

The drawdown rate of the watertable as a criterion index should be used with great care, because it does not specify how frequently the watertable rises to critically high levels. If not used with care, one runs the risk of developing drainage criteria for situations that seldom occur.

17.3.4 Steady-State Versus Unsteady-State Drainage Equations

In the design procedure, given the proper criteria and the correct environmental parameters, one can use steady-state and unsteady-state equations (Chapter 8) to determine the required characteristics of the drainage system (e.g. the depth and spacing of the drains). Both types of equations use the recharge to the drainage system, which can be found from the groundwater balance (Chapter 16). After introducing a drainage term q_d, we can rewrite Equation 16.5 as

$$q_d = R_d - \mu \frac{\Delta h}{\Delta t} \quad (17.1)$$

q_d = drain discharge (mm/d)
R_d = net recharge rate (mm/d)

μ = drainable pore space (–)
Δh = change in watertable depth (m)
Δt = period (d)

In a steady-state situation, the net recharge rate (R_d) equals the drain discharge (q_d) and the watertable is at the same level at the beginning and the end of the period (Δt) under consideration.

In unsteady-state, recharge and discharge are not equal. When $R_d > q_d$, the watertable is rising, and the discharge q_d increases and tends to become equal again to the recharge R_d. When $R_d < q_d$, a reverse process occurs. Hence, under natural conditions with a varying recharge over time, the watertable fluctuates about a certain equilibrium level: its average depth (Figure 17.4). The storage $\mu\Delta h$ is therefore a temporary, dynamic storage, which is needed to induce the drain discharge q_d. It is discerned from the storage of water which will not reach the drains and which can be called 'dead storage'.

Over a long time span (e.g. a season), the change in water level Δh is small compared with the recharge and the discharge, so that Equation 17.1 can be simplified to $q_d = R_d$ (i.e. the steady state). The expression 'steady state' does not deny that the watertable fluctuates during the period under consideration, and it would therefore also be possible to speak of an 'average state' or a 'dynamic equilibrium'.

If a better explanation of the yield variation is provided when the criterion index is taken as the average depth of the watertable over a prolonged period of time (e.g. a season), rather than the index representing short-term (e.g. daily) extreme values, it follows that the drainage design is preferably made with steady-state drainage equations.

The long-term, steady-state index of the watertable can also give a significant explanation of such object factors as the workability of the land and the subsidence of peat soil (Section 17.4.3). The design of drainage systems that have to take workability and subsidence into account can therefore also be done with steady-state equations.

When steady-state equations are used, the design drain discharge is taken equal to the average net recharge over the period of time used for the criterion index.

The steady-state drainage equations are easier to apply than the unsteady-state equations (e.g. the drainable porosity, μ, need not be known). In addition, the long-term averages can be determined with a higher statistical reliability than short-term extremes.

When the relationship between the level of the watertable and the object factor indicates that short-term extreme levels are more decisive than the long-term averages, the choice between steady-state and unsteady-state equations is determined by the ratio of the storage capacity of the envisaged drainage system to the volume of the infrequent, extreme, recharge and discharge over the defined short period (Oosterbaan 1988). This volume is usually so high in comparison with the storage capacity that storage effects can be neglected. Consequently, steady-state equations can also be used for drainage systems that have to cope with infrequent, extreme discharges of short duration. For example, collector and main drains are often required to cope with 24-hour design discharges having return periods of 10 years or more. Such discharges are so high that the volume of water transported through the drain in one day is very large compared with the volume of water stored in the drain. Hence, the Manning equation can be used to determine the system's dimensions and discharge capacity (Chapters 19, 20, and 21).

17.3.5 Critical Duration, Storage Capacity, and Design Discharge

The maximum permissible length of the period (the critical duration) to be used for the watertable index, and the degree to which this index explains the yield, are influenced by the storage capacity of the drainage system. The critical duration and storage capacity determine the design discharge, as will be explained below.

Reducing the surface or subsurface waterlogging by drainage creates a potential for both dynamic and dead storage of water during periods of peak recharge. Thus the drainage system creates a buffer capacity in the soil, ensuring that the discharge is steadier and smaller than the recharge. A large buffer capacity permits the adoption of a longer period of critical duration and the use of average recharge and discharge rates over this period. In contrast, a small buffer capacity needs an assessment of the infrequent, extreme, recharge and discharge rates and the adoption of shorter periods of critical duration.

Tubewell drainage systems, which can lower the watertable to a great depth (5 to 10 m), create a large buffer capacity. For these systems, the seasonal or yearly average depth of the watertable can be used as a criterion factor. In the water balance over the corresponding long period of time, the change in storage can be ignored. Consequently, one can calculate the design discharge from the average net recharge over a full season or year, and apply steady-state well-spacing formulas (Chapter 22).

Field drainage systems by pipes or ditches create a medium storage capacity. In regions with low rainfall intensities (say less than 100 mm/month) and in irrigated lands in arid or semi-arid regions, one can base the drainage design on average monthly or seasonal water levels, taking into account the month or season with the highest net recharge. As the change in storage over such periods is still small, the design discharge can be calculated from the average net recharge over the corresponding critical period.

In regions having seasons with high rainfall (say more than 100 mm per month), it is likely that the problem is one of surface drainage (i.e. waterlogging on the soil surface) rather than of subsurface drainage. Here, a subsurface system would not be appropriate, or it could be combined with a surface system. In a combined system, the design discharge of the subsurface system has to be calculated from a water balance after the discharge from the surface system has been deducted.

A surface field drainage system, consisting of beddings in flat lands or mildly graded field slopes in undulating lands, creates only small capacities for storage. Critical periods are therefore short (say 2 to 5 days). The design discharge must then be based on the recharge over the same short period, taking into account a recharge rate that is exceeded once or only a few times a year, or even once in 5 to 10 years. Surface systems that are able to cope with such rare recharges will also considerably reduce crop damage from any waterlogging that results from even more intensive, though more exceptional, recharges. The use of the water-level index as a criterion factor for surface field drainage systems is not common. This is because, unlike a subsurface field drainage system, the design of a surface field drainage system cannot easily be derived from such an index.

The design criteria for collector drainage systems depend on the type of field drainage system. When a collector drain serves subsurface systems only, its water level must be deep enough to permit the free outflow of water from the field drains. As the storage capacity of the collectors is relatively small, their design discharge is not based on the average monthly or seasonal discharge of the field drains, but on a higher, though less frequent, peak discharge as may occur during a shorter period (e.g. 10 days). Subsequently, the cross-section of the collectors can be calculated with Manning's steady-state formula.

When ditches are used as collectors for subsurface drainage systems, they are preferably narrow and deep to maintain a deep water level. For a collector that serves surface field drainage systems only, its water level can be much shallower and may come close to the soil surface. However, as the design of surface systems is based on the less frequent peak discharge of a shorter critical duration, and as the collector system has even less storage capacity than the field system, its design discharge is taken higher than that of the field drains. Manning's formula can also be used to calculate the cross-sections of collector drains for surface field drainage. In contrast to the narrow cross-sections of collectors for subsurface field drainage, those for surface field drainage are preferably wide and shallow.

When a collector drain serves both surface and subsurface field drainage systems, one often uses a combination of criterion values for the water level in the collector: there is a high water-level criterion (HW criterion) and a normal water-level criterion (NW criterion). Each of these levels is specified with a certain tolerable frequency of exceedance. The corresponding discharge requirement (design discharge) can then be calculated from a water balance. How the capacity and dimensions of the collector system are calculated will be illustrated in Section 17.5.1.

An example of the influence of the length of the critical duration on the average design discharge is presented in Table 17.1. It shows that the design discharge for drainage by pumped wells, with a critical duration of 6 to 12 months, can be taken as 1.1 to 1.6 mm/d, whereas drainage by pipes or ditches, with a critical period of 1 month to a growing season, requires a design discharge of 2.6 to 2.8 mm/d.

17.3.6 Irrigation, Soil Salinity, and Subsurface Drainage

Subsurface drainage systems are often used in irrigated, waterlogged, agricultural lands in arid and semi-arid regions to reduce or prevent soil salinity. The salt balance of these lands depends largely on the water balance, in which the amount of irrigation water is a dominant term (Chapter 15). When sufficient irrigation water is applied, the effect of drainage on the salt balance stems from the discharge of salts along with the drainage water. Hence, drainage for salinity control is primarily based on the discharge effect rather than on a lowering of the watertable. Criteria for salinity control should therefore be sought in the amount of irrigation water needed to provide sufficient leaching, rather than in the depth of the watertable.

With a well-designed and properly-operated irrigation system, the watertable need not be kept at extra deep levels to control soil salinity. If, on the other hand, the

Table 17.1 Average drainage rate (mm/d) as a function of length of the critical period in an irrigated area of Iraq (Euroconsult 1976)

Crop	Peak month	Growing season	Peak half year	Whole year
Wheat	2.0	1.6	-	-
Maize	3.0	2.3	-	-
Potatoes	4.5	2.6	-	-
Combination*	2.8	-	1.6	1.1

* A cropping pattern of 2/3 winter wheat, 1/3 spring potatoes and 1/3 summer maize

irrigation system is poorly designed and operated, even maintaining very deep watertables will not alleviate soil salinity. For example, Safwat Abdel-Dayem and Ritzema (1990) and Oosterbaan and Abu Senna (1990) have shown that, for Egypt's Nile Delta, average seasonal depths of the watertable in the range of 1.0 to 1.2 m are amply sufficient for effective salinity control, whereas maintaining deeper watertables may even negatively affect the irrigation efficiency. Also Rao et al. (1990) have shown that the time-averaged depth of the watertable during the critical drainage season (i.e. the monsoon season) need not be much more than 0.8 m below the soil surface to allow the adequate reclamation of saline soils.

Often, one relates the required depth of the watertable for salinity control to the upward capillary flow in the soil resulting from a constant depth of the watertable and a very dry topsoil. Such conditions imply that, in the absence of irrigation or rain, there is a steady upward seepage of groundwater from the aquifer. When such lands are irrigated and drained, these capillary-flow conditions no longer exist. Instead, there is a net downward percolation of water through the soil. Van Hoorn (1979) therefore writes: 'The argument for applying deep drainage systems to reduce capillary flow is often used in cases for which it is not valid.'

In semi-arid regions with pronounced wet and dry seasons, it is possible to restrict the drainage to the wet season only. The evacuation of salts during this period is sufficient to maintain a favourable salt balance in the soil, even though some resalinization may take place during the dry season. In addition, the use of salty drainage water with an electrical conductivity up to 10 dS/m for irrigation in the dry season does not negatively affect yields as long as sufficient leaching occurs in the wet season to prevent any annual salt accumulation (Sharma et al. 1990).

Using drainage water for irrigation in the dry season and evacuating it only in the wet season has two advantages:

- In the dry season, when the evacuation of salty drainage water into rivers with a low discharge is environmentally undesired, and when irrigation water is scarce, the drainage water can be used for additional irrigation and environmental problems are avoided;
- In the wet season, when the evacuation of salty drainage water into rivers with a high discharge is environmentally acceptable, and when irrigation is only complementary to rainfall, the drainage water can be evacuated for salinity control.

Rao et al. (1992) describe a successful experiment in which the drainage is completely stopped during the dry season so that the crops can profit from the capillary rise, and scarce irrigation water is saved.

Comparing the discharge from a drainage system in irrigated lands with that from rain-fed lands, we find that the discharge from irrigated lands is more regular. The reason is that the rainfall regime is usually erratic and the irrigation regime is not. This explains why, in irrigated lands, the steady-state drainage criteria are often successfully applied. The main reason for this is that the recharge from irrigation water is irregularly distributed in space, because the fields are not all irrigated at the same time. Thus, the resulting groundwater flow is three-dimensional because the flow occurs both in the direction of the drains and in the direction of neighbouring fields that have not recently been irrigated and therefore have a lower watertable than the irrigated field. This means that two-dimensional unsteady-state drainage formulas cannot be used. In the long run, the flow of groundwater from one field to the other can be ignored because, on other occasions, when the second field is irrigated and the first field is not, the direction of the groundwater flow is reversed. Hence, the two-dimensional steady-state drainage formulas indeed remain applicable, at least when the watertable index shows that long-term averages can be used, as was discussed in Section 17.3.3.

The design discharge of subsurface drainage systems in irrigated land is often determined on the basis of the field irrigation efficiency (Chapter 14) and the leaching requirement for salinity control (Chapter 15). Usually, the irrigation efficiency is quite low owing to high percolation losses, and the leaching requirement is therefore amply satisfied. When, in addition, rainfall also contributes to the leaching, the leaching requirement need not feature as a design factor. If, on the other hand, the irrigation is insufficient to produce the required leaching, a drainage system based on the leaching requirement will be ineffective for salinity control.

The leaching requirement for salinity control is based on a 'leaching efficiency', but, in irrigated arid lands with very little rainfall, the irregularity with which the irrigation water is distributed over the field also has to be taken into account. Here, we should distinguish between 'systematic irregularity' and 'random irregularity'.

Systematic irregularity stems from the irrigation technique. With surface-flow irrigation in basins, furrows, or border strips, the irrigation water is normally introduced at one end of the field. While running down the field, the water infiltrates into the soil. As the contact time between water and soil is longer in the upstream part of the field than in its downstream part, more water infiltrates at the upper end

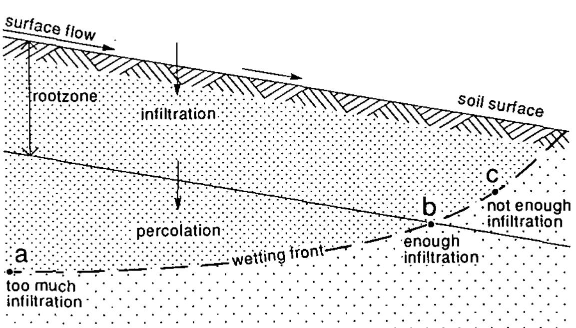


Figure 17.12 Illustration of the systematic irregularity in the spatial distribution of the deep percolation in an irrigated field

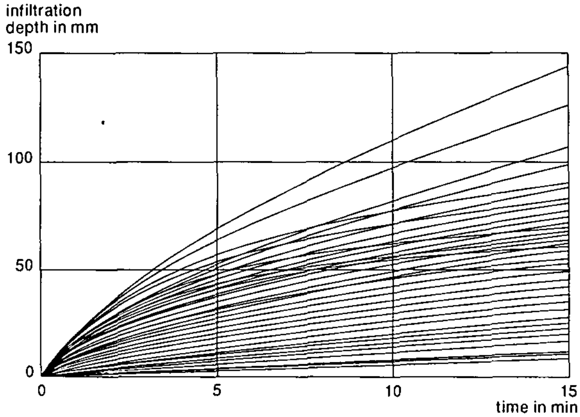
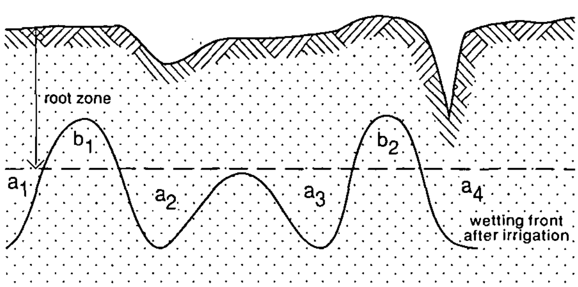


Figure 17.13 Accumulated infiltration versus time measured with 63 infiltrometers set at 1.0 m spacing on a 7 by 9 m grid in a sandy loam soil (Jaynes et al. 1988)

than at the lower end (Figure 17.12). Hence, the leaching requirement is sometimes not covered in the lower parts, where insufficient deep percolation takes place and where salinization may occur even though there is a low field irrigation efficiency.

The random irregularity stems from natural random differences in infiltration capacity (Figure 17.13) and in the water-holding capacity of the soil, as well as from irregularities in the surface level of the soil. This is illustrated in Figure 17.14. In places where the soil surface has a relatively high elevation, even if the difference is only a few centimetres, or in places with a low infiltration and/or water-holding capacity, the leaching requirement may not be met. This phenomenon often gives rise to a patchy development of soil salinity.

The problems of insufficient leaching are more pronounced as the irrigation water is scarcer. Although, with water scarcity, a high field irrigation efficiency may be achieved, there may be insufficient water for full evapotranspiration by the crop and for leaching.



a_1 excess due to high infiltration capacity
b_1 shortage due to low infiltration capacity
a_2 excess due to depression in soil surface
a_3 excess due to low moisture holding capacity
b_2 shortage due to elevation of soil surface
a_4 excess due to cracking

Figure 17.14 Illustration of the random irregularity in the spatial distribution of the deep percolation in an irrigated field

It follows from the above considerations that, if the irrigation system is inadequate, a drainage system cannot guarantee proper salinity control. In other words, with a scarcity of irrigation water, poor land levelling, and/or randomly irregular soils, salinity problems are difficult to cure, even with an intensive drainage system.

17.3.7 Summary: Formulation of Agricultural Drainage Criteria

The previous discussion of field drainage criteria can be summarized as follows.

If one expresses the agricultural drainage criterion as the permissible minimum value of the average depth of the watertable during a prolonged period, one has formulated a long-term, steady-state criterion. An example of a long-term, steady-state criterion for a subsurface drainage system in irrigated agricultural land is: 'The average depth of the watertable during the irrigation season should be at least 0.8 m, but need not be more than 1.0 m'. An example for humid areas is: 'The average depth of the watertable during the critical humid season should be at least 0.6 m, but need not be more than 0.8 m'. The critical humid season may be either the winter period, as in the temperate zones of Europe where the excess rainfall occurs mainly in winter (off-season drainage), or the summer/cropping season, as in those tropical or subtropical regions where the excess rainfall occurs during the summer or during an important cropping period (in-season drainage). The corresponding discharge rate of the drainage system must be calculated from a water balance as an average rate during the corresponding period, whereby the storage term may be ignored.

When one expresses the agricultural drainage criterion in terms of a critically high level above which the watertable may rise only infrequently and for short periods, one has formulated a short-term, unsteady-state criterion. An example of such a short-term criterion for a subsurface drainage system is: 'The watertable may be higher than 0.3 m below the soil surface only for one day a year'. The corresponding discharge rate of the drainage system then has to be calculated from a short-term water balance with an infrequent, extreme, recharge whereby the dynamic storage term must be taken into account. This complicates the calculations considerably. In irrigated lands, the presence of three-dimensional flow of groundwater complicates the assessment of the storage even more.

The decision as to which type of criterion to apply should be based on the considerations discussed in the previous sections.

There are certain types of criteria that use conditional statements, for example:

- When the watertable reaches a specified height (h) above the drain level, the drains should be able to function at a specified rate of discharge (q). The ratio h/q or q/h is then often employed as a drainage criterion;
- When, after a sudden recharge, the watertable has reached a specified critical height (h_o) above drain level, the drainage system should be able to effect a specified drawdown of the watertable to a height (h_t) in a specified period of time (t) after the recharge has ceased. The ratio h_t/h_o is then often employed as a criterion.

These criteria can only be used where extensive local experience is available. One has to know how frequently the specified events occur and to which drain depth they